INSTITUTE
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REMOTE SENSING IN HYDROLOGY

by

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ABSTRACT

This report is based on a thesis presented to the Open University for the degree of Bachelor of Philosophy. It provides a background knowledge of remote sensing theory and its relevance to hydrology. The advantages and difficulties of applying remote sensing techniques to measurement problems are described and sources of further information about remote sensing applications which have already been undertaken in this field are listed.

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1. INTRODUCTION

Remote sensing, which may be defined as 'the collection and interpretation of emitted or reflected radiation from a body', offers the potential for more accurate interpolation of surface data than may be achieved from the ground and even for its direct measurement on scales ranging from local to world wide.

Although various forms of remote sensing (notably aerial photography) have been used extensively for several decades, it is only recently that, through the development of new instruments and techniques, the versatility and potential of remote sensing for the qualitative and quantitative measurement of earth resources has been realised. Military requirements in the Second World War resulted in the development of such techniques as radar tracking, sonar echo sounding, the detection of camouflage using infra-red colour film and in the vast improvement of photogrammetry, aerial photography and methods of interpretation. After the War, these and other techniques gradually evolved, but then a rapid acceleration in remote sensing technology followed the first orbital photographs of the Earth taken from the unmanned MA-4 Mercury spacecraft in 1961. The vast quantities of money which were subsequently injected into the space and associated industries, especially in the USA, have resulted in an unusually rapid growth of remote sensing investigations, which in turn have produced a world wide proliferation of literature on the subject. The value of some remote sensing techniques for investigating various hydrological occurrences has frequently been noted (Refs 1-3), but as yet, no complete study has been made with respect to hydrological applications in the United Kingdom.

From a comprehensive search of the literature on remote sensing techniques, instrumentation, data handling and ground control, this report compares the capabilities of present remote sensing measurement methods with hydrological measurement requirements and presents the information in a form which will enable hydrologists to evaluate the usefulness of remote sensing as a tool. Its will generally be restricted to the types of hydrological problems likely to be encountered in the United Kingdom, but reference will be made to other climatic zones where relevant.

2. HYDROLOGICAL DATA REQUIREMENTS

2.1 Nature of hydrological variables

The nature of the hydrological cycle is such that changes in hydrological variables occur over a wide range of space and time scales which may themselves also be subject to change. The commonest example of this occurrence is atmospheric precipitation where the quantity of water reaching the Earth's surface in the form of rain can vary rapidly in both time and space during the passage of say summer convectional thunderstorms, whereas in contrast anti-cyclonic rainfall can often produce steady, continuous intensities of little variation over large areas. Snow, the other major form of precipitation, is generally even more susceptible to variations than rain. Changes in wind direction and velocity, topography and altitude all intermingle to produce a very complex and mobile distribution.

Soil moisture and evaporation tend to be less variable than precipitation and their distribution can to a certain degree be predicted. Measurements show that soil moisture varies with (amongst other things) the physical characteristics of a site such as its slope, soil type or proximity of the water table. Similarly evaporation rates are dependent on site exposure, surface type and albedo coefficients. However, as most of these factors remain relatively constant at any point, the effects of antecedent and real time climatic conditions will be responsible for the majority of temporal soil moisture and evaporation changes. Thus, where physical and climatic conditions are known, fairly coarse sampling of soil moisture and evaporation conditions may be adequate.

In the prediction of surface runoff volumes (usually measured as stream or storm pipe discharges), catchment characteristics such as area and mean slope are required initially, but as for most purposes they do not change, further monitoring is not generally needed. Weather and ground state measurements are required however on a short term recurring basis (e.g. daily) as both are subject to change and both affect surface runoff volumes.

Thus, many hydrological studies require accurate mapping of the relevant static physical features within an area, followed by the statistically acceptable sampling of parameters which are subject to change. Remote sensing techniques can often be useful in fulfilling or aiding both of these measurement requirements.

2.2 Sampling of data

To obtain useful measurements of hydrological variables, fairly frequent and even continuous observations are often required, together with a relatively high degree of precision both in the measurement itself and in its location. The degree of point accuracy required and the frequency of observation depends solely on the ultimate use of the data.

At the outset of any hydrological measurement programme it is necessary to decide on the limits of errors to be tolerated in the final results. Starting with these limits in mind, statistical techniques should be used to take into account the area for which data is required, the precision of the measuring technique to be employed, the physical distribution of likely measurement points over the area and any relevant physical variations such as surface topography or vegetation distribution. All these factors should be optimised to determine the minimum number of measurement points and the required frequency of measurement necessary to comply with the error limits of the objective. Depending on the variability of the parameter under observation, it may be found that a large number of measurements of low accuracy can provide more meaningful information than a handful of high precision measurements. The final choice however must often be a compromise between that which is ideally required and that which can be afforded in terms of instrument cost, installation and operation.

2.3 Measurement problems

1. One of the main difficulties of taking many hydrological measurements with conventional instruments is that the presence of the instrument itself disturbs the natural environment and thus affects in some way the variable which is being measured. Raingauges for example, no matter how carefully placed, will always cause a certain amount of air turbulence which can result in either positive or negative errors of measurement. The insertion of access tubes into the ground in order to measure soil moisture levels by neutron scattering techniques must inevitably result in some disturbance of the surrounding soil which affects its physical properties and hence the accuracy of the readings. Similarly, the insertion of any sampling apparatus into a flowing water body must cause disturbance of the flow which can locally alter the amount of sediment carried in suspension - the variable which is being measured. From an installation point of view, the selection of a suitable instrument site which is free from extraneous influences can prove very difficult, especially in urban areas where the possibility of interference and vandalism must be minimised. As a result of these and sampling reasons, hydrological instruments are often sited in remote or poorly accessible areas. This makes their installation difficult if construction work is necessary, and their running and maintenance becomes a time consuming and costly business.

As frequent measurements are often required in hydrological studies, efforts are continually being made to develop automatic instruments which will function without attention for days or possibly weeks at a time. Of major concern with such instruments are the effects exerted upon them by the climate and climatic variations. Perfect air tight or water tight seals are difficult to achieve when mechanical or electrical linkages are required between sensor and recorder. Even if this is possible, changes in air temperature can cause condensation to form within an instrument with drastic results. Dampness, ice, corrosion, dirt and ultra-violet light can bring the apparently sturdiest and most fool-proof of instruments to a rapid halt. The effect of instrument failure for any of the above (or other) reasons is that a break occurs in the continuity of the data, unless back-up instrumentation is provided. If the data is being used for statistical analyses or prediction purposes, a loss of this kind can create many analytical problems, especially if the information is being used in conjunction with other continuous data or if an event of interest occurred during the period of instrument failure. Of even greater concern is the possibility of an instrument malfunction which results in incorrect data recording, as this is often very difficult to detect.

Where continuous monitoring of a hydrological variable is not required, but rather the detection and measurement of a specific event, speed is of the essence, as often large numbers of measurements are required over a large area as quickly as possible - a good example of this being the monitoring of flood events. Where long term studies require information on slowly changing phenomena such as land use or erosional and depositional features, tedious surveys are often required which in the past have been both time consuming and costly.

3. ADVANTAGES OF REMOTE SENSING FOR HYDROLOGICAL MEASUREMENT

3.1 Speed of operation

Probably one of the main advantages of remote sensing when applied to hydrology is that in most cases, great savings can be made in the length of time which personnel spend in the field. Although it is essential that accurate ground measurements must always be taken during any remote sensing exercise as a reference control to the sensed data, (6.8) the time spent in obtaining these measurements is usually small when considering the overall data return. This saving in field time is most marked in the distributional mapping of surface features. Whereas in the past a team of surveyors may have spent months or years within an area mapping physical or vegetational features, these can now be recorded within seconds from many types of aerial platform, with ground control checks being completed possibly within a matter of days (Ref 5). The interpretation of this permanent data record can then be carried out at any time in the future, indoors in conditions where personnel can work most efficiently.

As many hydrological occurrences are very short lived, the ability to 'freeze' information from a very large area until such time as personnel are available to deal with it can increase the scope and capacity of small research or operational bodies. Thus, instead of spending long periods observing individual stretches of river to monitor the effects of storms of known intensity on say floodwater extent or erosional and depositional features, a whole river system could be studied at once after the passage of only a single storm by using suitable remote sensing recording techniques (Ref 6). A major problem encountered in snow studies is the constant redistribution of snow due to wind. This makes the assessment of snow conditions over an area at a given time very difficult as snow movement may take place before conventional measurements can be completed. Aerial or ground based stereo-photography on the other hand (see *metric cameras* p. 29 *snow depth* p.139 and 142) could record the location and depth of snow over a large area within a very short time so that overall storage volume or depth distribution could be calculated later indoors using suitable stereo-plotting equipment.

In addition to speeding the detection and mapping of surface features, remote sensing has opened up new boundaries in the detection of previously unplotted hydrological features. For example, the use of airborne infrared line scanners (see p.45) enables water surface temperatures to be detected (Ref 7). Such features as coastal freshwater intrusions can be located where fissures in the sea bed allow the discharge of groundwater into the surrounding sea mass which is of a different temperature (Ref 8). Similar groundwater outflows can be detected in lakes and river beds, and the tracking over great distances of warm water from the outflows of power stations has also been demonstrated (Ref 9). With conventional techniques, the monitoring and plotting of water temperatures would have been necessary on a huge scale to detect such features, representing a colossal input in time and manpower. In most cases the required expenditure would have been too great to justify the measurements and so such features have gone largely undetected until remote sensing techniques were applied.

3.2 Distribution of manpower

The fact that many field measurements can be speeded up using remote sensing has been shown to lead to a reduction in necessary manpower. What is also taking place is essentially a redistribution of manpower resulting in greater efficiency. Conventionally, a large proportion of the manpower has been absorbed by field measurement requirements, with personnel either physically taking measurements and observations or else having to maintain instruments which would do this for them. In many cases their work is dependent on climatic conditions, so that in good weather they may be very busy, but when conditions are unfavourable there will be little for them to do - a very inefficient system. When using a remote sensing data collection system, far fewer people are involved in the collection of field data, thus releasing more people to deal with the problems of data processing and analysis.

In general terms, the greater the altitude of the sensor platform, the more obvious is the redistribution of manpower. Ground based remote sensors may be a great improvement on conventional instruments, but they are limited in their field of view at any one time and would thus require a relatively large number of operators or man-hours to monitor a unit area of ground. It may be possible, however, for a pilot and operator to monitor the same unit of ground from a light aircraft, along with two or three people providing ground control, whilst a single satellite image could provide information on several hundred unit areas.

3.3 Measurement accuracy

The major advantage of many types of remote sensing data, especially when in the form of imagery (see *physical data transference* p 60) is the frequent ability to achieve high degrees of cartographic accuracy. When metric cameras are used (see p 29) (either from ground based or aerial platforms) together with suitable ground control, overall accuracies similar to those achieved with normal triangulation surveys are possible (Ref 10). When electronic imaging systems are used (see *Vidicon cameras* p 32 *and scanning radiometers* p 42), distortions of the image may result from the scanning action of the sensors, but rectification of these known distortions is generally possible to allow areal accuracies which are adequate for many mapping requirements. For example, the Earth Resources

Technology Satellite imaging multi-spectral scanner has a ground resolution of only 80 metres (see p. 48) but, as a single image covers an area of 100 nautical miles square, such resolution is adequate for the production of maps of up to 1:250,000 scale (Ref 11).

Of great use when investigating a specific feature from a remote platform is the ability to look at its emitted or reflected radiation in discrete wave bands. Using methods described later, it is possible to detect radiation in wavelengths outside the conventionally used visible spectrum. By carefully selecting wavelength ranges, it is often possible to enhance the boundaries of features under observation. It is found for example, that in the near infra-red part of the spectrum, the boundary between water features and land is greatly enhanced or sharpened as a result of their differential reflectance of this wavelength, thus enabling the mapping of water features to be carried out much more quickly and generally more accurately (Ref 12). Similar enhancement effects can often be obtained for other features by the correct selection of wavebands, but as the wavelength increases, the relative ground resolution decreases for any particular sensor and platform to target distance.

In addition to the accurate location of features using remote sensing, methods are available to enable measurements of their condition to be made. For example, surface temperature can be measured to a high degree of accuracy using thermal infra-red radiometers (see p 36), whilst water depths (p 89), snow depths (p 139) and water turbidity values (p 92) can all be estimated using techniques described in Chapter 7. However, the precision of remotely sensed measurements is generally poorer than those of ground-based instruments, because of signal degradation caused by atmospheric effects (see p 17 to 20) and also resulting from deficiencies in sensor design.

3.4 Sampling frequency

Conventional measuring techniques often rely on accurate point readings of hydrological features such as snow depths, and attempt to interpolate between these points when distributional estimates are required. With remote sensing techniques, the precision of measurement may be inferior to the ground-based equivalent, but the possibility of inaccuracies resulting from unrepresentative sampling is reduced by increasing the number of measurements taken over a given area. Generally, where variable hydrological parameters are being sampled, an overall increase in accuracy results from the use of remotely sensed data.

Whilst an increase in the spatial sampling interval of field measurements would greatly increase the overall cost of an exercise, a similar sampling increase from remotely sensed data would result in only a marginal increase in cost. Although these two sampling methods could statistically provide similar answers, the remote sensing method is often more suited to the measurement of hydrological parameters as more insight is given into their distribution, which may be useful for physical process studies.

One area in which remote sensing generally cannot match the performance of ground-based instrumentation is in frequency of observation.

Whilst ground-based instruments can be set to record at almost any desired frequency, the frequency of observation of aerial remote sensors is largely governed by the capabilities of their platform. Thus, instruments operating from towers, tethered balloons or geostationary satellites may be capable of matching their ground-based counterparts, but those in aircraft, helicopters, rockets and orbiting satellites are more restricted in their frequency of observation.

As many hydrological occurrences are subject to different rates of change and since data of their behaviour is used for many different purposes, it follows that the required frequency and precision of any sample measurements will vary greatly according to the type of occurrence and data requirement.

3.5 Data processing

Considerable efforts are required to process conventional hydrological data as measurements are often recorded on paper charts either in the form of line graphs or event marks. Ground surveys consist of masses of measurements and observations which must be later reconstructed. Due to the large quantities of measurements involved, much of this data nowadays has then to be converted into a computer compatible form involving the re-writing of data sheets, punching of computer cards and subsequent transference of the data onto magnetic tapes or discs. Some recent instrument developments have resulted in measurements being recorded directly onto magnetic tape (Ref 13) but these are not yet widely used.

Remotely sensed data on the other hand is normally produced in a form which is much more conducive to computer handling. Due to the vast quantity of information stored on photographic film or on linescan images for example, direct computer processing is often the most efficient method of interpreting and classifying this type of data (Ref 14). Photographic images can be quickly converted into a computer compatible digital form by densitometer scanning (see p 61), whilst most other sensors have some form of electrical output signal which can be stored on magnetic tape and quickly converted for computer analysis. Great savings in time and manpower can thus be achieved through not having to subject data to several stages of processing. Statistical analysis and computer techniques for the automatic processing of remotely sensed data are as yet at an early stage of development and it is here that significant improvements can be most readily made. As these improvements are made, along with improved sensor resolutions and capabilities, then remote sensing methods will become progressively more advantageous.

3.6 Cost effectiveness

The type of remote sensing techniques used to tackle any hydrological measurement problem must be carefully considered in order to remain cost effective in comparison to normal methods. As most remote sensors are capable of handling large amounts of information, they generally become more cost advantageous the longer they are in use and the more data they are required to produce. It is unlikely therefore that remote sensors will ever replace conventional instruments where only single point measurement of say water quality is required. For a land use inventory however, a single photographic mission from a light aircraft may prove cheaper than a ground based survey, whereas the commission of an aerial photographic mapping firm to carry out such a task may be out of the question on a cost basis. The service of such a firm may prove highly cost effective however if, say, an accurate topographic survey is required of a previously poorly mapped river catchment area where the only other alternative would be a time-taking ground based survey. Provided therefore that remote sensing methods are not chosen for projects which are unsuited to their capabilities, they can often provide a highly cost effective solution to many hydrologically-related mapping and measurement problems.

4. REMOTE SENSING THEORY

4.1 The electromagnetic spectrum

The electromagnetic spectrum is a continuum consisting of the ordered arrangement of radiation according to wavelength, frequency or photon energy and includes waves of every length, from fractions of microns to kilometres (see Figure 1). The frequency, (f) and wavelength (λ) of any electromagnetic radiation, have a reciprocal relationship as shown by the equation

$$\lambda = \frac{c}{f}$$

where c is the speed of electromagnetic radiation (3×10^8 m/sec).

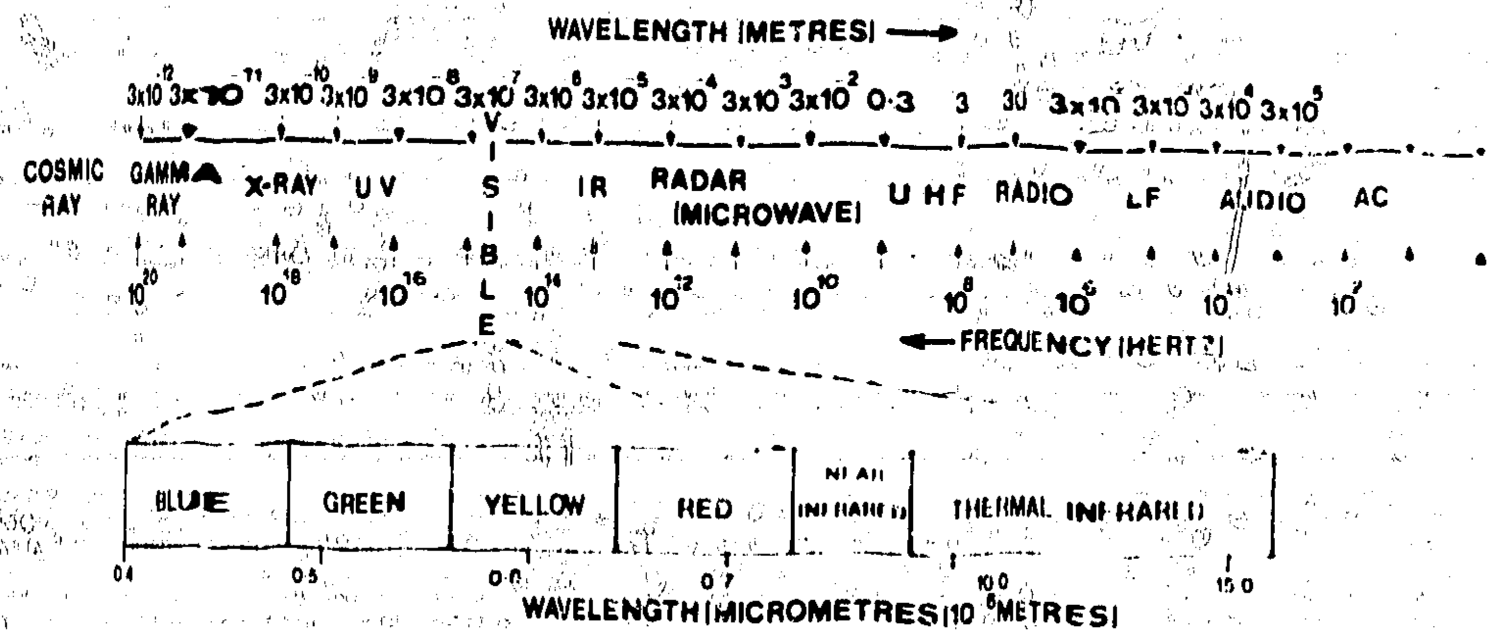


FIGURE 1 The electromagnetic spectrum

As there is no single instrument which is capable of detecting the whole spectral range, the electromagnetic spectrum is usually arbitrarily segmented into those regions which require different techniques for their generation, isolation or detection. Table 1 shows the main electromagnetic groupings with indications of typical methods of generation and detection.

TABLE 1 SOURCE AND DETECTION OF ELECTROMAGNETIC RADIATION

KINDS OF WAVES	WAVELENGTH	FREQUENCY	USUAL SOURCE	USUAL METHOD OF DETECTION
Gamma Rays	1.5×10^{-5} µm - 1.0×10^{-3} µm	3×10^{20} - 3×10^{18}	Atomic Explosions Radioactive elements	Fluorescence Chemical effect Ionization Scintillometers
X-Rays	1.0×10^{-3} µm - 0.1 µm	3×10^{17}	Cathode ray impacts	Same as above NaI crystals
Ultra-violet	0.25µm - 0.39µm	3×10^{15}	Disturbances of intermediate electrons	Fluorescence Chemical effect
Visible Light	0.39µm - 0.75µm	$77\text{-}38 \times 10^{13}$	Disturbance of valence electrons	Eye, chemical effect, photo-detectors
	Near 0.75µm - 1.0µm	47.3×10^{13}	Laser	
Infrared	Mid 1.0µm - 30 µm Far 30 µm - 1 mm	4.34×10^{13} to 1000 GHz 1000 GHz - 300 GHz	Disturbances of atoms and molecules (thermal sources.) IR lasers	Thermopile Bolometer Radiometer Photodetectors
Microwaves	1mm - 1cm	30-300 GHz	Short oscillations, high frequency discharge	Diodes Bolometers
Microwaves	1cm - 1m	3-30 GHz	Electrical resonance in tuned circuits, Thermal generated IR, solid state devices	Solid state crystals diodes, tubes
UHF	10cm - 1m	300MHz-3GHz	Short oscillations klystrons, magnetrons, triodes, solid state devices	Electrical resonance in tuned circuits, diode detectors
VHF	1m - 10m	30-300 MHz		
Radio	10m - 10^3m	30KHz-30MHz	Circuits including large capacitors and inductors	Electrical resonance Electro-magnetic induction
VLF	10^3m - 10^4m	3-30 KHz	Alternating current generators, solid state vacuum tubes	Oscillographs, diodes, heterodyne receiver
ELF Direct current	> 10^4m	< 3KHz	Alternating current generators, solid state, vac. tubes	Oscillographs, diodes, heterodyne receiver

The main electromagnetic spectrum groups are as follows:

(a) *Gamma Rays* 1.5 x 10^{-5} µm - 1 x 10^{-3} µm. Gamma rays are produced by radioactive breakdown or decay in the material of the Earth and its soil cover. This natural gamma radiation is very weak, but its rate of release changes very little in time although spatial variations are apparent. Gamma rays are attenuated by snow, ice and water and so estimations of water equivalent depths can be made by studying the amount of natural gamma attenuation taking place at a given point (p 143). Alternatively, a stronger artificial gamma source may be buried in the ground to increase the accuracy of the measurements which are made with a gamma ray scintillometer (Ref 15).

(b) *X-rays* 1 x 10^{-3} µm - 0.1 µm. X-rays are produced by cathode ray impacts and can thus be artificially generated with ease. They are capable of penetrating many solid substances and are attenuated according to the strength of the original source and the concentration or density of the solid or liquid. The intensity of the X-rays after their passage through the given material, are recorded on photographic plates and are most widely used for the 'remote sensing' of animal body condition.

(c) *Ultra-violet* 0.25 µm - 0.39 µm. The Sun is the main source of electromagnetic radiation, but strong atmospheric absorption generally restricts the application of UV radiation to very short atmospheric paths. However, the use of UV is increasing as new technology and materials are resulting in improved sensing systems. UV radiation is almost totally reflected by water surfaces.

(d) *Visible Spectrum* 0.39 µm - 0.75 µm. The incoming radiation from the Sun reaches a peak irradiance value at around 0.5 µm with nearly 50% of the Sun's radiated EMR occurring within the 0.39 - 0.75 µm visible range (see Figure 2). This is the region where passive remote sensors can obtain the maximum signal strength and should therefore always form the starting point in any investigation, as our knowledge and interpretative abilities are most highly developed here. It is usual therefore for all investigations to refer at some point to the visible signal as the standard reference datum. One of the main problems in this region, however, is atmospheric attenuation which often restricts the use of visible radiation, especially from high altitudes (see p. 17 to 20). Such sensing techniques as black and white photography and vidicon (television) systems, record the visible spectrum in a single continuous tone, but image interpretation is generally simplified by splitting the visible spectrum into narrow bands and recording them separately as different colours (as for example with colour photographic emulsions) because the human eye can distinguish colours more easily than monotone densities.

(e) *Infrared* 0.75 µm - 1 mm. Infrared frequencies are that portion of the EM spectrum lying between the visible and microwave regions and they can be conveniently subdivided into near, intermediate and far infrared, in relation to the visible region.

'Near' infrared normally applies to the 0.75 µm - 1.0 µm range which corresponds approximately with the sensitivity of suitably filtered

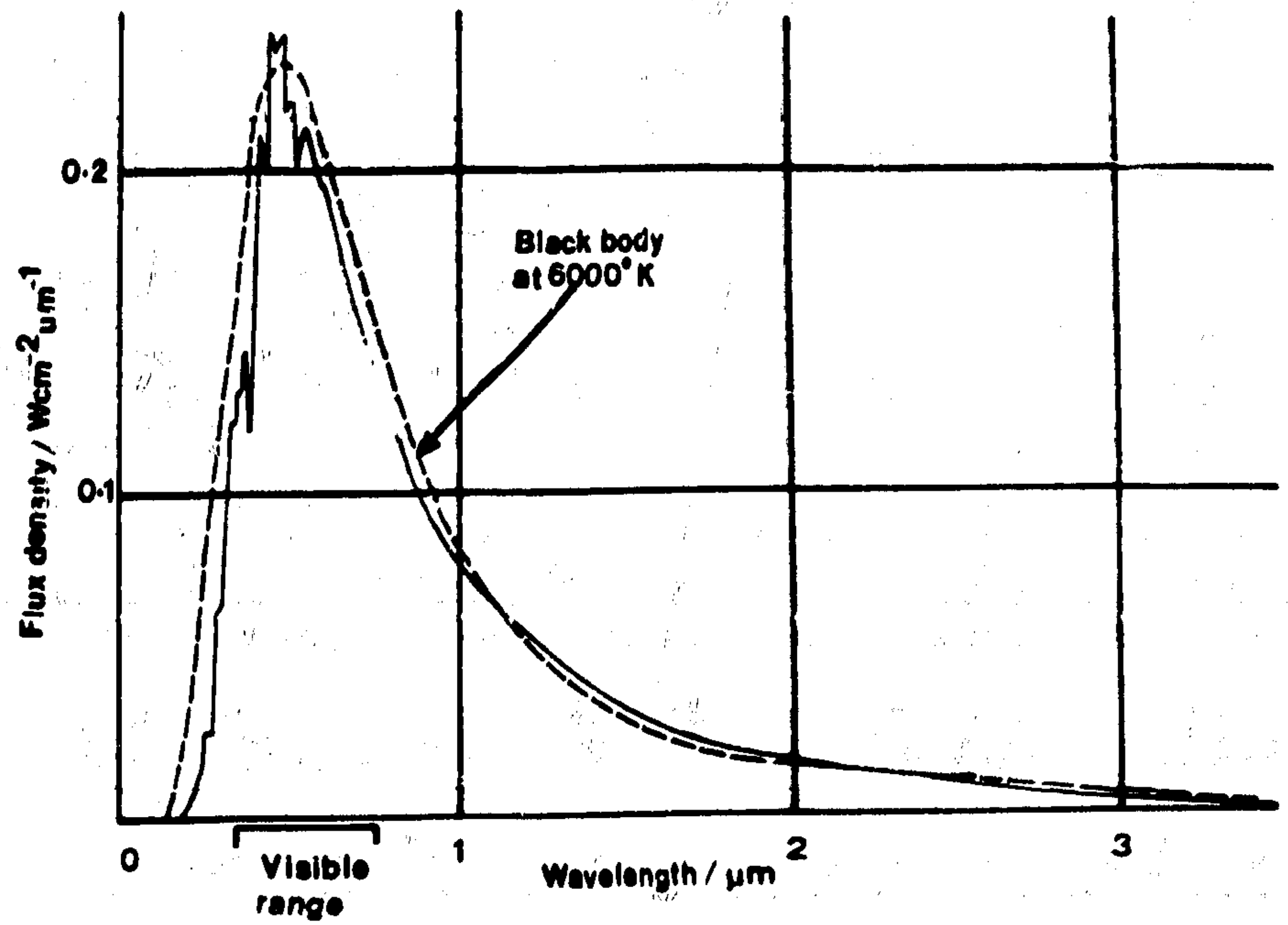


FIGURE 2 The sun's emission spectrum

black and white infrared film and the upper sensitivity of Ektachrome colour infrared film. In this region, only reflected infrared radiation is detected and NOT emitted radiation which is a function of the body's temperature. Thus, night-time sensing is not possible in this wavelength region unless an artificial near infrared source is provided. Atmospheric penetration through haze and light mist is better than in the visible region, but clouds, snow and ice particles, or falling rain are not penetrated. Water bodies absorb most near infrared radiation and thus appear very dark (see p. 82), whereas healthy vegetation has a high infrared reflectance and appears light on black and white film and magenta on colour infrared film (see p. 82).

Sensors of the intermediate infrared region (1.0 µm - 30 µm) are usually constructed to operate in the atmospheric 'windows' between 3-5 µm and 8-14 µm (Ref 16) (see also p.18). These wavelengths can be classified as 'thermal' because an absolute temperature change in an object is detected as a change in its signal brightness. With sensors possessing an internal constant temperature reference (see *infrared radiometers p* 36) a direct measurement of surface temperature can be made to generally better than ± 0.5°C (Ref 17), provided that the emissivity of the surface is known. Night-time sensing is possible in this region, but signal attenuation by snow and cloud is still strong.

The far infrared region (30 µm - 1 mm) is not yet as highly utilised for remote sensing purposes as the near and intermediate regions, due largely to problems associated with instrument design and performance. When these problems are overcome, this region may yield useful additional information.

(f) *Microwaves* 1 mm - 1 metre. Passive microwave sensors rely only on naturally occurring reflected and emitted radiation for their information, whereas active microwave sensors such as radar produce their own radiation source and monitor the resulting reflected signal from the target. At the millimetre end of this spectral region, it is possible to construct small, relatively high resolution antennas for use in aircraft and satellites. Above 25 mm wavelengths, all-weather day and night sensing is possible due to low atmospheric attenuation, but a major problem is that the antenna size required to produce very narrow beamwidths, suitable for resolving Earth materials, is too large for installation in most aircraft and spacecraft. It is possible however to overcome this at the data processing stage by the artificial modelling of a large antenna from small antenna data (see "*Microwave radar* p. 52

(g) *Radiowaves* > 1 metre. In the past, these wavelengths have been used almost solely for communication purposes and thus a great deal of information is available on their electromagnetic propagation and collection. An increasing amount of research is being carried out to assess their potential for earth science investigations.

4.2 Electromagnetic radiation of the sun and earth

Under natural conditions the Earth is illuminated by the Sun, either directly, or after reflection from the Moon's surface, the Earth's atmosphere or the sky beyond. As the radiation temperature of the sky is very low however, its contribution can generally be ignored. When considering sensors at high altitude directed toward the Earth, the radiance they receive will be a combination of four distinct components as shown in Figure 3, namely (1) solar radiation reflected by the Earth's surface (2) the radiation emitted from the Earth's surface as a function of its black body temperature (3) upward radiation from the atmosphere caused largely by scattered incoming solar radiation and (4) downward radiation of the atmosphere reflected upwards by the Earth's surface.

Most Earth materials, both natural and man-made, re-radiate or produce less than the theoretical maximum amount of EMR for their temperature. All materials at temperatures above absolute zero (0^{o}K) produce EMR which is caused by the motions of the charged particles which make up their atoms, the frequency and intensity of the radiation being primarily dependent on the temperature of the body. The emissivity or deviation from the theoretical amount of EMR that a body should emit at a given temperature is dependent mainly on the chemical composition and physical state of the body. In addition, the emissivity is strongly dependent on the frequency or wavelength of the EMR (Fig 4) and on the roughness of the body surface in relation to the wavelength.

In dealing with the production of EMR, the concept of ideal or 'black-body' radiation is often used. Such an ideally radiating body or surface re-radiates all the EMR that it receives; in other words, the total amount of EMR emitted by the body or surface is the theoretical maximum at any given temperature.

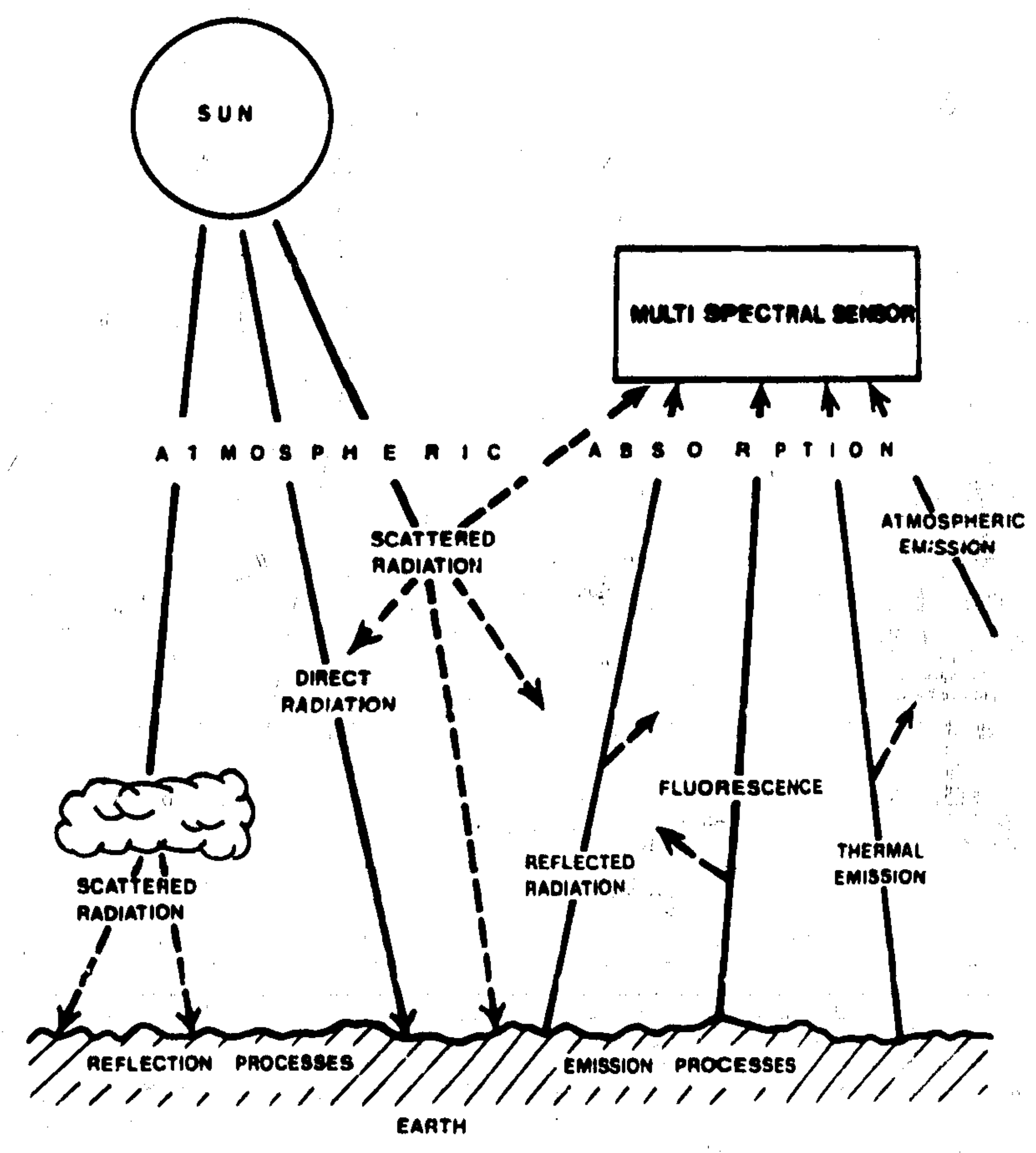


FIGURE 3 Radiation received by a remote sensor

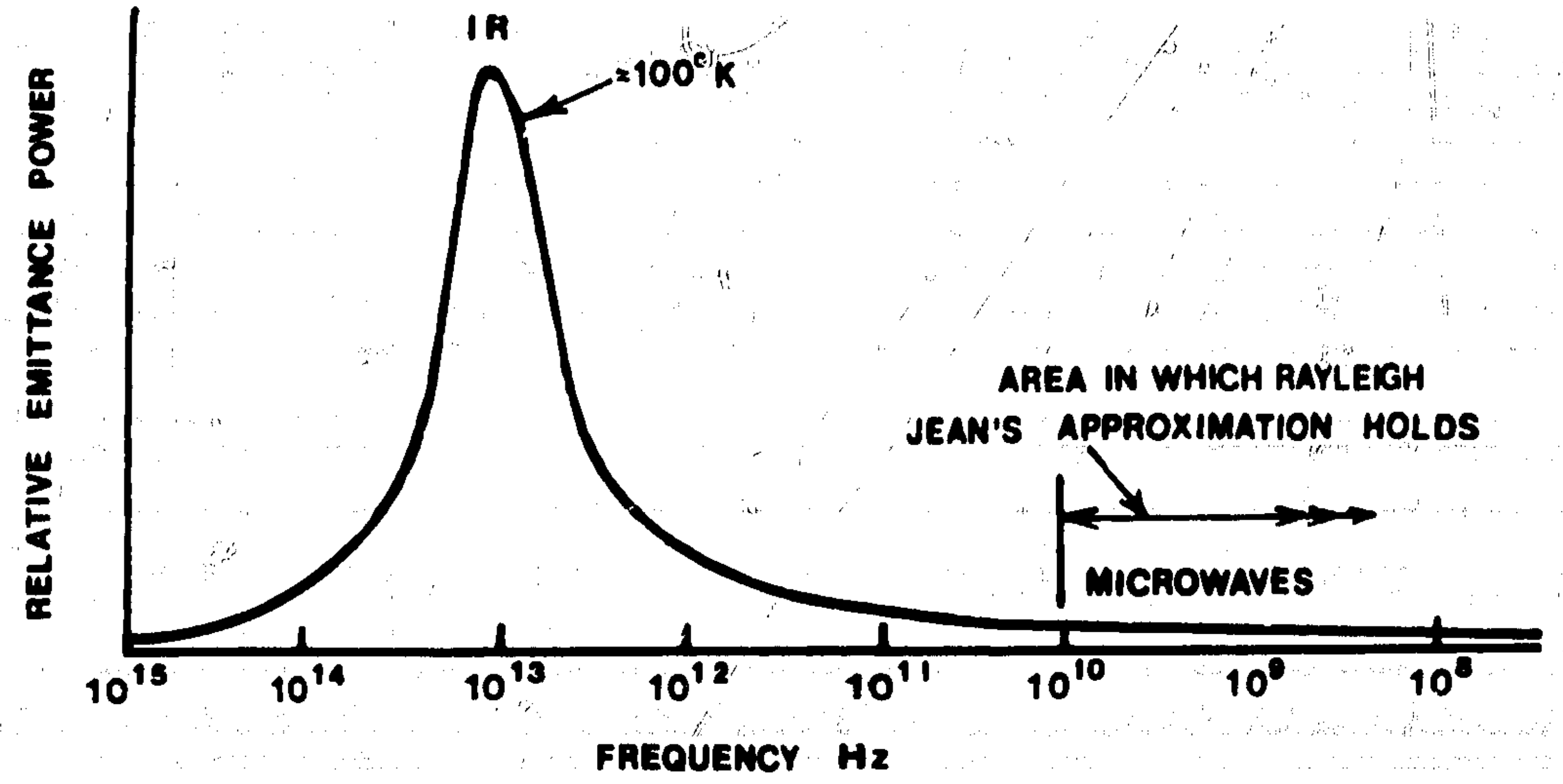


FIGURE 4 Thermal radiation available for radiometers

Whereas the Sun's radiance may be regarded as constant, the thermal emission of the Earth's surface displays diurnal, seasonal and weather based variations. Atmospheric radiance is also affected by these variations, especially in the downwards direction, due to weather changes and also to local variations in atmospheric transmittance due to the presence of dust, smoke, water vapour etc. Minor Earth radiances such as radio may also cause interference.

It is only by reference to the Sun's spectrum that terrestrial objects can be identified on the basis of their reflective spectral radiance, and it can be seen from Figure 2 that the Sun's spectrum is very similar to that of a black body at 6000°K up to ultra-violet frequencies. The Earth as a whole approximates closely to the emittance of a black body at T = 290°K (Figure 5) and according to Wiens displacement law (Ref.37), maximum emission of energy occurs at wavelength

$\lambda o = \frac{2899}{T}$; thus around 10 microns for the Earth and 0.45 microns for the Sun. The fact that nearly half of the Sun's radiated electromagnetic energy falls within the range 0.4 - 0.75 microns has led to the evolutionary choice of this spectral band as an efficient, high signal-to-noise region for animals' remote sensing organs - the eyes. The first man-made imaging remote sensor, (the photographic camera) also operated within this spectral region because of the high surface reflection required to activate the relatively insensitive early photographic emulsions.

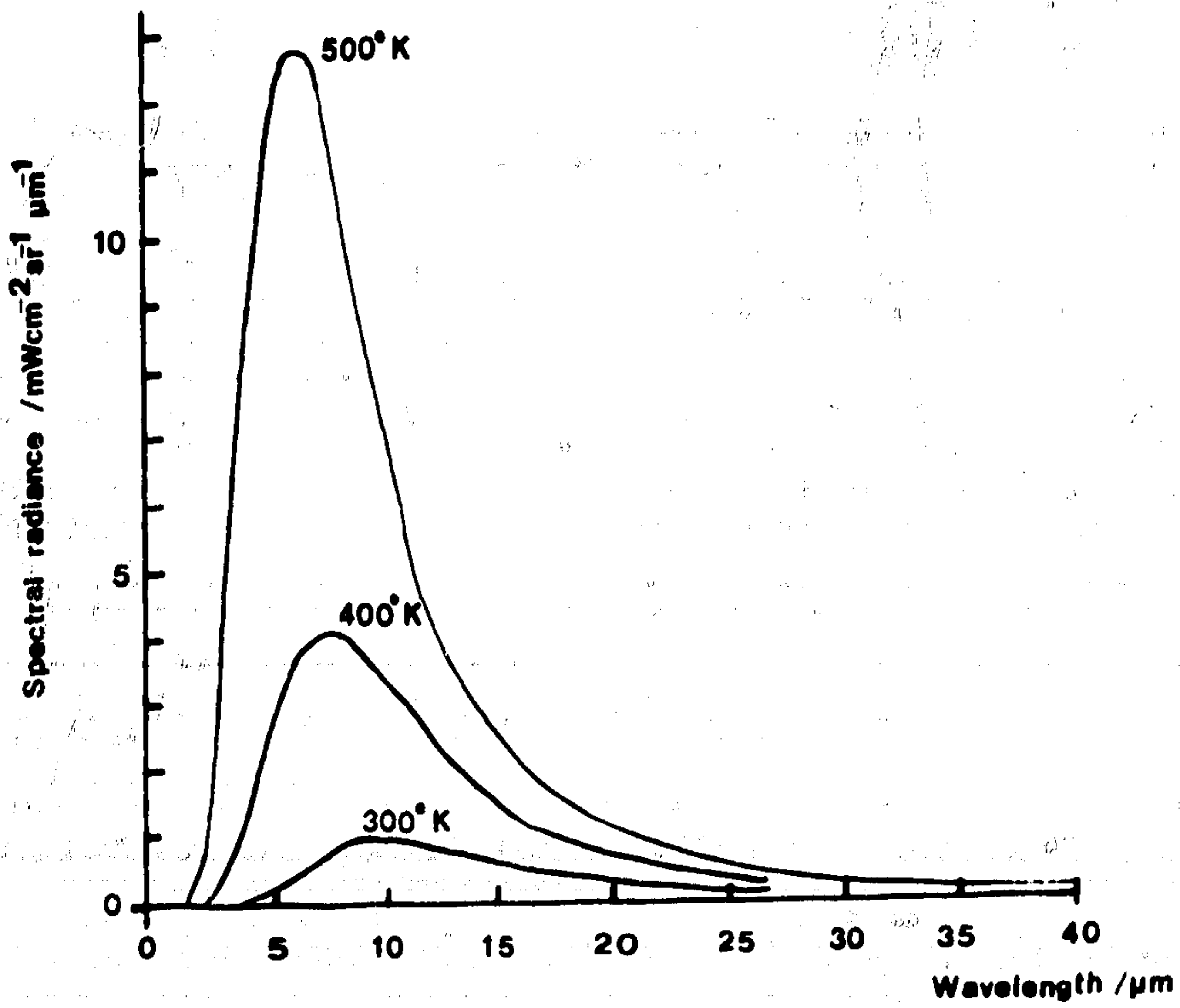


FIGURE 5 Black body radiance

4.3 Interaction of electromagnetic radiation with solid and liquid bodies

Surface reflection

EMR which is incident on surfaces or objects which does not penetrate into the materials of which they are composed, is reflected from them. The reflection may be termed 'specular' or 'diffuse' depending on the surface type and roughness, the wavelength of the EMR and its angle of incidence.

Specular reflection (see Figure 6A) occurs when the surface is smooth in relation to the incoming radiation wavelength and its angle of incidence with the surface. Thus, reflection may be specular up to a certain angle of incidence, then it may become increasingly diffuse as the angle increases. With specular reflection, almost all of the EMR is reflected away from the source whenever the incident angle θ is less than 90°, the angle of reflection being equal to the angle of incidence.

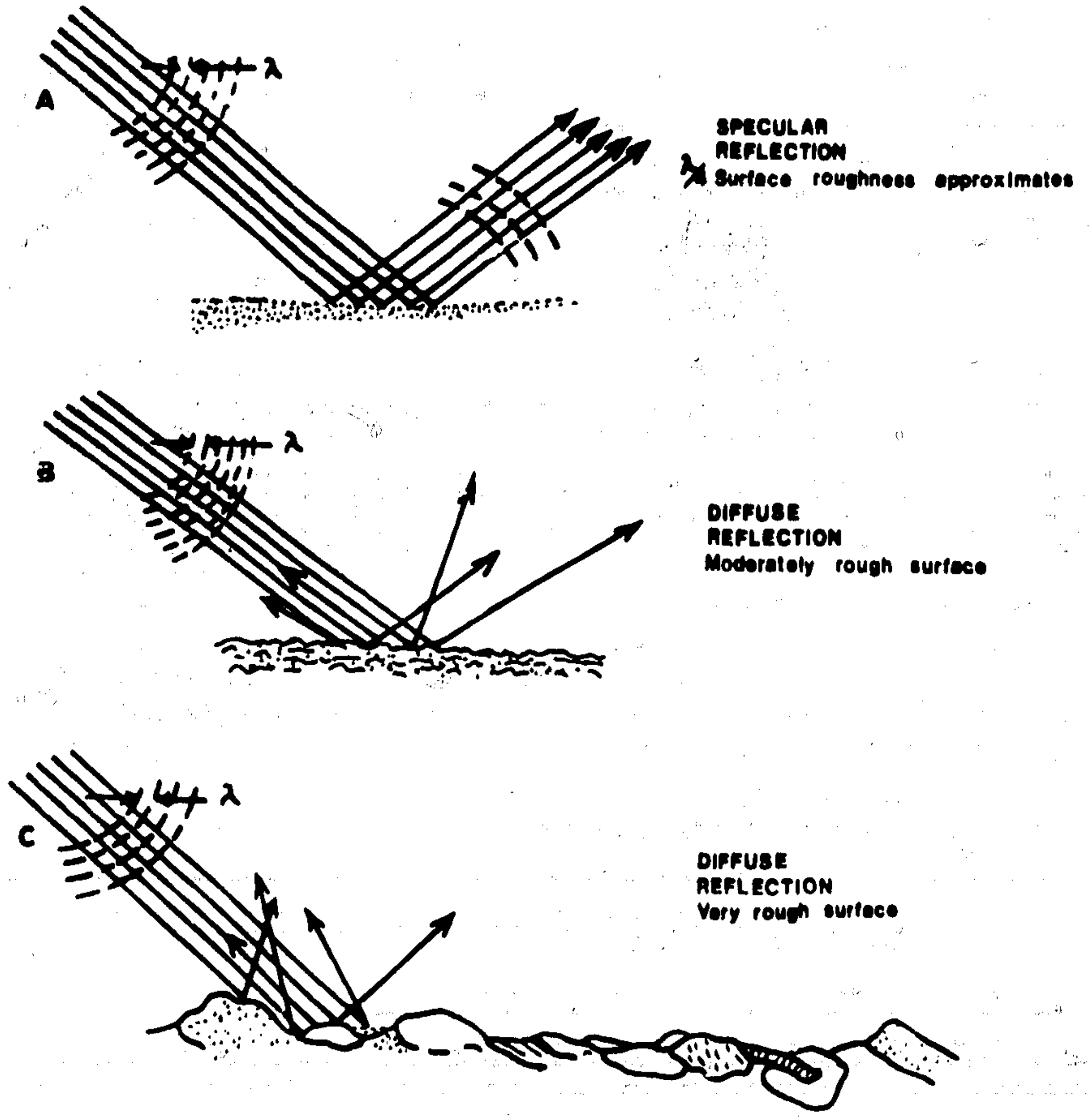


FIGURE 6 Reflection of electromagnetic radiation at a surface

Diffuse reflection occurs when a significant amount of EMR is not reflected from the surface at the same angle at which it strikes (Figure 6B). Here the EMR is scattered in many directions depending on its wavelength and the nature of the surface roughness (Figure 6C). Some of the EMR is backscattered along its path and it is this backscattering effect which active remote sensors such as radar record (see Section 5.3).

Polarisation

This is the direction of the electric vector of an EM wave relative to the terrain and is thus commonly expressed in terms of 'horizontal' or vertical polarisation. In specular and more so in diffuse reflection, the polarisation characteristics or direction of propogation of the EMR waves are often changed by the reflection process, especially at high frequencies. As with backscattering, polarisation is influenced chiefly by the nature of the surface, and a measure of this polarisation can often provide useful additional information about a remotely sensed surface (see *topography* p 72). In theory, the smooth surfaces of still water and polished metal do not affect the direction of polarisation of reflected EMR, whilst rough surfaces such as bare earth or vegetation have a strong de-polarising tendency.

Absorption

EMR which is not reflected at the surface of a body undergoes either internal refraction or is absorbed by the body (see p 18) and is subsequently re-radiated as thermal energy.

Phenomena specific to Liquid Bodies

When a body of water is viewed by a remote sensor, it receives EMR from incoming radiation (sunlight) which has been backscattered by the water and atmosphere (see Figure 3), plus that which has been reflected from the water body floor and from the air/water interface (see Figure 7). Reflection from the air/water interface may be either specular or diffuse depending on the roughness of the water surface and may sometimes be detected as sun glare or glint. Because that portion of EMR which has been reflected from the floor of the water body must pass through an intervening absorbing water layer, the power received by the remote sensor will be dependent upon the depth of water at the point of observation (see p 87 and 89) and upon the concentrations of suspended particles, biological matter and pollutants (see *water quality and turbidity* p 92). The maximum transmission of light is in the .47 - .48 micron blue/green spectral region with the water acting as an optical filter, progressively absorbing radiant energy at longer wavelengths until almost complete absorption occurs in the near infrared (Ref 18 and Figure 8). Suspended sediments, biological material and pollutants (according to their types and concentration) attenuate light transmission and tend to shift the water 'window' from the blue-green toward the longer green and yellow spectral regions. Heavy concentrations of suspended matter eventually restrict remote sensing to surface or near surface spectral or spatial information in all bands, due to almost complete internal reflection (scattering) of incoming EMR other than that which is reflected from the surface. The effects of bottom reflectance in such cases thus becomes negligible.

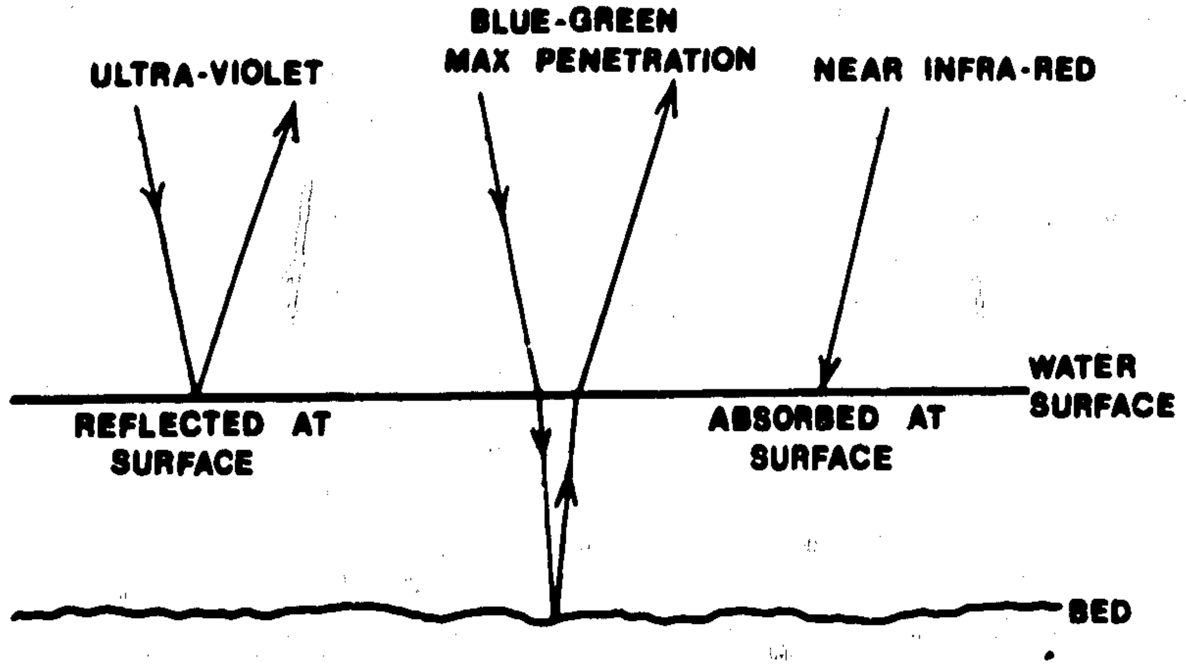


FIGURE 7 Interaction of electromagnetic radiation with a water body

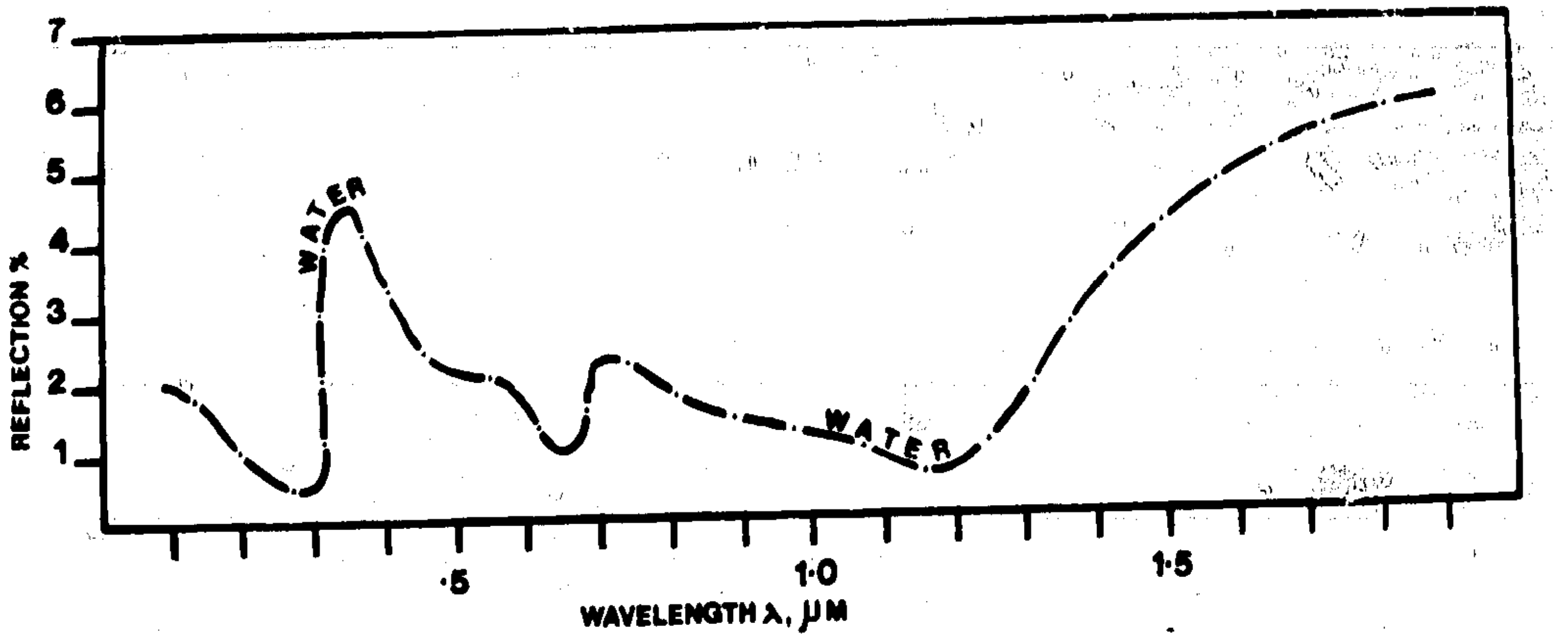


FIGURE 8 Reflectivity of water

4.4 Interaction of electromagnetic radiation with the atmosphere

Scattering

The EMR received by a remote sensor (and that transmitted in the case of active sensors) must pass through a portion or all of the atmosphere. As the electromagnetic field of the radiation interacts with the atmosphere, a reduction in field strength takes place and at certain frequencies the EMR may be totally absorbed. This attenuation is caused by the loss of energy from the EMR to the gas and other molecules of the atmosphere, the amount of attenuation depending largely on the frequency of the EMR (generally the higher the frequency, the higher the attenuation). At high frequencies where wavelengths approach the mean diameter of atmospheric particles and molecules, scattering becomes apparent.

Scattering and attenuation of the incoming EMR to the Earth and the reflected EMR from the Earth's surface is caused primarily by the presence of oxygen, ozone, carbon dioxide, water and other molecules in the atmosphere, as well as dust and smoke particles. Scattering caused solely by gas molecules is known as 'Rayleigh scattering' which predominates between 5,000 - 10,000 metres (Ref 19). In the lower atmosphere the presence of water particles, dust, smoke, industrial byproducts, pollen and other aerosols cause what is known as 'Mie-scattering' which varies greatly according to location (especially to the proximity of large urban or industrial areas), meteorological conditions, time of day, etc. In the visible region, Rayleigh scattering is approximately proportional to λ^{-4}, whereas a combination of Mie and Rayleigh scattering as found in the lower atmosphere was found by Curcio (Ref 20) to be proportional to $\lambda^{-1{\cdot}3 \pm 0{\cdot}6}$. Scattering is the major cause of EMR interference in the visible portion of the spectrum where absorption is found to be insignificant. In the portion of the spectrum lying to either side of the visible however, absorption is much more important, whilst in the longer wavelengths, scattering become insignificant.

Absorption

Energy which is absorbed by the atmosphere produces an increase in its temperature and is re-radiated as thermal energy. Absorption of EMR takes place as a result of the energy necessary to move electrons in the atoms and molecules of the atmosphere from lower to higher energy states. The smaller the binding force between the nucleus and electrons of the atoms that make up the atmospheric gas molecule, the less energy is required to displace the electron to a higher energy level. Also, the higher the frequency, the higher is the available energy of the EMR. Thus for most solid substances, this required energy occurs in the infrared and shorter wavelengths, whilst for most atmospheric gases and vapours, the energy required to produce absorption and resonance is in the longer infrared and microwave regions. Because of this absorption, certain frequencies or bands in the infrared and microwave regions cannot be used for remote sensing purposes (see Figure 9).

Atmospheric spectral windows

It has been shown that the Earth's atmosphere interferes in a complex manner with incoming and outgoing EMR and is subject to considerable variation. Nevertheless, so-called 'spectral windows' can be identified where, at certain frequencies, the amount of atmospheric interference is low. Figure 10 shows an approximation of spectral transmittance of the atmosphere and ionosphere for a range of wavelengths. It is common to attempt to restrict the spectral range of aerially mounted earth sensors to specific atmospheric spectral windows within the EMR frequency range of interest. An example of the 'window' effect is shown in Figure 9 for the attenuation of microwaves by oxygen and water vapour. In

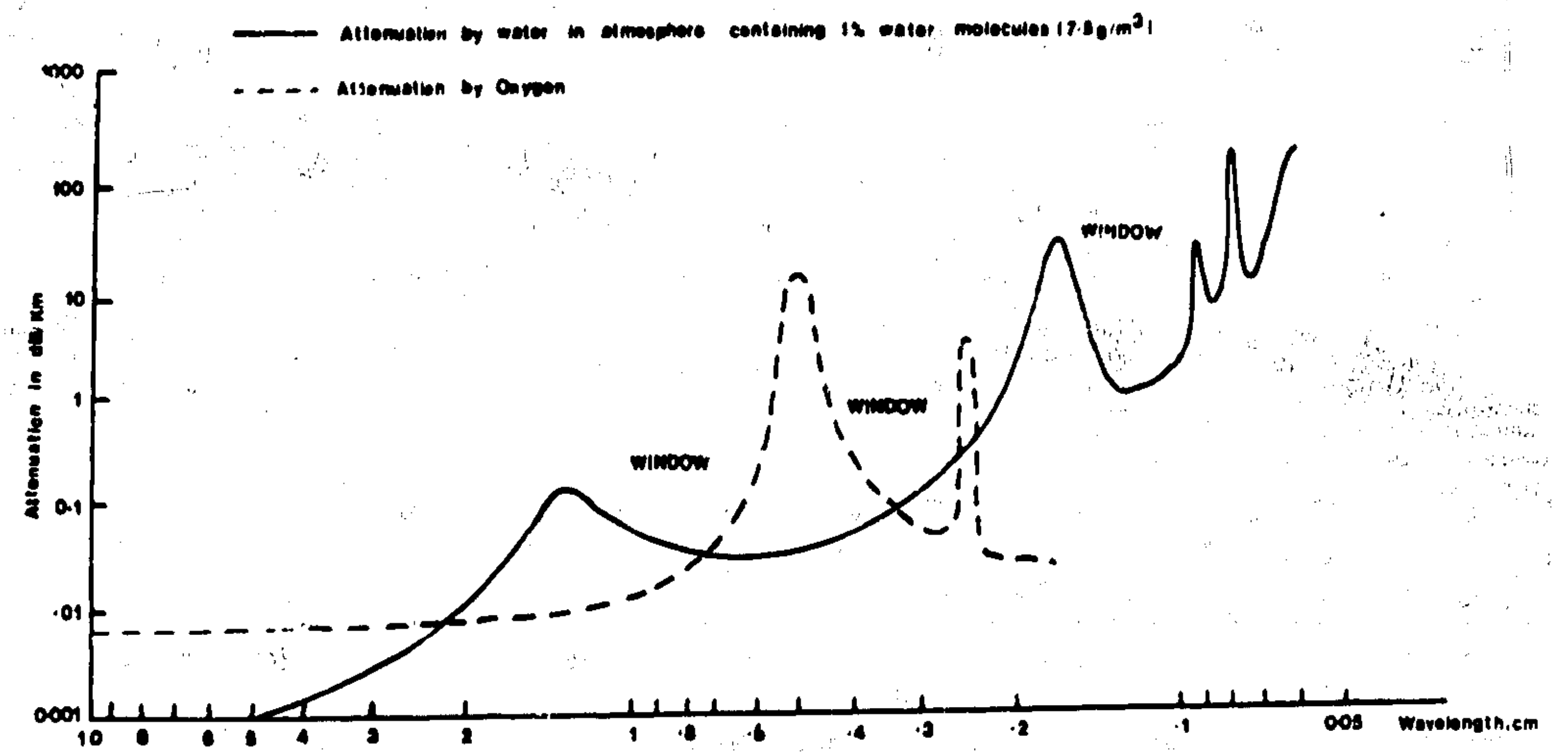


FIGURE 9 Atmospheric transmission windows in the microwave region

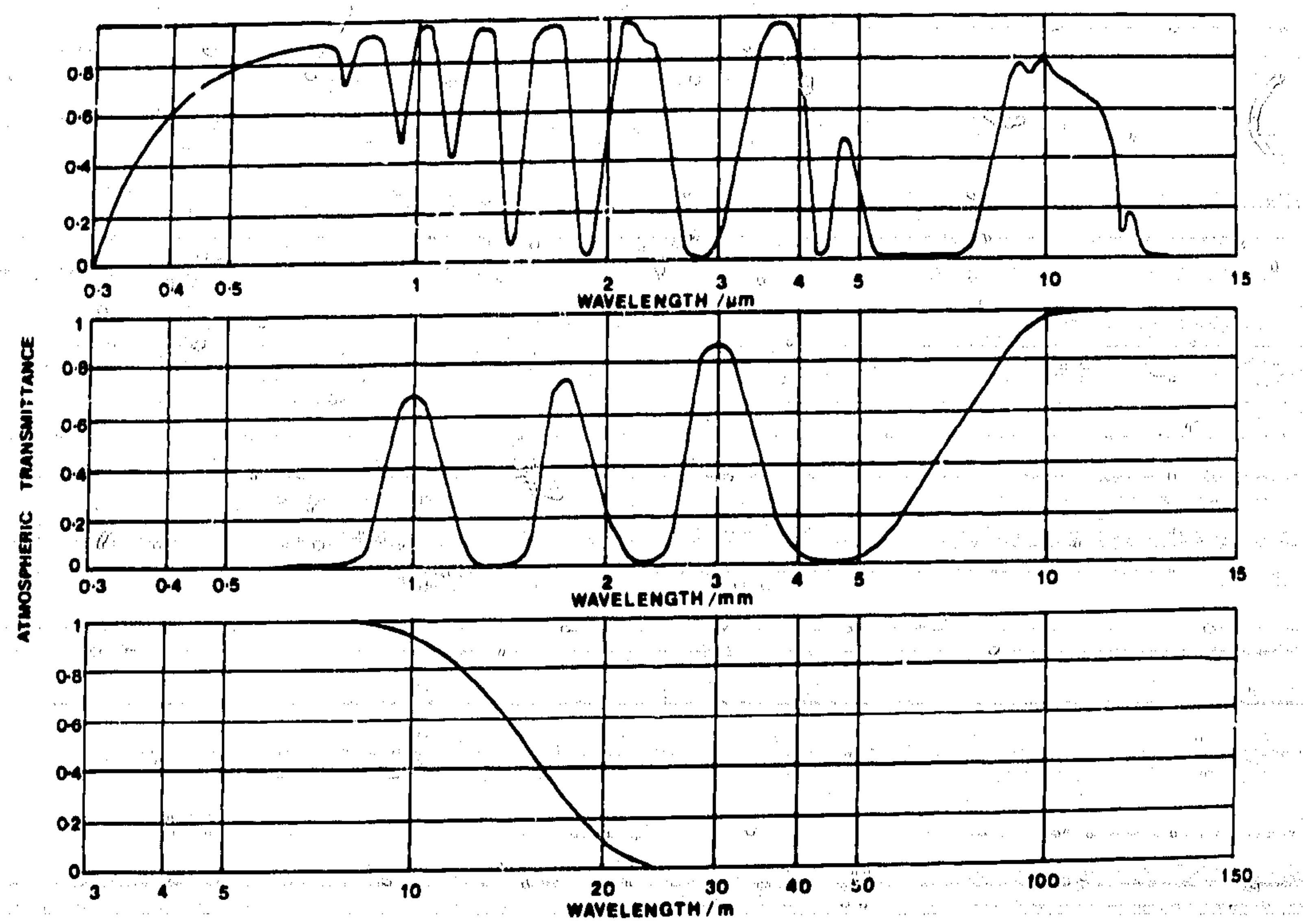


FIGURE 10 Spectral transmittance of atmosphere and ionosphere (trend)

practice it is not always possible simply to choose a suitable 'window', through which to sense. A compromise is often necessary between the ideal frequency required to yield the maximum information about the subject and that frequency which provides minimum signal degradation due to atmospheric effects. It is also possible that the type of sensor needed to receive such a frequency is not suited for use on a particular aerial platform. All these factors must therefore be carefully considered before a suitable sensor/platform/frequency of observation combination can be selected.

5. SENSING APPARATUS

5.1 Sensor platforms

The type of sensor platform chosen to carry out remote sensing observations depends on numerous different factors relating to the nature of the measurement problem to be tackled and the type of data output required. The type of sensor to be used, coupled with the required accuracy, spatial and temporal frequency and duration of observations are important factors to be considered, but equally important factors such as operational costs and their effectiveness, manpower requirements and data processing requirements must be assessed before deciding on the use of a particular platform. Table 2 gives an indication of likely platform capabilities.

TABLE 2 PERFORMANCE OF SOME TYPICAL SENSOR PLATFORMS

Facility	Maximum Payload (kg)	Service Ceiling (km)	Effective Ground Speed (km hr^{-1})
Hydraulic Platform	510	0.03	-
Cross Country Vehicle	7000	-	-
Free Balloon	2000	48	Variable
Tethered Balloon	5000	4	0
Airship	1500	1.5	0 - 80
Aircraft - civil	18000	9	200 - 600
Aircraft - military	4000	22	≈ 2000
Helicopter	3000	5	0 - 300
Sounding Rocket	600		≈ 1400

Ground based platforms

The remote sensing of terrestrial objects from a ground base generally allows the highest possible accuracy of point measurement to be made, coupled with the capability of precise point location and complete control over the frequency of measurement. Good examples of this type of sensing are terrestrial photogrammetric studies (Ref 21 - see also *snow depth p* 139). With many ground-based installations, instrument mountings may be relatively simple to install and when mains electricity is available, power supplies are unlimited. Horizontal atmospheric attenuation may be a problem and in some cases only relatively small areas can be 'viewed' at once, rendering large scale surveys costly. Restrictions on instrument type are few, these being largely governed by the prevailing environmental conditions. Typical instrumentation can range from simple hand held radiometers possessing a visual scale output (Ref 22) to permanently based radar installations linked directly to a computer either for instrument control or for on line processing of data (Ref 23 - see also *ground based techniques* p139). It is normal practice to use ground based measurements to test the validity of information gathered from higher altitudes, but it is not generally valid to calibrate high altitude sensors at ground level due to the unpredictable effects of atmospheric attenuation.

Towers and similar structures

Unless ground based sensors are sited in areas of high relief, only a very oblique view of the ground is possible. To overcome this, towers or similar elevated structures allow the sensors' angle of incidence to the ground to be increased, which is especially useful when studying the EMR of crops or of small controlled experiments. For studies requiring wide spatial sampling, mobile hydraulic-arm platforms commonly known as 'cherry-pickers' allow great flexibility and speed of use and may be capable of lifting an operator with a variety of sensors up to a height of 30 metres (Ref 24). However, the purchase cost or rental of the large variety of such vehicles is rather high.

Low cost remotely controlled platforms

In order to gain a truly 'aerial' view for a small outlay, various types of model aircraft, model helicopters and kites have been used to carry simple sensors up to heights of 500 metres and more (Refs 25, 26 and 27). As special permission is required in the UK to fly model aircraft having a gross weight of more than 10 lbs, the type of sensors carried so far appear to have been restricted to various forms of automatic amateur photographic camera. However, with future improvements in electronics technology, it is quite feasible that simple vidicon systems could be flown and this would overcome the main problem of lack of positional control. The cheapness and speed of operation of this type of platform, coupled with their ability to operate from unprepared ground make their future development highly desirable, especially for the monitoring of many short-lived hydrological events which at present are very difficult to record.

Balloons

Three types of balloon are considered here, but for all three the same principles of buoyancy apply which allow the gross payload or maximum operational altitude to be calculated (Ref 24), the main variables being 1) the volume of the balloon, 2) the type of gas used to inflate it 3) the temperatures of the gas and surrounding air at any time during flight.

Free-flight balloons such as those used for meteorological observations are relatively cheap and can attain altitudes of 50 kilometres, or alternatively they can be set to 'float' at a given altitude. No control over their positioning is possible and wind speeds at all altitudes must be allowed for. Maximum payload capabilities depend on the balloon volume and required operational altitude, but may lie between 5 - 2000 kg. Instrumentation must be automatic and may be retrievable by parachute. Manned hot air balloons are capable of carrying more varied instrumentation, but directional control is still not possible.

Tethered balloons can operate up to an altitude of 5 kilometres with a fair degree of positional control. Smaller versions operating at heights of a few hundred metres have been successfully used in much the same way as model aircraft, but with the disadvantage of longer pre-flight preparation procedures. Winds of up to 35 km/hour have not created problems (Ref 28) and photogrammetric mapping is feasible.

After considerable use during the 1920's, airships are once again being manufactured and promise to offer a relatively stable and controllable platform capable of supporting a payload of about 1500 kg although cases for the economic manufacture of much larger airships have been put forward (Ref 29). As well [illegible] positional accuracy, airships have the advantage over aircraft of being able to remain stationary while airborne for long periods if necessary. A large work area could enable several sensor systems to be operated simultaneously and operational heights of up to 1500 metres are typical. Conventional line scanning sensors could not be used in airships due to their low forward velocity, but it should be possible to design a suitable new scanning or recording system.

Helicopters

Modern helicopters come in many different forms with widely varying payload capabilities (up to several thousand kilograms) and maximum speeds (up to about 300 km/hour). Their obvious advantages lie in their manoeuvring and hovering ability and their capability of vertical take off and landing from unprepared areas. This favours their operation in mountainous or inaccessible areas where they may act both as sensor platform and as transportation for ground observation teams. Disadvantages are their high operation costs (about four times that of aircraft having similar payload capabilities) and high body vibration which necessitates special shock absorbing mountings for other than hand held sensors. Servicing requirements are much more critical for helicopters than aircraft and daily checks may be necessary.

Low altitude aircraft (< 4000 metres)

Aircraft are probably the most widely used form of aerial platform, due partially to their availability, but also because of their suitability

for carrying all types of sensors over a very wide range of speeds and altitudes. They are especially suited for the operation of line-scanning equipment (see p. 42) and they do not have such pronounced vibration problems as helicopters.

Remote sensing below 4000 metres altitude can be carried out from any aircraft, with the final choice being dependent on such factors as aircraft stability, running or rental costs, the type of sensors to be used, maximum airborne time, availability of on board navigational aids, necessary pre-flight preparation time, etc. Most sensors require some form of mounting system which is attached to the airframe in order to either maintain a known sensor altitude in relation to the aircraft, or more commonly, with the aid of a gymbal or gyroscope system, to maintain a constant attitude in relation to the ground (Ref 30). If the aircraft is only occasionally required to carry remote sensing equipment, it may be possible to attach the sensors to the outside of the aircraft and cover them with an aerodynamic pod. This is often necessary with military aircraft where internal space is short. For regular use however, it is more convenient to mount instruments internally and cut a hole in the fuselage floor in order to obtain a vertical field of view, whilst providing in-flight access to the sensors.

When very accurate aircraft positioning is required, such as for blanket photogrammetric surveys, it is usual to choose a relatively large aircraft with good stability characteristics in order to minimise the effect of air turbulence; this being most pronounced at low altitudes. Also, the more sophisticated navigational aids and autopilots are not usually fitted to light aircraft. For qualitative surveys however, light, single engined aircraft are often quite adequate and have the advantage of considerably lower operational costs. For both types of survey, high wing designs are desirable because of their superior downward visibility. The necessary electrical power consumption of several sensors and recording equipment, gyro mounts and de-icing facilities may occasionally be a limiting factor on the use of small aircraft.

High altitude aircraft (> 4000 metres)

Aircraft operating above about 3500 metres require either an oxygen supply or a cabin pressurisation system for the crew and an optical window or de-icing system for the sensors is advisable. Flying at very high altitude is costly because of the type of aircraft required, but aircraft performance and range are increased because of the less dense air so that some large area surveys may become more cost effective from high altitudes. Up to altitudes of 10 km, large aircraft are often favoured (eg Hercules, Belfast) as several sensors can be operated simultaneously, and costs may therefore be reduced if several organisations can share the same aircraft for test or experimental flights. Above 10 km altitude, however, high performance military aircraft are required which are generally of a smaller bodied variety (eg Lockheed U2) with less payload capability.

Although the majority of signal attenuation occurs in the lower atmosphere there is still a gradual increase with increasing altitude which may prove restrictive and costly if high performance aircraft are to be kept on stand-by until clear conditions exist. For this reason, infrared and microwave sensors become most cost advantageous when used in such aircraft, because of their haze and cloud penetration capabilities.

Remote sensing from high altitudes allows instantaneous monitoring of large ground areas, with all the advantages which this entails, plus the fact that a reduction in ground resolution is likely to occur. This can sometimes be used to advantage however as it is, in effect, a form of data compression (6.3) which could enable surface trends such as fault lines, ocean currents, etc to be followed (Refs 31 and 32).

Alternatively, if sensors with smaller fields of view are chosen (ie with longer focal lengths), edge distortions become less apparent and topographic measurement accuracies are less affected by large variations in relief (Ref 33). This, coupled with the fact that positional control is often easier at higher altitudes due to calmer air, means that less rectification of data may be necessary.

Rockets

Only rockets or rocket-launched satellites can carry sensors above 100 km altitude. Sounding rockets typically attain maximum heights (apogee) of between 100-2000 km with payload capabilities ranging from 10 kg to several thousand kilograms (Ref 24). In addition to their high altitude ability, rockets can be rapidly launched in order to either monitor short lived events or to take advantage of clear weather conditions. In such cases (assuming sensor compatibility) the use of small rockets may be more economical than keeping a high altitude aircraft on standby. In undeveloped regions rockets may again have the advantage that they can be launched from mobile platforms, whereas high altitude aircraft require long, high quality, runway facilities. As payloads are generally recoverable from sounding rockets, on-board data recording and storage systems are normally used (Ref 34) and direct photographic recording techniques are often favoured (Ref 35) but line-scanning or vidicon systems may also be used (Ref 24).

Some major disadvantages of rockets are that (a) only very short periods of surveillance are possible - typically less than 10 minutes, (b) cost increases rapidly with increase in payload weight or volume, (c) instrumentation must be automatic and capable of withstanding severe shocks, (d) rocket operations are generally restricted to low population areas where motor parts can fall to ground without causing danger and where sensors and data can be recovered and finally (e) the possibility of rocket or system failure must be allowed for as their reliability may be around 90%.

Satellites

Satellites may be at present classified as either free flying unmanned; free flying manned; or shuttle attached spacecraft. Generally, free flying unmanned satellites have the most flexible orbit possibilities due to their relatively low launch mass, but this also acts as a restriction to on board sensing equipment which must function automatically for long periods. Equipment costs are thus very high due to the rigorous specifications and extensive ground test procedures. Manned space stations are altogether larger, making possible the use and interchange of several complementary sensors which allow specific experiments to be undertaken under the direct control of the 'laboratory' crew. The use of less sophisticated instrumentation is also possible. Direct data recording on photographic emulsion is often favoured on manned satellites as the recorded ground resolutions are superior to transmitted data and the first order imagery may be conveniently returned to Earth with the crew. A problem with both manned and unmanned orbiting satellites is that their orbit cannot be greatly altered during flight, and hence the chosen orbit is usually a compromise between several mission requirements. However, future manned orbiting satellites which will have shuttle links to Earth, should be capable of major orbital changes via the mother shuttle (Ref 36) along with greater flexibility of sensor instrumentation.

The synoptic view of the Earth attainable from satellite platforms allows countrywide surveys to be undertaken without the time lag problems associated with obtaining data from similar low altitude surveys. However, as the field of view of any sensor increases, be it due to increased altitude or increased acceptance angle, its resulting ground resolving ability is reduced. Present satellite imagery is thus unsuitable for many ground studies due to its relatively low ground resolution, especially when sensing in the longer wavelengths.

The nature of a satellite's orbit affects the frequency at which observations may be made at any one point on the Earth's surface. Frequencies of several passes per day are possible if coverage over only a single point is required, but where global cover is called for, this may increase to, for example, one pass in 18 days in the case of LANDSAT 1 and 2 satellites. A geostationary orbit may be chosen to enable continuous monitoring of a part of the Earth's surface, but the area under observation is restricted to mid-latitudes unless an inclined or eccentric circular 24 hour orbit is used (Ref 37). The use of single vector linescanning devices is however not possible in geostationary satellites due to the lack of relative motion between sensor and ground.

Of all remote sensing exercises, those relying on satellites as instrument platforms require by far the greatest advanced planning effort and outlay in terms of time, manpower and overall cost and as such it is essential to establish that the benefits accruing from such exercises can justify their initiation.

5.2 Passive sensors

Passive sensors rely on the reflected radiation component of the incoming solar illumination in the ultraviolet, visible and near infrared wavelengths, or upon the emission of radiation in the intermediate (or thermal) infrared and microwave frequencies. In addition, very short wave gamma radiation is emitted from the Earth as a result of natural radioactive breakdown and may be detected from low altitudes. 'Active' sensors provide their own source of electromagnetic illumination and it is the reflection of this illumination from the target of interest which is detected. An example of a simple 'active' sensing system is the recording of an object in total darkness using a photographic camera fitted with an electronic flash attachment. In the ultraviolet to infrared wavelength range, lasers may be used as the illumination source for active remote sensing, whilst in the microwave and radio region, radars are employed. Extensive technical details and operational considerations of the main sensor types can be found in such documents as the EMI Handbook of Remote Sensing Techniques (Ref 24), but some of the most important factors will be summarised here.

Photographic Cameras

The photographic camera is undoubtedly the most well known and still by far the most widely used type of remote sensor, albeit in many different forms. The basic principles of operation of the photographic camera will therefore not be described, but only those special factors which must be considered for its use as a scientific instrument. This is not to say that all cameras used for remote sensing purposes need be specially designed - indeed, as the quality of mass produced optics is constantly improving, more and more off-the-shelf 'amateur' equipment is being selected for basic remote sensing work.

In comparison with other remote sensors, the photographic camera is efficient in that its image resolution is very high and thus a large amount of data can be collected virtually instantaneously over the whole frame. Typically, 10 million data bits can be stored on a single 70 mm x 70 mm film negative (Ref 38). In addition, as a result of extensive testing and development, most established photographic systems have a high reliability factor. Photographic cameras can record EMR from about 0.3 microns to 0.9 microns, the lower figure being determined by the limit of transmittance of optical glass and the higher figure due to the sensitivity limit of present film emulsions. Special lenses such as quartz or fluorite may extend this range (Ref 39). The geometric and transmission properties of a lens depend on its composition and design, the quality of its surface grinding, the stability of its index of refraction and the effect of coatings applied to reduce reflection and improve colour rendition. Even with the use of high quality materials and techniques, a considerable loss in electromagnetic transmission occurs, especially in the ultra violet and infrared wavelengths, during its passage through the multiple elements of a refractive lens. For this reason reflective optics (ie mirrors) are sometimes used in these high loss regions where the advantage of increased signal strength at the recording film end outweighs the slight loss in geometric accuracy of the reflective optics.

For any lens/film combination, a measure of the image quality is often quoted as a function of resolving power in relation to the original scene. Thus, if a test card is used, under the prevailing conditions of light intensity, image-object distance, camera setting etc., a resolution of say 100 lines/mm may be recorded on the resulting negative for a particular camera. This however gives no indication of the contrast of the original scene or how accurately it has been reproduced. A more meaningful measure of system performance is that of its modulation

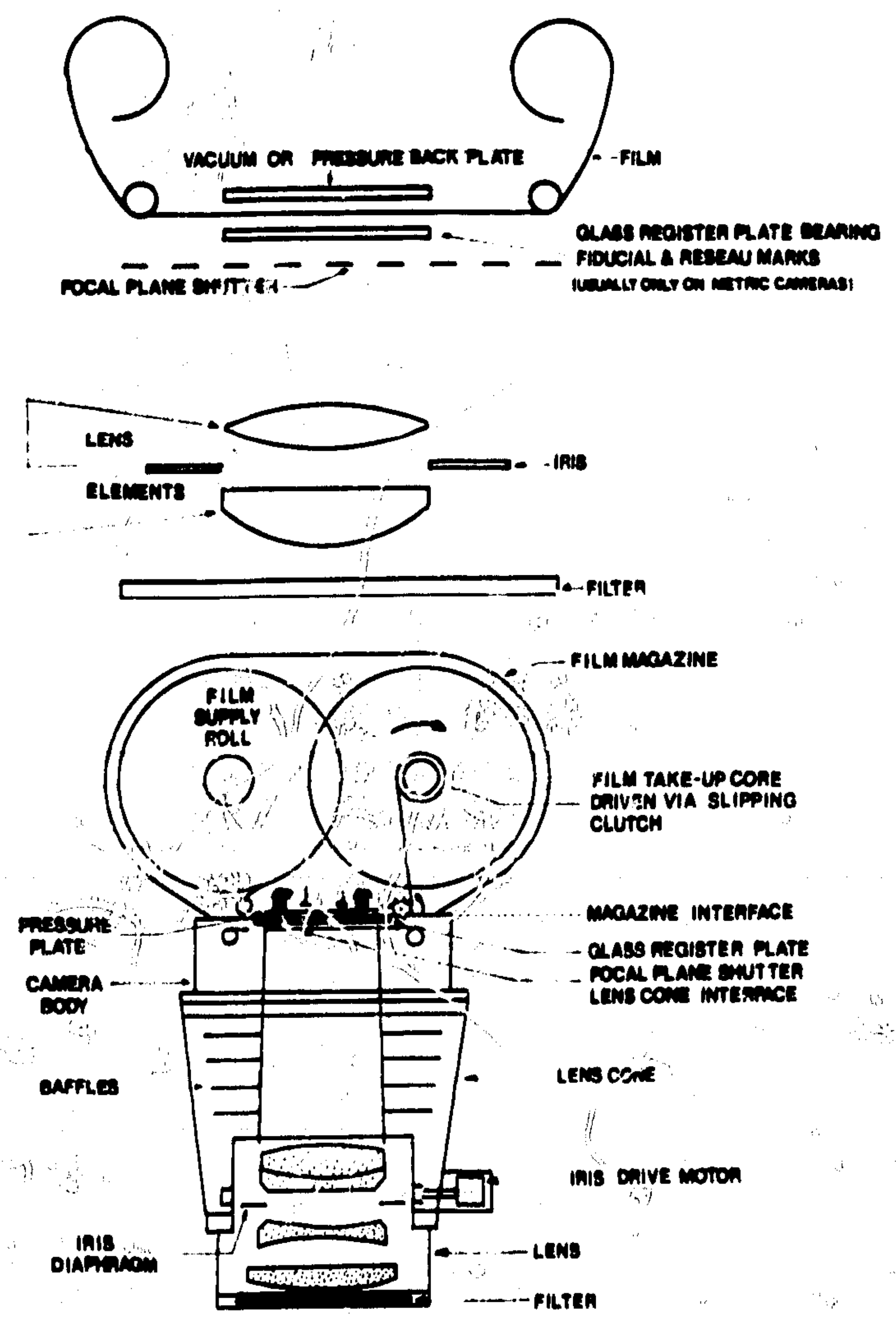


FIGURE 11 Schematic of photographic camera

transfer function (Ref 57). Basically this shows in graphical form the ability of the lens or lens/film combination to reproduce a series of grid lines which modulate, both in their contrast to the background, and in their spacing density. To enable such a function to be established, however, a densitometric analysis of the film negative is required (see p 61).

The wavelength of EMR passing through a lens can be controlled by the insertion of filters in the optical path, but their presence introduces more geometric distortions to the final image. The quality of materials used in a filter determines how sharp is the cutoff of unwanted EMR and so the mistake should not be made of placing poor quality filters on a high quality camera system. Some typical filter spectrophotometric curves are given in the 'Kodak Range of Light Filters' publication (Ref 40).

Other factors which affect image quality when operating from a moving platform are the effectiveness of stabilisation of the camera and the ability to compensate for object motion - both of these effects being normally reduced by the use of very high shutter speeds. In extreme cases obvious blurring of the image occurs, but otherwise the loss of image quality may be difficult to pinpoint. Loss of image quality may also occur as a result of incorrect film exposure which may be difficult to assess from aerial platforms. The presence of atmospheric scattering from haze, mist and pollutants can cause direct exposure readings to be incorrect. For aircraft photography, exposure calculators have been devised which take into account solar altitude, aircraft altitude and speed, film type and haze condition to enable correct exposure to be computed (Ref 41).

Table 3 shows the characteristics of some well known aerial films and it can be seen that as film sensitivity and resolving power vary greatly, careful matching of film type to survey requirement is necessary. This is especially so if the first order film must be used for the production of different types of second order copy, or if information on widely differing surface features must be extracted from the one film base. In addition to the composition of the film emulsion, the stability of the film base is very important especially when used for photogrammetric purposes. Most aerial films are now 'ester' or 'mylar' polyester based, as this material is considerably stronger and more stable to temperature and humidity variations than the old acetate variety. To reduce the possibility of additional distortions occurring during film exposure, all cameras have some form of film flattening device, which may simply be a polished metal pressure plate acting on the film, or the film may be more positively sandwiched between the pressure plate and a sheet of flat optical glass (see Figure 11 and *metric cameras* p 29).

Film development must be carried out to repeatably high standards, which requires strict control over chemical temperature, quality and freshness, film humidity and cleanliness, to ensure that the quality obtained on exposing the film is not degraded during its processing (a possibility which is sometimes not fully appreciated).

The main types of photographic camera which are used for remote sensing purposes are as follows:-

(a) *Amateur Cameras*. The term 'amateur' refers to equipment which can be readily purchased by the general public from photographic shops etc. Amateur cameras can be used successfully in situations where a high degree of spatial precision is not required. Their main advantage over professional equipment is their lower purchase cost resulting from mass production techniques and lower running costs as a consequence of the availability of a wide range of cheap film and accessories (Ref 53). Although their main application lies in the recording of qualitative information (Ref 42), it has been possible to obtain quite accurate photogrammetric ground measurements with good quality 35 mm equipment, provided that the internal orientation of the camera system is known (Ref 43). Where a larger film format is required, 70 mm x 70 mm cameras such as the Hasselblad EL are extremely versatile and are widely used for remote sensing purposes both in standard form (Ref 44) or after the inclusion of a register plate as in the space modified version (Ref 45) which can almost be classified as a metric camera.

TABLE 3 SENSITIVITY AND RESOLUTION OF KODAK AERIAL FILMS

Type	Sensitivity (aerial film speed)[a]	Resolving power (lines/mm) at test object contrast: 1000:1	1.6:1
High definition aerial 3414	8	630	250
Panatomic X 3400	64	160	63
Plus X Aerographic 2402	200	100	50
Double X Aerographic 2405	320	80	40
Tri X Aerographic 2403	640	80	20
Infra-red Aerographic 2424	200	80	32
Aerochrome Infra-red 2443	40	63	32
Ektachrome Aerographic 2448	32	80	40

[a] Aerial film speed for monochrome negative material is defined as 3/2E where E is the exposure (in metre-candela-seconds) at the point on the characteristic curve where the density is 0.3 above base plus fog density, under strictly defined conditions given in ANSI Standard PH2.34-1969. A doubling of aerial film speed number denotes a doubling of sensitivity.

(b) *Metric Cameras*. These are cameras with which precise photogrammetric measurements can be taken due to the fact that any geometric distortions imposed on the image by the camera are known (Ref 46) and can be allowed for at the data plotting stage by the use of corrector plates. The film emulsion used in this type of camera was often laid on a glass base to ensure high stability, but now ester based film is generally used in eithersheet or roll film form. The film is kept flat against an optical-flat, glass register plate, normally by a vacuum system. The register plate has accurate fiducial marks engraved on it which define the optical centre in the final image, and a grid system or Reseau may also be engraved to aid imagery scaling (Ref 47). Additional data such as frame number, real time, aircraft altitude or attitude may be displayed along the edge of the image frame (Ref 48).

Metric cameras used in aerial surveys are usually of a 9" x 9" film format with standard lens focal lengths of 6 inches and 9 inches. However, with recent improvements in lens technology, some wide angle lenses such as the 90° Orbigon are becoming more widely used (Ref 49). Metric cameras designed for taking ground based photogrammetric measurements possess similar features to their aerial equivalent, but are generally of a smaller image format. For distant measurements, the addition of an accurate directional aiming facility is required which may be inbuilt into the camera (Ref 50) or the camera may be attached to a theodolite (Ref 51). Using these facilities, a single camera may be used to take stereo pairs of photographs (see *snow depth* p139). Where relatively close-up measurements are required, a pair of permanently orientated cameras mounted on an adjustable boom allows instantaneous stereo photography (Ref 52).

The final choice of camera for a particular mission depends on many variables, but Clegg and Scherz list admirably the virtues and shortcomings of the 9", 70 mm and 35 mm format types (Ref 53).

(c) *Multispectral Cameras*. Multispectral photographs may be taken either by mounting together several identical cameras or by using an arrangement in which several identical lenses record their separate images on a common film. In both cases selected filters are fitted to the various lenses in order to record different spectral ranges. In the past, up to sixteen-lens systems have been used to investigate narrow band changes in EMR of bodies subject to various controlled conditions. Such systems may be suitable for initial testing purposes, but the quantity of data they produce is too large to justify their regular use. Four-camera systems have now become popular for operational multi-spectral surveys, and several manufacturers such as Hasselblad and Vinten produce suitable mountings and camera linkages to enable their cameras to be used for this purpose (Ref 54). The advantage of having separate cameras is that different film types can be used, but it is essential that the cameras be accurately bore-sighted and their shutters accurately synchronised to allow identical scene coverage. With a common-film camera (Ref 55), filtration and exposure settings are the only factors which differ for each image, as the lens optical axes are pre-aligned and a common focal plane shutter with multiple slits ensures perfect synchronisation. A very useful and time saving advantage of the common-film variety (usually 9" roll film) is that, when interpreting the images on a suitable multispectral viewing device (Ref 55), once one set of images have been aligned to give accurate superimposition, all sets of subsequent images should remain in register. This is not so when separate films are used and often tedious image adjustments are necessary to obtain acceptable registration.

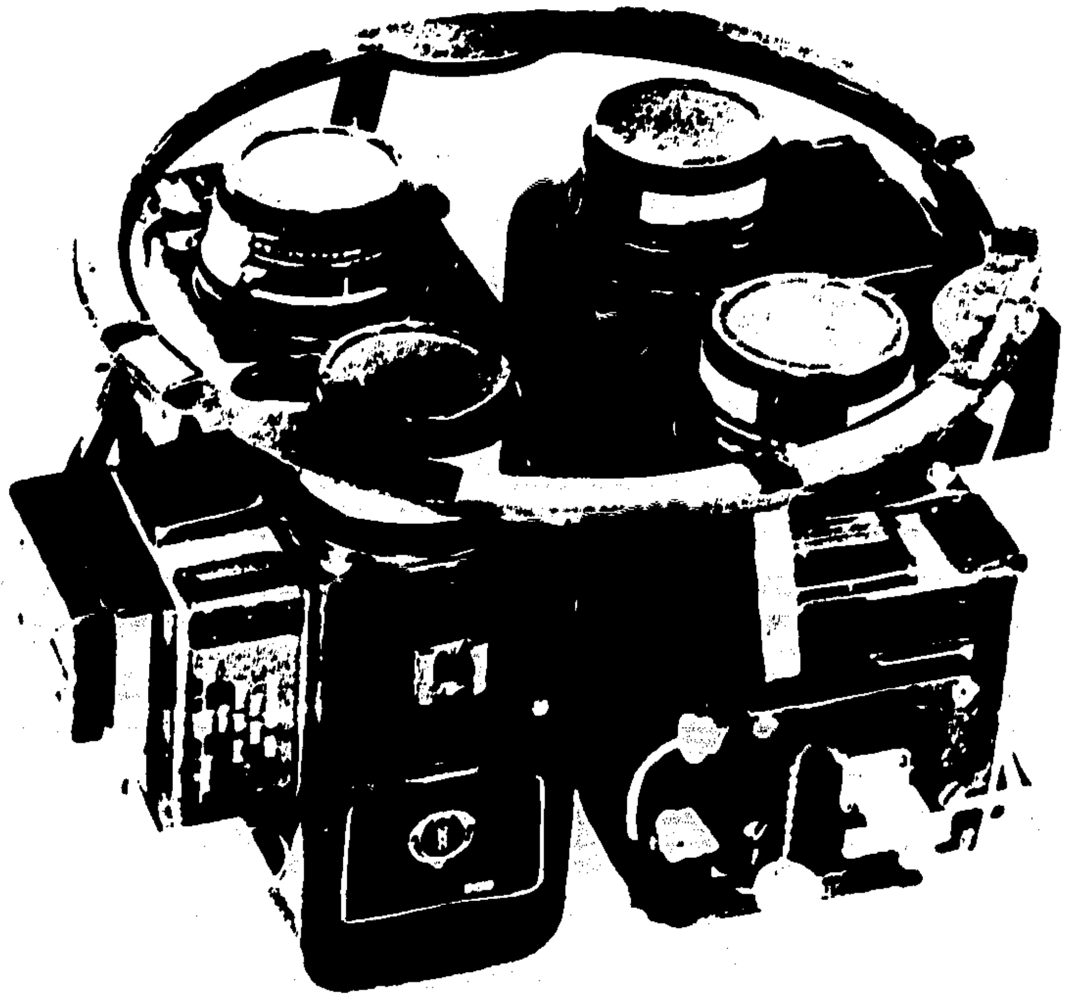


FIGURE 12 Multi-body, multispectral camera

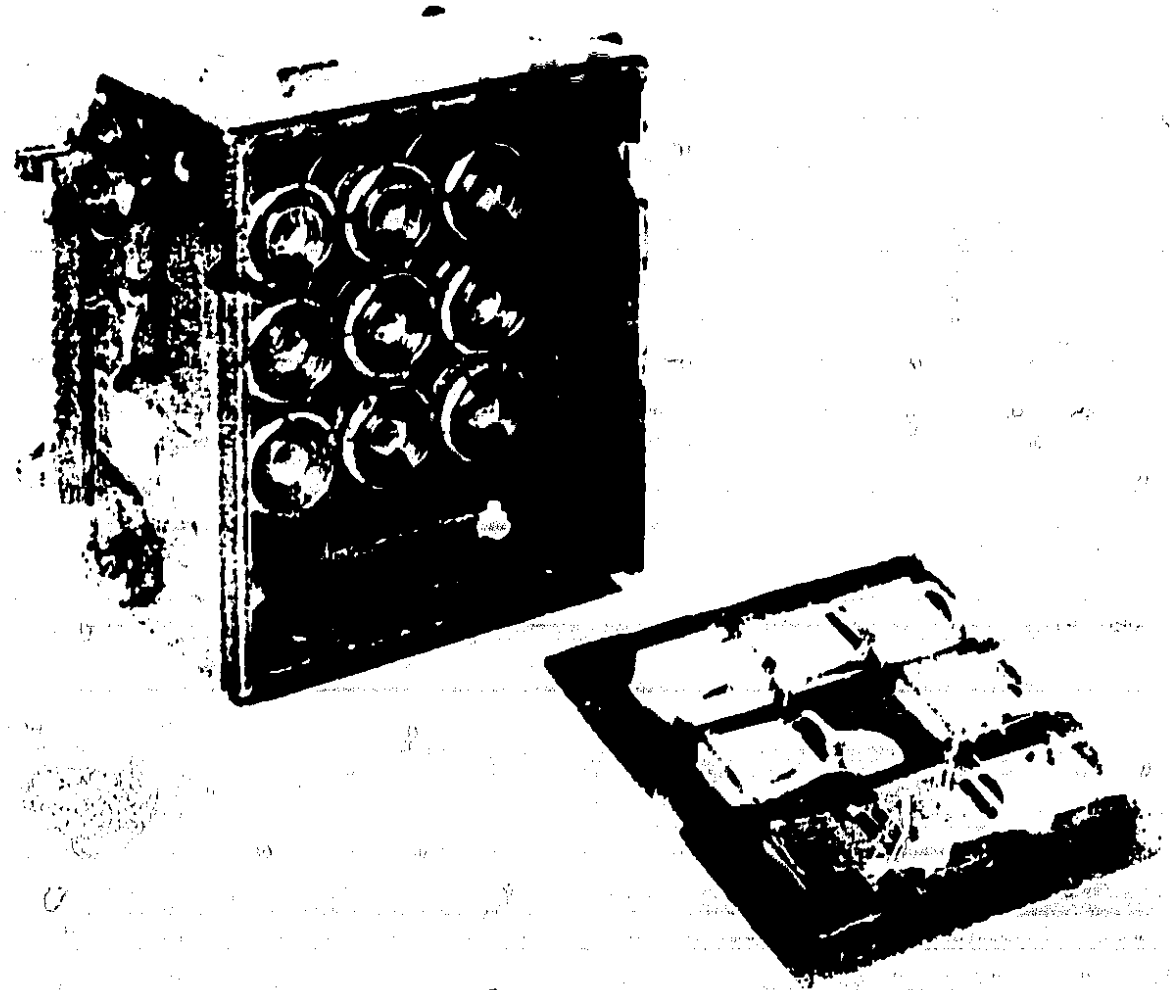


FIGURE 13 Multi-lens, multispectral camera

(d) *Strip Cameras.* This type of camera allows a continuous record of the ground below the flight path of an aerial platform to be made. A stationary lens provides the image in the normal way, but a slit plate, placed in front of the film, only allows a fine line across the film to be exposed at any instant. The film is transported at a speed relative to the height and speed of the platform so that no blurring of the image occurs and a continuous record of the flight-path results. This type of camera is generally used for flight-path recording to aid the location of other non-continuous imagery rather than as a sole data source.

(e) *Panoramic Cameras.* Panoramic scenes (typically horizon to horizon) can be obtained from aerial platforms in various ways. The use of superwide-angle 'fish-eye' lenses on conventional cameras can produce 180° all round vision in a single exposure, but the distortion of the image, especially towards the edges, is excessive. A horizon to horizon strip effect, in a plane normal to the flight path, is produced by the old principle, scanning lens camera which produces a less distorted, high resolution image. This basic idea is continued in the highly sophisticated military reconnaissance panorama cameras which, in combination with the strip camera principle, provide continuous very high resolution, low distortion imagery (Ref 56).

Although the direct photographic system is a very simple and efficient way of storing vast quantities of information, computer controlled data analysis techniques cannot be carried out directly from the photo image. The image must first be scanned by a densitometer in order to convert the emulsion grain densities into digital or analogue form. This conversion process is time consuming, costly and must inevitably result in some loss of image quality.

Vidicon Cameras

The necessity to convert from photographic image to digital or analogue signal to carry out computer processing is by-passed by using a vidicon (television) camera. Vidicons also have the added reliability advantage of no or very few moving parts. Also, the vidicon camera retains the synoptic advantage of the photographic camera in that all points in the image are derived at virtually the same instant in time by the incorporation of a shutter mechanism, unlike the various forms of linescanner which will be described shortly. There are two type of vidicon camera, the direct beam and the return beam.

(a) *Direct Beam Vidicon.* A diagrammatic arrangement of a basic direct beam vidicon tube is shown in Figure 14. The tube is normally an evacuated glass envelope containing an electron gun which faces a thin photoconductive insulating layer (the target) deposited on the end window of the tube. The electron beam is scanned over the surface of the target, thus removing any positive charge and stabilizing the target at zero voltage. Between the target and the inner window surface is a transparent film of conducting material held at a positive potential of about 30 volts. When an image is formed on the target, its illuminated regions become slightly conductive and start to collect a positive potential from the charged layer in proportion to the brightness of the illumination. This positive charged pattern is retained without degradation until the electron beam scans the surface again and restores it to zero equilibrium by depositing electrons. An analogue signal then appears as a displacement current in the back-plate connection and this is then amplified to be subsequently stored or displayed in some form.

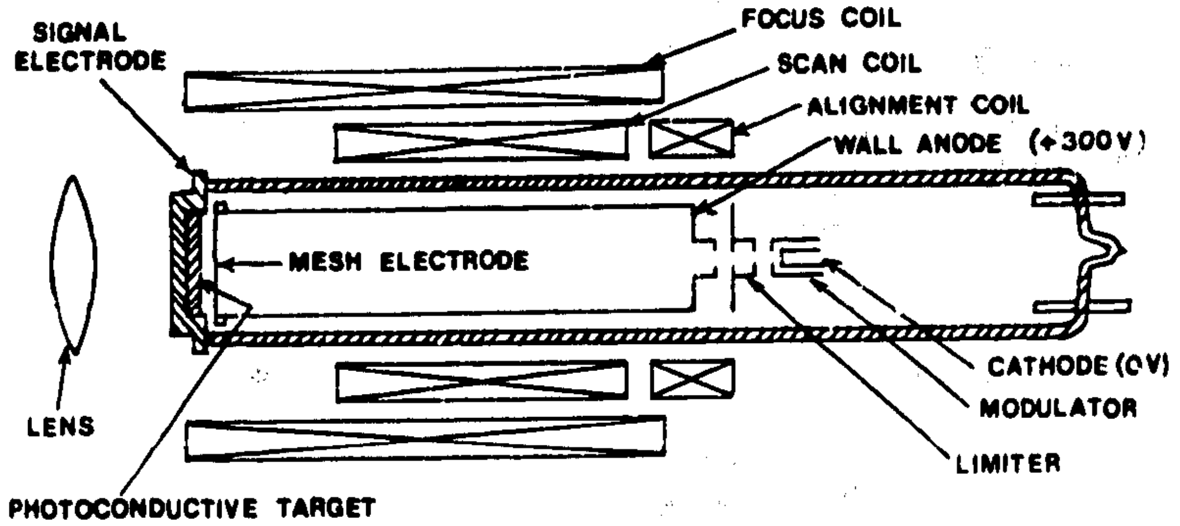


FIGURE 14 **Diagrammatic arrangement of basic vidicon tube**

Direct beam vidicons have been extensively used in the past from aerial platforms and have the advantage of a very large useful dynamic light range (variation in scene brightness) typically of between 100:1 and 1000:1 in bright conditions. The use of a lens aperture system can extend this range up to 10^5:1. An extensive account of the capabilities of both direct and return beam vidicons and of the possible modifications to the basic vidicon principle are given in Ref 58, a NASA report on Advanced Scanners and Imaging System for Earth Observations.

(b) *Return Beam Vidicon (RBV).* This is probably the most widely used form of vidicon tube, due mainly to its higher efficiency at low light levels. Whereas the direct beam vidicon relies on the strength of the incoming radiation to induce a signal, the return beam version relies on the strength of the returning electron beam after it has neutralised the charge on the target. This means that the system can operate in poorer light and that the target can be made smaller without loss of resolution. Figure 15 shows a simplified RBV layout. High target illumination results in a high induced charge and a weak returning electron beam which is then amplifiedin an electron multiplier. As in the direct beam vidicon, the image production on the target is instantaneous and by means of a photographic camera type shutter, the photo induced image can be retained for several seconds. This is often necessary, (on satellite platforms for instance) where target scanning must be carried out slowly because of the limitations of the on board recording and telemetry systems. Also, slower scan rates allow higher resolutions and higher signal/noise ratios can be achieved. Although the image resolution is higher with RBV's, they have a lower dynamic range, ie they cannot handle extremes of light. The LANDSAT satellite RBV system for instance has a dynamic range of only 30:1.

The spectral sensitivity of the vidicon is dependent on the composition of the photoconductor target (Ref 58). Their electromagnetic sensitivity extends from the ultra violet to near infrared wavelengths (Figure 16) and with special materials thermal infra red sensing is

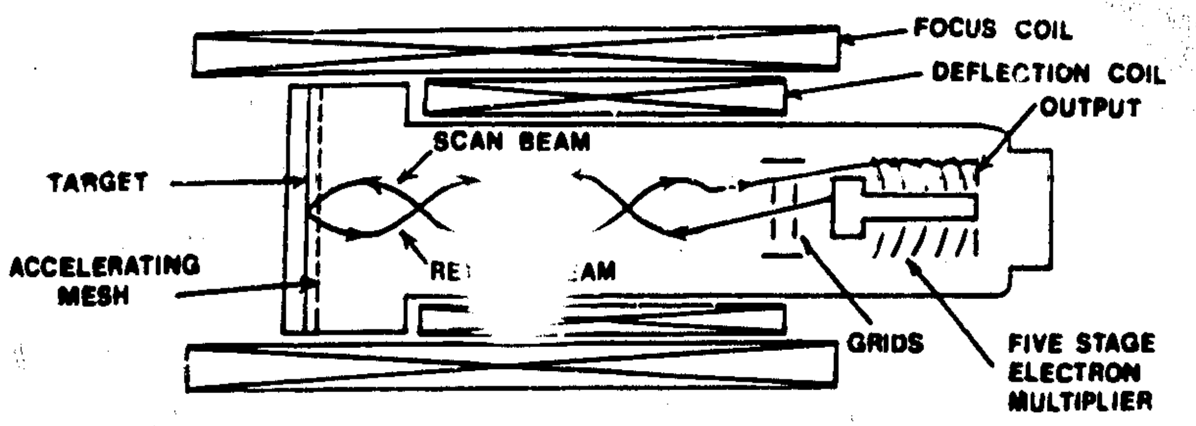


FIGURE 15 Diagrammatic arrangement of return beam vidicon tube

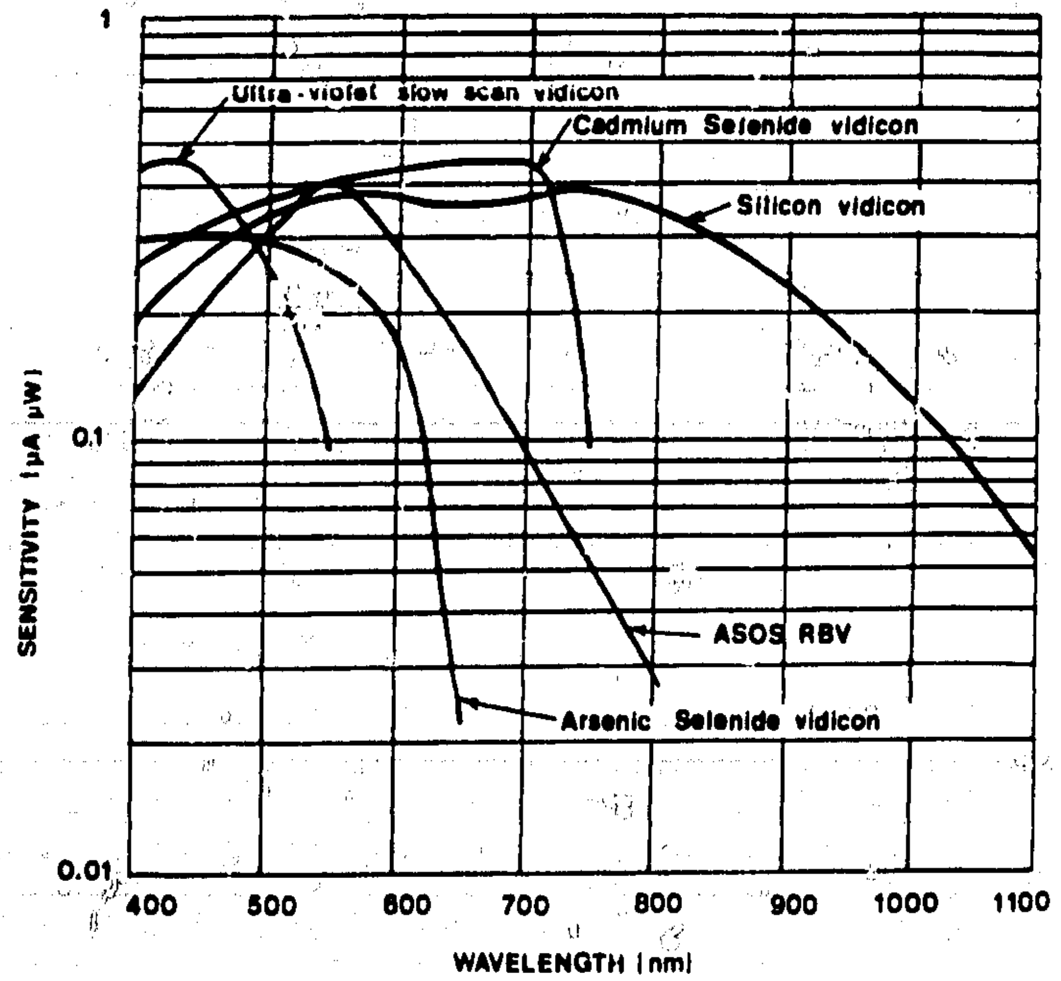


FIGURE 16 Spectral sensitivity of some slow scan vidicon photoconductive insulators

possible. Within this range, discrete wavebands can be monitored by placing filters within the cameras optical path. However, because of the slow cycle period required to ensure good photometric accuracy (typically 15-30 seconds), the lag time between different spectral bands, using only one vidicon, would be unacceptable. To produce simultaneous multispectral imagery, either separate boresighted vidicon tubes must be used, or, for better image registration, one optical image may be split (using for example dichroic mirrors) and directed to each vidicon (Figure 17). Alternatively where exact registration of images is not essential, a single, fast-cycle tube can be used, with each separately filtered image being stored in a video memory unit, prior to its recording (Ref 59).

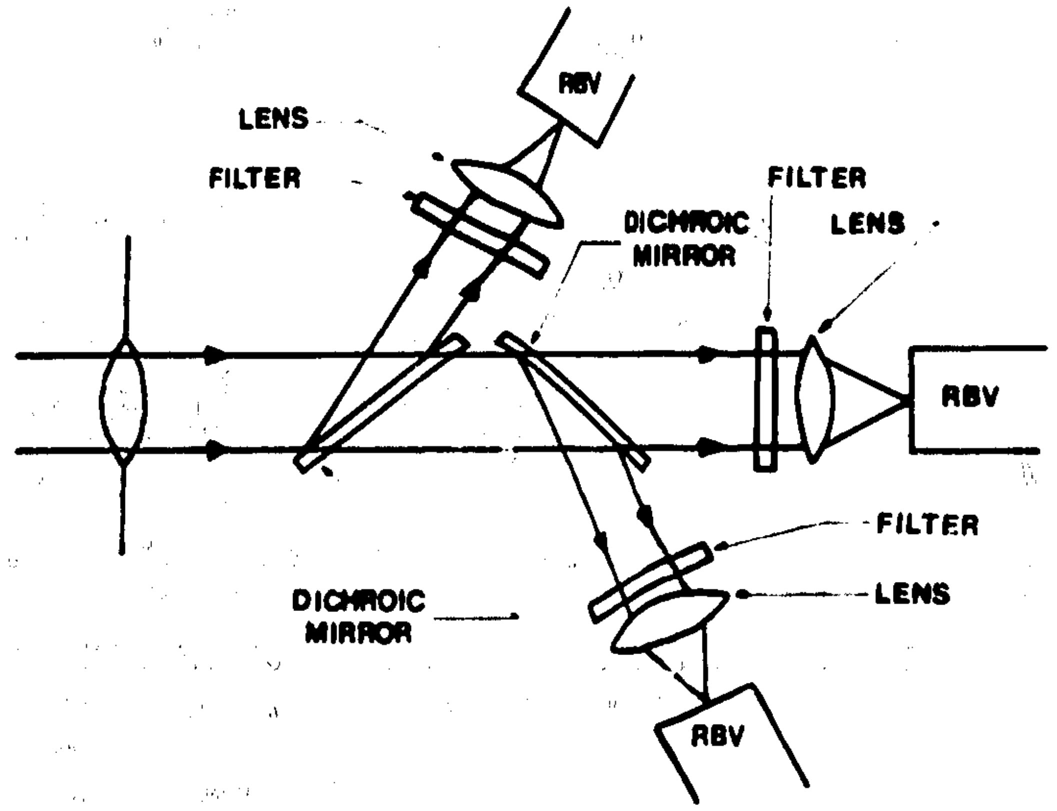


FIGURE 17 Optical arrangement of a typical multispectral vidicon

For daylight remote sensing from manned platforms, direct photographic recording is at the moment probably more desirable than the use of vidicon recording techniques. However, in poor light conditions or when operating from unmanned platforms, the advantages of vidicons far outweigh those of the photographic camera, especially when their possible thermal capabilities are taken into account.

Non-scanning radiometers

The main components of a remote sensing radiometer are (1) a lens system to concentrate the EMR, (2) filters to limit its wavelength, (3) a detector to convert the EMR into electrical energy, (4) electronics to amplify the signal, (5) a signal recorder or display system, (6) an optional int[illegible] reference radiation source to allow absolute radiation measure[illegible] made. Their function is to measure the magnitude of the [illegible]ce which arises from reflected or scattered solar radiation o[illegible]mission from the Earth's surface or atmosphere. The elect[illegible] power available at the radiometers detector head is proportional to [illegible] field of view of its optics. Spot radiometer measurements taken from aerial platforms are limited in use due to their predetermined field of view and spectral range. Narrow angle radiometers can sample only a very small percentage of the available scene, and although their resolution and measurement accuracy may be high, their results are difficult to relate to spatially variable parameters. In contrast, wide angle radiometers produce a mean radiation value for a given field which may be useful for monitoring changes in large uniform bodies such as se[illegible] or snow surfaces. Non-scanning radiometers are often used as back-up instrumentation to more comprehensive sensors. For example a spot radiometer may record absolute EMR values along the central path of a photographic aerial survey, from which further information may be extrapolated, using scene brightness values, from the photographs.

Radiometers may be used to measure EMR throughout the range from ultraviolet wavelengths to radio frequencies, but are most commonly used in the infrared and microwave regions. Portable infrared radiometers for example allow very accurate ground verification measurements of surface temperature to be taken (Ref 22).

(a) *Visible Light Radiometer*. A very simple form of radiometer is the well known photographic light meter. Figure 18 is a circuit diagram of a typical exposure meter in which the electromagnetic detector is in the form of a cadmium sulphide photo resistor which changes its electrical resistance inversely to the strength of visible EMR falling on its surface. This variable resistance changes the current passing around the circuit which is recorded on a visual ammeter scale.

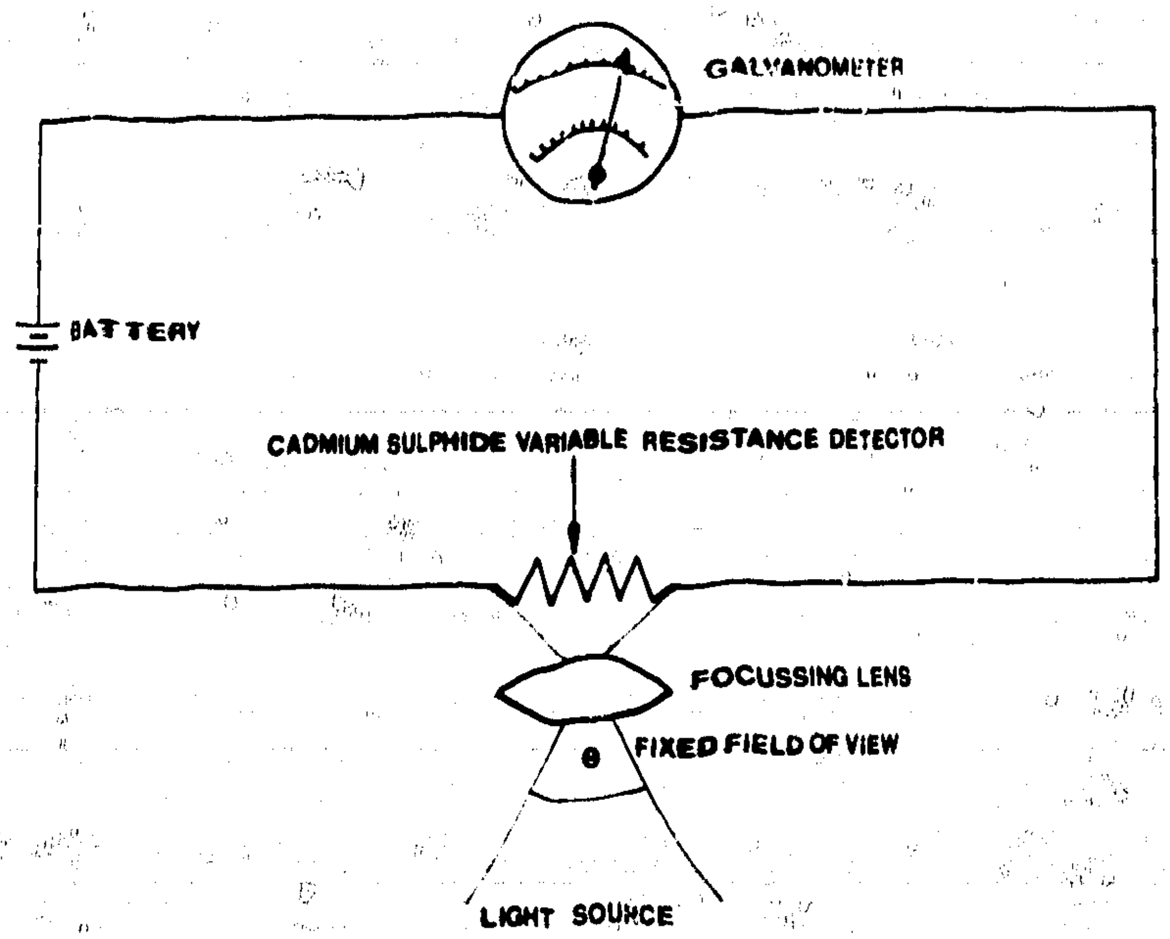


FIGURE 18 Circuit diagram of a simple light meter

(b) *Infrared Radiometers*. A schematic drawing of a simple infrared radiometer is shown in Figure 19. The objective lens concentrates the radiation onto the temperature controlled infrared detector. The chopper, which is a rotating set of reflective vanes, alternately allows the detector to be directly illuminated by incoming radiation and then after cutting off this source, it allows the detector only to receive precisely known reflected radiation from its own radiation reference cavity. The detector converts these alternate radiation values into a small alternating electrical signal, the amplitude of which is directly related to the absolute temperature of the target. This signal is then amplified and may be recorded on magnetic tape, digital or dial output or graph (Ref 22).

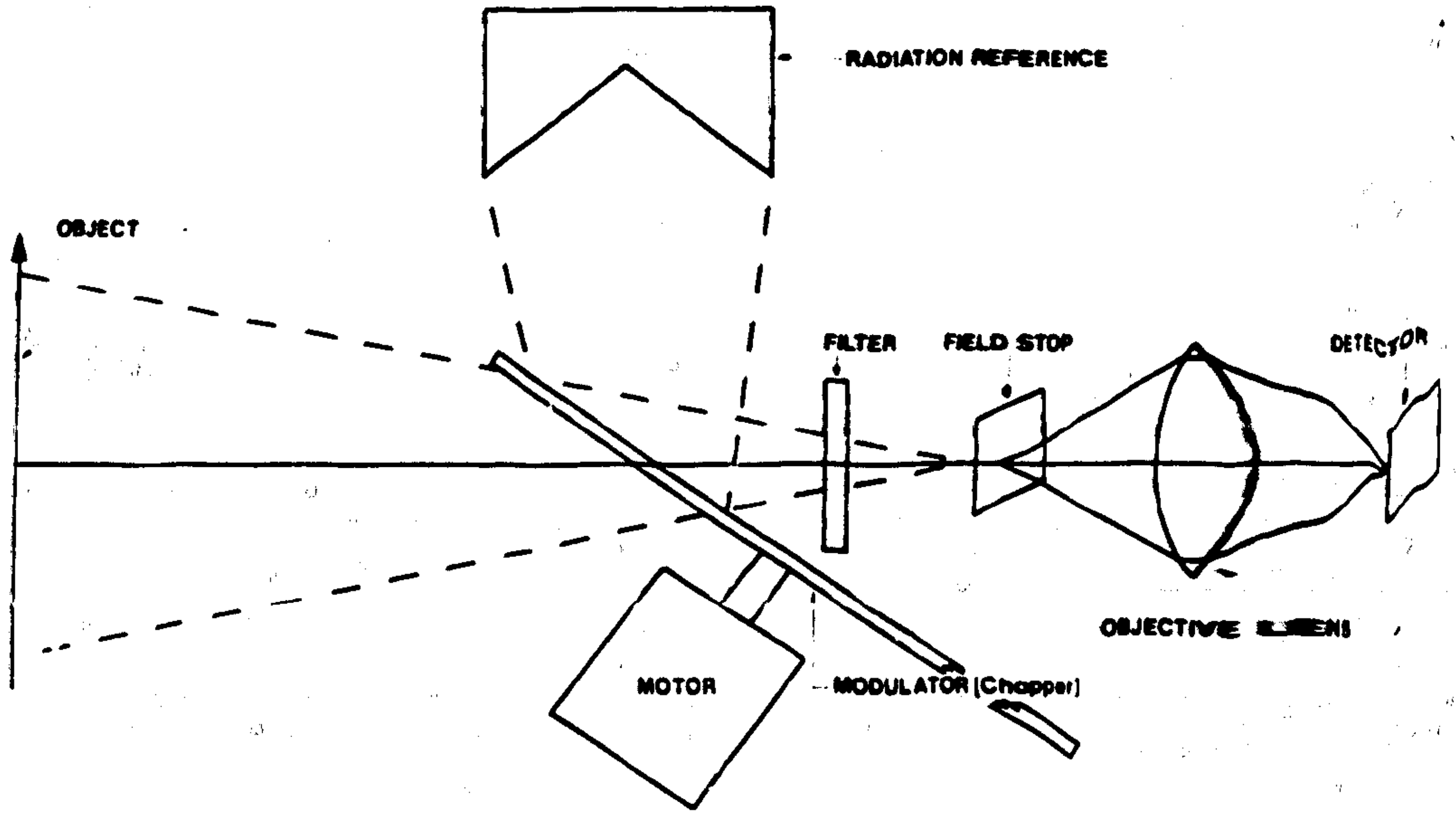


FIGURE 19 Typical infrared radiometer with internal reference source

(c) *Microwave Radiometers*. Microwave radiometers record emitted radiation in the 1 mm-1 metre wavelength region, but are normally restricted to one of the several microwave 'windows' which occur at approximate frequencies of 1.4, 5.0, 13.5, 37 and 90 GHz (see Figure 11 for equivalent wavelengths). The microwave radiometer measures brightness temperature which is a function of both the temperature and dielectric constant of the ground and may be expressed by the function:

$$T_a = e\,T_g + (1-e)\,T_s$$

where T_a = brightness temperature measured at the antenna

T_g = temperature of ground in degrees Kelvin

T_s = brightness temperature of the sky

e = emissivity

$1-e$ = reflection coefficient.

Emissivity is a function of the dielectric constant and to a lesser degree, the roughness of a surface. In the microwave region, useful additional information can be obtained by measuring separately the horizontally and vertically polarised emission of a body (Ref 60 and Figure 20). For instance, surface roughness effects are more apparent in the brightness temperature measured by vertically polarized microwaves.

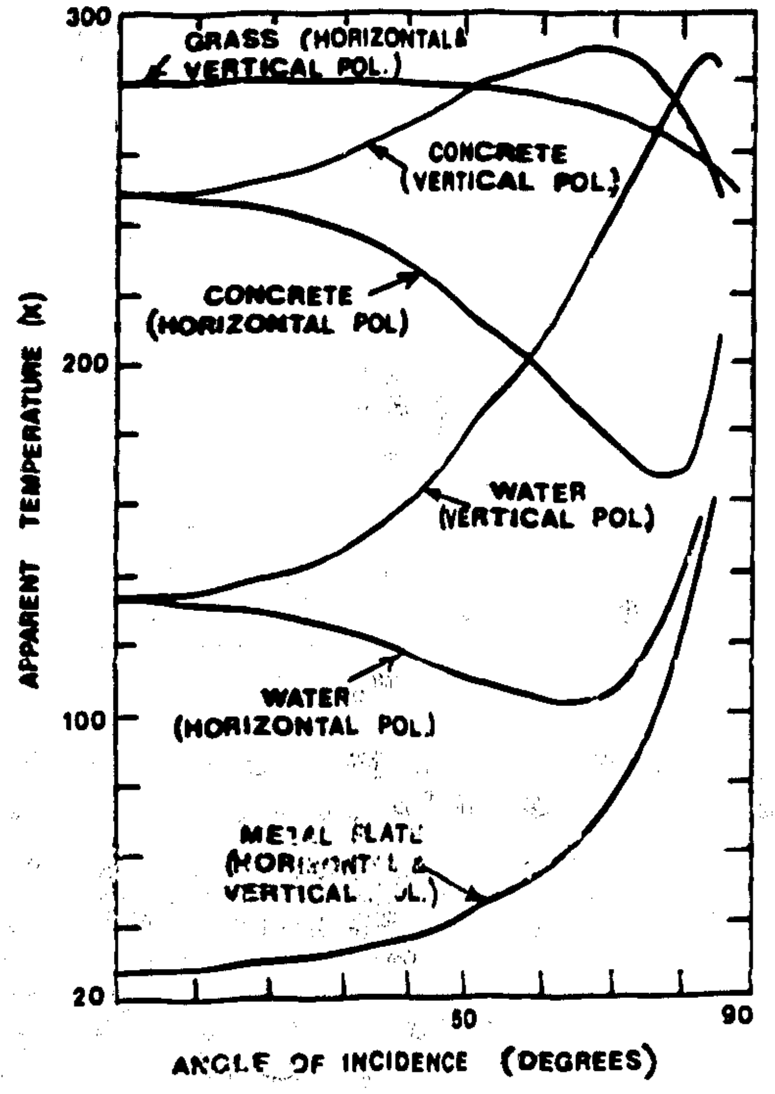


FIGURE 20

Horizontal and vertical polarisation. Apparent temperatures of surfaces at 19.4 GHz

Whilst infrared radiation can be collected with a small optical system, signal strength is so small in the microwave region that some form of antenna is required for its collection, the size of which determines the maximum spatial resolution of the signal. The pencil beam antenna is the most commonly used and here the maximum signal intensity is concentrated in a small round spot (see Figure 21). The parabolic reflector concentrates the incoming radiation onto a small horn which further concentrates the energy prior to its amplification. Takeoff feeds can be mounted so as to select a horizontally or vertically polarized signal. A description of different antenna designs is given in the European Space Research Organisation Report CR-71 (Ref 61).

The broad band EMR detected by a microwave detector does not differ statistically from the EM noise produced by the receiver itself, or by the background noise which is fed to the receiver by the antenna, therefore the receiver must be highly sensitive (their power rating generally lies between 10^{-11} and 10^{-20} watts). The most commonly used receiver configuration is the signal modulated Dicke type (Figure 22). Here, the incoming microwave signal is alternated with a constant source reference signal prior to its amplification, which means that any variations in receiver-gain act on both the signal and reference so that their relationship is not altered. The signal may then be filtered to the required band width and then recorded in either analogue or digital form. Aircraft microwave radiometers of the Dicke type have been used for frequencies ranging from 1.4-100 GHz (20-0.3 cm wavelength).

The signal received by a pencil beam antenna is not exactly as its name implies, the difference between the ideal and actual configuration

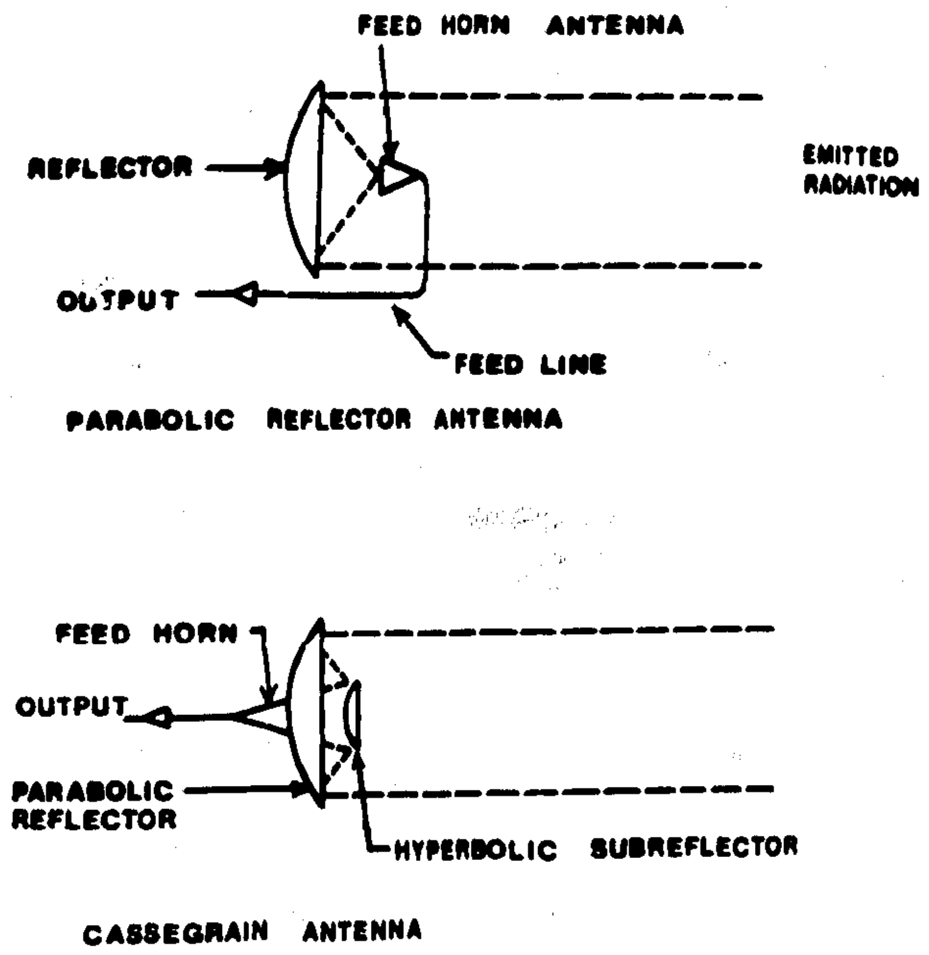


FIGURE 21

Pencil beam antennas for microwave radiometers

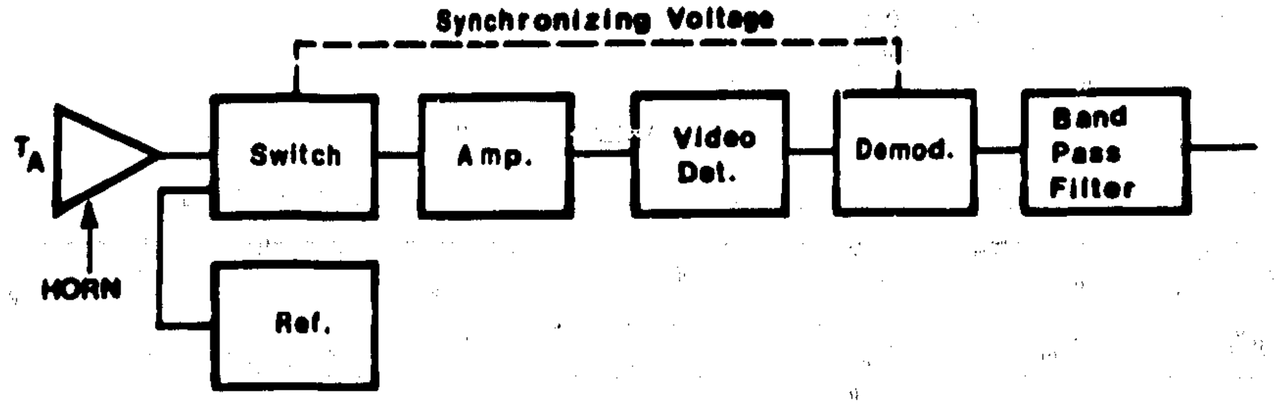


FIGURE 22 Signal modulated radiometer receiver

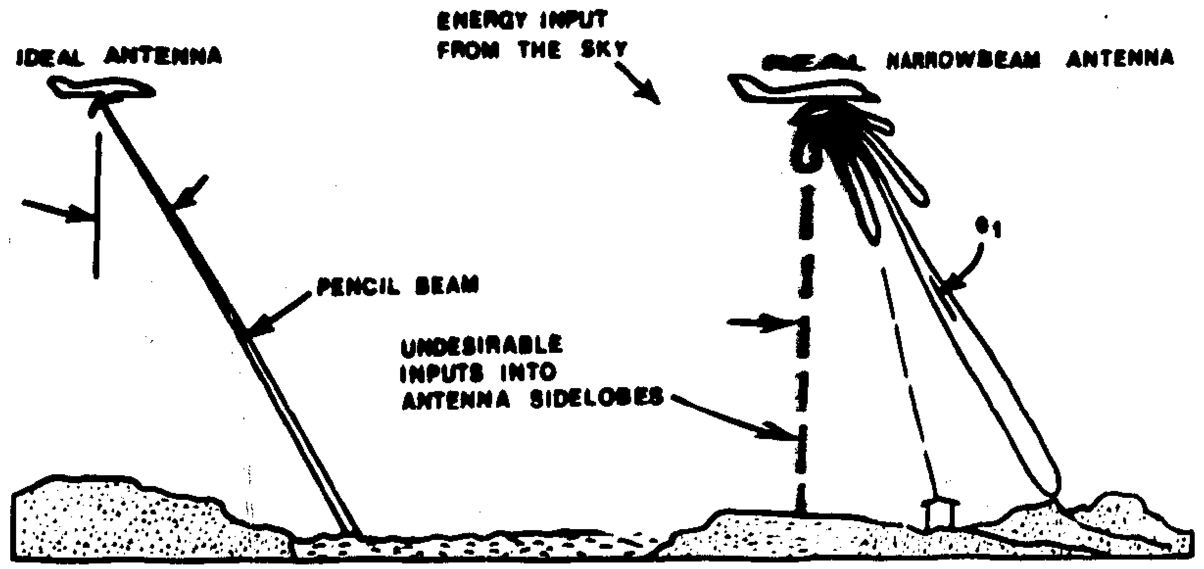
being shown in Figure 23a and the resulting output signal as shown in Figure 23b. The effect of the side lobes is to produce signal noise and therefore complete rectification of the signal is complex. However, values of surface temperature correct to ± 0.1 - 0.5°K are possible using microwave systems, this representing the mean value of the ground resolution element. The ground resolution is related to the altitude of the platform and to the beam width of the radiometer antenna; the beamwidth being a function of wavelength and size of antenna aperture, thus:-

$$\theta_B = 1.2 \times \frac{\lambda}{D} \text{ radians}$$

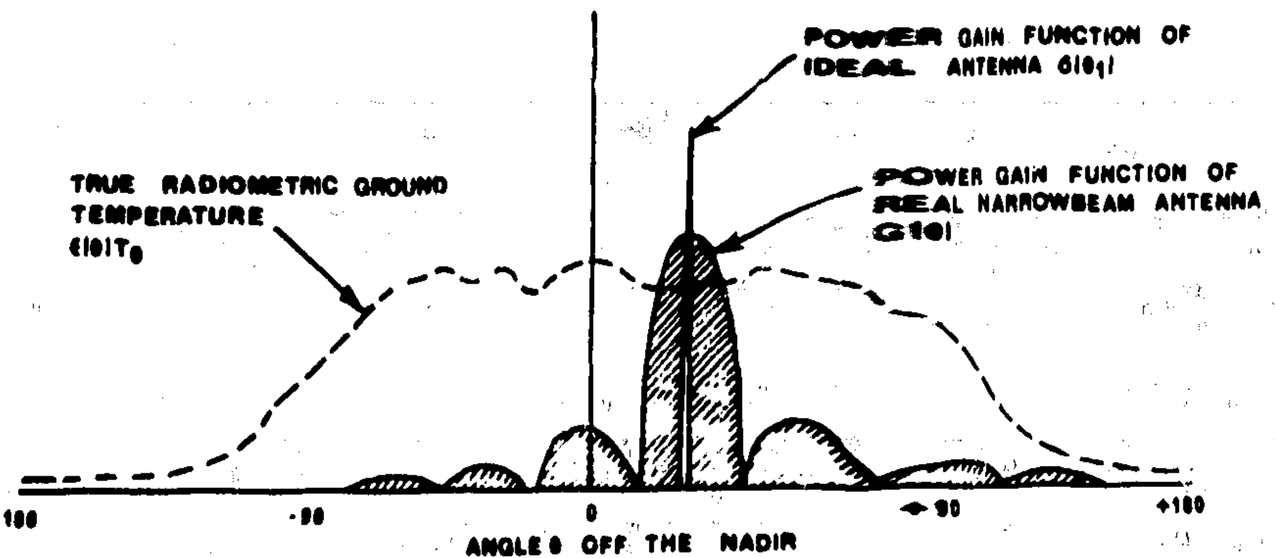
where θ_B = beamwidth

λ = wavelength

D = diameter of antenna.



a Measurement of Radiometric Temperature at θ1



b Degradation of True, or Absolute, Temperature by Antenna Side Lobes

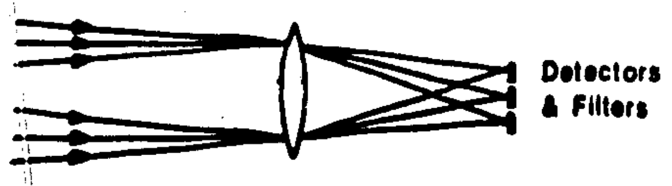
FIGURE 23 Temperature measurement with narrow beam radiometer

For a platform at a height H, the effective ground resolution would be $H\theta_B$. For example, assuming λ = 30 mm, and D = 1 metre, at a platform height of 5 km, the ground resolution would be 180 metres and at a satellite altitude of 500 km the ground resolution would be 18 kilometres! Thus, in order to achieve acceptable ground resolutions, very large antennas are required, especially at the longer wavelengths.

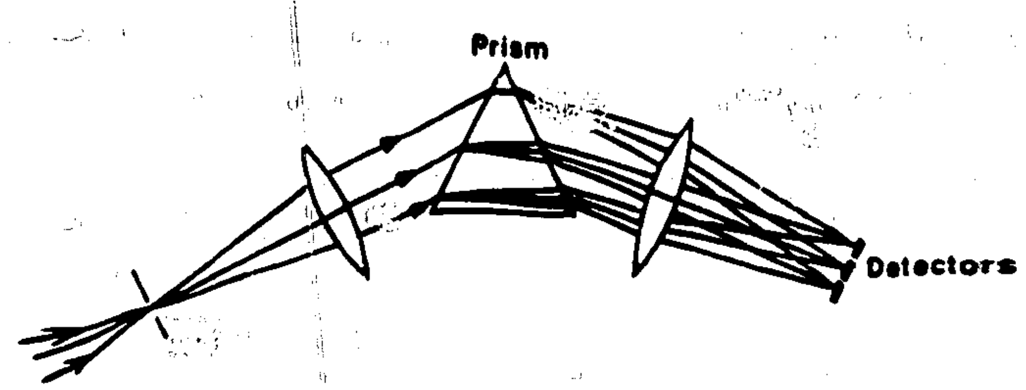
Spectrometers

Spectrometers detect EMR in a similar way to radiometers, but have the addition of a dispersive element within their optical path such as a prism, optical grating or variable interference filter (Figure 24 and Ref 62). This breaks the incoming EMR into narrow spectral bands which may be measured separately using various types of detector. If a mechanical or electrical chopping system is included to allow a signal from an internal white or black body reference to be alternately viewed by the detector, then absolute levels of signal strength may be derived (see Figure 25). The use of circular variable interference filters as the dispersive element, enables a narrow band-pass (eg 8-14 microns) to be sampled across the whole wavelength range of the instrument to a high degree of precision - any given wavelength being selected by the rotation of the wheel to a particular angle.

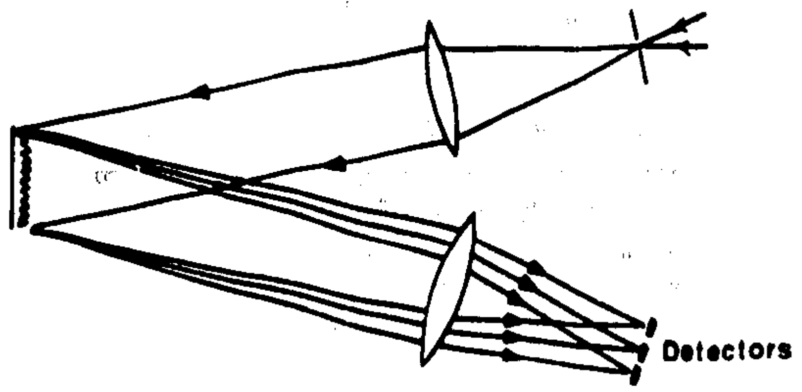
Such a system is especially suited to high speed computer controlled operation and data handling as may be found in satellite systems, and it has the advantage of requiring only a single detector (Ref 63).



DISCRETE FILTER SPECTROMETER

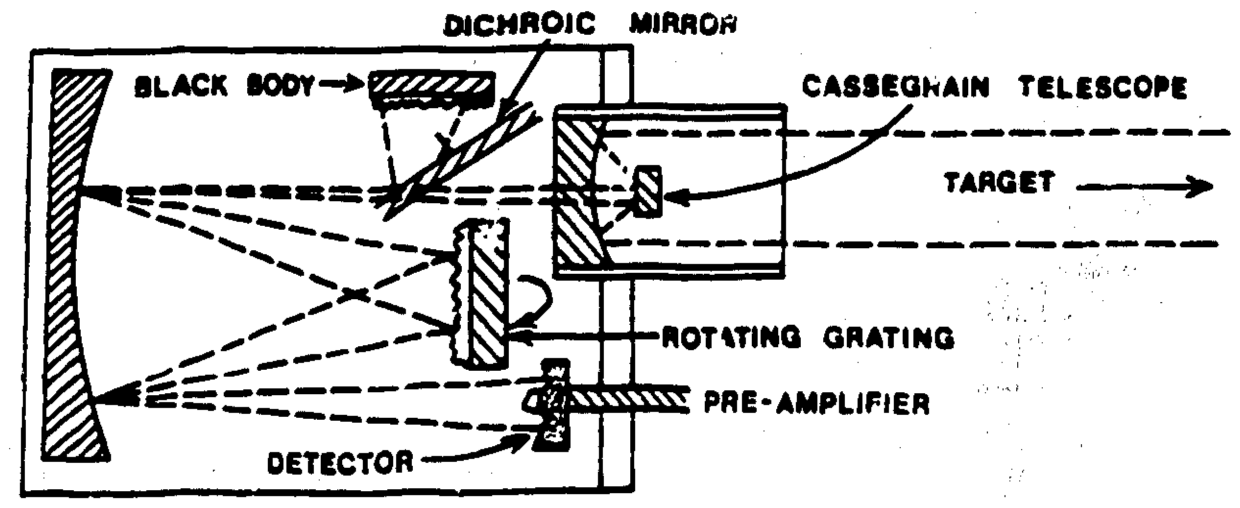


PRISM SPECTROMETER

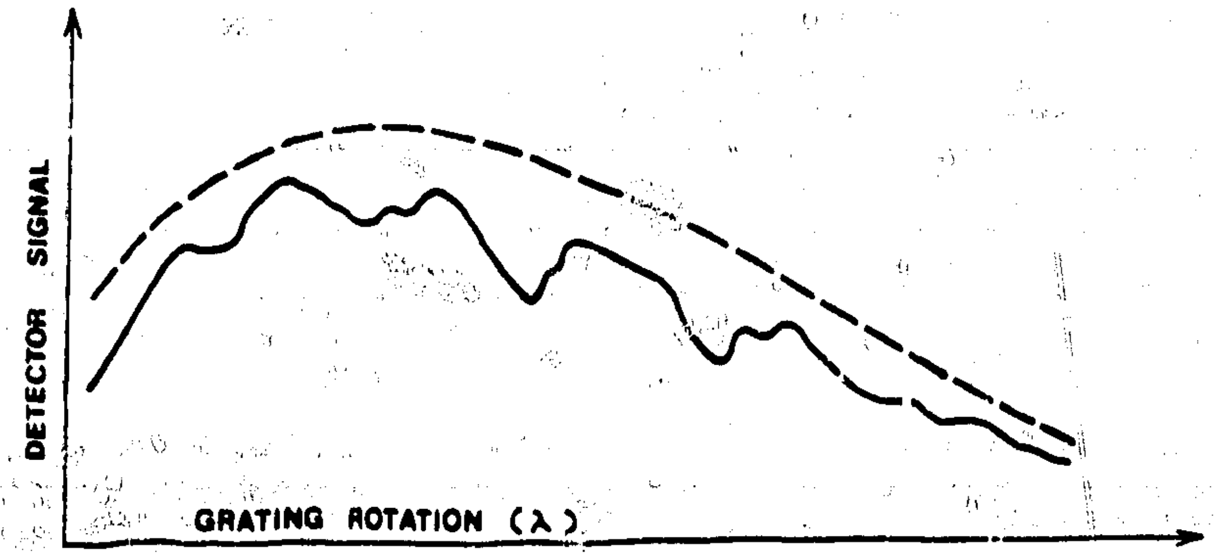


GRATING SPECTROMETER

FIGURE 24 Spectrometer configurations



SINGLE BEAM (FASTIE) EBERT-TYPE SPECTROMETER



BLACK BODY REFERENCE AND SPECTRAL CURVES DERIVED FROM SINGLE BEAM SPECTROMETER

FIGURE 25 Operation of single beam spectrometer

For terrestrial remote sensing from aerial platforms, spectrometers are mainly used for the detection of atmospheric and water-bound pollutants (Ref 64), for the detection of certain gases above mineral deposits or for the detection of specific rock compounds, but their potential for feature identification is great. Ground based spectrometers are used extensively for obtaining accurate ground reference observations.

Scanning radiometers

In order to combine a high radiometer resolution ability with a large ground sampling ability, some form of scanning system must be incorporated into the radiometer optics. If the sensor platform is to remain stationary, a scanning system which operates in both the X and Y planes must be devised. In most cases, however, the relatively uniform forward motion of the platform (aircraft and satellites being most commonly used) provides a single continuous X scan, whilst an optical/mechanical or electronic system provides the Y scan.

Figure 26 shows the most commonly used scanning configuration in which, ideally, strips of ground perpendicular to the flight path are scanned at a rate relative to the speed and altitude of the aircraft and to the resolution of the radiometer, so that no gaps or overlapping of ground strips occur. Image distortion occurs as a result of the changing incident angles of the optical path to the ground and because of the resulting variation in scale due to changing surface relief and to erratic platform movements (more so with aircraft than with satellites). These distortions can largely be overcome by the use of suitable inertial detectors and rectification procedures with the result that in the case of the LANDSAT multispectral scanner imagery for example, (where the high platform altitude helps to reduce scanning distortions), quite high cartographic accuracies can be achieved (Ref 65).

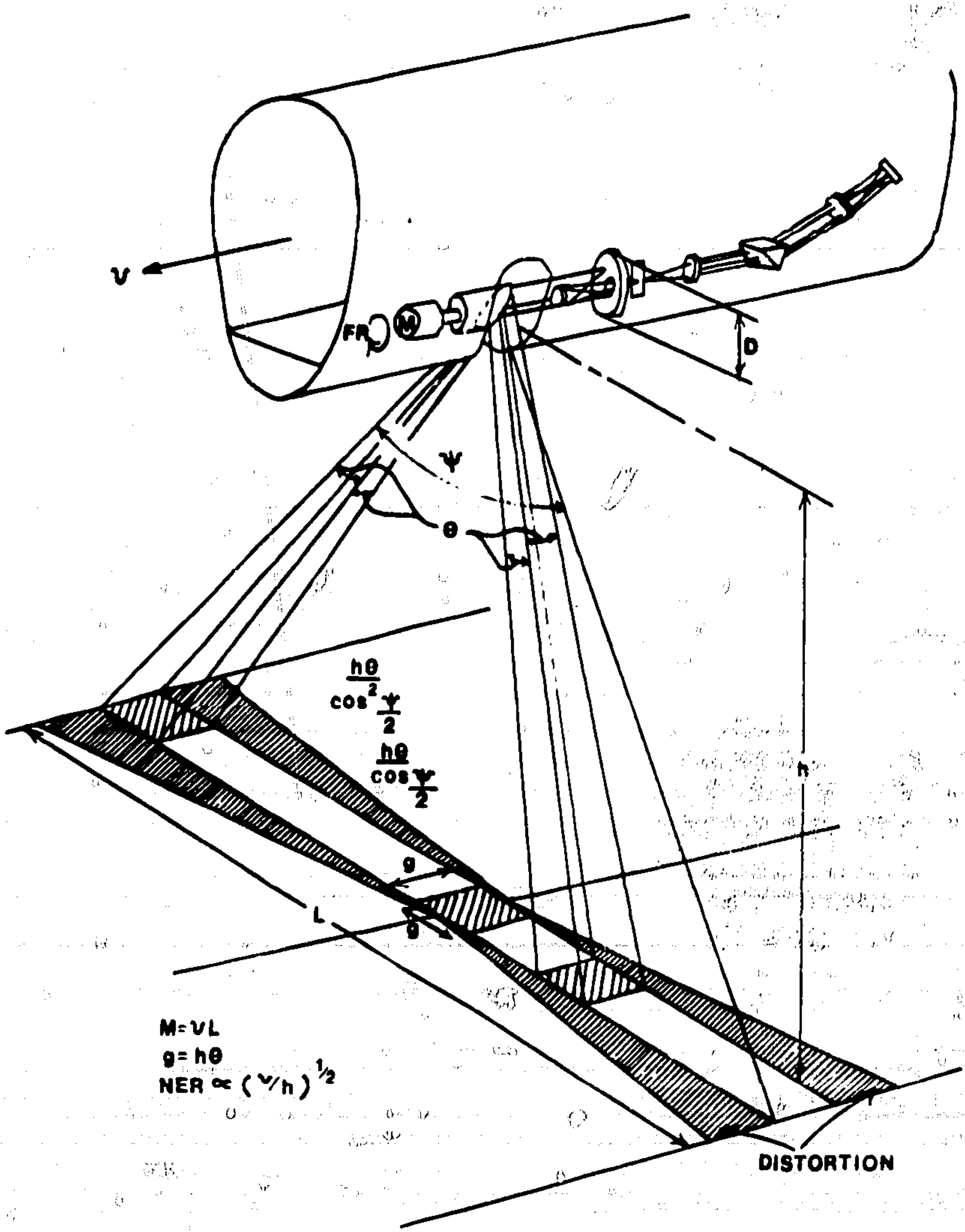
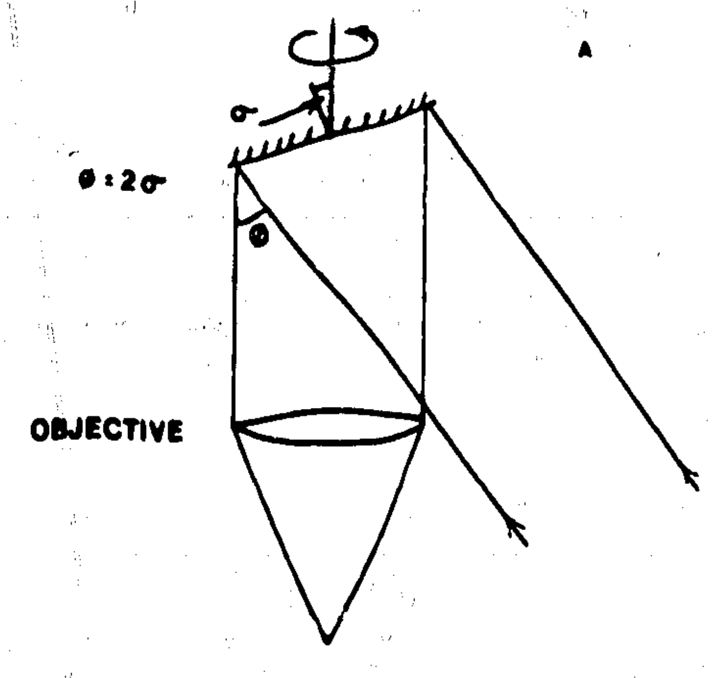
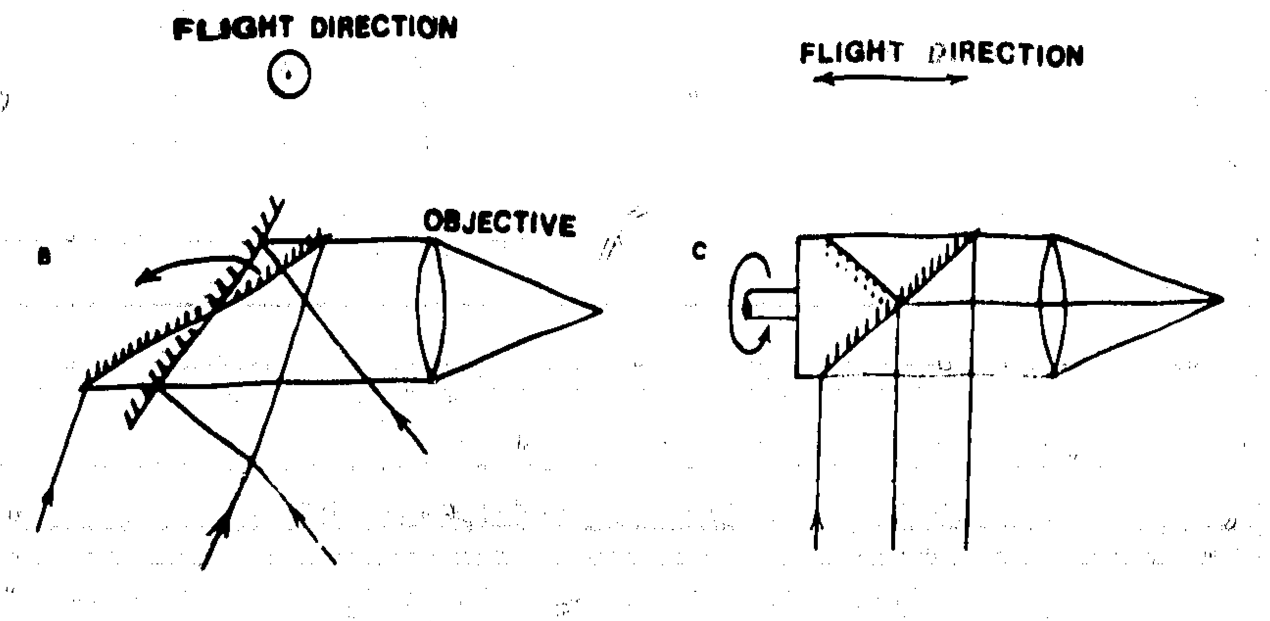


FIGURE 26 Geometry of basic airborne scanning system

A schematic layout of the most commonly used single scanning radiometer head is shown in Figure 27c. This design achieves a ground scanning action by the mechanical rotation of an elliptical mirror inclined at 45° to its rotational axis which is set parallel to the platform flight line. As the mirror traverses the ground swath, the relative orientation of the incoming radiation path through the objective of the instrument does not change, because the system is entirely symmetrical about its axis. This makes the design ideal for the inclusion of an absolute radiometric calibration source. This would normally be sited above the ground-facing aperture so that alternate ground and calibration signals are obtained for each mirror revolution. Many other means of scanning exist which may produce oscillating, linear or conical scanning actions (see Figure 27a and b and Ref 62) but the above rotational system is the most commonly used. Scanner heads having a single mirror rather than two or more mirror facets are generally favoured because of the difficulty in achieving identical performance from each facet of a multifacet system.



OBJECT SPACE CONICAL SCANNER



VIBRATING MIRROR SCANNER

45° ELLIPTICAL MIRROR SCANNER (AXE-BLADE SCANNER, DOTTED)

FIGURE 27 Scanning actions of linescanner mirrors

(a) *Infrared Linescanners*. These generally operate in the atmospheric infrared 'windows' of 3 - 5 microns and 8 - 14 microns wavelength, thus allowing day or night time surface temperature sensing, but not cloud penetration. The strength of infrared radiation of the Earth's surface, as measured by a line scanner, is a function of surface emissivity and temperature, thus:-

$$E = kw(T)^4$$

where E = infrared radiation

k = a constant

w = emissivity of the viewed object

T = ground temperature.

A typical infrared scanning and image recording system is shown in Figure 28 in which the incoming infrared EMR is focussed onto a suitable detector (Ref 66) such as mercury cadmium telluride which is normally super-cooled by a liquid inert gas to increase its sensitivity. The mirror is rotated by an electric motor, at normally several thousand r.p.m., so that for each resolution, it views first the ground source then the cooled black body signal. Recording of the detector's linear electronic video output, after amplification, can be either directly onto magnetic tape, or by the exposure of a photographic film via a glow

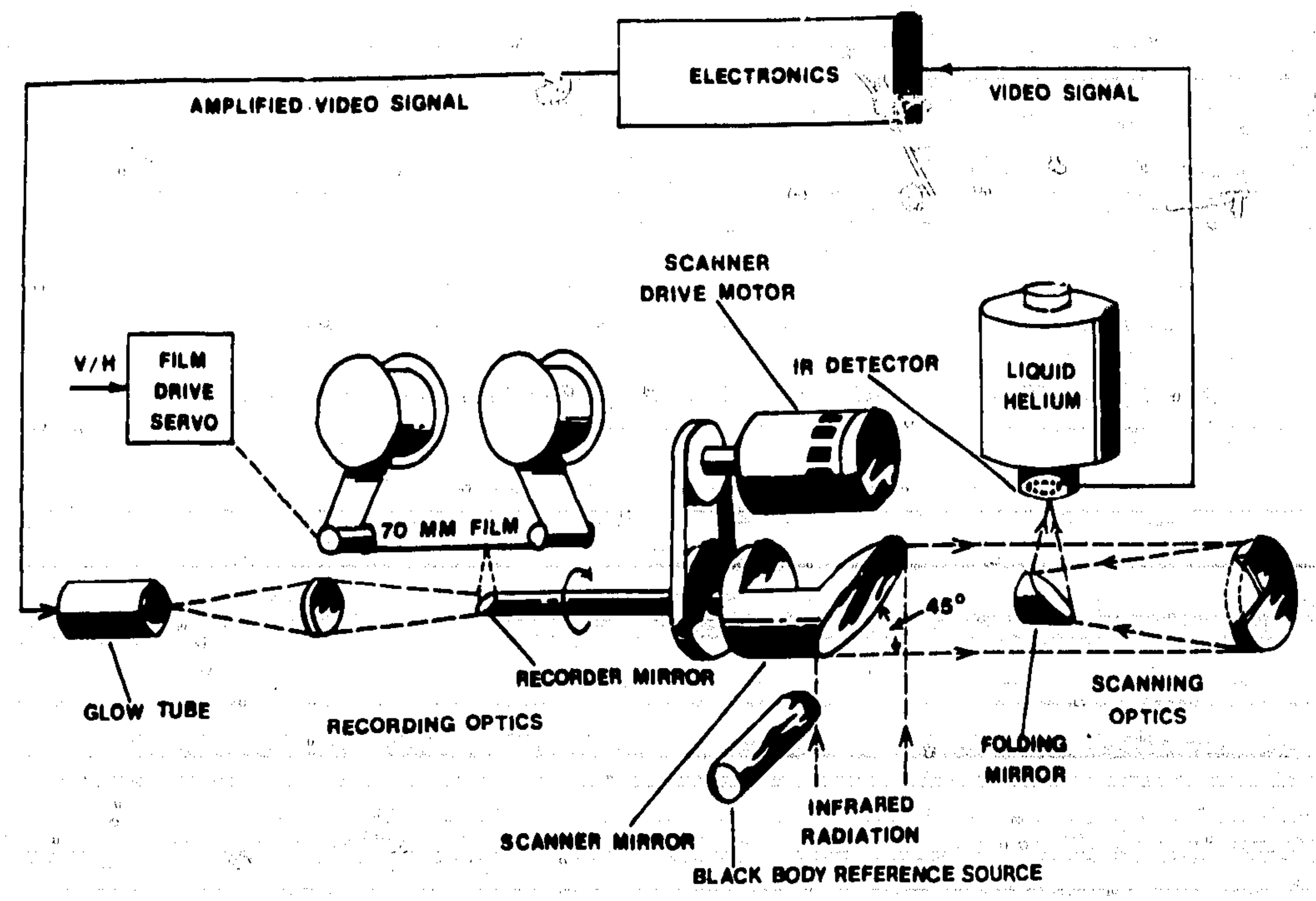


FIGURE 28 Schematic diagram of an airborne infrared scanning system

tube, the brightness of which is made proportional to the intensity of the detected infrared radiation in relation to the black body reference source. If this method of recording is used, some removal of image distortion can be accomplished by curving the film as it is exposed, to reproduce in reverse the scanner ground trigonometry (Figure 29). Detailed descriptions of infrared scanning systems are numerous (eg Ref 58) and a good account of theoretical scanner performance and calibration is given in Reference 197.

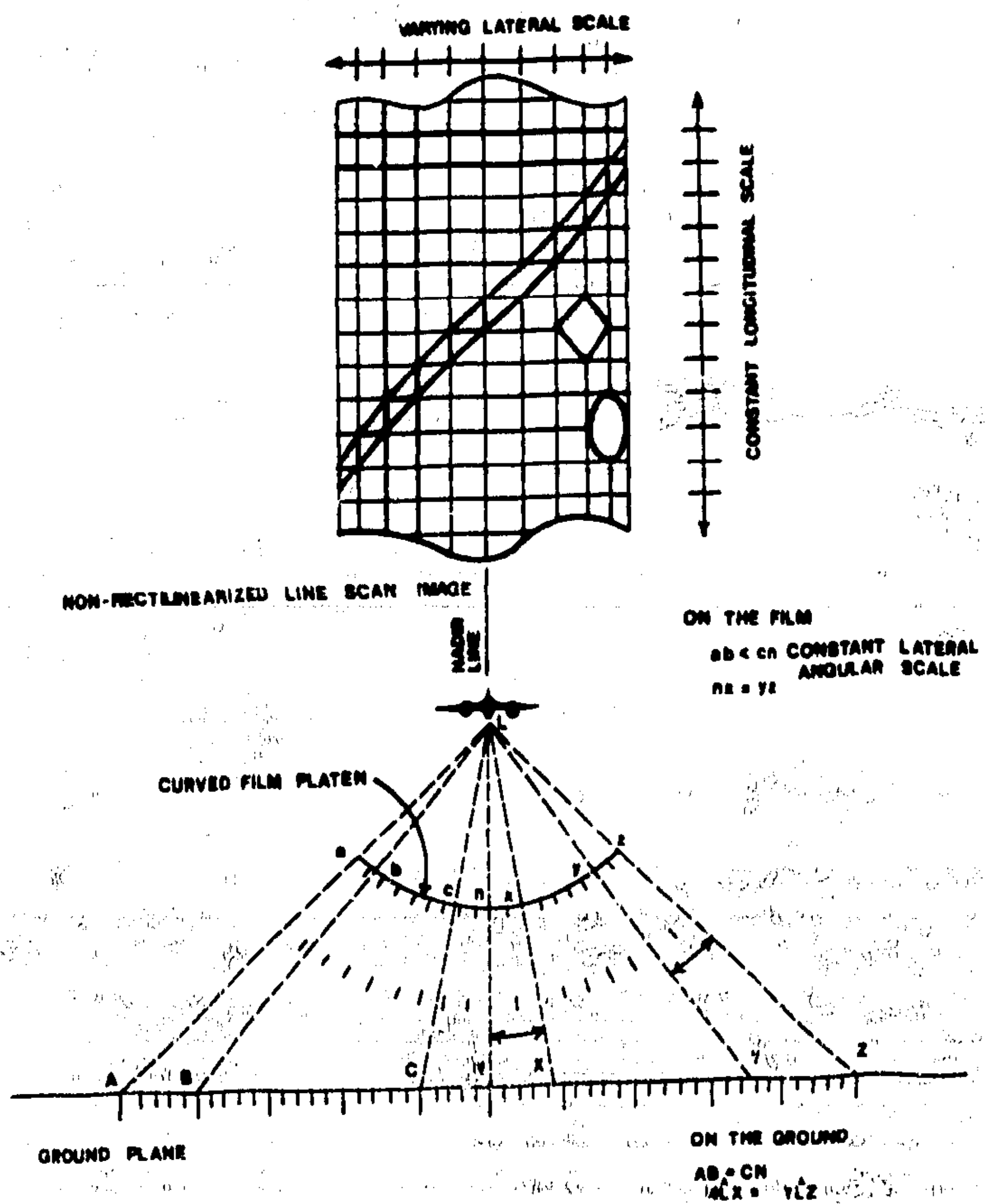


FIGURE 29 Geometry of line scan image *(from W R Stingelin 1968)*

(b) *Microwave Linescanners*. The principle of microwave detection is identical to that of the non-imaging microwave radiometer but with the addition of a scanning action which may be achieved either mechanically or electronically. The mechanical scanner uses a narrow beam antenna similar to that described in *microwave radiometers* p 37 which is continuously moved through a designated angular range, perpendicular to the flight path of the platform, the forward motion of which produces a raster scan effect. The length of the swath is generally 2-3 times the platform altitude. As with the fixed microwave antennas, dual take-off feeds are provided to record either vertically or horizontally

polarised signals. The scan rate is dependent on the platform height and velocity, but normally lies between 0.1 - 10 scans/sec. In most cases the scanner beam path is tilted away from the vertical to enable easier identification of surface types to be made through their differential angular emission properties (Ref 67).

More efficient scanning can be accomplished through the use of several antenna lobes (normally three set 120° apart) which are rotated around a single axis (Figure 30). The lobes are either switched in turn to the receiver as they can pass through the desired angle or else each lobe may have its own receiver. The latter facilitates better resolution of temperature as a result of longer signal integration time in the receiver. If two angularly locked lobes, set n metres apart are connected to separate receivers, it is possible to process the signals by computer so as to reproduce the effect of a single antenna n metres in diameter. This has the advantage of giving higher ground resolution without the need of a very large antenna. More comprehensive details of scanner design and operational modes can be found in the ESRO report CR-71 (Ref 61).

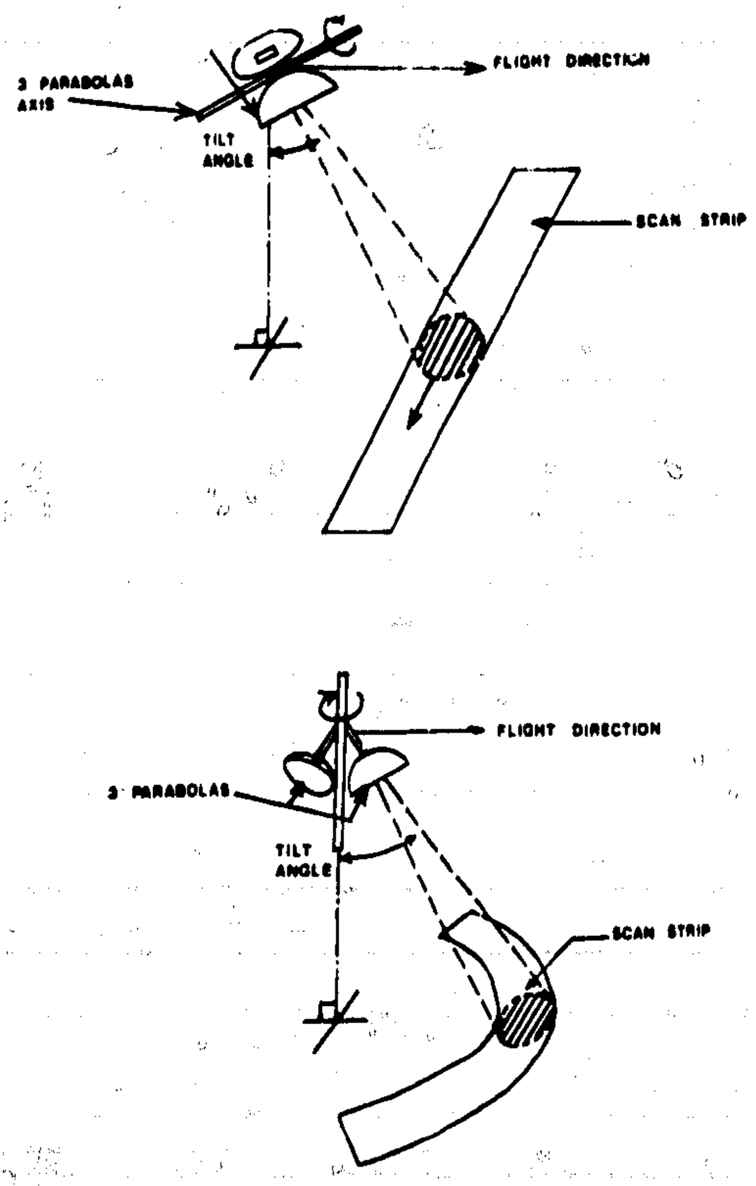


FIGURE 30 Geometry of mechanically scanning passive microwave radiometers

The large physical dimensions of mechanical microwave scanners renders them unsuitable for many applications, especially for spaceborne sensing and for this reason, electronic scanning devices have been developed. Figure 31 shows an electronic microwave aerial which consists of an array of detecting elements whose phase can be controlled in order to reproduce the properties of a large scanning antenna (Ref 68). The main advantages of this type of scanning system is that no moveable or mechanical parts are required, a fast scanning ability is possible and computer control of the phase and amplitude of each element allows great flexibility of data collection. For an antenna matrix having a large number of elements, not only can the antenna beam shape, width and polarisation be changed through computer control, but also a variety of scan modes such as linear, circular or conical can be included in the program. The high purchase cost of electrical scanning systems at present limits their use, but improved technology should result in a future lowering of cost. Similarly, at the moment, technical problems preclude their use at longer wavelengths, but these also should eventually be overcome.

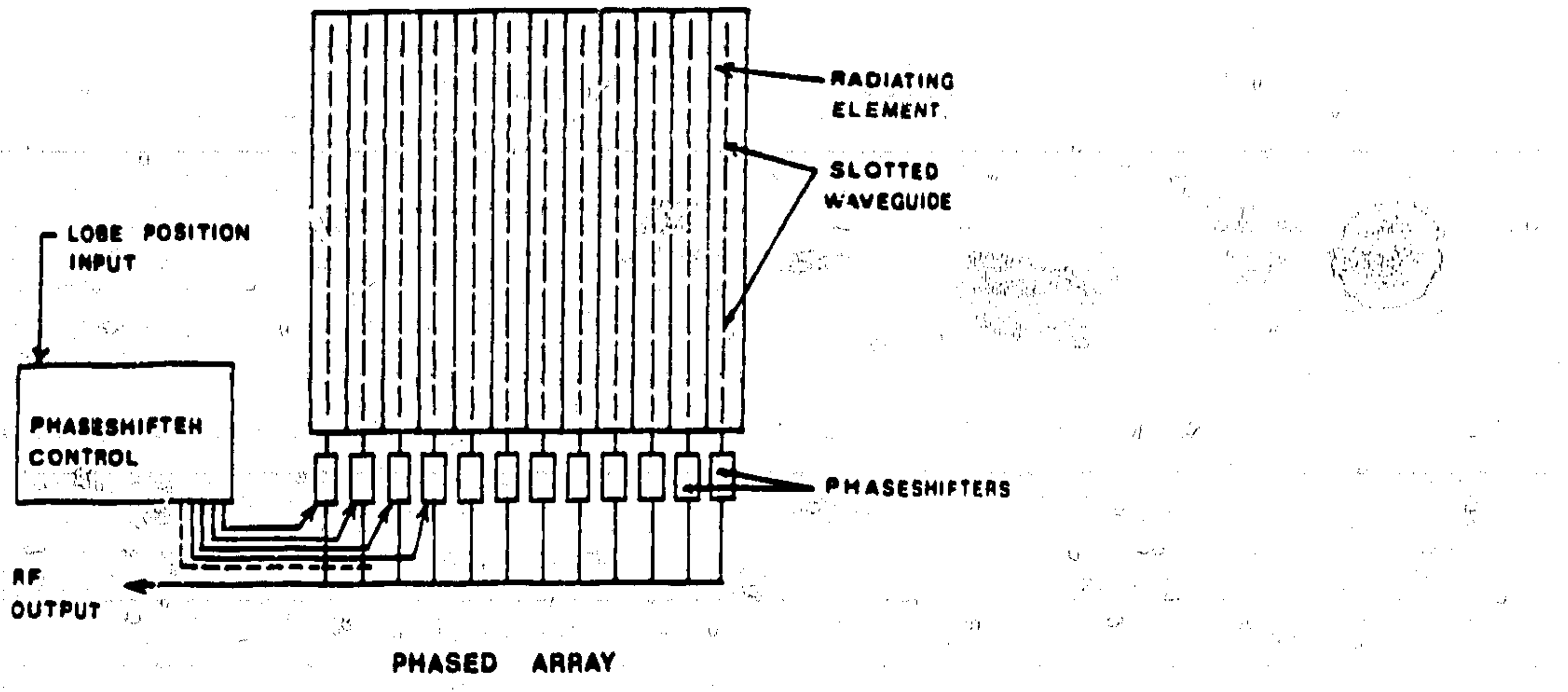


FIGURE 31 Electrical scanning phased array microwave aerial

A series of excellent contractor report publications produced for ESRO cover all aspects of passive microwave radiometry and have the following identification codes:- CR-71, CR-74, CR-75, CR-116 (see also Ref 61).

(c) *Multispectral Linescanners.* The multispectral linescanner combines the abilities of both spectrometer and linescanner (Figure 34). Whereas the previously described scanners detect ground radiation in only a single spectral band, be it wide or narrow, the multispectral scanner has the capability of recording a ground scene in two or more spectral regions, identical in both time and space. The advantage of this is that a more accurate identification of ground features is possible, coupled with a greater understanding of their conditions if a greater proportion of their spectral signature can be identified. For example, take the case of the theoretical spectral signatures of the two dissimilar Earth materials X and Y in Figure 32. If a single band radiometric measurement was taken in regions A or C, the mean radiation detected from the two materials would be very similar. If however a second measurement was taken at B or D, the difference would become immediately apparent. The approximate spectral reflectance for some Earth materials is shown in Figure 33. The study of the spectra of such bodies under different environmental conditions is the subject of much research and some of the best documented relationships are described at length in Reference 69.

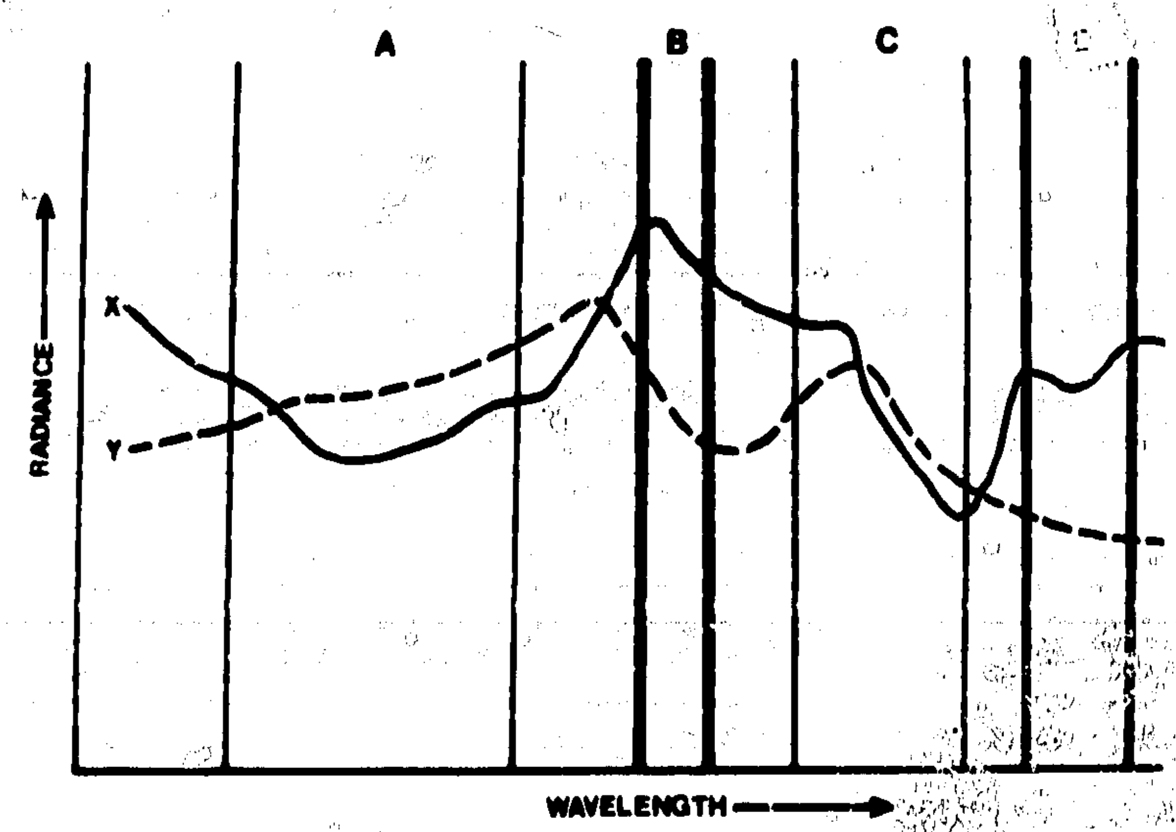


FIGURE 32 Feature separation using multispectral analysis

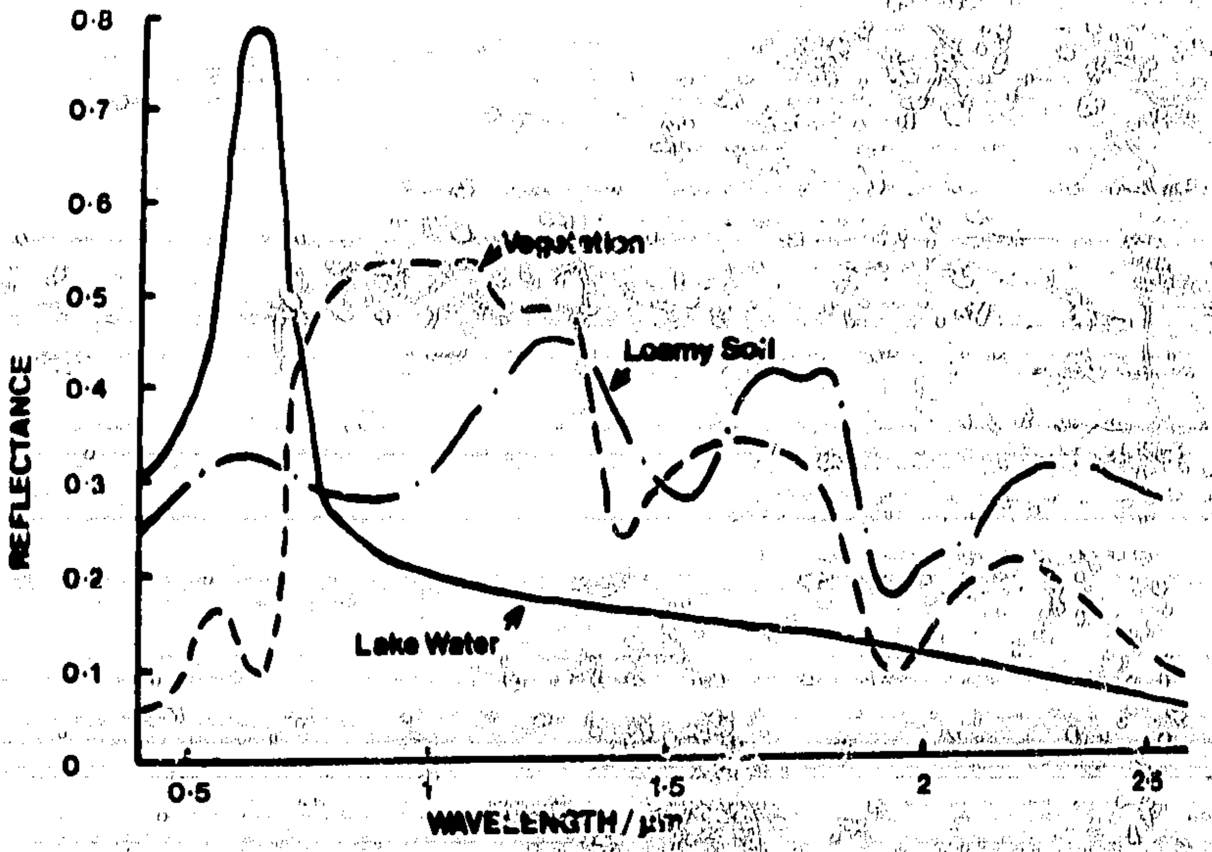


FIGURE 33 Spectral reflectances in the visual and near infra-red regions of typical earth surfaces

The basic imaging multispectral scanner is identical to the single channel scanning radiometer, as described in *scanning radiometers* p 42 with the addition of some form of dispersive element in the optical path as incorporated in the spectrometer described on p 40. Generally more widely spaced spectral bands are selected in the multispectral scanner however than [illegible] spectrometer. Figure 34 shows a schematic multispectral scanner. [illegible] optical system may consist of a series of lenses or mirrors [illegible] design (Ref 24), but the function of all of them is to accurately define the instrument field of view and to efficiently collect enough EMR in all of the selected spectral bands in order to achieve a high signal-to-noise ratio. For minimum signal loss, mirror optics are often preferred to lenses. The electromagnetic energy collected by the optical system is focussed onto an aperture, the size of which defines the system instant field of view and which forms the input to an appropriate beam splitter (Figure 35). In this case a dichroic mirror is used, which, when placed at 45° to the optical path, allows half of the EMR to pass straight through its half silvered glass and reflects the other half through 90° (Fig 36). Detector heads, sensitive to different spectral bands can be placed in the path of the resulting identical beams. The cutoff of the spectra sensed by each detector, can be modified if necessary by placing suitable filters in the optical path prior to the detector, (not shown in Figure 34).

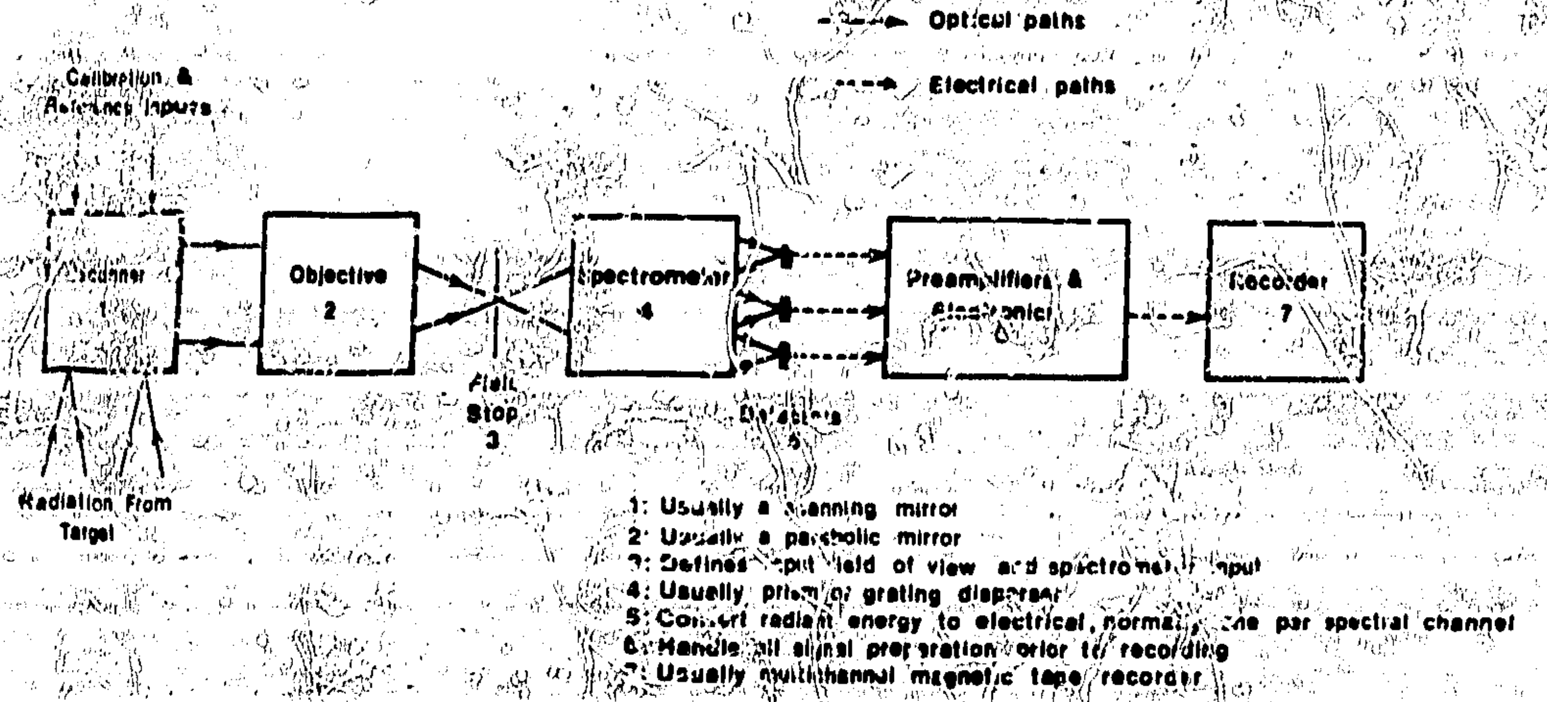


FIGURE 34 Schematic of typical airborne MSS instrument

Two basic detector types exist - quantum detectors in which the number of impinging photons is detected, and thermal detectors whose surface temperature is minutely changed by the incoming radiation. With thermal detectors, radiation adsorption and detector sensitivity can be made to be wavelength independent, whereas with quantum detectors the output responds linearly to the rate of incident photons and will therefore reflect dependent characteristics. Thermal detectors are generally less able to resolve small changes in radiation than quantum devices but can give useful performance at longer wavelengths without the absolute

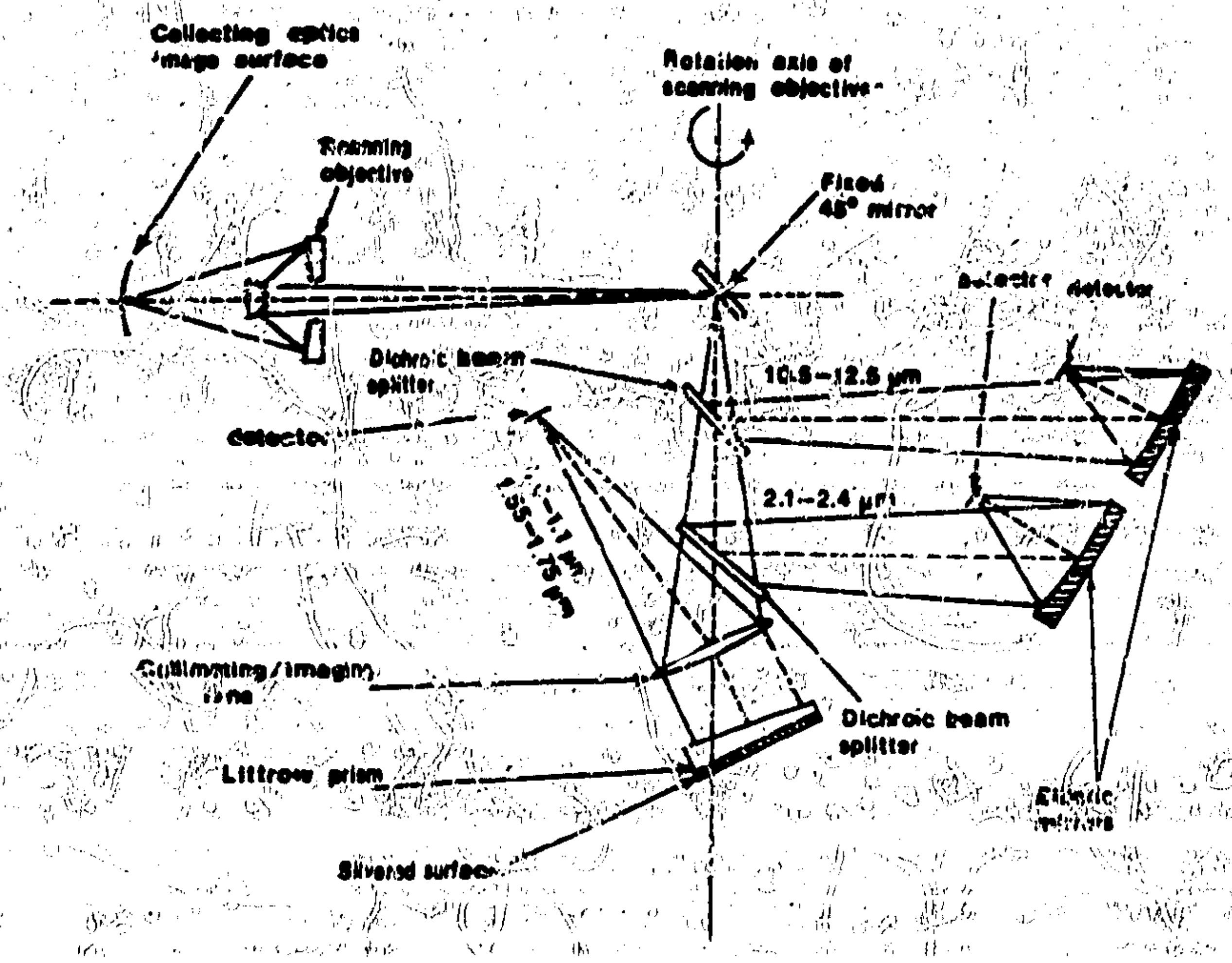


FIGURE 35 Multi-spectral (image plane) scanner using spectral dispersion

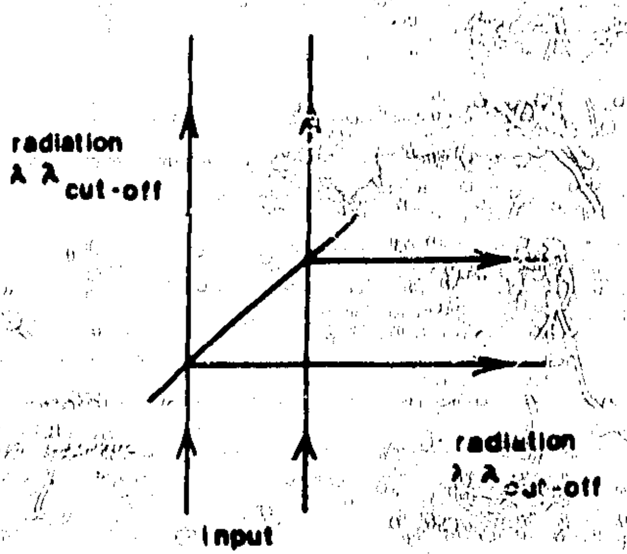


FIGURE 36 Principle of dichroic mirror beam splitter

necessity of cooling. Quantum detectors are used for most multispectral applications for wavelengths less than 14 microns whilst photomultiplier detectors may be used below 1 micron wavelength. Even with quantum detectors, head cooling improves detector performance.

Internal calibration of multispectral scanners is normally achieved with suitable temperature controlled reference bodies as employed in single channel scanners. Multispectral scanner data is invariably recorded on magnetic tape with separate channels for each band but multichannel visual output may be secondarily provided. More detailed information on multispectral scanning systems is available in contractor reports as given in Reference 69 and details of some specific instrumentation similar to that described in this section can be found in the Directory of Advanced European Remote Sensing Instruments (Ref 70).

5.3 Active sensors

Active sensors provide their own source of electromagnetic illumination and it is the reflection of this illumination from the target of interest which is detected. An example of a simple 'active' sensing system is the recording of an object in total darkness using a photographic camera fitted with an electronic flash attachment. In the ultraviolet to infrared wavelength range, lasers may be used as the illumination source for active remote sensing, whilst in the microwave and radio region, radars are employed.

Microwave radar

Microwave radar receivers function in much the same way as passive microwave systems but they record the return signal from their own microwave illumination source rather than being reliant on naturally occurring radiation. Microwave radars may operate at wavelengths ranging from about 6mm - 1 m, but any one system generally operates at only a single frequency. This allows good operational repeatability which facilitates the possibility of surface recognition, independent of weather conditions. Many types of radar exist but the version generally used for Earth resources observations is the sideways-looking variety, briefly described here.

Figure 37a shows an idealised configuration of the fan shaped radar pulse which is emitted in a plane normal to the flight path of the aerial platform. The total width of the ground illuminated (w) is a function of the platform altitude, the transmitter angular spread (βe) and the depression angle (θ). The short pulses of microwave radiation (shaded area) travel radially from the transmitter until their leading edge comes in contact with the ground. At this instant, the ground element from which the energy is returned to the radar is the small shaded area (X). The pulse continues in the direction towards A followed by the corresponding ground return signal. In addition to the return from the pulse main lobe, noise occurs from side lobe effects (Figure 37b) which must be removed during signal processing. The dimension of the ground resolution g across the swath depends on the radar pulse width τ and grows with increasing depression angle, thus:-

$$g = \frac{c\tau}{2 \cos \theta}$$

where c = velocity of EMR. In order to retain a satisfactory ground resolution, the observation must be oblique or 'side-looking', normally between depression angle limits of 30° and 60°.

Two major classes of microwave radar exist, namely real-aperture and synthetic-aperture systems. (In radar terminology the antenna or aerial size is usually called the aperture). In most real-aperture systems, the ground resolution across the film record is up to ten times better than that along the film in the direction of flight. The along track resolution is limited by the real antenna beam width; the narrower the beam width, the better the resolution, and the only way of decreasing beam width is to increase the real antenna diameter, this being ultimately determined by the aircraft length. A simplified layout of the main components of a real aperture radar is shown in Figure 38.

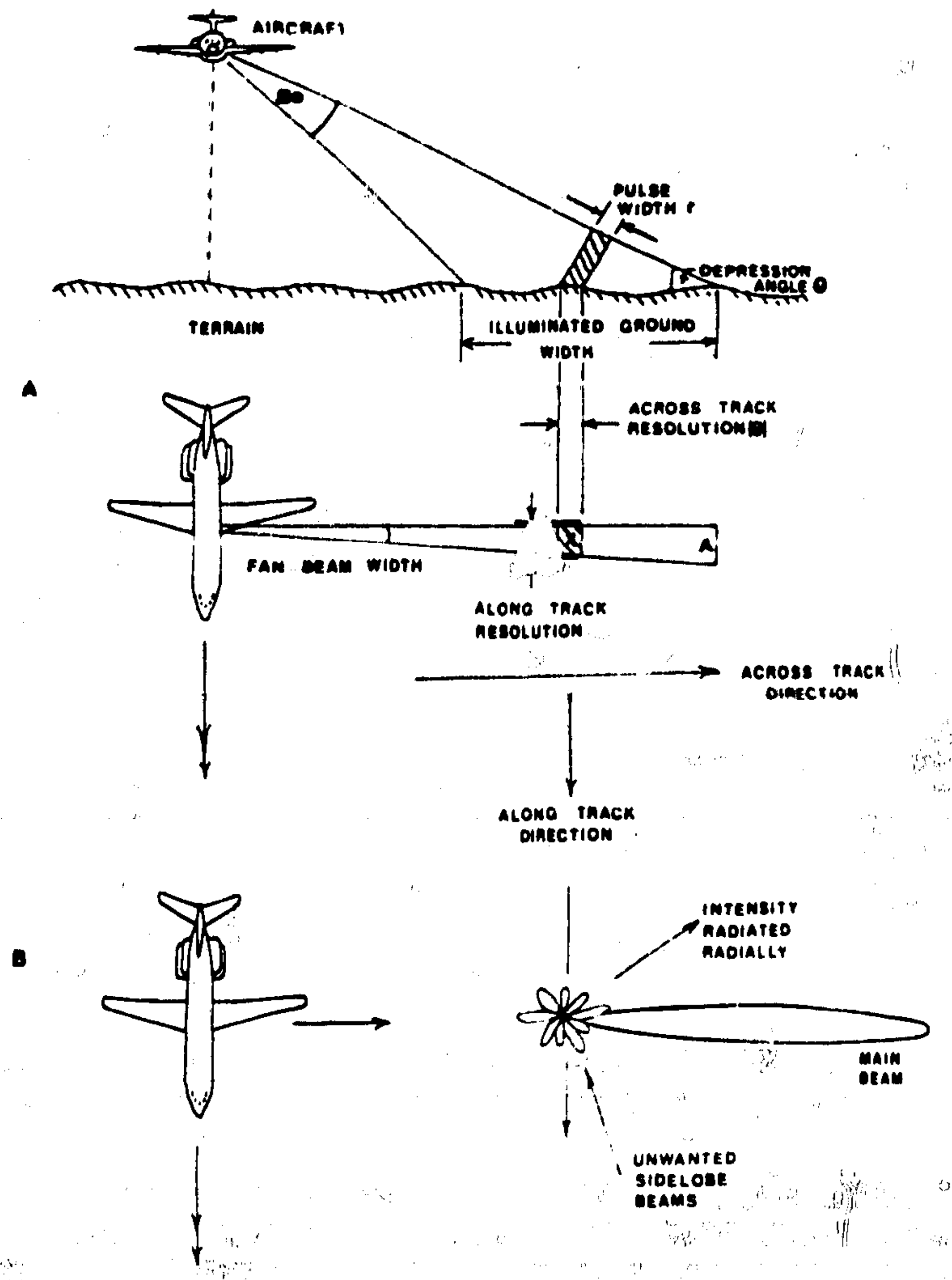


FIGURE 37 **Basic side-looking radar geometry**

Short pulses are generated by the pulse generator (between 1,000 and 10,000/sec which in turn trigger bursts of microwave energy from the transmitter to the antenna, thus producing the side-look fan beam. The return echoes are received on the same antenna microseconds after the

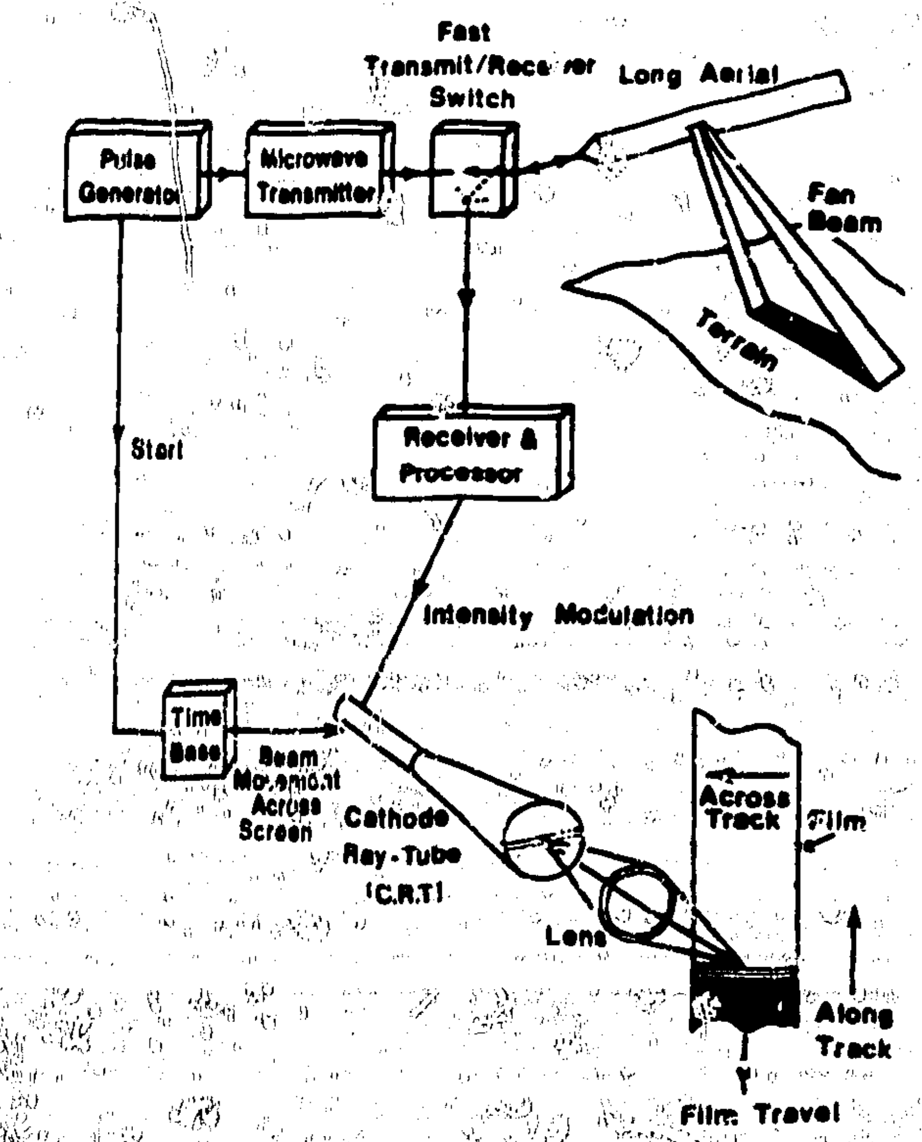


FIGURE 38 Basic elements of a real aperture side looking radar system

transmission is completed and are switched through to the receiver and processor. The slant range to the ground is measured by the timebase which takes the form of a slowly rising voltage which causes a spot of light to be moved across the face of a cathode ray tube. The intensity of the return signal is used to modulate the spot brightness. A lens system focuses the line trace onto a film which is transported at a rate proportional to the aircraft speed so that an image is built up, line by line - each line being the record from a single radar pulse.

Generally real aperture antennas transmit in a single polarised plane and receive in the same plane. The addition of a second aerial receiving in a plane offset 90° to the first allows more information to be gathered about the ground surface characteristics, thus enabling more accurate identification of features (Ref 71).

Synthetic aperture systems were developed in order to model the effect of a very large real aperture antenna which would allow high ground resolutions to be recorded (Figure 39). The method of synthesis is quite complex, but essentially what is done is to record on photographic film, via a cathode ray tube, both the phase and amplitude of the ground return signal from different platform positions in relation to the phase of a very stable reference oscillator. This continuous film record

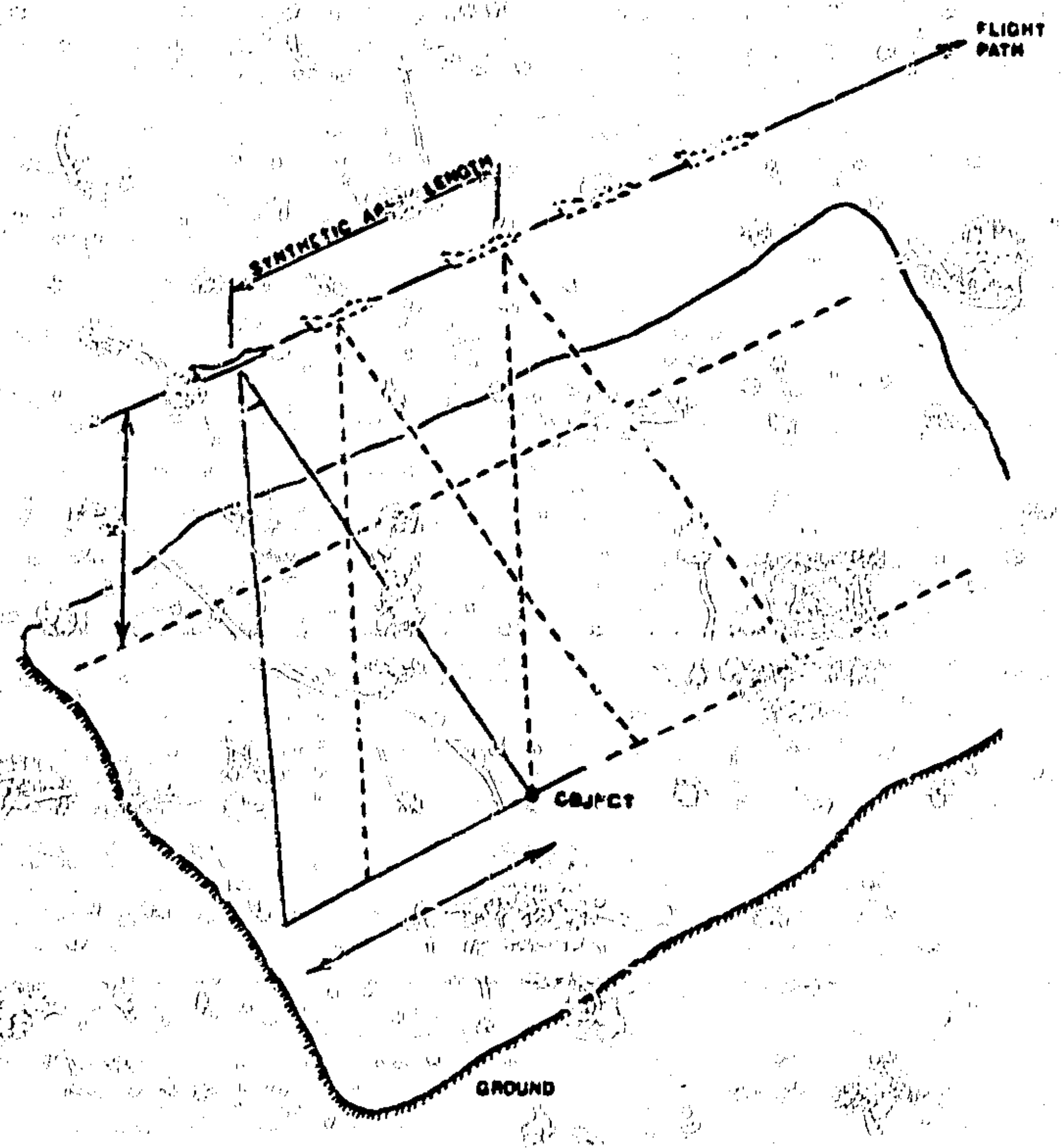


FIGURE 39 Geometry of synthetic aperture side looking radar systems

of the mission is then processed on ground based optical or digital computer holographic processors which reconstruct the ground scene as if produced by a single, very large aperture antenna. As with real aperture radar, the signals may be vertically, horizontally or cross polarised and will contain the same information about the ground scene.

A comprehensive account of side look radar systems and their application to both resource surveys is given in the ESRO contractor report series (Ref 71) and in the EMI report (Ref 24).

Scatterometers

Scatterometers are instruments used to *measure* radar scattering coefficients of given targets or in experimental programmes thay may be used to determine optimum characteristics (eg wavelength, polarisation) for side look radar. The intensity of the backscattered EMR, however, is recorded as a percentage of that transmitted and is recorded sequentially from first to last returns (Figure 40). By co-ordinating these time intervals with the geometry of the beam, it is possible to obtain the values of backscattering from the same ground point for different radar incident angles to the surface as the platform moves forward, and thus to gain a greater knowledge of the surface geometry (Figure 41).

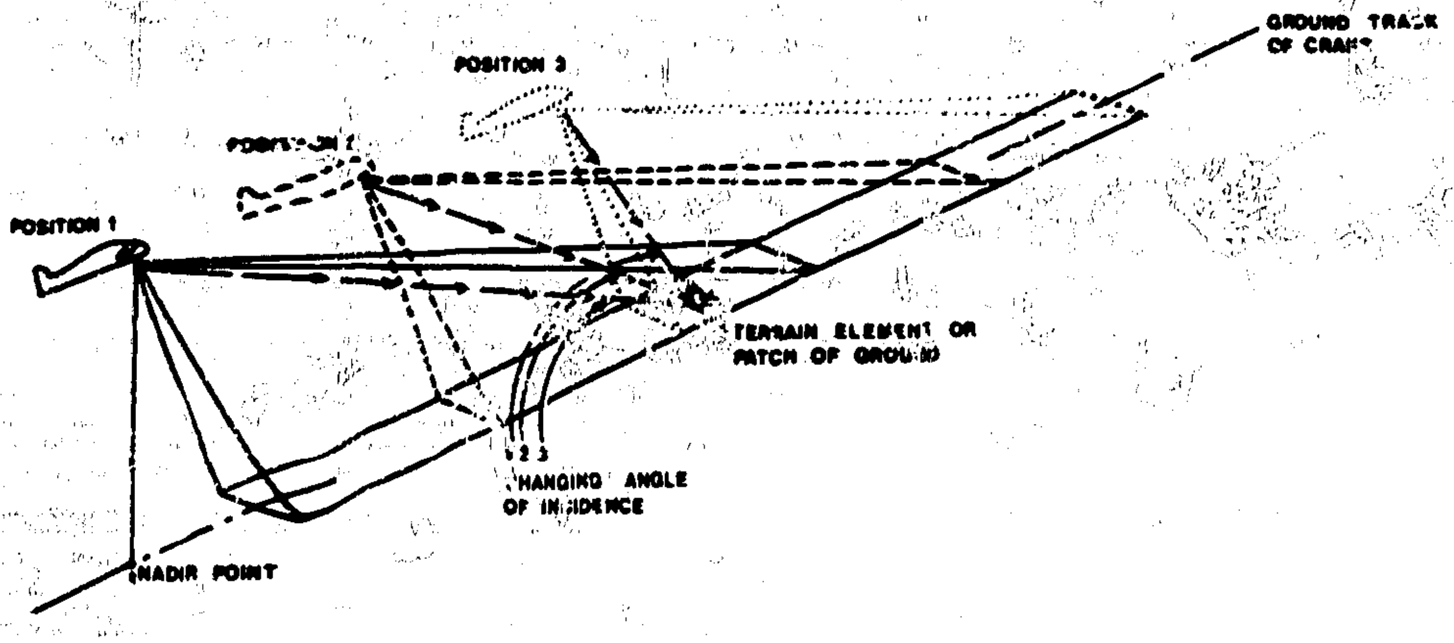
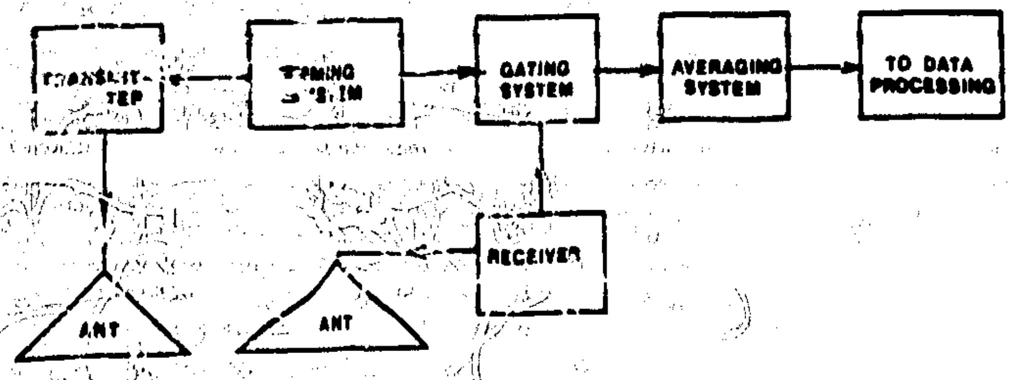
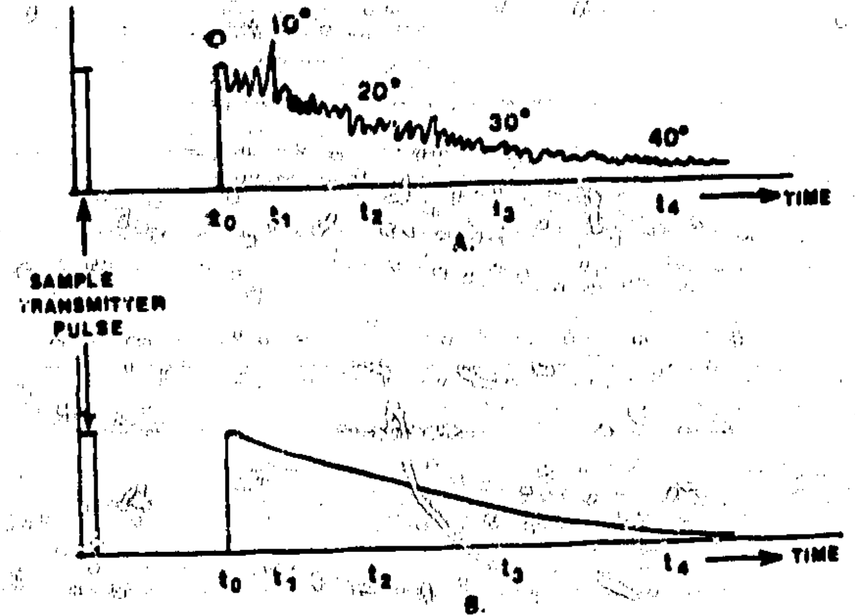


FIGURE 40 Principle and geometry of scatterometry



PULSE SCATTERMETER (AFTER MOORE, 1968)



RECEIVED PULSE FROM A FAN BEAM SCATTEROMETER
A. ACTUAL SIGNAL B. AVERAGED SIGNAL
(AFTER MOORE 1968)

FIGURE 41 Schematic of scatterometer operations

The continuous wave Doppler scatterometer records the change in frequency of a continuously transmitted radar beam due to the forward motion of the platform and the reflecting and backscattering effects of the terrain. At the same time a rearward pointing antenna records the fall in frequency due to the receding beam returns and, once again, data on specific ground points can be obtained from more than one incident angle (Figure 42 and Ref 16).

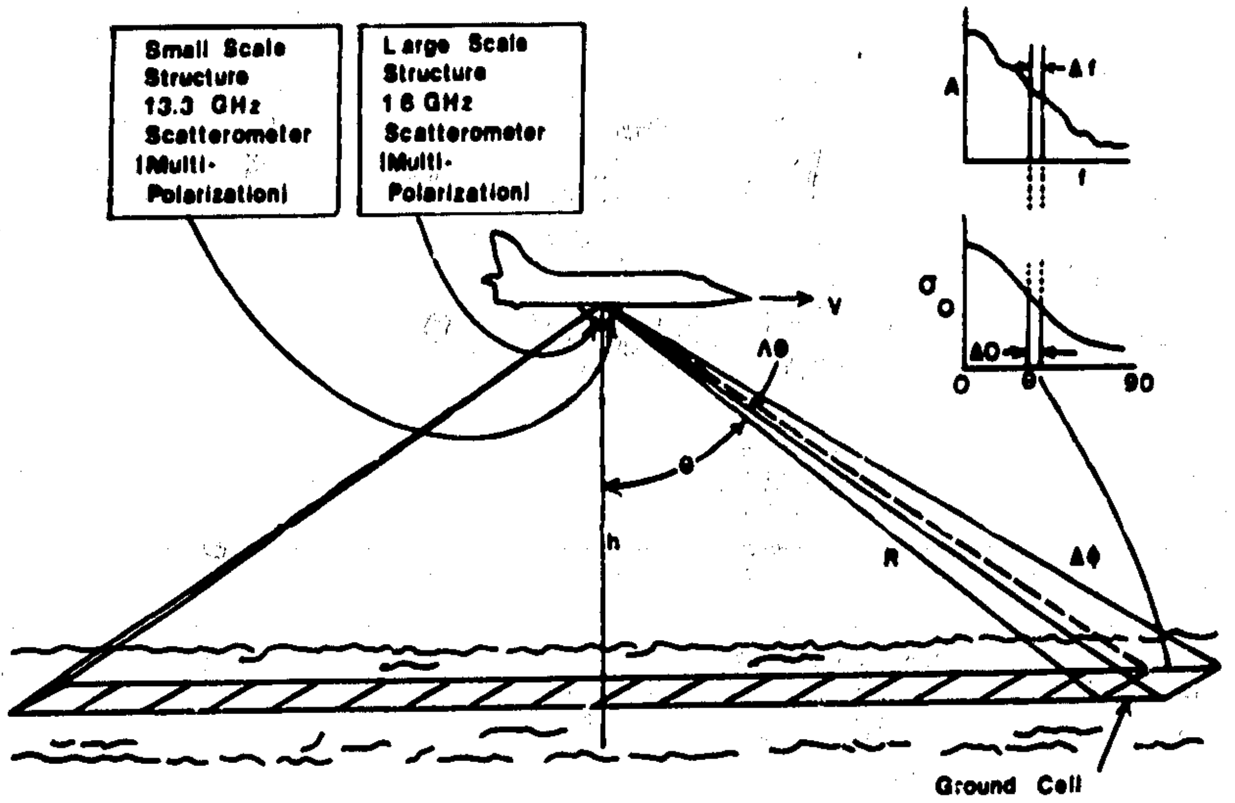


FIGURE 42 Geometry of Doppler wave scatterometry

Lasers

Lasers operate in the ultra violet, visible and near infrared electromagnetic region, their most significant feature being the coherence of the beam of EMR which they emit. A high power light source (generally a gas discharge tube) emitting in the wavelength of interest is accurately centred on the focal point of an optical train designed to concentrate the electromagnetic energy into a narrow beam of parallel radiation (Figure 43), this sometimes being achieved by also passing the EMR through a crystal of uniform molecular structure. It may be necessary to cool the unit if high beam outputs are required. By electronically or mechanically pulsing the light output and recording the round trip time of travel to a surface, a simple ranging device can be constructed (Ref 16) which may be referred to as a LIDAR (light detection and ranging). A typical layout of a laser transmitter and receiver is shown in Figure 44.

According to the degree and nature of scatter and polarisation in the return signal, information can be obtained on surface texture such as sea surface conditions, or the presence of pollution on, or within, a water body (Ref 72). In order to detect the spectral shifts in the returning beam, a spectrometer grating may be introduced into the

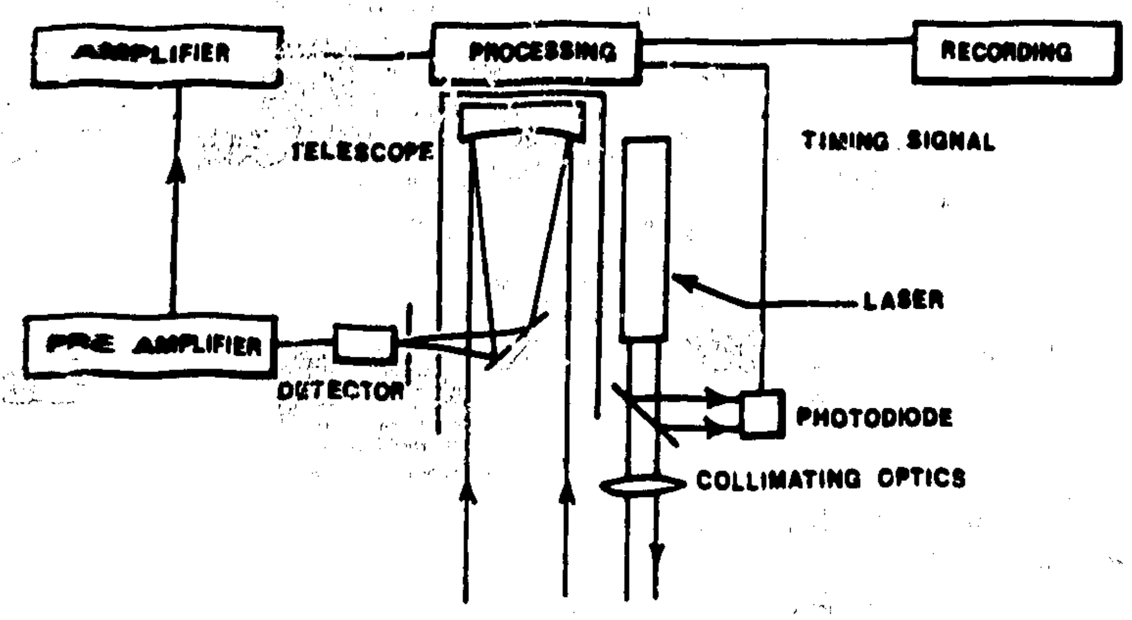


FIGURE 43 Functional diagram of laser profiler

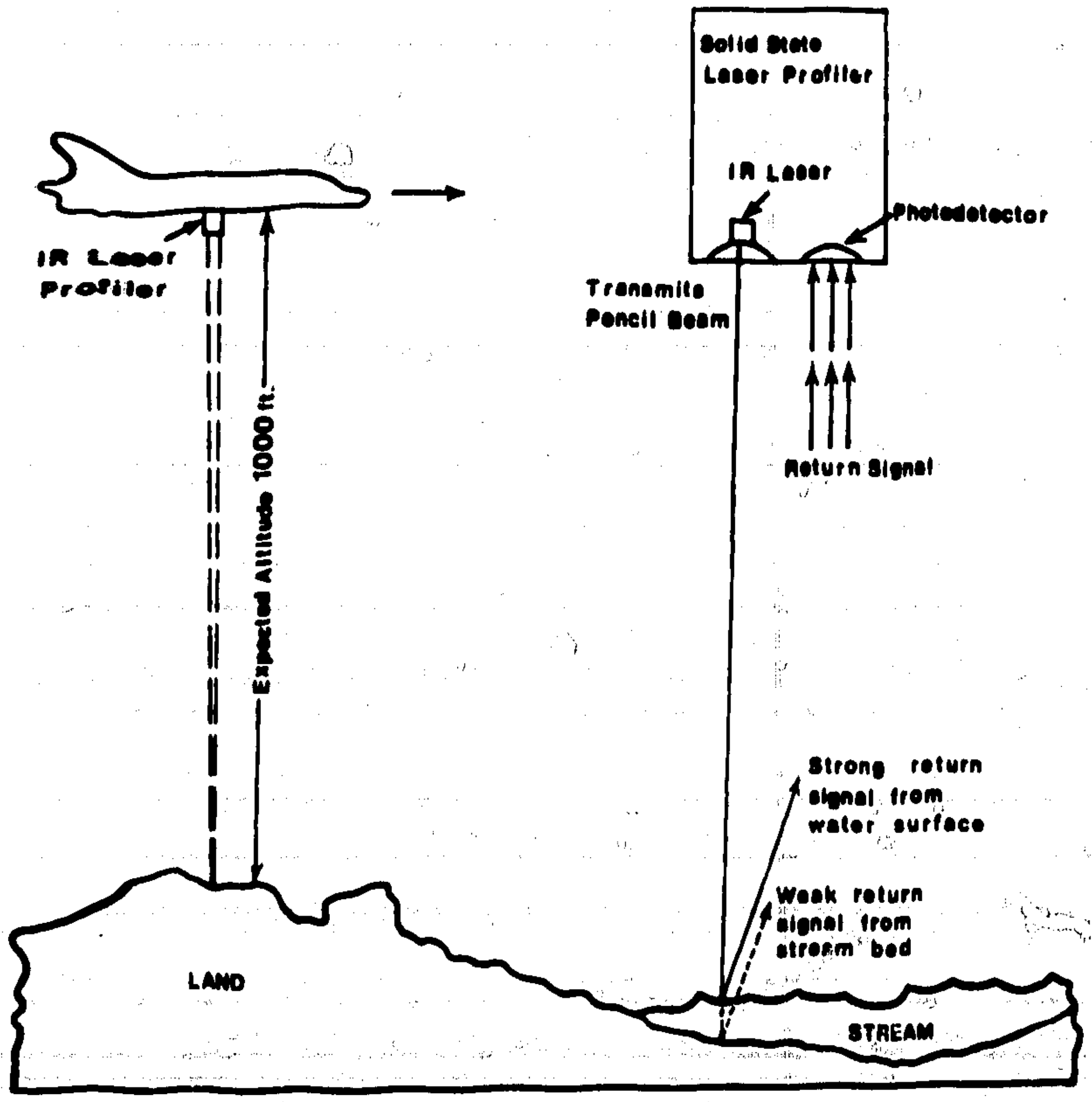


FIGURE 44 Mode of operation of laser altimeter or profiler

detector optical train, whilst the added ability to alter the wavelength of the transmitted laser beam with variable dye filters (often called a tunable laser) enables the most suitable wavelength to be selected for a given situation, e.g. water depth measurement as described on page

Only the main categories of remote sensor have been described briefly in this chapter and many variations on the basic design exist according to data requirements.

6. DATA ANALYSIS

6.1 Data recording and transmission

This section describes the main ways in which remotely sensed data may be recorded and returned to a data centre where information may be extracted from it. The same systems are applicable for both ground based and aerial platforms and in both cases the main factor governing the methods of data recording is whether a physical transference of the record to the data centre is possible, or whether a transmitted message must carry the information.

Physical Data Transference

Where a physical transference of stored data is possible, one of the simplest and most efficient forms of data collection is direct photography (see p 27). With a photographic system, a large volume of high resolution data can be rapidly collected and stored prior to its transference to a ground base where processing and interpretation can be carried out. The main problem with this system, especially for small space-craft platforms, is the relatively large amount of space required for film storage. In addition to direct photographic techniques, photographic film may be used indirectly to store information from other imaging sensors. For example, the modulated electrical output from linescanners, vidicons or radar can be used to vary the brightness of a glow tube or cathode ray tube which in turn transfers the information onto a photographic film through progressive exposure of the film (see p 42). Alternatively, graphical cathode ray tube outputs or radar traces may be instantaneously recorded with a photographic recording camera.

For non-imaging sensors, data output may be recorded on paper rolls in the form of graphs (eg microwave radiometer), type digital output, or punched tape (eg gamma ray scintillometer). Again, the volume of paper produced may cause problems, so in spacecraft, paper output is virtually never used.

Nowadays, probably the most widely used and flexible data recording medium is magnetic tape. Large volumes of data may be stored on tapes having 12 tracks or more, the main advantage being that the recorded signal is first generation ie it has come directly from the sensor without transformation other than amplification, and should therefore be of the highest quality. Generally an analogue signal is recorded at a high packing density, but it may occasionally be possible, with prior conversion, to record a computer compatible tape in the first instance. This may be necessary in some satellite installations where onboard computer processing of data must be carried out. (Ref 73).

Transmitted Data Transference

Where physical data transference is not possible, or is undesirable, the sensed data must be converted by some means into a radio signal which can be received at the ground station. When the sensor output is an electrically pulsed or modulated signal, its conversion to a radio signal is relatively straightforward, involving simple electronics. In some cases (eg orbital satellites) it may not be possible to transmit the data immediately, so that data recording by one of the previously mentioned methods may still be necessary prior to its radio transmission. Such intermediate steps cause additional data degradation however and should be avoided wherever possible.

If the original data is recorded photographically, the image information, (which will be in the form of emulsion grain densities) must be converted first into an analogue electrical signal, then into a radio signal. The first process may be carried out by one of several film scanning methods which are described in the following section and whose principles of operation are very similar for both aerial and ground installations. All film scanners convert the photographic image into a 'video' signal which, after further electronic conversion, can be telemetred as a radio signal.

In addition to the raw data, other information on sensor operational performance (such as reference voltages, electrical component functions and stabilities) which enable sensor-induced errors and drifts to be calculated, must also be relayed to the receiving station. For this reason, most transmitted data must pass through further transference procedures at the ground base before analysis is possible. (Ref. 73).

6.2 Data handling

The process of data handling normally takes place at a ground-based data processing centre, the first stage usually being a straightforward conversion of the data into a more manageable form (this being dependent on the data interpretation processes to be used). The raw data normally arrives in one of the following forms:- photographic image, analogue magnetic tape, digital magnetic tape, punched paper tape, printed paper tape, graphical trace, or modulated radio signal, and any of these may in theory be converted to any of the following forms by data handling techniques:- photographic image, analogue computer compatible tape (CCT), digital CCT, computer compatible punched tape or card, graphical form, printed digital form (could be

[illegible] (printout), map or plan form, television picture etc. Of course, in some cases the raw data may already be in an acceptable form, and no conversion will be necessary. The available methods of conversion of one data form to another are too vast to describe here, but some of the more commonly used ones are described below.

Direct photographic techniques

Exposed photographic film is processed to provide, in most cases, either positive prints or positive transparencies. Unaided visual interpretation of these images may provide all the required information, in which case the imagery will undergo no further processes (Ref 74) other than possible rectification, which may be necessary to minimise unwanted distortion.

Photo-optical aids.

Optical equipment such as stereoscopic viewers, photogrammetric stereo-plotters (Ref 75) image transfer systems (slide projectors, split image viewers, enlarging or reducing cameras etc. (Ref 76) may allow topographic heights or contours to be extracted, surface features to be interpreted and delineated and qualitative comparisons of surface features to be drawn from data which has been recorded, or can be converted to imagery.

Planimeters and co-ordinate digitisers.

Manually operated planimeters allow areas to be measured directly from photographic images or (if the photo scale is not known) proportional comparisons to be made. The co-ordinate digitizer does the same, but via a computer programme which processes the digital co-ordinates of a feature as traced by a cursor head (Ref 77). By applying suitable computer programmes, the co-ordinate digitiser can also be used for handling graphical data in order to either measure the area under a particular trace or to convert a graphical line onto a digital form for further computer manipulation.

Densitometers

These are used to convert the modulating densities of a photographic image into a computer compatible analogue or digital form. Single photographic images may be scanned on a drum densitometer arrangement (Ref 78) in which the film is wrapped around a transparent transport drum which is made to rotate. A light source is situated on one side of the film and a small photodetector on the other so that the light intensity as sensed by the detector is dependent on the intervening photo-emulsion density (Fig 45). As the drum and image rotates, the light and detector move in a direction perpendicular to the rotation so that the image is scanned. Output from the detector is a modulated analogue signal which is normally recorded on magnetic tape. The above system can be reversed if a photographic image is to be produced from an analogue signal. The signal is used to control the intensity of a light-emitting device which gradually exposes the film as it rotates on the drum. Traditional light sources are usually slow to react and so maximum scan rates are restricted. If a laser light source is used

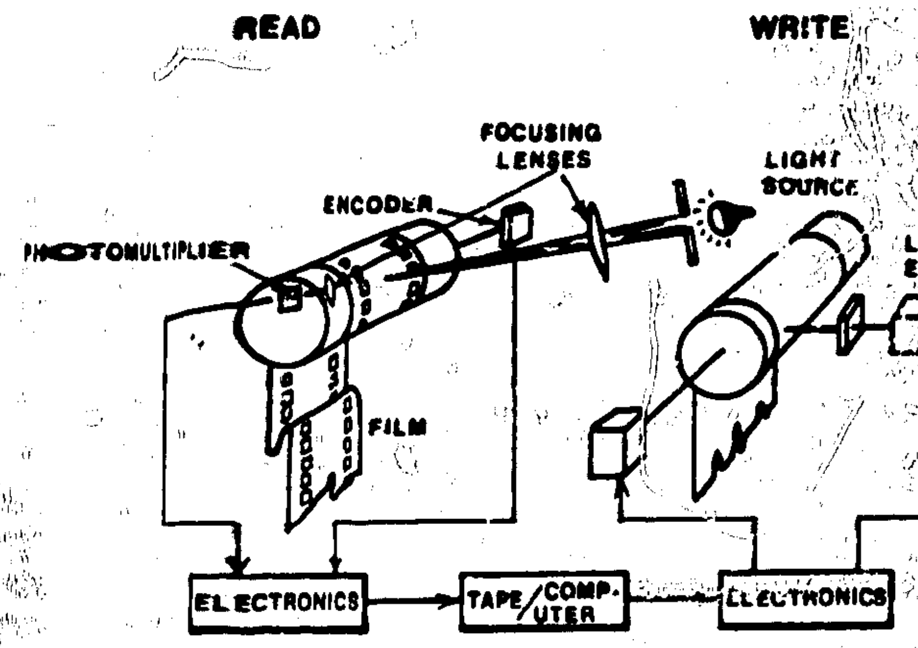


FIGURE 45 Read, write, drum microdensitometer

however, very fast scan rates can be achieved as a result of the intensity and fast reaction of the light emitting system. Where large quantities of imagery are to be handled, flying spot scanners or vidicons may be used for extra speed, but with a loss of resolution. Fig 46 compares typical resolution and geometric fidelity capabilities of some scanner/recorders.

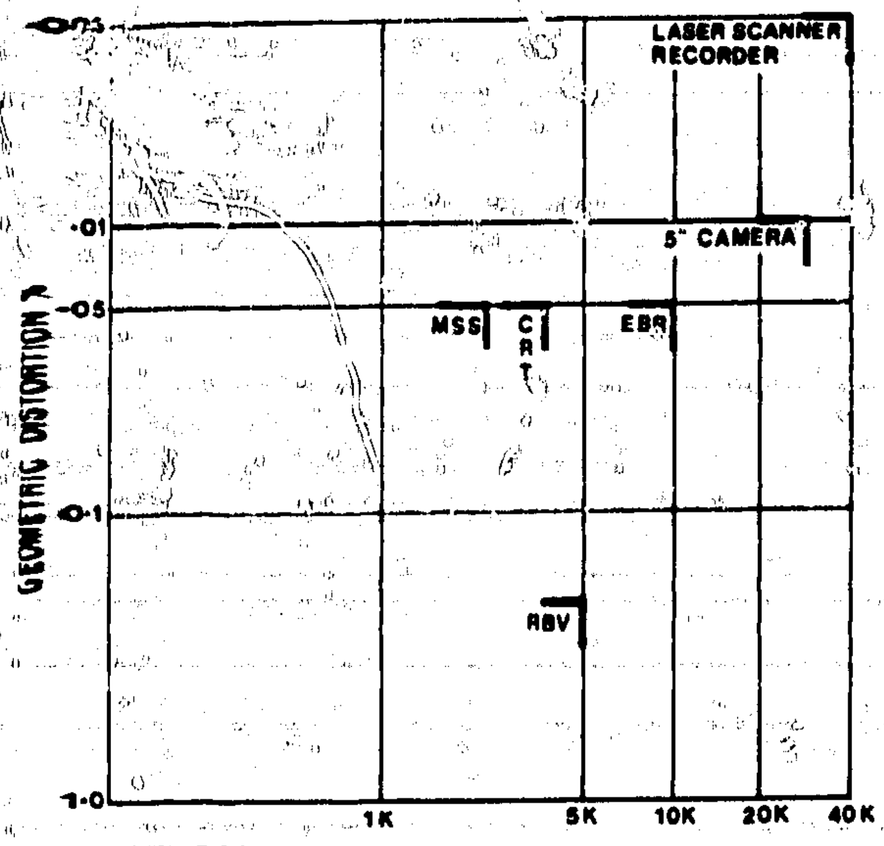


FIGURE 46 Resolution and geometric fidelity of various imaging systems *(Source: Horton & Dobbins)*

Figure 47 shows a flying spot scanner schematic in read and write mode. When extracting information from a photographic image, the cathode ray tube provides a constant light source which scans the image face. The light, modulated by the film density, is then focussed onto a photo-multiplier tube (PMT) which records the light intensity. In the write mode, the intensity of the cathode ray tube scanning dot is modulated according to the data input and this exposes the film in a scanning action. (Ref 79) These processes can be easily and very rapidly controlled by computer methods and are suitable for adaptation to more advanced information abstraction techniques (Ref 80).

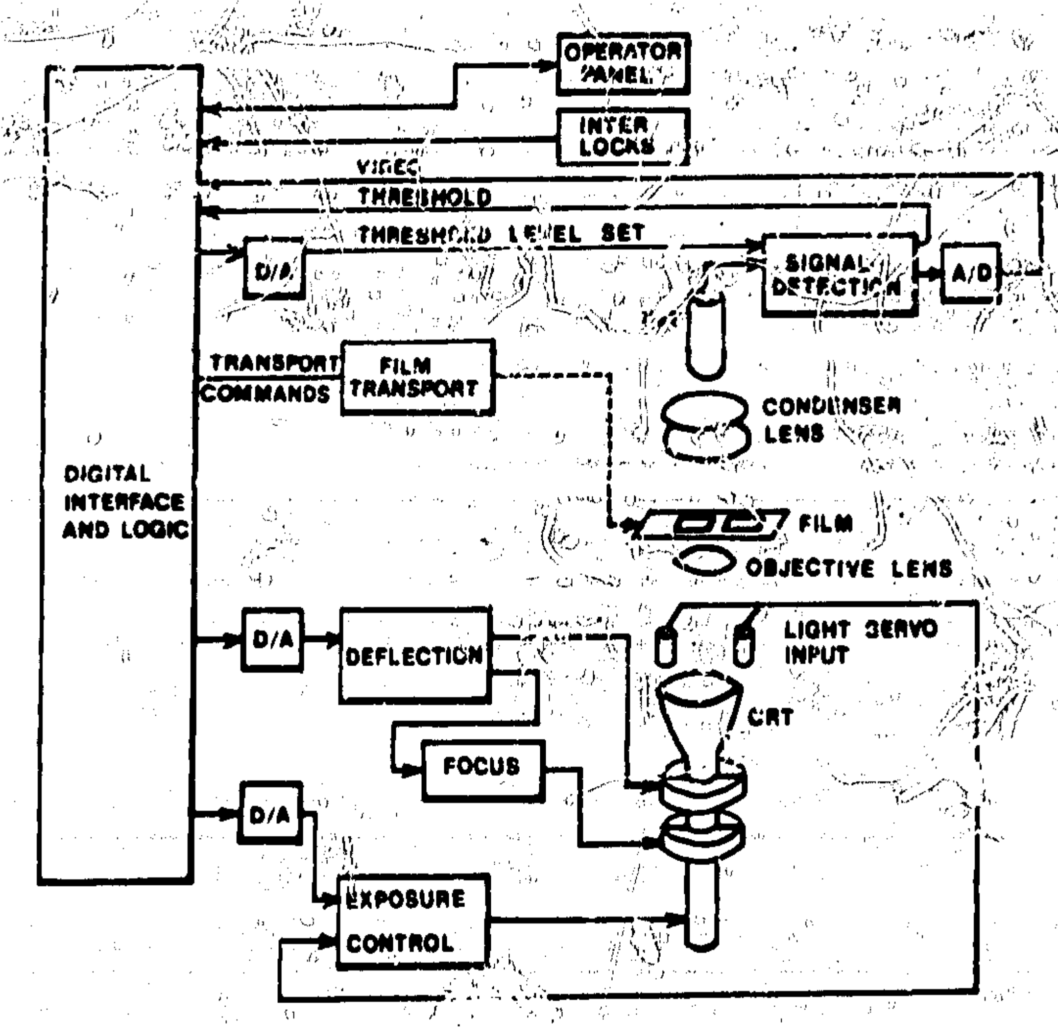


FIGURE 47 Flying spot scanner functional block diagram

Another form of very high precision laser scanner/recorder which works on principles similar to the scanning radiometer (see p 42) is used with long film strips rather than with individual frames. In the scanning mode, the constant light source is a fine laser beam (Fig 48) which, after reflection off a rotating pyramidal reflector is focussed onto the film surface and scans across the film strip. The film is curved to the radius of the focussed beam and is transported in a direction parallel to the scanner axis. The light transmitted by the film is recorded by a photomultiplier which produces a modulated analogue signal. In the write mode the laser beam is modulated according to the data signal and the film is exposed line by line as with the other systems. (Ref 81, Vol 1, p 3-19).

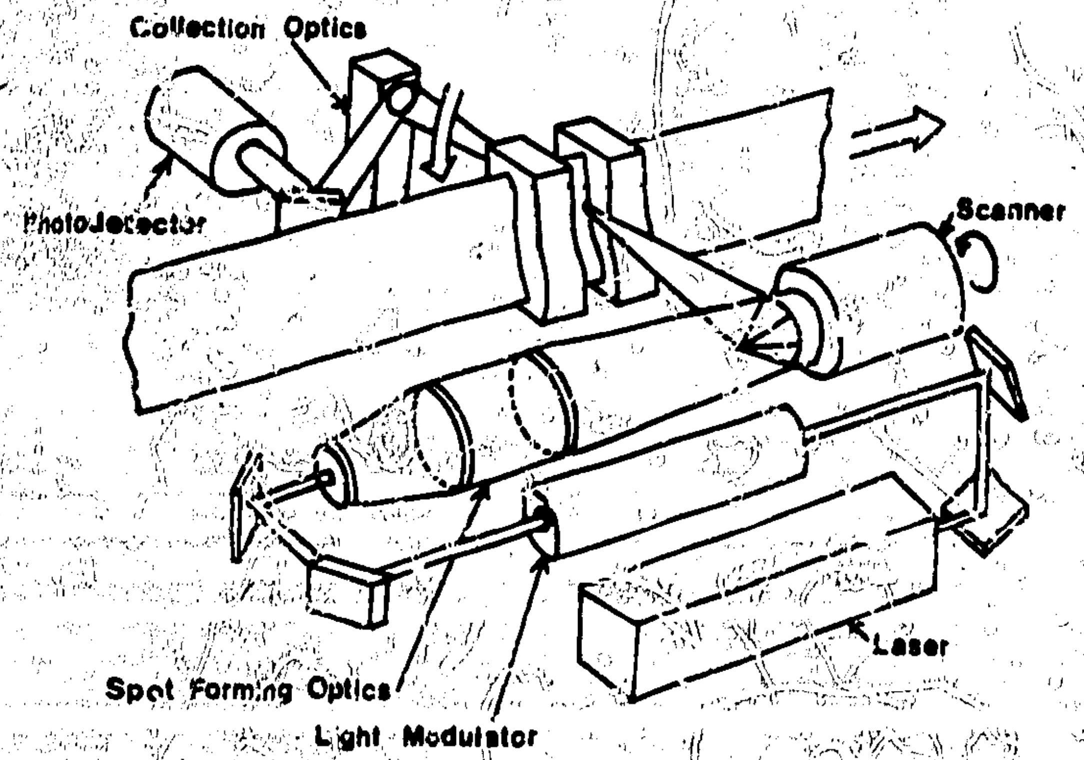


FIGURE 48 Optical layout of typical laser scanner/recorder

Magnetic tape converters

Although remotely sensed data may be stored on magnetic tape, it is unlikely that the original tape will be computer compatible. Even if no digital to analogue or analogue to digital conversion is necessary, it is normal for data storage tapes to have bits of data packed much more tightly than is acceptable for a computer input. Also, certain errors will be present in the original tape which may be corrected prior to computer processing. For these and other reasons, the original magnetic tape record must undergo a conversion process. There are many different types of processor which [illegible] varying degrees of data correction to be accomplished, [illegible] not be discussed here. Some useful information on analogue-[illegible] digital-analogue and digital-digital conversions are given in [illegible] 1. Vol. 1 p 3-24 to 3-34. After data transference to CCT, almost limitless adjustments to the original data can be made to suit the ultimate requirement.

Image production from magnetic tape.

The latent image stored on a magnetic tape may be re-converted into a photographic image either before or after adjustment or enhancement by any of the previously mentioned densitometers which have a 'write' mode. Where very high image resolution is not required, the drum densitometer or flying spot scanner may be used, but for production of the highest quality imagery, the laser beam recorder is the most accurate, followed by the electron beam recorder, a simplified diagram of which is shown in Fig 49. Special film is used which is sensitive to electron illumination and which has an ultra-fine grain, this being essential for the production of high quality imagery. The film is placed in a chamber which is held in the same vacuum as the electron gun, so that the electron beam may fall directly onto the film surface, thereby elimintating any losses or distortions which may be present in other recorder designs due to the effect of intermediate lenses, phosphor screens etc. Very accurate scanning control of the electron beam is possible due to the careful design of the deflection and focus coils and of the control of their power supplies.

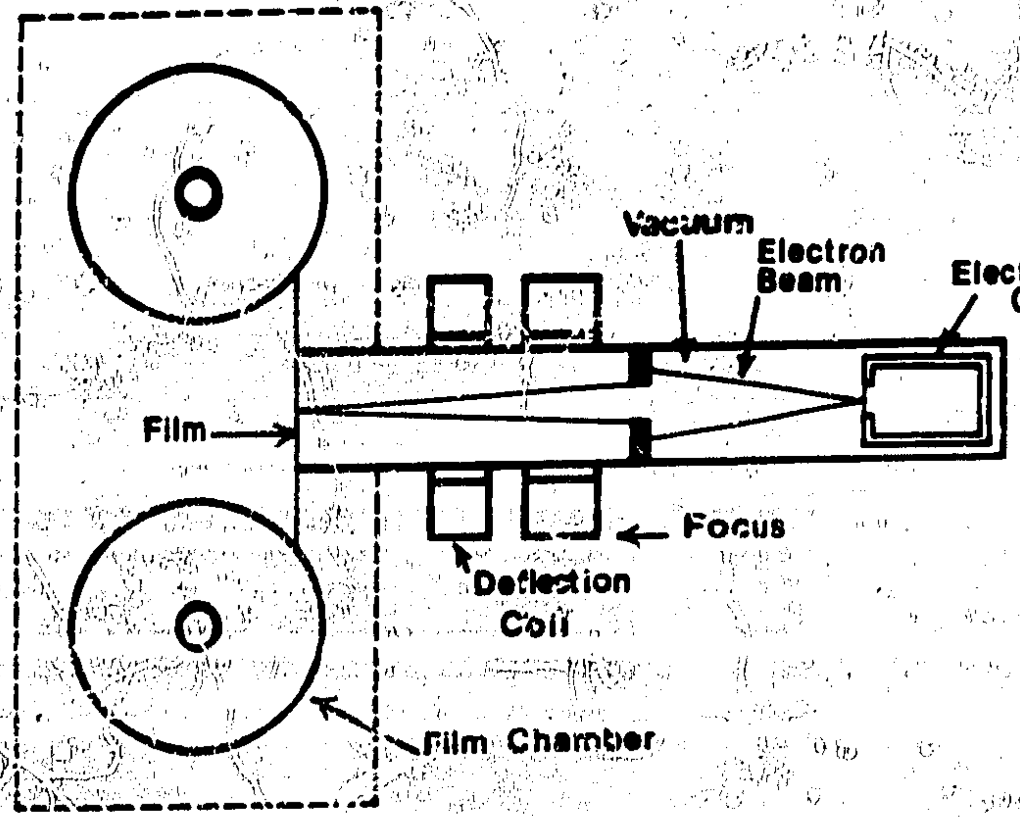


FIGURE 49 Electron beam recorder

6.3 Data compression

No matter how remotely sensed data is stored prior to its analysis, individual data units or picture elements (pixels) can be recognised, these being the smallest areal changes in signal which are detectable using a particular sensing and recording system. For example, on a photographic record, a pixel might be an individual grain of the film emulsion, assuming that the camera lens was capable of such a fine resolution. Clearly, the number of pixels recorded on any single image is going to be very large (several millions for example on a photographic negative) and even with computer processing, difficulties will occur in trying to handle so many pieces of information. Because of this, virtually all sensed data is subject to some form of 'compression' in order that only the relevant pieces of information are used. What must be ensured however is that those data which are not immediately relevant, should not be discarded irretrievably, but should simply be put to one side in case they are later needed. Similarly, much compression is possible with data which records equipment function. Generally when electrical components are functioning within their specified tolerance, the signals confirming this can be ignored. Only those which register deviations need be kept.

In its simplest form, 'data compression' could be the encircling of an area of interest on an aerial photograph to show that further investigations should only be done within that area, the rest of the photograph being ignored for the time being. A different form of data compression might be, for example, to classify a number of recognisable tree species on a colour photograph into the broad groupings of either deciduous or coniferous. Taking an imagery example once again, if one wished simply to distinguish between grass and concrete distribution from an aerial view of an airport, it would only be necessary to recognise the boundary between the two surfaces and all other data relating to the main bodies of grass or concrete would become redundant. When computer controlled compression techniques are carried out on individual pixels of data, end products very similar to these examples may result, although their method of execution will be more quantitative and statistical in nature.

Where no (or limited) changes of value occur from one pixel, or data-bit, to the next, then such data may be made redundant. Adaptive sampling methods alter the frequency of data-bit sampling according to the expected response rate of the signal - the faster the response rate, the higher is the sampling frequency necessary in order to detect any possible changes. (Ref 82). Approximation techniques in effect remove signal noise, in that one value is assigned to all features lying within a certain percentage of that value. This has the effect of reducing an image from continuous tone to a series of specific flat tones. By using other sampling techniques, only boundary or contour lines can be retained, with subsequent reduction of inter-line data. A detailed account of data compression methods is given in Ref 81, Vol 1 & 2, which concludes with some useful additional references.

6.4 Geometric manipulations

Geometric manipulations are the often complex rectification procedures necessary to correct any geometric distortions prevalent in the remotely sensed imagery. Distortions are largely induced by variations in the relative geometry of a sensor to the ground, either due to platform movement, or to variations in surface relief, or to inaccuracies in the way the sensor has recorded the ground scene (Fig 50). Optical rectification procedures, for the correction of photographs taken from metric cameras, have been used for many years and their scale and image reconstruction methods are well refined (Ref 83). The more recent use of many different types of optical/mechanical/electrical sensors has initiated the development of new rectification techniques to handle the possible variations in sensor output and (in the case of linescanners for example) to overcome any image distortions inherent in the design of the sensor (Fig 25).

The inclusion of very sensitive inertial or gyro-stabilised recorders on platforms may allow some geometric or internal instrument adjustments to be made in flight, or may allow later adjustments for platform movement to be more easily made (Ref. 84). Generally, rectification of linescanner-produced imagery is much more difficult than instantaneous synoptically produced imagery, as instrument and platform changes can occur during scan movements. (Ref. 73).

A simple method of aiding location on a distorted image is to overlay a map projection grid on the image using recognisable reference points,

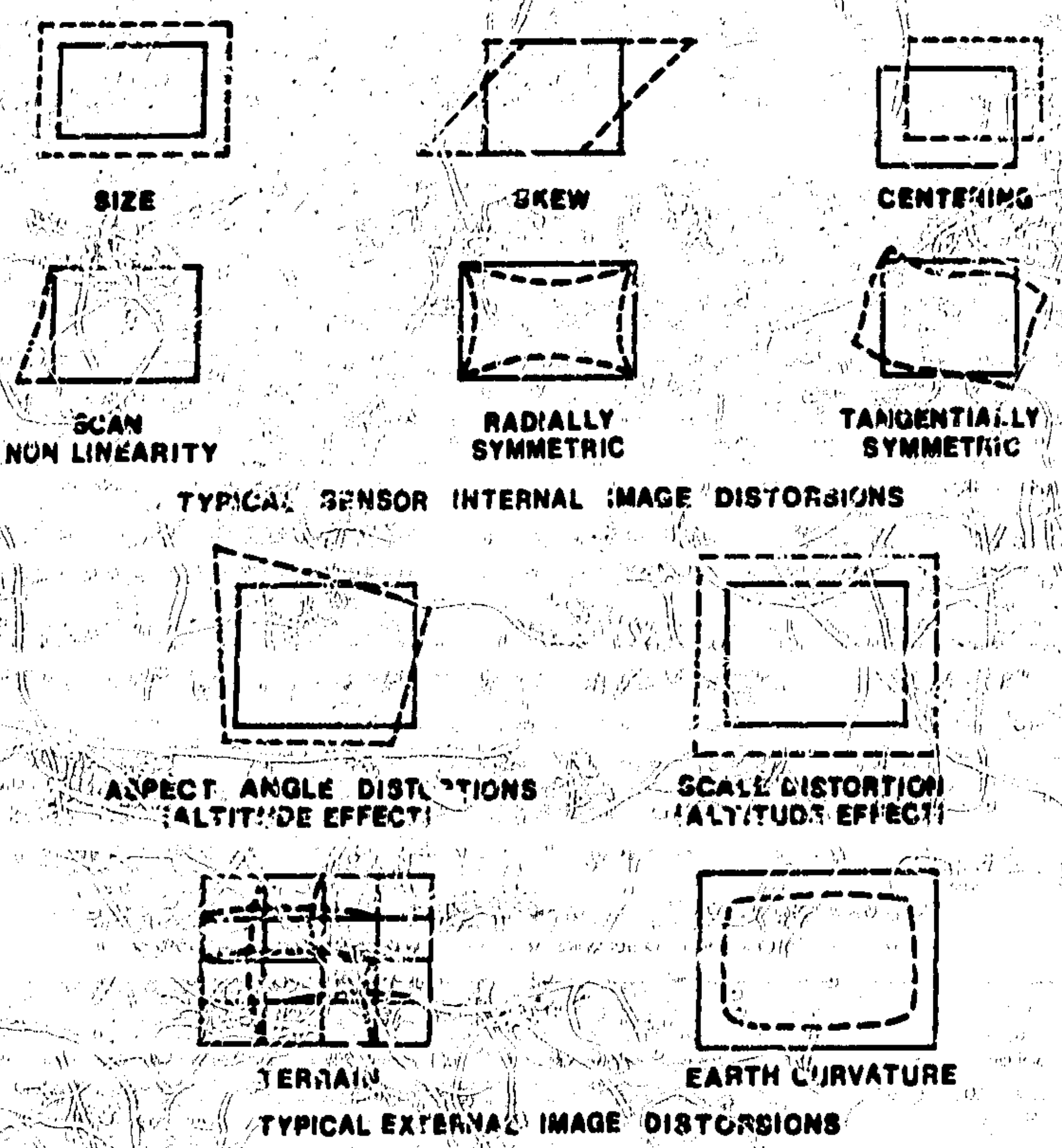


FIGURE 50 Characteristic geometric image distortions

or by taking into account measurable geometric distortions. A warped grid is the result, which allows the eye to be aware of the direction and amount of distortion present. The only fully acceptable method however, is complete image reconstruction where (to within given limits) all errors are removed. To accomplish this, computer techniques must be used whereby sensor calibration data, platform location data and external factors such as Earth curvature, atmospheric refraction etc must be taken into account. Final adjustments may be made in a similar way to photogrammetric rectification whereby several ground control points of known relative position are correctly reconstructed in the image. Such rectification techniques are different for each application, but some methods of approach are given in Ref. 81 Vol. 1 p 5-1 to 5-22.

A different form of rectification is called for when different images of the same scene are to be superimposed. When simultaneous imaging of a scene is undertaken from the same platform but with different sensors, image matching may not be too difficult, but complex differences may exist between images taken at different times, possibly even from different platform types. In such a case, a large number of recognisable points on both images must be correlated so as to be certain that any geometric differences have been removed. The final combined image may of course still be distorted in relation to the actual ground scene, but this may not matter if only scene differences between the two images are required. For the interpretation of multi-spectral imagery, exact image registration is essential otherwise incorrect interpretations may be made. (Ref. 85).

6.5 Data pre-processing

Prior to the enhacement of data, it may be possible to carry out further adjustments to the signal in order to replace predictable losses in the sensing or transmission system such as those of high frequencies. Corrections can also be made to remove the effect of other predictable or measurable components such as surface shading or sun angle effect, the effect of sensor look angle on surface reflections and emission and on the resulting atmospheric attenuation. At this stage some ground control information may be used to enable unwanted ground variation effects to be accounted for, such as changes in surface temperature, soil moisture or different agricultural practices on otherwise identical surface types.

Whereas geometric manipulations alter the geometry of an image but leave its radiometric content unchanged, pre-processing techniques are generally radiometric transformations in which the grey level or colour of an image is altered, but its geometry is left unchanged. Generally such radiometric transformations are performed on images in order to enhance certain features of importance.

Density slicing

For a monochromatic image, the whole density range covered in the image is first divided into a number of segments. The density of each data point is measured and all those falling within a particular segment density range are assigned a single grey level density. The overall effect is to reduce a continuous tone image to one composed of several grey steps. At the boundary of consecutive grey levels, an image density 'contour' is formed (Ref 86).

Colour addition

If, in order to retain detail, a large number of grey levels are chosen in the density slicing process, it is often difficult for the human eye to easily distinguish between them. To make this recognition process easier, colours can be assigned to each grey level. Whilst in monochrome only 6 or 7 density steps can be easily recognised, this can be extended to upwards of 60 using a combination of different colour densities (Ref. 87).

Density ratioing

Where multispectral images of the same scene are available, density

Contrast stretching

In order to amplify the tonal changes in an image, the image is first segmented into several density ranges, then each grey level range is extended to a full tonal range ie almost black to white. Subtle contrast changes are thus more easily recognised (Ref. 88).

Image smoothing

This process reduces the effect of random 'noise' which often occurs when sensing at short wavelengths. It is carried out by averaging density values around each data bit which once again allows subtle tonal changes to be detected which would otherwise be lost in the 'noise'. Frequency smoothing may also be carried out in a similar way (Ref. [illegible]).

Edge enhancement

This is a method whereby lines can be produced where large density differences are detected. A line-drawing effect results in which such features as roads, buildings, field boundaries etc are sharply outlined (Ref. 81, Vol 2 p.14-8). A similar result can be obtained photographically with the use of Agfacontour film (Ref. 90 & 91).

Spatial frequency filtering

The removal of unwanted frequencies from the Fourier transform of a signal can be achieved in this way. The Fourier transfer function is the response of a piece of data to a simple frequency sine wave input. Once the response is known, the complex data record can be split into a series of simple sine waves of different frequency and amplitude (Fourier analysis). Each of these sine components can be transformed by means of the transfer function and when added together, a reconstruction of the original signal should be possible. The removal of some of these frequency components may allow certain features to be enhanced; in effect a frequency 'noise' removal (Ref. 92 & 93).

Directional filtering

This operation retains or eliminates all picture information at all frequencies in a certain spatial direction and therefore results in enhancement of features set perpendicularly to that direction. The effect is somewhat similar to polarisation and is used to enhance linear ground features such as crop rows, geological faults and bedding planes, lattice drainage patterns etc. (Ref. 94).

Cluster analysis

This is in effect a mathematical technique which results in data reduction and edge enhancement. Each data bit is taken separately and compared with its surrounding neighbours within a given distance. A threshold range is defined whereby neighbouring points may be regarded as being the same as, or being different to, the central point, the aim being to create clusters of similar points as large as possible. Further reduction may take place by regarding each cluster as a single point and repeating the process with wider range limits. Boundaries can then be drawn between clusters of differing value (Ref. 95).

Flicker analysis

This is a viewing process which allows multispectral or time separated images of the same scene to be viewed alternately in quick succession either by switching of the two image illumination sources or by linked mechanical chopping of two light sources. The effect is to accentuate any differences in the two images. Where no differences exist the image will appear still, whereas flickering of the image indicates a change of state, (the more obvious the flickering, the greater is the change (Ref. 96)). This type of analysis requires exact registration of the two images. Television display systems are also capable of flicker projection of digitsed data.

6.6 Feature extraction

Computer controlled methods of feature extraction are necessary where large amounts of data (especially when recorded in digital form) are to be handled on an operational or day to day basis. The methods used for 'automatic' feature recognition are too complex to be described here, and they may often be 'automatic' only for the recognition of fairly simple or specific features. In most cases, considerable direct control and decision making is required by the operator who uses the computer as a tool to speed his feature extraction capability. Where complex interpretive decisions are required, the human brain, with its vast a-priori knowledge, is still the most efficient feature recognition, extraction and classification system. Nevertheless, both 'eyeball' and computer controlled extraction techniques rely on the same basic principles of feature extraction. Individual features may be recognised largely by their shape, their image density (tone or brightness) in a single waveband, their spatial pattern (or texture) or their spectral signature when multispectral or other spectral discriminating imaging is used (Ref. 99).

For a single waveband image, the image density is proportional to signal brightness and, in the case of monochrome photography, this, coupled with signal pattern enables an enormous amount of information about a scene to be recorded. Simple, recognisable and repeatable patterns may be formed by crop management practices (row widths, plant spacing, contour ploughing, terracing etc), geological features (bedding planes, faults), linear features (roads, railways, rivers, canals, field boundaries) and other man made features such as buildings. Textural differences may further pinpoint variations in any of these features. Where such definite features are to be expected in computer handled imagery, 'a-priori' information can be included in the programme so that the remotely sensed signal can be compared to a set of expected signals. (Ref. 100). Where no 'a-priori' knowledge is included, 'features' may be recognisable merely by their difference, with interpretation procedures being undertaken after their extraction. (Ref. 101).

When multispectral imagery of a ground scene is available, more specific spectral 'signatures' can be recognised and a fairly precise definition of the feature is often possible (see p. 48). For this reason, multispectral data is better suited to computer handling techniques and very high feature recognition success rates have been achieved which enable crop and vegetation types to be defined (Ref. 102) along with most other homogeneous surface features. Water bodies for example can be recognised to a very high degree of success due to their almost total absorption of infrared wavelengths (Ref. 103). An introduction to some basic feature extraction techniques is given in Ref. 81 and also in section 5 of the EMI Handbook of Remote Sensing Techniques (Ref. 24), whilst more specific and advanced techniques are to be found in the numerous LARS (Laboratory of Advanced Remote Sensing) information notes of Purdue University, Indiana.

6.7 Feature classification

This is generally the last process to be carried out on remotely sensed data, but if the required degree of classification precision is known before data handling procedures are started, the whole system can be geared toward that end. It would be pointless for example to distinguish between different crop types or different types of impervious surface at the image enhancement or feature extraction stage if the required classification was only for urban and agricultural areas to be defined.

Assuming that the information requirement from the data is tightly defined, it is advisable to keep its classification as simple as possible, (using the least number of classification groups), in order to minimise data handling procedures. If, however, the end requirement is not particularly clear, it may be advantageous to increase the number of classification groups in the first stage rather than being forced to reprocess the data because of lack of information.

Where automatic classification procedures are employed, the decisional criteria are generally statistical in nature. 'Supervised' classification techniques rely on means of comparing known features with those to be classified. 'Unsupervised' methods such as clustering (see p. 69) first separate different components and then assign each to a particular class, with the advantage of reduced computer time and less reliance on extensive ground truth information. 'Adaptive' techniques adapt the decision rule to the data being recognised, and as recognition decisions are being made, the already classified data is used to update and increase the efficiency of the decision rule. The main advantages of this are that high recognition accuracies are possible and a reduction in necessary ground truth information (Ref. 104) can be achieved.

The problem of data analysis has been tackled as a series of logical steps through which one must pass in order to obtain maximum information from a piece of remotely sensed imagery. In practice, however, (depending on the requirement) this procedure need not be rigidly adhered to and short cuts to the end product may sometimes be possible. Similarly, it may be found that, using a certain technique, several of the given data analysis stages may be covered in one procedure.

It is very useful however to be able to split the analysis procedure into stages, as the prospect of tackling 'Data analysis' en-bloc is rather daunting and useful available information contained within the imagery may possibly be overlooked.

6.8 Ground verification measurements

Accurate remotely sensed image interpretation is only possible if high quality ground truth observations are available, both as a basis and a confirmation of correct ground classification and state. The easiest way of reducing errors in such a system is to ensure that the timing of ground truth observations and the remote sensing of a particular scene are coincident, especially where quantitative or ground state information is required. The accuracy, frequency and distributional pattern of ground state measurements must be carefully tailored to the requirements and limitations of a remote sensing mission. For example, it would be wasteful and unnecessary to take water surface temperature measurements every 5 metres to an accuracy of ± 0.1°C if the sensor was only capable of resolving a 100 metre ground element to an average temperature of ± 1°C. Similarly it would be incorrect to interpolate surface water isotherms at 0.1°C intervals if ground verification measurements were correct to only ± 0.5°C. When high ground resolutions are attainable, it is advantageous to physically mark the position of ground measurements by putting out reference markers which will be visible in the final imagery (Ref. 74 & 79). This then accurately fixes a correct point of measurement on the image. An extension of this procedure is the laying out of a series of reference panels of known colour, brightness temperature or reflectance - probably the best control available where temporal variations are to be measured (Ref. 98). For lower resolution imagery, ground measurements could be sited at easily located points such as at river or road junctions to allow accurate location on the image, provided that by doing so, no bias is introduced into the ground element sampling.

7. THE MEASUREMENT OF HYDROLOGICAL VARIABLES USING REMOTE SENSING TECHNIQUES

This chapter describes how remote sensing techniques can be used to measure each of the hydrological variables. The choice of a particular technique depends on the required frequency and accuracy of measurement: Table 4 shows some typical hydrological measurement requirements.

7.1 Topography and land use

Topography

Most Earth science studies of specific areas require an understanding of the effects of such physical surface parameters as altitude and

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TABLE 4A TYPICAL MEASUREMENT REQUIREMENTS OF HYDROLOGICAL VARIABLES

Hydrological Element	*Resolution (metres)			Accuracy	Frequency		
	A	B	C				
DRAINAGE BASIN CHARACTERISTICS							
Drainage area	30	30	100	(±1% of watershed area)	(every 10 years)		
Channel dimensions and patterns	30	30	100	(±5% of length)	(every 5 years or after major flood event)		
Overland flow length	30	30	100	(±5% of length)	(every 5 years)		
Surface slope	30	30	100	(±5% hor. ±5 cm vert.)	(every 5 years)		
Land cover type	100	100	100	(±1% of watershed area)	(every year)		
Albedo	100	300	1,000	(5%)	(6 hourly)		
SURFACE WATER					A	B	C
Areal extent	10	30	100	(5%)	(daily)	(daily)	(4 days)
Saturated soil area	10	30	100	(5%)	(daily)	(daily)	(4 days)
Flood extent	10	30	100	(5%)	(1 hour)	(12 hrs)	(1 day)
Flood plain boundaries	10	10	10	(5%)	(5 yrs) (& after major flood events)	(5 yrs)	(5 yrs)
Lake or river stage	-	-	-	±1 cm	(10 min) (30 min)	(15 min) (1 hour)	(1 hr) (4 hrs)
WATER QUALITY							
Turbidity	30	100	1,000	(±0.5 FTU)	(daily)		
Suspended sediment	30	100	1,000	(±10 ppm)	(daily)		
Colour	30	100	1,000	(±10 mg Pt/1)	(daily)		
Aglae bloom	30	100	1,000	-	(2-3 days)		
Surface film detection	30	100	1,000	-	(daily)		
Surface water temperature	30	100	1,000	(±0.03°C in 0-1° range) ±0.1°C in 1-4 range otherwise ±1°C)	(6 hours)		
Temperature profile	-	1,000	10,000	(±0.25°C)	(2-3 days)		
PRECIPITATION	100	1,000	5,000	±2 mm if <40mm ±5% if > 40 mm	6-hourly		
EVAPORATION OR EVAPOTRANSPIRATION	100	1,000	5,000	±0.5 mm	daily		

* Estimates for drainage basins of the following sizes:-

A - < 100 km^2
B - 100 - 1,000 km^2
C - >1,000 km^2

TABLE 4B TYPICAL MEASUREMENT REQUIREMENTS OF HYDROLOGICAL VARIABLES

Hydrological Element	*Resolution			Accuracy	Frequency
	A	B	C		
SNOW					
Snowline	30	100	1,000	-	(Daily)
Snow cover	300	1,000	10,000	(± 5% of snow area)	(Daily)
Water equivalent	100	300	1,000)	± 2 mm if <2cm	Daily
Free water content	100	300	1,000)	±10% if >2cm	
Snow surface temperature	100	300	1,000	± 1°C	(6-hourly)
Surface albedo	100	300	1,000	(5%)	(6-hourly)
GROUNDWATER DETECTION					
Aquifer mapping	100	100	100	-	(5 years)
Location of discharge to rivers	30	30	30	-	(weekly)
Location of discharge to lakes	100	100	100	-	(weekly)
Location of springs	30	30	30	-	(5 years)
GROUNDWATER LEVEL	300	1,000	1,000	(1 cm)	(daily)
SOIL TYPE	100	1,000	1,000	-	(5 years)
UNSATURATED ZONE					
Moisture content profile	100	300	1,000	10% of field capacity	(daily)
Temperature profile	100	300	1,000	(0.5°C)	(daily)
Infiltration/Percolation	100	300	1,000	(10%)	(daily)
Depth of seasonal frost	100	300	1,000	(10%)	(weekly)

* Estimates for drainage basins of the following sizes:-

A - < 100 km^2
B - 100 - 1,000 km^2
C - >1000 km^2

TABLE 4C DATA REQUIREMENTS FOR LARGE SCALE ATMOSPHERIC WATER BALANCE ESTIMATION

Hydrological Element	Resolution	Accuracy	Frequency
Precipitation	100 km	± 2 mm if < 40 mm ± 5% if > 40 mm	6-hourly
Evaporation, Evapo transpiration	100 km	(± 5%)	(6-hourly)
Atmospheric Moisture Storage	100 km	(± 5%)	(6-hourly)
Atmospheric Moisture Flux divergence	100 km	(± 5%)	(6-hourly)

magnitude and direction of ground slope. This is especially true for hydrological process studies and for catchment water-balance studies. The actual surface shape may be of interest in detecting hydrological features such as sink holes, stream heads or erosional and depositional structures such as water-bearing gravel deposits. Surface texture or roughness measurements may be required in order to estimate surface water storage capabilities, as an indication of possible over-land storm-water flow rates, or for surface evaporation estimates.

Active microwave imaging probably has the greatest potential for delineating variations in surface topography. Unlike spectral sensing methods where the electromagnetic signal received from a body is highly dependent upon its chemical composition, the return signal from an active microwave sensor (see p. 52) is less affected by body composition, but is highly dependent on its surface physical state. This is because the ground surface is illuminated from a discrete point source (the antenna) as opposed to the relatively diffuse atmospheric radiation. The intensity of the reflected return signal is largely dependent on the angle of incidence of the body surface to this source. Thus, hill slopes facing the antenna will appear brighter than similar slopes falling away from the antenna (see Fig. 51). The surface roughness characteristics of the body in relation to the wavelength of the microwave illumination used also affects the return signal strength. For example, both ploughed and harrowed fields may produce the same brightness signal at long wave lengths (say 30 cm) whereas a marked difference would be apparent at say 2 cm. Concave surfaces larger than one wavelength will concentrate the return signal, resulting in a bright image, whereas convex surfaces will tend to scatter the beam, resulting in a darker image (see Fig. 51).

Though microwave radar imagery is very much in its infancy, there has been considerable success in the use of sideways looking radar (see p. 52) for surface topographic studies (Ref 106), stream network analyses from upland topographic information (Ref 106), and geological interpretation from surface features (Ref 107). By detecting the polarising effect on the original signal (p. 54), considerable additional information can be obtained on surface types, especially for the enhancement of trends such as geological fractures, lattice drainage types, sand ridges etc. Although active microwave techniques appear to have great future potential for morphometric classification, several sensor operation difficulties exist such as loss of data in shadow areas, inaccurate image positioning due to 'layover' (see Fig. 52) and variable errors caused by uncorrected platform movements and navigational drift (Ref 108). High image resolutions are attainable using synthetic aperture techniques, but with real aperture systems, resolution is mediocre (see p. 52). Some additional disadvantages of radar for small projects are the high cost, poor availability in the U.K., necessity for experienced interpreters and the requirement of extensive ground control (Ref 109). The ability of active microwaves to enhance small surface features is of great advantage to many topographic studies, but their all-weather capability would only occasionally be a prerequisite where consistently extensive cloud cover is experienced.

Normally therefore, first consideration should be given to conventional

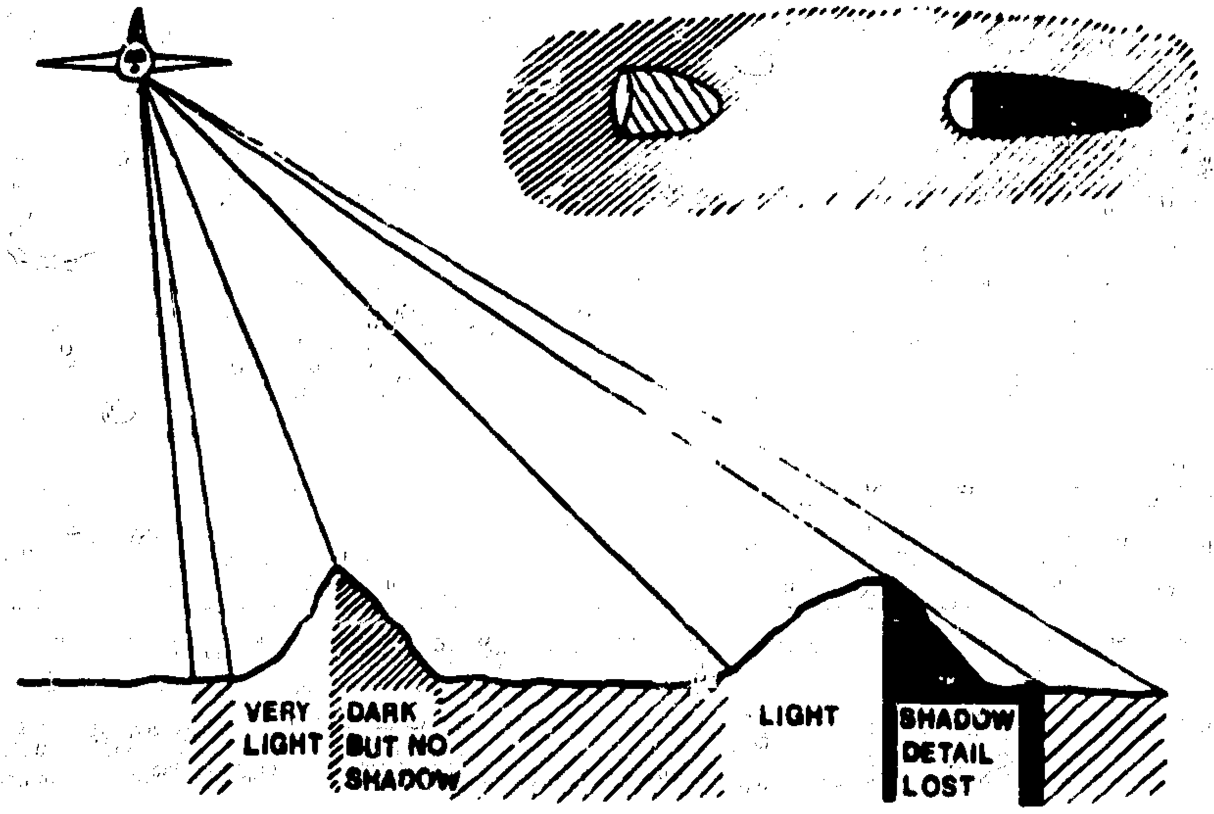
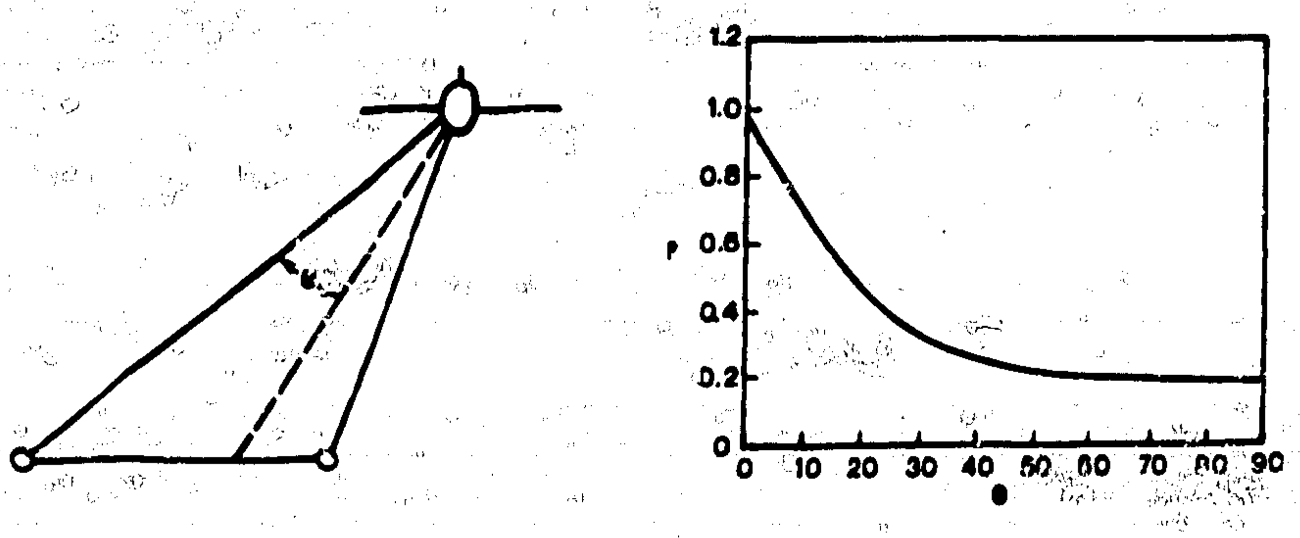


IMAGE DISTORTIONS



VARIATION OF REFLECTIVITY AS A FUNCTION OF ANGLE (ACTIVE SYSTEM)

FIGURE 51 Effect of look angle and topography on SLAR imagery

stereo aerial photography taken from a height conducive to the surface detail requirement. Using imagery of photogrammetric quality, topographic heights or contours of the ground can be constructed, from which ground slope and aspect can be measured much more quickly than from ground surveys. As an alternative to conventional mapping, the production of orthophoto maps (Ref 110) combines topographic map detail with the additional infilling of tonal photographic information without any loss in map accuracy. In order to enhance surface texture and relief, photographs should be taken at a time of low sun angle to increase the shadow effect, exposure and development of the film must be such as to retain shadow detail and colour film should be used where possible to improve detail in the shadow areas (Ref 112). In poorly

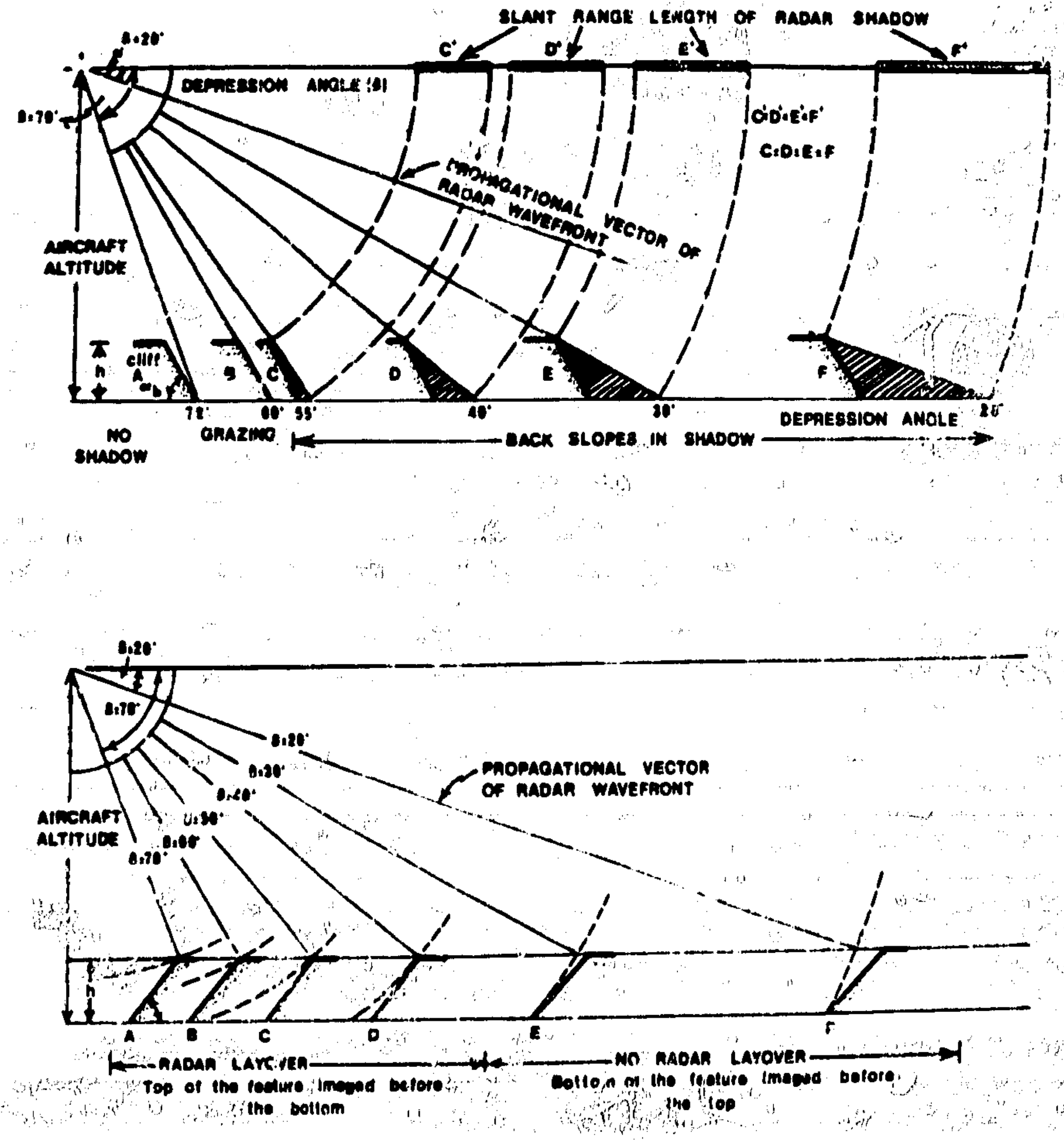


FIGURE 52 Layover and shadowing effects on SLAR imagery

mapped areas, where satellite imagery may be the prime data source, imagery taken in autumn or spring should be chosen when sun angles are low (Ref 113). Again, it may be advantageous to retain image detail in the form of an orthophoto map and using LANDSAT imagery for example, maps of scales up to 1:100,000 can be produced to accuracies similar to those achieved by conventional methods (Ref 114).

Although the U.K. has probably the most extensive ground survey coverage in the world, much is still not available at the required scale, or is often out of date. When specific information is required, such as urban or rural land-use, the situation becomes even worse. This, of course, is understandable as the Ordnance Survey could not possibly expect to keep pace with countrywide land-use changes in sufficient detail to allow regular updating of all categories of large scale maps - at least, not through the use of conventional ground survey techniques.

As an attempt to overcome this problem, map revision from aerial photographs is now being used for some Ordnance Survey editions whereby transparent ortho-corrected photographs are overlaid on previous edition maps and any changes noted. For example in 1969, the R.A.F. completed black and white aerial photography of the U.K. and Fairey Surveys used largely this aerial information to produce 1:50,000 updated urban land use maps by overlay techniques (Ref 115). Computerised methods of map updating are being developed by the Experimental Carographic Unit (Ref 116) and a more widespread acceptance of automated map revision and eventually automated map surveys and production can be expected in the future (Ref 117). At the moment however, automatic methods are used largely for feature generalisation in the production of small scale maps. For map revision, the automatic recognition of sharply defined boundaries, such as roads, field boundaries or buildings can be achieved by digitisation of the aerial photograph (see densitometers p. 61) to reduce it to a computer-compatible form in order that edge detecting algorithms can be applied (Ref 118). Feature boundaries can then be displayed on a graph plotter or similar output. When automatic classification as well as feature delineation is required, more complex spectral or textural recognition techniques must be employed.

In rural areas, land use classification may be required in hydrological studies for the estimation of catchment water balance, where the vegetation type may affect evaporation, interception and surface runoff rates. Vegetation vigour, or the occurrence of certain species, may be indicative of soil moisture conditions (Ref 119), of the occurrence of near surface ground water or springs (Ref 120), or of surface lithology of hydrological significance (Ref 121). The delineation of permanent wetland or of flood plain pastureland may be important for the prediction of storage volumes of storm water or likely river flood levels, whilst the recognition of certain cultivation practices such as contour ploughing or slope terracing, could significantly affect the prediction of rainfall runoff rates.

As any of the above hydrologically related land use effects may be very variable in surface distribution and as some may also change rapidly in time, the most efficient way of monitoring such changes is from an aerial viewpoint where a planimetric view of the ground can be obtained. Even without the skills of an experienced photointerpreter, a great deal of land use information can be obtained from the simplest of aerial photographs. Where existing large-scale maps of an area exist, accurate updating of major land use categories can be accomplished by visual interpretation of low level oblique or vertical photographs, coupled with suitable ground control observations. In urban areas for example, it has been found that, using low level (1500 ft) true colour 35 mm photography, taken from a light aircraft, eight categories of impervious surface types could be accurately distinguished (Ref 122). In several cases, where discrepancies occurred between the interpreted surface type and the actual ground observation, the error was found to lie in the ground survey. This was generally due to difficulty of access preventing an adequate view of a particular site e.g. awkwardly placed roofs, surfaces within large industrial complexes, hidden back gardens etc., all of which were readily observed from the aerial viewpoint. It must be remembered that high success rates in this type of image interpretation are largely due to the past knowledge and familiarity of the interpreter with, in this case, a typical U.K. urban scene. If totally unfamiliar photography were tackled in the same way, it is most likely that feature recognition would be less successful. For this reason, it is highly advantageous that persons involved with photo-interpretation should have a first hand knowledge of the ground scene, or of a similar area. Interpreter learning also means that repetitive surveys become progressively more efficient, with one-off measures being the least efficient.

For more extensive land use surveys, the stereo image afforded by photogrammetric quality imagery may facilitate easier interpretation of land use types. Although a considerable amount of information can be obtained from black and white photographs, it is widely accepted that colour photography is superior in defining land use types (Ref 123), as the human eye can distinguish more shades of colour than levels of greyness. For the separation of different vegetation types, colour infrared film may be better still, as changes in near infrared leaf reflectance may distinguish species having almost identical visible colouration (Ref 124). Colour infrared film has been used in aerial surveys for forest inventories (Ref 125), for the delineation of coustal wetlands by recognition of vegetation species (Ref 126), and for the delineation of river flood plains in forested areas by identification of phreatophyte species (Ref 127). An additional advantage of colour infrared film is that, within a given plant species, changes in foliage area, density and condition can often be detected as variations in the magneta coloured near-infrared sensitive layer of the film (see Fig. 53). Such changes in plant condition may be indicative of hydrologically related factors which will be discussed later.

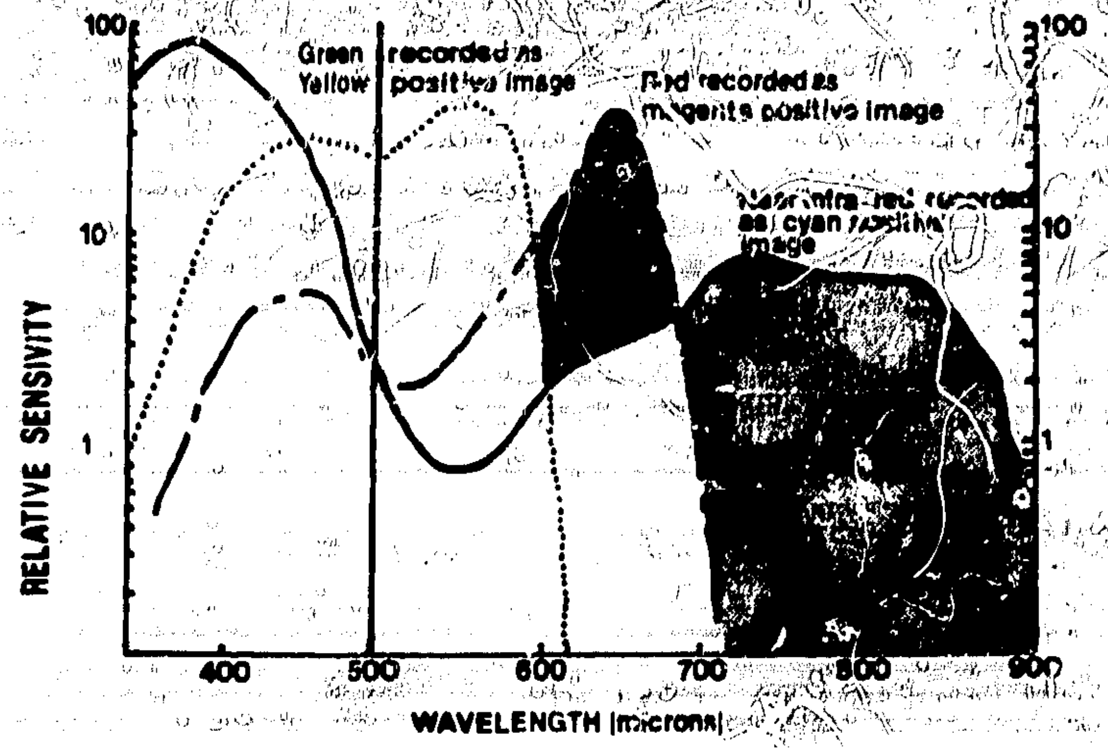


FIGURE 53 Spectral sensitivity of colour infrared film

Visual image interpretation techniques are usually most cost effective when only small quantities of data are to be handled or when broad land use categories are required, such as can be readily extracted from the previously mentioned film types. For countrywide land use surveys, automatic recognition techniques are more likely to be cost effective. Where subtle variations between surface types must be resolved, then multispectral methods must be considered.

As explained on p. 48, objects can often be recognised by their spectral signature i.e. the intensity of electromagnetic radiation (EMR) emitted by them at different wavelengths. Multispectral imaging effectively samples portions of a body's spectral signature, by measuring the EMR within specific ranges of wavelength. In the case of multispectral photography for example, the mean intensity of EMR recorded in each of the (normally four) wavebands generally enables the spectral response to be attributed to a particular body (see Fig. 33). If the separation of only a few specific features is required, the multispectral bands can be selected at wavelengths where maximum separation of the spectral curves exists e.g. at the points B and D in Figure 32. The normal procedure for choosing the most suitable bands is first to take ground spectro-radiometric readings of features of interest, in order to determine their spectral response (Ref 128) usually in relation to a reference target. Suitable filters can then be used to observe the features in narrow wavebands where maximum response differences occur e.g. in Figure 54, in order to separate the moss from the holly, a narrow band pass filter in the 5.5 µm region could be used. The use of four different spectral bands (often blue, green, red and near infrared) enables classification of many land use types without producing unmanageable amounts of data and indeed fewer bands should be used if these would give adequate results. However, to fully utilise the available information from multispectral sources, computer pre-processing and classification techniques, as described in 6.5 to 6.7 are desirable and considerable research has been carried out in perfecting such land use recognition methods. One of the leaders in this field is the Laboratory for Applications of Remote Sensing at Purdue University who have had great success in crop and land use identification (Ref 129), and of remote monitoring of changes in plant physiology (Ref 130).

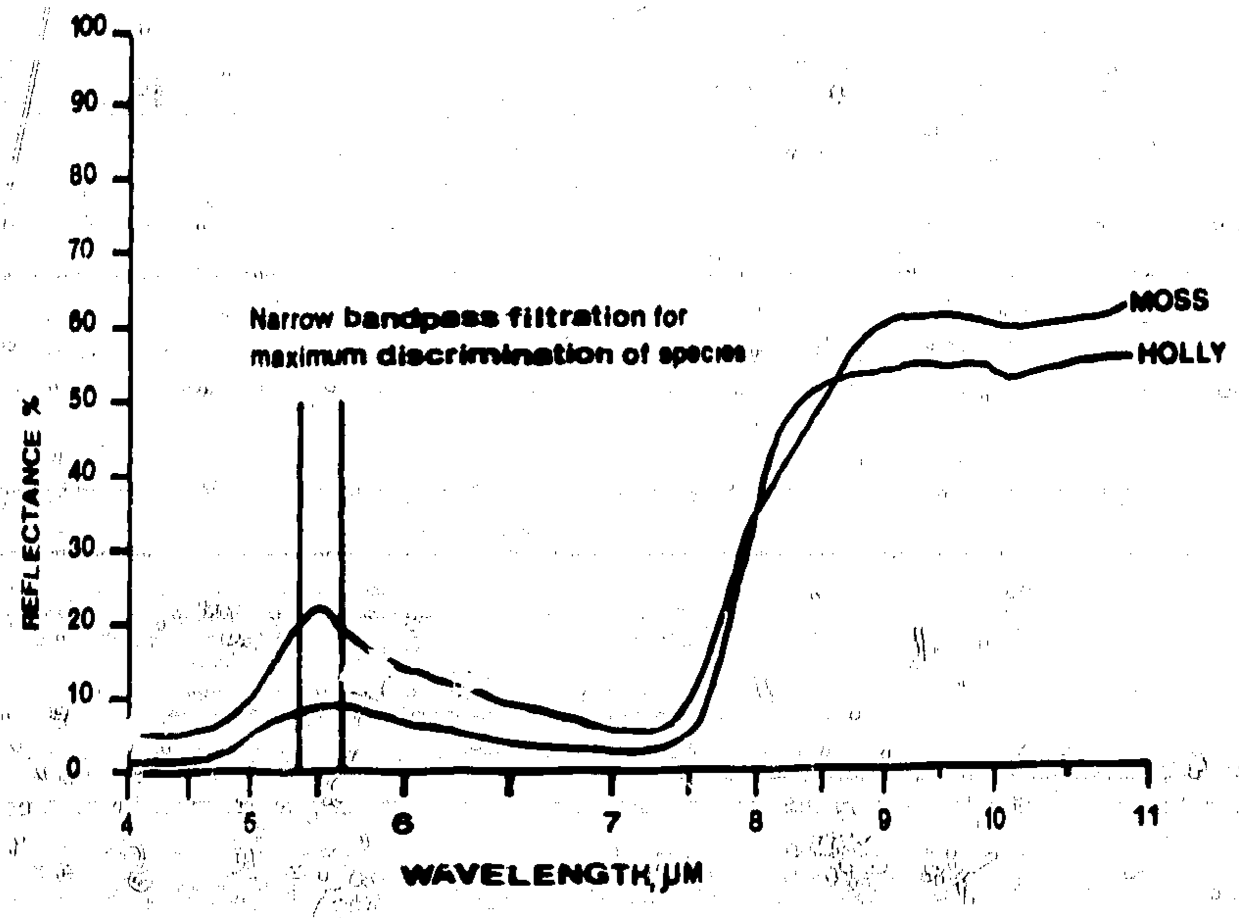


FIGURE 54 Spectral reflectance of two plant species

The cheapest form of multispectral imagery is obtained photographically using suitably filtered cameras, of which the main types are described on p. 30 . Colour additive display techniques can be applied directly to the photographic negatives to allow visual interpretation and require a capital outlay of around £3,000-5,000 for the display instrument. Computer analysis of photographic imagery may however be costly, as densitometric scanning of the image is first necessary to reduce it to a digital form (see densitometers p. 61). Where high data acquisition rates are expected, the higher purchase cost of a multispectral scanner will probably be offset in the long term by cheaper data analysis costs, the output already being in a computer compatible form (see p. 48). In the U.K., it is unlikely that individual organisations other than survey companies could justify the cost of a multispectral scanning system, but several camera systems are already in use by air survey firms, research bodies and universities (Ref 131). For any type of multispectral survey, however, high quality ground control measurements are vital, as changing incoming radiation levels, film processing or instrument variations etc. can all greatly affect the final image and must thus be fully accounted for if temporal comparisons are to be made.

Considerable success has been achieved in mapping land use categories from orbital altitudes. The greatest volume of work has, of course, been carried out on LANDSAT data, but some of the most detailed mapping has been achieved using high resolution photography from the Skylab manned satellite. The approximate ground resolution of 30 ft afforded by the RC8 mapping camera was used to produce land use maps in both urban and rural areas in which at least 17 categories of land use were distinguished (Ref 132). The 18 day orbital frequency of LANDSAT does not cause problems for most land use mapping requirements, as imagery can be chosen when weather conditions are clearest. The multispectral capability of LANDSAT makes up to a certain extent for its poorer resolution in relation to Skylab, so that land use mapping and especially the recognition of long term land use change, have become the greatest overall contribution of LANDSAT imagery. A review of some LANDSAT land use work is given in the Manual of Remote Sensing (Ref 133) and several papers in the Commonwealth Survey Officer Conference (Ref 134 and 135) were concerned with the cartographic capabilities of LANDSAT data. From a hydrological point of view, the synoptic capability of satellite data is of enormous advantage over aircraft acquired data, as whole regions can be recorded in a single image, thus allowing large scale surface trends to be observed. Such changes would often be lost in the mosaicing of aerial photographs and direct comparisons could not be made because of both the time lag between the photographic exposure of widely separated images, and because of the likely differences in photographic processing of time separate images. The latter problem may still occur in satellite imagery, due to sensor drift, but internal calibration reference sources help overcome this (see p.51). The importance of synoptic variations will be more fully explained in the following sections relating to specific hydrological problems.

7.2 Water extent

Open water surfaces

The detection of previously unmapped water bodies, or the measurement of known water body extent is generally an awkward and time consuming exercise when attempted at ground level, due often to the difficulty of access afforded by water bodies and their immediate surroundings. By adopting an aerial viewpoint, water extent is much easier to assess, as shielding by vegetation is usually only effective around the perimeter of large water bodies. Water extent is probably the easiest earth feature for remote sensing systems to delineate due to its high contrast with land features in certain wavelengths (see Fig. 33). In addition, ground verification of water extent is straightforward in that a definite yes/no answer can often be given with fewer grades of qualification than with other variables such as soil moisture, which requires considerable additional explanation of related ground state.

Undoubtedly one of the most effective remote sensing methods of detecting water is through the use of sensors operating in the near infrared region (approximately 0.75 - 1.0 microns). This spectral band (see p. 8) is especially useful for differentiating vegetation and water, and can, to a moderate degree, overcome the previously mentioned shielding problem often affected by vegetation of varying density. The reason for this is that water almost totally absorbs near infrared radiation, whilst healthy vegetation is a strong near infrared reflector. On colour infrared film for example, a high contrast exists between the recorded deep blue of water and the bright magenta-red of healthy, green vegetation (see Figs 53 and 55). On natural colour film, however, vegetation often appears as varying shades of olive whilst water in the shade of trees may be a grey/green colour making differentiation of the two very difficult. Water, as recorded on true colour film can vary greatly in colour according to its depth and to the colour of any dissolved or suspended solids etc (see p. 92). With colour infrared film, although variations in colour do occur, the predominant blue colour of water features is retained, thus allowing more consistent water recognition. Land/water contrast is so strong in the near infrared band that automatic recognition of water is possible using computer processed multispectral data. Tests carried out at Purdue University (Ref 136) indicate that water bodies above a given size can be correctly recognised 95 times out of 100 using such techniques, and NASA (National Aeronautics and Space Administration) have now produced a low cost programme for handling LANDSAT data which enables bodies of water greater than 6 acres to be recognised correctly with better than 95% precision whilst water features greater than 4 hectares can be recognised with almost 100% precision (Ref 137). Although a LANDSAT pixel has a ground resolution of approximately 4.3 acres, recent proportional data processing

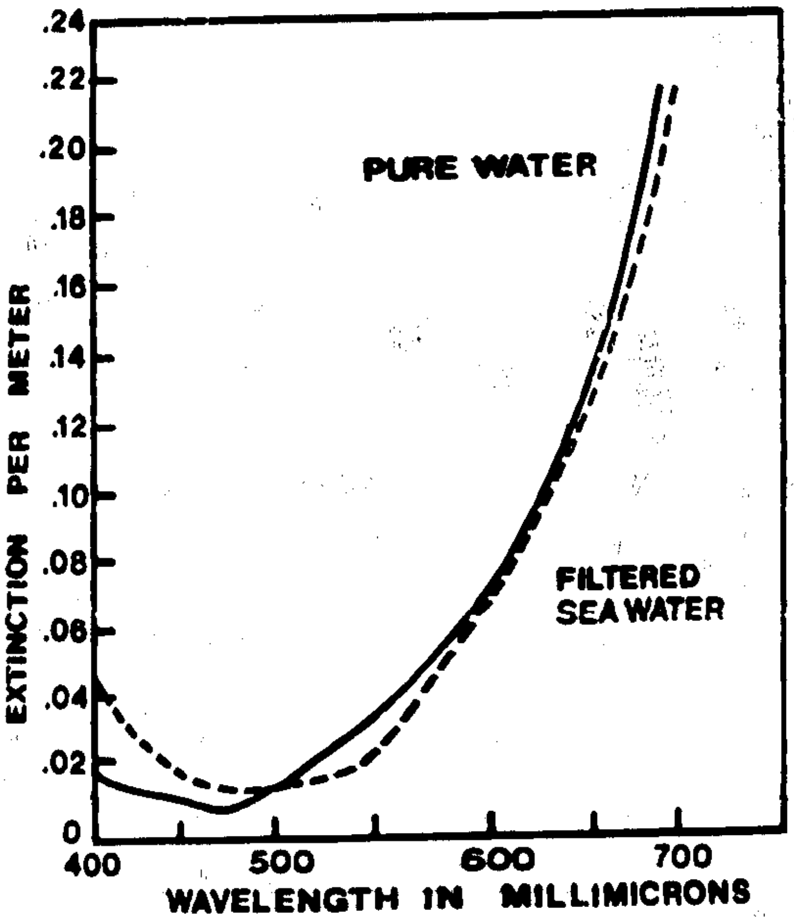


FIGURE 55

Extinction coefficients of distilled and sea water

techniques suggest that the presence of water bodies as small as 1.33 acres can be detected as a result of their strong spectral signature (Ref 137). Although LANDSAT imagery has been used for monitoring the extent of Playa Lakes and wetlands in California (Refs 138 and 139), for such a technique to be of use in Europe for water resource management, much higher ground resolutions would be necessary; this being confirmed by the findings of the World Meteorological Organisation meeting on Satellite Applications in Hydrology (Ref 140). Of course it can be argued that satellite monitoring of water extent is not required in Europe, as adequate measures are taken already from the ground. An alternative approach might be to telemeter water level recorder information from a dense network of instruments to a central point for water management purposes. Real-time data could be obtained to accuracies similar to or better than present satellite data without being reliant on cloud cover conditions (Ref 141). The problem of extensive cloud cover over Europe restricts satellite monitoring systems to the use of microwave sensors. Although high altitude aircraft could supply the required quality of data their operation is uneconomical for repetitive monitoring of large areas and they are susceptible to cloud restraints.

Where extensive water extent data is required, the method of collection must be carefully matched to the overall requirement - remote sensing methods sometimes, but not always being the most satisfactory solution. Thermal infrared radiometry may be used to delineate water features, as generally they exhibit a different temperature to the surrounding land, although not always. For best thermal separation of land and water, observations should be made generally before sunrise. Unless thermal information is required in addition to water extent information, thermal infrared techniques would not normally be the first choice for water feature mapping.

Streams and rivers

Whilst relatively large water bodies such as lakes and reservoirs can be directly sensed using the aforementioned techniques, for the recognition of stream networks, inferential methods may be required due to the small surface area of open water involved. For example, it was found that the low resolution of an airborne scanning thermal radiometer created difficulties in the delineation of small streams, even though a good land/water temperature gradient existed. However, Brown and Holz (Ref 142) found that low level (750 metres) infrared scanner imagery was capable of resolving streams 1.5 m wide. Side looking radar (see p. 52) provides excellent definition of surface topography, from which, the location of stream channels can often be inferred, especially in areas of high relief (Ref 142). However, field checks should be undertaken to confirm that streams do exist and that dry valleys are not to be expected. In addition, where streams are large enough to be detected on side looking radar, they appear black due to their low microwave reflectance. The all weather capability of side looking radar would therefore make it the first choice for such requirements as defining potential reservoir catchment characteristics in mountainous regions possessing a high incidence of cloud (Ref 106).

With small scale or low resolution data, such as satellite imagery, the presence of minor streams is often apparent due to the linear enhancement effect of changes in vegetation, topography, or human land use, rather than from the water signal itself. Thus in open moorland areas, such as are found in the Central Pennines for example, the presence of very low order streams only a few feet wide can be clearly inferred from LANDSAT images as a result of topographic enhancement even though the ground resolution of the LANDSAT sensors is only 80 metres. On the other hand, great difficulty may be experienced in visually identifying quite large rivers in flat terrain, such as the Fenland and Wash area, where vegetation is similar on both river banks (Ref 122). Where computer processing of digital information is used however, the minimum width of a river which should theoretically always be detectable as water is 2 x the sensor pixel size (Ref 138).

Satellite imagery may be of great value for delineating stream networks in poorly mapped areas such as the Middle East or parts of the U.S.A. (Ref 144) but it is of little value in the U.K. where 1" O.S. maps accurately delineate much smaller streams than are visible from satellite platforms. Although the high resolution capability of low level infrared photography may be in theory capable of resolving first order streams, thus allowing the definition of a complete U.K. stream network, in practice, shading problems are often encountered due to the presence of hedges, trees, buildings etc. Even if the water surface of a complete stream network were visible, the information would be of much greater value for runoff predictions for example, using contributing area models (Ref 145) if a positive indication of water movement were also obtainable. Without this knowledge, an overestimate of the contributing area will result, due to the inclusion of stationary sections of impounded water in the upper stream channel reaches. Although some measurement of water velocity is possible using remote sensing methods (see section 7.6) it is unlikely that velocities below 30 cm/sec will be practically detectable. For overseas applications, the detection and mapping of spasmodic stream systems (wadis etc) may be of great importance in water resource studies (Ref 146), for which purposes the synoptic coverage of satellite data is likely to be the most suitable. In the U.K., the detection of unusual surface storm runoff would be of great advantage for structure design purposes and for studies of land use change effects and low cost aerial photography may often be adequate for such requirements.

Flooding

In the United States, LANDSAT multispectral imagery has been successfully used for mapping inundated areas of large river flood plains such as the Mississippi (Ref 147) in order to identify priority areas for flood relief aid. Because of the physiological stress placed on the vegetation by water-logging, its near infrared reflectances were reduced for extended periods. This allowed successful retrospective mapping of the inundated areas for at least five days after the flood water recession. Later work suggests that the effect may be apparent in some cases for several weeks after flooding (Ref 148) but this is more likely to be due to a long-term vegetational change rather than continued plant stressing. Personal work in the U.K. has shown that flood boundaries over arable and grassland areas are often detectable for at least five days after flood recession, using low altitude colour infrared photography as the sensing medium from which flood boundaries can be drawn (see Figure 56 and Ref 149). For vegetated areas it may therefore be feasible to carry out low cost flood monitoring of a whole river system after a flood in order to identify areas requiring flood alleviation attention for example. Due to the great pressures of housing and industrial expansion on land availability, new building is often established in areas which may be subject to infrequent flood (Ref 150). Aerially established flood frequency limits would provide a permanent record of past flooding which could be used to great advantage in the siting of new development, and when available, such records are now being used.

Wetlands

When direct vision of water surfaces is impaired, such as in marsh or other permanent wetland areas, it is often possible to determine the extent of waterlogging by the recognition of marshland plant species. Ground based ecological studies have shown that in many climatic regions, plant species distribution is highly dependent on the prevailing ground state in the transition zones between water bodies and dry ground (Ref 151). Thus it may be possible to distinguish summer and winter water levels purely by identification of the dominant plant species (Ref 152 - 155). If the indicator species is markedly different in colour or texture to its neighbours, then conventional black and white, true colour or colour infrared film may be adequate for its delineation. However, for more positive identification of similar species, multispectral photography or multispectral linescan (see p. 80 and p. 48) would normally be used, after establishing the spectral signature of the species of interest from ground radiometric measurements. Microwave sensing

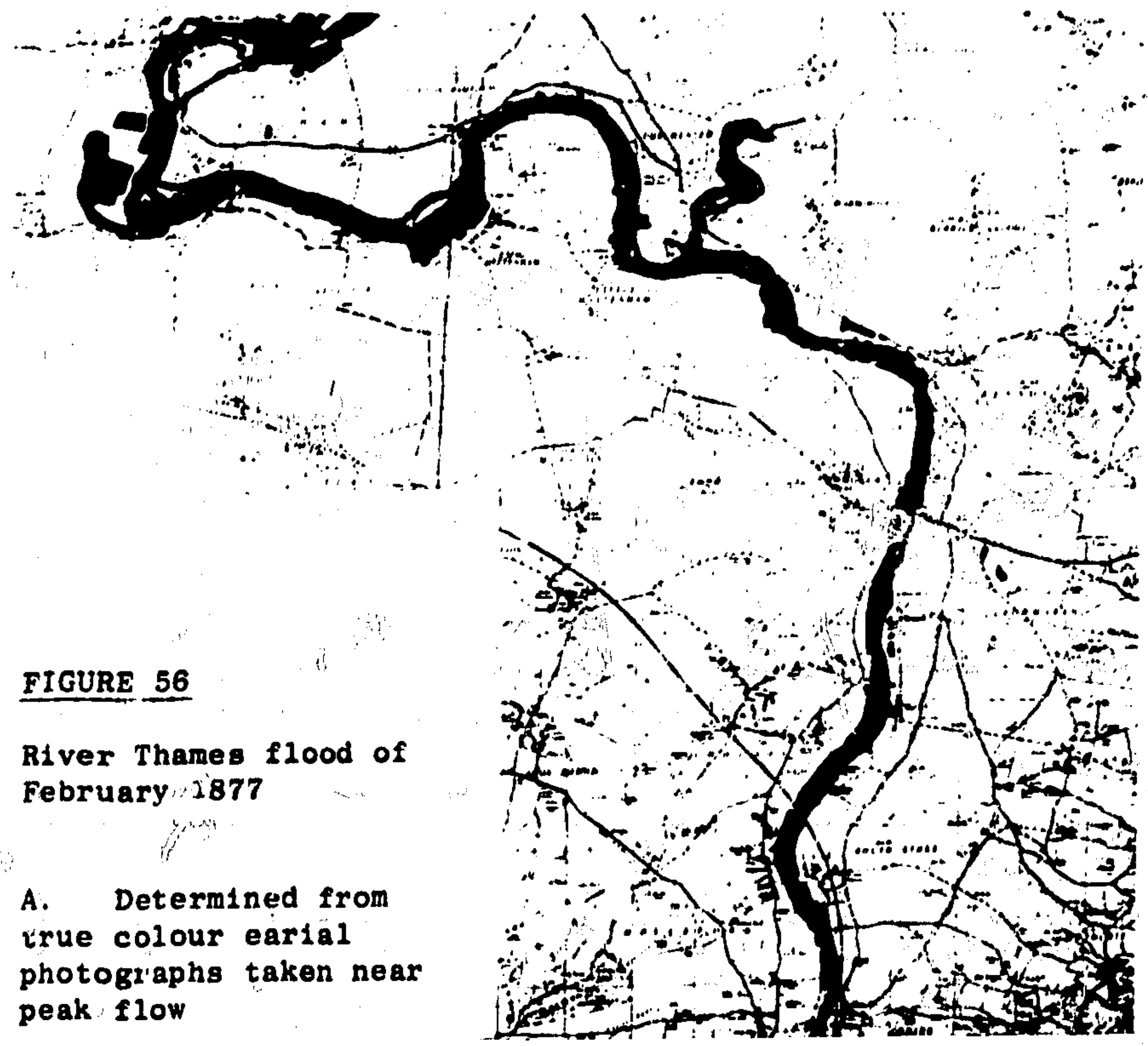
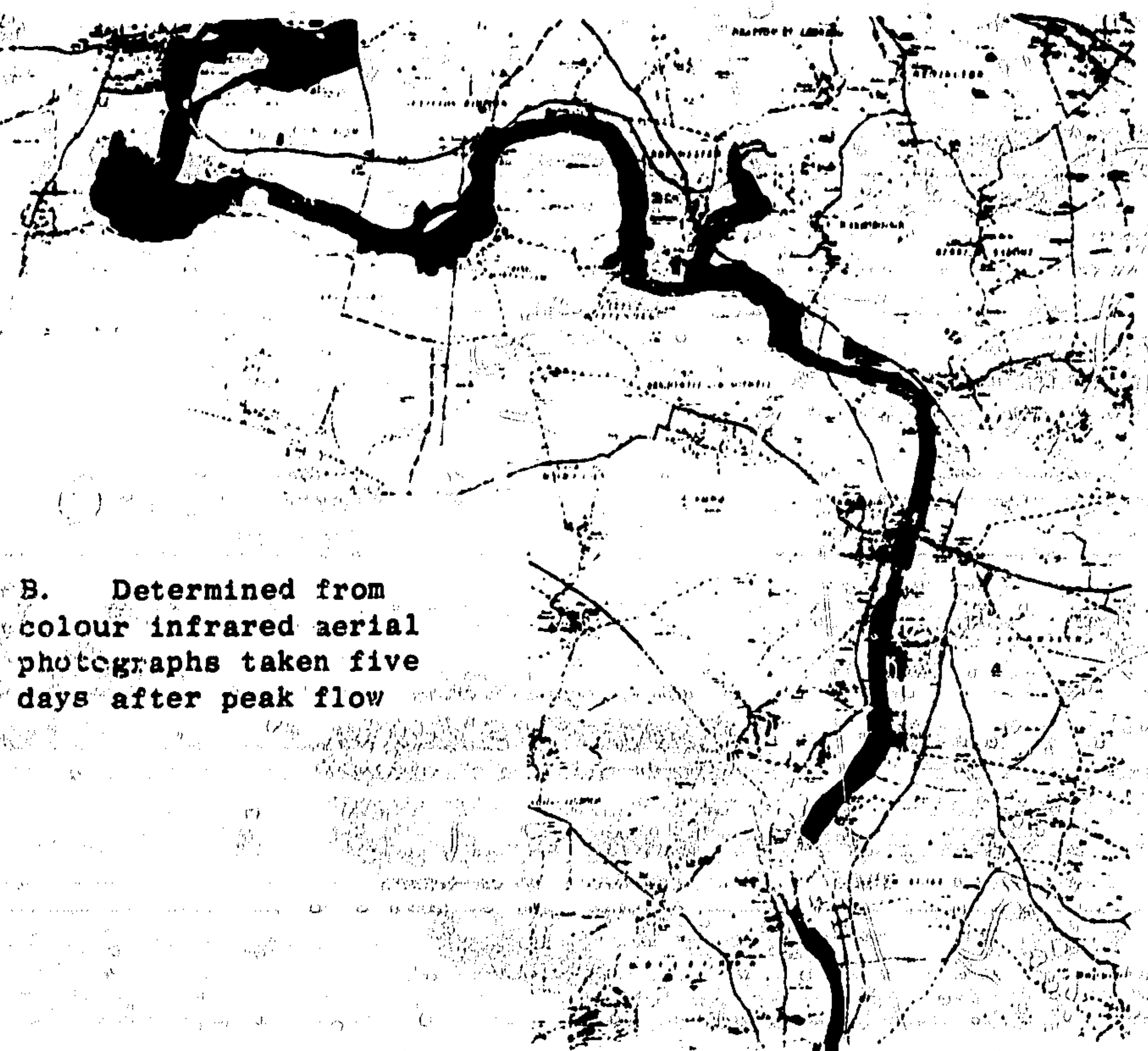


FIGURE 56

River Thames flood of February 1877

A. Determined from true colour earial photographs taken near peak flow



B. Determined from colour infrared aerial photographs taken five days after peak flow

systems, especially of the longer wavelengths (around 20 cm), would derive only a small proportion of their ground signal from short marshland vegetation so that an overall low signal would be recorded as a result of the underlying water, thus allowing adequate delineation of its extent (Ref 106).

7.3 Water penetration and depth measurement

Water penetration for sub-surface mapping

Before attempting to assess water penetration properties or water depth estimation using remote sensing techniques, it is worth recapping on the basic reflectance properties of water bodies (see also section 4.3). Incoming solar radiation incident on a water surface, is partially reflected at the surface, this being largely specular reflectance (see p. 15), but it may be diffuse when the water surface is very rough. The remainder of the radiation entering a bottomless water body is subject to depletion as a result of either absorption and scattering by the pure water molecules, or by scattering, diffraction and reflection by dissolved or suspended particles in the water. In completely clear water, sunlight may penetrate several hundred metres (Ref 156) and so, theoretically a small amount of backscattered radiation should also be present from this depth. In practice, signal levels from such depth are too small to be recognisable amongst instrument noise and atmospheric variations, which may be large. As can be seen in Figure 55, the maximum transmission of light in distilled water lies near 0.48 microns. Underwater measurements of downwelling light made by Yost and Wenderoth (Ref 157) also indicate that, in relatively clear water, maximum light transmission occurs in the blue/green region of about 0.5 microns (see Figure 57) and primarily due to absorption, the transmittance values at longer and shorter wavelengths within the visible spectrum, fall off rapidly.

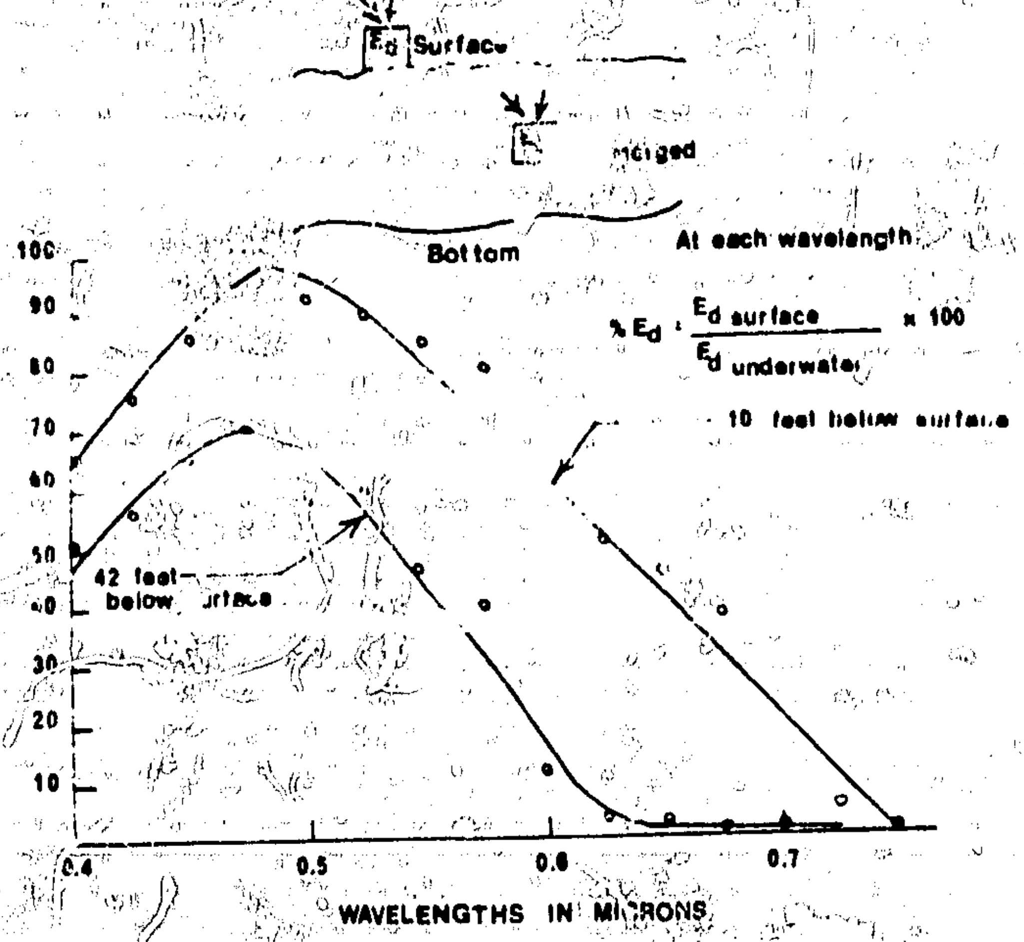


FIGURE 57

Downwelling irradiance in clear ocean water

Because of this, it is not surprising to find that tests using different types of both available and experimental film emulsions, have shown that those most sensitive to radiance in the 0.5 micron region are most suitable for water penetration and for the detection of ocean bottom detail (Ref 158). Lockwood et al concluded from their tests that the most suitable film for general sub-surface detail mapping, was the readily available Ektachrome EF Aerographic with Wratten 3 haze filter, giving a spectral sensitivity of 0.45 - 0.65 microns. A 2 layer film specially devised for water penetration (Refs 159 and 160) with spectral peaks at 0.48 and 0.55 microns, was capable of similar penetration to the Ektachrome film, but lacked colour contrast. Keller (Ref 161) quotes natural colour film as having a penetration capability of around 75 ft in clear waters and compares the suitability of readily available film emulsions for different types of ocean observation work.

Extensive studies have been undertaken using satellite imagery to map coastal water features, and in the majority of those utilising LANDSAT imagery, either the green RBV (return beam vidicon) band of 0.475-0.575 microns was found to be most suitable for mapping underwater features and turbidity variations, or more commonly, when using the MSS (multispectral scanner) data, the green 0.5-0.6 micron band was found superior for water penetration and sediment mapping purposes (Ref 162). From LANDSAT imagery, it has been possible in shallow coastal waters to map within useful accuracies, such variables as sea bed vegetation (Ref 163) sediment types and sand bars (Ref 164) and ocean depth up to about 20 metres (Ref 165).

So far, we have been looking at restricted but still moderately broad band techniques of sensing sub-surface water detail. Because of the complexity of factors affecting the transmittance of under water detail such as surface roughness, size and colour of suspended particulate matter, bottom type (Ref 156) etc. narrow band multispectral methods can be more carefully 'tuned' to the prevailing conditions and therefore offer better chances of success than fixed broad band methods. For example in clear, deep ocean water, sensing in the blue region is best, whereas for heavily sedimented coastal water, sensing in the green-yellow region would yield better results (see Table 5). Yost and Wenderoth (Ref 166) took multispectral photographs of coloured targets both on and below the sea water surface in order to measure the attenuation of the water at different wavelengths. Their measurements indicated that (for coastal water in the Gulf of Mexico) the ability to detect underwater objects was best in the 0.493 - 0.543 micron band, and also, very importantly, that considerable additional film exposure was necessary to reveal underwater detail compared to exposure correct for surface light conditions. The enhancement of underwater objects and of subtle changes of water colour due to changes in suspended particles (see p. 92) was achieved by using a purely spectral identification technique whereby the large variations in scene brightness as found in coastal waters, were completely removed. Generally, these findings and techniques can be applied to imagery taken from all altitudes, except that atmospheric haze effects increase with increase in altitude, with a resulting loss of contrast below about 0.5 microns. For this reason, a compromise is often necessary between choosing the optimum wavelength for penetration of a water body and its correspondence with a suitable atmospheric 'window' (see p. 17).

TABLE 5   TYPICAL TRANSMISSION CHARACTERISTICS OF LARGE WATER BODIES

Types of Ocean Water	Wavelengths of maximum transmission (in microns)	Per cent transmission per metre
Clearest oceans	0.47	98.1
Average oceans	0.475	89.0
Clearest coastal	0.50	88.6
Average coastal	0.55	72.1
Average inshore	0.60	60.8

Water depth measurement

The aerial measurement of water depth can be either absolute, using direct measurement techniques, or it can be inferred by estimating water absorption effects, or by the analysis of surface wave patterns. Direct techniques include photogrammetry, laser profiling and sonar echo sounding.

If coastal water is exceptionally clear, it is possible to contour underwater features using conventional aerial photogrammetric techniques (Refs 167 and 168) by the measurement of parallax in stereo-pair photographs. The constraints of normal photogrammetry still hold in that at least three reference targets or points of known relative position are required in each photograph, to enable the stereo model to be reconstructed (Ref 10). Surface water conditions must of course be relatively calm and accuracies are likely to better where a textured sea bed exists, such as rocks or vegetation as opposed to a uniform, sandy bed.

Accurate profiling of water depth can be accomplished with lasers, whereby a pulsed, coherent laser light source (see p. 57) is pointed downwards from the sensor platform so as to strike the water surface at right angles. A strong reflected light signal is received from the water surface, followed closely by a weaker reflected signal from the floor of the water body (see Fig 41). The depth to which the laser beam can effectively penetrate primarily depends on the water clarity, atmospheric attenuation and laser strength and frequency, but in clear waters, depth measurements down to about 50 metres should be feasible from aircraft and to about 20 metres from satellites (Ref 169). If only a single frequency laser is available, one operating in the blue-green region will give good water penetration (Ref 170), but with tunable lasers, the best wavelength can be chosen to suit the water colour. The calculation of water depth is a function of time of travel of a given pulse of light for the round trip from laser gun to water bed and back to the detector head, minus the round trip time from the sensor to the water surface and back. An average index of refraction measurement of the water body is also required, but this value does not change very rapidly.

Laser profilers allow the most accurate aerial measurement of water depth, but only at a point or along a flight line, which offers rather a poor sample. For this reason laser profilers are best used in conjunction with imaging depth estimation techniques where they provide an accurate depth reference along the centre line of an image, which can then be extrapolated to the whole image frame. In their report on 'Photometric and Polarimetric Mapping of Water Turbidity and Water Depth' (Ref 171), the Grumman Aerospace Corporation repeatedly expressed how useful a laser ranging system would have been in providing accurate depth measurements along the centre line of their passive imaging scanner data. Only occasional manual checks of water depth should be required to check the laser performance.

Acoustic methods of water depth measurement have been in wide use for many years in the well known form of shipborne 'Sonar' echo sounders. Their mode of operation is similar to the laser profiler in that water depth is directly proportional to the time of travel of a sound wave from the sensor to the ocean bed. The main restrictions of shipborne sonar is their slow areal mapping rate, their restriction to 'safe' waters and their poor resolution. Sonar surveys in the past may have suffered from low positional accuracy and Polcyn and Sattinger (Ref 172) illustrate the number of doubtful soundings made by sonar techniques. Often sonars underestimate water depth due to echoes resulting from intermediate scattering layers which are often present in water bodies. Nevertheless, for local surveys, small craft fitted with sonar provide the cheapest underwater mapping method.

The greatest potential for remote water depth mapping is in lakes, estuaries and shallow coastal waters. In relatively shallow water, the reflected daylight components from the bed of the water body is large and it is the attenuation of this component upon which many inferred water depth estimates rely (see Section 4.3 and Fig. 9). Polcyn and Sattinger (Ref 172) realised however that only in areas where bottom type and water clarity are uniform, can there be a reliable correlation between recorded signal and depth of water. The use of multispectral scanning methods (see p. 80) enables two or more narrow bands of data to be used to sample the spectral signature of each underwater resolution element. Polcyn and Sattinger devised a method of water depth determination by measuring the differences of attenuation of two such narrow wavebands, brought about by the selective transmission of a given uniform body of water. Because of water's marked differential absorption of say, red and blue wavelengths, a relatively large difference will exist in the light extinction coefficients of these wavelengths (a function of the depth to which light of a given wavelength will penetrate a pure water column - see Fig. 55). If the transmissivity of the water body is known and also the ratio of the reflectance of the bottom material for the two chosen wavelengths (established by on-site measurements), then the ratio of the red to blue reflected light will be a function of the water depth. Other variables such as the intensity and angle of illumination, sensor angle, atmospheric effects, sea surface roughness etc., will be constant at any given instant and therefore should not greatly affect the ratio value. In areas of uniform water transmissivity and smooth sandy bottom characteristics, water depth measurements were possible using this method down to 28 ft with an accuracy of ± 20%, but under better lighting conditions, measurements down to about 50 ft could be

expected (Ref 173). More recent work by the Grumman Aerospace Corporation (Ref 171) using this technique with a digital photometric mapper has shown that depth increments as small as 1 ft in 35 ft of coastal water can be resolved. Generally, however, accuracies of about 10% at 50 ft depths using three spectral bands are normal. Such techniques are best conducted from low altitudes, otherwise differential atmospheric attenuation effects would have to be measured.

Kolipinski *et al* (Ref 174) also used multispectral scanner data to recognise water of different depth ranges, but by a much simpler method. They relied on comparisons of multispectral data of unmapped areas, with the spectral signatures of known depth local control points or 'training areas' and were able reliably to identify water between 0-3 ft, 3-5 ft and 5-15 ft. The false detection of tree shadows as deep water constituted about 1.5% of the total deep water recognition area. They also found that in the Everglades region of Florida, different depths of shallow water could be inferred from the dominant plant species distribution, which could be readily classified using multispectral data. Sutcliffe (Ref 155) also related species types to water depth ranges in the Southern Sudd swamp region of the White Nile, and similar relationships are to be found in salt and freshwater wetland in the U.K. (Ref 151).

Whilst multispectral scanner data has been used for most of the above water depth measurements, analysis of multispectral photography would provide similar relationships, but very strict control of film exposure and processing would be required, followed by densitometric analysis of the imagery. Multispectral scanner data is therefore more reliable and is easier and cheaper to process.

The characteristics of surface waves, such as their wavelength and periodicity, (which may be recorded on aerial imagery), can also be used to estimate water depth, some of these methods being described in Ref 172. Waves advancing through unrestricted deep water, have a velocity which is related to their wave period and wavelength. As the waves approach water of depth less than about half a wavelength, their velocity and subsequently their wavelength decreases considerably. By measuring their wavelength in deep water (L) and also in shallow water (L_o) (this often being possible from a single photograph) the wavelength ratio L/L_o can be found, which is functionally related to d/L_o, so that water depth (d) can be determined. If it is not possible to monitor the wave trains as they pass from deep to shallow water, it is still possible to calculate water depth over shallow water only, provided that successive, short interval photographs can be taken. Using this method, the velocity of the waves can be measured in relation to some fixed reference point which must be present within each photograph. Given the velocity and wavelength in shallow water, the mean water depth can be estimated with an accuracy largely dependent on the regularity of the wave patterns as once $d/L_o \lesssim \frac{1}{2}$ the wave velocity becomes proportional to $\sqrt{d}$. Such methods of depth estimation are suitable for many large lake shorelines and coastal waters of fairly uniform slope, but not for small water bodies or physically complex shorelines. Their main advantage over the multispectral techniques is that no specialised equipment is really necessary and data analysis is straightforward. Optical Fourier processing (see page 69) of the wave pattern images has however been used to highlight slight wave diffractions caused by underwater shoals, and to speed depth calculations over large areas. A method has been used which measures such refractive effects on the wave trains caused by changing water depth, but its applications are really restricted to straight beaches having parallel contours; otherwise very complex calculations are necessary. The likely presence of underwater shoals can also be roughly located by visual analysis if Fourier transform methods are not available.

7.4 Water quality and turbidity

Many of the remote sensing methods used to achieve water penetration and to estimate water depth must take account of water quality effects and so it is often a small step to redesign such methods to observe variations in water quality when the water depth and bottom characteristics are known. Many remote water quality sensing techniques work more successfully in deep water where bottom effects are negligible, and therefore in shallow lakes and rivers more control observations are generally required. As the effects of suspended organic and inorganic material and those of dissolved minerals are somewhat similar from a remote sensing point of view, they will all be dealt with in this section. Most suspended materials and some dissolved materials generally cause a change in emitted light intensity from a water body or a change in its colour due to their presence. Using simple photographic recording techniques, differences in water colour or brightness can frequently be recognised either as variations in image density in the case of black and white film, or more usefully as changes in colour hue, saturation and brightness with colour film. Although differences in water colour can be detected and mapped with unfiltered black and white panchromatic film, the use of colour film represents the first step towards identification of the organic, inorganic or chemical cause of the colour change. Thus, effluent outfalls from certain types of industry may be recognisable, for example the bright red waste colouration from a tomato canning factory (Ref 175) dense white from the waste materials used in paper making (Ref 176), black from coal washings (Ref 177) etc. Similarly, if the colour of a suspended sediment can be detected, it may be possible to determine whether it derives from a particular source of erosion (Ref 178). As long as only qualitative information is required from aerial photographs, uncontrolled photography with minimal ground verification may satisfy the requirements.

Materials in suspension

Once measures of suspended sediment concentrations or dissolved chemical concentrations are required, many more factors must be taken into consideration such as the intensity and angle of sun illumination, atmospheric and water surface conditions, water depth and bottom reflectance, film exposure and processing variations and of course ground control aspects, most of these effects having been dealt with in outline in Chapter 4. Good descriptions exist of the basic physical and optical properties of natural water bodies bearing dissolved and suspended materials, eg the ESRO Contractor Report on Spectral Properties of Materials (Ref 156) (see also Refs 175 and 179). The following Figures have been included however to illustrate some of the basic relationships which take place in idealised uniform water bodies.

Figure 58 shows the relative importance of scattering and absorption as mechanisms of attenuation and how they are dependent upon wavelength within the visible region of the spectrum. Table 5 shows the attenuation/wavelength relationship as found in typical surface waters, whilst Figure 59 shows a typical alteration of the reflectance spectra of a deep body of water when increasing concentrations of particulate matter of constant colour are added.

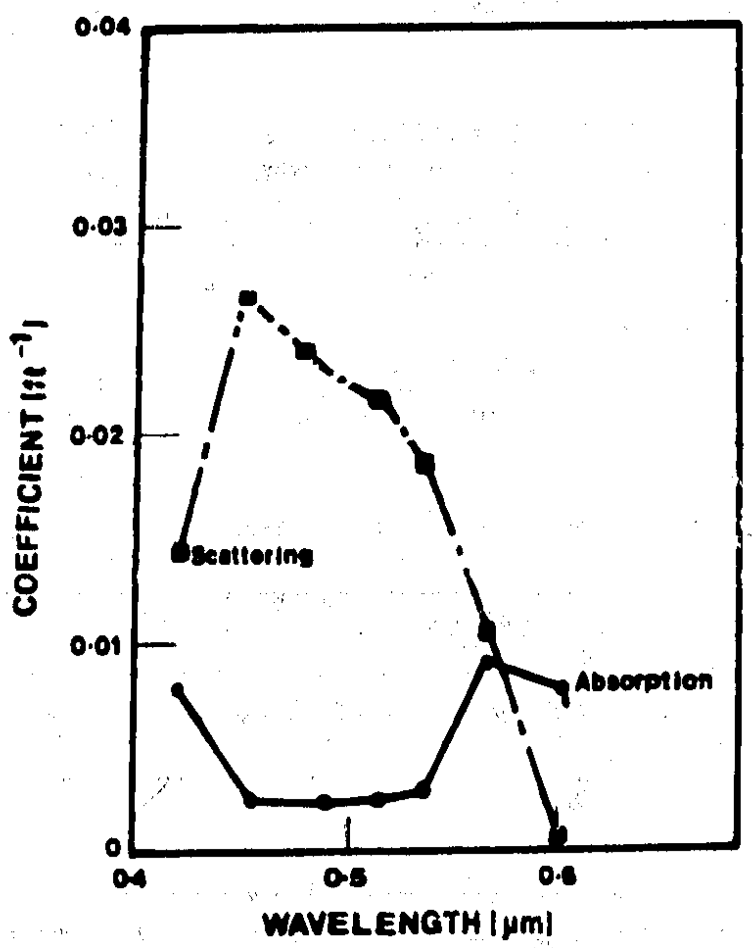


FIGURE 58

Typical relationship between scattering and absorption for near shore waters

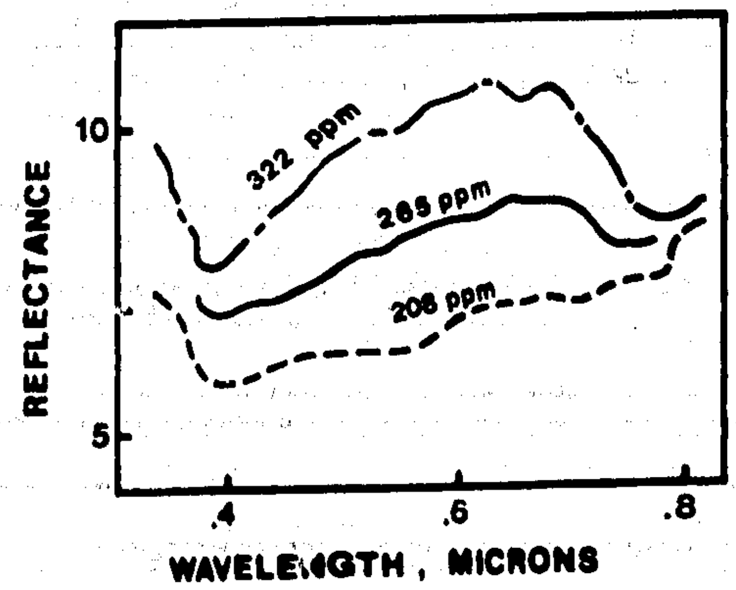


FIGURE 59

Change in reflectance of a water body as a function of suspended sediment concentration

Turbidity is a measure of light attenuation through a body of water and is commonly measured in Jackson Units which are based on one candle-power of light. As the shape, size and composition of suspended particles can all affect the scattering of light, it is not possible to relate turbidity directly to weight per unit volume of material in suspension for different sites. The relationship must first be determined by on site measurement of water transmission and by analysis of suspended sediment samples which should be taken coincidentally with the remote sensing overflights.

Probably the most that can be achieved with the use of broad band photographic film is to relate image or colour density with the integrated measured concentration of suspended or dissolved solids in a body of water. If a simple relationship can be shown to exist between these two variables, then contouring of the water's concentration over a given depth may be possible. A drastic reduction in the number of water samples required can thus be expected when compared to conventional water quality mapping methods which rely solely on point water sampling. Such an exercise was carried out by Lillesand *et al* (Ref 180) who used colour infrared film to monitor the waste outfall plume from a paper mill into the Lower Falls River, Wisconsin. The results of their work showed that, "For typical non-thermal discharges, photo-image density measurements can be used quantitatively to predict water quality throughout the mixing zone if (1) a systematic relationship is determined between water sample reflectance and some measure of water quality (suspended solids, turbidity, etc); (2) the relationship between film exposure and scene reflectance is accounted for; and (3) the relationship between film density and film exposure is adequately approximated. If these three criteria are met, the measured image densities can be used to find film exposure levels, film exposure levels can be used to find scene reflectance levels and scene reflectance levels can be used to predict water quality parameter values". Similar work was carried out by Psuty and Allen (Ref 181) on digitised 35 mm photographs of a coastal sewage outfall plume. They carried out trend surface analysis of the data and found a high correlation between the image density effects caused by the sewage presence and of in-situ dissolved oxygen concentrations. Blanchard and Leamer (Ref 182) made spectral reflectance measurements of water from various sources containing suspended sediment and found that peak sediment reflectance generally occurred around .57 µm. In order to gain some measure of effluent concentrations at different depths within a water body rather than simply surface or depth integrated estimates, it is necessary to return once again to multi-spectral sensing techniques. Because different wavelengths of light are absorbed by water bodies to varying degrees depending on their state, certain wavelengths are capable of greater depth penetration into the water than others (see Figs. 55 and 57), and therefore the resulting radiation corresponding to each waveband will result from different column depths of water. Coker *et al* (Ref 183) looked at the response of LANDSAT R B V imagery to a turbidity plume caused by dredging in Tampa Bay, Florida. The three spectral bands used were green, red and near infrared. The near infrared radiation was almost totally absorbed by the surface water so that only particulate matter at the very surface caused a reflection of the radiation, which appeared as a small, light toned area on the image (see Fig. 60). The light area on the red band was much larger than in the infrared, whilst the area of the plume recorded in the green band was subsequently larger than the red. Also in each band the centre of the area was observed to be lighter than the outer edges which gradually faded to dark tones. These confirmed that turbidity concentration of the light coloured sediment was highest in the centre of the plume and that the outer areas either contained less particulate matter in suspension or else that the particles were at a greater settling depth. Thus, although a definite measure of sediment concentration with depth was not possible, considerable information on the three dimensional dynamics of the plume was obtained and its outward spread coupled with its increase in depth could be readily inferred. However with the addition of point water samples taken within the three dimensions of the sediment plume, a complete model could be reconstructed (see also Ref 184). Although we have been dealing here with variations in suspended sediment, dissolved solids including tracer dyes are observed to behave in a somewhat similar fashion (but with less light scattering effects) and can similarly be observed as changes in recorded image signal strength.

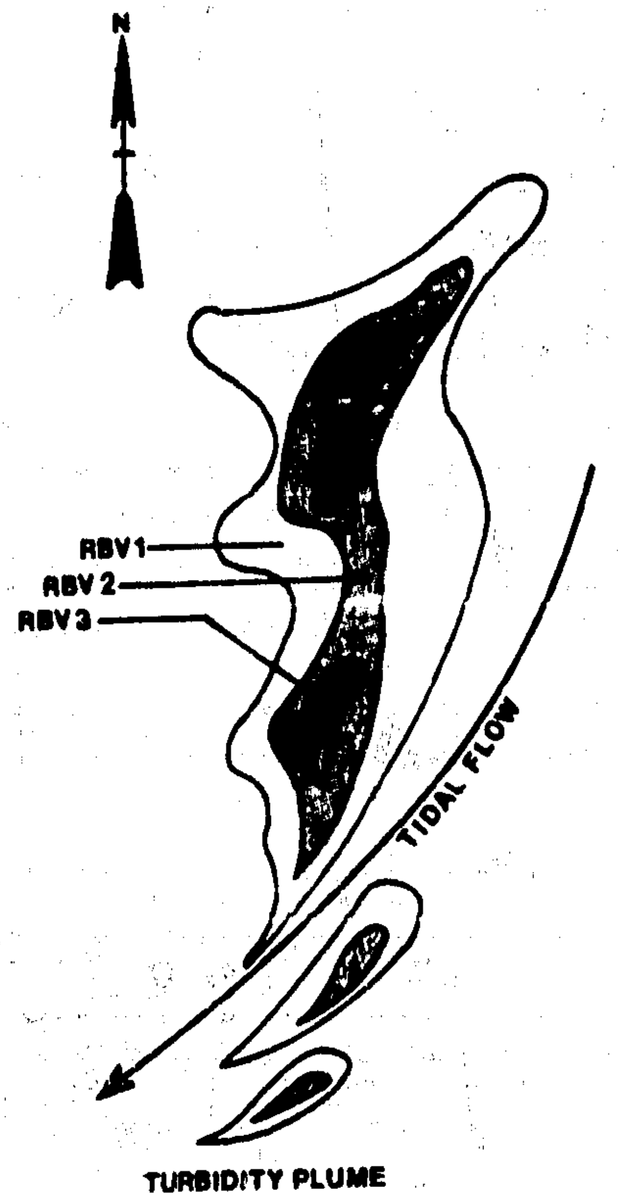


FIGURE 60

Extent of turbidity plume as recorded on bands 1, 2 & 3 of Landsat RBV

In order to obtain truly three-dimensional remotely sensed information on water quality variations using multispectral techniques, complex spectroradiometric calculations are necessary which are generally best applied by computer processing. Ref 171 describes how subsurface turbidity profiles were achieved using a 'digital photometric mapper' which is basically a very stable single channel vidicon (see p. 32) which may be operated through narrow band-pass filters. The analog output from this instrument and from a non-scanning photometer operating along the centre line of the scanned field was converted to a digital form and was stored directly onto computer compatible tape (CCT). Using this equipment configuration, it was possible to construct a model of water depth which accounted for the effects of water attenuation of different wavelengths along with the effects of bottom reflectance, water reflectance, sky reflectance, polarisation etc. on a given water body. By taking measurements in different spectral bands such as the green and red, different measured signal attenuation could be used to calculate water depth as described on page 90 . It was observed that an increase in turbidity may often result in a decrease in reflectance in the blue part of the spectrum, but in an increase in the red part due to different forms of light scattering. In order to evaluate the degree of particular contamination, a measurable effect in either direction must be present. Successful estimations of water turbidity at given depths were carried out by measuring the resulting reduction of polarisation of light in the red region, but different modelling approaches were found necessary for different physical situations. Although the polarmetric approach was found to be the best single method, it was concluded that a combination of polarimetric, multi-spectral and laser techniques coupled with in situ water sampling and measurements of incoming solar radiation would be the best combination. Computer compatible sensor outputs would be necessary for the complex calculations involved.

Materials in solution

The delineation of dissolved solids may often be straightforward if they exhibit a different colour against their background water mass. Airborne spectrometers (see p. 40) and especially tunable laser spectrometers (see p. 57 and Fig. 61) have been used very successfully for identifying solute types and considerable literature is available on the types of sensors and analytical techniques used. (For some examples see Refs 185 and 187) Laser-Raman spectroscopy is well suited for remote sensing as the spectrometer detects the effect on the dissolved molecules of its own laser illumination source, thereby reducing the effect of changing solar illumination. This results in a more sensitive and more system in comparison with conventional spectrometers. When a monochromatic beam of light is shone into an aqueous solution, the molecules constituting that solution have a scattering effect on the incoming light and the resulting small changes in wavelength (Raman shifts) provide precise identification of the chemical composition of the solution. A good introduction to the Raman spectroscopy technique is given in Ref 188. As low concentrations of materials in solution may often be difficult to detect above the relatively high background water signal, it is highly desirable to have a continuously tunable light source so that the wavelength causing greatest resonance with the desired molecules can be selected (Ref 189). This is known as Resonance Raman Spectroscopy. By additionally pulsing the light beam (generally a laser) a measure of time of travel can be used to calculate the object distance which enables three dimensional measurements of solute concentration to be made. This measurement is only available in point form or along a line of travel, as scanning systems have not yet been developed, but equipment of this type has the potential for use at all altitudes above the Earth's surface. Whilst the increasingly complex instrumentation chosen for water quality monitoring obviously results in increased costs, these may be somewhat offset by the ability to provide accurate data with less intense ground verification; a factor which may be of great importance in poorly accessible regions.

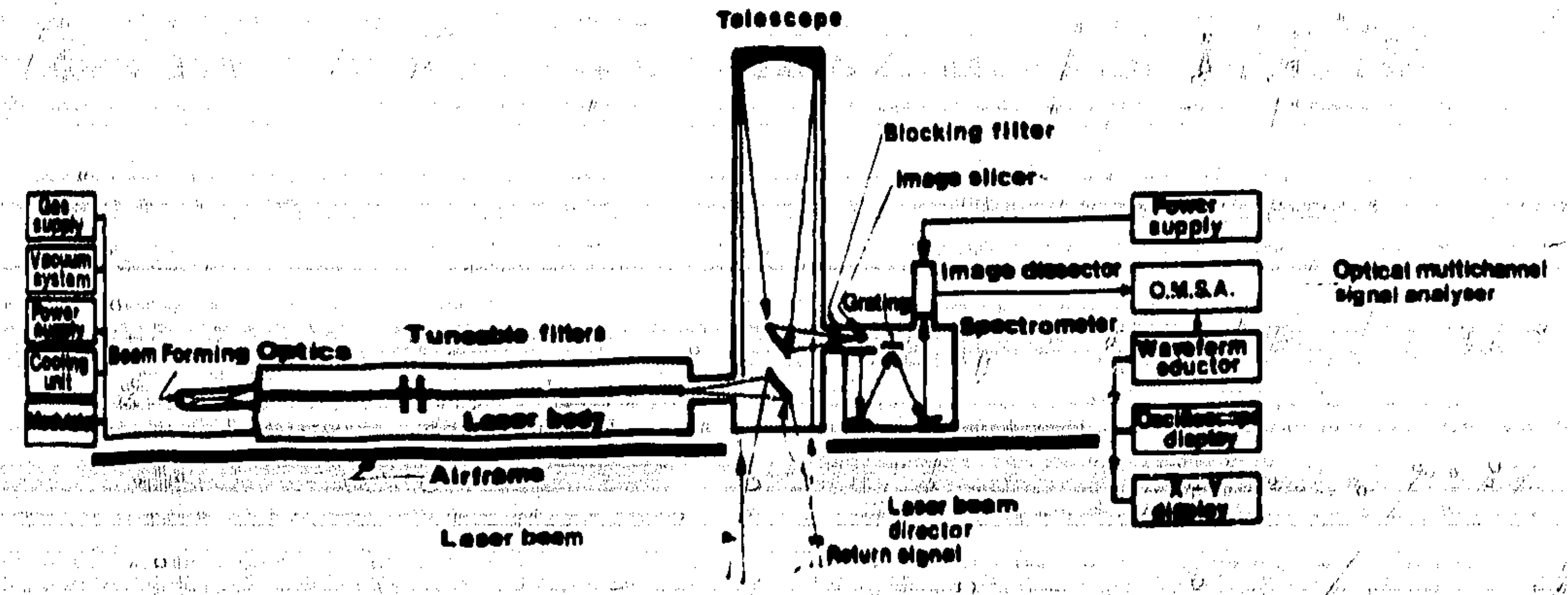


FIGURE 61 **Schematic of tunable laser spectrometer**

7.5 Water temperature

Surface effects

When compared to many of the hydrological variables covered in this chapter, water temperature measurement can be regarded as being relatively straightforward using remote sensing techniques. What must be stressed at the outset however, is that only the temperature of the surface of a water body is normally sensed and that this can only be used as an indicator of possible subsurface water state. In order to extrapolate the surface temperature to greater depths, accurate models of water circulation or of water temperature profiles must be established. To enable calculations such as evaporation rates from open water bodies to be made (see p.126) temperature measurements within the top few millimetres of water may be adequate, but if surface temperature is to be used as an indicator of say current behaviour, additional information, possibly in the form of in situ sampling would be required. Another important phenomenon which must be recognised when using remotely sensed water temperature data is the boundary layer effect. As a result of heat exchange between the atmosphere and the water surface (see Fig. 62) the top few millimetres of water are normally at a different temperature to the underlying water by as much as 1-2°C except in turbulent conditions. Such boundary layer effects can generally be allowed for when relating remotely sensed data to in situ water temperature measurements, but where high accuracies are required, great difficulty has been found in taking contact temperature measurements in such a thin surface 'skin' of water (Ref 156 (section 7.2)). Additional errors may result from unrepresentative surface variations caused by density effects where the less saline or warmer water tends to ride over the more dense layers.

The most common and as yet the most successful sensor used for remote surface temperature sensing is the infrared radiometer which may be used either for taking temperature readings at a point or temperature profiles

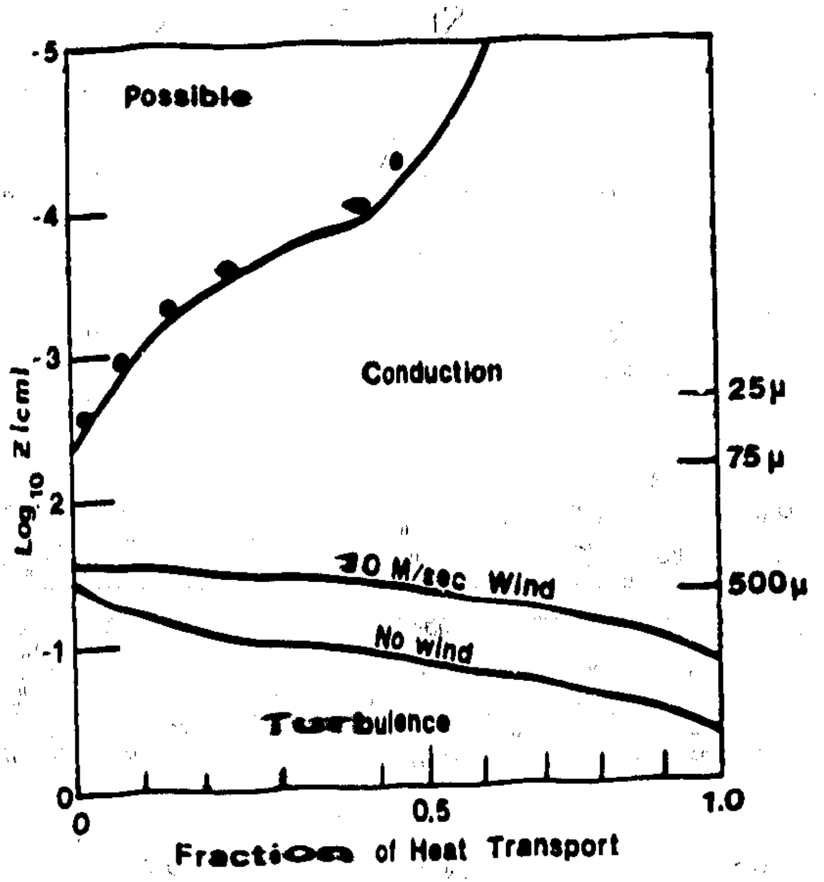


FIGURE 62

Mechanisms of heat transport in water/air boundary layer

along a line (see p. 36). In linescanner form it is capable of measuring changes in surfaces temperature over an area, this often being recorded as variations in tone of a photographic image (see p. 45). By correlating image density with measured surface temperature at several points within an image, intermediate image densities can be assigned an assumed temperature (Ref 191). However, most infrared radiometers nowadays are fitted with an internal reference source of known temperature and emmissivity which enables absolute temperature measurements to be made (Ref 179). Nevertheless, the received signal from the ground varies with look angle and is likely to be distored by atmospheric effects and these must be quantified before absolute surface temperatures can be given, especially when sensing from orbital altitudes.

Correction of atmospheric effects

Accurate allowance for atmospheric effects can be made simply by relating the sensed signal to a known surface temperature on the ground. This may be a reasonable approach for very small areas, but it is a rather unsatisfactory calibration technique for large areas, as local atmospheric variations cannot be allowed for without the provision of extensive ground control. Because of this attenuation by the atmosphere, infrared sensors are generally filtered or have detectors made sensitive to radiation in one of the 'window' wavelength regions (see p 18), the most common being the 8.0 - 13.5 micron region. In this wavelength region, the emissivity of a water surface is about 90% provided that the angle of incidence of the sensor is almost normal to the surface (Ref 190). This means that even in sunlight, only a very small proportion of the infra-red signal detected by the sensor is reflected radiation, and therefore the measured signal is directly related to the actual surface temperature of the water. Although night time sensing is thus possible, strong absorption still results from the presence of cloud and atmospheric haze (Ref 192) thus precluding an all-weather capability.

By measuring the proportions of water vapour, carbon dioxide, ozone, particulates and air temperature of an atmospheric column, models can be constructed to estimate the likely absorption, emission and scattering of the infrared signal so that corrections can be made to the apparent ground temperature. For detailed explanations of atmospheric effects on infrared wavelengths, reports such as those of the ESRO CR series are ideal (Ref 192). Because the effects of atmospheric attenuation are more pronounced as the path length increases, more complex calculations may be needed for satellite borne sensing. However, for platforms operating at a height of only a few hundred metres in clear conditions, atmospheric effects may lie within the range of acceptable temperature measurement error, in which case no allowances would be necessary. Normally errors caused by the atmosphere increase almost linearly up to about 1000 metres and then increase less quickly above this height due to the thinning air. The main cause of error is the difference in temperature between the atmosphere and the target, and the humidity distribution within the intervening block of atmosphere. In adverse clear weather conditions these effects could result in a combined error of around 1°C at 300 metres sensor altitude, whilst the presence of thin cloud could increase this error by 3 or 4°C or even more (Ref 193). Atmospheric effects can often be lessened by narrowing the spectral range of sensitivity of the instrument to coincide with regions of low atmospheric absorption for example from 18-14 microns to 9-11 microns. However a lower signal level would then result and hence a compromise between the two requirements may sometimes be necessary.

As monitoring of atmospheric constituents by direct sampling is very difficult, an alternative approach is to have sensors operating in at least two different wavelengths. As surface radiance is attenuated and path radiance from the atmosphere is added with increasing altitude, such a multispectral approach becomes more desirable as sensor altitudes increase. Absorption by gases is strongly wavelength dependent, so comparison between ground signals at two wavelengths which are absorbed by different amounts, enables correction for the effect of the absorbing material to be made. Anding *et al* (Ref 194) recommended the use of three narrow infrared channels centred at 4.9, 9.1 and 11.0 microns. Under cloud free conditions, the ratio of signals recorded in these channels allows very accurate measurements of varying molecular absorption such as water vapour, carbon dioxide, ozone etc and partial correction for the presence of clouds was found possible, along with some correction for atmospheric scattering effects. An alternative but less accurate atmospheric correction technique is to observe a given target at two or more path angles. If for example a target is viewed vertically and also at a 60° oblique angle, then the atmospheric path length is doubled and comparison of the two recorded signals allows correction for the transmission loss. Strong layering in the atmosphere would cause error using this correction method, and account must also be taken of changes in surface characteristics such as reflectance, emittance and roughness with changing look angle.

Thermal infrared sensing

Infrared radiometry has been extensively and successfully used for mapping the surface temperature of many different water types and in general, scanning or imaging radiometers have proved to be most popular.

From relatively low altitude aircraft equipped with scanning infrared radiometers, stream and river surface temperatures have been mapped, often with the aim of detecting ground water or pollution inputs (Ref 195), and their mixing characteristics with the main water body. Dinelli *et al* (Ref 196) describe the mapping of river temperatures at 1°C intervals in order to trace the outfall from a paper mill and power station using an 8-14 micron scanner, whilst Atwell *et al* (Ref 193) using the same spectral range, claim surface temperature measurements in river experiments to be correct to ± 0.3°C from an altitude of 3000 ft. The remotely sensed data was verified by measurements of water temperature using thermistor thermometers which were accurate to ± 0.1°C. Souto-Maior used 8-14 micron thermal scanner data taken from 500-600 metres altitude for very small scale studies of water flow in the vicinity of a refuse tip by detecting seeps, springs and the location of ground water into small natural drainage channels (Ref 195). Shoreline springs were detected in lakewater (Ref 197) by the use of a Bendix infrared scanner operating in both the 3-5.5 micron and 8-14 micron regions, and spring flows of <0.1 litres/sec were readily observed as they mixed with the warmer lake water. It was found that sensor altitude variations below 900 metres did not have any noticeable effect on the resulting data, indicating that atmospheric attenuation up to 900 metres was small. Similarly Boettcher *et al* successfully located ground water inflows into several large rivers in Montana and Idaho (Ref 198).

Temperature sensing over the sea has been successfully used for detecting and tracking sewage and power station outfall waste (Ref 199 and 200), for monitoring river outfall plumes (Ref 201) and for mapping nearshore currents (Ref 202). McAlister (Ref 203) found that sudden surface temperature discontinuities such as convection cells, wind streaks, breaking waves etc were particularly easy to record. Water temperature sensing from satellites is of greatest application over large lakes and oceans where surface resolutions of often several kilometres may be advantageous in acting as a form of data reduction for obtaining mean water temperatures. Platt and Troup (Ref 204) compared satellite and aircraft infrared data of the same area. The satellite was NIMBUS IV with a 10.5-12.5 micron THIR radiometer providing 8 km resolution from a height of 112 km. The aircraft flying at 3 km was equipped with a similar scanner having a ground resolution of 20 metres. After correction for atmospheric effects, the mean temperature of a test site was found to be 21.4°C from NIMBUS and 21.7°C from the aircraft - a good indication of the state of the technology in this field of remote sensing. NOAA 2-4 imagery has been widely used for surface temperature mapping using the 10.5 - 12.5 micron VHRR sensors and on clear days temperature mapping of the Great Lakes has been possible to stated accuracies of 2°c (Ref 205 and see also Ref 206).

For coarse resolution, low frequency, clear weather thermal sensing requirements, satellites such as NIMBUS, NOAA, EXPLORER etc can, or will have some limited hydrological use (see for example p.134). For more local requirements, aircraft infrared scanner surveys can be very costly as very few operational systems are as yet available in the U.K. However the overall size of infrared scanners need not be great and their operation from light aircraft is feasible provided that navigational accuracy and platform stability can be maintained to prevent large distortions. (Some manufacturers of infrared and multispectral scanners are given in Ref. 24). For basic thermal sensing of small areas, relatively low cost and light weight imaging equipment is already available, such as the Aga 680 Thermovision system which allows video recording of a cathcode ray image. Even so, purchase costs are of the order of £25,000 but these could well be reduced with the future use of non-cooled vidicon sensors (Ref 207). When thermal data is obtained it must be remembered that only surface temperatures are recorded which means that considerable in situ measurements will be necessary if sub-surface temperature information is to be extrapolated. However the potential for future applications is great, especially in relatively cloud-free regions and with the further development of digital processing techniques and suitable algorithmic expressions (Ref 196), improved three dimensional modelling of water body temperature should be feasible.

Microwave sensing

In order to overcome the weather dependence of infrared sensors, water surface temperature can be measured using microwave techniques even though the amount of microwave energy emitted by a water body is very small. The temperature measured by microwave sensors is very dependent on the emissivity of the water surface, which in turn is dependent on its wave state and surface roughness (Ref 208). Ryan (Ref 209) describes the testing of a 1.55 cm (19.4 GHz) electrically scanning passive microwave radiometer which, from an altitude of 10,000 metres had a resolution cell size of approximately 500 x 500 metres. Using a computer controlled colour quantization process, 32 shades of colour could be assigned to a scene to delineate variations in surface temperature more easily. Images of ground and water surfaces could be obtained under all-weather, day or night conditions, flooded river areas being readily visible through dense cloud cover. By altering the brightness temperature range of the sensor, clouds (which have a high emissivity) could be observed and estimates of their density and water content could be made. Surface water temperature discrimination of about ± 2°C was possible.

In the long term, the all-weather capability of microwave systems offers greater potential than infrared systems and the achieved ground resolution of 25 metres for the SEASAT microwave radiometer demonstrates that high ground resolutions are already feasible.

7.6 Water velocity and stream discharge

The aerial measurement of water velocity is mainly of use for the estimation of water circulatory patterns in rivers, lakes and estuaries and for the estimation of water discharge where conventional measuring structures are not available. As with the measurement of water temperature, the main drawback with remote sensing of water velocity is that only water surface measurements are possible which means that discharge rates or bulk circulatory patterns can only be estimated if hydraulic flow models can be constructed for each situation. If, for example, at a given time the surface velocity at points across the width of a river is known, then, given the cross sectional dimensions and surface roughness of the river bed and sides, along with an estimate of river slope or energy gradient a reasonable estimate of the river discharge can be made (Ref 132, p.1492 and Ref 210). Although estimates of river sections have been made directly from underwater information recorded on aerial photographs from surface turbulence patterns (Ref 211) these would normally be obtained from ground information or from aerial sensing at times of low water level. For estimating flow within large water bodies such as lakes or open sea, (which can be regarded as essentially bottomless), additional in situ information is required such as water temperature and salinity profiles in order to account for laminar flow effects (Refs 161, 180 and 212). One of the simplest methods of remotely estimating surface and subsurface water velocity is by the tracking of buoys or markers and these methods will be considered first.

Tracking of artificial markers

The movement of the surface of a water body can be more easily observed by the addition of floating markers which can be of any convenient buoyant material. If only surface velocities are required, the buoyant marker alone would be used, whilst by the addition of suitably designed drogues, velocities at given depths or even depth integrated velocities can be estimated (see Figure 63). Ideally, markers should have a mass only slightly less than that of water and a small vertical surface area above water level so as to minimise wind resistance. If the markers are to be viewed from the air, a large horizontal area should be presented of a colour and material which would provide high contrast against the water background at the sensor operation wavelength. For monitoring from high altitudes quite large markers will be required and therefore cost may restrict the numbers which can be used. The tracking of large markers from both helicopters and aeroplanes is commonplace in estuary and coastal circulatory surveying (Ref 161) and as an alternative to visible or radar monitoring of the markers positions, individual transmitters may be fitted to each buoy so that a radio positional fix may be achieved (Ref 162). On a still larger scale, the TWERLE oceanographic experiment in the North and Norwegian Sea relied on the transmission of the position of buoys fitted with drogues at selected depths, to the NIMBUS-6 satellite and a similar procedure is planned for the SEASAT programme. It is unlikely however that such large scale techniques would be used for hydrological purposes except possibly on very large lakes or reservoirs. Where detailed information of local water movements are required, small targets may be scattered on the water surface from boat or aeroplanes and may be tracked using time lapse photography (Ref 214). Powdered aluminium has been found to be suitable for this purpose as it disperses harmlessly after a few hours unlike expanded polystyrene or similar materials. With the use of aerial photogrammetric techniques the movements of surface drift cards have been measured to velocity accuracies of ±2 cm/sec and to directional accuracies of 3° (Ref 212).

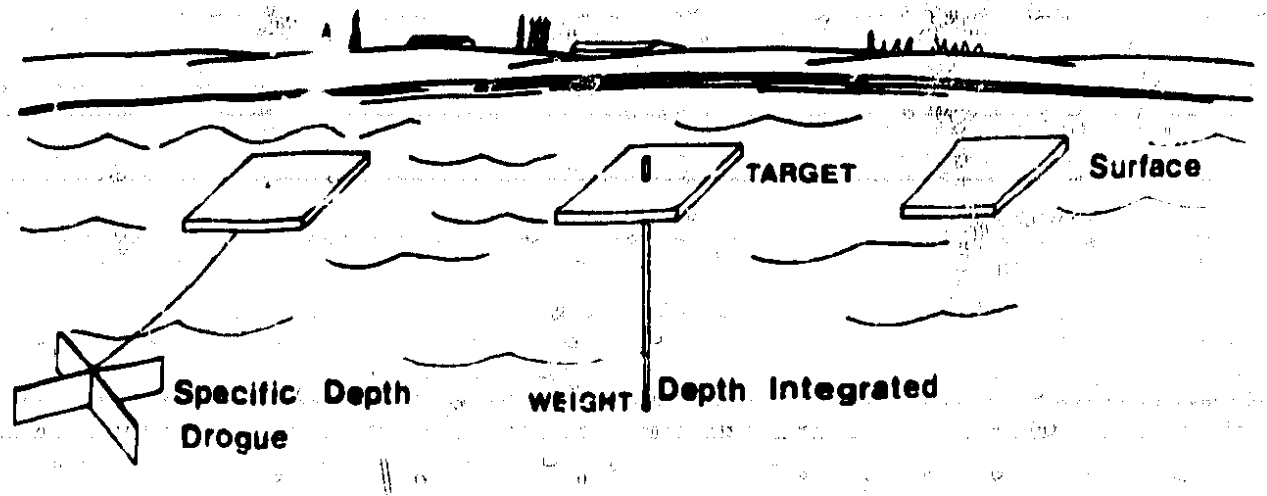


FIGURE 63 Surface markers for estimation of water velocity

Tracking of natural surface markers

It is feasible to track natural surface water features such as foam streaks, debris, algal patches (Ref 180), white water or individual waves and to measure their movement by photogrammetry. The principle relies on the measurement of parallax differences as recorded on stereo photographs of the water surface (see Figure 64). No parallax is observed for points which have remained stationary during the time interval between

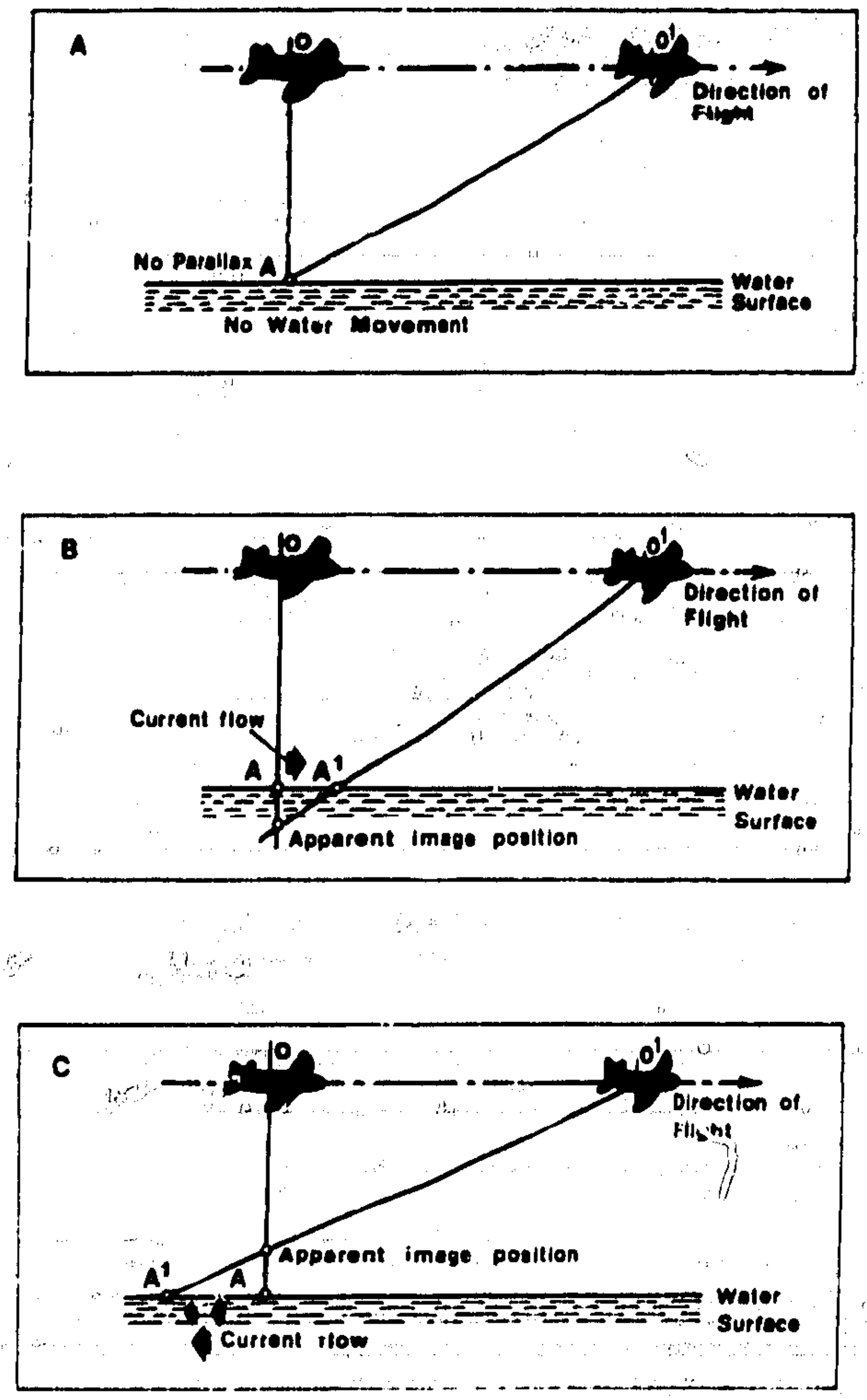


FIGURE 64 Measurement of surface water movement with stereo-photography

exposure of the two photographs. Features which have moved in the same direction as the aircraft will appear to lie below the water surface when viewed stereoscopically, those which moved in the opposite direction to the aircraft will appear to lie above the water surface, whereas movements sideways will be recorded directly. This can be done for all recognisable features on the water surface and thus a synoptic plot of water movement can be obtained. Stationary markers or land features should be present in both photographs in order to permit correct reconstruction of the stereoscopic model. This technique should be particularly useful for measuring the surface water velocity of rivers in remote areas where in situ gauging methods would not be possible and also for flooded rivers where normal flow gauging structures may be overtopped and where it would be dangerous to venture by boat in order to take current meter measurements. Such a velocity sampling technique, coupled with the delineation of maximum flood water extent (see p. 85) and if necessary with the provision of aerially determined flood plain cross sections, could provide a complete remote sensing package for flood discharge estimation in inaccessible areas.

Tracking of natural water colour and artificial dye

Numerous types of dye have been used in the past for tracking water movement, probably the most widely used being fluorescein and rhodamine varieties (Ref 215). After injection into water bodies, a measure of the dye's dispersion is generally obtained by either taking water samples and analysing them for dye concentration, or by in situ measurement of the dye's fluorescence for example, in the case of fluorescent dyes. For dye sampling in large water bodies, boats have normally been used, but this generally causes appreciable disturbance of the water under investigation. In both rivers and open water bodies, only a limited number of water samples can be taken, with the result that often very approximate trend lines between sample points must be relied upon for dispersion information. More recently, helicopters have been used to increase the number of samples taken in a given period (Ref 216), but still only a small proportion of the available information is used and conditions may still change during the sampling operation. Point sampling by helicopter may be speeded by the use of discrete chemical sensors such as the Fraunhofer Line Discriminator or continuous monitoring along a flight line may be possible with the use of a suitable fluorimeter. (Fraunhofer line discriminators sense both the incoming radiation from the sun and the radiation from the water body and compare a selected Fraunhofer line (known dark line) in the solar spectrum with the spectrum of the water body (see Fig 65)). However, in order to fully appreciate the mechanism of dispersion of an injected dye an aerial imaging record is required. Although actual chemical concentrations cannot be measured to the same accuracy as with in-situ sampling, the overall comparative picture is likely to yield more meaningful information. In most cases, water sampling would still be carried out during aerial sensing in order to provide known points within the comparative picture. At its simplest, remote sensing of dye can be in the form of miniature camera photography using either colour, colour infrared or filtered black and white emulsions, depending on the type of dye to be detected. For example, by choosing colour infrared film, the red colour of rhodamine dye would stand out strongly as a yellow colour against the deep blue background of water. In many cases where effluent discharges

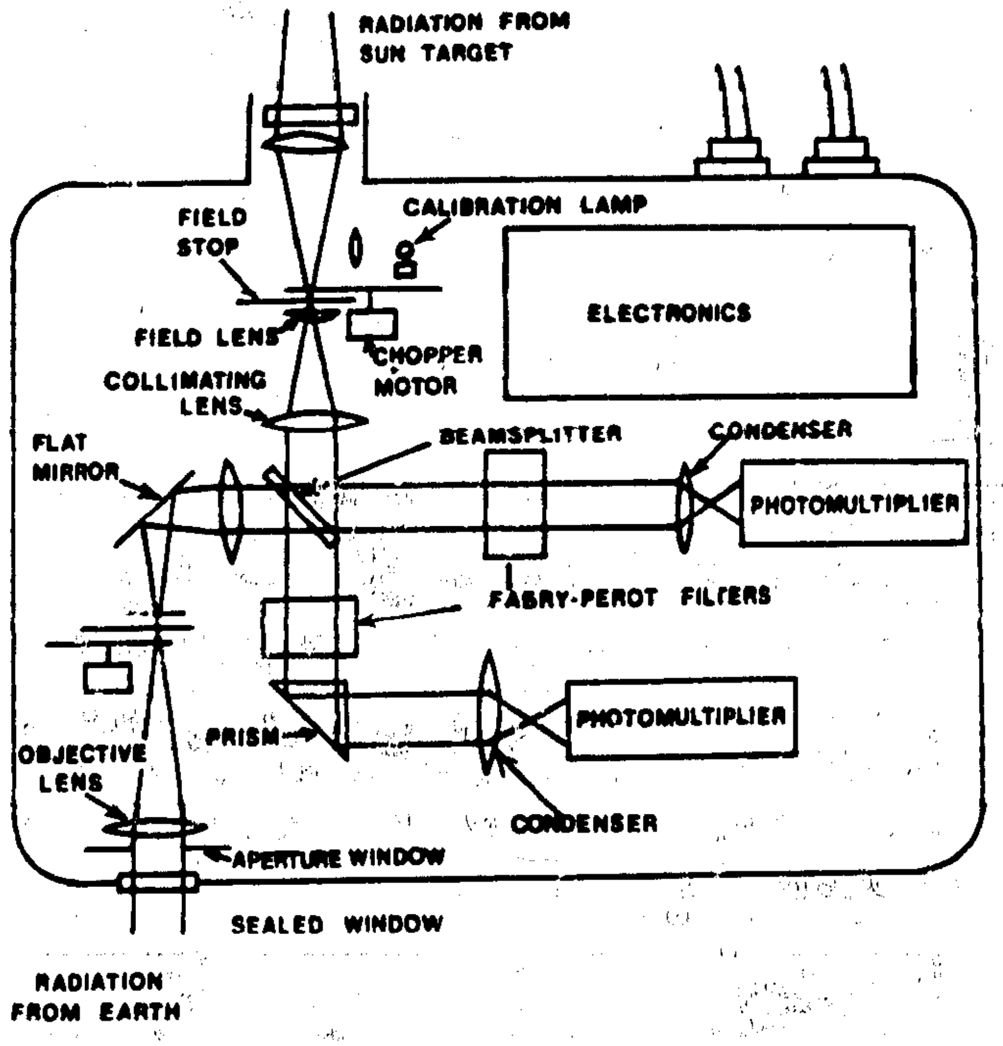


FIGURE 65 **Schematic diagram showing optical and electronic components in the Fraunhofer line discriminator**

into rivers or lakes, its colour contrast with the surrounding water is sufficient to enable aerial recording of its movement from which effluent discharge rates and water velocities may be inferred. For example, microdensitometer measurements of the image density of a paper mill outfall plume, as recorded on vertical 35 mm aerial photographs, were used as a measure of the turbidity of the plume (Ref 180). These together with similar photographic records of rhodamine WT dye tracer, were used to estimate the direction of flow of river currents and rates of dispersion of the plume, in conjunction of course with in-situ sampling. More accurate measures of surface water movement have been carried out using a fluorescent tracer dye imaging system (Ref 217). The sensing system provides a real time image of the dye dispersion in relation to reference features such as shore lines, marker buoys etc. By using two or more narrow spectral channels (one in the wavelength region of high fluorescence and one beyond the fluorescence emission of the dye as a reference to the water reflection) high signal to noise ratios are possible even at very low dye concentrations (<5 parts per billion). The information is recorded in digital form for subsequent computer processing which is essential to obtain the necessary accuracies. Accurate contouring of dye concentration was possible which enabled mean water velocities to be inferred after correction to in-situ point velocity measurements. As was previously stressed, many of these sensing techniques either measure surface water velocity or, in the case of tracer dye tracking, an integration of water velocity over a given depth.

In an attempt to measure the velocity profile with depth, Hodder (Ref 218) released discretely coloured dyes at different depths within a large water body and used narrow band interference filters to discriminate between dyes. The releases were made at depths which matched the extinction depth (see p. 87) for light within the respective dye bandwidth, so that each dye would be invisible below that depth. The technique had not been fully perfected when reported, but it obviously offers considerable scope for future research in situations where detailed information is required on local water movements.

Doppler radar techniques

The principle of pulsed compression radar as described on page 52 shows how outgoing radar pulses are encoded in some way so that they may be recognised on their return after reflection from the target. Doppler radar measures the change in frequency between the outgoing and return radar signal which results from any relative movement between target and sensor, (Ref 219). Doppler radar has been widely used as a method of aircraft navigation whereby the doppler shift returns of four radar beams directed to left and right forward and left and right backwards from the aircraft are compared in order to calculate the ground velocity vector of the aircraft. When this system was initially used over a moving water body, navigational errors resulted and it was then realised that this discrepancy could be put to good use as a means of calculating water velocity, provided that an alternative, accurate means of navigation was available such as by ground reference beacons or on board inertial systems (Ref 12). At the moment such water velocity measurements are only possible over relatively large water bodies due to the spread of the four beams. An imaging forward looking military radar or scatterometer (see p. 55 and Fig 42) designed for the detection of ground based moving vehicles relies on the same doppler shift principle and has a greater potential for measuring the velocity of small water bodies such as rivers, due to its better resolution. In its present state of development it should be possible to discriminate water velocities as low as 0.5 metres/sec. (Ref 12), but future improvements can be expected.

Conventional sidelooking radar has been shown to be capable of detecting sheet surface runoff after heavy rainfall (Ref 209 section 7.4) and also floodwater extent within which areas of greatest water movement can be delineated. The future refinement of such systems would obviously be of great benefit to hydrologists, but it must be realised that aircraft fitted with sophisticated navigational equipment are extremely expensive to operate and that this level of expense would probably only be justified for major operations.

Assessment of stream dynamics

An alternative to the direct measurement of river discharge is the possibility that the dynamic properties of stream networks can be used as likely indicators of total system discharge. It has been shown that a positive relationship between total flowing stream length within an impervious clay catchment and total catchment discharge can exist (Ref 145) indicating that it may be feasible to estimate river discharge from an

aerial survey of contributing stream length. Using a more empirical approach, information regarding geometric and physical characteristics of catchments such as area, mean slope, stream network geometry, amount of open water, type and area of vegetation cover, area of snow cover etc., can all be used to help predict likely runoff rates and can all be most suitably measured from an aerial viewpoint. LANDSAT imagery has been shown to be useful for this type of measurement (Refs 220 & 221) but perhaps airborne radar (see p. 52) has the greatest potential use for mapping such features due to its oblique viewing angle and all weather capability, which is essential when regular monitoring is required. Information of similar quality to that obtained on 1:24,000 topographic maps can be expected from SLAR systems (Ref 106 pp 67-74). Kalinin (Ref 222) describes methods of predicting basin runoff from satellite measurements of water body surface area, flooded areas and length of stream network. He also presents predictive methods of estimating spring floods from snow cover measurement, but this form of discharge prediction will be dealt with more fully in section 7.12. A good account of the use of remotely sensed drainage basin physical characteristics for discharge predictions, predictions of hydrograph form and hydrological comparisons between different drainage basins is given in Ref 132 pp 1490-1493.

7.7 Erosion and sediment deposition

In UK and northern Europe, soil erosion is not generally regarded as a major problem, largely because of the temperate climate and good vegetation cover which discourages surface stripping. Stream and river bank erosion is not normally excessive as areas prone to such erosion are often now protected by bank stabilisation schemes. However, even in northern Europe, the costs of erosion prevention may rate very highly in certain situations due to the nature of the civil engineering work required, and when floods do occur, the costs due to both life and property can be high. Assessment of total flood damage costs is difficult because of intangible factors such as inconvenience and suffering, but Penning-Rowsell (Ref 223) has attempted this through the use of comprehensive look-up tables. As with erosion, sediment deposition is most marked after major flood events (Ref 224 & 225) but its effect is still felt in the short term, as river and estuary shipping channels often require regular dredging due to the action of sediment transport by normal currents and tides. Jansen and Painter (Ref 226) developed linear regression models to relate the annual average sediment yield of 79 river basin catchments (of area greater than 5,000 km^2) throughout the world and concluded that erosion rates were lowest in continental and tropical forest climates, intermediate in the arid and semi-arid climates and very high in Mediterranean climates, with extreme values in areas of high altitude and relief. A global denudation rate of 26.7 x 10^9 tonnes/year was also estimated. The use of remote sensing techniques for the estimation of erosion and sediment deposition are likely therefore to be of greatest general value in Mediterranean climates, but also in specific areas possessing more than one of the following:- high annual rainfall, high altitude or relief, high mean temperature, low vegetation cover, or high erodability of surface rock and soil.

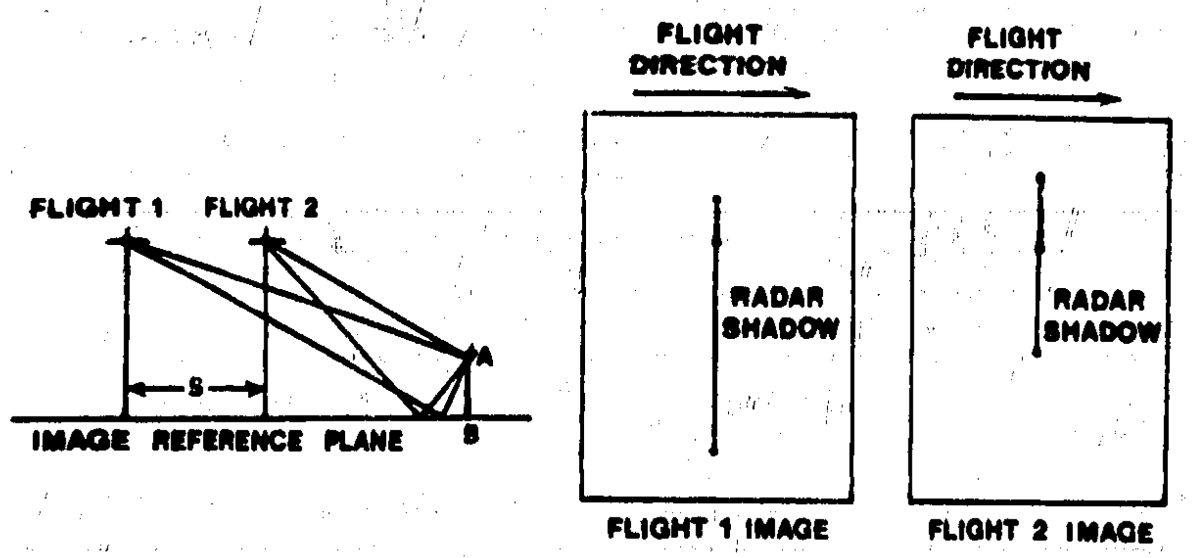
Identification of sediment erosion and deposition features

In both the arid and European situation, topographic erosional and depositional features can be strongly enhanced by the oblique illumination of side looking radar (see p. 72). As the brightness of the radar return signal is largely determined by the angle of incidence of the radar beam to the ground surface, any small variations in the surface, such as those caused by gullying, land collapse, levée sedimentation, scree slope deposits etc. will be strongly enhanced. Because of the oblique angle of view which is recorded on a SLAR image, direct measurements of ground dimensions cannot be made as would be the case with vertically viewing sensors. However, suitable nomographs have been developed which allow horizontal ground dimensions to be calculated relatively easily (Refs 239-241), but the measurement of volumes still remains a problem. Also as a result of the oblique illumination, the resulting shadowing causes loss of data which can be prohibitive in areas of high relief. Such data loss can generally be overcome by viewing an area of interest from different aspects, but increased flying and data handling costs result. For the optimum use of SLAR, system considerations such as the angle of depression, type of polarisation and direction of view (see p. 75) must be chosen carefully to suit the terrain. These and other factors are dealt with extensively in the Active Microwave Workshop Report (Ref 106) which covers the application of SLAR in all of the earth sciences.

Volume measurement

Conventionally, measurements of erosion or deposition are carried out by ground survey from which volumes of transported material may be calculated. These may frequently be only inferred calculations unless previous surveys had been carried out in the area of interest before the erosion or deposition took place. For small areas, measurement accuracies can be very high, but the methods used are very slow for extensive studies. A technique which is being increasingly used now is ground-based photogrammetry whereby metric cameras (see p. 29) are used to obtain stereo-paired photographs of ground features, from which surface contours can be accurately plotted (Ref 227). The advantages of this technique are that, once reference targets are established on the site of interest, surveys can be quickly carried out with minimal time in the field, enabling changes in topography due to erosion or deposition to be rapidly calculated (Ref 228). The field of view of ground based systems is somewhat limited in flat terrain, but in regions of high relief, much larger areas can be observed. Ground based photogrammetry is ideally suited to the measurement of local river bank erosion, river and estuary shoaling, hillslope gully erosion etc. For process studies measurement accuracies of a few millimetres are possible, with the added advantage that the soil surface need not be disturbed as would be the case with conventional surveying. As an extension of this technique, aerial photogrammetry enables large areas to be rapidly height contoured with a compromise having to be drawn between measurement accuracy and field of view. If necessary, accuracies of ± 5 cm are possible (Ref 229) but equipment costs will be high in order to achive this. Conventional aerial photogrammetry only becomes cost effective when surveys of large areas are required, but such surveys are normally only carried out in excellent weather conditions which may occur on less than ten days a year in UK. Where less accurate but frequent aerial measurements are required, it is feasible to use low cost or non-metric cameras in helicopters or light aircraft and still obtain acceptable results (Refs 230 & 231). If it is not possible to wait for clear weather conditions in order to undertake photographic surveys, then microwave topographic surveys could be considered (see p. 72). Estimates of volume using stereo-radar techniques are possible when an object can be imaged twice either at two different look angles from the same altitude (see Fig. 66a) or at two different altitudes from the same look direction (Ref 106). Where dual beam radar is available, single flight stereoscopy may be possible (see Fig. 66b). However, in steep areas, radar shadowing and lateral distortion may result in significant loss of data (see Fig. 67) which may be sufficient to negate the use of stereoscopy. In areas of shallow slope (such as flood plains, estuaries etc) the technique is worthy of consideration as the measurement capabilities become more sensitive at small incident angles.

a) TWO FLIGHT STEREO RADAR TECHNIQUE



b) SINGLE FLIGHT STEREO RADAR TECHNIQUE

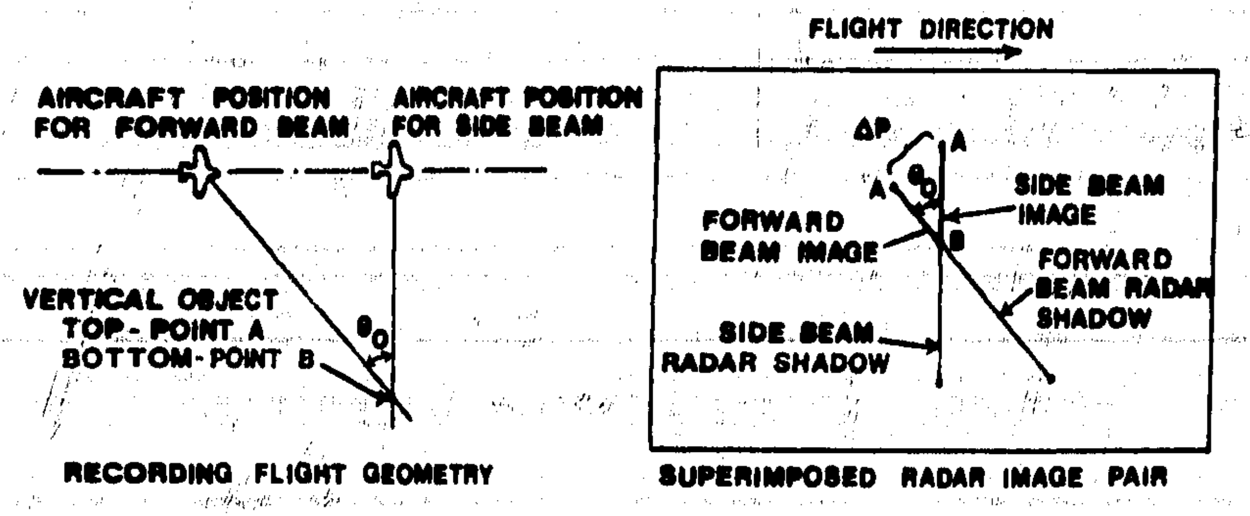


FIGURE 66 Geometry of stereo radar

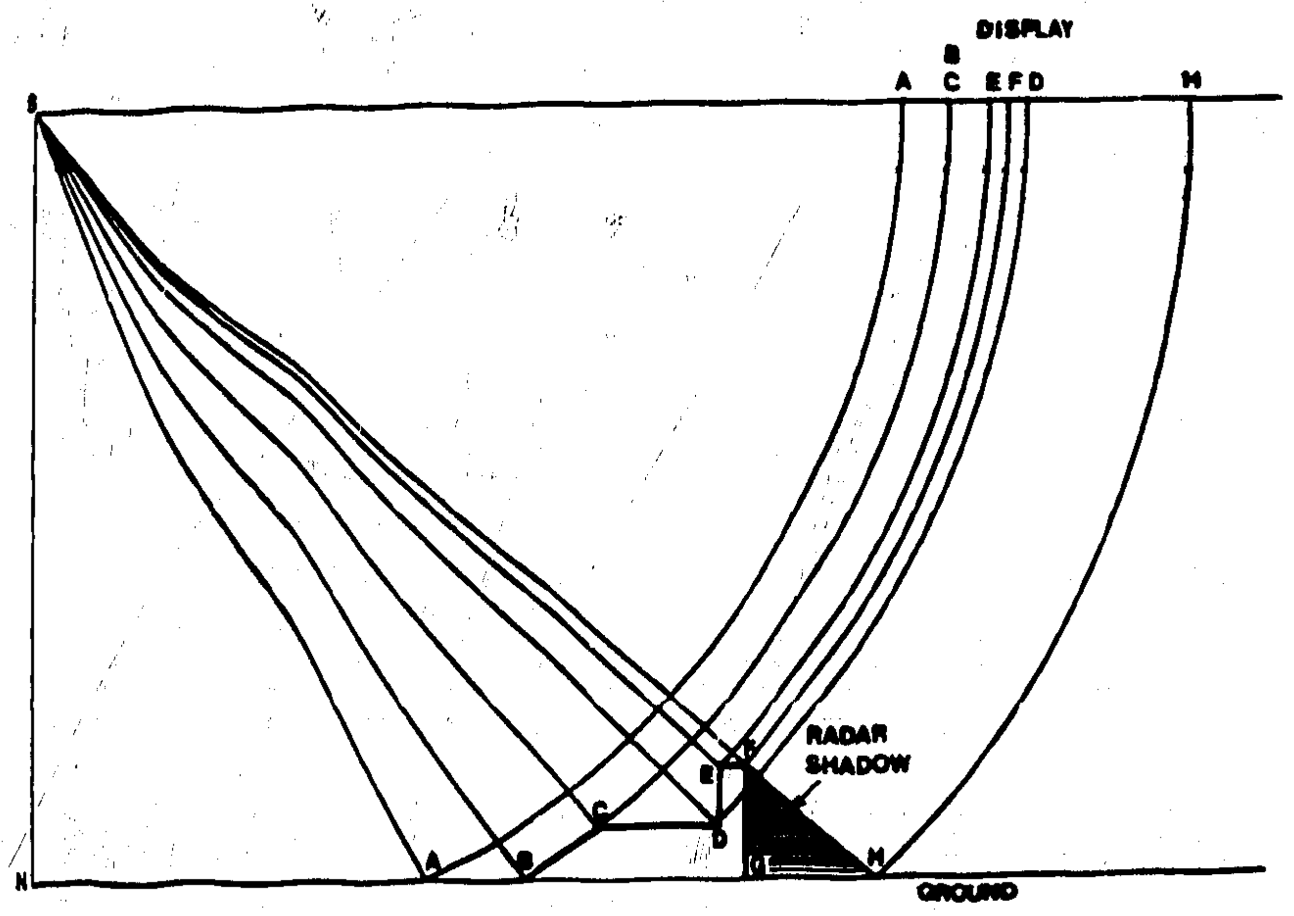


FIGURE 67 **Lateral distortion of elevated objects in side looking radar imagery**

Identification of sediment type

For the identification of sediment types in exposed or shallow water situations and subsequently for the identification of erosion source areas, conventional colour aerial photography may be adequate, provided that sufficient colour contrast is exhibited between sediment types, (Ref 232). When different sediments exhibit little colour difference, multispectral photography may often allow their easier delineation especially if the spectral signatures of the sediments to be defined are first measured and the most suitable filters for their separation are then chosen (Ref 233). It may be possible to lessen the masking effect of a shallow cover of water over sediment by photography in bands suitable for water penetration or by density slicing or ratioing of multispectral images (see p. 68). In a study of the lower Mekong Basin (Ref 234), heavy siltation in parts of reservoirs was observable on LANDSAT imagery by comparison of the apparent land/water boundary as observed in bands 5 (green, for water penetration) and 7 (near infrared, for land/water definition). LANDSAT imagery has also been successfully used for the detection of large scale sediment deposits. It was found that after extensive flooding of the Gila River in California, areas of severe sand and gravel deposition could best be seen in band 5 (0.6 - 0.7 microns) of the LANDSAT multispectral imagery, and that also areas of maximum erosion could be identified (Ref 235). Band 5 was also found to be of most use in the detection of areas of readily erodable material in a four group classification of surface erodability types for southern Arizona (Ref 236). Whilst LANDSAT imagery has also proved to be suitable for studies of sediment movement and the distribution of sand barriers in estuary situations such as the Wash (Ref 237), only very major erosional features such as mud flows or land slides are likely to be discernible from satellite studies. The identification and monitoring of changing wadi erosion and subsequent sand and alluvial deposits from satellite images has provided useful information on sporadic water movement in poorly mapped desert areas (Ref 146) whereas water courses covered by shallow sedimentation in desert areas were best detected by night time thermal scanners than by day time photography (Ref 238). The frequent application of remote sensing to the study of sedimentation and erosion in arid areas is due not only to the lack of obscuring vegetation, but also due to the complete visibility of water course beds once flood waters have subsided, together with cloud free conditions.

In summary therefore, from a European point of view, satellite borne sensors could provide long term information on changes in river courses and meander migrations (Ref 242), coastal erosion, reservoir and estuary siltation etc. where high temporal frequencies are not required and where frequent cloud cover does not create great problems. On a short term basis however, satellites are unlikely to be of a great value until the problems associated with extensive cloud cover are resolved. For regional information, aircraft photographic (or in the future, microwave surveys) are well suited to the occasional requirement of data updating, whilst ground base methods are better suited to local requirements which often demand measurements of high accuracy.

7.8 Soil moisture

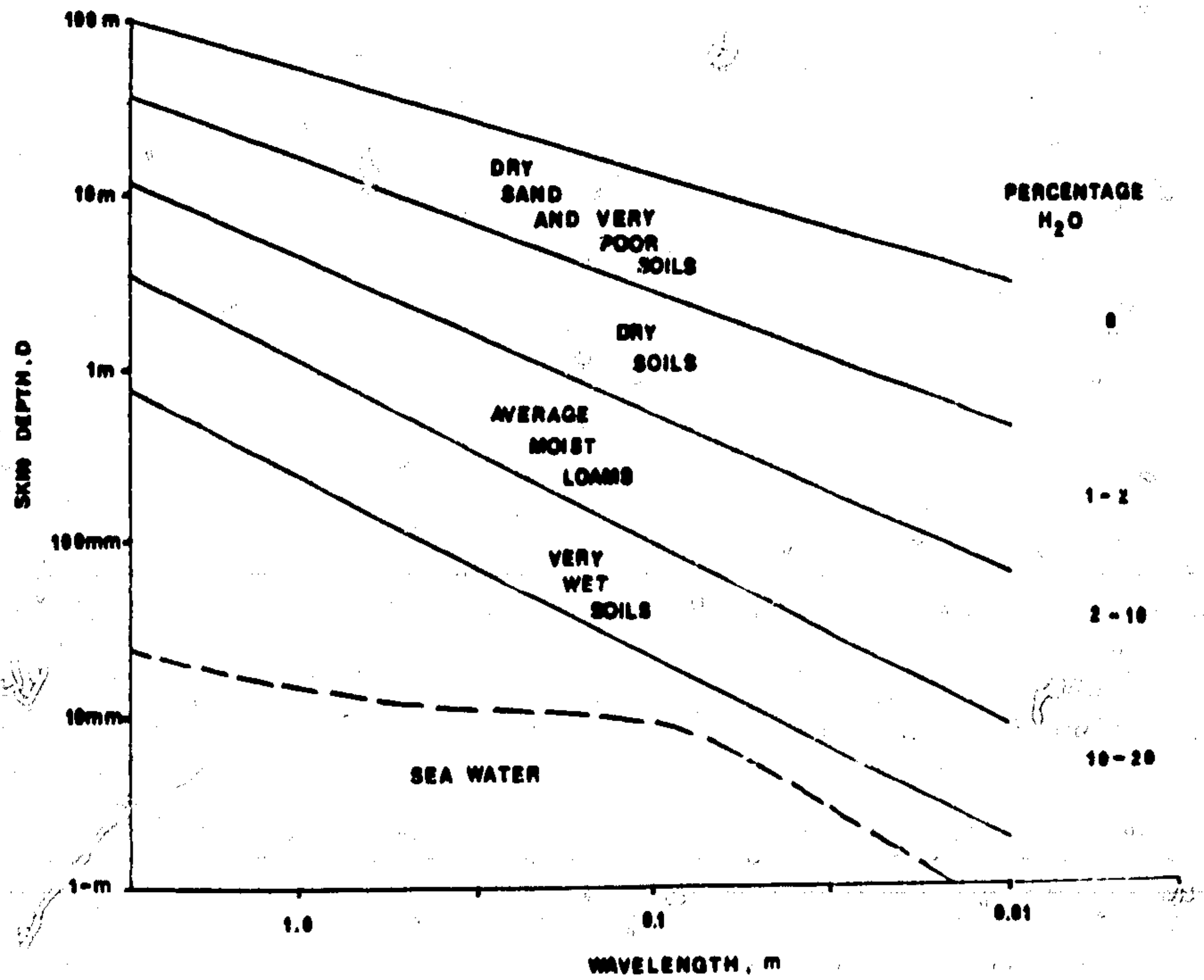
An adequate knowledge of the distribution of moisture in soil and of its variations in time and space is fundamental to the understanding of the hydrological cycle. Quantitative knowledge of the soil moisture regime is needed in order to construct water balance models for water resources purposes, for vegetation studies and crop management and for surface and sub-surface flow predictions, whilst qualitative indications of soil wetness may also help in the prediction of catastrophic events such as land slides or flash floods. Conventional ways of measuring soil moisture include gravimetric soil sampling, neutron scattering methods, soil lysimetry, tensiometry and measurement of soil electrical resistance. These methods represent the highest achievable measure of soil moisture content, but only at a given point or series of points. This is a definite disadvantage as spatially, soil moisture values can be highly variable, therefore only fairly crude estimates of total soil moisture content can be made even when numerous point samples are taken. It is unlikely that remotely sensed measurement of soil moisture at a point can ever be as accurate as ground measurements, but they do have the potential of providing mean values of surface soil moisture over large areas, which is simply not possible using conventional methods. The main disadvantage of remotely sensing soil moisture is that only the surface or near surface soil layers contribute to the sensed signal and these often give little indication of sub-surface soil moisture state. However, by combining the information provided by both the ground sampled and the remotely sensed measurements, a much better understanding of soil moisture variability and of soil moisture processes should be possible.

Visible and near infrared sensing

In the U.S.A., attempts at remote sensing of soil moisture have normally been highly quantitative and strongly based on soil physics and radiation theory. As these theories are too complex to be dealt with in a broad study such as this, only descriptions of the positive findings will be given. Similarly, results of controlled laboratory tests will not be given here in detail as few have produced results which can be directly applied to field conditions. In the USSR a more qualitative approach has often been favoured in which certain topographic and vegetational combinations have been recognised as indicators of soil moisture state. Nefedov and Popova (Ref 243), relied on their extensive knowledge of the preferences of plant species in terms of soil type, acidity, available water etc. to determine likely moisture and groundwater conditions from aerial photographs. A simple example of this is the marked change in plant species or plant vigour which often occurs where ground water approaches the soil surface.

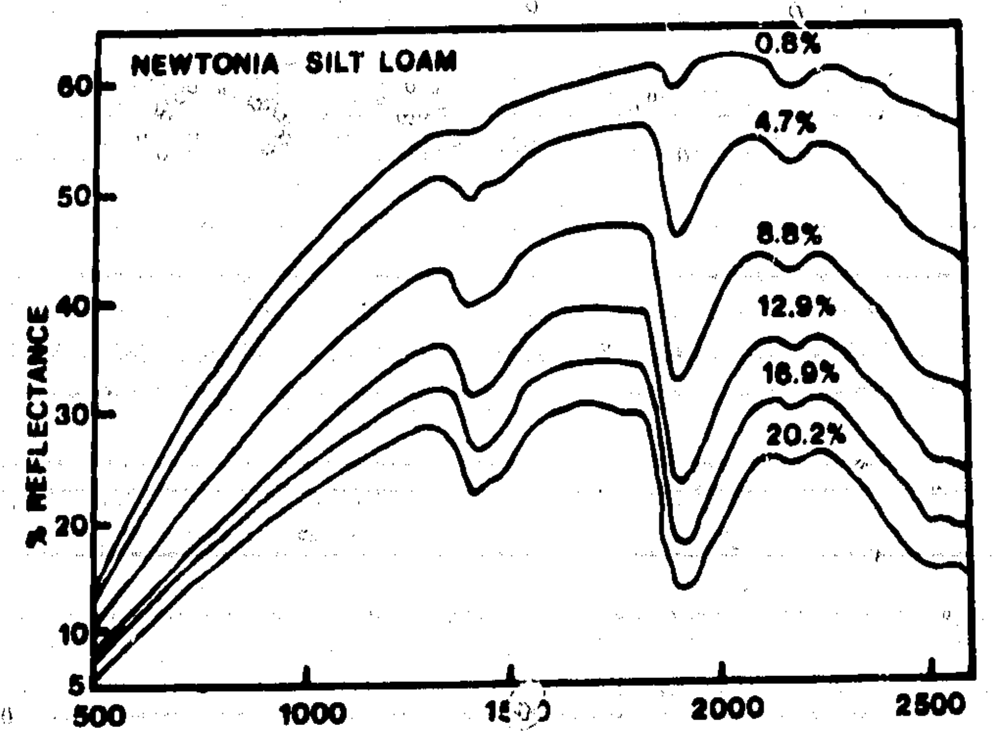
In the USA, test site correlations were run between the available soil moisture (< 15 bars) in an irrigated and non irrigated field of grain sorghum, and the image density of filtered black and white and also colour infrared film of the fields. The results indicated that for the whole of the crop growing cycle, the red band (after correction for seasonal radiative changes) of spectral range 0.59 - 0.70 microns, provided best correlation with soil moisture and after mid-July when the canopy was well developed, almost all correlations were significantly different from zero at the 99.99% confidence level where the number of observations was 195, with some correlations being above 0.9. Near infrared bands were good for indicating plant stress due to excesses or lack of soil moisture (Ref 244 and also flooding p. 85) but under normal growing conditions, very erratic correlations were observed.

At the present state-of-the-art it is likely that vegetationally derived measures of soil moisture will be more useful than many direct electromagnetic techniques, as an indication of moisture in the top 10-30 cm of soil may result. The major disadvantage of all direct radiative measures of soil moisture based on wavelengths of less than tens of centimetres is that only moisture in the thin surface layer is sensed (assuming there are no vegetational effects) (see Fig 68). This is probably only of use for estimates of bare soil evaporation rates as the important underlying soil may have an entirely different and unpredictable moisture content. Hoffer and Johannsen (Ref 245) noted that a dry surface crust could form on a soil surface within only a few hours after rainfall, whilst the underlying soil was still wet. A definite relationship would therefore have to be established between moisture levels in these two zones through extensive ground measurements before useful spatial information could be extracted. Also, much of the work carried out so far has established soil moisture radiation relationships with bare homogeneous soil surfaces and has taken little account of vegetation and other random surface effects which are generally found in 'real' conditions (Ref 246). However it is generally agreed that reflectance from a bare homogeneous soil is reduced as soil moisture content is increased (Ref 245 & Figs 69 & 70) and because of this effect it is possible to map areas where rain has



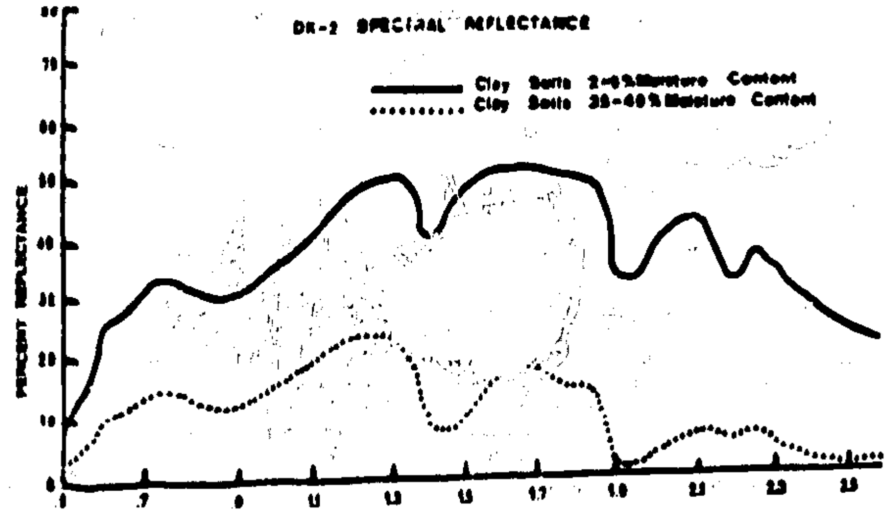
Calculated from Dielectric Constant Measurements

FIGURE 68 Theoretical skin depth/wavelength relationship for soils of different moisture content

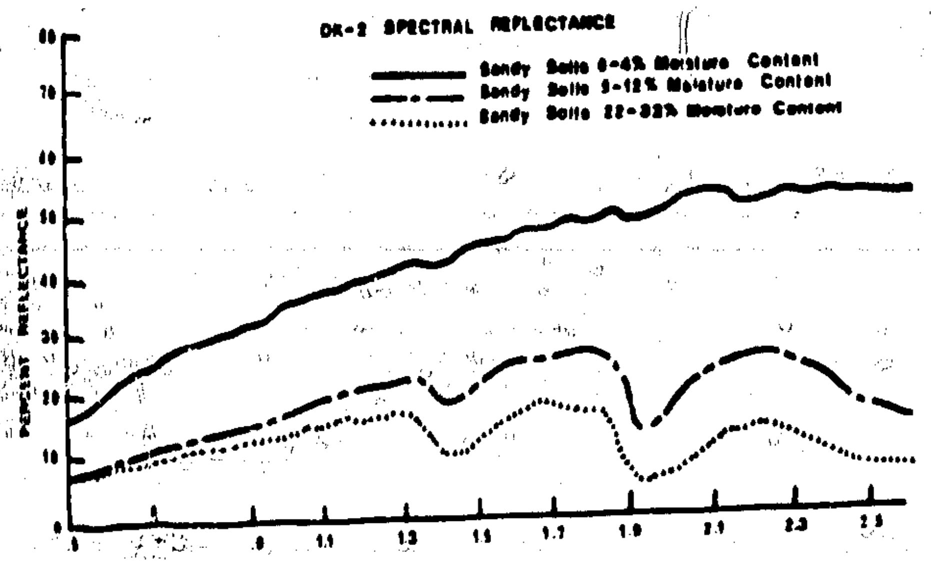


Percent reflectance vs wavelength of incident radiation at various moisture contents indicated directly above each curve (Bowers & Hanks)

FIGURE 69 Variation of surface soil reflectance with changing soil moisture



Clay Soils at Two Moisture Levels



Sandy Soils at Three Moisture Levels

FIGURE 70

Spectral reflectance of clay and sandy soils at different moisture contents

recently fallen on dry ground. This has been possible in arid areas using satellite data (see p.137) but it must be realised that the surface reflectance of soil is also dependent on such things as its emissivity, surface roughness, the prevailing intensity and angle of incoming radiation and the sensor viewing angle (Fig 71). The polarisation of light in visible wavelengths has been shown to increase with increasing surface soil moisture content (Ref 247 & Fig 72), but this too is dependent on the above mentioned variables. Both of these techniques however should be adequate for the delineation of waterlogged areas.

The effects of surface wetting also vary greatly according to soil type. Dry, sandy soils have a very flat spectral reflectance curve, but with slight wetting (more than 4% moisture content by weight) strong water absorption bands form at approximately 1.45 and 1.95 microns (see Fig 70). Clay soils however always show the water absorption bands even when air dry due to their molecularly bound water (Ref 245), making any transition from dry to wet less obvious than with sandy soils. For light clay loams, the greatest change in reflectance is generally between 2-12% of field capacity, for clays it is between 5-25% and for humic gley soils it is between 7-30%, whilst the greatest magnitude in reflectance

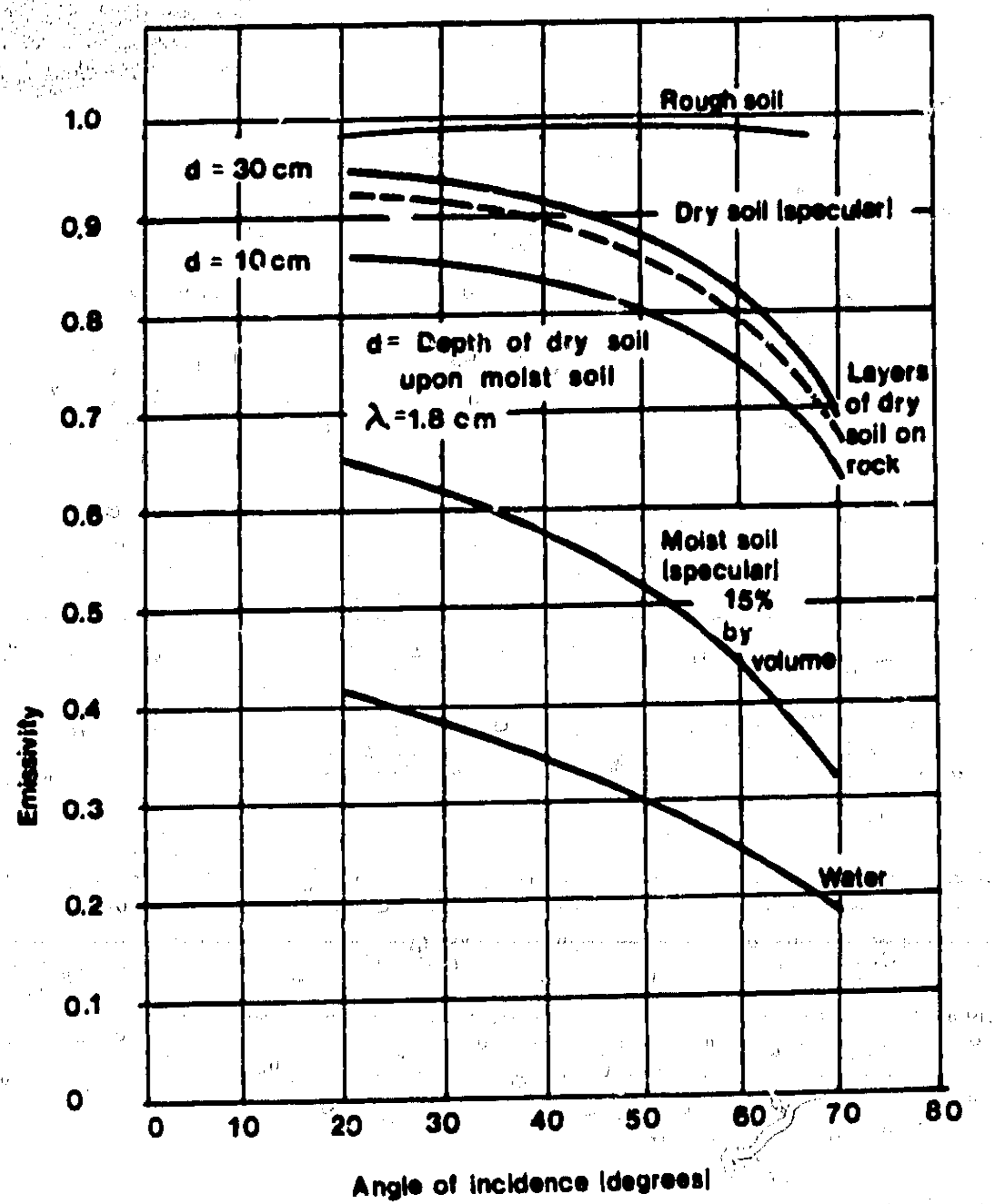


FIGURE 71

Emissivities of natural surfaces with changing viewing angle at microwave frequencies

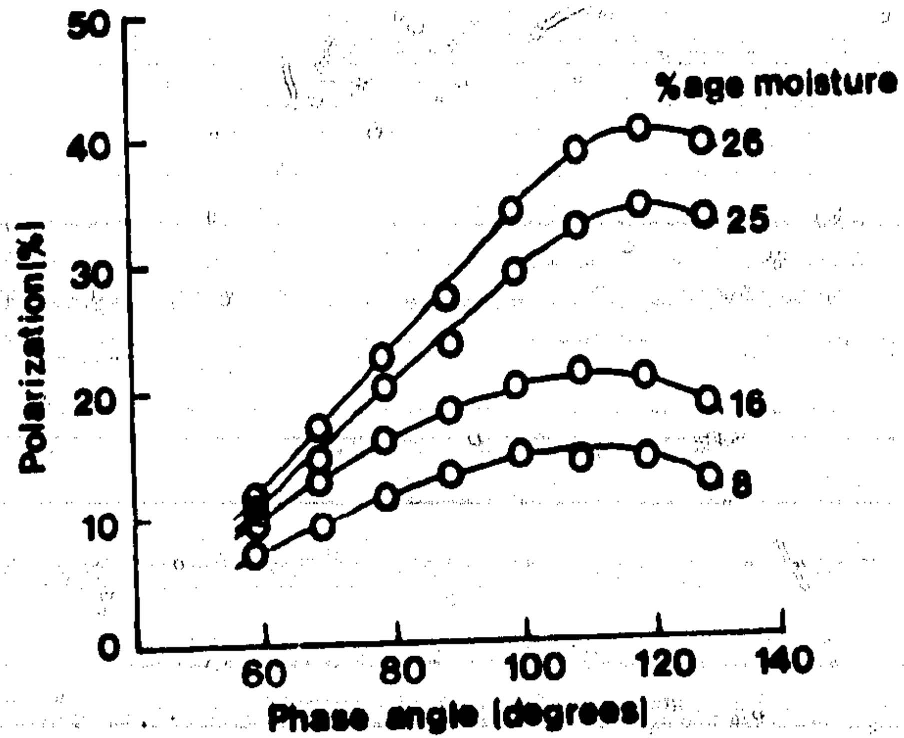


FIGURE 72 Polarization in plane of incidence with changing soil moisture *(Stockhoff & Frost)*

change has been found in dark soils having a high humic content (Ref 248). The results of a study to assess the capability of the NIMBUS-3 near infrared radiometer (0.7-1.3 microns) to monitor changes in soil moisture and resulting vegetational effects in a low level non-forested area of the Mississippi (Ref 248) showed that mean surface reflectances could be related to mean seasonal soil moisture change. The greatest problem encountered was the patchiness and variability of precipitation events over the area which in turn resulted in great local variability in surface reflectance and created statistical sampling and ground verification problems. It is to be expected that this type of precipitation problem would be encountered in the U.K. and therefore greater chances of success are likely in areas of more uniform rainfall. Nevertheless, having made the point that rainfall variability does cause problems, we shall go on to look at remote sensing techniques using longer wavelengths which promise to yield more useful information on soil moisture distributions.

Thermal sensing

Measurements of ground surface temperature are theoretically capable of providing soil moisture information, but as with reflected ground radiation, problems are encountered with calibration and once again only surface information is directly available. Since water has a higher specific heat and therefore a higher thermal capacity than soil, the wetter soil becomes, the higher will be its thermal capacity and conductivity (Ref 249). A measure of a soil's thermal inertia (conductivity x thermal capacity)$^{\frac{1}{2}}$ is most easily obtained by taking daily maximum and minimum soil temperature measurements, where, under similar conditions, high diurnal temperature variations should result from dry soils and low diurnal variations from wet soils with a predictable relationship between the two extremes. Figure 73 shows the effect of a gradually drying soil on diurnal temperature variation. However, in addition to the marked effect of air temperature variations the ground surface temperature is also dependent on such things as wind velocity, surface roughness and associated evaporative cooling, its positional exposure, slope and aspect and most importantly, the nature of any vegetational cover. Because of these additional variables, it is likely that only gross or long term changes in soil moisture can be recognised with any degree of confidence using thermal techniques, especially when sensing from high altitudes where atmospheric effects cannot be readily accounted for. The effect of surface emissivity variations on thermal inertia measurements can be reduced, provided that diurnal measurements can be repeated at known points and provided than no change in moisture state occurs between measurements (Ref 246). Atmospheric effects can be largely overcome by sensing in completely cloud and haze free conditions although this becomes an unworkable solution in regions such as the U.K. where consecutive day and night clear conditions can only be expected a few times each year. It is claimed that such temperature measurements give indications of soil moisture state down to a depth of 7-10 cm as a result of heat conduction and theoretical physical models have been constructed in an attempt to account for the process of soil/atmosphere heat exchange (Refs 250 & 251 & Fig 74). Plants behave in a similar way to soil in that their diurnal temperature range falls with increasing water content and so some indication of gross changes in soil moisture may be possible. For aerial sensing, homogeneous areas of a single land use type should be chosen in order to reduce the effects of species variation as much as possible.

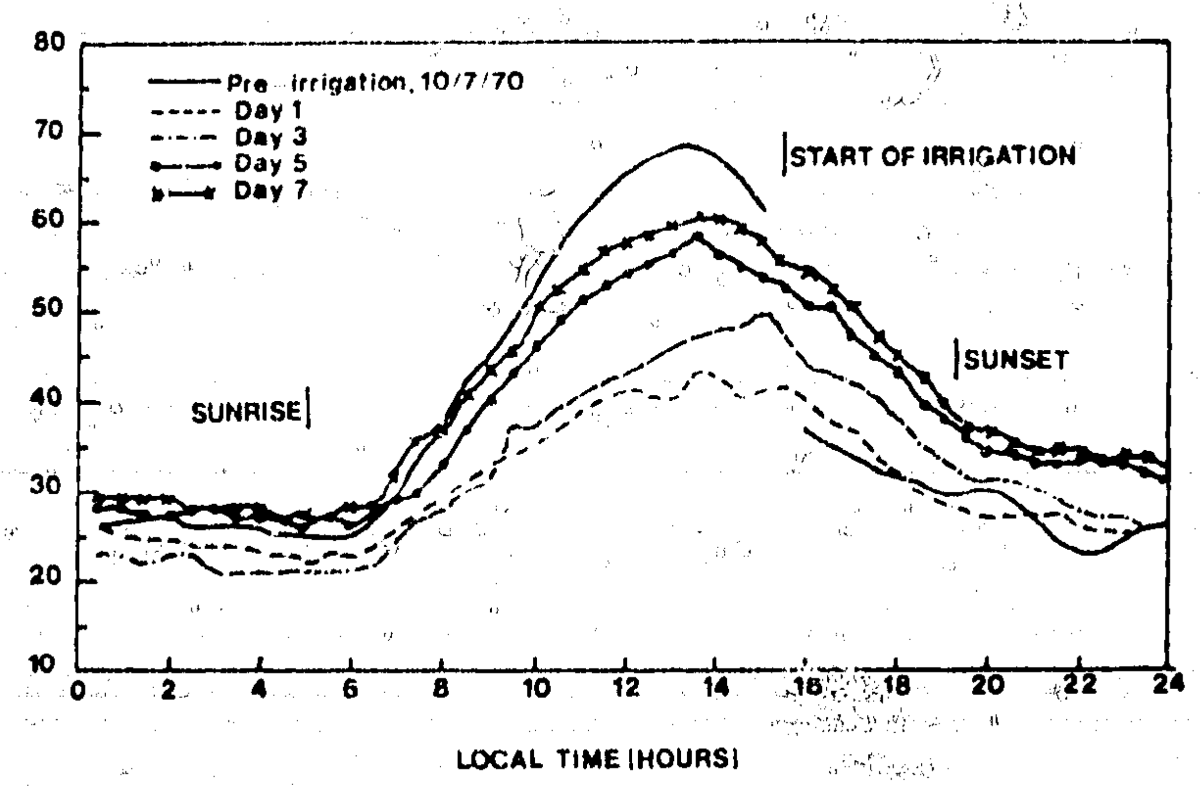


FIGURE 73 Diurnal surface temperature variation with changing soil moisture

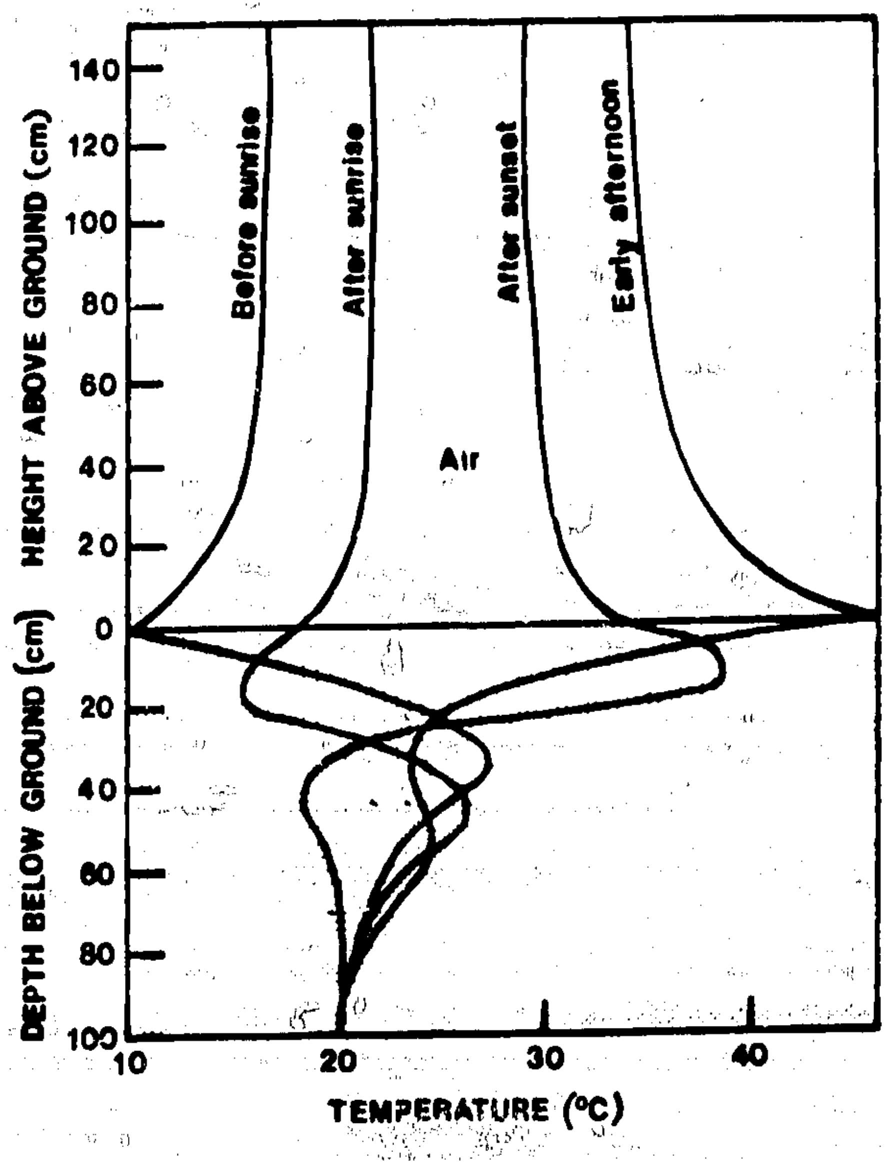


FIGURE 74 Diurnal temperature variations at the soil/atmosphere interface

Microwave sensing

Microwave measurements of soil moisture have two outstanding advantages over the other methods described so far, (i) little atmospheric attenuation is experienced, enabling measurements to be taken day or night in all weathers (ii) they have the potential to integrate sub-surface moisture values.

a) *Passive Microwave* systems (see p. 37) measure the natural radiation from a body, which is dependent on the body's emissivity and its temperature. The natural microwave emission from a soil target is very dependent on its surface roughness and on its bulk electrical properties. A change in soil moisture causes a change in a soil's dielectric constant (see Fig. 75) which is generally less than 5 for dry soil and about 80 for pure water. This results in an emissivity change from about 0.9 for dry soil to about 0.6 for wet soil (see Fig 71). Thus a change in water content of a soil target would be recorded as an apparent change in its temperature. The depth at which the bulk of the energy originates is determined by the sensor wavelength and the water content profile of the soil and may vary from several metres in dry sand when sensing at long wavelengths, to only a few centimetres in wet soil (see Fig 68). For example, the 21 cm wavelength S.194 passive radiometer on Skylab has been quoted as measuring radiation primarily from the top 2.5 cm when the soil was 'wet' and from the top 15 cm when 'dry'. Reference 253 is an extensive publication on the results of Skylab experiments which gives à full and clear account of the theories behind passive and active microwave sensing of soil moisture, especially from satellite altitudes. The results of their tests indicate that the S.194 radiometer was very sensitive to soil moisture content even under varying vegetation, atmospheric and soil conditions. The mean correlation of five passes over a test site was -0.96 which corresponded to a stated soil moisture measurement accuracy of ± 5%.

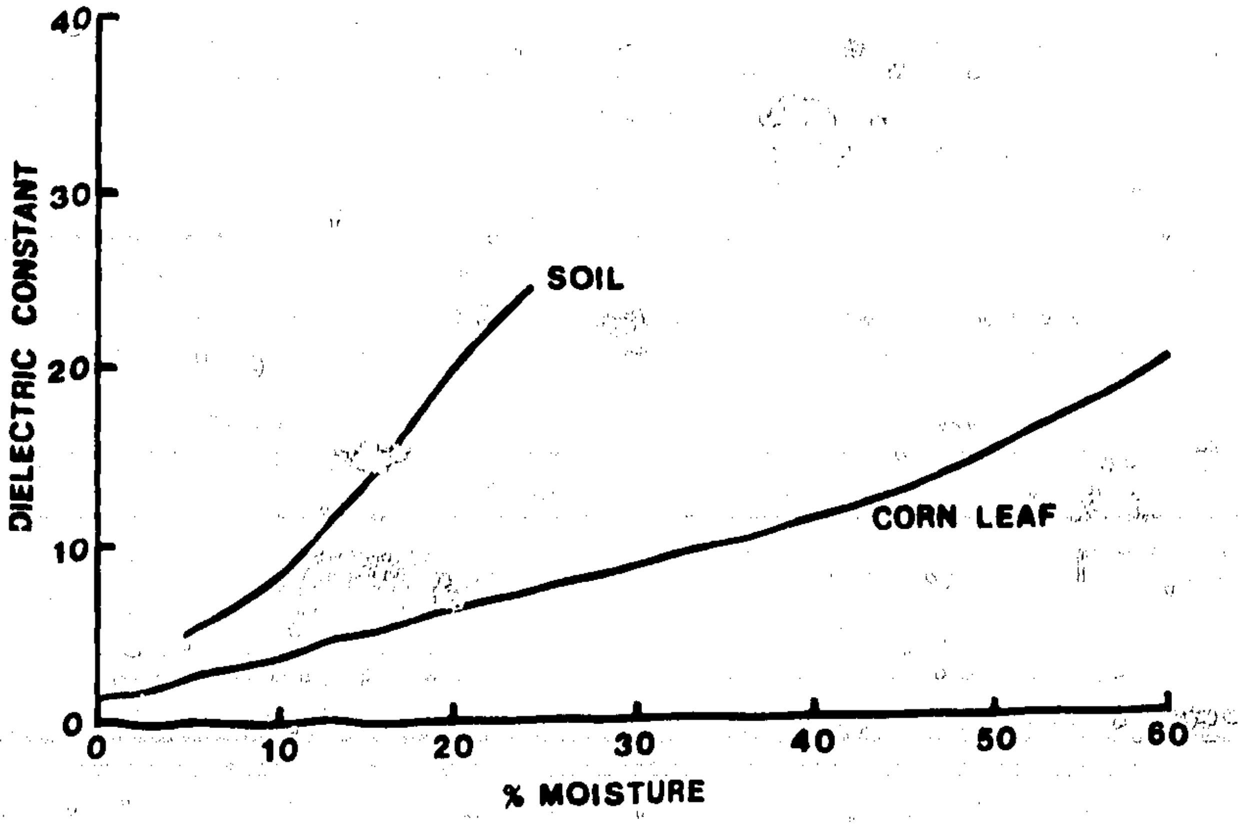


FIGURE 75 Dielectric constant of soil and corn leaf as a function of moisture content

In order to compare emission data more easily, from soils of different types, their soil moisture content is best expressed as a percentage of their field capacity. Low altitude tests by Schmugge (Ref 254) concluded that a 21 cm wavelength passive radiometer was responding generally to the top ½ cm of soil, whereas a 1.55 cm radiometer only responded to surface moisture. Also, the longer wavelength radiometer still responded linearly to soil moisture when there was a vegetation cover 15 - 20 cm high, whereas the 1.55 cm radiometer gave results which were independent of soil moisture and only responded to variations in vegetation emission. Longer wavelengths are also less affected by variations in surface roughness, although they will still react to variations of the same order of magnitude as their wavelengths. It was also found that by measuring both horizontally and vertically polarised signals from a soil surface, additional information on soil moisture variations could often be inferred and that the observed brightness temperature of the surface was highly dependent upon sensor viewing angle (see Fig 76). Passive microwave radiometry is somewhat restricted by the large physical dimensions of antennas which are required to achieve satisfactory resolutions, especially if imaging of the target is required (see microwave linescanners p. 46).

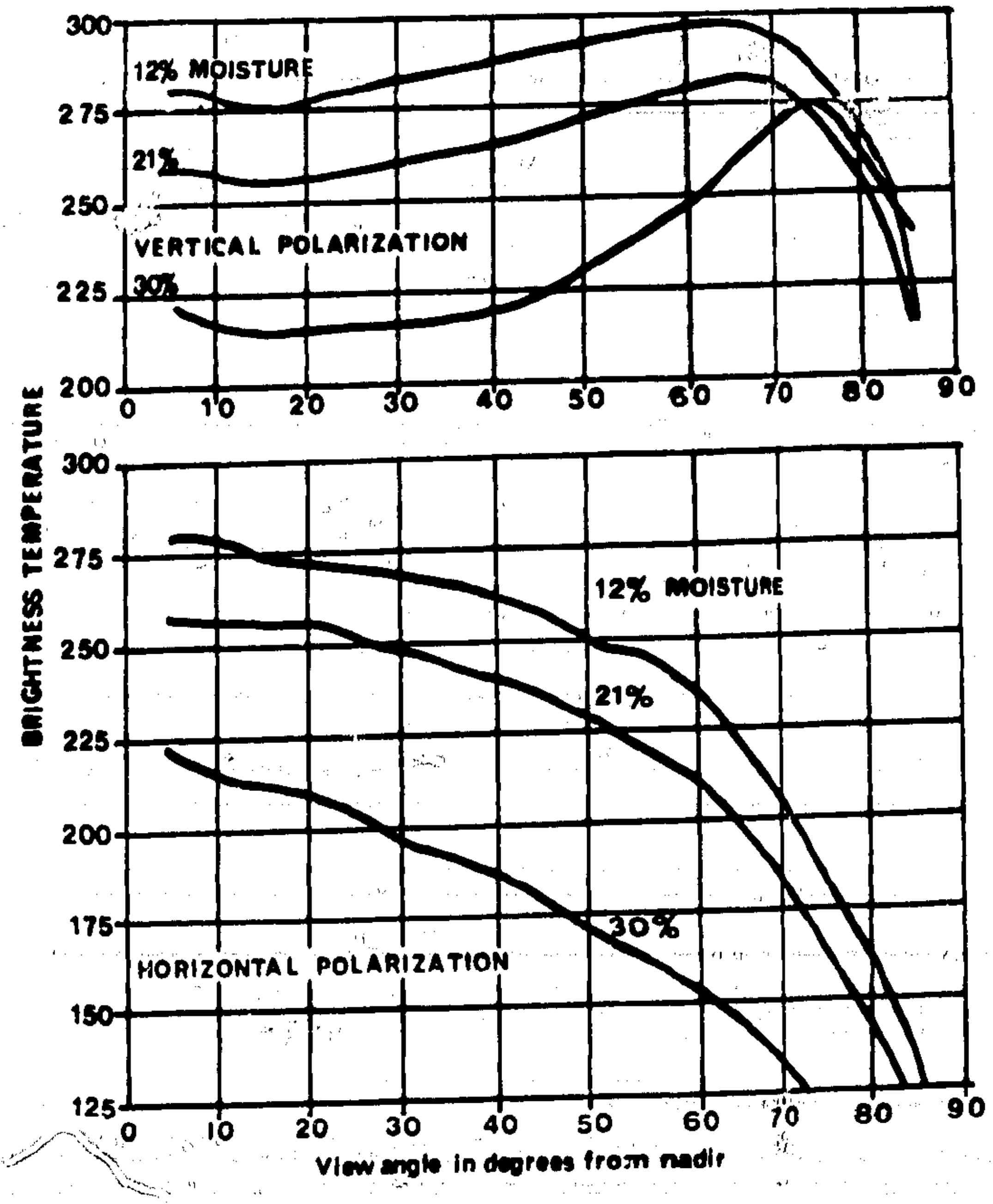


FIGURE 76 Brightness temperature of playa sediments as recorded by passive microwave radiometry (13.5 GHz)

b) *Active Microwave* systems are not so restricted because electrically scanning synthetic apertures can be used as described in Section 5.3 para. 6. With active microwave systems (radar), the backscattering of an emitted signal from a soil surface is dependent on the surface roughness of the soil and its moisture related dielectric properties (given that wavelength, polarisation and angle of incidence are constant). Depending on the wavelength chosen and the mean surface roughness, optimum look angles can be calculated for measuring soil moisture content, but generally the best relationships occur as nadir is approached (and therefore the apparent surface roughness effect is reduced, 5° - 10° off nadir being normal (Ref 219 p 121)). High spatial resolutions along the flight path are not a prerequisite for soil moisture estimation and with synthetic aperture radars, across-track resolution does not deteriorate with distance from target. Satellite based systems are therefore quite feasible assuming that sufficient power can be generated, and their all weather capability makes them especially desirable. The radar sensor on the SEASAT satellite achieved ground resolutions of 25 metres, but the data is unlikely now to be adequately evaluated for soil moisture estimation.

The collection of information on soil moisture profiles is in principle possible using a single wavelength radar, whilst the use of a focussed synthetic aperture system would allow theoretical ground resolutions of about 5 metres to be achieved from satellite altitudes. However, any sub-surface signal will be weak in comparison to the surface return so that the pulse duration must be made very short and the range resolution must be extremely precise in order to de-code the signal into the form of a soil profile (Ref 255). An alternative and probably a more desirable method would be to utilise a multi-frequency or continuous frequency system. Waite et al (Ref 256) describe a continuous frequency radar system which operates in the 4 - 26.5 GHz range, at various incident angles and with a horizontal and vertical polarisation facility. As approximately one half of the incident microwave energy is reflected from the soil surface, the remainder of the signal will be derived from different 'skin' depths according to the instrument frequency. By comparing these weaker signals, an estimate of soil moisture content throughout a shallow soil profile is possible. Moreover, by comparing the main surface brightness temperature signal for each wavelength, an estimate of surface roughness can be made. This was found to be very necessary because roughness changes can cause more brightness temperature variation than changes in soil moisture, and it was found that even at very long wavelengths the effect of surface roughness could not be ignored. (See Ref 106 pp 399-420 for detailed surface roughness experimental data).

Although the multifrequency approach appears to be the ultimate answer, suitable equipment is not yet readily available in the U.K. As an alternative approach, it should be possible to correlate radar signatures of the same surface type when at different moisture states. If a library of signatures is collected for different surface types it may be possible to obtain best fits by comparing known data with new data (Ref 255). [illegible] problem once again will be the highly variable effect of different vegetation cover types at different stages of development. Possibly a multifrequency approach will eventually be able to deal with such vegetation problems, but for the next few years at least, remote sensing measurements of soil moisture will be largely restricted to bare soil or short

vegetation situations such as pasture. In any event, considerable amounts of additional ground information will be required for both microwave and any other remote method of soil moisture estimation. Whilst many remote sensing techniques can be applied most easily to arid situations, the use of microwaves for soil moisture sensing may not always be the best method for desert situations. Microwave's good penetration of dry sands have some potential for the identification of near surface aquifers (Ref 257) but they are of little use in measuring differences in soil moisture below about 10% as no direct relationship exists with dielectric constant (Ref 258) which in desert situations may be also influenced by variations in soil salinity.

Radio waves

Radio wave theory of soil moisture measurement is similar to that of microwave theory in that soil dielectric constant varies with soil moisture value and it is this which affects the radio wave signals. As yet, it appears that only ground based experiments have been carried out using radio waves (Ref 259). By passing radio waves (170 MHz) between two ground based antennae, the measured strength of the received signal can be related to soil moisture values (see Fig 77). Vertically polarised waves are not affected greatly by the ground, whereas horizontally polarised waves are short circuited and induce a current flow through the earth which is dependent on its conductivity and hence on the soil moisture value of the ground lying between the antennae. Optimum antennae separation distance depends on the radio frequency used, but it must be large enough to eliminate direct induction effects from the transmitter, whilst at the same time retaining good field strengths over the prevailing soil types. Generally antennae separations of greater than eight wavelengths are used, whilst the height of the antennae above the ground was also found to be of importance. Numerous ground tests indicated that mean soil moisture could be measured between the antennae even when trees lay in the main path. Green vertical vegetation such as cereals attenuated the vertically polarised signal and caused spurious results, this being the major drawback of the technique which could only be overcome by calibration allowances made for

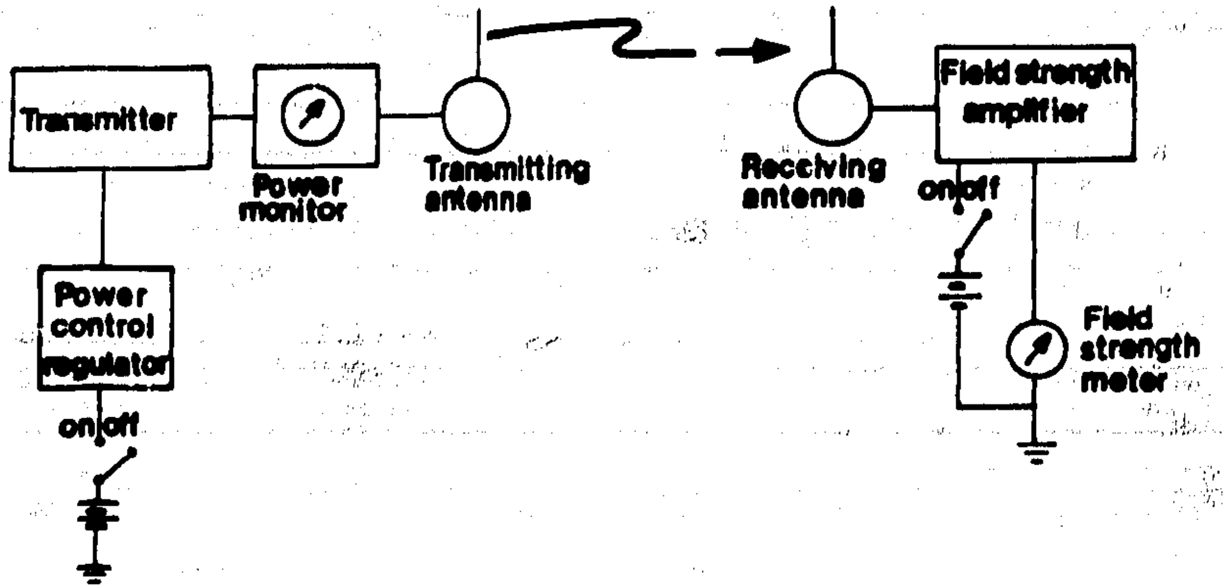


FIGURE 77 Instrument configuration for radio wave soil moisture measurement

each stage of vegetation growth. Where no dense vertical vegetation is present, calibration is necessary only at soil field capacity and at wilting point, the signal relationship being linear between these states. While the technique has great potential as a means of providing mean ground soil moisture verification values for calibrating aerially sensed data, the physical problems involved, make its use from moving aerial platforms unlikely. Any aerial methods would have to rely on data from a reflected ground signal, this being transmitted and received by the same antenna, as in active microwave systems. The advantage of this type of sensing at radio wavelengths is that soil moisture information from a deeper column of soil may be available (See Fig 78) and this possibility warrants further investigation of the technique.

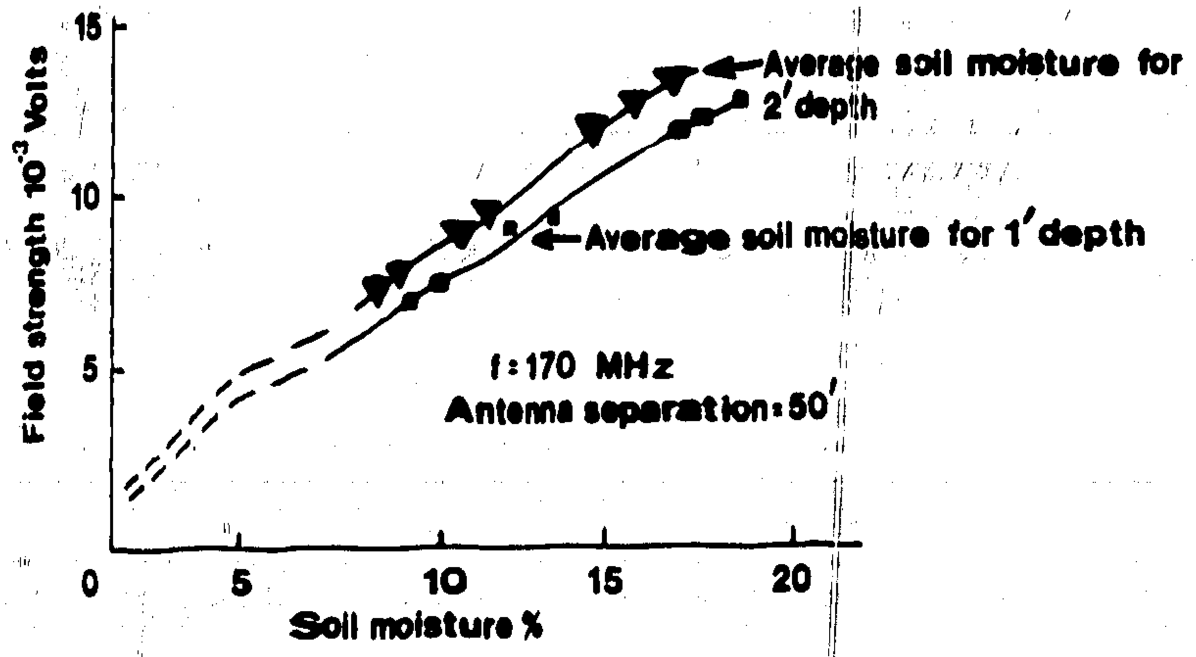


FIGURE 78 Relationship of radio field strength to mean soil moisture between antenna

Natural gamma radiation

This method of soil moisture estimation relies on the highly constant rate of natural gamma photons which is radiated from the Earth's surface at any given point. 75% of the gamma rays from the ground come from the top 10 cm of the soil and almost nothing is detected from below 40 cm due to the strong absorbance of the surface soil water. The limitations of this technique are therefore once again that only near surface soil moisture values can be estimated. As the level of radiation from this thin layer of surface soil is very weak, attenuation by atmospheric gases and water particles is so strong that sensors must be flown no higher than 100-200 metres. In order to be able to calculate soil moisture values, an area or flight path must be first overflown when at a known soil moisture state, in order to obtain a reference signature from which to work. Subsequent gamma measurements over the same area will be subject to greater or lesser amounts of attenuation as a result of variations in the amount of moisture in the top 10 cm or so of soil. As the half-life of gamma radiation is several thousand years, no change in source values will occur, but it is necessary to measure the atmospheric pressure and temperature at the time of overflights in order to calculate the density of the attenuating air column and also the pressure of atmospheric water (Ref 247).

The natural gamma technique has been used for some years in the USA for calculating snow water equivalent (see p.140) and during these programmes, tests conducted to estimate soil water content were encouraging and repeatable (Ref 260). Practical problems such as flying repeatedly at low altitudes over a given flight path became obvious, whilst the low altitude restriction meant only small areas could be covered at a time. Helicopters were well suited to this type of survey and in areas of high relief they would be invaluable. Considerable research is needed to verify the usefulness of this technique for soil moisture measurement as operational costs would be high, but accuracies of ± 5% of soil moisture volume would appear to be feasible (Ref 247).

7.9 Groundwater

As the presence of deep groundwater cannot be detected directly using present remote sensing techniques, indirect inferential methods must be adopted. Most of these methods rely either on the recognition of surface moisture or moisture anomalies and their related vegetational effects as being indicators of possible groundwater presence (Ref 243) or on the interpretation of geologic and topographic information (Ref 261). Many of the available remote sensing methods will have already been covered in previous sections of this chapter (see soil moisture, land use and water temperature sections) so these will not be dealt with separately here. When groundwater approaches the surface of the ground in quantities large enough to produce springs or when inputs into rivers or water bodies occur beneath surface water levels, these can often be detected by temperature sensing methods (Refs 262 & 263) which may allow the extent of the groundwater resource to be assessed. Because of the high level of soil moisture and vegetation cover in temperate climates, even long wavelength sensing techniques offer little hope of detecting groundwater deeper than a few centimetres below the soil surface. In very arid regions where surface lithology is dry and little vegetation is present, some possibilities do however exist, so these will be briefly covered for completeness.

Microwave sensing

The effect of soil state on passive and active microwave signals was discussed on p 118 - 121 where it was concluded that the soil penetration ability of microwaves was mainly dependent on the water content of the soil. Figure 69 shows the theoretical penetration capabilities of microwaves of different wavelengths into typical soil types and it can be seen that at metre wavelengths, penetration depths of 50 m or more could theoretically be achieved. This assumes that a homogeneous sandy soil is present to such a depth, but in practice the presence of rock layers, or traces of water lying in cracks and fissures would prevent further microwave penetration. More detailed explanations of microwave theory will be found in the ESRO Contractor Report series CR71-75 (Ref 208) and in the Active Microwave Workshop Report (Ref 106).

Electrical induction and radiowave methods

In the exploration for mineral deposits, sensors which are sensitive to radioactivity, (such as geiger counters and scintillometers) have been widely used, along with force field sensors such as magnetometers and gravimeters (Refs 16 & 264). It is quite possible that the presence of very large underground masses of water may produce effects which can be detected using this type of equipment, but this possibility will not be further explored here. One mineral exploration technique which does appear worthy of further explanation is known by the somewhat confusing term as 'electromagnetic' sensing. This method relies on either ground induction of electrical currents or radio interference effects similar to those described on p. 121 for the ground-based measurement of soil moisture.

With the induction method, a strong alternating current of frequency generally between 100 Hz to 4000 Hz is generated in a primary coil carried on board an aircraft. The AC magnetic field generated by this current induces eddy currents in the ground which in turn can generate a secondary magnetic field which can be detected by a secondary coil carried either in the aircraft, on the end of a drogue line behind the aircraft, or even in a second aircraft. The power and form of the e.m.f. generated in the pick up coil provides information on the conductivity of the ground below. Generally only ground discontinuities in a horizontal plane can be detected, so that extensive homogenous aquifers may not be recognisable, whereas rock fissure storage or vertical permeability changes may allow an aquifer to be recognised (Ref 265). For this type of operation, flying heights are usually kept below about 100 metres and because low air speeds are also preferrable, helicopters are often used.

Radiowave methods detect variations in radio signals (from distant ground based transmitters) caused by large changes in conductance of the ground, such as may be caused by large ore deposits or large vertically variable masses of waterbearing rocks. The detectors required for this are quite small and are generally carried at low altitudes in either helicopters or light aircraft. Neither of the above techniques have been extensively tested for applications towards groundwater prospecting, but a potential exists where high conductivity anomalies can be expected between the water bearing and surrounding rocks (Ref 265). In carbonate terrains especially, the association of ground water storage in deep fractures has enabled exploration through radar detection of surface linearments, (Ref 266).

Thermal inertia measurement

Large masses of near surface groundwater may act as 'heat sinks' due to their high thermal inertia, which may result in surface temperature differences with the surrounding land. Cartwright (Ref 267) claimed to have detected aquifers as much as 50 ft below ground level due to the surface temperature variations of up to 2°C above the groundwater area. The thermal inertia effect should be most apparent by comparing diurnal variations in surface temperature such as that available from the American "Explorer - A" satellite's infrared data, as land under the influence of a groundwater mass would be expected to have a low diurnal temperature variation (Ref 268). Such effects may be detectable in very arid regions, but in temperate climates variations in surface soil moisture, vegetation, air temperature, soil and geology would almost certainly overrule the use of such an exploration technique.

For temperate regions therefore, the most profitable methods of groundwater detection and delineation rely on interpretative methods of surface indicator features such as geological outcrops and fracture linearments, surface lithology, soil moisture and vegetation and occasionally groundwater discharge. Remote sensing methods can efficiently provide the necessary synoptic information.

7.10 Evaporation and evapotranspiration

Evaporation can broadly be regarded as the vaporisation of water from inorganic substances and from free water surfaces whereas evapotranspiration relates to the vaporisation of water from the surface of a plant and the transpiration of water within the body of a plant via its stomata. In both cases, for the vaporisation process to take place, there must be available:-

1) Heat, to bring about the water's physical change from liquid to vapour.

2) Unsaturated moving air to remove the vapour.

3) Liquid water at an air/water interface.

It is unlikely that remote sensing methods can be used to measure all three requirements to adequate accuracies to enable good estimates of evaporation to be made, but in combination with ground based point measurements, better evaporation estimates over large areas should be possible. In estimating evaporation and evapotranspiration rates, measurement of the albedo of a surface is important as it can be used to calculate approximate surface/atmosphere heat transfer values.

Measurement of albedo

Albedo is defined as, 'the ratio of incoming solar radiation of all wavelengths at a point, at any instant in time, to the emitted radiation from that point at the same instant in time'. Emitted radiation measurements should be corrected to account for radiation leaving that point at any angle i.e. within a hemisphere around the point (Ref 269) this being especially necessary when dealing with rough surface such as vegetation. The measurement of albedo or surface emittance is important as it is a measure of the amount of energy retained by a surface which may be available for heat exchange processes such as evaporation. As no single instrument exists for measuring all incoming and outgoing wavelengths, radiation in known wavebands is normally measured and total radiation is then calculated according to both the spectral emittances of the sun and of the ground material under the prevailing atmospheric conditions. It is normal to choose wavebands where radiation maxima occur in order to minimise errors, and for aerial studies, these maxima will fall in the atmospheric 'windows' of the visible and thermal infrared regions (see p. 18). Typically about three times as much energy is radiated from the Earth's surface in the thermal region than in the visible (Ref 132 p 1784). If radiation measurements are taken from an aerial platform, full allowance must be made for the effects of the atmosphere between the sensor and the ground surface in order that the ground level albedo value may be calculated. Otterman and Fraser (Ref 269) computed surface albedo values of arid surface types for the entire solar spectrum based on LANDSAT multispectral data, and their results were very close to those obtained from ground observations. Generally, in order to arrive at meaningful albedo values from multispectral data, either clear or average atmospheric conditions must be chosen if direct measurement of its attenuation is not possible, and sun azimuth and elevation must also be known. For comparative albedo studies, restrictive wavelength measurements may provide adequate information on their own or else simplified transformation factors may be used in order to estimate total albedo. However, when comparing different surface or vegetation types, the wavelength/emissivity spectra must be carefully studied (see Fig 33 for examples) before any attempt can be made to relate measurements of restricted wavelength to total albedo. For vegetation studies especially, illumination and viewing angles can greatly affect the apparent albedo (see Ref 120 pp 96-107). However, Khorram and Thomas (Ref 270) made estimates of net radiant flux from satellite visible albedo measurements and satellite thermal data of ground surface temperature and coupled these to ground measurements of daily sunshine values, incoming radiation intensities and empirically defined constants for given latitudes. Acceptable results were obtained for river catchment energy budget requirements.

Evaporation from open water

Water surface temperature, is one of the most important factors affecting open water evaporation rate, the primary sensor being the infrared radiometer which can if necessary measure temperature to a precision of ± 0.1°C (see p. 36). Spot radiometers allow surface temperature profiles to be made across water bodies, but if more information regarding areal variation of surface temperature is required, scanning radiometers can be employed. Corrections for the effects of atmospheric attenuation must of course be made and sensor operation would be restricted to cloud-free conditions. Sensing from satellites in the microwave region, would allow daily monitoring of water surface temperature, irrespective of cloud cover conditions and either passive or active microwave sensors could be used (see p. 37, p.48 and p. 52) both having advantages and disadvantages over infrared sensors. However, considerable additional input from conventional ground data would still be required before accurate estimates of evaporation could be achieved.

Under laboratory conditions, water temperature can be measured to similar accuracies using either infrared or microwave sensors, but in natural situations, microwaves are more sensitive to variations in water emissivity caused by changes in surface roughness or by the presence of foam, debris etc. Various opinions have been expressed as to the best ways of overcoming these problems and these are discussed in Ref 271. Ultimately it would appear however that microwave sensing, probably of the multifrequency or variable polarization variety could provide the most comprehensive water surface data from only a single sensor, albeit

for high cost. Estimates of surface roughness could thus be made directly, which is important, as increasing roughness means increasing surface area and hence increasing evaporation. Surface roughness can also be used indirectly to estimate wind velocity (Ref 106) as could the observation of cloud movement (Ref 219) or direct measurements could be made using doppler methods (Ref 219 pp 169-172). By using more than one wavelength, temperature measurements over different 'skin depths' (see p. 97) should be possible. This would enable the temperature gradient in the boundary layer to be calculated, assuming a calm water surface, and thus the heat transfer rates at the air/water interface (Ref 273) which directly affects evaporation rate. Air humidity at water level must be estimated from source meteorological data, but the future possibility of using spectrometer or microwave molecular absorption measuring techniques exists in theory (Ref 219 p 345), but has yet to be proved feasible on an operational basis. Whilst the above system is theoretically possible, the amount of data processing time required to adequately estimate evaporation would be excessive using present technology.

Estimates of annual evaporation over whole oceans such as the Baltic have been made using very sparse aerological information (Ref 274) but if remotely sensed information had been incorporated into these calculations, more meaningful results could have been expected. On a synoptic scale, the measurement of evaporation from reservoirs, rivers and irrigation canals would provide much needed information for water resource studies especially in hot climates.

Evaporation from soil surfaces

a) *Temperature.* Remote sensing methods of estimating evaporation rates from bare soil surfaces are somewhat similar to those described for open water bodies but the associated problems are considerably greater. Surface temperature measurement can be obtained as on p 126 but, of course, it must be remembered that ground surface temperature and the overlying air temperature are frequently very different. As the air temperature and humidity determine the rate at which evaporation can occur, either meteorological point observations of air temperature must be relied upon or else systems similar to the Raman Lidar air temperature profiler must be further developed (Ref 275).

b) *Surface moisture.* Measurement of the availability of water at the evaporating surface may be attempted using techniques described in section 7.8 on soil moisture measurement.

c) *Surface cover.* Except in very arid regions, only a proportion of the land surface will be bare soil at any given time, so remote sensing can admirably locate and provide area measurements of given surface types (see p. 77). This can be achieved through the use of simple aerial photography, multispectral photography or any type of imaging sensor, at an altitude determined largely by the required accuracy of measurements.

d) *Surface roughness.* The rate of evaporation is directly related to surface area, therefore surface roughness must be measured. The inclination and direction of slope of a surface may also be required if empirical estimates of surface heating are to be made (this however would not be as important if direct thermal sensing was to be used). Ground surface configuration can be provided by numerous optical and scanning methods as described on p. 72, but active microwave methods are probably best suited to slope and roughness calculation as they rely on their own reproducible oblique illumination source. With multispectral microwave systems, direct estimates of surface roughness can be made (Ref 219 pp 401-420) but failing this, ground verification measurements must be more heavily relied upon.

e) *Windspeed.* The estimation of wind speed over a land surface can sometimes be made by observing the disturbance of tall vegetation; this being similar to wave observations on water surfaces. Optical crosswind measurements have been successfully carried out using a pulsed laser light source to record variations in refractive index of the air and profiles of wind speed along the beam path have been calculated (Ref 272). A more advanced and potentially more useful technique relies on natural light reflected from a given surface. Interference patterns caused by different light intensities and angles of arrival are used as a measure of mean wind speed (Ref 272). Yet another method relies on the measurement of Doppler shift in the return signal of an 'acoustic' radar of single frequency, enabling mean wind velocities at up to 1 km distance to be estimated (Ref 276). The obvious disadvantage of these methods at the moment is that they cannot be easily used from a moving platform and so for the near future, the most reliable estimations of surface wind speed will probably result form extrapolation of ground based readings.

f) *Albedo.* It has been shown that the presence of even less than 10% vegetation on certain bare soil or rock surfaces can greatly reduce their surface emission and can alter their spectral signature beyond recognition (Ref 277). Naturally, such an effect is dependent on the properties of the soil or of the vegetation type; the greatest effect on albedo being when a highly emitting soil such as chalk is encroached by vegetation of low emittance. Green grass even in small quantities was found to prevent identification of underlying soil. Dead or dry vegetation was found to give a significant albedo change especially on dark soils, but the spectral signature masking was much less apparent than with green vegetation (Ref 277). Such possible vegetation effects must be fully accounted for when estimating evaporation from bare soil surfaces by the inclusion of ground-based observation.

Evapotranspiration

a) *Species identification.* Growing vegetation often has a very peaky and well defined spectral signature which enables major species to be recognized relatively easily using multispectral methods (see Fig. 33 and 54). Thus, factors which may affect evaporation rate and which are peculiar to certain species (such as vegetation height or roughness, interception characteristics etc.) can be fairly easily assigned from remotely sensed data. However, as the physical process of evaporation from vegetation is so complex, only very approximate evaporation estimates can be expected using only remote sensing techniques, their main application being for areal extension of ground measurements. Energy balance models have been developed which attempt to relate remotely sensed crop canopy temperature to evapotranspiration rates, but these have yet to be fully tested in field conditions (Ref 250 and 278). However some correlation tests do indicate that leaf temperature can vary by up to 5°C as a result of moisture stress, this being an approximate indicator of evapotranspiration rate (Ref 279). In poorly mapped areas, the recognition and area measurement of broad vegetation classes can go a long way towards improving evaporation estimates for water resources and land management purposes (Ref 120 pp 1480-1483) and a land-use survey should therefore precede any evapotranspiration study. Khorram and Thomas (Ref 270) used a three tier system to estimate catchment evaporation rates. Homogenous land use categories were recognised from LANDSAT images and each category was sampled using aerial photography, from which typical areas were chosen in which to install ground meteorological equipment. Results from these few ground stations were then extrapolated to cover the whole catchment.

b) *Temperature.* The measurement of canopy surface temperature will approximate very closely to the canopy air temperature for tall vegetation such as trees but may be very different to surface air temperature for short vegetation such as grass under strong heating or cooling conditions (Ref 280). Incoming radiation from the sun is either reflected from the vegetation surface or is absorbed by the plant, part of this being emitted as thermal radiation. The difference between the incoming and outgoing radiation is the thermal input to the plant system for both photosynthesis and evapotranspiration purposes and aerial sensors are most suitable for carrying out this type of measurement over large areas, provided that atmospheric effects can be accounted for. Pease and Nichols (Ref 281) produced energy balance maps from multispectral imagery by choosing bands in both the visible and thermal wavelengths to allow measurement of surface albedo, energy absorption and net radiation. Measures of the surface area of vegetation can aid the calculation of evaporation rates and some measure of this may be possible by recording of the near infrared signal from a plant canopy. Laboratory tests have shown that near infrared reflection increases with leaf density (Ref 245) whilst other physical factors such as species, height and girth could be obtained using low level photogrammetric techniques (Ref 282).

In summary, many theoretical techniques exist for the calculation of evaporation and evapotranspiration using remote sensing methods (Ref 132 pp 1480 and 1784-1789). Similarly much laboratory experimentation relates controlled physiological changes of vegetation to measured canopy radiation values, the LARS Purdue work being one of the most advanced in this field (Ref 283). Before field measurements are applied however, the exact physical processes of evaporation involved for a particular vegetation type, location and climate must be fully understood otherwise remotely sensed information could be highly misleading and even completely useless. Unless complete knowledge of these processes exists and suitable ground equipment is available for monitoring these relationships, the occasional user is advised to use remotely sensed information only for qualitative or empirical comparisons of gross evaporation variations. For example, maximum evaporation over forests occurs when the canopy is wet after precipitation (Ref 284). This is typically three times that resulting from normal transpiration under similar conditions, therefore a remote sensing system which could detect this would be of real value, whereas complex modelling of heat budget processes is unlikely to be cost advantageous for large scale operational requirements.

7.11 Precipitation

Remote sensing methods of estimating precipitation can be classified into three major groups. (1) Those methods which measure rain as it is falling, (2) rainfall prediction methods based on cloud information and (3) post rainfall estimates based on resultant ground conditions. The factor common to all of these methods is that they are all highly reliant on conventional ground measurements of rainfall for calibration purposes / the better the ground information, the more accurate can be the remotely sensed rainfall estimate.

Measurement of falling rain

(a) *Ground Based Techniques.* Quantitative measurements of falling rain are possible using radar techniques either by measuring the attenuation of radar signal after its passage through falling rain, or by measuring the intensity of the radar echo received from the rainfall. These techniques are possible because the radar signal is virtually unaffected by the atmosphere except for relatively large water particles or ice crystals, (the latter causing the greatest attenuation) (Ref 285). Because atmospheric penetration increases with increasing wavelengths, only short wavelength radars (< 1.5 cm) can be used for rainfall attenuation measurements. This limits the distance over which measurements can be made to about 30 km (Ref 286 p 271). Radar pulses are generally emitted horizontally from a central transmitter/receiver and the signal is returned to the same antenna from large fixed reflectors situated around the perimeter of the area of interest. Although this method can provide accurate rainfall estimates, its application is limited by topographic constraints, and normally the reflective method is favoured.

The ground based radar reflective method has been used for many years for local, regional and river cathment estimation of falling rain, especially in the USA where a National Radar Weather Service has been expanding and which will eventually give country-wide coverage (Ref 287). In the UK, the Dee Weather Radar Project was in operation for several years. A single 10 cm wavelength narrow beam (2°) radar was situated near the centre of the River Dee catchment and was capable of providing rainfall information for the whole catchment area. A network of about 60 ground level recording raingauges was used to retrospectively calibrate the radar information and later a number of telemetering raingauges were used for real time rainfall estimation (Ref 288). With the addition of telemetered river levels, forecasts of river flows and reservoir levels were possible.

With the reflective method, the strength of the returning microwave signal is proportional to the range of the rainfall target, to the intensity of the precipitation and to the proportion of the beam width which is filled by a uniform mass of falling rain. Some simple relationships are given by Grinsted (Ref 286 p 267-285) to account for these variations. As the last of the above controls is difficult to assess, the beam width is generally kept as narrow as possible to ensure that as large a proportion of the beam as possible is filled. If the beam is not filled but is assumed to be so, an underestimation of rainfall intensity will result. The siting of the radar antenna is most important as an unobstructed field of view of the area of interest is required. This is often difficult to achieve as the angle of inclination of the radar beam is generally kept as near to the horizontal as possible. This is necessary in order to avoid vertical spread of the top of the beam at maximum range into cloud layers which may possess highly reflective ice crystals. Even if only a small proportion of the beam was reflected off ice particles, gross overestimation of rainfall intensity could result. Also, by measuring rainfall at as low an altitude as possible, there is a greater chance of rainfall drop size being more uniform and therefore a better estimate of rainfall intensity can be made. Also at low altitudes less horizontal drift of falling rain will occur between the point of measurement and its point of contact with the ground. The presence of high ground within the beam path can be partially compensated for by establishing a dry weather wet ground signal for the surrounding area and subtracting this from the signal measured during rainfall. The measurement of rainfall intensity distribution is made possible by transmitting a pulsed signal (typically several hundred pulses per second) as the antenna is scanning across its azimuth. Thus return signals can be attributed to specific blocks of space and mean rainfall intensities can be assigned to each block after calibration against raingauge measurements. To facilitate real time rainfall estimation, telemetering raingauges must be used and considerable thought must be given to the selection of sites and raingauge network densities necessary for the adequate sampling of rainfall distribution (see Ref 289). In the Dee Weather Radar Project, radar derived rainfall has been shown to correspond to raingauge derived volumes to within 20% for hourly periods over small areas, but over longer periods or larger areas, discrepancies are reduced.

As the cost of installing a single radar station may be of the order of £0.5 million and running costs may be £50,000 per annum (Ref 288) their use is generally only justifiable for large basins where real-time data is required. Countrywide interrelating systems appear feasible when real time monitoring of major storm systems can be undertaken for river management and flood forecasting purposes. The US National Weather Service radar network provides mean rainfall estimates for each 50 mile square block of the USA. As a result of the low resolution, only a fairly crude index of rainfall intensity can be allocated, but when linked to duration of rainfall measurements, the system has been capable of pinpointing danger areas or those lying within the path of a major storm. As a result of storm monitoring over the past 18 years, the conclusions are that rainfall totals should be made at fairly short intervals (2-6 hours) to be of any assistance in forecasting areas of potential flash flooding (Ref 287). It is expected that greater use can be made of the US National system as it is gradually updated to provide computer processed, real time information as, in the past, flooding has often occurred before the danger area has been successfully pinpointed by the radar. NOAA have developed an automatic technique known as D/RADEX for searching data obtained from several radars and this should improve rainfall forecasting as it becomes more widely available (Ref 290).

As radar systems can only give indications of rainfall intensity in the sense that for accurate measurements, conventional raingauges are still continuously required for real time calibration purposes, it is likely that a national network of telemetering raingauges could provide cheaper and comparable information for a relatively small country such as UK. With the prospect of future cheap satellite telemetering systems relaying information from ground based instruments to central data processing centres (Ref 291), the feasibility of rainfall monitoring by radar must be carefully considered on a cost/benefit basis. However, simple low cost radars are capable of providing advanced warning of approaching rainstorms which can be put to good use in hydrological catchment and process studies (Ref 292) and may be especially useful where satellite ground truth measurements must be linked to given synoptic weather states.

For local process studies covering only a few square kilometres, detailed information on storm movement may be required, eg for modelling of urban storm runoff. For such local requirements lidar attenuation (see p. 57) can be used for rainfall intensity estimation in a similar manner to radar. The return signal from a coherent light source after being scattered by rain clouds is used as a measure of rainfall intensity (Ref 132 p 1635) and instrument costs are likely to be considerably lower than with radar.

(b) *Satellite Based Techniques.* For the direct estimation of rainfall from satellites, only microwave techniques need be considered. Passive microwave systems measure the emitted radiation from a column of falling rain and are capable of providing mean estimates over longish periods, whereas active sensors have the potential for more specific short term measurements. The first use of passive microwave sensors for satellite monitoring of precipitating clouds was carried out from the NIMBUS 5 satellite in 1972. The results obtained from its electrically scanning microwave radiometer (ESMR) and microwave spectrometer (NEMS) indicate that "over the oceans (usi[illegible] the total precipitable water in a column of atmosphere can be est[illegible] within ± 10%, the liquid water content of clouds can be estimated to within ± 25% (using ESMR) and areas of precipitation can be delineated and broad estimates of the precipitation rate (within a factor of 2) obtained" (Ref 293). The NIMBUS F scanning microwave spectrometer (SCAMS) and ESMR can provide similar information to NIMBUS 5, but the wavelengths chosen allow for the first time, cloud liquid-water content to be also measured over land.

Very frequent observations are necessary for adequate rainfall forecasting and tracking of rainstorms from satellite altitudes. They can be achieved either by using a series of orbiting satellites or by using a single geo-stationary satellite. Observations made from single orbiting satellites will give indications of rainfall distribution at a given time but are of little use for forecasting over short time periods. The technology of an optimum radar system for satellite observation of rainfall is highly complex and is considered fully in Ref 106, pp 287-335.

A dual or multi-frequency radar will be capable of observing lower precipitation rates because the effect of ground echo or clutter can be more easily identified and removed. Also, because the path length through the precipitation will be shorter than that experienced by ground based radars, shorter microwave wavelengths can be considered thus allowing a greater choice of sensor configuration. The major advantage of active over passive microwave techniques, from a meteorological point of view, is that active systems would have a vertical rainfall distribution capability enabling 3-dimensional models or precipitation within active cloud systems to be developed. From the hydrological point of view, the ability of active sensors to measure the height of the 'bright band' where ice particles melt to form raindrops, gives an additional indication of likely rainfall intensity.

The use of radar from geo-stationary altitudes poses severe technical problems which will probably necessitate the use of even shorter wavelengths (about 3 mm) centred on an atmospheric window to minimise attenuation. The major problem at the moment with geostationary systems is the loss of height resolution away from nadir which may limit useful height observations to near equatorial regions.

Future improvements in sensor capability will inevitably lead to better satellite based rainfall estimates. But, if all the available advanced techniques were applied (pulsed, multi-frequency, dual polarised, Doppler instrumentation), the volume of data which would have to be analysed to yield rainfall estimates would be vast, so that the ultimate hurdles are likely to be in the financing of such operational systems. Although it may be some time before regional satellite forcasts of rainfall will be available, it should shortly be feasible to estimate global rainfall values on say a 1 degree grid basis. Although the absolute values may not be highly accurate, the observed rainfall frequencies should help to provide an improved picture of world rainfall distribution. Immediate questions which could be tackled using present satellite capabilities could be for example (1) what are the fluxes of water vapour into and out of large drainage basins, large lakes or whole continents and how do these fluxes vary with time? (2) What are the evaporation and transpiration losses along major river systems in arid regions? (3) Can the frequency, intensity and distribution of infrequent storms, floods, and groundwater recharge in arid regions be quantified through synoptic detection of water vapour transport, precipitation and/or surface soil moisture changes?

Many of the direct satellite methods of rainfall estimation have not been particularly successful as great reliance is placed on the accuracy of sensors which therefore require extensive calibration checks. When absolute measurements cannot be fully relied upon, statistical analysis of cloud characteristics can provide useful rainfall estimates even from low resolution satellite imagery.

Rainfall prediction from cloud characteristics

It is possible to distinguish precipitating clouds from non-precipitating clouds at satellite altitudes by their lower cloud top temperature and subsequently their higher brightness value in visible wavelengths. In general, the colder and brighter the cloud top, the greater is the probability of it producing precipitation (Ref 132 p 1652-1658). A large proportion of existing and planned satellites can provide data suitable for this type of analysis on a global scale. For studies of particular countries, for example, high resolution, low frequency orbital data can often be combined with low resolution, high frequency data (such as provided by geo-stationary satellites) in order to provide short or long term rainfall estimates. Such techniques observe cloud types and assign weights to each type so as to predict rainfall likelihoods, depending on the synoptic conditions at the time. Attempts using ESSA 7 and 9 visible satellite imagery (Ref 294) were made to determine the number of cloud pattern types which must be recognised to estimate monthly and weekly precipitation amounts over a 90 miles square instrumented catchment. Using sample data it was found that the classification of 9 cloud categories allowed better rainfall estimates to be made than by measuring cloud top brightness. Estimates of mean rainfall were made for 15 day periods during sporadic autumn rain and for 7 day periods during more settled spring rainfall. More recently Barrett (Ref 286 pp 243-266) has devised rainfall prediction models for tropical Far East and UK synoptic situations. Table 6 shows how five cloud types were weighted according to their likely indication of rainfall. A simple equation based on cloud information and standard meteorological data allowed monthly rainfall to be estimated. By comparing these estimates with recorded monthly rainfall totals, a regression equation can be constructed for specific synoptic conditions. With this information, complete monthly rainfall forecasts can be made from satellite derived cloud analyses or, with the aid of further calibration from raingauge data, isohyets can be more accurately drawn in data sparce regions. Results using this type of technique are largely dependent on the reproducibility of rainfall from a given weather condition and for this reason, considerable meteorological knowledge and skill in applying the satellite information is a prerequisite of this form of forecasting.

TABLE 6 RAINFALL PROBABILITIES AND INTENSITIES RELATED TO DOMINANT CLOUD-TYPE CATEGORIES FOR THE TROPICAL FAR EAST

Cloud type category	Relative probability of rainfall	Relative intensity of rainfall	Rainfall indicator compounded from columns 2 and 3	Rainfall indicator in area of 'synoptically significant' cloudiness
Cumulonimbus	0.90	0.80	0.72	2.88
Stratiform	0.50	0.50	0.25	1.00
Cumuliform	0.10	0.20	0.02	-
Stratocumuliform	0.10	0.01	0.001	-
Cirriform	0.10	0.01	0.001	-
Clear skies	-	-	-	-

Barrett made daily estimates of rainfall for tropical latitudes by considering the 3 cloud types which were felt to be the chief rain producers - cumulonimbus, nimbostratus and cumulus congestus and these were assigned empirical rainfall coefficients of 0.72, 0.25 and 0.02 respectively. Satellite images were then analysed to determine the exact percentage of each cloud family across selected areas. As may be expected, the results were very dependent upon the individual characteristics of the areas, but initial indications appear to be encouraging (see Fig 79).

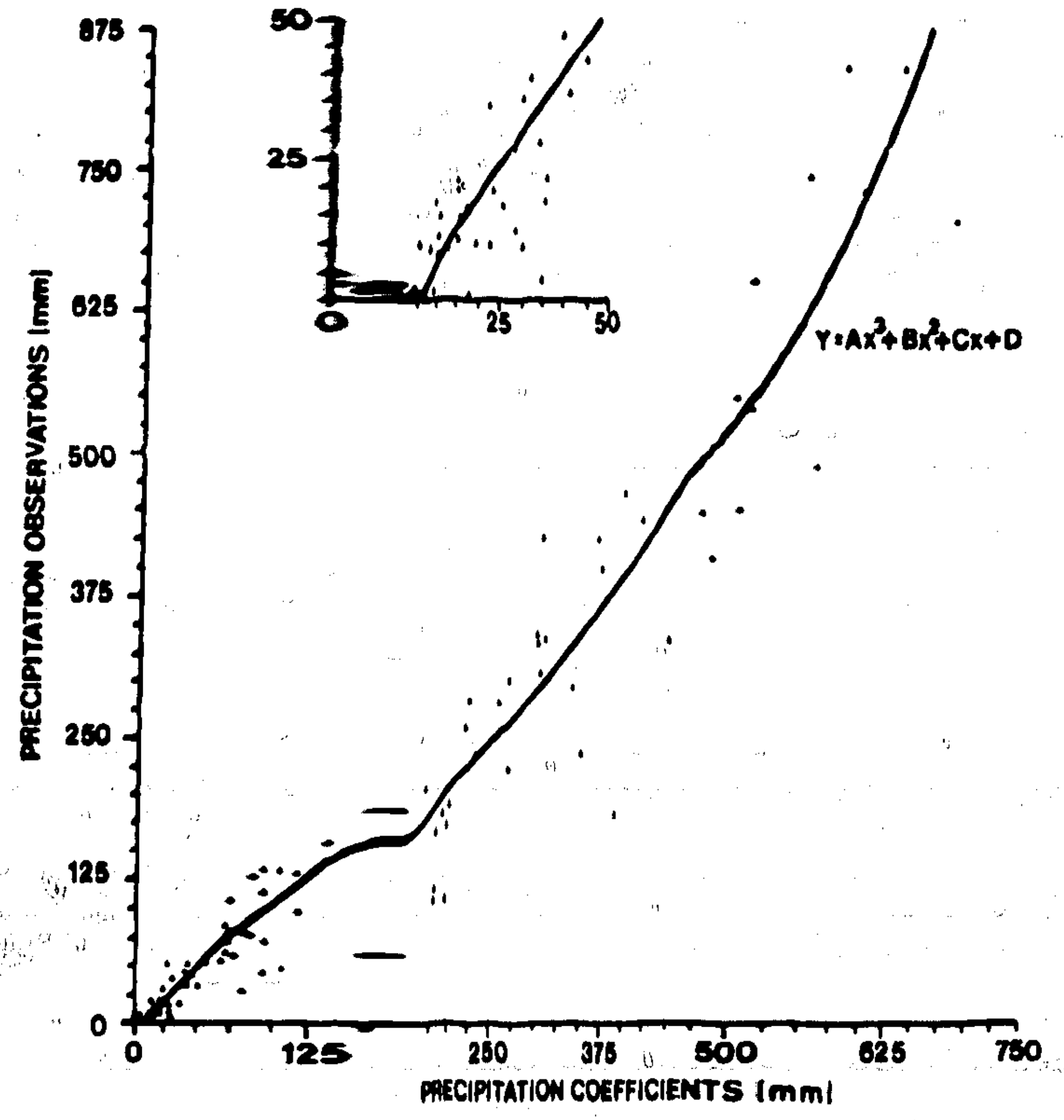


FIGURE 79 Regression analysis of estimated and recorded monthly precipitation at 29 stations in the tropical Far East, March-June 1966

A method for mid-latitudes was produced where relatively slow moving cloud systems producing advectional rain could be expected. For a daily rainfall estimate at Valentia, cloud types were studied upwind of the station to a distance within a quadrant related to the speed of movement of the approaching weather within the forecast period (1 day in this case). A rainfall prediction index was formed as the product of a synoptic weather index (which is an assessment of rainfall probability); a cloud cover index (assessing rainfall continuity) and a rainfall intensity index related to the present type of clouds. After classifying rainfall intensities into four groups namely: heavy, moderate, light and no rain, after

6 months of daily predictions, the overall ratio of right:wrong forecasts was 74.3% when comparing the satellite derived classification to ground rainfall measurements.

In conclusion, this type of statistical approach does not require careful control over sensor parameters and can be achieved without data handling by computer, so that operational costs are likely to be considerably lower than 'direct' satellite measurement techniques. At present its great hydrological potential lies in the extrapolation of rainfall measurements at a relatively simple level for data sparse regions. With the possible future use of automatic cloud classification techniques (Ref 295), fully computerised rainfall forecasting systems using real time geo-stationary satellite data can be envisaged at not unreasonable costs. Initially, cloud types may be classified using brightness and texture information, but later, more detailed information on cloud structure (temperature and liquid water profiles) are likely to be incorporated by the use of multifrequency microwave techniques to achieve better classification. The main problem with single imaging sensors is the considerable difficulty experienced in separating cloud information from snow lying on the ground beneath. Methods of overcoming this are described later on page 145.

Rainfall estimation from ground effects

Any estimate of rainfall made from resulting ground effects will be qualitative as, at best, such techniques will only give an indication that rainfall has recently occurred. The concept around which most of these methods are based is that most surfaces exhibit a different spectral signature when wet, compared to their normal dry signature. The most easily recognisable effect is on bare soil, where a fall in reflectance occurs in most of the spectrum from visible to microwave due to surface wetting (see p 114, Figures 69 and 70 and Refs. 296 and 120 p 93-95). Similarly, surface wetting of vegetation normally results in a lowering of reflectance, especially in the near infrared wavelengths (see Figure 80). Considerable laboratory and field research on such effects have been carried out at Purdue University in their Laboratory for Application of Remote Sensing (LARS) and numerous information notes have been produced with reference to multispectral reflectance characteristics of soils and vegetation (eg. Ref 297). Unfortunately, surface wetting is not the only factor which induces changes in surface reflection as, for example, changes in soil or vegetation types, variations in surface roughness, light shadowing effects, sub-surface effects etc. can all produce areal reductions in reflection of soil or vegetation surfaces. Because of these interfering factors, it is very difficult to relate reflection changes solely to surface moisture changes, so that any inference to rainfall must be purely qualitative.

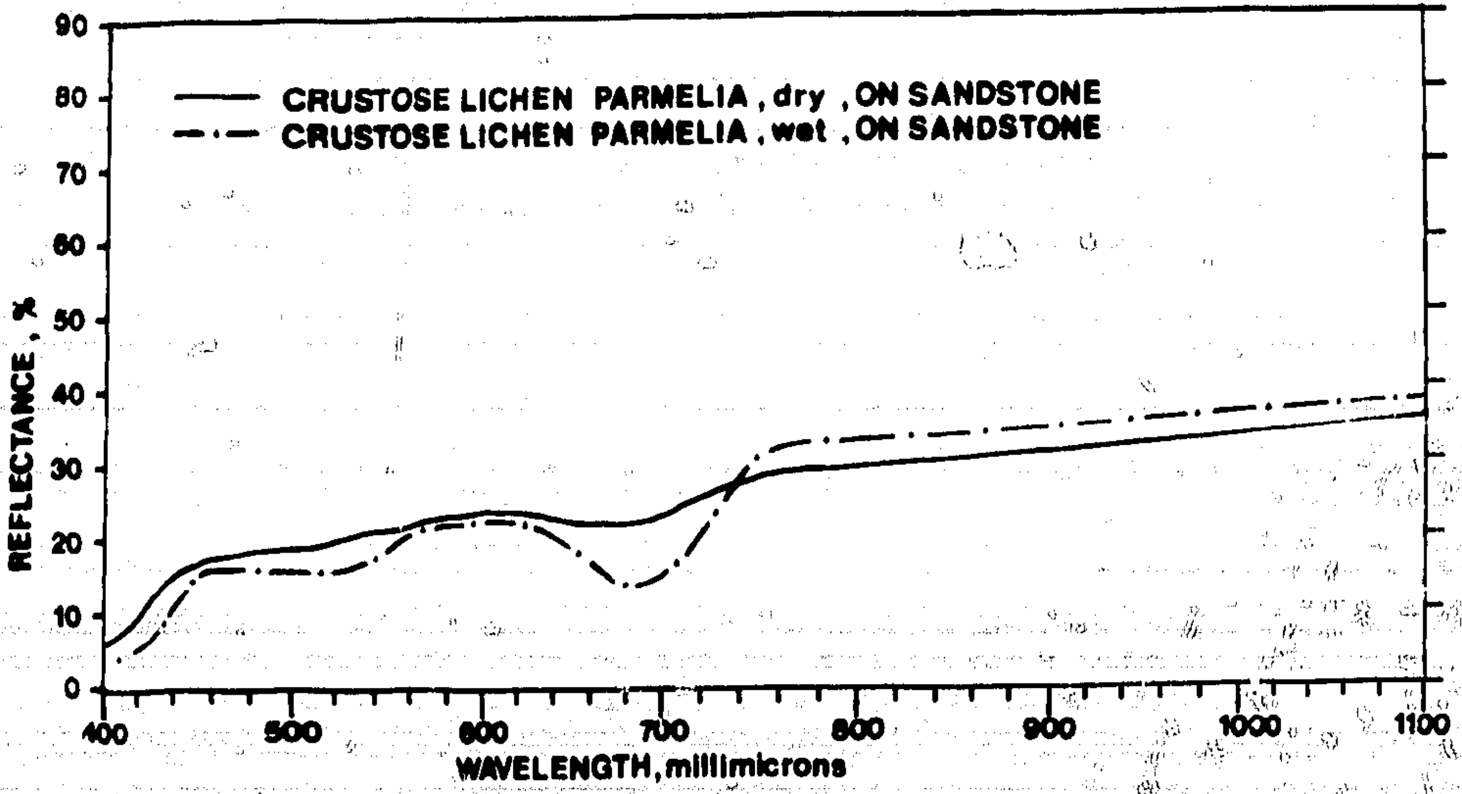


FIGURE 80 Change in vegetation reflectance as a result of surface wetting

The effects of surface wetting due to rainstorms is most apparent in arid regions where background reflectances are normally high. The area affected by local storms could be adequately recorded from high altitude aircraft using basic photographic techniques. In North Africa, LANDSAT imagery has been used to locate areas of recent rainfall in order to pinpoint possible locust breeding sites (Ref 298). If the satellite coverage is not achieved early enough to detect the 'damp' darker areas, the wetted ground is often still apparent for several weeks as a result of vegetation flushes. Thus, in areas of such sparse rainfall, basic indications of its presence may be adequate. From a water resources viewpoint, the detection of recently active wadi storm drainage routes from satellite altitudes can be of great use for determining areas of possible groundwater recharge (Ref 146).

Poe *et al* (Ref 299) describe the effects of recent rainfall on the brightness temperature of sparsely vegetated soil in Arizona, as recorded by a passive, dual polarised microwave radiometer operating in the 2.2 cm - 6.0 cm wavelength region. Although detailed correlations between ground based and airborne observations were not possible, significant changes in microwave brightness temperatures were observed along a flight test path before and after precipitation. Merritt and Hall (Ref 300) describe NIMBUS-3 near infrared observations of the Mississippi valley and attempt to relate reflectance values to the average rainfall in the 24 hours prior to satellite observations. Useful relationships were found in periods of uniform stratiform-type precipitation, but random cumuliform convective rainfall was too scattered to relate to ground observations or satellite data.

In areas having reasonable ground-based rainfall observations, post rainfall aerial observations are generally not considered as they are unlikely to yield any additional information. In temperate regions such methods could yield easily observable results in dry summer months, and likely applications would probably be restricted to the observation of individual storm events where local rainfall distribution is of interest. If such areal observations are essential in poorly suited regions (ie non-arid) then a multispectral approach should yield the best information eg. a combined near infrared and thermal infrared observation.

In conclusion, rainfall estimation using remote sensing techniques is invariably more successful in regions having simple weather systems, with convective rainstorm cells being probably the most predictable in behaviour. Generally, remote sensing methods tend to be more easily applied to arid environments, whilst for temperate regions, improved telemetering raingauge systems are likely to be more reliable than aerial observations.

7.12 Snow and ice

As the majority of the world literature on remote sensing originates from the USA, and as the measurement of snow as hydrological precipitation input is of major importance over much of the North American continent, it is not surprising that a vast amount of literature exists on the use of remote sensing methods to aid snow measurement programmes. The methods reported and the conclusions given in much of the available literature are closely linked to the physical conditions experienced in these areas and therefore it cannot be assumed that such methods will be necessarily successful under European conditions. It is nevertheless possible to gauge the adaptability of many of the techniques developed in areas of high annual snowfall with related studies based largely in Scandinavia and the Alps. It is inevitable however, that when dealing with shallow snow depths and small areas which are typical of the U.K., some of the techniques described here would cease to function on a cost effective basis. Also because the measurement of ice is of minor importance in U.K. this will not be dealt with in great detail.

Ground based methods

a) *Snow extent.* Few remote sensing methods can be adequately used from the ground for monitoring snow extent due to their restricted field of view. Photography can be useful especially in highland regions where overviews can be achieved to record the initial onset of lying snow and more importantly, snow ablation patterns and perennial snow patches. Ödegaard and Skorve (Ref 301) used ground based and low level aerial photography to assess the percentage of snow cover below the snow line as a check on satellite interpreted snow extent. For small scale process studies, time lapse photography can provide useful information on snow accretion and drifting patterns. Tennyson et al (Ref 302) successfully used time lapse photography to model snow interception on a stand of Ponderosa Pine trees. Such measurements are purely empirical, but accurate measurements can be made if necessary using photogrammetric techniques described here.

b) *Snow depth.* Ground based photogrammetry enables very accurate measurements of the area of snow patches to be made, but its main advantage lies in its three dimensional measurement capability which is made possible by stereoscopic recording of an object's shape in reference to a number of fixed points of known location. The principle is identical to the production of topographic maps from stereo-paired aerial photographs. Blyth et al (Ref 303) described a ground-based photogrammetric method for measuring snow depth on a steep hill-slope in mid-Wales (See Figure 81). Permanent camera plinths and ground control markers were concreted firmly in place so that their relative position remained unchanged throughout the whole winter period. A grid of ground surface heights were measured in the summer and snow surface heights were measured at the same grid points in winter, the snow depth at each point being calculated by subtraction. When compared to an intensive hand sampling check of snow depth, the photogrammetric method gave a mean depth to within 10% of the hand calibrated mean over the 3 hectare site. The photogrammetric method allows repeated depth measurement without disturbance of the snow surface and requires considerably less survey time in the field. Depth estimates can thus be made on inaccessible or dangerous slopes, the techniques also being ideally suited for glacier surveying. The main drawback is that the photographic quality and hence the survey accuracy is very dependent on good visibility, so that in areas of known persistent bad weather, a back up system of snow course sampling is advisable.

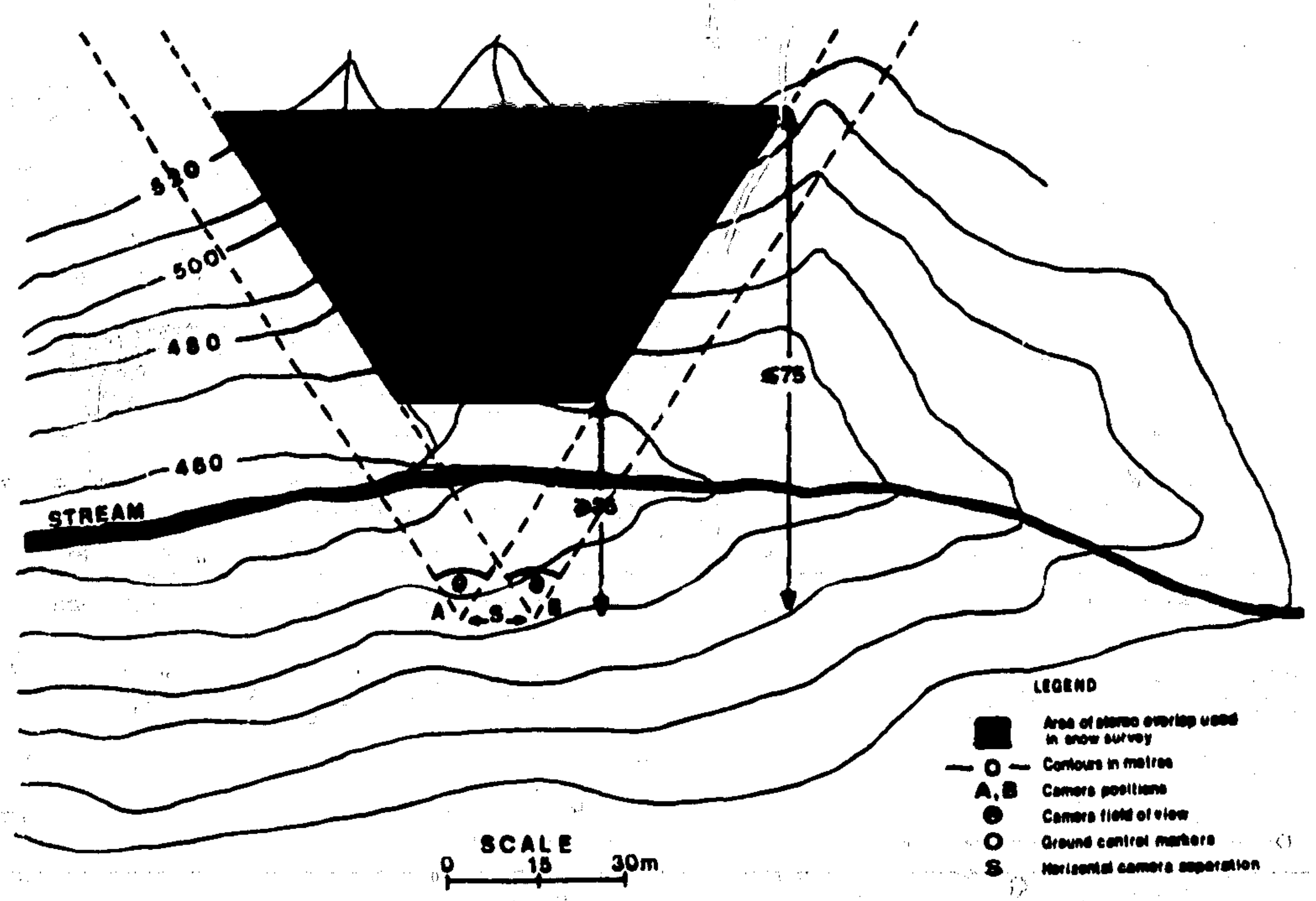


FIGURE 81 Plan of typical snow depth measuring site using photogrammetry

Another indirect method of estimating mean snow depth over small plots is by the time lapse photographic observation of snow stakes which are set into the ground at different heights. From a distance, the approximate snow depth can be determined by counting the number of stakes not yet covered by snow. Twenty groups of such stakes were recorded in a camera field of view to give an estimate of depth over a hill slope site (Ref 304).

c) *Water equivalent.* The water equivalent of a snowpack is generally less spatially variable than its depth, so that less frequent sampling is often acceptable. Where continuous monitoring of snow water equivalent is required at a point, the artificial gamma source method may be considered. This comprises a weak radioactive gamma source at, or slightly below, ground level with a scintillometer or Geiger-Muller counter suspended several feet above it (or vice versa) on a supporting structure (Refs 305 and 306). As snow builds up between source and sensor, the radiation signal suffers attenuation in proportion to the water equivalent of the intervening snow, and accuracies of ± 5% water equivalent are typical. Shreve and Brown (Ref 307) described a simpler system where accuracies of ± 10% water equivalent for snow depths up to 18 feet are quoted. When more extensive snow pack sampling is required, a similar snow radiation attenuation method can be used which utilizes the Earth's natural gamma radiation as a constant reference source. Although the level of radiation varies locally on the Earth's surface, the emission at a given point is, for most purposes, constant. Much more sensitive detectors are required than for the above artificial gamma source system, but the principle is very similar. By recording natural gamma emission levels along a known course in no-snow and snow conditions, a profile of snow water equivalent along the course can be constructed. Bissel and Peck (Ref 308) quote errors of ± 6% in the 5–13 cm water eqivalent range and ± 4% in the 25-40 cm water equivalent range for natural gamma measurements taken at ground level. The detector can be operated from a boom carried on a cross country snow vehicle, the main source of error appearing to be from the deposition of radioactive aerosols on the snow surface by precipitation and also from large variations in soil moisture.

In spite of the problems which falling snow causes to rainfall monitoring radars (see p 130), reasonable measures of snow water equivalent have been reported using radars specifically designed for this purpose. Wilson (Ref 309) describes a snowfall monitoring system very similar to the River Dee Weather Radar System (see p 130). A network of 75 reference snow gauges were used to aid calibration of the radar system and water equivalent precisions similar to those achieved by rainfall radars are possible, provided that empirically derived range corrections are applied to account for the greater signal attenuation caused by falling snow. This attenuation also results in a reduction of range within which acceptable measurements can be made with a maximum of 80-100 km being expected. Best accuracies were achieved for large storms where high altitude snowflake growth occurred, whereas the development of low level snowfall resulted in poorest accuracy.

Aircraft methods

a) *Snow and ice extent.* Aerial photography has been used extensively to monitor areas of lying snow, usually for river catchment runoff prediction purposes, with the advantage that the type of photography can be easily matched to suit snow measurement accuracy requirements. Low level oblique photography using light aircraft and amateur cameras would allow an index of snow cover to be made at low cost for areas up to several hundred square miles. For higher accuracy, vertical photography would be required, whilst for ultimate aerial measurement accuracy coupled with a direct heighting capability, photogrammetric techniques could be employed. The cost of snow surveys would rise dramatically if the latter system were used (Ref 310), but lower accuracies are often acceptable. Tollan overcame this problem of expense by utilising Air Force aerial photographic facilities. Martinec (Ref 311) describes how snow area was measured from aerial photography using a Quantimet 720 Image Analyser. The imagery, taken from an altitude of 8500 metres, of a river catchment in the Swiss Alps, was subject to deep shadowing, but by suitable adjustment of instrument sensitivity to image density, shadow areas with snow cover could still be differentiated from no snow areas. On a simpler level Higuchi and Iozawa (Ref 312) compiled an atlas of perennial snow patches in central Japan using available air survey photography coupled with hand held vertical and oblique 70 mm and 35 mm photographs taken by the authors. Both monochrome and colour film can provide good snowline delineation but colour film tends to show more detail in shadow areas, which can often be very important in areas of high relief. Colour infrared film is not recommended for snow mapping due to the confusing effect of the predominantly blue tones. As with all visible recording techniques, aerial photography of snow is very weather dependent, and this is undoubtedly its main drawback.

Thermal infrared linescanners can provide useful information on snow surface temperature which may be indicative of certain underlying conditions. Because the relationships between emissivity, spectral reflectance and transmissivity of snow varies according to its condition and because similar effects could be caused by ice or soil variations, a single thermal scan may produce hugely anomalous results unless considerable knowledge exists of the ground condition at that time. For this reason, thermal infrared sensing would rate below visible sensing for straightforward snow extent mapping, but for local studies, considerable additional information could be obtained (Ref 313). The effect of variations in permafrost condition on soil surface temperature is readily detected using infrared methods, whilst mapping of glacier ice under surface moraines and detrital material has been facilitated with the use of infrared scanner data (Ref 314).

Present knowledge of microwave return signals from snow is somewhat limited due to the complex effect of different snow types of different thicknesses and layering regimes having different free water contents and also of underlying soil of different types. Under certain conditions, microwave remote sensing may strongly delineate snow from its no-snow surroundings, yet under different temperature and moisture conditions, the brightness temperature of the snow and its surroundings may be very similar. For example, Waite and Macdonald (Ref 315) studied the effects of K-band imaging radar ($\lambda \sim 15$ mm) on various snow and ice types and found that old perennial firn appeared as an extremely strong signal when using cross polarisation, and small patches could be readily identified. However, using similar equipment, a large area of freshly fallen snow, as identified on coincident 35 mm aerial photography, was not detectable on the radar return signal, indicating that penetration to the underlying ground had occurred. Thus, although active and passive microwave sensors have the great advantage of all weather sensing, they must be used with great care for snow delineation purposes. They can be used with confidence however for the delineation of ice/water boundaries, which may be important for monitoring lake and river ice breakup which can be used as an indication of the onset of spring thaw for water resources planning.

b) *Snow depth.* In remote regions where daily snowfalls may be measured in tens of centimetres, quite crude estimates of snow depth at relatively few points may be adequate for total runoff estimates to be made. A widely used technique in areas of high snowfall is to install snow depth markers in the form of telegraph poles or similar, with cross bars set at regular intervals. The lying snow depth can be calculated by counting the number of cross bars still visible above the snow, with the advantage that observations can be carried out either from the ground or from low flying aircraft, the latter being capable of large area cover. Where specific targets are not installed, aerial estimates of snow depth can be made visually from photographs by relating the snow surface to known fence posts, trees, telegraph poles etc.

Aerial photogrammetry has been used successfully to either contour or to take numerous sample spot heights of a snow surface. Cooper et al (Ref 317 and 318) describe how snow depths were calculated by first carrying out an aerial photogrammetric survey of the ground surface of a highland region in summer conditions, after the installation of several ground reference points. When snow was lying, a second photogrammetric survey was carried out on the snow surface with reference to the same visible ground reference points, the data being automatically digitised from the stereo-plotting machine for later computer analysis. Statistical analysis of the photogrammetrically acquired data and ground control data indicated that individual point accuracies had a standard deviation error of 0.7 ft, but the standard error of the mean snow depth from the photogrammetry was only 0.02 ft due to the large number of point samples taken. They concluded that snow depths of less than 0.5 ft could be measured with satisfactory precision. This technique could be used for measuring changes in surface configuration of glaciers and ice sheets, provided that stationary reference points are included in the camera field of view.

Active microwaves have the ability to penetrate dry continental ice to considerable depths and so by comparing the time of the ice surface return signal to the following echo from the ice/ground interface a good estimate of ice depth can be made (Ref 319), assuming that areally, the ice structure is fairly homogeneous. The microwave return signal from a snow body is highly dependent on the structure of the snow and especially on its wetness (Ref 320), and therefore considerable on-site information would be required to enable snow depth to be correlated to radar return signals. This method is only likely to be feasible where homogeneous snow conditions exist. Meyer (Ref 321) describes how a monocyle v.h.f. radar was used from a helicopter to measure lake ice and snow depth to an accuracy of ± 1 cm. Theoretically, there is reasonable potential for the use of radio or acoustic wavelengths for snow depth monitoring, but little work has been carried out in this field as yet.

Assuming that snow depth can be measured by remote sensing techniques, a conversion to water equivalent is needed for this to be of use to the hydrologist. As snow water equivalent tends to be spatially less variable than snow depth, ground sampling procedures may be somewhat simpler. Ideally though, a direct measure of snow water equivalent is preferred to the indirect conversion of snow depth.

c) *Snow water equivalent.* The main methods of estimating snow water eqivalent from the air are simply extensions of the gamma radiation techniques described for ground based systems on p.140. For point measurements, the artificial gamma ray source method can still be applied,

but a slightly more powerful isotope is used. The source is buried in the soil and is shielded by a lead collimator which allows a cone of radiation to be sent skyward. The aircraft or helicopter flying at a height of 100-300 ft carries scintillation detection equipment and electronics to calculate the time period spent within the cone of influence. Accuracies of ± 7% have been quoted in reference to ground measured water equivalents (Ref 322).

By far the most widely used method for estimating areal snow water equivalent is that of natural gamma attenuation (see p 140) which has proved favourable for both American and European snow conditions. As the Earth's natural emission of gamma radiation is very weak and considerable absorption occurs in the atmosphere, platform altitudes must be kept as low as possible. For this reason, and especially in rough terrain, helicopters are generally favoured, with flying altitudes of 20 metres being typical. Bissell (Ref 322) discusses the nuclear physics aspects relating to isotropic processes of natural radiation, and pinpoints the major source of error in the technique - variations in soil moisture being the most significant as over 70% of the radiation can come from the top 10 cm of soil. The most common sampling technique is to fly a linear course before and after snow and to either monitor gamma radiation levels every few seconds or to sum counts over specified distances in order to obtain a mean value (Ref 323). The aerial flight lines should correspond to conventional snow course sampling lines where snow depth, water equivalent and surface soil moisture samples are taken. Typical sampling procedures are explained by Grasty et al (Ref 324). From surveys carried out in the Fillefjell region of Norway using helicopters, Dahl and Ødegaard (Ref 325) found that the standard deviation of their measurements varied by ± 10% compared to the standard deviation values of standard gravimetric measurements for snow water equivalents in the 0-30 cm range. Tollan (Ref 310) found that in mountainous areas of the Fillefjell, (where rock was exposed in parts) the effect was to lower the apparent water equivalent value by 25% compared to gravimetric samples. Obviously, best results are to be obtained in flat homogeneous terrain having high background gamma counts and uniform soil moisture levels where large areas can be covered by low flying aircraft. However, for difficult upland areas this is probably the only technique which can still produce reasonable water equivalent estimates, but the widespread use of helicopters carrying specialised equipment will result in a costly data collection system (Ref 326).

Very little controlled research has been conducted on the effect of shallow snow and ice on the return signal from active microwave systems such as SLAR. What little work has been done comprises mostly post-event attempts to explain anomalous signals from various snow and ice types and therefore until more evidence exists, the possibility of microwave sensing of snow water equivalent can only be subjective.

Generally, microwaves can penetrate freshly fallen dry snow and the resulting return signal is often lower than the surrounding bare ground. Glacier ice produces a very low return signal when in a pure form. Old snow or firn however produces an extremely high return and so, by daily monitoring of a snow field, the onset of melting should be detectable (Ref 315). As variations in snow dielectric property and bulk effects are recorded differentially according to sensor wavelength, a multi-frequency microwave system may have the potential to measure water equivalent, but data processing costs are likely to be high. One of the findings at the Banff Symposium on the Role of Snow and Ice in Hydrology (Ref 327) was that for the U.K., the likely economic benefits resulting from remote sensing of snow conditions would often not justify the cost involved, whereas in areas of high snowfall, a small improvement in measurement accuracy could result in large savings of water resources, flood drainage costs etc. Nevertheless, the likelihood of flooding after snow is still a major problem in the U.K. and Ref 327 describes techniques which enable estimates of snowmelt/rainfall flood discharges to be made.

Satellite methods

a) *Snow and ice extent.* The mapping of snow extent from satellite data has been shown to be feasible to the extent that it is one of the few hydrological parameters which is measured by satellites on an operational basis. The main reasons for this are probably that the presence of snow can be recognised on a yes/no basis with the result that quantitative analysis is not necessarily required (although as techniques improve this is already being incorporated into the programmes). Also, in the visible and infrared wavelengths, snow normally has a high signal/noise ratio and so expensive data processing and enhancement are not necessary in order to observe its presence. Because the observation of snow is not restricted to narrow spectra, data from many satellites can be used. The major drawback against mapping snow from high altitudes is the confusion caused by intervening clouds. When aircraft-borne sensors are used, snow monitoring is either restricted to clear sky conditions or else the presence of cloud is carefully recorded. With satellite data the decision regarding cloud presence must either be made directly from the recorded imagery or else by checking with meteorological ground observations across the whole area of interest.

The most precise mapping of snow extent has been carried out using ERTS/LANDSAT data by both subjective visual analysis and by computer digital analysis to try and derive a "snow-line". Ödegaard and Skorve (Ref 301) found that it was visually impossible to define a single line representing snow extent in their study in Norway, especially during the spring melt when the transgression from complete snow cover to no snow may occur over tens of miles. However, with the help of photographic density slicing (see p. 68) using Agfacontour film, two levels of image brightness were defined which delineated the extent of continuous snow cover, and an arbitrary value of thickest snow cover within that area. This was not found to be particularly useful and it was felt that an index giving 'percentage snow cover' within a river catchment basin would be more meaningful. Haefner (Ref 329) compared ERTS imagery with an experimental area in the Swiss Alps, but found that complete studies could not be undertaken as only one good quality ERTS image was available during the test period. Automatic recognition of the snow was not immediately possible due to the "different brightness caused by dry and thawing snow, different exposure, slope angle, snow and sun shadow etc" and pre-processing techniques had to be devised to overcome these difficulties. A Quantimet 720 image analyser was then used to density slice the resulting image to produce a 'snowline', the area within this line then being calculated. Also the distribution of dry and melting snow was determined by density ratioing of band 4 and 5 with band 7 because strong infrared absorption occurred with wet snow. Band 5 (0.6 - 0.7 microns) was felt to be the best for dry snow mapping, as more contrast was apparent. This is also confirmed by Barnes and Bowley (Ref 330). In a report sponsored by the U.S. Department of the Interior (Ref 331) a snowline altitude accuracy of 60 metres is said to be achievable using ERTS-I imagery, whilst Meier (Ref 332) in addition to quoting the same altitude accuracy, claims that on specific drainage basins, snowcover was measured using video density sliced ERTS imagery to a repeatable accuracy of ± 4% (by area) of the actual snow cover. Although such accuracies may be possible under ideal conditions, all authors agreed that the presence of forest vegetation greatly reduces snowline definition so that 'snowlines' become almost impossible to draw to any degree of accuracy using a single image. However, Draeger and Lauer (Ref 333) devised a training method to help interpret snowlines in forested areas. Using ERTS imagery, high altitude U2 aircraft photographs and ground data, snow extent was carefully determined in forested areas, and these were used in training sets in combination with no snow photographs of the same area. After experience with these samples, interpreters could distinguish snow extent from new ERTS imagery, provided that no-snow imagery of the area was also available as a reference to forest density, distribution, maturity etc. This could be achieved to ± 5% of the percentage cover estimated from low level aerial photography. In addition to problems created by cloud cover and vegetation, Meier found that the ability to map snow cover also depended greatly on the ground slope, terrain roughness, sun angle, radiometric fidelity of the image and amount of spectral information available. For these reasons he believes that a fully automatic mapping system would be impossible to achieve and that interactive control of the process by an experienced image interpreter is necessary.

The methods employed to overcome the effects of cloud on snow identification are all very similar. Snow presence in mountainous regions is closely related to altitude, with the result that characteristic dendritic patterns are formed. In low lying areas, a snow cover has a very even appearance and possesses quite uniform reflectance, whereas clouds vary considerably in texture and often have a mottled appearance due to shadowing on one another. Where a 'snowline' does occur, its definition is usually very sharp in contrast to cloud edges which normally appear diffuse from satellite altitudes. When clouds are present, ground shadows are often visible, but where snow is present ground features can normally be recognised and may even be enhanced eg. river, roads, forest boundaries etc. The biggest problems arise when fog, orographic cloud and cloud formations possessing sharp edges are present. Where imagery of high temporal frequency is available, such cloud formations may be identifiable by their movement (see Ref 334).

Serebreny (Ref 335) discusses the use of time lapse processing techniques of LANDSAT 1 derived snow data in order to estimate snow accumulation and melting rates throughout a season, but the poor temporal frequency of LANDSAT 1 did not make it entirely satisfactory for this type of study. In certain areas, the 18 day frequency of LANDSAT 1, or the combined frequency of LANDSAT 1 and 2 may be adequate, provided that cloud cover is infrequent. In the UK however, the chance of having clear weather for two consecutive LANDSAT passes is very small (Ref 336). Because of this, the continental mapping of snow extent has been based on lower resolution but high temporal frequency satellite data such as afforded by the ESSA, NIMBUS, NOAA and TIROS-N weather satellite series (see Table 7).

Whereas the sensors on LANDSAT have a ground resolution of approximately 80 metres, the resolution of the imaging weather satellites ranges from about 1 km to several kilometres. Barnes and Bowley (Ref 334) produced an Operational Guide for Mapping Snow Cover from Satellite Photography to cover the period 1963-1968 when the early TIROS and ESSA series were in operation. Although the quality of imagery has much improved since then, the problems encountered and the methods of tackling them are much the same, and the manual would be useful for anyone interested in high altitude aircraft or satellite snow data. Some early snow mapping using the NIMBUS-3 visible and infrared data is described by Weisnet and McGinnis (Ref 337), and McGinnis et al (Ref 338) describe the more recent work using NOAA 2-4 data which have had a temporal frequency of up to two passes per day, enabling any clear sky areas to be mapped when they occur. The sensors used are a visible and thermal infrared scanner (see p. 45) which have a maximum resolution of approximately 1 km, but no microwave sensors are available which would allow cloud penetration. Snow boundaries located by eye were transferred from the unrectified satellite imagery to base maps after optical rectification. The location of the snow line in relation to ground features was found to be easiest when drainage patterns were visible as no snow areas and best accuracy of ± 8 km was claimed, with overall accuracy of ± 10 km of the ground observed snowline. The National Environmental Satellite Service (NESS) branch of the National Oceanic and Atmospheric Administration (NOAA) in Washington have been producing mean monthly snowline charts for the whole of the northern hemisphere since winter of 1972 from NOAA satellite data. Snow and ice boundary maps are first prepared from one weeks satellite data, where cloud cover permits, and then the resultant boundaries are averaged to give the mean monthly boundary (Ref 339). Unfortunately, the data only extends northwards to latitude 52°N, as it was felt that beyond this, little continental variation occurred in winter. No mapping has therefore been carried out for any of UK or Northern Europe. After analysing this data over a 9 year period, Weisnet and Matson (Ref 340) suggest that an Antecedent Snowcover Technique may allow forecasts to be made on a 30, 60 and 90 day basis, but that further verification may be necessary.

In addition to snow mapping by visual techniques, considerable experimentation in semi-automated recognition methods has been carried out, but these are too lengthy to be discussed here. Some of these methods are described in the publication 'Snow Survey from Earth Satellites' produced by WMO (Ref 341) and this basically updates the previously mentioned Barnes and Bowley handbook. Most of the described methods rely on image threshold brightness values for snow recognition purposes (Ref 342), but as mentioned earlier, allowance must be made for the effects of vegetation, lighting aspects and snow wetness variations which often require human interpretation. Such methods also rely heavily on accurace sensor calibration of brightness values and therefore anomalies caused by sensor or recorder drift can sometimes occur. A major processing improvement however is the capability of removing cloud effects through time-lapse processing. With the use of daily imagery such as NOAA, daily data over a period of at least 5 days is

TABLE 7 SATELLITES AND SENSORS USED IN MAPPING NORTHERN HEMISPHERE SNOW AND ICE COVER

Satellite	Sensor*	Spectral band	Subpoint resolution	Period of operations
ESSA 3	AVCS	0.5-0.75 µm	3.7	Oct. 2, 1966-Oct. 9, 1968
ESSA 4	APT	0.5-0.75 µm	3.7	Jan.26, 1967-Dec. 6, 1967
ESSA 7	AVCS	0.5-0.75 µm	3.7	Aug.16, 1968-July 19,1969
ESSA 8	APT	0.5-0.75 µm	3.7	Dec.15, 1968 - present
ESSA 9	AVCS	0.5-0.75 µm	3.7	Feb.26, 1969-Dec.15, 1973
ITOS 1	AVCS	0.5-0.75 µm	3.7	Jan.23, 1970-June 17,1971
	APT	0.5-0.75 µm	3.7	
	SR	0.52-0.73 µm	3.7	
		10.5-12.5 µm	7.4	
NOAA 2	VHRR	0.6-0.75 µm	1-1.9	Oct.15, 1972-Jan.30, 1975
		10.5-12.5 µm	1-1.9	
	SR**	0.52-0.73 µm	3.7	
		10.5-12.5 µm	7.4	
NOAA 3	VHRR	Same as NOAA 2		Oct. 6, 1973 - present
	SR	Same as NOAA 2		
NOAA 4	VHRR	Same as NOAA 2		Nov.15, 1974 - present
	SR	Same as NOAA 2		
SMS-1 (GOES)	VISSR	0.55-0.70 µm	1-7.4	May 17, 1974 - present
		10.5-12.5 µm	7.4-14.8	

*Camera and sensors:

AVCS - Advanced Vidicon Camera System
APT - Automatic Picture Transmission
SR - Scanning Radiometer
VHRR - Very High Resolution Radiometer
VISSR - Visible and Infrared Spin Scan Radiometer

**SR - N 016, failed 3/3/74
Visible channel spectral band 0.5 - 0.94 µm

processed simultaneously. By removing all but the lowest brightness value of these images at a given point during this period, most of the effects of moving cloud masses are removed. These and other computer processing techniques developed for snow depth estimation could not possibly be carried out by eye. In addition to snow mapping, satellite thermal infrared imagery has been used extensively for mapping lake, river and near shore ice and some of the findings are described in Ref 120.

b) *Snow depth.* In the visible wavelength regions, several attempts have been made to relate satellite derived snow signal brightness to snow depth, and the results have all been very similar. Using NOAA VHRR visible data, McGinnis et al (Ref 338) found that measured snow depths correlated well with image brightness. For snow depth less than 30 cm, marked increases in brightness corresponded to increasing snow depth. Above 30 cm, little increase in brightness was evident, although the brightest areas still coincided with the areas of deepest snow. Similarly, densitometric measurements of ESSA imagery of Fraser Basin, Canada (Ref 341) allowed 4 distinct ground conditions to be recognised:

1) Areas free from snow which appeared dark or black.
2) Snow cover up to 10 cm deep showed as grey with some dark patches.
3) Snow cover 10-30 cm deep showed as continuous light areas with occasional mottled grey patches.
4) Snow deeper than 30 cm showed as a continuous bright white.

The earlier work of Barnes and Bowley suggested that brightness/depth relationships in non-forested areas existed for snow depths up to about 4 inches. Using LANDSAT imagery, Ödegaard and Skorve (Ref 301) carried out image density slicing and were able to separate areas of thickest snow in open land, due to its highest reflectance. In forested areas, those with no snow can usually be distinguished from those with snow, but little or no variation in brightness is apparent with increasing snow depth. Usually the decision on the positioning of a 'snow line' is much more difficult to make in forested areas.

The use of thermal infrared sensing cannot be recommended as a technique for estimating snow depth, although useful information may be obtained regarding the snow surface condition. Although occasions may occur when snow surface temperature does relate to snow depth, a lot of ground information would be required to establish this and changes could still occur very rapidly. The presence of melt water on the snow surface for example can raise the sensed temperature to 10° or 15° above 273°K (Ref 343) and from satellite altitudes, the presence of warmer bare ground within a resolution cell can boost the mean temperature well above that of the true snow temperature. Similarly with microwave sensing, a snow depth/signal response correlation may well occur in fresh, dry snow conditions overlying frozen ground as recorded by the Skylab S194 passive microwave radiometer (Ref 344). In wetter conditions however, the sensor is more likely to respond to variations in soil moisture or free water within the snowpack, rather than to the snow depth. Initial tests using the Skylab S-193 2 cm scatterometer (Ref 344) resulted

in a positive correlation of return signal to snow depth, but with a wide degree of scatter. Further intensive testing is required before microwave results can be used with confidence however.

c) *Snow water equivalent.* Because microwave responses from snow are greatly affected by the dielectric constant of the snow or snow/soil profile, and taking into account their all weather capability, microwave sensing techniques must offer the greatest potential for snow condition monitoring from satellite altitudes. Even if a reasonable estimate of snow water equivalent cannot be made, the daily monitoring of a snow pack with microwave sensors would enable important changes such as the onset of snow melt to be observed. Microwave sensors are well suited to sensing snow melt water and Edgerton et al (Ref 345) found that microwave brightness temperatures were responsive when the snow's free water content exceeded 2.5% by volume. In addition to the dielectric effect, Waite and McDonald (Ref 315) believe that the physical structure of a snowpack plays an equally important role in the determination of signal return magnitude, especially in the case of old firn which produces an unusually high return signal. Schmugge et al (Ref 320) found that these effects of "volume scattering" became noticeable for free space wavelengths shorter than about 3 cm. When liquid water is present however, these effects are overruled. At wavelengths from 11 cm - 21 cm, scattering appears to be less important and dielectric properties become more important. The rise in brightness temperature for wet snow indicates that it may be possible to detect the onset of snow melt by measuring temperature.

Although microwave sensing is used extensively in lake and river ice studies (Ref 346) and in mountain and polar ice-cap studies (Ref 106 pp 214-220 and Ref 347), difficulties have been experienced in modelling microwave emissions from snow and ice surfaces (Ref 348) and considerable research is still required in that direction. However, as wavelengths shorter than those of microwaves are incapable of any snow penetration, any satellite derived relationships to snow water equivalent can at best be only inferred when using short wavelengths. It is certain therefore that as synthetic aperature radar systems come into more widespread use on satellites such as SEASAT, techniques will be developed to better understand their signal response from snow pack. Satellite derived snow cover data have been incorporated into catchment hydrological models for the purposes of run-off prediction (Ref 349), and improved methods of water equivalent estimation would be of major significance in water resources studies.

8. THE FUTURE APPLICATION OF REMOTE SENSING IN HYDROLOGY

8.1 On a global scale the potential for data collection and monitoring change through remote sensing is enormous. But what is the likelihood that remote sensing will play an important role in the future collection of hydrological data? Even at the present state-of-the-art, remote sensing (largely from United States satellites and aircraft multi-sensor surveys) is providing hydrological or related information which has been hitherto unobtainable in remote regions of the world and in poorly developed countries. It is in these regions where remote sensing is likely to continue as the major source of hydrological information, primarily because conventional ground measurement networks are either non-existent or are inadequate. However, the prime function of remote sensing is likely to lie in the provision of information on the areal distribution of variables between points of known value as measured on the ground, rather than as the sole data source. For those areas of the world which are favoured with low annual or seasonal cloud cover, a large proportion of the presently available data could be applied now to hydrological problems and therefore it is in these regions where research into hydrological applications of satellite data should be concentrated. In this way, first hand experience of the problems of relating satellite data of high temporal frequency to say, operational water resources requirements can be obtained with the aim of ultimately applying this knowledge to the U.K. situation when regular satellite data is available.

At the moment, the greatest barrier acting against the application of satellite derived data of the U.K. is that of cloud cover. When the frequency of satellite overpasses is less than about once per two days the chances of even two consecutive overpasses occurring in clear weather conditions are remote. For many hydrological purposes, frequent monitoring of the ground situation is required (see Table 4a and b) and therefore a large proportion of possible satellite applications are immediately ruled out through this inability to provide regular data. There appears to be only two ways of dealing with this problem:

(1) develop models of hydrological systems which are capable of running on conventional ground based data, but which will accept intermittent remotely sensed data as a bonus towards the distribution of point data, or (2) use data from all-weather sensors. The former can still only work efficiently when the period of change of the variable is larger than the period between satellite observations, but as the aim is to make the models as accurate as possible (within largely economic limitations), all efforts should be made towards the incorporation of any additional useful information (such as remotely sensed data) even if its contribution is infrequent. Ultimately however, the aim in U.K. and northern Europe must be towards the provision and use of all-weather satellite data such as can only be provided by sensors operating at wavelengths of around 25 mm or above (ie microwaves or radiowaves). The early failure of the SEASAT-A synthetic aperture radar precluded its proper evaluation from a hydrological viewpoint, but all indications suggest that its 25 metre resolution data was of high quality, independent of prevailing weather conditions. The technology for the provision of high resolution all-weather satellite sensors has therefore been demonstrated to exist. What is required now is the research to enable hydrologists to interpret microwave data, which is complicated by the interacting effects of surface roughness and emissivity, surface dielectric properties and temperature. Considerable work is required in this field before microwave data can be confidently applied to basic mapping of different land features and still more work will be required before the measurement of such variables as soil moisture can be tackled on an operational basis. The future supply of suitable satellite data for research

purposes appears to be assured through the European Remote Sensing Space Programme prepared by the European Space Agency. The development of a European all-weather satellite system has been given high priority within the programme and first testing of a synthetic aperture radar which has been designed to suit European requirements will take place in early 1980 aboard Spacelab-1. Proposals have also been made for the launching of satellites in 1985 and 1987 which will also carry microwave sensors. It is therefore highly desirable that research into the hydrological application of microwave data is started now using aircraft mounted sensors, in order to prepare the path for future satellite data.

Neither Water Authorities nor research bodies have the facilities to undertake such research on their own, but the continued growth of the National Centre for Remote Sensing based at the Royal Aircraft Establishment, Farnborough, should enable research projects of this type to be undertaken through the use of central, Government research facilities. It is hoped that in the near future, an aircraft equipped with a selection of remote sensors, including those operating in the microwave region will be made available for the collection of data for research purposes. Large amounts of data are produced from test flights (mainly in the form of magnetic tape records) which necessitates suitable computer-based handling facilities. Again, the National Centre for Remote Sensing is expected to play a major role in the centralisation of large computer processing facilities (such as their present IDP 3000 image processor) and of personnel who can undertake or advise on data handling methods.

One of the main advantages of satellite sensing is the synoptic view which is available and often, the whole of the U.K. may be recorded within the swath width of a single overpass. Because of the large amounts of data which would be produced by a high temporal frequency operational satellite, it would therefore be most efficient to process data for the whole of the country at once. It is envisaged that the interpretation of satellite data for operational hydrological purposes would ideally be undertaken by a central body who would distribute the end product to the Water Authorities for their application. In addition, the dissemination of synoptic data would more easily facilitate a co-ordinated countrywide approach to be made to the prediction and management of water resources, effluent disposal, flooding etc.

This look into the not too distant future is probably of little relevance to the hydrologist who is requiring local information now. He should remember that remote sensing is not restricted to sensors operating only from satellite platforms; indeed satellite data may be totally inadequate for providing many types of information. If for example an erosion feature can be adequately recorded from a riverbank with an Instamatic camera, then why bother with satellite imagery? On the other hand, a desk study of erosion over the whole river catchment within the last 50 years using archived aerial photographs may yield a better understanding of the erosion problem than either the single Instamatic photograph or the satellite data.

Hence, although we may be looking to the more distant future for remote sensing to aid the handling of national water related problems, there are numerous applications on a local scale where remote sensing techniques of all levels of sophistication (as outlined in Chapter 4) could be used to advantage now. In many instances the individual may be unwilling to pursue the use of remote sensing techniques because, after initial investigation, they are found to be incapable of providing all of the required information on their own. Once this disappointment is overcome and remote sensing is instead looked upon as "as additional instrument in the toolbox" which is to be carefully integrated into conventional data collection systems, then its application should be much more readily acceptable.

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GLOSSARY

Aerial (measurement): A measurement of a surface or object taken from an aerial platform (e.g. aeroplane).

Areal (measurement): A measurement of area or variations of value over a given area.

Absorption: The process by which radiant energy is absorbed and converted into other forms of energy.

Across track: Any line running perpendicular to the direction of flight of a sensor platform.

Active sensor (or system): 1. A sensor (or system) having its own source of EMR e.g. radar. 2. A sensor (or system) that measures EMR which is reflected from a surface or object and not emitted by the surface or object. (see passive sensor for comparison).

Albedo: The ratio of the amount of total EMR reflected by a body to the amount incident upon it.

Angle of depression: 1. Any angle measured from the horizontal to an object situated below the observer. 2. In radar, the angle formed by the horizontal plane and the line of the radar beam to the ground feature.

Along track: Any line running parallel to the direction of flight of a sensor platform.

Angle of incidence: The angle at which EMR strikes a surface as measured from the normal to the surface at the point of incidence.

Angle of reflection: The angle which EMR reflected from a surface makes with the perpendicular (normal) to the surface.

Attenuation: Any process in which the flux density (or power, amplitude or intensity) of a parallel beam of energy decreases with increasing distance from the energy source.

Backscatter: The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the same side as the incident ray. In radar usage, backscatter generally refers to that radiation reflected back towards the antenna.

Band-pass filter: A wave filter which has a single transmission band extending from a lower cutoff frequency greater than zero, to a finite upper cutoff frequency.

Black-body: An ideal emitter which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature. A black body also absorbs all the radiant energy incident upon it.

Black-body radiation: The theoretical maximum amount of radiant energy of all wavelengths which can be emitted by a body at a given temperature.

Boresight: To align the axis of an instrument with another, generally by optical means.

Brightness: 1. A visual perception by which an area appears to emit more or less light than another. 2. The unit of brightness, the Lambert is defined as the brightness of a surface which emits or reflects one/π lumen per square centimetre per steradian.

Brightness temperature: 1. The temperature of a black-body radiating the same amount of energy per unit area at the wavelengths under consideration as the observed body. 2. The apparent temperature of a non-black-body determined by measurement with a radiometer.

Brilliance: The degree of intensity of a colour.

Chopper: A device, which usually rotates in order to interrupt a continuous EMR signal in a transmitter or receiver.

Colour: The property of an object which is dependent on the wavelength of the light which it reflects or in the case of luminescent [illegible], the wavelength of light which it emits. If the light is of a single wavelength, the colour is termed a pure spectral colour, but if light of two or more wavelengths is emitted, the colour will be mixed.

Dielectric constant (ε): The ratio of the electric flux density D to the electric field E.

Diffuse radiation: Radiation that does not reach the subject from a single direction eg sunlight which has been scattered by the atmosphere or clouds.

Diffusion: The scattering of EMR upon reflection from a rough (at the wavelength of the EMR) surface, or upon transmission through a translucent medium.

Dispersion: 1. The separation of EMR into its spectral component by its passage through a diffraction grating or by refraction such as through a prism. 2. The spreading of a signal caused by variation of velocity of propagation with frequency.

Doppler effect: A change in the observed frequency of electromagnetic or other waves as a result of relative motion between the source and the observer.

Effective terrestrial radiation: The amount by which outgoing infrared terrestrial radiation of the Earth's surface exceeds in coming infrared radiation from the atmosphere.

Electromagnetic radiation (EMR): Energy propagated through space or through material media in the form of an advancing interaction between electric and magnetic fields.

Emission: The process by which a body emits EMR, usually as a consequence of its temperature only.

Emission spectrum: The array of wavelengths and relative intensities of EMR emitted by a given radiator.

Emissivity: A special case of exitance, a fundamental property of a material that has a specular surface and is sufficiently thick to be opaque. Most natural objects including soil, plant leaves and water have emissivities > 0.9 but < 1.0.

Emittance: 1. The ratio of the emitted radiant flux per unit area of a sample, to that of a black body radiator at the same temperature and under the same conditions. 2. The obsolete term for the radiant flux per unit area emitted by a body (now known as exitance).

Equivalent blackbody temperature: The temperature measured radiometrically corresponding to that which a blackbody would have.

Exitance: The radiant flux per unit area emitted by a body or surface.

Extinction: (Synonymous with attenuation) The combination of processes causing reduction of radiant flux (in a specified part of the spectrum, angular direction or spatial region of propagation) when such flux impinges on a body.

Fluorescence: Property possessed by certain substances of emitting light following exposure to external radiation.

Flux: 1. The rate of flow of some quantity, often used in reference to the flow of some form of energy. 2. In nuclear physics - the number of radioactive particles per unit volume times their mean velocity.

Flux density: The rate of flow (flux) of any quantity (usually some form of energy) through a unit area of specified surface (Note: this is not a volumetric density like radiant density).

Forward scatter: (see backscatter) The scattered radiant energy on the opposite side of the plane to backscatter.

Ground data: Supporting data collected on the ground, and information derived therefrom, as an aid to the interpretation of remotely-recorded surveys such as airborne imagery etc. Generally this should be performed concurrently with the airborne survey. Data such as weather, soils and vegetation types, surface temperature etc are typical.

Ground track: The vertical projection of the actual flight path of an aerial or space vehicle onto the surface of the Earth or other body.

Hue: That ~~attribute~~ of a colour by virtue of which it differs from grey of the same brilliance and which allows it to be classified as red, yellow, green, blue or intermediate shades of these colours.

Illumination: The intensity of light striking a unit surface is known as the specific illumination of luminous flux. It varies directly with the intensity of the light source and inversely as the square of the distance between the illuminated surface and the source. It is measured in a unit called the lux. The total illumination is obtained by multiplying the specific illumination by the area of the surface which the light strikes. The unit of total illumination is the lumen.

Incandescence: Emission of light due to high temperature of the emitting material. Any other emission of light is called luminescence.

Inverse square law: The illumination on a unit surface and consequently the brightness of the surface vary inversely with the square of the distance from a point of light source.

Irradiance: The measure in power units of radiant flux, incident on a surface. It has the dimension of energy per unit time (eg watts).

Laser: Derived from light amplification by stimulated emission of radiation. A device for producing light by emission of energy stored in a molecular or atomic system when stimulated by an input signal.

Layover: Displacement of the top of an elevated feature with respect to its base on the radar image.

Look angle: (generally in radar) The direction of 'look' or direction in which the antenna is pointing when transmitting and receiving from a particular cell.

Luminance: (see also brightness) A measure of the intrinsic luminous intensity emitted by a source of light in a given direction. Luminance is a measure only of light, the comparable term for EMR in general is radiance.

Mie scattering: Any scattering produced by spherical particles without special regard to comparative size of EMR wavelength and particle diameter.

Multispectral: Generally used for remote sensing in two or more spectral bands.

Nadir: That point on the ground vertically below the observer. The point on the ground below the perspective centre of a vertically pointing camera lens or other imaging sensor.

Noise: Any undesired erratic intermittent or random background signal in remotely sensed data.

Passive sensor (or system): A sensing system that detects or measures radiation emitted by the target (see also active sensor).

Permittivity: The ratio of the electric flux density to the electric field strength (also called dielectric constant).

Pixel: (Short for picture element) the smallest element on the ground which is distinguishable on the final image.

Polarisation: The direction of the electric vector in an EM wave.

Polarising filter: A filter which only allows the passage of light waves in one plane of polarisation

Propagation: The combination of all processes other than absorption which take place when radiant energy falls on a body; it is the sum of reflection (specular and diffuse) and transmission.

Radiance: The accepted term for radiant flux in power units (eg watts) and not for flux density per solid angle (eg watts/cm^2 sr).

Radiancy: Emitted radiant flux density measured as power per unit area (eg watts/cm^2).

Radiant power: Rate of change of radiant energy with time.

Radiation: The emission and propagation of energy through space or through a material medium in the form of waves. The process of emitting radiant energy.

Rayleigh scattering: Scattering by particles small in size compared with the wavelengths being scattered, eg scattering of blue light by the atmosphere.

Rectification: The removal of distortion in imagery due to the effects of relief or sensor movement away from the vetical.

Reflection: EMR neither absorbed nor transmitted is reflected. Reflection may be either diffuse when the incident radiation is scattered upon being reflected from the surface or specular when all or most angles of reflection equal the angle of incidence.

Refraction: The bending of EMR rays when they pass from one medium to another having a different index of refraction.

Resolution: The ability of an entire remote sensing system to render a sharply defined image. It may be expressed in many ways, depending on the type of sensor.

Resolution cell: The smallest element on the ground which is distinguishable on the final image or bit of data. (see pixel).

Saturation: Degree of intensity difference between a colour and an achromatic light source colour of the same brightness.

Scattering: 1. The process by which small particles suspended in a medium of a different index of refraction, diffuse a portion of the incident radiation in all directions. 2. The process by which a rough surface reradiates EMR incident upon it.

Spectral signature: Quantitative measurement of the properties of an object at one or several wavelength intervals.

[illegible]: A device to measure the spectral distribution of EMR.

Texture: The frequency of change and arrangement of tones in an image.

Transmission: The amount of radiation of different wavelengths which a filter, lens or film will transmit.

Transmittance: The ratio of the radiant energy transmitted through a body to that incident upon it.

Note:- The definitions for these terms have been derived from the Manual of Remote Sensing. For a more comprehensive glossary of terms see Reference 120 pages 2061 - 2110.

ABBREVIATIONS

CCT	-	Computer compatible tape
DBV	-	Direct beam vidicon
EM	-	Electromagnetic
EMR	-	Electromagnetic radiation
ESA	-	European Space Agency
ESMR	-	Electrically scanning microwave radiometer
ESRO	-	European Space Research Organisation
IR	-	Infrared
MS	-	Multispectral
MSS	-	Multispectral scanner
NASA	-	National Aeronautical and Space Administration
NESS	-	National Environment Satellite Service
NOAA	-	National Oceanic and Atmospheric Administration
PMT	-	Photo-multiplier tube
RBV	-	Return beam vidicon
SLAR	-	Side-looking airborne radar
THIR	-	Temperature-humidity infrared radiometer
UV	-	Ultra violet
VHRR	-	Very high resolution radiometer