Selected Papers on Infrared Physics and Techniques

Applications of Remote Sensing

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PROSPECTING BY SATELLITE

E S Owen-Jones

A review of the techniques used in *exploring* the earth's resources from orbiting spacecraft

In the twenty years which have elapsed since the first 'Sputnik' was launched a total of over two thousand unmanned spacecraft have orbited the earth and it is somewhat surprising to realise that, after excluding military, weather, communications and purely scientific satellites, less than ten have contributed to the study and evaluation of earth resources. This small group includes Landsat-1 and -2, Skylab and some of the Nimbus series of satellites. Additionally, conventional photography has been acquired from the manned Mercury, Gemini, Apollo and Skylab missions. The considerable amount of attention which has been paid to the physical principles of prospecting from spacecraft has not hitherto been translated into practical results. However this situation is likely to improve in the near future. Further developments in prospecting will take place in the next two years with the Landsat-3, Nimbus-G, Heat Capacity Mapping Mission (HCMM) and Spacelab projects.

The word 'prospecting' has, in the past, often been associated with the search for gold and diamonds. In relation to spacecraft, or even aircraft prospecting, gold and diamonds obviously cannot be detected directly, but formations or structures favourable to their occurrence can be recognised. Prospecting, in fact, covers an enormous range of substances from metallic oxides and sulphides, limestone and phosphate rocks to coal and oil. These substances collectively are, of course, industrially and economically orders of magnitude more important than gold and diamonds.

The information and data acquired by spacecraft sensors are essentially physical and, while some of the information can be qualitatively or even superficially interpreted, a full interpretation requires a knowledge of the underlying physics. Consequently

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there is a tendency towards the establishment of multidisciplinary teams containing physicists, geologists and others. The fundamental processing of the data is undertaken by the physicist who then conveys the reduced data, or selected features from it, to the other disciplines for subsequent comparison with information derived from field work and ground exploration.

The conventional sequence of events in a mineral exploration programme is for the initial regional geological mapping to be followed by detailed field mapping. Ground geophysical exploration may then be undertaken, followed finally by drilling operations. As the stages become successively more expensive there is a strong incentive to define the most promising areas as early as possible in the sequence. This is the aspect where the use of remote-sensing techniques from spacecraft offers the greatest potential.

The transition from ground to aircraft prospecting is not a radical one since many ground techniques can be performed equally well, if not better, from aircraft. Since a spacecraft must have a perigee of at least 250 km in order to have an acceptable lifetime, the extrapolation of low-level techniques to spacecraft altitudes requires a very different approach. The traditional low-level techniques include measurements of gravitational and geomagnetic fields, VLF radio-wave phase and amplitude, seismic wave propagation, HF induced polarisation and x-ray detection. These are not generally applicable at spacecraft altitudes. Instead, recourse must be made entirely to the electromagnetic spectrum and in particular to wavelengths for which adequate resolution can be obtained at the required altitudes. Within this overall mechanism the radiation received at the satellite can be subdivided into *passive* (that is, emitted by the target) or *active* (that is, reflected by the target). In this latter case the source may be the sun or a satellite-borne transmitter.

Although the electromagnetic spectrum is infinitely wide there are practical limitations on the regions which may be used. The x-ray region and most of the ultraviolet region are rendered unusable by atmospheric attenuation, as is the infrared region between 16 μm and 1000 μm. At the far end of the spectrum, in the band from approximately 1–10 m, the limitation on spatial resolution is unacceptable while, at lower frequencies, the radiation is totally reflected by the ionosphere. The usable parts of the spectrum which remain are the ultraviolet from 0·35 μm to 0·4 μm, the visible region from 0·4 μm to 0·7 μm, infrared bands from 0·7 μm to 2·5 μm, 3–5 μm and 8–14 μm, and the microwave region from 1 mm (1000 μm) to about 1 m. The radiation in each of these regions, whether reflected or emitted, provides characteristic information about the target. There will also, of course, be different mechanisms for the loss of signal in traversing the atmosphere and for the addition of extraneous signals, including noise from external sources. The principal features and importance of each of these regions will now be considered in relation to the type of information which they yield.

The ultraviolet region

Because of the narrow ultraviolet waveband region (0·35–0·4 μm) transmitted by the atmosphere, and the significant attenuation of even this band, only very limited use of this radiation has been made or proposed. The principal and most promising technique uses the phenomenon of fluorescence, with solar radiation as the source of excitation.

The technique developed so far involves the selection of an appropriate Fraunhofer absorption line and measurement of the ratio of the intensity at the centre of that line to that at a point approximately 0·5 nm away from the line for the incoming solar radiation. This ratio is then compared with the corresponding ratio for the solar radiation which has been reflected from the object under investigation. If the object ratio is greater than the incident ratio then the object is fluorescing. The system is pointed alternately to the sky and to the ground in order to monitor this ratio continuously. Precise wavelengths are achieved by the use of Fabry–Pérot filters. This technique can clearly be used only during daylight but, given appropriate laboratory measurements, it offers the promise of a means of detecting those minerals that exhibit fluorescence.

A further development which has been performed from an aircraft is the stimulation of fluorescence by illumination of the target with a laser beam of predetermined wavelength. Current laser technology makes it feasible to incorporate such a system in a spacecraft and also allows specifically suitable wavelengths to be chosen. The fluorescence method generally is not, of course, limited to the ultraviolet region but can also be extended to the visible region.

Although not a direct mineral technique, it might be noted that ultraviolet fluorescence has already been used for the detection from aircraft of oil slicks at sea. Diesel oil, for example, exhibits fluorescence at 0·38 μm while crude oil fluoresces at 0·52 μm. Clearly, sunlight and favourable meteorological conditions are required for this method and the opportunities for using it are very restricted in temperate climates.

The visible and near-infrared regions

The human eye can directly interpret images generated in the visible or near-infrared (0·7–1·0 μm) parts of the spectrum. These images may be conventional colour photographs, false-colour infrared photographs, false-colour infrared composites generated from Landsat images, or single spectral-band images from these satellites. In the initial stages of mineral detection from space the photogeologist may apply two qualitative approaches to the interpretation of such imagery. One involves the detection of linear features and the other the division of the image into different soil and rock units. The information from each approach may be used independently or on a complementary basis.

Linear features may be classified as fractures and faults, which tend to be short, or as lineaments which are longer. The presence of these linear features may be related to differential movement of the adjoining sides and has particular geological significance in relation to the presence of mineral deposits. Traditionally, linear features are detected visually and their directions used as a guide to indicate areas which are potentially favourable to mineralisation. This visual assessment is a subjective one and comparative tests with individual geologists independently assessing linear features on a given image have shown that, although agreement was reached on regional trends, there were widely differing interpretations for individual lineaments. A promising technique which will produce an objective answer to this problem is that of obtaining the optical Fourier transform of the appropriate part of the image, when the orientation of the linear features will be given by the position of the spots in the diffraction pattern.

The division of an area into soil and rock units is an important one and can be done irrespective of whether or not the identities of the units are known. This also is normally done visually and therefore is essentially subjective. If the image is a monochromatic one (that is, with all the information from the spectral range to which the emulsion is sensitive combined into a single grey scale) then machine techniques will be of little value. If, however, the image is produced by a colour film which incorporates three channels of information, or by a multispectral scanner which may have ten or more channels, then computer-based machine techniques offer great promise in the classification of an image into soil, rock and vegetation units.

The original concept behind this automatic classification of an image was essentially that every object, whether natural or man-made, could be specified by its spectral signature. This is a numerical representation of the reflection coefficient of the surface of the object as a function of wavelength over the range of interest. For a particular image the spectral signature for each type of material of interest would be analysed by a computer and, by the use of decision theory, every picture element in the image would be allocated to one of the specified materials, thereby classifying the image. Considerable effort was put into compiling 'dictionaries' of spectral signatures applicable on a global scale. These compilations proved to have disadvantages, and spectral signatures are now normally obtained from small representative areas known as training sets within or close to the area under investigation. Very high accuracies of classification have been obtained from satellite-acquired images but almost entirely in agricultural applications where relatively large homogeneous targets exist.

The classification of an image for geological and mineral purposes is more difficult, primarily because large homogeneous areas occur infrequently in areas of potential mineralisation. For mineral prospecting there are two particular reasons why machine classification of an image can be advantageous.

Firstly, in areas where man's cultural activities have had little impact on the surface cover, the natural vegetation distribution can often indicate the presence of metals in the surface or immediate sub-surface material. For instance, only a very few and well recognised species will tolerate a high lead content in the soil while, in Australia, every miner knows that the occurrence of the 'copper weed' invariably indicates the presence of copper in the soil. The presence of many other metals is indicated by the growth of their own particular 'indicator' plants. Thus, if the spectral signature of a particular indicator plant is provided, the image can be scanned and a map printed displaying only those picture elements that contain vegetation classified as being of the indicator species.

Figure 1a shows a monochrome reproduction of an aerial colour image of a region in Queensland. By selecting a very small training area for each of the seven required classes of soil or vegetation, an automatically classified image can be generated as shown in figure 1b, where each shading represents one of the classes. The narrow, pale grey, almost horizontal band crossing the centre of the image in

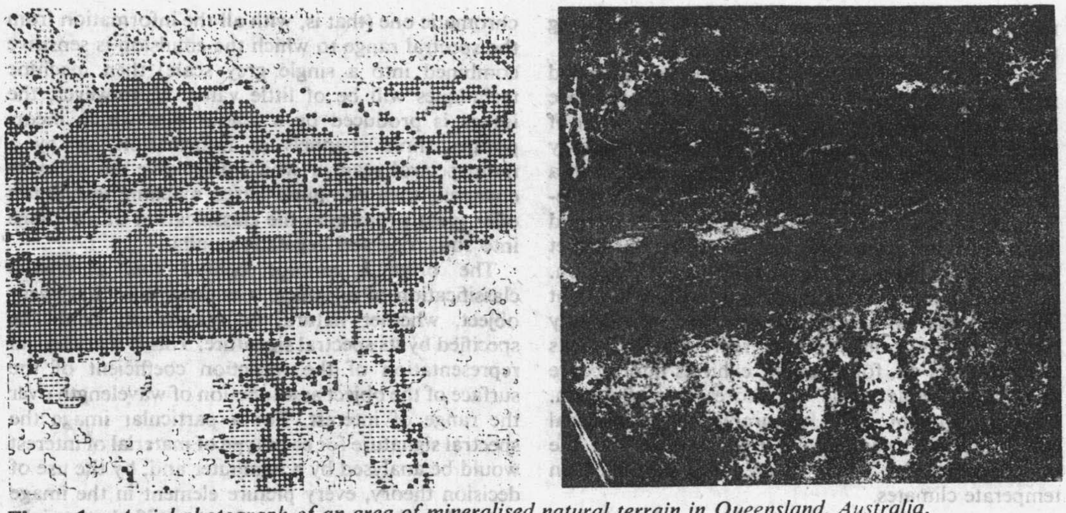


Figure 1a: *Aerial photograph of an area of mineralised natural terrain in Queensland, Australia.*
b: *Computer classification into seven rock and soil types of the same area*

fact corresponds to a zone of copper mineralisation and is seen to be accurately mapped by the computer.

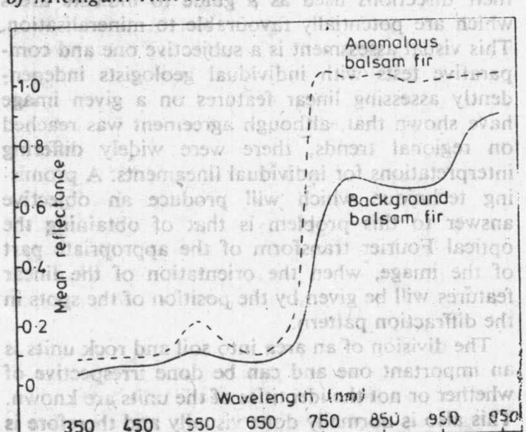
Secondly, when a metal is present in sufficient concentration in the soil to modify the physiological processes in the vegetation, the reflection coefficient may be differentially altered as a function of wavelength as compared with the information from unstressed vegetation. Figure 2 shows an example of this effect. For different vegetation–metal combinations the reflection coefficient may be increased or decreased. Again, therefore, a map can be generated showing two classes or areas of vegetation, one having normal and the other anomalous reflection coefficients. Whether this latter technique is feasible from spacecraft altitudes is not yet proven since not only are the areas of known stressed vegetation near the limits of current optical resolution but the uptake of metal into the vegetation depends very much on local conditions, such as the pH value and the moisture content of the soil.

Another computer-based technique involves generating an image which portrays the variation of the ratio of the intensities in two spectral bands over the area of interest. In a more sophisticated version this technique appears to be capable of delineating rocks with a high clay mineral content through the presence of the hydroxyl and ferric ions.

The thermal infrared band

For a mean terrestrial temperature of 300 K (27 °C) the wavelength of maximum emitted radiation intensity occurs at 10 μm compared with a peak at 0·5 μm for the incoming solar radiation. The transmission characteristics of the earth's atmosphere provide only two relatively narrow windows in the entire thermal infrared band and it is thus perhaps fortunate that, from the standpoint of spacecraft observations of the earth's surface, these windows are situated near 10 μm. One extends from 8–12 μm and so includes this wavelength while the other extends approximately from 3–5 μm. Any sensor looking down at the earth's surface will receive not only emitted thermal radiation but also any reflected solar radiation derived from the incoming solar radiation after modification by the earth's atmosphere and by the reflection characteristics of the target. The reflected solar radiation intensity is approximately equal to the emitted radiation intensity at 3 μm, with a tolerance of about 0·5 μm

Figure 2 *Reflectance spectra of Balsam Fir. The vegetation of the anomalous Balsam Fir contains high concentrations of copper and molyblenum. (From Yost and Wendouth 1971, Proc. 7th Int. Symp. Remote Sensing of Environment (University of Michigan: Ann Arbor))*



depending on a number of variables. Below 3 μm, reflected solar radiation will dominate, while above this wavelength emitted thermal radiation will dominate. A sensor which is sensitive to the 8–12 μm band will thus record effectively only thermal radiation, whereas one sensitive to the 3–5 μm band may well contain a significant amount of reflected radiation, depending particularly on the sun angle and the target reflection coefficient and emissivity. Interpretation of data from sensors in this latter band has proved very difficult, only night-time data being unambiguous, whereas data from the 8–12 μm band are unambiguous at all times and are thus experimentally preferable.

The dependence upon wavelength and temperature of the intensity of the radiation emitted from an object is, of course, governed by Planck's law. It is found empirically that, for a particular narrow wavelength band, the total radiation intensity in that band has a temperature dependence varying between T^4 and T^8. The emissivity (ϵ) must also be incorporated for the radiation from a grey body. For the normal range of values of ϵ for terrestrial objects the high-power dependence upon T will predominate over the small variation in ϵ and so sensor measurements of the radiation intensity over the detector bandwidth may be interpreted directly in terms of the temperature of the target.

The emitted radiation levels are measured by a scanner in which the optical system is entirely reflective since transmission raises severe problems at these wavelengths. Solid-state detectors are invariably used and, in the 8–12 μm band, the only detector available until recently could be operated only at very low temperatures and this has largely precluded its use in spacecraft. This technical limitation has led to the predominant use of the 3–5 μm band in spacecraft.

Some aircraft-borne thermal scanners incorporate one or two 'standard' objects at known temperatures; these are scanned when the rotating mirror is pointing in a skyward direction. The radiation level from a target on the ground can thus be calibrated in actual temperature by comparison with the intensities from the reference levels. For a satellite-borne thermal scanner such calibration is essential if any quantitative analysis is to be made of the thermal properties of the area under investigation.

The incidence of solar radiation on the ground surface at sunrise represents the application of a thermal impulse. Correspondingly, the temperature response of the surface and immediate sub-surface material will be a function of the 'thermal inertia'; this is given by the square root of the product of conductivity, density and specific heat. The response will also be affected by the absorption coefficient and emissivity of the surface. There will thus be a diurnal temperature variation governed primarily by these physical properties. Figure 3 shows the theoretical diurnal temperature variation for various rocks having different physical characteristics and it is clear that there are optimum times of day at which to discriminate between them.

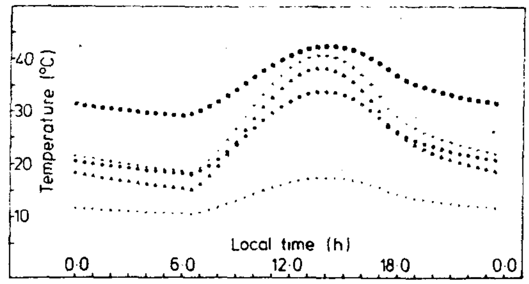


Figure 3 *Computed diurnal temperature variations for minerals having different thermal inertias. Key: ●–calcite, ▲–limestone, +–granite, ×–quartz rock, ■–hematite*

A thermal image of the terrain beneath the spacecraft (in the 8–12 μm band at any time or the 3–5 μm band at night) will reveal variations in the grey-tones which are indicative of surface temperature variations. A boundary separating two areas of significantly different grey-tones does not necessarily imply a change in the soil or rock type. Such a temperature change across a boundary may arise from a shadow cast by a nearby ridge, or may itself represent a ridge or valley with the solar radiation having markedly different angles of incidence on each side.

A single thermal image cannot in general, therefore, be used to map an area into regions of different thermal inertias which, in turn, would imply different rock types or minerals. The problem can be overcome if two thermal images of a given area are obtained within a 24-hour period, since it then becomes possible to calculate the thermal inertia. This technique will be employed with the HCMM satellite, which will provide just such a coverage with a resolution of 500 m and with a spectral band of 10·5–12·5 μm. (A visible channel operated in the daytime will allow the reflection coefficient to be incorporated into the calculations.) A thermal inertia map should thus provide a good indication of the boundaries between the principal surface soil and rock types. This in itself would be a great aid to prospecting and it has already been found possible to discriminate quartz veins under thin soil cover from thermal inertia measurements.

Theoretical calculations indicate that the presence of moisture in the material under consideration will alter its thermal inertia and hence the amplitude of the diurnal temperature curve, but with possibly no change in the reflection coefficient and hence in the visual appearance. It may thus become possible in areas of normally dry soil or of desert to detect the presence of water near the surface through the presence on a thermal image of temperature anomalies in areas of otherwise uniform temperature. A complete analytical treatment of this problem is very complicated since the effect of the latent heat of evaporation from the moist surface material must also be considered.

Water is not strictly a mineral but its detection is of paramount importance, and a relevant possibility may be mentioned. In some parts of the world, such as the Great Artesian Basin in Australia, warm water leaks up onto the surface at various locations. There may well be other locations where rock strata near the surface trap this warm water. The presence of this rock might thus be indicated by a temperature anomaly. Anomalies may, of course, arise from many other sources but the reduction of a large overall area to a finite number of points means that the cost of a drilling programme could well be drastically reduced.

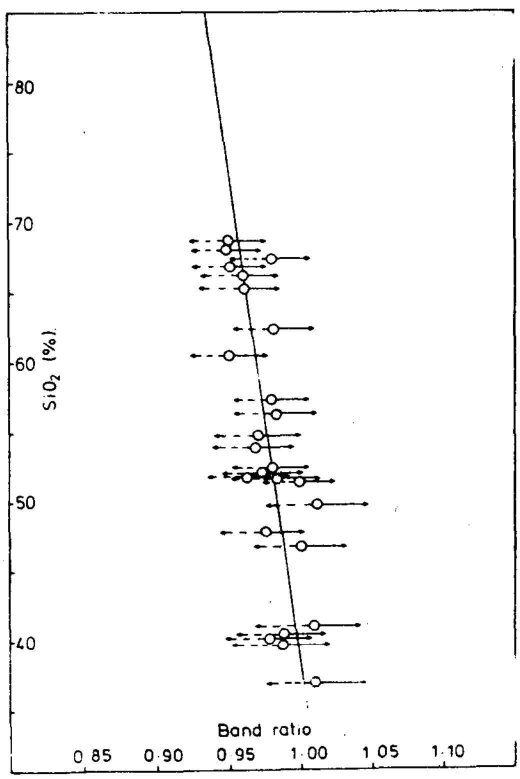
In terms of the direct detection of ore bodies there are two possibilities which have been widely discussed but on which no definitive conclusions have yet been reached. One concerns deposits of sulphide ore bodies having a surface 'expression'. The very slight permeability of the ore will allow it to oxidise over a very long period of time and, as the oxidation process is an exothermic one, the result may be that the ore body may have a very slightly elevated temperature relative to the ambient rock; this may permit its thermal detection. The other possibility occurs in the presence of rock containing radioactive elements whose decay will produce a temperature rise in the rock.

The temperature increases from these effects are likely to be very small and the trade-off required with the detectors may well mean that a detector possessing the necessary temperature sensitivity may have its spatial resolution degraded to the extent that it cannot detect the elevated temperature in the ore body.

The above techniques utilise only the bulk properties of the emitting material. In addition there are certain molecular processes which are characteristic of many minerals. These are associated with relatively sharp minima in the emissivity occurring in the region 7–15 μm wavelength band. The minima are known as reststrahlen bands and result from vibrational transitions of the principal mineral anion. For the phosphate, sulphate and silicate anions the minima lie between 9 and 10 μm while, for the carbonate and nitrate anions, the minima occur at 7·00–7·25 μm. Measurements of the radiation over a wavelength band which includes one of these minima will thus indicate a reduced radiometric brightness temperature. Most work to date has been concentrated on silicate rocks, which comprise about a quarter of all mineral species. The Si–O stretching mode has a fundamental frequency at about 10 μm and it has been shown that the position of the emissivity minimum associated with this frequency varies with the amount of SiO_2 in the rock. For acidic rocks with an SiO_2 content of more than 65% the minimum lies at about 9 μm while, for ultrabasic rocks with less than 45% of SiO_2, the minimum occurs at about 11 μm. Although the precise mechanism for the shift in the emissivity minimum is not well defined it nevertheless offers a potential basis for classifying certain rock types on the basis of emitted radiation. If the ratio of the total radiation in the 8·2–10·9 μm band to that in the 9·4–12·1 μm band is plotted against SiO_2 content a relationship such as that in figure 4 is obtained. These results were derived from aircraft measurements. Exactly similar results would not be anticipated from an extrapolation to satellite altitudes because ozone, which is particularly concentrated in the ozonosphere at 25–40 km altitude, has a strong absorption band between 9·5 μm and 10 μm. The development of narrow-band detectors with improved sensitivity may overcome this problem and still permit the discrimination of certain rock types by utilising this reststrahlen emissivity minimum.

It should be stressed that, despite their potential, these methods using diurnal temperature variations or local thermal anomalies are likely to be effective only when the rock has little or no surface covering of soil or other material. Obviously this is because the presence of even a few centimetres of surface

Figure 4 *Ratio of radiance in 8·2–10·9 μm band divided by radiance in 9·4–12·1 μm band for silicate rocks containing various amounts of SiO_2*
Key: ○–rock temperature, $T=300$ K, ⟶ $T=320$ K, ⟵ – – $T=280$ K. (From Vincent and Thompson 1972 J. Geophysical Res. 77 2465–72)



covering may mask the required underlying temperature variations; the detector will be responding essentially to the thermal and physical characteristics of the surface layer.

With visible and near-infrared band imagery the effects of atmospheric temperature and humidity and variations in ground moisture are relatively unimportant while those produced by changes in the sun's angle can be corrected if computer processing of the data is undertaken. With thermal imagery these factors are most important, with the result that emission levels vary continuously with time. It is therefore very difficult to construct a mosaic with a number of thermal images obtained from aircraft altitudes because of the finite time needed to acquire each image. This means that at boundaries between adjacent images there will, in general, be discontinuities in the emission levels from homogeneous areas straddling the boundaries. This makes qualitative, let alone quantitative, interpretation difficult. Thermal imagery obtained from a satellite, however, has the advantage that the scanner provides virtually instantaneous synoptic cover of large areas. With the Landsat-3 satellite an area measuring some 160 km × 160 km is imaged in a fraction of a second with a resolution cell of about 240 m × 240 m.

The microwave band

Systems which use the microwave part of the spectrum can be divided into two categories. In the passive mode the black-body radiation in the microwave band emitted by the ground area under investigation is measured by the sensor. In the active mode a transmitter on the satellite illuminates the ground and the reflected radiation is recorded by the satellite-mounted detector. This latter arrangement is essentially a radar system and will be considered first because of its present superiority over the passive system.

The general principles of operation of a radar system are well known but the particular system used in reconnaissance and remote sensing is of the 'side-looking' type (SLAR). A thin, fan-shaped, beam is transmitted perpendicular to the direction of motion of the vehicle and illuminates a swath of ground below the transmitter.

Forward motion of the vehicle provides the second dimension of the image. There is an additional distinction between real and synthetic aperture SLAR. In the former, resolution of the system is a function of range while, in the latter, the resolution has the very important property of being independent of range. This means that a given synthetic aperture radar system will have the same ground resolution whether it is mounted in an aircraft at 1 km altitude or a satellite at 800 km altitude. This type of radar is mounted in the Seasat-A satellite and at an 800 km altitude has a ground resolution of 25 m, better than the 40 m resolution in the visible band of the second-generation Landsat-3 satellite. In a synthetic aperture radar the antenna motion is used to simulate a larger antenna and produces an effect similar to that of a long phased array. The signal processing is however much more complicated and costly than with a real-aperture radar. The very high data flow rate with SLAR, compared with systems operating in other spectral bands, together with the large transmitter power demand, are the main reasons why it is only now that the scientific (as opposed to military) satellite Seasat-A is being launched with an operational SLAR system.

The two basic parameters which control the strength of the reflected signal with SLAR are the surface roughness and the dielectric properties. There will be an interaction between the incident signal and the ground, the degree of interaction being dependent upon the relative magnitudes of the wavelength and the surface roughness or texture. For the millimetre and centimetre waves used in SLAR there will be significant interaction since much terrain has a surface texture with characteristic dimensions in this range. The complex dielectric constant depends strongly on the moisture content of the ground and thus changes in moisture content of soils and rocks are detectable by SLAR. Such changes are not directly related to the presence of minerals but indirectly they can provide useful information in conjunction with that derived from other spectral bands.

Because SLAR is an active system it has a day and night capability and, with the appropriate choice of wavelength, can also penetrate cloud cover. This all-weather capability may well prove to be of value for certain low-latitude regions which are almost perpetually cloud-covered and for which, at best, poor quality imagery has been obtained with the Landsat-1 and -2 satellites. The extrapolation of radar spectral signatures, determined by laboratory measurements, to the machine classification of a SLAR image still poses many problems so that, with present knowledge, it would appear that the principal use of SLAR will lie in reconnaissance mapping, particularly in those areas which have poor photographic coverage due to cloud cover problems.

Earlier, I commented on the use of faults and lineaments whose presence can, under certain circumstances, be indicative of potentially favourable mineralised terrain. These features appear to be particularly evident on SLAR imagery and it should thus be possible to obtain information on their density and preferred orientation by an optical Fourier transform of the image. The immediate problem is that, because the SLAR beam is always orthogonal to the flight direction, fault directions parallel to the flight direction are always more favourably recorded than those perpendicular to it, thereby automatically introducing a bias into the analysis.

In the long term there is one characteristic of SLAR which is not possessed by any of the other spectral bands and which may prove to be advantageous. This is the ability of the waves to penetrate the ground to a significant depth and thereby, in theory, to provide information about rock layers covered by soil. Since the 'skin depth' is frequency-dependent, a multifrequency SLAR might thus be able to provide three-dimensional information on the shape of rock layers dipping below ground level. This information would be of considerable value to geologists in, for example, attempting to predict the subsurface extension of a partially exposed inclined ore deposit.

As an example the 20 cm band SLAR on Seasat-A, although designed primarily for maritime applications, would have a penetration depth ranging from 50 mm in very wet soils to 20 m in dry sand and very poor soils. The major technical limitation which can be foreseen is that the greater the required depth of penetration the longer is the wavelength that must be used. This in turn means that the antenna must be larger and for satellite-borne SLAR there will clearly be severe practical limits to this parameter. The SLAR on Seasat-A for instance has an antenna 11 m long for use in the 20 cm band.

It may also be noted that polarisation effects are important with SLAR because the receiving antenna will only respond to one plane of polarisation. It is therefore set to receive the component which is either the same as, or orthogonal to, the transmitted signal. For many targets the return is the same in either plane of polarisation. When specific interest is attached to the detection of linear features consideration has to be given to the choice of polarisation since, if the incident-wave polarisation plane is parallel to a linear feature, the return will be a maximum in the same plane and a minimum in the orthogonal plane.

The wavelengths used in passive microwave radiometry are the same as those used in the active SLAR and so have the same limited capability for ground penetration. Unlike SLAR this system records the black- (or grey-) body radiation in the microwave band. The actual measurements are presented to the interpreter in terms of the 'equivalent brightness temperature'. This is equal to the product of the emissivity and temperature of the object.

Emissivities in the microwave band have a wide range of values, typically ranging from 1 for grass, 0·5 for water, to less than 0·1 for metals (which of course have a correspondingly high reflection coefficient). For any one particular target the received signal is also a function of the angle of incidence and depends upon whether the horizontally or vertically polarised component is being measured. In general, as the angle of incidence is increased, so the difference in the apparent brightness temperature for horizontal and vertical polarisation increases. For this and other reasons microwave radiometers frequently scan a ground swath ahead of the vehicle, unlike all the other sensors referred to here which scan in a direction perpendicular to the flight path. The apparent brightness temperature is, indirectly, very sensitive to changes in moisture content because of the high value of the relative dielectric constant for water. The direct detection of minerals by utilising some distinctive physical property is currently no easier with passive microwave radiometry than it is with SLAR.

Furthermore, this technique suffers from having a markedly inferior spatial resolution compared to other sensing systems. In the Nimbus-G spacecraft for instance, due to be launched in late 1978, the scanning microwave radiometers will have resolutions ranging from about 25 km at 37 GHz to about 190 km at 5 GHz.

The greatest potential of microwave radiometry for the detection of surface or shallow mineral deposits would thus appear to be in the production of apparent-brightness temperature maps. Changes in this quantity produced by variations in moisture content, or a comparison of the separate maps produced by the two polarisation components, may then assist geologists in the detection of surface or shallow buried structures which are favourable for the presence of mineralisation. The weathering products, such as soil, which cover these rocks normally have a high electrical conductivity when moist and a few metres depth of such material may thus completely obscure the radiation from the underlying rock. This may occur irrespective of whether the cover is derived from the underlying rock or has been moved there by a transportation process.

Passive microwave radiometry may appear to have only a limited potential for mineral detection but until a prolonged and comprehensive experiment is performed its utility cannot be described with certainty.

Future role of satellite prospecting

The above account has been deliberately biased to emphasise the role which physical devices, allied to a knowledge of the underlying physics, can play in prospecting for minerals from space. In some cases the feasibility of a technique is already established, whereas in others the theory has yet to be translated into practice. It should not therefore be thought that the traditional role of visual interpretation, with all its subjective limitations, is exhausted for it will remain an essential technique for many years to come. However, as the more obvious surface minerals in the readily accessible parts of the world are now largely recognised, so recourse will have to be made to the more sophisticated methods described in this article for the detection of the largely unmapped immediate subsurface deposits. For the less accessible parts of the world, of course, the use of satellite-borne sensors is, in effect, the only way of acquiring a comprehensive regional knowledge from which to proceed to local ground exploration.

Over the next two to three years the availability of thermal imagery in the 8–12 μm band from the Landsat-3 and HCMM spacecraft with resolutions of 240 m and 500 m respectively, and possibly SLAR imagery with a resolution of 25 m from the Seasat-A spacecraft, should help considerably towards resolving whether many of the proposed techniques for the detection of minerals from space are feasible.

THE NEW LANDSAT

Introduction

On 5 March 1978 the National Aeronautics and Space Administration launched a new, improved satellite from the Western Test Range in California to monitor the Earth's natural resources. The 900 kg (1,980 lb.) Landsat 3 entered a 917 km (570 mile) circular, near polar orbit. Circling the globe every 102 minutes, its remote sensors view a 185 km (115 mile) wide strip of the Earth running nearly north-to-south at an angle to the equator of 99 deg.

In this type of orbit, surface coverage of the Earth proceeds westward, with a slight overlap, such that the globe is covered once every 18 days. The spacecraft's orbit is synchronous with the Sun. Thus Landsat 3 (like Landsat 2) crosses the equator at the same time (9:30 a.m. local time) every orbit. This results in consistent and constant lighting of Earth, the best condition for the spacecraft's imaging systems. Synoptic, repetitive coverage of Earth's surface under consistent observation conditions is required for maximum utilisation of the multispectral imagery.

Large-scale Perspective

The most common value attributed to the Landsat system is the large-scale perspective. Structural elements, perhaps irregular or even discontinuous within the confines of a smaller area, may be revealed as regional or even semi-continental in extent.

Another major asset is the system's repetitive observation which makes possible the detection of short-period changes – as frequently as every nine days using two satellites.

Most Important Data Uses

The three most important potential uses of the Landsat data identified so far correspond to three of the major problems confronting the world today. These are energy supplies, food production and global large-scale environmental monitoring.

Innovations in the Landsat-3 multispectral scanner system (MSS) provide for the detection of temperature differences in vegetation, bodies of water and urban areas – day or night.

Improvements in the return beam vidicom (RBV) sensor has increased the resolution of its recorded images by 50 per cent. Thus, areas as small as half an acre – about two urban house lots – can be identified and studied.

In addition to its two major remote sensing systems, the Landsat 3 carries a data collection system (DCS). This versatile experiment collects radioed data directly from as many as 1,000 remote ground platforms and relays them to a Landsat data acquisition station. Volcano activity, stream flow, water and snow depth, water temperature and sediment density are some of the measurements collected.

Secondary Payloads

Landsat 3 was launched from the Western Test Range (WTR) aboard a two-stage Delta launch vehicle. In addition to Landsat 3, riding piggyback aboard the rocket was an amateur radio communications satellite, OSCAR-D. This satellite is being used by amateur radio buffs around the globe for a variety of purposes, particularly with small fixed and mobile stations. Primary emphasis is placed on its application as a teaching aid in secondary schools.

Another experiment attached to the second stage of the expendable Delta rocket is a unit to help designers of future space systems. This unit, called the Plasma Interaction Experiment (PIX), will remain in orbit at an altitude lower than either the Landsat 3 or the OSCAR-D. It is designed to provide information on how to control detrimental interactions between high voltage systems and the electrically charged plasma fields in space.

HEAT SCANNER. America's latest Earth resources satellite, Landsat 3, launched on 5 March scans the Earth around the clock providing scientists with information on energy sources, thermal water pollution, temperature variations and ocean currents. The Hughes Aircraft multispectral scanner (shown here) produces infrared pictures night and day, which are sent in electronic form to Earth for processing. The technician is examining the instrument's aperture which contains reflective mirror and telescopic optics.

Hughes Aircraft Company

The Landsat sensors are improved versions of the MSS and the RBV units carried by the two earlier Landsats. All three satellites carry the same DCS experiment.

The improved sensors on Landsat 3 supply data significantly improved over those used in the proven application of Landsats 1 and 2. In agriculture, for instance, the added thermal infrared channel on the MSS is the major improvement. The thermal data provides information on plant stress, vigour and other changes characterised by temperature differences. The improved resolution RBV system provides more accurate measurements of agricultural fields to improve the crop yield projection.

NASA's research programme is being geared to assess the value of these improved data sources as well as to incorporate their information content in the current operational applications of Landsat data by other federal, state and industrial users.

In providing more accurate discrimination between suburban areas and surrounding rural or farm lands (important for census studies) the improved Landsat 3 will increase researchers ability to recognise "heat islands" associated with urban and industrial developments; it also will permit improved monitoring of thermal sources such as mine fires and power plant effluents.

Ground Stations

Three NASA tracking and data acquisition facilities are equipped to receive sensor data from the Landsat spacecraft. The Landsat facilities at Goldstone, California, and at Goddard Space Flight Center, Greenbelt, Maryland, can receive sensor and DCS data directly from the spacecraft whenever it is in direct line-of-sight. The primary station at Fairbanks, Alaska, collects such data by commanding the satellite's tape recorders to replay during each orbit over the North Pole area.

International interest in Earth resources remote sensing is widespread and growing. Foreign-funded ground stations are now operating in Brazil, Italy and Canada (two facilities). Another station is under construction in Iran and others are being planned by Argentina, Chile, India and Zaire. Australia, Japan and Sweden are among other countries presently considering such an investment.

Landsat ground stations cost the host country some $4 to $7 million to establish and from $1 to $2 million per year to operate. In addition, countries operating these stations are paying the U.S. $200,000 per station a year as of July 1976. This charge was established by NASA to assist in defraying the cost for the space segment. Data from foreign stations is distributed directly by the organisations operating the stations.

Once Landsat data received in the U.S. is processed at Goddard Center, copies are forwarded to the Department of Interior's Earth Resources Observation Systems (EROS) Data Center at Sioux Falls, South Dakota. On receipt at Sioux Falls, data are in the public domain and copies can be purchased by anyone.

The overall Landsat programme is the responsibility of NASA's Office of Space and Terrestrial Applications, Washington D. C.

Project management for the Landsat spacecraft, the Delta launch vehicle, the NASA Image Processing Facility and the worldwide tracking network rests with the Goddard Center.

General Electric Company, Space Division, Valley Forge, Pennsylvania, is the prime contractor for the Landsat spacecraft, the data collection system and wideband video tape recorders aboard the spacecraft and the ground data handling system at Goddard.

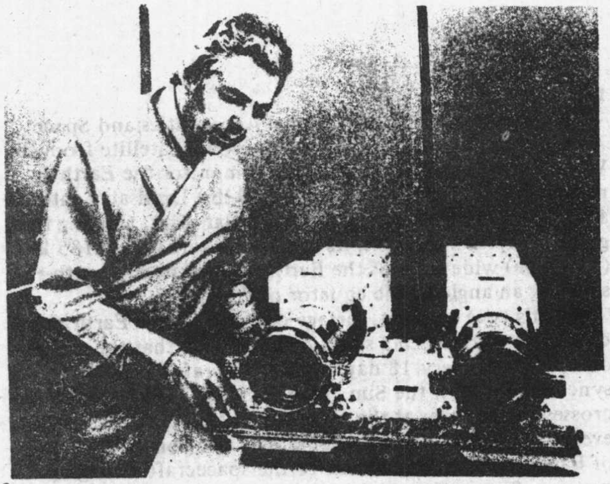
Hughes Aircraft Company, Space and Communications Group, El Segundo, California, is the prime contractor for the multispectral scanner; and RCA, Astro-Electronics, Princeton, New Jersey, is prime contractor for the return beam vidicon camera. The McDonnell Douglas Astronautics Company, Huntingdon Beach, California is prime contractor for the Delta launch vehicle.

NASA costs for the Landsat programme are about $251 million. This includes $149 million for three spacecraft and their instruments, $54 million for the data handling facility at Goddard Center and ground operations, $34 million for support of investigations and about $14 million for three launch vehicles.

Landsat Usage to Date

Images produced by the sensors onboard Landsats 1 and 2 have been subjected to intensive study and experimentation by hundreds of scientists in a broad range of disciplines. Many of these scientists, located throughout the United States and 52 other countries, were selected by NASA for formal sponsorship as principal investigators. This was done to induce systematic examinations of Landsat's potential value as a new tool in remote sensing.

The areas studied include agriculture, rangelands, forestry, water resources, environmental and marine resources, cartography, land use, demography and geologic survey and mineral/petroleum exploration.



2.
GLOBAL MAPPER. These new high-resolution TV cameras aboard Landsat 3 take pictures of the Earth in 50 by 50 square mile (130 square kilometre) frames. High quality maps can then be produced of remote regions of the Earth never before mapped in such accurate detail. The camera – built for NASA by RCA Astro-Electronics, Princeton, New Jersey – are seen being inspected by RCA Program Manager Bert Soltoff.

National Aeronautics and Space Administration

The volumes of scientific and technical literature on Landsat studies primarily address techniques of processing, analysis and interpretation. A limited number of quasi-operational projects also were undertaken.

Based on the research results to date, the following sections describe the current assessment of what Landsat multispectral data can be made to reveal, the extent to which these data respond to data requirements and the uses of these data.

Agriculture

Worldwide preoccupation with the food supply problem has focussed strong attention on the contribution of space remote sensing to better management of agricultural systems and more timely information on output of key agricultural commodities.

Investigations of the application of satellite sensing to U.S. agriculture have dealt principally with the inventory of crop acreage, forecasting of crop yield and soil survey.

Large Area Crop Inventory Experiment (LACIE)

The large Area Crop Inventory Experiment (LACIE) has been a major technological effort to determine how Landsat data can be used to monitor situations of major national or global importance. LACIE has been a three-year, joint experiment of USDA, NASA and NOAA to determine if foreign commodity production (wheat has been used as the example) can be forecast with an accuracy of 90 per cent, nine years our of ten. The third crop year, 1976-1977, has been completed and a final report on the three-year period is being compiled.

So far, LACIE has shown that when field sizes are large enough to be compatible with the resolution of Landsat data the results are compatible with the 90 per cent accuracy goal and the desired confidence goal.

Since the LACIE goal is stated in production terms, both acreage and yield components must be determined. While the acreage component has been determined from Landsat data, NOAA has led the effort to determine yield by using