Scoping Study on Environmental Remote Sensing:

Monitoring the tropospheric, aquatic and terrestrial environments

R & D Technical Report Number E1-070/TR

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EXECUTIVE SUMMARY

The Environment Agency has a duty to monitor and form an opinion on the state of the tropospheric, terrestrial and aquatic environments within England and Wales. Current Agency monitoring programmes, in general, use manual sampling and laboratory analysis techniques together with fixed sensors and analytical devices; such programmes are co-ordinated at a regional level. These methods are labour intensive and do not lend themselves to forming an accurate picture of spatial variations within the environment from which a more complete or holistic view can be obtained.

Remote sensing (RS) techniques offer the potential to replace some existing techniques with the advantage of providing this holistic view. The Agency already uses some remote sensing instruments such as CASI and LiDAR for certain applications.

The principal purpose of this scoping study was to assess the usefulness of current and future remote sensing capabilities to address the monitoring needs of the Agency. To this end, the specific objectives of the study were:

- the identification of the current and likely future monitoring requirements,
- the identification of current RS techniques and an assessment of their relevance to monitoring requirements and
- the identification of relevant research activities in remote sensing technologies and applications which may be of relevance.

The study was conducted through an extensive literature search using on-line databases such as Aerospace CDs, NTIS CDs, INSPEC, GEOBASE, etc. In addition, web searches and personal contact were used to provide further material. The main body of the report (section 3) describes the following remote sensing technologies and their applications relevant to the Environment Agency:

- Microwave (SAR and Passive Microwave)
- LiDAR
- Optical (Visible and near infra red)
- Hyperspectral
- Thermal infra red
- Fluorescence
- Spectroscopy
- Radiation (nuclear)
- Magnetometry

In each case a description is given of the key technical principles, of current sensors and (based on the literature search) of relevant applications. Section 4 considers each of the Environment application areas in turn (ie, Flood defence, Air quality, Inland water contamination, etc) and reviews the sensing techniques which are considered applicable, either now or after further development.

It was concluded that remote sensing has the potential to contribute to almost all the applications relevant to the Agency. Nevertheless, there are many areas where in situ measurements will continue to be required, eg, contamination of land and classification of waste. The study showed that there were widespread developments aimed at improving

performance (especially spatial resolution) and information content (eg, hyperspectral sensors and multipolarisation SAR) – this was particularly true for satellite borne sensors.

It was not possible to rank in priority order those sensors or techniques which should be considered for development by the Agency, but the following list indicates those which may be regarded as being of importance in the short to medium term:

- Development of a land cover database using satellite high resolution visible/NIR and hyperspectral sensors, with the aim of providing updates of specific regions as required using airborne or satellite imagery. This would help the land cover, land contamination, biodiversity and climate change applications.
- Set up a GIS system which would allow different data sets (from remote sensing or other measurements) to be incorporated with the land cover data base – this would allow data to be more effectively used across a number of applications.
- Investigate the use of satellite (or airborne) multipolarisation SAR for flood monitoring and pollution monitoring and flood defence.
- Investigate the use of interferometric SAR for change detection (and land use) and for illegal dumping and waste site monitoring.
- Investigate the use of airborne sensors (DIAL and DOAS) for more effective air quality measurements (in locations not served by ground based sensors).
- Investigate the use of hyperspectral sensors, particularly for land cover classification (and biodiversity) and inland and coastal water quality.
- Extend the use of the existing airborne CASI and LiDAR systems to support research on flood modelling, water quality measurement and vegetation classification.

The selection from this list will depend on the Agency's priorities and the specific requirements of each application.

1. INTRODUCTION

1.1 Purpose of Study

The Environment Agency has a duty to monitor and form an opinion on the state of the tropospheric, terrestrial and aquatic environments within England and Wales. Current Agency monitoring programmes, in general, use manual sampling and laboratory analysis techniques together with fixed sensors and analytical devices. Such programmes are co-ordinated at a regional level. These methods are labour intensive and do not lend themselves to forming an accurate picture of spatial variations within the environment from which a more complete or holistic view can be obtained.

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- the identification of the current and likely future monitoring requirements,
- the identification of current RS techniques and an assessment of their relevance to monitoring requirements and
- the identification of relevant research activities in remote sensing technologies and applications which may be of relevance.

As part of this study an extensive literature search has been carried out. This is explained in section 1.3.

1.2 Report Structure

The results of the scoping study are set out in this report with the following structure.

Section 1.3 gives details of the literature search conducted as part of this study. Significant findings of the literature review are reported in the relevant sub-sections of section 3.

In Section 2 details of the Agency's current and possible future monitoring requirements, captured during the initial phase of the study, are reported. The section identifies a number of 'application areas', for example, flood defence, land cover and biodiversity, which are referred to throughout the report.

Section 3 reviews current and future sensors and remote sensing techniques, which are considered of potential relevance to the Agency's requirements. The section is divided into the following broad sub-sections: microwave (SAR and passive microwave), LiDAR, optical (visible and near IR sensors), hyperspectral, thermal IR, fluorescence, spectroscopy, radiation and magnetometry. Under each sub-section, relevant sensors, environmental applications and current research activities in the application areas are described.

Section 4 takes each of the identified application areas in turn and addresses the capability of the full range of remote sensing techniques to measure the required parameters. The approach taken is to determine whether methods exist or are under development which could in principle measure the required parameters for a given application.

Conclusions and recommendations are given in Sections 6 and 7 respectively.

1.3 Description of Database Search

Extensive database searches were conducted for this study by professional Knowledge Agents based in the DERA information centre facilities. Searches were conducted on a sensor type basis and were specified and reviewed by the relevant sensor expert.

The following databases were searched during this study:

- Web of Science on-line
- Aerospace CDs
- NTIS CDs
- INSPEC
- Geobase

In addition, extensive use of internet searches was made.

To limit the quantity of material to manageable amounts it was necessary to limit the years searched to the last three years 1997-2000. This approach ensured that the most recent research work and application of techniques was thoroughly investigated. However, it is possible that more dated techniques could have been overlooked.

The search strategy had two strands. Firstly to identify sensors and find their technical descriptions and secondly to discover where particular types of sensors had been used for applications related to those of interest to the Agency. The literature search was designed to reveal areas of active research in relevant application areas.

The database searches were conducted to complement the core approach of the study, which involved the use of sensor experts to compile the relevant sensor sections and direct approaches to sensor operators and sensor specific documentation for information.

2. ENVIRONMENT AGENCY REQUIREMENTS

2.1 Introduction

The primary objective of the 'Scoping Study' was to establish the capabilities and relevance of existing and future remote sensing techniques to the Environment Agency's monitoring interests. In order to obtain a good understanding of the monitoring requirements of the agency, a meeting with key Environment Agency National Centre staff was set up at the start of the study. This section sets out the findings from that meeting. The contents of this section were circulated to the Agency for comment on accuracy and completeness, and the comments received have been incorporated below. The section was circulated to the sensor experts to provide guidance for their work during the study.

This section is structured by application area. Both statutory monitoring requirements and other activities, required to form a view on the state of the environment, are included.

2.2 Application Areas

2.2.1 Flood defence

Flood defence is by far the most costly activity of the agency. Activities include the building and maintaining of flood defences, including coastal defences, the production of flood risk maps, the monitoring of water levels and response.

River and tide gauges are used to constantly monitor water heights and feed information to a number of control rooms. These data, in conjunction with models of the relevant flood area, are used to respond to a potential flood by, for example, the operation of sluice gates.

Accurate terrain height data is required for the modelling of flood envelopes, this is currently achieved by LiDAR measurements in some cases.

Data on the extent of flooding from actual flooding events is useful for validation of the models.

2.2.2 Inland water quality

The assessment of water quality is another extensive and costly activity of the agency, consuming approximately half of its monitoring budget.

Each river is divided into stretches for monitoring purposes. The required water quality of each stretch is determined by its use, eg salmon fishing, recreational, industrial intake. In most cases (90%) water samples are collected from each stretch and analysed in a laboratory for dissolved oxygen, ammonia and numerous dissolved nitrites and nitrates and for metals. For some measurements (10%) in-situ techniques are used, the quantities monitored are temperature, pH and turbidity. Discharges into a given river stretch are permitted only at a level which maintains the required water quality.

The water quality of inland water bodies eg lakes, including algal blooms, is also monitored. Remote sensing may help in determining the optimum sites for water quality measurements.

2.2.3 Radioactivity

Radioactivity levels are monitored by the Agency only at authorised sites. There are two distinct areas of monitoring; on-site inspection of processes, where an Agency inspector is permanently based at a site, and the monitoring of any discharges to water and of sediment movement. Site monitoring also involves the inspection of radioactive waste storage.

No large scale mapping of any areas of the UK exists to indicate background levels of radioactivity. Therefore it would not be possible, for example, to accurately quantify the effect of a ‘Chernobyl-type’ incident. The provision of such a map may not be considered particularly desirable, for political reasons. However, a mapping of relevant sites may prove useful.

2.2.4 Air quality

The current Agency activity in this area comprises the inspection of records pertaining to the monitoring of emissions from authorised processes; such data being generally derived from stack monitoring instruments. This monitoring is a statutory duty of the Agency.

The monitored constituents are ozone, nitrous oxides, sulphur dioxides, benzene, 1:3 butadiene, carbon dioxide, aerosols. In each case, instrumentation is required to offer a limit of detection of at least 5 parts per billion.

The Agency does not currently make independent measurements of air pollutants. In addition, no general measurements of air quality are currently undertaken by the Agency.

The distribution of pollutants into the environment is currently determined by modelling. Data on plumes and dispersion to compare against such models would be useful.

Local authorities tend to look to the Agency for advice on air pollution measurement techniques.

2.2.5 Waste

The Agency has a requirement to monitor landfill sites. The main areas of interest are in the content and volume of deposited waste, the emissions of methane and the movement of any pollutants underground, ie into the underground hydrology.

Some work has been undertaken to employ LiDAR to determine volumes and available void spaces. Volumes deposited in landfill sites need to be declared quarterly for tax purposes so that this exercise provides some check on returns. In addition, estimates of the remaining capacity and fill-rates, allow the agency to plan future landfill strategy. The agency is also responsible for determining the suitability of voids for future land-fill sites.

Methane emissions from land-fill sites are currently estimated. Although measurement is possible this is not routinely carried out. Methane emission from land-fill sites is a major contributor to greenhouse gas emissions and consequently is of increasing interest and concern.

Monitoring the migration of pollutants into the underground hydrology is currently undertaken by laboratory analysis of water samples taken from bore holes.

2.2.6 Pollution incidents

The Agency is responsible for pollution incidents originating on land but is not formally responsible for pollution at sea (eg oil discharges). However, if an oil slick reaches the shore the Agency does have responsibility and this may require information on slick movement and extent.

The Agency would also have responsibility for the handling of pollution incidents in rivers.

2.2.7 Contamination of land

There are two principal areas of concern at present. One is the effect of heavy metal build-up in agricultural land brought about by the spreading of treated sewage sludge. The Agency has responsibility to authorise such spreading and needs geographically detailed information to allow such decisions to be made. The other is the use of fertilisers on land and more specifically the run-off of nitrates and phosphates into water systems. Determination of the location of crops associated with high levels of nitrate run-off, such as potatoes and sugar beet, could be used to target farm inspections.

In addition there is concern over land which may have been contaminated by past industrial practices, eg old industrial sites, buried waste sites. At present there is no UK map of such sites, many of which remain to be identified.

2.2.8 Climate change

The Agency is required to form an opinion on the state of the environment and therefore on the effect of climate change on the environment.

A number of areas of the Agency's activities and responsibilities can be considered under this subject. These include the monitoring of methane and CO_2 emissions, sea level rise, changes in the geographical and seasonal distribution of rainfall, changes in the frequency and severity of storms and flooding and the effect of climate change on species.

2.2.9 Biodiversity

Human activities, particularly pollution and the destruction of habitats, are leading to a change in biodiversity – the variety of life forms and ecosystems. Sensible and accessible indicators of biodiversity need to be established and hence changes monitored. Such monitoring would also hope to reveal the source of pressures on biodiversity, eg pollutants. The Agency needs to be able to provide, say, maps showing variations and distributions of species.

2.2.10 Land-use and land-cover

The Agency has an interest in land-use and land-cover. Changes in land-cover may impact on water quality or on the way in which rain/flood water is distributed. The Agency does not have a formal responsibility to monitor land-use or cover but it does impact on other applications eg biodiversity.

A high resolution, land-cover map of the UK would be desirable. To be useful such a map would need 3-4 meter resolution and data would need to be updated at least once a year, but preferably four times a year, once for each season. Such data should be capable of distinguishing crop types (eg cereal from root crops), identifying bare winter fields and distinguishing between spring and winter sown crops.

2.2.11 Marine and coastal water quality

Coastal waters are monitored for water quality, chlorophyll content, sediment concentrations and movements, and the movement of plumes. Much of this monitoring is carried out using an airborne CASI instrument. Algal blooms at sea are monitored using NASA's SeaWiFS sensor.

The CASI instrument is also used to monitor the extent of salt marshes, the species type on salt marshes and algae on mud flats in estuarine areas.

2.2.12 Others

In addition to the above there are a number of other applications which are of interest to the agency:

- Water quantity and flow rates in rivers.
- Detection and measurement of water extractions from rivers.
- Use of water for irrigation.
- Illegal tipping (eg in lay byes).
- Recreational uses (eg fishing on rivers)

2.3 Current Remote Sensing Techniques

The following list identifies remote sensing techniques currently used by the Agency. The techniques are divided into those which are considered established and those which are at a more experimental stage.

Established

- River gauges for flood monitoring.
- LiDAR is used for terrain mapping for flood defence purposes.

Experimental

- SeaWiFS sensor (NASA global ocean colour monitoring mission) is used for tracking algal blooms out at sea.
- An airborne CASI instrument (visible band hyperspectral imager) is used to map the extent and vegetation species types, growing on salt marshes (entire English and Welsh coast lines). CASI is also used to determine the chlorophyll content in near shore waters.
- Ground based LiDAR is employed in the determination of landfill site deposited volumes and voids.

2.4 Identified Shortcomings of Remote Sensing Techniques

The interpretation of CASI data requires ground data to be recorded at the time of flight. The accurate determination of chlorophyll content is still a problem. Improved species determination is required and a more robust determination of species type from one area to the next. The spatial accuracy (mapping CASI image to ordnance survey map) is currently only about 400m, this is being addressed and is expected to be improved.

The use of ground LiDAR for landfill site monitoring is found to be expensive and does not offer the required coverage of sites.

2.5 Priorities and Key Areas

The areas of flood defence and water quality have been identified as key areas for the Agency, in that these areas consume the largest portions of the Agency's budget. A cost-effective remote sensing solution to some of the monitoring requirements in these areas could therefore be very beneficial.

Other areas which it seems likely will grow in significance to the Agency in the next few years are greenhouse gas emissions and air quality. Future directives are likely to suggest targets such as:

- 65% reduction in biodegradable waste.
- 12.5% reduction in greenhouse gas emissions (methane, CO_2).
- 30% improvements in composting of household waste.

A recurring theme was the lack of national, thematic maps and bench marks against which to assess changes – ideally the Agency needs to monitor changes at a 5% change level to a confidence of 95%. Related to this was an inability to obtain a national assessment of the impact of stresses on the environment.

2.6 Timescales

The terms of this study call for a consideration of likely remote sensing capabilities within the next 5 years. However, the Agency has set aside a budget for the next two years to develop and/or assess one or more of the promising remote sensing technologies recommended by this study. Therefore, whilst not excluding capabilities expected to be available in the 5 year time frame, the study should focus on technologies which are relatively mature. The application may of course be an entirely novel one.

3 REVIEW OF SENSORS AND TECHNIQUES

3.1 Microwave (SAR and Passive Microwave)

3.1.1 Technical aspects of SAR

Basic principles

Most imaging radar systems are side looking radars which rely on the forward movement of the radar (usually carried on aircraft or satellite) to sweep out an imaged swath to one side of the flight track. The resultant radar image is a measure of the strength of the radar return at different points in the swath, brightly scattering features are either strongly conducting (eg, metallic) or have a roughness which is comparable with the radar wavelength. Different forms of vegetation will scatter radar signals in different ways depending on leaf size, shape and orientation and on their moisture content; this enables different land cover types to be identified in radar imagery. Equally, the radar will differentiate between smooth water and its surroundings although rough water may sometimes be confused with vegetation. Because of the radar's sensivity to surface conductivity, the radar image can also be used to measure soil moisture, although account has to be taken of the contribution of the presence of any vegetation.

The resolution of the radar image is determined by the pulse length and along track beam width - the latter being set by the radar frequency and antenna size. In order to provide a fine resolution it is usual to employ synthetic aperture radar (SAR) together with pulse compression; with these techniques resolutions of the order of 1m should be obtained, even from space. A consequence of the use of SAR is that the resultant image has a speckled appearance through the use of a coherent imaging process. Although the speckle can obscure some detail it can also be alleviated by use of speckle reduction algorithms.

From the above it is considered that radar remote sensing has *potential* to address a number of the Environment Agency's applications, ie:

- Flood monitoring.
- Flood prediction (from knowledge of land cover and soil moisture).
- Land cover (and hence biodiversity and impact of climate change).
- Waste site monitoring (using high resolution images).
- Oil pollution of water and shoreline.

The effectiveness of radar (or SAR) in satisfying these applications will depend on the extent to which vegetation classification can be reliably carried out. Some key developments in techniques which could improve the performance of SAR for these applications are described below.

Key developments in SAR imaging

One of the powerful developments in the past decade is the exploitation of the coherence property of SAR to form SAR interferograms – InSAR. Across track interferometry uses a sequence of two SAR images taken from slightly different positions to create an interferogram in which displacement of the interference fringes is a measure of changes in phase at different positions in the scene. These displacements can be used to derive changes in surface elevation and hence, to construct accurate digital elevation models. Such information can be used to generate hydrology models which can then assist in flood prediction. Subsequent interferograms of the same scene can be used to detect small changes in topography (Differential Interferometric SAR or DinSAR). The latter can be used to monitor land slips, subsidence and coastal erosion. Along track interferometry is used to measure phase shifts caused by movement of the surface; this may have applications for current measurement in rivers.

The formation of a good SAR interferogram requires that there is no change in the make up of the individual scatterers which comprise the scene. In practice, there may be a period of several days between the two SAR images (35 days in the case of the ESA ERS SAR satellites, see p16) and this means that significant changes can occur to the scatterers, for example growth of vegetation or movement of soil through action of wind or rain. These changes mean that the scenes lose their coherence and in the limit, make it difficult to form a good interferogram. However, the changes in coherence can be used as a method of classifying types of vegetation and *coherence maps* may be used to indicate variations in land cover within an image.

The changes in coherence described above are changes due to growth, weather or other similar causes. In some cases, localised changes of coherence may occur within a scene which is otherwise generally coherent. These localised changes may be the result of man made activities (eg, clear cutting in forests) or to natural effects such as erosion or subsidence. The detection of changes in coherence is therefore a powerful tool for *change detection* and hence potentially useful for detecting environmental changes.

Another key development is in the use of SAR polarimetry. Conventional radar transmits a single frequency at a single polarisation – linear or circular. The resultant image contains a measurement of backscattered power – a measure of the scattering coefficient of different parts of the imaged scene. In the case of SAR the backscattered information contains both the modulus and the phase; it is the latter which enables SAR interferometry. Some SAR systems can transmit a linearly polarised pulse in which the direction of polarisation is rotated by 90°, ie, from horizontal to vertical polarisation. In addition, the antenna can be set to receive both horizontal and vertical polarisation. Thus the radar can measure backscattered energy at the two different polarisations and this energy can vary depending on the nature of the surface; for example vertical stands of vegetation will tend to reflect more strongly at vertical polarisation.

The radar will also measure the *cross polarisation* return; this is energy in which the plane of polarisation has been rotated by scattering within the imaged surface or by multiple reflections from one scattering surface to another. An example is scattering within a forest canopy which typically produces a strong, cross-polarised backscattered. The combination of all backscattered signals (ie, horizontal polarisation, vertical polarisation and cross polarisation) together with the phase information enables a complete description of the polarisation scattering matrix for the surface to be obtained. This is usually known as quad (four channel) polarisation. This could greatly assist in the discrimination between different types of vegetated surface and hence, of land cover.

The combination of interferometric and polarimetric techniques (ie, *polarimetric interferometry*) is a very recent development in which interferometry is used to identify the position of scatterers within a canopy which are then classified using polarimetric techniques.

This development, while in its infancy, offers the potential for more detailed identification and discrimination of vegetation.

A further development is in the use of multifrequency radar or SAR systems. Different radar frequencies will vary in the way they are backscattered by surfaces; an area of short grass may appear bright when imaged at X band (9.8GHz or 3cm wavelength) but quite dark if imaged at L band (1.7GHz or 30cm wavelength). In addition, different frequencies will have different penetration capabilities; L band will be scattered by the lower parts of a forest canopy while X band will be scattered mainly by the top surfaces. The use of radar systems with two or more frequencies can therefore provide much more information and can in principle give a more precise classification of vegetation type and its characteristics.

Review of spaceborne radar/SAR sensors – present and planned

Table 3.1. lists the principal satellite SAR systems which are either in service or planned. Each system is described in the following paragraphs:

a) ERS-1/2

The ERS-1 satellite was developed by the European Space Agency (ESA) primarily as a maritime satellite. It carries a number of sensors:

- A wind scatterometer.
- An imaging radar (SAR).
- A radar altimeter.
- An infra red imager (Along track scanning radiometer).

The scatterometer and SAR are operated from the same microwave amplifier although different antennae are used. The choice of 5.3GHz and 23deg incidence was made in order to obtain maximum discrimination of sea surface features although the SAR has also been shown to be effective for land applications. The SAR image size is approximately 100km x 100km and the nominal resolution of 30m allows for some speckle reduction. The orbit is polar and sun synchronous with crossing times in the UK of approximately 1100 and 2300. The revisit period is 35 days although in the UK an approximate revisit occurs every 17 days. The nominal satellite life is 3 years and a second ERS satellite was launched in 1994 – this satellite is still in use but nearing the end of its life. There is no data storage on the satellite for SAR data so a network of ground stations has to be used. The UK ground station is located in Scotland and is operated by DERA although ERS data may also be obtained from the UK Processing Facility managed by Infoterra in Farnborough. The ERS satellite has been used to support applications development in many different fields and one of its most significant achievements was the realisation of satellite SAR interferometry with applications for terrain mapping and change detection.

Table 3.1. Satellite SAR systems: present and planned.

System	Frequency	Polar'n	Incidence Range	Revisit interval	Resolution	Image size	Launch date
ERS-1/2	5.3GHz	VV	23deg	35days	30m	95km	1994
Radarsat 1	5.3GHz	HH	20 to 50deg	24days	9m to 100m	50 to 500km	1994
Radarsat 2	5.3GHz	Quad-pol	10 to 60 deg	24days	3m to 100m	10 up to 500 km	2001
ENVISAT (ASAR)	5.3GHz	Dual-pol	15 to 45 deg	35days	30m to 100m	50 up to 400km	2001
ALOS (PalSAR)	1.7GHz	Dual-pol	18 to 48deg	45days	10m	70km	2002
SRTM	5.3GHz/ 9.8GHz	Quad-pol	20 to 60 deg	NA	25m	50km	2000
Lightsar	1.27GHz	Quad-pol	20 to 60 deg	8 to 10 days	3m to 100m	20 to 500km	TBD
TerraSAR	1.7/ 9.8GHz	Quad-pol	20 to 55 deg	11days	1m to 35m	10km to 200km	2003
Almaz 1B	8.59/3.13/0.43GHz	Dual pol 0.43 only	Not stated	Not stated	5m to 30m	20km to 170km	TBD
Skymed/ Cosmo	9.6GHz	Dual pol	20 to 55 deg	0.7 hours	3m	40km	2001
Radar 1	9.8GHz	HH	27 to 58 deg	1 day	1m	6km	TBD

b) RADARSAT 1

The Canadian RADARSAT 1 satellite carries only one sensor, a SAR. Although this has the same frequency as ERS (5.3GHz) it differs in being horizontally (HH) polarised and in having electronic steering. This means that the beam can be steered to different incidence angles (from 20° to 49°); it means that the sensor is much better suited to imaging land features. The electronic steering also enables a wide beam (Scansar) mode to be realised with a swath of up to 500km in width. It also means that the revisit time can be reduced from the nominal 24 days to about 5 days provided that the incidence angle is not critical. The satellite is in a 'dawn /dusk mission' in order to improve power efficiency, this means that passes occur at about 0600 or 1800. RADARSAT also has a fine resolution mode in which the resolution is improved from the nominal 28m to 9m (although speckle will be more intrusive). RADARSAT 1 has five modes of operation, as shown in Table 3.2:

Table 3.2 RADARSAT modes

Mode	Incidence angle range	Resolution (range/azimuth)	Swath width
Standard	20 – 49 degrees	25m/28m	100km
Wide	20 – 45 degrees	35m/28m	150km
Fine resolution	35 – 49 degrees	9m/9m	50km
Scansar(narrow)	20-40/32-46 degrees	50m/50m	300km
Scansar(wide)	20 – 50 degrees	100m/100m	500km
Extended high	50 – 60 degrees	25m/28m	75km
Extended low	10 – 20 degrees	25m/28m	75km

The table shows the flexibility introduced by electronic steering and the wide range of imaging options. RADARSAT 1 has an on board recorder which means that it can acquire data anywhere in the world; it does not require a ground station in the vicinity. Recorded data is downloaded in Canada but images collected of the UK and its surroundings can be received at the DERA ground station in Scotland.

RADARSAT 1 has been successfully used for ice mapping, monitoring fishing fleets and for a wide range of land applications. It has also been used for SAR interferometry.

c) RADARSAT 2

RADARSAT 2 is scheduled to be launched in 2001 as a replacement for RADARSAT 1. It will differ in having more modes of operation including polarimetric modes and a much finer resolution. The radar frequency is the same at 5.3GHz and the nominal revisit interval is also the same (24 days). It is claimed that at UK latitudes a given region could be imaged every two days. The table below shows the principle modes:

Table 3.3 Proposed RADARSAT 2 modes.

Mode	Incidence angles	Resolution	Number of looks	Swath width
Standard	20 - 50	25m/28m	1 x 4	100km
Wide	20 - 45	25m/28m	1 x 4	150km
Low incidence	10 - 20	40m/28m	1 x 4	170km
High incidence	50 - 60	20m/28m	1 x 4	70km
Fine	37 - 48	10m/9m	1 x 1	50km
Scansar wide	20 - 50	100m/100m	4 x 2	500km
Scansar narrow	20 - 46	50m/50m	2 x 2	300km
Standard Quad polarisation	20 - 41	25m/28m	1 x 4	25km
Fine quad polarisation	30 - 41	11m/9m	1	25km
Triple fine	30 - 50	11m/9m	3 x 1	50km
Ultra fine wide	30 - 40	3m/3m	1	20km
Ultra fine narrow	30 - 40	3m/3m	1	20km

Note that the reference to quad above implies that four channels of data are recorded; this is needed if the full polarisation signature of the surface is to be obtained. The recording of four channels means that the swath width is reduced in order to maintain the same data rate. For similar reasons the swath width is reduced for the ultra fine modes.

The RADARSAR 2 satellite could be particularly relevant for the Environment Agency's application because of the polarimetric modes and fine spatial resolution.

d) ENVISAT (ASAR)

The ENVISAT satellite is scheduled to be launched by ESA in 2001 and will carry a large number of core instruments:

- Medium resolution imaging spectrometer (MERIS).
- Michelson interferometric atmospheric sounder (MIPAS).
- Advanced radar altimeter (RA-2).
- Advanced synthetic aperture radar (ASAR).
- Global ozone monitoring by occultation of stars (GOMOS).
- Microwave radiometer (MWR).

In addition there are four 'announcement of opportunity' instruments supplied by member states. The ASAR sensor will have a frequency of 5.3GHz and will have electronic steering capability and dual polarisation. The latter differs from quad polarimetry in that two channels are recorded rather than four and this means that the full polarisation signature will not be obtained. Despite this, it will be possible to operate at vertical or horizontal polarisation and to collect both the parallel and cross polarisation signatures, thus providing an enhanced classification capability. The principal ASAR operating modes are shown below:

Table 3.4 ENVISAT ASAR modes.

Mode	Incidence angle range	Polarisations	Resolution	Swath width
Image	15 – 45 degrees	VV or HH	30m	56km to 120km
Alternating polarisation	15 – 45 degrees	VV+HH, VV+VH, HH+HV	30m	56km to 120km
Wide swath		VV or HH	100m	406km
Global monitoring		VV or HH	1000m	406km
Wave	15 – 45 degrees	VV or HH	30m	5km x 5km

The global monitoring mode is a lower data rate mode intended to allow very large areas to be imaged. The wave mode is intended to gather small images (5km x 5km) of the sea surface for wave measurements. The revisit interval is nominally 35 days although much shorter intervals will be obtained if the full incidence angle range is used.

Data will be received at a network of ground stations and it is planned that the DERA station will also receive ASAR data (and other ENVISAT sensors). In addition, some data will be acquired at the ESA station at Frascati via the Artemis data relay satellite.

e) ALOS (PALSAR)

The ALOS satellite is a Japanese satellite intended for land observations, it will succeed the ADEOS and JERS satellites. The latter carried an L band SAR which was used for land cover measurements, it's mission ended in 1998. ALOS will carry a suite of instruments one of which is a SAR – PALSAR. PALSAR will utilise an active phased array antenna (like ASAR) and will therefore be capable electronic beam steering. It will use L band and will be suited to measurements where some degree of foliage penetration is required, eg, woodland biomass and soil moisture. It is intended that there will be a range of modes similar to those of RADARSAT and ASAR, like ASAR it will have dual polarisation options (ie, HH or VV or cross polarisation).

f) SRTM

The Shuttle Radar Topography Mission (SRTM) is the latest in a series of space radar missions carried on the space shuttle. Earlier missions were flown in 1981 (SIR-A), 1984 (SIR-B) and 1994 (SIR-C). Each mission was of short duration (8-10 days), SIR-C was remarkable in that the radar operated at three frequencies and had quad polarisation modes. The SRTM mission carried two antennae one of which was carried on a long (60m) extendable boom. This allowed the radar to form interferometric pairs of images at the same instant thus avoiding the lack of coherence caused by movement of features (eg, vegetation) on the surface. The radar operated at two frequencies (C band and X band). The mission was launched in February 2000 and was able to image over 80% of the land surface, from which accurate topographical maps will be produced. The accuracy of the digital elevation maps will be approximately 1m, a higher accuracy may also be achievable.

g) LightSAR

LightSAR was intended as a low cost SAR mission to support the NASA ‘Mission to Planet Earth’. To minimise cost the mass would be kept small by use of a lightweight folding antenna operating at L band. The antenna would carry active elements and thus be capable of electronic beam steering; it would also offer quad polarisation modes. In January 2000 a meeting between NASA and the Oil Spill Liability Trust Fund (OSLTF) agreed to form a partnership to establish a new Space SAR mission which would provide an operational capability (for oil slick monitoring) and for environmental monitoring. This mission would use a dual frequency, polarimetric SAR which would effectively replace the LightSAR mission. Funding of the new mission is yet to be agreed and the launch date is to be decided.

h) TerraSAR

The TerraSAR satellite is intended to supply SAR imagery to a new business called Infoterra. This will be a partnership between UK and German industries (ie, Astrium, previously MMS and Dornier) and will aim to sell information rather than images. The business will focus on land applications (eg, crop monitoring) and the radar will operate at two frequencies. It will use L band in order to measure soil moisture and to obtain scattering measurements within the vegetation canopy and it will use X band to provide a high resolution mode for mapping surface detail (eg, set aside land). The L band mode will be quad polarimetric and the radar will have electronic steering. The radar will offer a wide range of products but the key modes are:

- X band spotlight – a high resolution mode with choice of HH or VV polarisation.
- X band strip map mode for larger area imaging again with VV or HH (or both).

- L band strip map mode for imaging large areas with a choice of dual or quad polarisation.

The revisit period will be of the order of 2 to 4 days for most European countries and the satellite will probably use a dawn/dusk orbit. The anticipated launch date is 2004/5 although, since the mission has been proposed for the ESA Earthwatch programme, the funding of the mission has yet to be confirmed.

i) ALMAZ

The Russian ALMAZ-1B mission is a successor to the ALMAZ-1 satellite launched in 1990. The spacecraft carries three radars and an optical sensor plus a LiDAR; the characteristics of the radars are shown below:

Table 3.5 ALMAZ SAR modes.

Radar system	**Wavelength (cm)**	**Resolution (m)**
SAR-3	3.49 (X band)	5 to 7
SLR-3	3.49 (X band)	1200-2000
SAR-10	9.58 (S band)	5-7, 15,30
SAR-70	70 (L band)	30

The SAR-10 radar can view the ground on either side of satellite track, the other radars view on opposite sides. The SAR-70 can also be operated in a quad polarisation mode. The SLR radar is a real aperture system intended to image a wide (450km) swath at coarse resolution. ALMAZ-1B was intended to be launched at the end of 1998 but the current planned launch date is unknown.

The Ukraine OKEAN satellite also carries an SLR radar system intended primarily for imaging sea ice as an aid to navigation. The OKEAN satellite will be followed by a new series (eg, SICH-1, 1M), SICH-2 may carry a SAR payload.

j) Skymed/Cosmo

This system has been proposed by the Italian space agency ASI as a system for monitoring the Mediterranean basin (COSMO – constellation of small satellites for Mediterranean basin observation). It is intended for disaster management, urban monitoring, law infringement monitoring, coastal observations, environment monitoring, agriculture and cartography and mapping. The system will use a constellation of four SAR satellites and three optical satellites. The SARs will be used for high resolution, all weather imaging and the optical for land cover classification – they will use medium and coarse resolution hyper spectral cameras. The system is to be developed by Alenia.

k) Radar1

Radar 1 is a low cost high resolution SAR concept conceived by the US firm RDL. It will use a parabolic antenna (to reduce system costs) and uses satellite rotation to point the radar beam at incidence angles from 27 to 58 degrees. It will use stripmap and spotlight modes to provide medium and high resolution images. The launch date is not yet known. It is planned as a commercial venture aimed at providing high resolution images to governments and industry.

Review of airborne radar/SAR sensors – present and planned

The following table lists the main characteristics of some currently available airborne SAR systems. Note, this list does not include operational military systems but it does include research systems which have been developed by defence research organisations such as DERA, DLR etc.

Table 3.6 Typical airborne SAR systems.

System	Aircraft range	Radar frequency	Polarisation	Radar modes	Resolution	Range	Swath width
ESR	800miles	9.7MHz	Quad pol	Strip, spot, MTI, InSAR	0.3m, 500MHz	100km	1km to 10km
E-SAR	400- 500 miles	9.6,5.3,1.3 0.45 GHz	Quad pol (1.3GHz)	Strip	2m	NS	3 to 15 km
PHARUS	NS	5.3GHz	Quad pol	Strip, spot	3.75x1m	30km	20km
AIRSAR	NS	5.3/1.2/0.4 GHz	Quad pol (all bands)	Polar, InSAR	2m to 10m	NS	5km to 15km
TESAR	NS	9.8GHz	Single pol	Strip, Spot	0.3m	10.8km	800m

a) ESR

The DERA ESR (enhanced surveillance radar) airborne system is a high resolution radar intended for research. The aircraft is a BAC1-11 with a range of 3.5hrs at a ground speed of 240kts. Normal operating height is 29,000ft. The radar modes are: strip map SAR, spot SAR (high resolution mode), all round scan, sector scan, quad polarimetric, interferometric and GMTI (moving target indication). The centre frequency is 9.7GHz and linear (H and V) and circularly polarized transmission is available. The radar look angles are grazing (0°) and 75° depression and the maximum bandwidth is 500MHz (equivalent to 0.4m range resolution). The swath width is limited by the number of range samples collected (4000 range gates). Using spotlight mode the along track resolution is 0.3m. The maximum coverage is limited by the overall flight duration but is typically about 1 hour. Image location accuracy (prior to registration) is approximately 25m at 100km range. Image processing is carried out on ground (after the flight – there is no electronic down link) and a turn round time of about 24hrs from data take to image delivery could be achieved if required. The processing is currently in slant range projection. Currently, the system is completing acceptance tests but it has already been used to support some experiments.

It should be noted that a helicopter borne SAR has also been developed by Racal as a research tool, primarily for high resolution multipolarisation SAR studies.

b) E-SAR

The E-SAR has been developed by the German DLR research centre and is a multifrequency (X, C, L and P bands) system carried on a Dornier 228 aircraft. Initially the radar had selectable vertical or horizontal polarisation but this has been extended to include quad polarisation for the L band mode. The SAR can also be operated in interferometric SAR modes. Under favourable conditions (ie, low wind speeds) the azimuth resolution can be improved to less than 1m. Although data is recorded on board (for subsequent ground processing) the aircraft also carries a real time processor. Normal altitude of operation is 12000ft and a typical mission lasts 3hrs. A range of products are available including single and multilook, single look complex, geocoded images and digital elevation models. The SAR is well calibrated and calibration flights are carried out to maintain system performance. The system has been extensively used to support research in Europe and has been used in a number of campaigns, eg, EMAC '94 and '95. It is planned that the aircraft will be used in the BNSC sponsored SHAC campaign in the UK in summer 2000.

c) PHARUS

The Pharus airborne SAR was developed in the Netherlands by collaboration between different research groups: TNO-FEL, NLR and TU Delft. It uses an active phased array antenna to steer the radar beam and to avoid antenna gimbaling systems. The radar is carried in a pod outside the aircraft and data is recorded and processed inside. Ground based processing may also be carried out. The radar is well calibrated (it uses an internal calibration system) and has programmable radar settings and modes including multipolarisation modes. It has been used for a number of research projects including crop classification, land cover mapping and oil slick detection.

d) AIRSAR

The NASA AirSAR is an airborne research laboratory operated by the Jet Propulsion Laboratory (JPL) in California which has seen world wide service including a number of sorties to Europe. The aircraft is a DC8 giving a range of several thousand miles. The radar has a number of modes:

- POLSAR – C, L, and P band polarimetry.
- ATI – along track interferometry (C and L band, VV polarisation).
- XTI – across track interferometry or TOPSAR (choice of four sub modes using combinations of interferometry and polarimetry).

Note, C, L and P band wavelengths are 0.057, 0.25 and 0.68 m respectively; the P band is particularly suited to ground or foliage penetration. Data is recorded on board, typically for 60km strips. On board processing is carried out and the instrument is well calibrated. The AirSAR has been widely used to support research, particularly for environmental applications, eg, measurement of forest biomass.

e) TESAR

This system is included as an example of the use of unmanned aircraft (UAV) for remote sensing. In this case the aircraft is the Predator UAV equipped with an X band SAR capable of producing high (0.3m) resolution imagery. A notable feature of this system is the near real time image processing and transmission to the ground based observer who is able to monitor the strip map image as the aircraft passes overhead. The strip map resolution is 1m but a high resolution spotlight mode (0.3m) is also available. The aircraft has been developed by the US DOD for military surveillance.

Ground based systems

A number of ground based radars have been developed for measuring surface backscatter. These have generally been developed for research purposes although some portable systems have been used for operational applications, eg, detection of underground pipes. Ground based scatterometers (ie, non imaging instruments) have been used in the US (eg, University of Kansas) and a comprehensive indoor scatterometer is operated by the JRC at Ispra, Italy. In the UK a unique ground based SAR is being developed. This is a research facility under development at the University of Sheffield [Morrison 2001]. It uses a 4m long linear scanner mounted on a hoist to provide an operating height of between 1 and 10m. The scanner carries a pair of antennae (horns) which are moved to form the synthetic aperture and to obtain the required ground resolution. It will operate at 1.5, 3, 6 and 10 GHz and have a maximum range of 60m. The sensitivity is of the order of -70 to -100 dBm^2. The hoist is mounted on a trailer which is towed by a four wheel drive vehicle; the latter also houses the control system and microwave subsystems. The system will be used to study backscatter processes from vegetation.

The JRC indoor facility is complemented by their mobile, linear SAR system , LISA, [Rudolf *et al.* 1999] which operates at frequencies ranging from 500MHz to 6GHz with dual polarisation modes. At a range of 100m the resolution is 50cm (in range) and 3cm (cross range).

Summary with indication of those developments important for the Environment Agency

It is considered that the developments most important to the Environment Agency are those with the following features:

- High resolution
- Multipolarisation
- Dual or multifrequency

Where airborne facilities are concerned, there are a number of systems available which could be used for applications research and development (eg, the DLR E-SAR) but have not yet been used for regular or routine use. There are a number of satellite borne systems which could be of importance; these include:

- ENVISAT ASAR (dual polarisation),
- RADARSAT 2 (higher resolution and multipolarisation),
- TerraSAR (as RADARSAT 2 but with dual frequency).

These systems will become operational in the next 1 to 5 years and should therefore be considered as potential sources of data for the Agency's applications.

3.1.2 Radar/SAR applications to meet Environment Agency requirements

Overview

As stated earlier, the Environment Agency applications which are considered addressable by radar or SAR are:

- Flood prediction.
- Flood monitoring.

- Land cover.
- Waste site monitoring.
- Oil pollution.

These topics are discussed in turn below together with examples taken from the literature survey.

Flood prediction and flood defence

Flood prediction is a key application for the Environment Agency and requires the development of accurate 2D hydraulic models to predict water movement over flood plains. The models need two dimensional data for calibration and validation and this is where remotely sensed data is useful. For calibration, the models need flood plain topography accurate to 10cm and also vegetation heights. In principle, Interferometric SAR (InSAR) might be used but 10cm order of accuracy has yet to be demonstrated, either from space or airborne systems. (In any case, airborne LiDAR has already been used to provide information both of ground topography and of vegetation height.) For validation of models, the flood extent can be measured with SAR for comparison with the model output. A problem here is the discrimination of the water edge from vegetation, especially in areas where the vegetation is partly submerged. Satellite SARs such as ERS-1 have been shown to be effective at measuring flood extent and are only handicapped by poor temporal coverage; however future SAR systems such as ENVISAT ASAR will be more effective because of their wide area coverage. This SAR may also be more effective at discriminating the water edge though use of multi-polarisation modes.

Bach, *et al* [1999] discuss an integrated flood forecast system based on elevation data and soil moisture obtained from satellite SAR. The need for high temporal and spatial resolution was stressed if accurate forecasts are to be obtained. The feasibility of measuring soil moisture in the top 5-10cm was shown by Biftu and Gan [1999] in experiments using RADARSAT data. They found that measurements became inaccurate at high moisture levels and that results were very sensitive to surface rms height. A detailed study [Laymon *et al.* 1999] using ground based radar operating at L, C and X bands detected soil moisture changes due to rainfall and subsequent evaporation. A similar experiment using airborne sensors is reported by Chauhan [1997]; in this case both SAR and passive microwave sensors were used and results showed excellent agreement with in-situ soil moisture measurements.

One of the problems in estimating soil moisture using radar is the presence of vegetation. DeRoo, *et al* [1999] have shown that polarimetric radar can be used together with a simple inversion algorithm to determine volumetric soil moisture and vegetation water mass in the presence of a vegetation canopy. Similar results were reported by Sarabindi and Ulaby [1997]. In a different approach, Nesti, *et al* [1999] showed that changes in moisture profile could be correlated with changes in phase of the backscattered signal although the phase – moisture relation is highly complex and also influenced by surface roughness. The role of surface roughness in measuring soil moisture was emphasised by Le Toan [1999] where an attempt was made to incorporate statistical information on surface roughness into moisture inversion models. Finally, the extraction of soil moisture from the effects of other parameters such as terrain relief, surface roughness and vegetation can be improved through use of multitemporal data. Verhoest, *et al* [1998] showed that a principal components analysis of a time series of eight ERS-1 SAR images allowed soil moisture patterns to be determined; these correlated well with observed rainfall runoff dynamics in the vicinity of a river.

A further problem in the prediction of flood occurrence is modelling of the impact of vegetation. This requires accurate information on vegetation type, height, etc and may be inferred from radar observations; this aspect is discussed under land cover. It should be noted that much work has been done on flood modelling and flood mapping in the UK by the Environmental Systems Science Centre (ESSC) who currently have existing projects in this area, [Horritt *et al*. (in press)].

Flood monitoring and flood damage assessment

In flood monitoring the radar would be used to monitor the extent of flooding (by identifying water/land boundaries) in order to provide information to rescue teams and to assist evacuation. Here the coverage would be very focussed on specific areas and would require frequent updates of the order of hours.

Hagg and Sties [1999] give a good account of how remote sensing, particularly SAR was used to monitor flooding of the Oder river in Germany. They found that Radarsat was better than ERS-1, partly because of the short revisit interval and partly through use of a shallower incidence angle. They commented on the difficulties of separating water and land when vegetation was present. Subsequent work by the same authors showed that fuzzy logic techniques could be used to develop an automated, unsupervised SAR classification system and this was demonstrated on the Oder River data.

Delmeire [1997] used ERS-1 SAR to distinguish between oceanic floods in the Rhone and torrential flooding in the Var valley. Data was obtained from before, during and after the floods and was successful in delineating oceanic floods but that torrential floods were less accurately mapped. The reason for this is the high turbulence of flood waters, making separation from land surfaces more difficult. Brackenridge *et al* [1998] used ERS-1 SAR to study flood water profiles in the Pecatonica River Valley and found that reasonably good agreement was obtained with hydrological models although the presence of obstructions such as raised railroad crossings caused the measured discharge rate to deviate from the model.

Heavy flooding is a recurrent problem in the Far East and airborne SAR is used by the Chinese [Huadong 1995] to map flood extent. The experiences in China have led to the development of a process for accurate flood assessment using satellite images [Prinet *et al.* 1999]. Here optical data from the SPOT satellite is used to provide the reference image with which the SAR image (containing flood information) is registered allowing flood extent to be obtained. The registration was done in this case by co registering identified features rather than by pixel to pixel correlation. It should be noted that similar approaches have been proposed for other sensors eg, [Lobanov and Usachev, 1999].

Land cover

Identification of different forms of land cover may be used to detect changes which could impact on other Agency application areas such as inland water quality or to indicate consequent changes in the diversity of species present. In this case a multipolarisation SAR could be used classify different types of vegetation and to indicate changes in their distribution (using coherence techniques). However, a more detailed classification would probably require the use of additional sensors, particularly hyper-spectral sensors.

A good review of the use of SAR for ecological applications is given by Kasischke, *et al* [1997]. This paper compares different systems for their effectiveness in measuring vegetation parameters and concludes that multifrequency systems with polarisation capabilities are ideally needed. This suggests that the proposed TerraSAR system should be of importance to the Environment Agency.

Waste monitoring

Waste monitoring might use high resolution SAR to measure infill capacity and hence to provide an estimate of waste volume. The SAR might also be used to classify waste (from scattering characteristics) although this is considered less feasible. No references were found which covered waste applications explicitly although there are several which discuss change detection techniques.

Pollution monitoring (coastal)

Oil pollution at sea dampens the wind driven capillary waves responsible for much of the radar backscatter and hence allows oil slicks to be easily detected in SAR images. A good account of the use of satellite SAR for this application is given by Gade and Alpers [1999] who showed that the presence of slicks varied with time of day (because much pollution occurred at night). It also varied with season (because of the higher wind speeds in winter, tending to break up slicks). Similar reports are made by Singh [1995] and Martinez and Moreno [1996]; the latter proposed a low cost system based on the use of satellite SAR for the detection of marine oil spills.

One of the problems in the use of SAR in this application is that oil spills are often indistinguishable from other slicks (formed by naturally occurring films). Espedal and Wahl [1999] showed that the interpretation of SAR images for this application can be aided by using a knowledge of wind history. This allows the shape and position of the slick to be matched against wind history in order to estimate slick age. Trivero, *et al* [1998] used a three band (P, L and C bands) airborne SAR to investigate the damping of sea surface waves. They found that there was good agreement between ratios of SAR pixel intensities obtained for slicked and unslicked water and ratios derived from wave gauge measurements. These results indicate that SAR can be used to accurately monitor surface water quality.

A good review of oil spill monitoring technology is given by Fingas and Brown [1997a]. Here they suggest that whilst radar might be suited for wide area, foul weather searches, laser fluorosensors are the only sensors which can accurately discriminate oil on beaches where the background is cluttered by seaweed and other debris.

Summary of key applications addressable by radar/SAR

The key Agency applications which are considered addressable by SAR are flood monitoring and land cover mapping, particularly vegetation mapping. Flood monitoring has been demonstrated on a number of occasions and its development is probably limited by relatively poor timeliness from satellites or by the cost of operating an airborne SAR system. Vegetation mapping using SAR is expected to become more comprehensive with the development of advanced SAR systems, especially satellite systems. However, significant research will be needed in order to develop reliable inversion algorithms for these systems.

3.1.3 Technical aspects of passive microwave systems

Basic principles

Passive microwave sensors are used to detect the self emitted (thermal) radiation from the atmosphere or from the ground at frequencies ranging from a few GHz to several hundred GHz. This radiation is very weak (compared with infra red intensities) and performance at the higher and stronger frequencies is inhibited by poor transmission through the atmosphere. In fact, a prime use of satellite borne passive microwave sensors is the measurement of atmospheric water content. For observations of the Earth's surface, passive microwave sensors are effective in measuring soil moisture content, for observations of snow or ice covered regions and also for detection of oil pollution at sea.

One of the factors limiting the use of passive microwave sensors for ground observations is the poor resolution (especially from space): in order to obtain a good resolution a large antenna would have to be used. Because the sensor is passive, synthetic aperture principles cannot normally be used but developments in such techniques may eventually provide an improved performance with smaller antennas.

The selection of frequency bands depends on the application, ground observation tend to make use of transmission 'windows' in the atmosphere (eg, soil moisture requires 1.4GHz) whilst atmospheric sensors operate at the absorption bands (eg, atmospheric water content at 21 or 22 GHz). Measurement of atmospheric water is usually needed to correct for radiation measurements at other frequencies.

Passive microwave sensors are radiometers and are often used simply to make measurement profiles as sounding instruments, eg, the Advanced Microwave Sounding Unit (AMSU) flown on many meteorological satellites. Other passive microwave sensors require some form of scanning mechanism to allow an image to be formed. An example is the Special Sensor Microwave Imager (SSMI) which is carried on the NOAA weather satellites; it can be used to form images of sea ice and snow covered regions. However, the relatively poor thermal sensitivity means that the scanning speed is generally limited. An important feature of passive microwave radiometry is the need for internal calibration in order that constant accuracy is maintained.

Passive microwave sensors are extensively used on weather satellites for atmospheric sensing and are a major source of data for meteorological applications. They are also used for oceanographic applications, eg, the Scanning Multichannel Microwave Radiometer (SMMR) used on the SEASAT and NIMBUS satellites and airborne sensors have been used for water salinity measurements and for determining the thickness of oil layers on the ocean surface. For both the atmospheric and ocean applications the relatively poor resolution does not present a significant disadvantage.

Passive microwave sensors are also of interest for military applications where all-weather, passive sensors are required for battlefield and short range operational applications. Here the ranges are such that the atmospheric propagation loss is small and higher frequencies can be considered, eg, up to 220GHz. The advances in solid state devices have enabled the sensitivity of such sensors to be increased, for weight and size to be reduced and for electronic scanning to be implemented.

For the Environment Agency, the principle benefit from use of passive microwave sensors would be in measurement of soil moisture as an input to flood forecast models. Passive microwave sensors would also have application in detecting oil slicks both on the sea and on the shore. Although passive microwave sensors may have some capability in discriminating some vegetation types it is not considered that any advantage would be offered over optical or SAR sensors.

Review of spaceborne passive microwave sensors

As stated earlier, a number of passive microwave sensors have been used on satellites, mainly for meteorological applications. Table 3.7 gives the characteristics of some current sensors together with details of new sensors which are under development.

Notes: NOAA: National Oceanographic and Atmospheric Agency polar orbiting meteorological satellite,
METOP: the ESA/EUMETSAT polar orbiter,
DMSP: Defense Meteorological Satellite Programme polar orbiting satellite,
AQUA: the NASA Earth Observation System polar orbiting satellite – equator crossing in pm,
ADEOS-II is the Japanese environment monitoring satellite.
AMSR-E supersedes the Multifrequency Imaging Microwave Radiometer (MIMR) which was to have been developed by ESA.

Table 3.7 Satellite passive microwave sensors, current and planned.

Sensor	**Satellite**	**Frequency range (GHz)**	**Swath (km)**	**Launch date**	**Application**
AMSU (B)	NOAA & METOP	89, 150, 183	2100	Operational	Atmosphere humidity profiles
AMSU (A)	NOAA & METOP	24 to 89 (15 channels)	2100	Operational	Atmosphere temperature profiles
SSMI	DMSP			Operational	
AMSR-E	AQUA (EOS-PM)	6.295, 10.65, 18.7, 23.8, 36.5, 89.0	1445	Dec 2000	Cloud properties, Precipitation, sea ice, snow cover, SST.
AMSR	ADEOS-II	tbc	tbc	2001	tbc
MHS	NOAA & METOP	As AMSU(B)	2100	2002	Humidity profiles

Review of airborne passive microwave sensors

A large number of airborne passive microwave sensors have been developed, the majority for meteorological applications. An excellent survey of these has been made by Tim Hewison [private communication] of the UK Meteorological Office; the list also includes ground based instruments. Sensors operated within the UK include the MARSS and DEIMOS radiometers. More advanced concepts use synthetic aperture techniques, examples of these are the HUT and ESTAR radiometers. The principle features of these systems are given in Table 3.8 below:

Table 3.8 Airborne passive microwave sensors

Sensor	Aircraft	Frequency range (GHz)	Swath	Application
MARSS	C130(UK)	89, 157, 183.31	10° beam	Cloud water/ice, precipitation, radiative transfer.
DEIMOS	C130(UK)	23.8, 50.1	11° beam	Surface characterisation, atmospheric water vapour, Oxygen absorption
ESTAR	C130(US)	1.41	200m ground res'n	Soil moisture
HUT system	Short SC-7	1.4	5 to 7° beam	Soil moisture, sea surface salinity

Notes:

1) MARSS and DEIMOS are both operated by the UK Meteorological Office and are used to validate models to support operational exploitation of satellite payloads such as AMSU.

2) The ESTAR [http://jazzman.gsfc.nasa.gov] and HUT [Rautiainen *et al.* 1999] systems are radiometers which use aperture synthesis to improve performance, this being particularly necessary since relatively low frequencies are required (for soil moisture measurements). The ESTAR (Electronically Scanned Thinned Array Radiometer) uses two antennas as components of a two element interferometer; it has been widely used as a research tool prior to possible development of a satellite borne instrument. The HUT sensor (Helsinki University of Technology) uses an array of 36 antennas arranged in groups each with single receiver unit and calibration unit and local oscillator. Both instruments use internal calibration systems.

Ground based systems

Some of the instruments identified above (eg, MARSS) have also been used as ground based systems but these are still used essentially for atmospheric applications. Other ground based systems include the DERA MITRE [Appleby. R, personal communication] system which uses a 1.2m square antenna operating at 94GHz to produce high resolution images at up to 1.5km range. Subsequent development of affordable 2-d detector arrays had led to the development of a real time imager – MERIT – which has 32 receive channels and currently operates at 28-33 GHz. The major feature of this instrument is that a 125 x 68 pixel image is produced by scanning the image across the 32 receive channels. These imagers have been used to produce good images of various objects – buildings, vehicles, people – in conditions of very poor visibility. However, it is unlikely that such systems would be of value to the Environment Agency for their current applications.

Summary

The developments which are expected to be of most interest to the Environment Agency are those in which synthetic aperture techniques are used to produce better resolution and sensitivity for applications such as soil moisture measurement and oil slick detection. At present there are no such sensors planned for satellite observations and only a few airborne facilities exist, mainly in the US. The UK airborne facilities are mainly used for atmospheric and meteorological research and are unlikely to be useful for Environment Agency applications. Despite this, sensors such as the satellite borne AMSR may have some application in cases where spatial resolution is not critical.

3.1.4 Passive microwave applications relevant to the Environment Agency

Soil moisture

The utility of satellite borne passive microwave sensors for soil moisture measurements was reported by Vinnikov, *et al*, [1999]. They used the Nimbus-7 scanning microwave multichannel radiometer (SMMR) and compared results obtained at 18GHz with in situ observations for 14 sites. They concluded that passive microwave has a distinct utility in areas where the vegetation is not too dense. Investigations using the airborne ESTAR sensor were conducted by Mattikalli and colleagues [1998]. In this case the frequency was L band (1.4GHz) and measurements were obtained at 200m resolution across a watershed. They found a direct correlation between soil moisture and soil texture and established that drainage was related to soil hydraulic properties and hence enabled more accurate estimation of hydrological modelling over a large area. Development of a model, 'Micro-sweat', is described by Simmonds and Burke [1998]. This model couples the emissivity at 1.4GHz with the water content in the upper 2cm of soil and accounts for differences in soil dielectric properties.

The use of active and passive techniques was reported by Chauhan [1997]. Here the data from the NASA AirSAR system was recorded with measurements made by the airborne push-broom Microwave Radiometer (PBMR) over an instrumented watershed which included fields with different crop types. The soil moisture was estimated using an algorithm which used brightness measurements from the PBMR together with vegetation and ground parameters from the SAR. Excellent agreement with in situ measurements were obtained. Njoku and Li [1999] have reported on approaches for retrieval of land surface parameters using the planned passive microwave sensor AMSR. They estimated that for regions where vegetation moisture was less than 1.5kg per square metre, accuracies of 0.06g/cu cm and 0.15g/cu cm would be obtained for soil and vegetation moisture respectively. Similarly, Njoku, *et al*, [1999] showed that a space borne inflatable antenna could be used for passive microwave soil moisture measurements and provide an accuracy of 0.04g/cu cm in areas where the vegetation content is less than 5kg per square metre. The frequency range for this system would be 1.41 to 2.69 GHz and the resolution would be 30km (for a 25m diameter antenna).

Oil pollution

An interesting review of sensors for oil pollution measurement is given by Fingas and Brown [1997]. This review suggests that a limitation of passive microwave sensors is the poor resolution (but this could be overcome using aperture synthesis techniques). The authors suggest that the most effective sensor would be a laser fluorosensor because of its unique capability to identify oil on different backgrounds, water, soil, ice and snow. The identification of different oil types using microwave radiometry is discussed by Pelyushenko [1997]. Here a scanning conical radiometer operating at 34 and 26 GHz and at different polarisations was used at incidence angles of 40 to 60 degrees to classify basic oil types with satisfactory accuracy. It should be noted that there is a cyclical relation between oil thickness and brightness temperature, see Ulaby, *et al* [1986], and this complicates the extraction of oil slick information. Because of this, Fingas and Brown conclude that passive microwave sensors are of uncertain value in this application at present.

Summary of key applications

The most important application for passive microwave sensors is considered to be soil moisture measurement in support of flood prediction and hence the development of effective flood defence measures. Oil pollution measurement would probably be more effective using SAR because of the better resolution. One further application area is the use of passive microwave techniques for air pollution; although no references have been obtained, there is evidence [Williams, personal communication] that passive microwave sensors can be used to detect carbon dioxide and other gases.

3.2 LiDAR

3.2.1 Introduction

The areas of application of LiDAR are far too numerous to cover in a comprehensive manner within the framework of this brief study. Therefore the approach taken has been to review the basic concepts and techniques with a view to the giving the Environment Agency a primer to those areas which might be of most interest. The references cited here will hopefully allow interested parties to elucidate further specific technologies pertinent to their requirements. Perhaps the best single introductory reference is the collection of review articles embodied in *Laser Remote Chemical Analysis* edited by R.M. Measures [1988].

The issue of system and operational cost for each application is not addressed since it would be highly dependent upon the number of equipments and the specific task required. Costings will be possible once a measurement scenario is firmly defined.

Soon after the invention of the laser in the early sixties the term LiDAR was adopted for Light/Laser Detection and Ranging by way of an analogy with the already established acronym, RADAR. Lasers have subsequently been developed that operate at numerous discrete wavelengths within the spectral region 0.1-20μm. LiDARs have been designed that operate at specific wavelengths in this broad spectral region, the basic requirement being that the chosen wavelength will propagate with sufficiently low loss through the atmosphere [Measures 1988, Hinkley 1976 and Grant 1995]. The range of LiDAR types is vast and system sizes vary from those which would fit in a matchbox to those which occupy a plot of land equivalent to a small housing estate. LiDARs have been deployed on terrestrial, balloon, rocket, aircraft, ship and space-based platforms and the range of parameters such systems have analysed is similarly diverse as is outlined in the later sections.

LiDAR and radar have a high degree of commonality since they both rely on transmitting and subsequently detecting a specific frequency of electromagnetic radiation. The only fundamental differences between the two are as a consequence of any inherent wavelength dependence in the physical phenomena involved. Diffraction, scattering, absorption and detection are four areas in which distinctions between the two technologies can be clearly drawn. For the benefit of those more familiar with radar, the following paragraph reviews some of the differences between radar and LiDAR.

Diffraction sets a limit on the angular resolution available from a given aperture size for a given wavelength. LiDAR can therefore achieve higher angular resolution than radar from a comparable aperture or, as is more usual, can operate with a substantially reduced aperture while still achieving high angular resolution. (*We note here that radar angular resolutions can be improved using SAR techniques, see section 3.1*). The relative size of the wavelength and the scatterer, as well as the characteristics of the scatterer itself, dictate the way in which the transmitted radiation is re-distributed after a scattering event. In the case of LiDAR, the scattering patterns and return power statistics can be influenced by a variety of factors including the complex refractive index of the scatterer, the surface roughness on a range of spatial scales and the number of independent scattering centers encountered in the measurement time.

The propagation characteristics of electromagnetic radiation in the atmosphere are not constant with wavelength. Radiation is absorbed by the various atmospheric constituents and some care must be taken to operate in a spectral region where there the attenuation is not excessive. In the microwave region these absorptions are primarily caused by rotational degrees of freedom in molecules with dipole moments. In the IR and visible wavelength utilised for LiDAR, the absorptions are caused by analogous vibrational and electronic transitions. Cloud and rain cause additional attenuation with the specific effects being a function of wavelength and the particle size distributions [Measures 1988].

Efficient detection of electromagnetic radiation in the microwave region is accomplished by the use of coherent mixing (heterodyne) techniques where the received scattered radiation is mixed with a local oscillator signal in the receiver. This detection scheme is a pre-requisite in this spectral region since the photon energies are small, the background radiation is not insignificant and coherent detection has an inherently higher sensitivity at longer wavelengths. This follows from the fact that the 'entendue' of a heterodyne system is proportional to the square of the wavelength. In the case of LiDAR both coherent and incoherent (also termed direct detection where a received photon directly generates an electrical carrier in a photo-receiver) operations are possible and the relative merits of the two approaches must be assessed for each application. The sensitivity of a LiDAR receiver to the backscattered signal photons depends upon the laser wavelength, the bandwidth of the signal and the receiver mode of operation. It is usual to characterise the operation of these optical receivers in terms of the dominant noise source [Kingston 1978]. The best that can be achieved is when the shot-noise inherent in the quantised nature of the laser-generated photons (either signal or local oscillator) is the limiting noise source. In this case the detection scheme is said to be shot noise limited and this represents the theoretical limit of sensitivity. Heterodyne operation allows access to this ultimate sensitivity in the IR whereas direct detection systems are limited by a combination of background radiation and detector leakage current. In the near IR and visible spectral regions where low noise, high gain detectors such as avalanche photo-diodes and photo-multiplier tubes are available, direct detection can achieve the ultimate sensitivity limit. We note here that more information is retained in the coherent mode of operation (see section 3.2.2) but for some applications this may be redundant. Coherent systems are in general more complex although recent developments in fiber optics and semiconductor lasers are allowing coherent systems to be constructed which are very simple and compact [Karlsson and Olsson 1999].

The precise wavelength and beam characteristics used by a LiDAR system determine whether it is safe for the human eye to observe directly. Systems which operate at wavelength longer than 1.5µm are generally considered eye-safe. At shorter wavelengths the safety depends upon the parameters of the transmitted radiation in terms of energy, pulse length, beam size etc. For practical, deployable systems this is clearly an important issue.

3.2.2 LiDAR modes of operation

There are numerous modes of LiDAR operation from which a whole variety of data products can be extracted. In this section the underlying principles of each of these modes of operation are briefly described and the salient features of the each are reviewed in terms of the information they provide and their relative level of maturity. Different categories of system can be distinguished according to the mode of LiDAR operation and the specific characteristics of the scatterer. Some systems illuminate a scene and seek to obtain information about a remote solid target. Others use a solid target as a remote reflector in order to analyse the intervening optical path through the atmosphere. A third technique uses naturally occurring distributed scatterers in the atmosphere such as aerosol particles or molecules. In this case both the properties of the distributed scatterers and the atmosphere in which they are suspended can be analysed with a suitably designed concept.

Direct detection, hard target

This is perhaps the simplest LiDAR concept where a continuous beam (cw) or a pulse of light is transmitted and subsequently detected after scattering from a remote target. Detection is via photon to electrical carrier conversion in a photo-detector and the information which can be extracted is signal strength in the former and both signal strength and the time of flight in the latter. Signal strength can be used to infer the reflectivity of the target and in some cases the degree of target de-polarisation can also be determined. In the pulsed case, the target range is determined to some degree of accuracy dependant primarily upon the length of the optical pulse. Early LiDAR experiments used this technique to measure the distance to the moon and range-finders for civilian and military applications became widely available in the early seventies [Measures 1988]. Today there exists a well developed network of LiDAR range-finders for monitoring of the earth via reflections from satellite-borne retro-reflectors. Road traffic speed monitors often employ this technique, inferring the speed or range-rate from the temporal variation in the measured range. AM modulated cw schemes can also be used to obtain range but depending upon the modulation rate, they are limited either in update rate or range/time ambiguity. Even so they have found application in a number of areas [Kamermann 1995].

As mentioned previously the short wavelength of LiDAR yields a narrow field of view with a small aperture. For example, at a wavelength of 1µm and an aperture of 1cm, the field of view is 100µrad, ie the beam diameter would theoretically be 10cm at a range of 1km. This illustrates the point that LiDAR is optimally suited to high spatial resolution remote sensing. In order to synthesise a larger field of view it is necessary to scan the beam. This technique has been used in conjunction with a pulsed laser to generate 3D images of scenes. Active imagers are of current interest in areas such as automatic vehicle cruise controls and military reconnaissance [Becherer 1995, Kamermann 1995]. Recent developments in very compact micro-chip lasers and integrated optical components from the telecommunications industry are leading to new applications of this type of system. Lightweight, compact and efficient devices mounted in light aircraft are becoming economically viable for surveying and DIAL type applications (see later).

Coherent detection, hard target

In coherent LiDAR the return radiation collected by the receiver aperture is combined with an optical local oscillator and focussed onto the surface of a photo-detector. Such detectors are square law devices which do not respond to the optical frequency. However if the frequency difference between the return radiation and the local oscillator is constrained to be in a known bandwidth (typically 0-100 MHz) then this difference frequency term is embodied on the detector output current. The optical local oscillator can be derived from the same laser that generated the transmitted beam or it can be from a separate laser. The full characteristics of the scattered optical field are preserved on the difference frequency component of the detector output current and consequently the amplitude and phase of the signal are available for analysis. Therefore in addition to the return signal strength, phase and rate of change of phase (ie velocity) can be determined. Such systems can operate in either a pulsed or cw mode, where we refer here to the transmitted waveform (the local oscillator is always cw) . Target bulk velocity and micro-velocity (vibration) can be analysed which have led to a range of applications in remote target analysis and system diagnostics [Measures 1988, Huffaker and Hardesty 1996]. A further mode of operation is possible where a frequency modulation is applied to a cw laser beam (FMCW coding). This usually takes the form of a repetitive linear frequency chirp. The target range and velocity can be deduced from the frequency difference between the transmitted and received radiation [Pearson and Collier 1999]. Moving target indicators and range finders for military applications were developed in the 70's and 80's using these types of technology [Measures 1988].

Direct detection, atmospheric probing via retroreflection

In the previous sub-section, the operation of a direct detection LiDAR system using reflections from a remote hard target was outlined.

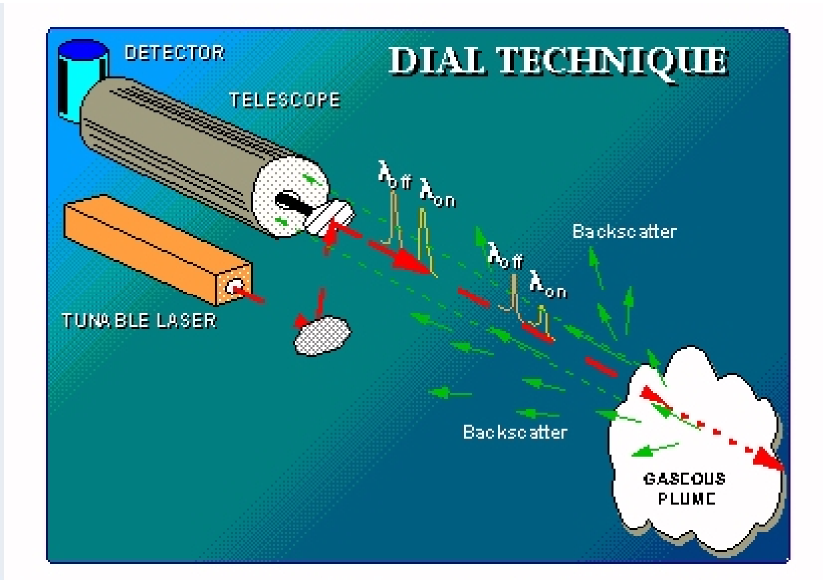


Figure 3.1 A schematic diagram of a monostatic, direct detection DIAL system employing distributed aerosol scatterers.

In this section this concept is extended to the case where the system is designed to operate in this basic mode but information is sought regarding the properties of the intervening path. This can be thought of as a long path absorption spectrometer where the associated long path actually extends across an area of terrain, see Figure 3.1.

Such systems necessarily produce path integrated or column content type data. Several different properties of the intervening path can, in principle, be determined. For example, the fluctuations in the received signal can give information on the level of turbulence. The strength of the signal at two different wavelengths can be used to measure the concentrations of different species in the atmosphere. This is done by choosing the wavelengths carefully so that one is more highly absorbed than the other by way of an absorption feature of that specific atmospheric constituent. In practice several wavelengths are sometimes used to resolve ambiguities between species. This technique is traditionally termed DIAL (DIfferential Absorption LiDAR), [Weckworth *et al.* 1999, Wulfmeyer and Boesenberg 1998, Milton and Woods 1987, Grant 1982, Grant 1991, Papayannis *et al*. 1990 and Grant 1986].

Direct detection, atmospheric probing via atmospheric backscatter

In addition to receiving backscattered radiation from solid targets, cw and pulsed LiDAR systems are also capable of detecting signals backscattered from distributed scattering centers within the atmosphere. Naturally occurring aerosol particles, water vapour clouds, molecular species, high altitude atomic layers, volcanically generated atmospheric layers (see Figure 3.2) and acoustic perturbations are all examples of distributed scattering sources which have been exploited in LiDAR systems.

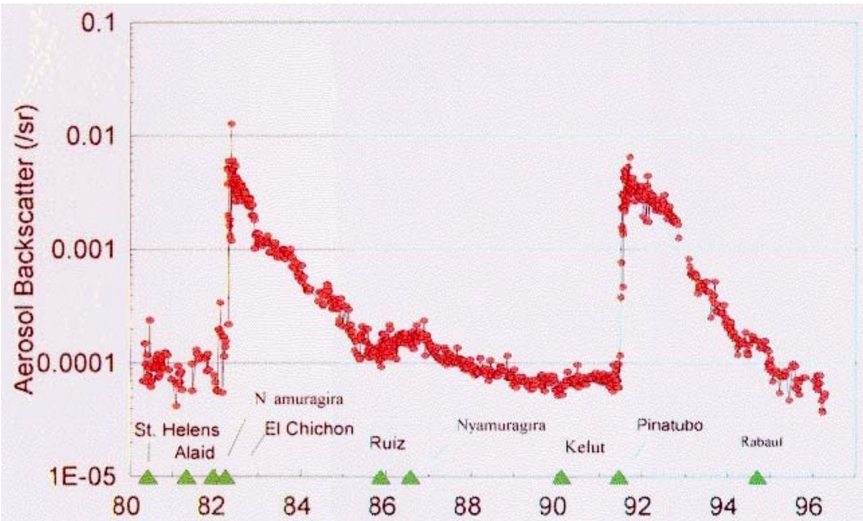


Figure 3.2. Aerosol backscatter versus year for the height interval 15.8-33km as measured form the Mauna Loa observatory with a pulsed LiDAR based on a ruby laser transmitter. Note the increased backscatter caused by volcano eruptions.

With a calibrated LiDAR system it is possible to derive the volumetric concentration of the scatterer along the line of sight of the laser beam and a pulsed system will additionally provide range resolution. A vast number of specific techniques have been developed using various combinations of laser wavelength and scattering centers. Elastic (where the scattering process purely redistributes the transmitted radiation with respect to the angular distribution of propagation directions) and inelastic scattering mechanisms (where associated with the scattering there is a characteristic wavelength shift) can be utilised. Examples of the former are Mie and Rayleigh scattering and examples of the latter are Raman and fluorescence. Aerosol distributions, cloud base height, atmospheric temperature/pressure, cloud particle size distributions and atmospheric constituents are examples of the types of information which can be extracted from LiDARs.

Atmospheric constituents are usually measured by DIAL schemes. Systems have been developed which can remotely measure a whole host of species which have suitable absorption bands. Examples of the atmospheric species detectable with DIAL include ozone, methane, sulphur dioxide, carbon dioxide, carbon monoxide, water vapour, mercury, ammonia, benzene and hydrazine [Measures 1988, p.305]. The absorption features can be either discrete lines or broadbands. Water vapour for example has many discrete absorption lines. In water vapour DIAL, laser pulses are transmitted at two wavelengths, one on a water vapour absorption line and another off-line. If the wavelengths are close together, then for both wavelengths the scattering by molecules and particles is essentially equal. The difference in the returns between the two wavelengths is then due entirely to absorption by water vapour molecules. Thus measurements of the ratio of the backscatter at the two wavelengths as a function of range can be used to calculate the water vapour concentration profile. DIAL measurements of ozone require less precise laser frequency control because ozone has a broad (~200 nm) absorption band instead of narrow lines like water vapour. This means that the on- and off- absorption wavelengths need to be chosen with sufficient wavelength separation to ensure a significant difference in their absorption. The wavelengths also need to be chosen to be compatible with the desired system range. Uncertainty in the changes of aerosol scattering between the wavelengths can introduce errors. The difference in aerosol scattering at can be extrapolated from a third measurement taken at a longer wavelength. Therefore, DIAL measurements with three wavelengths can be used to determine ozone concentration profiles to good accuracy [Papayannis *et al*. 1990]. Figure 3.1 shows a schematic of a *monostatic* (meaning common optics for transmit and receive channels) DIAL system for detection of a remote cloud. Numerous groups in Europe and the USA operate ground and airborne DIAL systems. NOAA and NASA both fly ozone DIAL systems for urban and high-level ozone assessment and commercial systems are available. However such systems are still relatively large and require a well educated operator. Future smaller, cheaper and simpler systems are a possibility but significant developments will only be driven by potentially large markets and these have yet to be clearly identified although urban pollution and air quality are potentially strong candidates.

CW, coherent detection, distributed aerosol targets

The coherent mode of operation is also possible with distributed targets. It is usually the case that a large number of scattering centers contribute to the return at any given instant in time and so this leads to a scrambling of the transmitted optical phase. For this reason, in the context of this mode of operation the scattering is usually referred to as incoherent. In this case the bandwidth of the return signal is dictated by the time scales of the particle motion. The main application of this technique has been for wind velocity and atmospheric backscatter analysis [Vaughan *et al*. 1996, Huffaker and Hardesty 1996]. The wind velocity is inferred from measurements of the Doppler shift imposed on the transmitted signal by the moving aerosol scatterers. The aerosols are sufficiently small that they act as tracers embedded in the ambient airflow. The magnitude of the Doppler shift at a laser wavelength of 10 μm is approximately $200kHz/ms^{-1}$ and a typical resolutions for this type of measurement is 10 cms^{-1} for an observation time of 100ms. Although these are unmodulated cw systems it is possible to obtain some range resolution. The signal detected can be biased in range so that it can usually be attributed to a certain remote region of space (typically ranges being 10-100m) [Foord *et al*. 1983, Sonnenschein and Horrigan 1971]. The word usually is used in the previous sentence because the localisation of the return signal with respect to range relies on the backscatter strength being uniform with respect to range. A distant strong scatterer such as a building or cloud will disrupt the range weighting scheme. The range selectivity is achieved as a consequence of focussing the beam. The effect of this is to weight the system response versus range to the region in space where the beam is focussed. The degree of range selectivity, which can be obtained, depends upon the system aperture and the wavelength of operation. The physics behind this effect is beyond the scope of this report but the interested reader is referred to [Sonnenschein and Horrigan 1971] for a detailed explanation. Ground based and airborne LiDARs operating in this way have been used for a variety of applications including boundary layer wind analysis and characterisation of the variability of atmospheric backscatter. Well engineered systems for true airspeed, wind shear and backscatter strength measurements on aircraft have been developed. Analogous systems have been used for aircraft wake vortex studies [Vaughan *et al*. 1996].

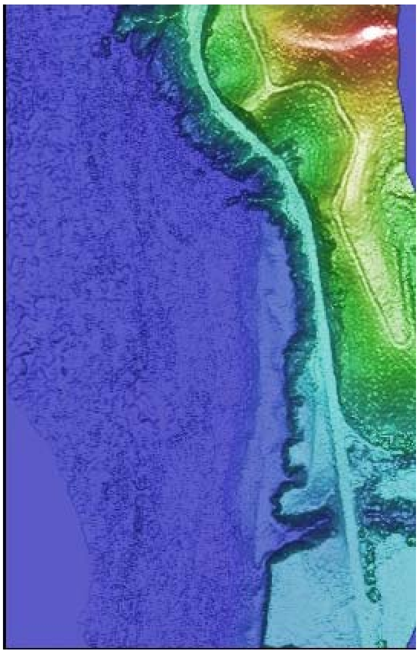
Pulsed, coherent detection, atmospheric probing via atmospheric backscatter

An extension of the concept outlined in the previous sub-section is to use a pulsed laser transmitter to obtain truly range resolved velocity and backscatter data from the atmosphere. In this case a pulsed laser transmitter and a cw local oscillator are required and the return time series is analysed to obtain the data products for a series of independent range gates whose length is determined primarily by the transmitted pulse length. Systems of this type have been used for similar studies to those mentioned in the previous sub-section but in this case data out to long ranges (10's km) can be obtained simultaneously and large areas can be monitored by a single sensor by scanning the beam [Huffaker and Hardesty 1996, Pearson and Collier 1999]. Systems have been used to study a variety of meteorological events such as mesoscale dynamics, air pollution, turbulence, diffusion and fluxes [Pottier *et al*. 1997, Banta *et al*. 1997, McKendry *et al*. 1998, McKendry *et al*. 1997, Ralph *et al*. 1997[a], Ralph *et al*. 1997[b], Banta 1996, Banta *et al*. 1996. Banta and Gannon 1995, Banta *et al. 1995,* Levinson and Banta 1995, Clark *et al*. 1994, Banta *et al*. 1993[a], Banta *et al*. 1993[b], Banta *et al*. 1992, Intrieri *et al*. 1990, Shapiro *et al*. 1990, Post and Neff 1986, Lenschow *et al*. (submitted), Wulfmeyer 1999[a], Wulfmeyer 1999[b], Mahrt *et al*. (submitted), Post *et al*. 1994, Gal-Chen *et al*. 1992, Eberhard *et al*. 1989, Eberhard and Chen 1989 and Eberhard *et al*. 1988]. Other phenomena investigated include drainage flows down mountain valleys, tropopause folding and sea breeze formation. LiDARs are particularly well suited to high resolution measurements near the ground because of their inherently high angular resolution and their immunity to clutter type issues which effect radar in this scenario.

3.2.3 Areas of application

Flood defence

The Environment Agency already uses LiDAR for terrain mapping for flood defence purposes; it is used to measure topography and vegetation height as an input to flood prediction models. However, in this section the general status of LiDAR applications is reviewed. The US National Oceanic and Atmospheric Administration has an on-going programme called ALACE for gathering accurate, cost effective information on coastal topography, erosion and shoreline position. The system (see Figure 3.3) is based upon an airborne laser altimeter (ATM). The platform is a DeHavilland Twin Otter aircraft and the altimeter is capable of collecting 5000 spot elevations per second as the aircraft travels at approximately 60 ms^{-1}. Using the ATM in conjunction with a global positioning system, researchers have been able to survey the terrain to a vertical accuracy of 20cm [csc.noaa.gov/crs/ALACE]. A comparable system, ALTMS, is fielded by NASA. Cited applications include flood plain assessment, forestry analysis, building elevation and general site surveying [q.eisl.harc.edu/www/lidar story.html].



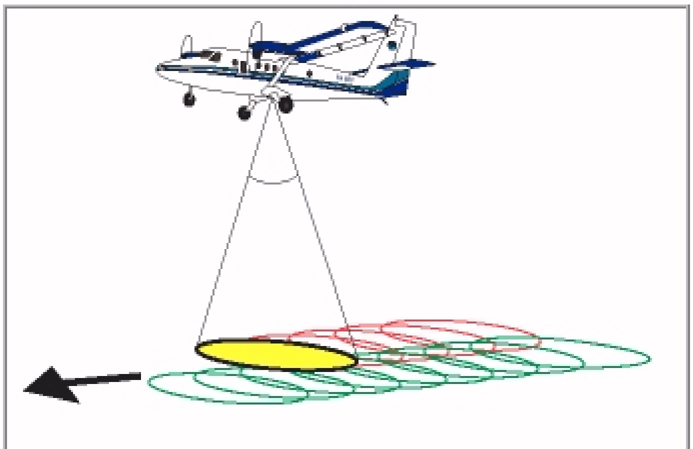


Figure 3.3. A topographic map of a portion of the California coastline generated from a compact LiDAR based imager and an illustration of the system configuration. The system was housed in a light aircraft and the colour coding represents surface height. The vertical resolution was approximately 30cm.

Inland, marine and coastal water quality

LiDAR systems are capable of measuring a number of parameters relevant to aquatic environments including depth, spatially resolved surface flow speed, turbidity, surface roughness heights, chlorophyll loading, fish abundance, oil slick identification and oil slick layer thickness [Bristow *et al*. 1981, Hoge and Swift 1981, Estep 1993, Narayanan and Kalshoven 1997, Feigels and Kopilevich 1996 and Kirk 1994]. Two specific examples are Bristow et al [1981] who used a helicopter based LiDAR with a dye laser transmitter to detect Raman shifted backscatter from water and fluorescence from chlorophyll and Hoge and Swift [1981] who used a slightly different scheme to perform a similar task from a P-3A aircraft flying at a height of 150m.

No specific references have been found to LiDAR measurements of dissolved nitrites, nitrates, metals etc. but there may be potential for novel systems for this task in the light of current DERA research into associated applications for novel inelastic and elastic remote detection schemes. Terra Surveys [www.terrasurveys.com] offer hydrographic surveying from the air on a commercial basis. Depth resolution is of the order of 5m.

Radioactivity

Remote sensing of radioactivity with LiDAR does not appear to be possible. Plume dispersion and general boundary layer dynamics can be monitored with pulsed Doppler LiDARs which might be relevant in the case of a leak from a nuclear installation. It has been highlighted in the national press recently that many nuclear power stations were located in low lying coastal regions to allow easy access to coolant and are consequently very vulnerable to rises in sea level. The terrain mapping LiDAR technologies detailed above for flood defence are therefore of particular interest for addressing this potentially serious issue.

Air quality

LiDAR systems are capable of providing range resolved concentration profiles of all the atmospheric constituents and pollutants listed in the requirement document. Plume dispersion and emission flux rates can also be determined with Doppler LiDAR since such systems gives velocity information. These dispersion and urban circulation issues are intended to be addressed with the Salford pulsed Doppler LiDAR [Pearson and Collier 1999] which was built for the University of Salford by DERA Malvern. The National Physical Laboratory (NPL) group performs remote atmospheric measurement surveys for large, inaccessible or hazardous areas using a mobile multi-wavelength DIAL. This facility is used regularly on behalf of UK government and industry for monitoring, for example, fugitive emissions of VOC's. Typical measurement sites include oil refineries, petrochemical processing plants, natural gas distribution/storage terminals, power stations, and road/rail loading terminals. Ambient air quality surveys and environmental site audits are also undertaken.

Some of the principal institutions and commercial concerns, which are currently involved with LiDAR remote sensing for air quality type applications, are listed below:

National Physical Laboratory, UK.
Contact: Martin Milton.
Areas of interest: DIAL, calibration

DERA, Malvern, UK.
Contact: David Willetts
Areas of Interest: All aspects of Coherent/incoherent elastic/inelastic scattering LiDAR and remote sensing.

Spectrasyne, UK.
Contact: Tony Wootton,
Areas of Interest: DIAL

Lund Institute of Technology, Sweden.
Contact: S. Svanberg
Areas of Interest: DIAL, plume dispersion

SRI, Arlington, VA and CA, USA.
Contact: John Carrico
Areas of Interest: General applications of LiDAR and remote sensing

NASA, (Langley, Marshall), USA.
Contact: Bill Grant and Michael Kavaya
Areas of Interest: DIAL, Doppler LiDAR, altimetry, imaging

JPL, Pasadena, USA.
Contact: Bob Menzies
Areas of Interest: Doppler LiDAR, backscatter LiDARs, calibration

University of Salford, UK.
Contact: Chris Collier
Areas of Interest: Atmospheric remote sensing

NOAA, Boulder, CO, USA.
Contact: Mike Hardesty
Areas of Interest: DIAL, Doppler LiDAR, atmospheric remote sensing

University of Wales, Aberystwyth.
Contact: Geraint Vaughan
Areas of Interest: Ozone and water vapour DIAL

CTI, Lafayette, CO, USA.
Contact: Sammy Henderson
Areas of Interest: All aspects of LiDAR

Elight Laser Systems, Berlin, FRG.
Contact: M. Ulbricht
Areas of Interest: DIAL

University Claude Bernard, Lyon, Fr.
Contact: Jean-Pierre Wolf
Areas of Interest: DIAL

Kayser-Threde GmbH, Munich, FRG
Contact: M. Resch
Areas of Interest: DIAL

DLR, Wessling, FRG.
Contact: Christian Werner.
Areas of Interest: LiDAR remote sensing

LMD, Palaiseau, Fr.
Contact: Pierre Flamant
Areas of Interest: Coherent LiDAR and DIAL, Signal Processing

FOA, Linkoping, Sweden.
Contact: Ove Steinvall
Areas of Interest: Underwater and atmospheric LiDAR

Max Planck Institute, Hamburg, FRG.
Contact: Jens Bosenberg
Areas of Interest: DIAL and Doppler LiDAR.

Waste

Two aspects of waste site monitoring may be suitable for remote sensing with LiDAR. These are methane emission via DIAL and volume estimation via terrain mapping. Both of these technologies have already been reviewed and several of the cited references deal specifically with this issue together with the associated remote sensing technologies of DOAS

(Differential optical absorption spectroscopy) and passive/active FTIR (Fourier transform infra-red) sensing [Schaefer 1997, Vo-Dinh, T 1995].

Pollution incidents and contamination of land

Application of LiDAR to vapour phase pollution monitoring has been reviewed in the sub-section covering air quality. Here we review some aspects of remote sensing for the detection of liquid and solid phase contamination present both on exposed surfaces and underground. Underground contamination is traditionally analysed by taking samples away for laboratory analysis. However there have been recent developments in the USA towards doing such measurements in-situ. This is done using a cone-penetrometer which is basically an instrumented pile which is driven into the ground by a large vehicle. A variety of optical instruments have been mounted on this device, some working *at the coal face* and others routing the optical signals to the surface for analysis with fiber optics [Vo-Dinh 1995]. Surface contamination is an issue which has been of interest to the military. Remote sensing of hazardous material at ranges of a few tens of meters would be of use for a number of military scenarios. Current research is addressing novel inelastic and elastic scattering techniques including photo-acoustics, differential reflection, Raman and active FTIR [Fallahi and Howden 1998, Lieberman 1997]. Oil slick detection and identification have also been demonstrated with LiDAR techniques [Narayanan and Kalshoven 1997].

Climate change

The composition of the atmosphere and the sea level are the two fundamental parameters relevant to climate change for which LiDAR can provide information. These applications have been covered in the preceding sections.

Biodiversity, land use and land cover

A variety of properties of the earth's surface can be sensed remotely using laser based systems. Several of these are extensions of what has already been outlined but there are two which are somewhat different and these are now briefly reviewed.

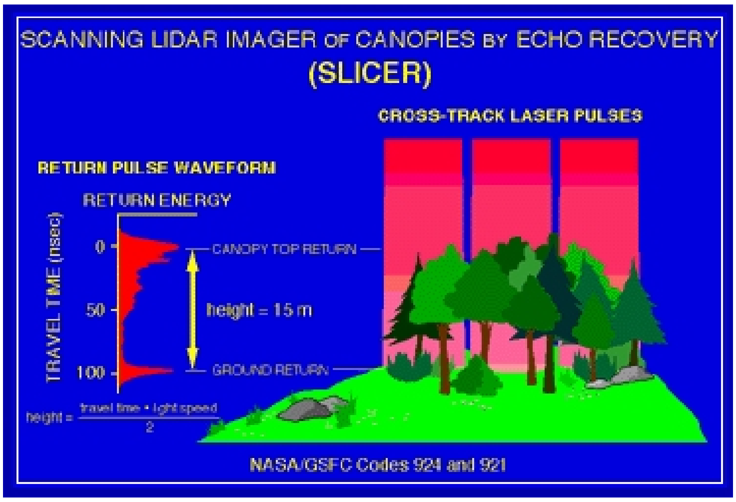


Figure 3.4. Illustration of the concept of the SLICER (Scanning LiDAR imager of canopies by echo recovery) instrument, an airborne system for vegetation canopy analysis.

The basic tenet of these schemes is remote spectroscopy, latching onto the characteristic spectral features in a similar way to hyperspectral passive imagery.

Airborne multi-wavelength LiDARs have been used to characterise the reflectance spectrum of the terrain allowing the rock type to be identified over large areas. This has been done primarily with a view to identifying potentially valuable mineral deposits [Narayanan and Kalshoven 1997]. Differential reflection and laser induced fluorescence have been used to study forest canopies, crop type and quality (see Figure 3.4). Full descriptions of these techniques are given in [Narayanan and Kalshoven 1997, Feigels and Kopilevich 1996, Becherer 1995].

3.2.4 Summary

LiDARs are important tools for environmental monitoring and it is significant that an airborne LiDAR is already in use by the Environment Agency for flood prediction. The use of LiDARs for other applications, particularly air pollution is also important

3.3 Optical (Visible and Near IR)

3.3.1 Introduction

The optical (or visible) and near infrared part of the spectrum extends from about 0.38 to 1.30 μm. Sensors operating in this spectral range make use of solar radiation reflected from the surface and almost all use a camera to form an image of the required scene. Such sensors include photographic (ie, recorded on film) cameras and electro-optic instruments (incorporating radio transmission and digital recording). Broad band mutlispectral sensors are now common but the increasing use of narrow band 'hyperspectral' sensors is discussed in section 3.4. Examples of both photographic cameras and electro-optic instrument are found on aircraft and manned spacecraft whereas it is usual (now) to find only electro-optic sensors on satellites. This section will consider these three topics: satellite borne electro-optic sensors, airborne electro-optic sensors and airborne photography.

3.3.2 Satellite electro-optic sensors

The main advances in these sensors, has been the progression to higher resolution and the increasing use of large CCD arrays. These have replaced the scanning mirrors of earlier satellite sensors and yield images with better pixel registration. The need to minimise mass means that the optical systems invariably use mirrors rather than lenses; future systems may use adaptive optics to reduce the distortions introduced by aberrations and atmosphere. It is convenient to illustrate system performance by considering low resolution, medium resolution and fine resolution sensors:

Low resolution sensors (ie, > 200m resolution)

Table 3.9 gives examples of some current and future low resolution sensors. Note, this table shows the low resolution instruments and the relevant satellite, in some cases a single satellite may carry a mixture of low, medium and high resolution sensors:

Table 3.9 Low resolution satellite sensors

Sensor	Resolution (m)	Spectral range (μm)	No. of bands[1]	Swath width (km)	Satellite	Launch date
AVHRR[2]	1100	0.58 – 0.68, 0.76	5, 1	3000	NOAA10/12/ 14	1986/91/ 94
AVHRR/3	1090	0.58 – 0.68, 0.725	6, 1	3000	NOAA/K/L/M & METOP	1998/ 2000/01
SeaWIFS[3]	1000	0.402 – 0.885	8	2800	ORBVIEW2	1997
OCM[4]	360	0.402 – 0.885	8	1420	IRS-P4	1999
MERIS[8]	250	0.4125 – 0.9	15	1150	ENVISAT	2001
MODIS[5]	1000[6]	0.438 – 1.25	36	2330	Terra(EOS-AM & EOS-PM)	1999/ 2001
ATSR & AATSR[7]	1000	0.555 – 0.865	3 (plus 5 in IR)	500	ERS-1/2, ENVISAT	1991/4, 2001

Notes: 1: Number of bands given for each spectral range
2: AVHRR: Advanced Very High Resolution Radiometer
3: SeaWIFS: Sea-viewing Wide Field of view Sensor
4: OCM: Ocean Colour Monitor
5: MODIS: Moderate Resolution Imaging Spectroradiometer
6: Some bands of MODIS have resolution of 250m or 500m.
7: (A)ATSR: (Advanced) Along Track Scanning Radiometer
8: MERIS: MEdium Resolution Imaging Spectrometer

SeaWIFS

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [http://seawifs.gsfc.nasa.gov] was launched on an extended Pegasus launch vehicle on August 1st 1997. Its main purpose is the monitoring of primary bio-mass in the ocean and the impact of climate change. SeaWiFS data is acquired in three different formats; High Resolution Picture Transmission (HRPT), Local Area Coverage (LAC) and Global Area Coverage (GAC). The spatial resolution of the LAC data is 1.1km at nadir. The GAC data are derived from on board sample averaging of the full-resolution LAC data. This produces a spatial resolution of 4.5km.

AVHRR:

The Advanced Very High Resolution Radiometer (AVHRR) [http://podaac-www.jpl.nasa.gov/sst] is a broad-band, four or five channel (depending on mode) scanner, sensing in the visible, near-infrared and thermal infrared portions of the electromagnetic spectrum. (The later versions –AVHRR-3, have 8 channels). This sensor is carried on NOAA's Polar Orbiting Environmental Satellites (POES). The sensor is primarily used for obtaining images of clouds and for sea surface temperature. AVHRR data is acquired in three formats; High Resolution Picture Transmission (HRPT), Local Area Coverage (LAC) and Global Area Coverage (GAC). The AVHRR sensor provides for global (pole to pole) on board collection of data from all spectral channels. Each pass of the satellite provides a 2399km wide swath. At present NOAA-10, NOAA-14 and NOAA-15 are operational.

AATSR

The Advanced Along Track Scanning Radiometer [http://envisat.estec.esa.nl/index.html] is one of ten instruments due to be launched on the Envisat satellite in June 2001. The AATSR instrument will address the needs of two disciplines; the assessment of precise sea-surface temperature measurements (to accuracies of 0.5K or better); and quantitative measurements over land surfaces, particularly vegetated areas, to provide information on vegetation biomass, vegetation moisture and vegetation health and growth stage.

MERIS

The Medium Resolution Imaging Spectrometer (MERIS)[http://envisat.estec.esa.nl/index.html] due to be launched on Envisat in June 2001. It is a push-broom instrument that is made up of five identical cameras that have slightly overlapping fields of view. Each camera images an across-track strip of the Earth's surface onto the entrance slit of an imaging optical grating spectrometer. Its spectral bands are:

NB, band centres given, in μm. Band width is programmable 1.26 to 26nm.

Band 1:	0.4125,	Band 2:	0.4425	Band 3:	0.490
Band 4:	0.510	Band 5:	0.560	Band 6:	0.620
Band 7:	0.665	Band 8:	0.6812	Band 9:	0.705
Band 10:	0.75375	Band 11:	0.760	Band 12:	0.775
Band 13:	0.865	Band 14:	0.890	Band 15:	0.900

MERIS will have a 1150km wide swath and it is aimed that it will provide global coverage. At full resolution the spatial resolution of MERIS will be 0.25 km at nadir. At reduced resolution the spatial resolution will be 1km.

Medium resolution sensors (20m to 200m resolution)

Table 3.10 shows a range of medium resolution satellite sensors:

Table 3.10 Medium resolution satellite sensors

Sensor	Resolution (m)	Spectral range (μm)	No of bands	Swath width (km)	Satellite	Launch date
Thematic mapper-TM	30	0.45 – 0.9	7	185	LANDSAT 5	1984
Extended TM	30	0.45 – 0.9	8	185	LANDSAT 7	1999
HRV[1]	20[2]	0.51 – 0.89	4	60	SPOT3/4	1993/98
LISS-3[3]	23	0.52 – 0.86	4	142	IRS-1C/1D	1995/97
CCO[4]	20	0.45 – 0.73	5	120	CBERS –1/2	1999/01
MSU-SK	160	0.5 – 1.1	4 plus IR band	600	RESURS-01	1994
ALI[5]	30[6]	0.433 – 1.3	10	37	EO-1	2000

Notes: 1: HRV: High Resolution Visible
2: HRV also has a 10m resolution panchromatic mode
3: LISS-3: Linear Imaging Self Scanning Sensor
4: CCD: High resolution CCD camera
5: ALI: Advanced Land Imager
6: ALI also has 10m panchromatic mode

Thematic mapper (LANDSAT)

The US Landsat ("land satellite") [http://geo.arc.nasa.gov/sge/landsat/landsat.html] was designed in the 1960s as the first satellite tailored specifically for broad-scale observation of the earth's land areas. Landsat-7 is the latest in the series of Landsat satellites, and was launched in April 1999. It carries onboard the Enhanced Thematic Mapper Plus (ETM+) which replicates the capabilities of the Thematic Mapper instruments on Landsats 4 and 5 (Landsat 5 is still operational). The ETM+ also includes new improved features that make it a more versatile and efficient instrument. Each pass of the Landsat 5 and Landsat-7 satellites produces a 185km wide swath. The satellites orbit the Earth, in a sun-synchronous motion, 233 times in a 16-day period at an altitude of 705km. The spatial resolution of the visible and near-infrared bands (bands 1-5 and 7) of Landsat 5 is 30 metres. The thermal infrared band 6 has a spatial resolution of 120 metres. Landsat 7 also has a spatial resolution of 30 metres on the ground in the visible and near-infrared bands (bands 1-5 and 7). The spatial resolution of the thermal infrared band 6 is 60 metres and the spatial resolution of the panchromatic band is 15 metres. At present Landsat-5 and Landsat-7 are in operation. Both systems have a repeat cycle of 16 days – i.e. they will revisit an exact point on the Earth's surface every 16 days. They pass overhead at 10am (± 15 minutes) local mean solar time. A combination of data obtained from both of the systems may result in a shorter revisit time.

HRV (SPOT)

SPOT (Satellite Probatoire d'Observation de la Terre) [http://www.spotimage.fr] is the French government sponsored civil Earth observation program. There have a number of satellites launched since the early 1980s. SPOT-4 carries the High Resolution Visible and Infrared Sensor (HRVIR) and the Vegetation sensor. The spectral bands are:

HRVIR			Vegetation	
MS	Band 1	0.50 – 0.59	Band 1	0.43 – 0.47
	Band 2	0.61 – 0.68	Band 2	0.61 – 0.68
	Band 3	0.79 – 0.89	Band 3	0.78 – 0.89
Pan	Band	0.51 – 0.73	Band 4	1.58 – 1.75

The SPOT 4 system provides global coverage between 87 degrees north latitude and 87 degrees south latitude. Each nominal scene covers a 60 square kilometre area. It has a sun-synchronous LEO orbit with a mean altitude of 832 km. The HRVIR instrument is steerable to either side of the ground track – east to west – by up to 27 degrees. The spatial resolution of the multispectral bands of the HRVIR is 20 metres, whilst the panchromatic band has a spatial resolution of 10 metres. The Vegetation sensor bands have a spatial resolution of 1.2km at nadir. At present SPOT-4, which was launched in March 1998, is in operation. It provides a revisit time of 26 days, passing overhead at 1030am local mean solar time.

LISS(IRS)

The Indian Remote Sensing Satellite (IRS) [http://www.isro.org] programme started with the launch of IRS-1A in March 1988. IRS-1B, a follow-up satellite following the same orbit with identical instruments, was launched in 1991. IRS-1C and IRS-1D, second generation, enhanced capability systems, were launched in December 1995 and September 1997, respectively. IRS-1A and IRS-1B operate in a polar sun-synchronous orbit at an altitude of 904km. IRS-1C and IRS-1D also operate in a polar sun-synchronous orbit but at a lower altitude of 817km. The swath width of all of the systems is between 142 and 148 km.

The spatial resolution of the LISS I system is 72-metres. The spatial resolution of the LISS II systems is 36-metres. The multispectal bands on the LISS III system have a spatial resolution of 25-metres, whilst the panchromatic band has a spatial resolution of 5-metres. The IRS-1A and IRS-1B systems have a revisit time of 22 days. The IRS-1C and IRS-1D systems have a revisit cycle of 24 days.

High resolution sensors (ie, better than 20m resolution)

Table 3.11 gives some examples of high resolution satellite sensors;

Table 3.11 High resolution satellite sensors

Sensors	Resolution (m)	Spectral range (μm)	No of bands	Swath width (km)	Satellite	Launch date
OV PM	4	0.45 – 0.9	4	8	ORBVIEW3	2001
Optical[1]	3.28	0.45 – 0.9	5	22	Quickbird 2	2001
Optical[1]	4[3]	0.45 – 0.69	5	11	IKONOS 2	1999
AVNIR[2]	10	0.42 – 0.89	5	70	ALOS	2003
Optical[1]	2.5		1	15	TOPSAT	2003

Notes: 1: These high resolution instruments have no specific name.
2: AVNIR: Advanced Visible and Near Infrared Radiometer
3: The panchromatic band resolution is 1m

IKONOS

The launch, on September 24th 1999, of Space Imaging's IKONOS, [http://wwwspaceimaging.com] commercial remote sensing satellite, marked the beginning of a new series of high-resolution 1-metre satellite imagery. Its spectral range is:

Multispectral	Band 1	0.45 – 0.52
	Band 2	0.52 – 0.60
	Band 3	0.63 – 0.69
	Band 4	0.76 – 0.90
Panchromatic (1m)	Band	0.45 – 0.90

Ikonos has a nominal swath width of 13km at nadir. This means that the size of a single image is 13 x 13 km. However, strips of 11 x 100km up to 11 x 1000km can be produced, as well as image mosaics of up to 12 000 square km. The ground resolution of each of the multispectral bands is 4 metres. The ground resolution of the panchromatic band is 1 metre. Ikonos orbits in a sun-synchronous pattern with an orbit period of 98 minutes. The revisit time is 2.9 days at 1-metre resolution and 1.5 days at 1.5-metre resolution.

Quickbird

Quickbird-1 is a US commercial satellite operated by EarthWatch Spacecraft [http://www.digitalglobe.com]. It is currently due for launch in May 2000. Quickbird-1 will be the only system of its type to be launched in a non-sun synchronous, non-polar orbit. This will give it the unique ability to observe locations on the earth at different times of day under different lighting conditions. Quickbird-2 will be launched into a sun-synchronous near polar orbit and will offer same-time observations under consistent viewing conditions. Quickbird will have a number of different imaging modes. It will be able to acquire a single 'snapshot' of 22 x 22km, an area of 40 x 40 km, a strip of 22 x 200 km and a stereo image of 20 x 20 km. The ground resolution for each of the multispectral bands will be 4 metres. The ground resolution of the panchromatic band will be 1 metre. Quickbirds will have a 66 degree medium-inclination non-sun synchronous orbit. This means that it will have a variable revisit time that will be, on average, between 1 and 5 days, depending on latitude.

ORBVIEW

Orbview is a US satellite system operated by Orbimage [http://www.orbimage.com]. Orbview 3 is due for launch in April 2000.It will produce high resolution imagery for commercial Earth Observation use. Orbview 4 will carry an identical system to Orbview 3, however it will have the addition of a hyperspectral instrument (this will be reviewed in section 3.4).

TOPSAT

TOPSAT is a low cost high resolution imaging satellite [Brooks 2001] which is currently being developed by DERA in partnership with Surrey Satellite Technology Ltd (SSTL) and RAL (Rutherford Appleton Laboratory). The aim of this development is to demonstrate that high performance can be obtained using small, low cost satellites. With a significant reduction in cost it will then be possible for constellations of satellites to be produced, offering much improved revisit time and coverage.

Summary of satellite visible/near IR sensors

The key developments are in the provision of high resolution imagery – up to 1m – and of multispectral images with more bands and/or higher resolution. This combination of multispectral performance at high (4m) resolution should be of value to Environment Agency applications where classification of small areas of vegetation may be required.

3.3.3 Airborne electro-optic systems

Most airborne electro-optic systems are in use by the military or by police forces. The principal advantages of these systems (compared with photographic sensors), is the ability to acquire and transmit information in real time to control units or headquarters. These systems often have low light imaging capabilities and the ability to acquire imagery at oblique angles. In many cases the imagery is unsuitable for photogrammetry, although some military electro-optic systems are used to generate data for map production. For police work still cameras are often superseded by video cameras.

There are a large number of airborne systems in existence and their performance will generally be a combination of the sensor with a particular airborne platform. The following is an example of the type of technology available:

Vinten Type 8010/11/12 Electro-optical sensor

- Push broom CCD array with 4096 or 6144 pixels,
- Pixel size: 12μm or 8μm,
- Scan speeds: 1,900 or 1,200 cycles/sec,
- Lens options: 38, 76 and 152mm (focal lengths)
- Field of view: 65.6deg, 35.7deg and 18.3deg respectively.

At an altitude of 10km and using the long focal length lens a resolution of roughly 0.5m could be obtained, together with an image size of 2.3 x 2.3km. The sensor can be used in a variety of aircraft (manned or unmanned) for a variety of roles; police, coastguard, drug enforcement, fishery protection. On board processing can be used to remove (or compensate for) haze and the output image can be exploited in real time or recorded digitally.

3.3.4 Airborne photographic systems

Despite the use of more sophisticated imaging systems, aerial photography remains one of the most reliable and most widely used forms of remotely sensed imagery. Most civilian aerial photography has been acquired using metric cameras. These are cameras designed to provide high-quality images with a minimum of optical and geometric error. Such images are used in photogrammetry to enable precise measurements of land features or topography. As with airborne electro-optic sensors, the performance of airborne photography depends on the altitude and stability of the aircraft and on air quality. Apart from these it is the lens and film which determine image quality. (Note; refractive optics are more often used for aircraft since their weight is less important and the refractive optics allows better control of some aberrations. Mirrors are more likely to be used for space systems where mass is a premium, and where off axis performance is less critical.)

There are a number of airborne photographic systems available for use within the UK, eg, the MAFF ADAS system [http://www.adas.co.uk] which uses Zeiss motion compensating cameras. The following paragraphs give some examples of systems overseas:

Partenavia Observer 2
The Partenavia Observer 2 [http://www.erim-int.com/CONF/4th_airborne/11.html] is operated by the US Fish and Wildlife Service. It carries a varied range of remote sensing equipment:

- Accuphoto Flight Management System.
- Jana LMK 1000 Format Camera (9" x 9" negative size) B/W, Color, Color Infrared Films.
- Videography: 2 CCD Cameras (Wide-Angle up to 15x Zoom lens).
- Kodak DCS-420 High-Resolution 35mm Digital Camera (Color and Color Infrared Images).
- Inframetrics Model 445G-MKII.
- Thermal Infrared Sensor.
- Color video integrated with a thermal sensor.

The Observer 2 is also equipped with a large camera port that can easily be reconfigured as a remote sensing platform with a wide spectrum of image collectors, some of which can be operated simultaneously. These are fixed to a gyro-stabilised mount and coupled to the flight management system's Global Positioning System unit for accurate data collection and recording. The remote sensing systems are extremely cost effective (up to a 60% savings) when compared to commercial operations.

Cessna Citation 550 (N10EG)
The United States' Department of Energy has a Cessna Citation 550 (N10EG) [http://www.nc.noaa.gov/aoc/aircraft/citation/citation.html]. It is equipped with a Leica RC30 metric camera. This camera has a 9 x 9 inch film format and is fitted with a 6-inch focal-length lens. This camera can use any of the Kodak film types such as natural colour, colour infrared, black and white panchromatic, and black and white infrared film. Photographic applications include photo interpretation for cover-type mapping, mensuration, and generation of digital elevation models. It also has a Daedalus 1260 or 1268 multispectral scanner. This can be included in a low to medium altitude mission for exceptional spectral and spatial resolution or a high altitude mission (up to 43 000 feet) for a broad-area coverage of mapping-quality photography. Aircraft steering and camera operation are performed using

a state-of-the-art navigation system that, with input from a differential Global Position System provides precise flight-line navigation to the pilot and records the geographic coordinates for each photo taken along the flight path.

3.3.5 Applications

Flood Defence

This section will focus on the use of optical satellite and aerial imagery for flood management. Data from these sources have been used to quantify catchment physical parameters, such as watershed boundaries, elevation and slope, land cover, as well as catchment variables such as temperature and vegetation indices. They have been used operationally for flood monitoring and mapping and damage assessment.

Two main fields of interest can be defined for the use of optical remote sensing data in the flood domain:

i) *A detailed mapping approach*. This is required for the production of hazard assessment maps and for the input to various types of hydrological models. These mapping approaches can be used at regional and local scales and contribute to the hazard and vulnerability aspects of flooding [Ziwei *et al*. 1998].

ii) *A larger scale approach* that looks at the general flood situation within a river catchment or coastal belt with the aim of identifying areas at greatest risk and in the need of immediate assistance. Optical remote sensing may contribute to the initialisation of numerical weather prediction models and weather forecasts and for mapping inundated areas, mainly at a regional level [Prinet, *et al* 1999].

The subject of Flood Defence can be considered to involve: prevention, mitigation and prediction, forecasting and response; these will be considered separately:

Prevention

Prevention involves history, corporate memory, and climatology. This is the classical hazard approach in which the individual input data depend on the scale factor. For regional methodologies, the essential input data are geomorphology, hydrological analysis, historical investigation of past events, and climatological data. Remote sensing may help mapping geomorphic elements and land use, providing meteorological data for hydrological modelling and contributing to mapping historical events.

Investigations on the local scale include topography, hydraulic data, riverbed roughness, sediment grain size, hydraulic calculations, land cover, and surface roughness. Remote sensing may contribute for mapping topography (generation of DEMs) and in defining surface roughness and land cover. Potential users are land planners (local municipality), hydro meteorologists, and those in water management. Hazard data obtained on the local scale can be combined with vulnerability data on population, land use, type of buildings, type of contents, infrastructures, and activities to assess the risk. In this case, remote sensing may contribute to updating cartography for land use. Cartographic updates are a critical aspect of remote sensing since there are often delays in some public administration for maintaining updated official cartography as well as illegal constructions in some areas that are not reported on official maps.

Mitigation and Prediction

Hydrologic models play a major role in assessing and forecasting flood risk. Model predictions of potential flood extent can help emergency managers develop contingency plans well in advance of an actual event to help facilitate a more efficient and effective response. The hydrologic models require several types of data as input such as land use, soil type, soil moisture, stream/river base flow, rainfall amount/intensity, snow pack characterisation, digital elevation model (DEM) data, and static data such as drainage basin size [Flood Hazard Team Report 1999]. Complex terrain and land utilisation in many areas result in a requirement for very high spatial resolution data over very large areas which can only be practically obtained by remote sensing systems.

Figure 3.5 shows the requirements for hydrologic models and indicates potential non-weather satellite platforms that can provide the data required from a satellite such as SPOT can provide DEM data at resolutions of about 10 meters. Land use information can be determined through the use of AVHRR, Landsat and SPOT data. The rainfall component can be determined through the use of existing POES and GOES platforms (meteorological satellites on board the NOAA platform). Although there are no operational data sources for estimating soil type, soil moisture, snow water equivalent and stream/river base flow there has been considerable research on the extraction of these parameters from exiting optical (and microwave) polar orbiting satellites.

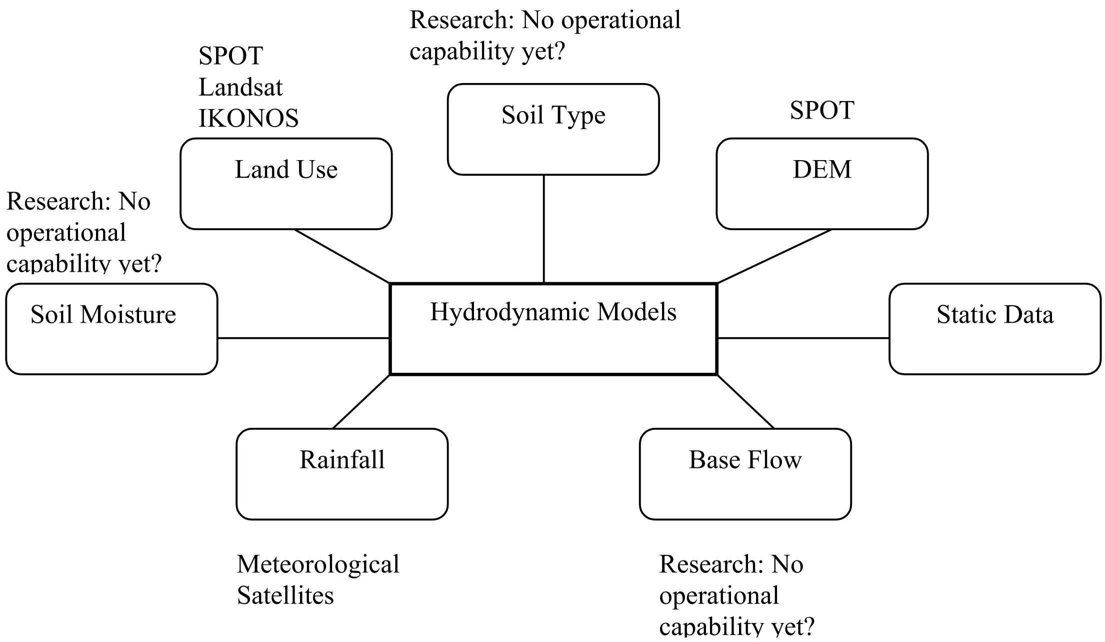


Figure 3.5 Hydrological model requirements

Models can also assist in the mitigation of coastal flooding. Wave run-up simulations can help planners determine the degree of coastal inundation to be expected under different, user-specified storm conditions. These types of models require detailed near-shore bathymetry for accurate wave effect predictions. While airborne sensors provide the best resolution data at present, this data source can be cost-prohibitive when trying to assess large areas of coastline.

Forecasting

To establish flood-warning systems, environmental factors and conditions leading to flood are monitored and studied. These factors include meteorology, ice and snow conditions (coverage and depth), soil moisture, tidal conditions in coastal areas, water levels and flow, topography, land cover, surface roughness, river bed roughness, soil type, and permeability. Weather satellites can provide information on precipitation, moisture, temperature, winds, and soil (surface) wetness. Satellite-derived parameters are also used in assimilation techniques to help initialise numerical weather prediction. Hydrologic models are executed to simulate different situations and policies and systems are implemented to forewarn and evacuate inhabitants living on flood plains.

In all the above-mentioned input data there is a contribution from remote sensing, with the only exception of riverbed roughness. Except for the meteorological applications of NOWCASTING (defined below) and prediction, the benefit from the use of remote sensing techniques may not be essential in well instrumentally monitored areas. In these areas remote sensing can assist in providing better spatial estimates of hydrological parameters, when integrated with in situ measurements. As such, more accurate flood predictions are possible and remote sensing is the only cost effective method to monitor the spatial extent of flooding. Remote sensing is particularly important in those areas not instrumentally monitored.

Response

The response category can also be called “relief” and refers to actions taken during and immediately after a disaster. During a flood, timely and detailed situation reports are required in order to locate and identify the affected areas and make corresponding damage mitigation. It is essential that information be accurate and timely to address emergency situations (for example, handling diversion of flood water, evacuation, rescue, resettlement, water pollution, health hazards, and handling the interruption of utilities etc.).

For remote sensing, this often takes the form of damage assessment. This is the most delicate management category due to rescue operations and the safeguard of people and property. The following is information used and analysed in real time:

- Extent mapping and real time monitoring (satellite, airborne, and direct survey).
- Damage to buildings (remote sensing and direct inspections).
- Damage to infrastructures (remote sensing and direct inspection).
- Meteorological NOWCASTS (important real-time input from remote sensing data as to intensity/estimates; movement and expected duration of rainfall for the next 0 - 3 hours).
- Evaluation of secondary disasters like waste pollution to be detected and assessed during the crisis (remote sensing and others).

Inland water quality

Remote sensing is a practical tool for inland water quality monitoring since it ensures synoptical measurements of the optical returns from target water bodies. This optical return must be transformed, through appropriate models, algorithms or methodologies for estimating water quality parameters.

The general approach taken is based on the use of optical bands ranging from blue to near infra-red in order to explore the relationships between surface irradiance reflectance (volume reflectance) and water bio-physical parameters, mainly water transparency and chlorophyll concentrations, and total suspended solids, both mineral and organic.

Giardino *et al.* [1997] used both airborne and Landsat-5 TM remote sensing data to obtain information about the characteristics of Lake Iseo in northern Italy. Lake Iseo is a warm oligomitic lake with a hypolimnion temperature which never falls below 4ºC. According to the Organisation for Economic Co-operation and Development protocols the lake is mesoeutrophic with an infesting macrophytes proliferation and with an average 32 mg/m^3 of total P concentration.

They convert the radiance values of the data to chromacity coordinates; blue (representing the transparency of the water), green (representing the chlorophyll load of the water) and red (representing the amount of suspended matter). The chromacity coefficients are defined as:

$$Blue = \frac{L_1}{\sum L_1} \qquad Green = \frac{L_2}{\sum L_2} \qquad \mathrm{Re}\, d = \frac{L_3}{\sum L_3}$$

where L_1, L_2 and L_3, are the spectral radiances recorded in Landsat-5 TM bands 1, 2 and 3 and the corresponding channels of the airborne remote sensing data. The chromaticy coordinates are then normalised to aquatic brightness values (the total spectral radiance recorded over the water body by the sensor).

Waters with low concentrations of suspended materials, low chlorophyll and low dissolved organic carbon display dominant wavelengths in the colour range from blue to cyan. Waters with low concentrations of suspended mineral and chlorophyll but moderate concentrations of dissolved organic carbon display dominant wavelengths in the colour range green to brown. Waters with high loads of suspended mineral and/or chlorophyll and /or dissolved organic carbon display a restricted range of dominant wavelengths in the brown colour range.

The results obtained by Giardino *et al.* [1997] confirm previous knowledge that Lake Iseo has a trophic status. They also illustrate the advantage of remote sensing techniques for multi-temporal analysis of inland water quality.

Marine and coastal water quality

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) project provides quantitative data on global ocean bio-physical properties. Subtle changes in ocean colour signify various types and quantities of marine phytoplankton, dissolved organic chemicals and sediments in a similar way to those techniques described above for inland water quality. Since SeaWiFS has a revisit time of 1 day it can be used to monitor changes in the colour of ocean water over time.

Schofield *et al.* [1999] have investigated the use of optical remote sensing techniques for the prediction and monitoring of harmful algal blooms. The techniques that they use depend on the identification of chlorophyll-a and chlorophyll-c containing algae. They have tested both in-situ instruments and airborne and spaceborne remote sensing instruments.

In-situ optical measurements

Recently in situ spectral absorption and attenuation meters have become commercially available and can provide robust measurements of absorption and attenuation (and, therefore, scattering) at numerous wavelengths of light. These measurements can be used to determine the particulate spectrum of a sample, which can be deconvolved into the respective absorption of phytoplankton, detritus and sediments.

Remote sensing measurements

Several satellite and aircraft remote sensing systems (such as SeaWiFS) are currently used to determine above water ocean colour. The derived products they can produce include chlorophyll-a, biomass, CDOM, sediment, primary productivity and potentially community classification (phycobilin and nonphycobilin –containing algae).

Early detection of algal blooms and identification of algae species is important to allow assessment of the potential risk to be made. Forecast of bloom development, based on sea surface temperature and ocean colour is also highly desirable. Harmful algal blooms commonly have red or brown coloration and can be identified with multispectral sensors.

Algal blooms can be detected by both passive and active optical sensors. Current operational sensors include the satellite based SeaWiFS and MOS instruments and airborne systems such as CASI.

The MERIS instrument, to be launched on ENVISAT next year, will significantly enhance ocean colour monitoring capability. Its spatial resolution will be 300m in coastal regions enhancing the ability to monitor such regions. The instrument will use a 1200m resolution for oceanic regions. The AATSR instrument, also mounted on ENVISAT, will provide the sea surface temperature providing synergy with the ocean colour measurements and overcoming problems from sensors such as SEAWIFS and AVHRR being on different platforms.

MERIS has a relatively narrow waveband at 682.5nm to detect the solar stimulated chlorophyll fluorescence peak. The possibility of remote sensing this peak has been demonstrated with an airborne fluorescence line imager [Gower and Borstadt 1990]. The aim of MERIS is to identify 30 classes of pigment concentration over the naturally occurring range. The accuracy of the atmospheric correction will be crucial to accurate concentration determination, The atmospheric correction and inverse modelling will take account of additional optical components, such as suspended sediments and dissolved organic matter, to improve the chlorophyll concentrations which are generally overestimated in coastal regions [Earth Observation Sciences 1998]. The sensitivity of MERIS data for detecting chlorophyll in coastal and inland waters has been addressed by Hoogenboom and Dekker [1998].

Coastal erosion and sediment transport

In coastal waters the suspended sediment content significantly affects the reflective properties of the water. Suspended sediment strongly backscatters radiation, and in turbid conditions overwhelms the reflectance signal of phytoplankton pigments and DOM absorption. Remotely sensed data in turbid coastal regions could be utilised for a number of applications relevant to the Environment Agency: mapping of sediment removal and dispersal would provide predictions of coastal erosion and input for coastal defence strategies, dispersion models could be used to forecast the dispersal of pollutants.

A number of projects in this area are in progress, for example:

- The Land-Ocean Interaction Study (LOIS) is a 6 year project, sponsored by NERC, to quantify the exchange, transformation and storage of materials at the land-ocean boundary. LOIS interacts strongly with RACS (the Rivers, Atmosphere, Estuaries and

Coasts Study). NERC employ a CASI combined with an airborne thematic mapper (ATM) to provide ocean colour and sea surface temperature imagery in riverine and coastal waters.

- The Bedford Institute of Oceanography (Nova Scotia, Canada) has carried out extensive research, using satellite and aircraft imagery in turbid water in the Bay of Fundy and Beaufort Sea.

Remote sensing of coastal areas has been limited by a lack of suitable resolution instruments. Spatial resolutions better than 1km have only been available from Landsat (30m) and SPOT (20m), but these instruments are not optimised for the low reflectivities of coastal regions. Airborne systems could be employed but such systems are relatively rare and offer limited coverage.

When MERIS becomes available it will offer improved spatial resolution, as already discussed, and will have a larger and more optimal selection of wavebands allowing a detailed analysis of the particles to be performed.

Air quality

A number of satellite multispectral sensors, eg MODIS, MERIS, POLDER, MOS, AVHRR and LANDSAT TM, offer aerosol products. However, atmospheric particulate pollution is considered a difficult parameter to determine even at ground level. The use of narrow spectral bands over dense dark vegetation (DDV) can be utilised to determine PM10 (particles of 10μm and smaller) concentration and type [Gower and Borstadt 1990]. Measurements require the retrieval of the aerosol optical depth (visibility), multi-angle measurements and multispectral reflectance properties to allow differentiation of particulate size and type.

A number of authors have recently shown how total atmospheric content of PM2.5 and PM10 particles can be monitored from ground-based sun photometer measurements [Earth Observation Sciences 1998, Kaufman *et al*. 1997] and from airborne and spaceborne measurements [Kaufman *et al.* 1994, Kaufman and Holben 1996 and Flowerdew and Haigh 1996].

Recovery of atmospheric aerosol information over land is difficult to achieve due to the anisotropic reflectance of the land surface being unknown. However, the surface bidirectional reflectance distribution function (BRDF) will be collected with the MODIS instrument. MERIS will also collect BRDF data and aerosol parameters.

Over urban areas, where aerosol distributions will be of key interest, polarisation data coupled with narrow spectral data can be employed [Herman *et al*. 1997, Leroy *et al*. 1997]. The POLDER project is currently developing algorithms to allow retrieval of aerosol properties from polarised radiance at 865nm.

The MERIS sensor will provide aerosol concentration and type determination over DDVs, given suitable external data (POLDER aerosol climatology and surface BRDFs). MERIS's ability to provide aerosol data over bright regions, such as urban areas, remains to be quantified.

The characterisation of aerosols over land and sea with space sensors has recently (1998) been reviewed for the European Commission. General conclusions were that for present and near future sensors the aerosol characterisation was reasonably accurate but offered inconvenient spatial and temporal coverage and that the potential usefulness of the remotely sensed data rested with its coupling with ground-based information and integration into dynamic models.

Land cover and land use

Recent advances in remote-sensing technology and equipment suggest that satellite-borne and airborne earth observation techniques have great potential for providing and updating land cover information in a timely and cost-effective manner. The availability of multispectral data from sensors such as AVHRR has provided the capability to directly compile broad-scale land cover maps and data over a short period of time (10 days to 2 weeks). Medium and high –resolution satellites, such as Landsat and IKONOS, together with aerial photography can provide more detailed information of land cover.

Land cover can be mapped by applying image classification techniques to optical imagery. In principle the process is straightforward, in practice, however, many of the most significant factors are concealed among apparently routine considerations.

i) Selection of images: Success of classification for land cover analysis depends on astute selection of images with respect to season and date. What season or time of year will provide the optimum contrasts between the classes to be mapped? Possibly two or more dates will be required to separate all of the classes of significance. A combination of different types of imagery (e.g. optical and SAR imagery) may be required, either to combat meteorological conditions (such as cloud cover) or to provide more accurate class distinction.

ii) Pre-processing: Accurate registration of images and correction for atmospheric and system errors is essential for an accurate result.

iii) Selection of a classification algorithm: Some classification algorithms will provide accurate results in landscapes dominated by large, homogenous patches but will be less effective on areas with many smaller heterogeneous parcels.

iv) Selection of training data: Training data for each class must be carefully examined to ensure that they are represented by an appropriate selection of spectral subclasses, to account for variations in spectral appearance due to shadowing, composition and so on.

v) Assignment of spectral classes to informational classes: A key process is the aggregation of spectral classes and their assignment to informational classes. For example, accurate classification of the informational class deciduous forest may require several spectral subclasses, such as north-facing forest, south-facing forest and shadowed forest. When the classification is complete these subclasses classes in the remotely sensed images is sensible. That is to say, that the classification classes have should be assigned a common symbol to represent a single information class.

The USGS has devised a land-use and land-cover classification system [Anderson, 1976]. Ideally land-use and land-cover would be mapped separately, however, where remotely sensed data provided the major inputs to the mapping, a classification system based on the separability of been devised so that all areas on the surface of the earth can be placed into one or other class, based on the remotely sensed data, with a high degree of reliability. The USGS classification scheme is designed to have four levels of information. Levels I and II, which provide information on a nationwide scale, are specified by the USGS. These are shown in Table 3.12.

Table 3.12 USGS Land-use / Land-cover classification system for use with remote sensor data.

Level I		**Level II**	
No.	**Description**	**No.**	**Description**
1	Urban or built-up land	11	Residential
		12	Commercial and service
		13	Industrial
		14	Transportation, communications and utilities
		15	Industrial and commercial complexes
		16	Mixed urban or built-up land
		17	Other urban or built-up land
2	Agricultural land	21	Cropland and pasture
		22	Orchards, groves, vineyards, nurseries and ornamental horticultural areas.
		23	Confined feeding operations
		24	Other agricultural land
3	Rangeland	31	Herbaceous range land
		32	Shrub and brush range land
		33	Mixed range land
4	Forest land	41	Deciduous forest land
		42	Evergreen forest land
		43	Mixed forest land
5	Water	51	Streams and canals
		52	Lakes
		53	Reservoirs
		54	Bays and estuaries
6	Wetland	61	Forested wetland
		62	Non-forested wetland
7	Barren land	71	Dry salt flats
		72	Beaches
		73	Sandy areas other than beaches
		74	Bare exposed rock
		75	Strip mines, quarries and gravel pits
		76	Transitional areas
		77	Mixed barren land
8	Tundra	81	Shrub and brush tundra
		82	Herbaceous tundra
		83	Bare ground tundra
		84	Wet tundra
		85	Mixed tundra
9	Perennial snow or ice	91	Perennial snowfields
		92	Glaciers

Multispectal data have been shown to be of considerable utility for the production and updating of land cover maps and databases [Smits and Annoni 1999]. The availability of high spatial resolution satellite multispectral sensors is expected to have a significant impact on land cover mapping. In the future, hyperspectral instruments can be expected to provide more detailed information about land cover types. Hyperspectral sensors are discussed in more detail in section 3.4.

Biodiversity
Optical remote sensing imagery can provide landcover and vegetation-type information as an input into biodiversity monitoring [Stoms and Estes 1993]. It can provide multitemporal data for monitoring vegetation species distribution changes with time. For more specific vegetation species identification hyperspectral data may provide more precise information.

3.4 Hyperspectral

3.4.1 Introduction

Hyperspectral sensors collect high-resolution spectral information from the scene, with each image pixel being accompanied by a spectrum. Such sensors detect sunlight reflected from the scene or thermally emitted radiation. Sensors operating from the visible to about 3μm region of spectrum utilise reflected light; beyond this wavelength there is little solar radiation and sensors detect thermally emitted radiation. In the MWIR region (~3-5μm) both reflected and emitted radiation components are significant.

The utility of remotely sensed data, for a number of applications, is expected to be significantly enhanced by the availability of higher-resolution spectral information. Whilst the term hyperspectral has no formal definition, sensors with about 100 bands or more would certainly fall into this category. For the purposes of this report, sensors with more than about 15 bands have also been included.

Airborne hyperspectral sensors have been available for some years, although significant research activities in the sensor and application areas is on-going. There is now a significant interest in space-based sensors and a number of sensors have either been recently launched or are nearing launch. The first space-borne hyperspectral sensors, HIS and LEISA, were mounted on board the NASA sponsored Lewis spacecraft which unfortunately was lost shortly after launch in 1997. This has led to a considerable delay in the availability of space-borne hyperspectral data.

3.4.2 Hyperspectral Space-based sensors

A number of space-based hyperspectral sensors are being prepared for launch in the next few years. Table 3.13 summarises the characteristics of the proposed sensors and further details of each of the sensors are given below.

Table 3.13 Summary of current and planned space-based hyperspectral sensors

Sensor	Spectral details	Spatial resolution	Proposed launch data
ARIES	VIS/NIR 64 bands 400 to 1100nm, SWIR 32 bands 2000 to 2500nm	30m at NADIR	2004
Warfighter (on Orbview 4)	200 bands, 450-2500nm	8m degraded to 24m for commercial release	2001
MODIS (EOS)	36 specific bands, covering Vis, NIR, SWIR, MWIR and LWIR	Band dependent, 250 to 1000m	First sensor launched 1999.
COIS	210, 10nm bands, 400-2500nm	30m	2001/2
FTHSI (on MightySat II)	256 bands (2-6nm), VIS to NIR	50m	Launched July 2000
GLI (on ADOES II)	36 narrow bands, spanning from VIS to LWIR	1km or 250m	2001
PRISM	450 to 2350nm at 10nm res. 8 to 12.3µm at 1µm res.	50m	N/K
Hyperion (on EO-1)	220 bands, 400 to 2500nm	30m	Launched Nov 2000
CHRIS (on PROBA)	1–10nm res., 450 to 1050nm	25m	2001

ARIES

The Australian Resource Information and Environmental Satellite (ARIES) is a sensor primarily intended for mining applications and therefore offers wide-area coverage to allow use over of large, poorly mapped areas. The sensor design specification is given in Table 3.14 This is a commercial project to launch a hyperspectral imager into LEO during 2004.

Table 3.14 ARIES design specification

Weight	<500kg
Orbit	500km polar sun synchronous
VIS/NIR coverage	64 contiguous bands 400 to 1100nm
VIS/NIR noise requirements	>600:1 @600nm
SWIR coverage	32 contiguous bands 2000-2500nm
SWIR noise requirements	>400:1 @2100nm
Spatial resolution	30m at nadir
Ground swath	15km at nadir
Off track capability	Up to 30^{o} off vertical
Revisit time	7 days (@30^{o} look angle)
Data reception	Australia and overseas
Launch date	2000
Panchromatic sensor	10m spatial resolution

Warfighter (Orbview 4)

The US airforce has funded the addition of a hyperspectral sensor to the Orbview 4 commercial satellite. The hyperspectral instrument will produce 8m resolution imagery which will be co-registered with images from the 1m resolution panchromatic sensor and the 4m resolution multispectral sensor onboard. The satellite will revisit each location on earth in less than 3 days with an ability to turn from side-to-side up to 45^o from a polar orbital path.

The capabilities of the hyperspectral sensor are given in Table 3.15 along with the complementary panchromatic and multispectral sensors for comparison.

Table 3.15 Orbview-4 instrument capabilities

Imaging mode:	**Panchromatic**	**Multispectral**	**Hyperspectral**
Spatial resolution	1m	4m	8m
Channels	1	4	200
Spectral range	450-900nm	450-520nm 520-600nm 625-695nm 760-900nm	450-2500nm
Swath width	8km	8km	5km
Image area	$64km^2$	$64km^2$	$25km^2$
Revisit time	3 days	3 days	3 days
Orbital altitude	470 km	470 km	470 km
Nodal crossing	10:30	10:30	10:30
Turn ability	Side-to-side up to 45^o	Side-to-side up to 45^o	Side-to-side up to 45^o
System design life	5 years	5 years	5 years

Orbview have negotiated rights to sell the hyperspectral imagery on a commercial basis. This was originally assumed by Orbview to be the full 8m resolution data. However, their current licence permits them to sell only data degraded to 24m. Orbview are continuing to press for the right to sell higher resolution data but this is unlikely to be granted.

MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) is the primary payload of the Earth Observing System (EOS) AM-1 and PM-1 satellites. The EOS is part of NASA's Mission to Planet Earth and EOS AM-1 will be the first of a series of launches into polar sun-synchronous orbits.

The MODIS instrument will provide global observation of the earth's surface every two days and will collect data in 36, non-contiguous, narrow spectral bands covering the visible to the LWIR. The instrument will have moderate spatial resolution and is designed for wide-area applications.

The principal MODIS data products will include:

- Cloud masks at 250m and 1000m resolution
- Aerosol concentration and optical properties

- Vegetation and land-surface cover
- Snow and sea-ice cover and reflectance
- Surface temperature
- Ocean colour

The specification for MODIS is given in Table 3.16.

Table 3.16 MODIS design specification

Weight	250kg
Orbit	705km polar sun-synchronous
Nodal crossing	10:30am descending node (AM-1) or 1:30pm ascending node (PM-1)
Scan rate	20.3rpm
Swath dimensions	2330km (cross track) by 10km (along track at nadir)
Telescope	17.78cm diam. Off-axis, afocal (collimated), with intermediate field stop
Size	1.0 x 1.6 x 1.0 m
Power	162.5 W (single orbit average)
Data rate	10.8 Mbps (peak daytime); 6.2 Mbps (orbital average)
Quantisation	12 bits
Spatial resolution	250m (bands 1-2) 500m (bands 3-7) 1000m (bands 8-36)
Design life	6 years

The MODIS wavebands with their primary uses, spectral radiance and SNR are given in Table 3.17.

Table 3.17 MODIS Waveband details with primary uses

Band	Primary use	Bandwidth	Spectral radiance	SNR or NEΔT (K)
1	Land/cloud boundaries	620-670nm	2180μF	128 SNR
2	Land/cloud boundaries	841-876nm	2470μF	201 SNR
3	Land/cloud properties	459-479nm	3530μF	243 SNR
4	Land/cloud properties	545-565nm	2900μF	228 SNR
5	Land/cloud properties	1230-1250nm	540μF	74 SNR
6	Land/cloud properties	1628-1652nm	730μF	275 SNR
7	Land/cloud properties	2105-2155nm	100μF	110 SNR
8	Ocean colour/phytoplankton/biogeochemistry	405-420nm	4490μF	880 SNR
9	Ocean colour/phytoplankton/biogeochemistry	438-448nm	4190μF	838 SNR
10	Ocean colour/phytoplankton/biogeochemistry	483-493nm	3210μF	802 SNR
11	Ocean colour/phytoplankton/biogeochemistry	526-536nm	2790μF	754 SNR
12	Ocean colour/phytoplankton/biogeochemistry	546-556nm	2100μF	750 SNR
13	Ocean colour/phytoplankton/biogeochemistry	662-672nm	950μF	910 SNR
14	Ocean colour/phytoplankton/biogeochemistry	673-683nm	870μF	1087 SNR
15	Ocean colour/phytoplankton/biogeochemistry	743-753nm	1020μF	586 SNR
16	Ocean colour/phytoplankton/biogeochemistry	862-877nm	620μF	516 SNR
17	Atmospheric water vapour	890-920nm	1000μF	167 SNR
18	Atmospheric water vapour	931-941nm	360μF	57 SNR
19	Atmospheric water vapour	915-965nm	1500μF	250 SNR
20	Surface/cloud temperature	3.660-3.840μm	45μF	0.05 NEΔT
21	Surface/cloud temperature	3.929-3.989μm	238μF	2.00 NEΔT
22	Surface/cloud temperature	3.929-3.989μm	67μF	0.07 NEΔT
23	Surface/cloud temperature	4.020-4.080μm	79μF	0.07 NEΔT
24	Atmospheric temperature	4.433-4.498μm	17μF	0.25 NEΔT
25	Atmospheric temperature	4.482-4.549μm	59μF	0.25 NEΔT
26	Cirrus clouds/water vapour	1.360-1.390μm	600μF	150 SNR
27	Cirrus clouds/water vapour	6.535-6.895μm	116μF	0.25 NEΔT
28	Cirrus clouds/water vapour	7.175-7.475μm	218μF	0.25 NEΔT
29	Cirrus clouds/water vapour	8.400-8.700μm	958μF	0.05 NEΔT
30	Ozone	9.580-9.880μm	369μF	0.25 NEΔT
31	Surface/cloud temperature	10.780-11.280μm	955μF	0.05 NEΔT
32	Surface/cloud temperature	11.770-12.270μm	894μF	0.05 NEΔT
33	Cloud top altitude	13.185-13.485μm	452μF	0.25 NEΔT
34	Cloud top altitude	13.485-13.785μm	376μF	0.25 NEΔT
35	Cloud top altitude	13.785-14.085μm	311μF	0.25 NEΔT
36	Cloud top altitude	14.085-14.385μm	208μF	0.35 NEΔT

EOS AM-1 was launched during 1999 and EOS PM-1 was planned for launch in 2000. These initial satellites will be followed by AM-2 and PM-2 after about 4 years.

COIS

The Coastal Imaging Spectrometer (COIS) is the primary sensor on the Naval Earth Map Observer satellite (NEMO) due for launch in 2001/2. NEMO is jointly owned by the US Naval Research Laboratory and Space Technology Development Corporation (STDC). STDC will offer commercial imagery and products through its EarthMap subsidiary.

COIS will collect moderate resolution imagery (30/60m GSD) over a 30km wide swath. A co-registered panchromatic imaging camera will be included in the payload. COIS employs a three mirror off-axis anastigmat, 12cm aperture telescope and two spectrometers which cover the 0.4-1.0μm and 1.0 – 2.5μm spectral regions. The primary characteristics are listed in Table 3.18.

NEMO will also trial ORASIS which is NRL's Optical Teal-time Adaptive Signature Identification System, a complete hyperspectral processing algorithm which has the added advantage of data compression with minimal loss of information.

Table 3.18 Characteristics of COIS instrument

Launch	2001/2
Orbit	605km polar sun synchronous
Nodal crossing	10:30 ascending
Repeat cycle	7 day repeat, 2.5 day global re-access
Spectral range	400-2500nm
Spectral resolution	10nm (210 bands)
Swath width	30km
Spatial resolution	30m GSD
Signal to Noise ratio	>200 over 0.4 to 1.0μm, using ground motion compensation
Panchromatic camera	Long linear array – 6000 pixels Waveband 0.5-0.7μm Swath width 30km Spatial resolution 5m GSD
Lifetime	3 year mission, 5 year design
Data rates	High rate –150 Mbps X-band Low rate – 1 Mbps S-Band (processed imagery for tactical support demonstration) Command uplink – 1 kbps
Data	Average daily collection 227-500Gbits
On-board storage	48 Gbits (solid state)
On-board processing	ORASIS
Processing power	2.5Gflops

NEMO will also trial ORASIS which is NRL's Optical Teal-time Adaptive Signature Identification System, a complete hyperspectral processing algorithm which has the added advantage of data compression with minimal loss of information.

FTHSI

The FTHSI (Fourier Transform Hypserspectral Imager) is one of the instruments launched on MightySat II in 2000 and is functioning well. MightySat II (also known as Sindri) is a mullti-mission small satellite programme run by the US Air Force Research Laboratory and the Hyperspectral instrument is sponsored by DoD. The availability of commercial data from the instrument is currently unknown. The principal instrument characteristics are given in Table 3.19.

Table 3.19 Characteristics of FTHSI

Number of bands	256
Spectral coverage	Vis – NIR
Spectral sampling	2-6nm
Swath width	15km
Mode of operation	Pushbroom
Spatial sampling	50m

GLI

The Global Imager (GLI) is a medium spatial resolution sensor to be flown on NASDA's (Japanese Space Agency) ADEOS-II satellite, now planned for launch in 2001. The GLI instrument will have 36 narrow bands, spanning the spectrum from the visible to the LWIR and is intended for observation of oceans, land and cloud. The principal characteristics of the GLI instrument are given in Table 3.20.

Table 3.20 Characteristics of GLI instrument

Orbit altitude	803 km
Orbit	Sun-synchronous 98.6°
Nodal crossing	10.30
Spatial resolution at nadir	1km or 250m
Data rate	4.1 Mbps
VNIR spectral bands nm Bandwidth nm Spatial resolution O:Ocean L:Land A:Atmosphere C: Cryosphere	1) 380,10,1km,OAC 2) 400,10,1km,O 3) 412,10,1km,O 4) 443,10,1km,OLAC 5) 460,10,1km,OLAC 6) 490,10,1km,O 7) 520,10,1km,OAC 8) 545,10,1km,OAC 9) 565,10,1km,OL 10) 625,10,1km,O 11) 666,10,1km,O 12) 680,10,1km,O 13) 678,10,1km,LAC 14) 710,10,1km,O 15) 710,10,1km,LAC 16) 749,10,1km,O 17) 763,8,1km,LA 18) 865,20,1km,O 19) 865,10,1km,LAC 20) 460,70,250m,LAC 21) 545,50,250m,LAC 22) 660,60,250m,LAC 23) 825,110,250m,LAC
SWIR spectral bands nm Bandwidth nm Spatial resolution O:Ocean L:Land A:Atmosphere C: Cryosphere	24) 1050,20,1km,LAC 25) 1135,70,1km,A 26) 1240,20,1km,LAC 27) 1380,40,1km,A 28) 1640,200,250m,LAC 29) 2210,220,250m,LAC
LWIR spectral bands µm Bandwidth µm Spatial resolution O:Ocean L:Land A:Atmosphere C: Cryosphere	30) 3.715,0.33,1km,OAC 31) 6.7,0.5,1km,A 32) 7.3,0.5,1km,A 33) 7.5,0.5,1km,A 34) 8.6,0.5,1km,OLAC 35) 10.8,1.0,1km,OLAC 36) 12.0,1.0,1km,OLAC
S/N,NEΔT	800,0.1K
Quantisation	12 bits
Polarisation sensitivity	<2%
Tilting angles	-20°,0°,20°
MTF	0.35

PRISM

In May 1996 nine candidate missions were selected for the European Space Agency's (ESA) Earth Explorer missions, one of the Land-Surface Processes and Interactions Mission was recommended for Phase A study. The payload for this mission is called PRISM.

PRISM comprises a hyperspectral spectrometer combining the features of two earlier instruments HITIR (High-Resolution Thermal Infrared) and HRIS (High Resolution Imaging Spectrometer), in the thermal infrared PRISM will operate as a radiometer with a number of bands likely to be 1µm or so in width. SIRA Electro-Optics and Deutsche Aerospace (DASA) prepared these concepts. The main features for the instrument and satellite are described in Table 3.21.

Table 3.21 Characteristics of the PRISM instrument

Spatial resolution	50 m
Swath width	50 km
Collection mode	Pushbroom
Revisit interval	3 days
Spectral coverage	0.45-2.35 µm (VIS/NIR/SWIR) 8-12.3µm (LWIR)
Wavebands	150 (VIS/NIR/SWIR) ~2 (LWIR)
Spectral sampling	10nm (VIS/NIR/SWIR) 1µm (LWIR)
Spectral accuracy	0.5nm (VIS/NIR/SWIR)
Orbit	Sun-synchronous, 772 km
Nodal crossing	11.00 (descending node)
Satellite mass	950kg
Power generation	1200 W
Date collection rate	250 Mbps (per site)
Downlink	100 Mbps
Pointing capability	+/-30° (BRDF)
Detectors	Si CCD (VIS/NIR) MCT (SW/LWIR)

Hyperion

The Hyperion instrument is a modified re-flight of the hyperspectral Lewis instrument lost at launch in 1997. It will form part of a suite of instruments on NASA's NMP/EO-1 (New Millenium Programme/ Earth Orbiter-1) mission due for launch in April 2000. The satellite will be placed into an orbit one minute behind Landsat 7. EO-1 is a testbed for technologies that will eventually replace the Landsat instruments and it is believed unlikely that data will initially be made commercially available.

The principal characteristics of the Hyperion instrument are given in Table 3.22.

Table 3.22 Characteristics of Hyperion

Number of bands	220
Spectral coverage	0.4-2.5µm
GSD	30m
Swath	7.5km wide, 100km long
Focal planes (based on LEWIS spares)	VNIR + SWIR
Orbit	705km circular sun-synchronous 98.7^o (1 minute behind Landsat 7)

CHRIS

The CHRIS (Compact High Resolution Imaging Spectrometer) instrument has been designed and built in the UK by SIRA and is the primary payload on ESA's PROBA (project for onboard autonomy) mission. CHRIS is designed with considerable off track pointing capabilities and a primary interest is in measuring BRDF for agricultural applications in order to support the interpretation of data from future satellite missions. Launch is scheduled for late 2000 and the mission is planned to last one year. SIRA expect to retain full data rights.

The principal characteristics of the instrument are given in Table 3.23.

Table 3.23 Characteristics of the CHRIS instrument

Ground resolution	25m
Swath	19km x 19km
Spectral coverage	450-1050nm
Spectral resolution	1-10nm
Number of bands	10-15 (up to 30 bands possible)
Off track pointing capability	±50^o along track ±30^o across track

3.4.3 Airborne hyperspectral sensors

A number of airborne hyperspectal sensors are available either to buy or to be accessed via a survey service. Table 3.24 summarises the main features of some example sensors, which are described in more detail below.

Table 3.24 Summary of example air-borne hyperspectral sensors

Sensor	Spectral details	Spatial resolution	Commercial availability
SEBASS	2.5 to 5.5 µm MWIR, 128 bands 7.8 to 13.5 µm LWIR, 128 bands	Altitude dependent (1m typical)128 spatial elements across track.	In theory sensor is commercially available, in practice considered unlikely.
AVIRIS	400 to 2500nm, <10nm	Swath width 614 pixels (20m typical)	Commercial surveys provided
Hymap	400 to 2500nm, 10-20nm res.	3-10m typical (512 pixels swath width)	Commercial surveys provided
HYDICE	400 to 2500nm, 10-15nm res.	312 pixels across track, <1m res. typical.	No commercial availability currently expected.
CASI	400 to 1000nm, up to 288 channels	512 pixel across track,), 0.5 to 10m res. typical	Environment Agency owns a CASI sensor.
DAIS 7915	Various Vis, NIR, SWIR, MWIR, LWIR	512 pixels, 3 to 20m typical	Commercial surveys provided.
GER	Various sensors covering Vis to SWIR and LWIR	2-20m res. typical	Commercial surveys provided.
MIVIS	430nm to 2500nm, 92 bands. 8.2 to 12.7µm, 10 bands	755 pixels per scan line	Commercial surveys available in Europe through CNR

SEBASS

The Spatially Enhanced Broadband Array Spectrograph System is a US MWIR/ LWIR imaging spectroradiometer developed and operated by Aerospace Corporation. The sensor was originally a ground-based sensor, which has subsequently been modified for use into air platforms: a high altitude WB-57 (derivative of UK Canberra) and a low altitude Twin Otter. Both airborne versions of SEBASS provide approximately the same GSD.

It is unlikely that data from the sensor would be made commercially available.

The main characteristics of the SEBASS sensor are given in Table 3.25.

Table 3.25 Characteristics of the airborne SEBASS sensor

Spectral coverage	2.5-5.5µm (MWIR),7.8-13.5µm (LWIR)
No of spectral channels	128 (MWIR), 128 (LWIR)
No of spatial samples (across track)	128
Spectral resolution	~0.03µm (MWIR), ~0.05µm (LWIR)
FoV	1.11 mrad (per pixel)
Maximum data file size	4000 lines (512 Mbytes airborne)
On-board storage	>20 Gbytes (airborne)
NESR	<1 µflick [10^{-6} W /(cm^2 Sr µm)]
Radiometric calibration	Two blackbodies
Digitisation	14 bits
Airborne platforms	WB-57/Twin Otter
Stabilisation/cal time (altitude changes)	~15 mins (airborne)
Navigation	On-board DGPS
Exploitabilty time	~24 hours
Tie points	Reflective panels (in imagery)
Spatial repeatability	20-30m (with skilled pilot)

AVIRIS

The Airborne Visible Infrared Imaging Spectrometer (AVIRIS) was developed by JPL/NASA mainly to collect data for the scientific community. AVIRIS covers the visible to SWIR region in 224 contiguous bands at 20m GSD (when flown on a NASA ER-2). Recently AVIRIS has been installed and operated from a Twin Otter with typical GSDs of 3.8m.

Table 3.26 Characteristics of the AVIRIS instrument.

Imager type	Whiskbroom 12Hz
Dispersion	Four grating spectrometers (A, B, C, D)
Detectors	A,B (32,64) Si C,D (64,64) InSb
Digitisation	12 bits
Data rate	20 Mbits/sec
Spectral rate	7300 spectra/sec
Data capacity	>10 Gbytes
Spectral range	0.4-2.5µm
Spectral sampling	<10 nm
Spectral resolution	10 nm (FWHM)
Spectral calibration	0.2 nm
Swath width	614 pixels

Some of the AVIRIS system parameters are shown in Table 3.26 AVIRIS images the ground using a scanning mirror working in pushbroom mode. Four grating spectrometers are used to cover the full spectral range, Si technology covers the visible and InSb the NIR.

Hymap

This is an airborne commercial sensor developed in the last few years by Integrated Spectronics in Australia, four systems have been sold to date. The system is designed along the same lines as the ARIES satellite and is primarily intended for wide area mining and geology applications. Hymap system features include: gyro stabilised platform for geometric correction, sealed optics and operation from range of platforms.

The principal characteristics are given in Table 3.27.

Table 3.27 HyMap characteristics

No of bands	126
Spectral bandwidth	10-20 nm
Spectral range	0.4-2.5µm
Data collection mode	Whiskbroom
SNR	>1000:1
Spatial resolution	3-10m
Swath width	62° (512 pixels)
Calibration	On-board
Stabilisation	3-axis gyro
Geometric correction	DGPS + C-Migits (Hyvista Hymap)

DERA, in collaboration with other international partners, carried out trials with the Hyvista HyMap sensor in May 2000. Images for evaluation are therefore available within the UK.

HYDICE

HYDICE is a US airborne pushbroom system operating in the spectral region 0.4-2.5µm. No commercial availability of the sensor is currently expected. The main characteristics are given in Table 3.28.

Table 3.28 Characteristics of HYDICE instrument.

Spectral coverage	0.4-2.5µm
Spectral resolution	10-15 nm (FWHM)
Spectral dispersion	Single prism
Spatial samples	312 pixels (across track)
IFOV	0.5 mrad
GSD	0.76m at 1524m GSD

CASI

The CASI (Compact Airborne Spectrographic Imager) sensor consists of a 512 by 288 element array. The sensor operates in a pushbroom mode with steering capability, the 512 element dimension is orientated across the line of flight. A single line imaged on the ground is spectrally dispersed across the 288 element dimension of the sensor. The sensor operates in a spectral range extending from 0.4 to 1.0µm.

The major characteristics of the CASI sensor are described in Table 3.29.

Table 3.29 CASI sensor characteristics

Spectral resolution	FWHM 2.2nm
Spectral sampling	1.9nm
Spectral channels	Up to 288
Spectral coverage	0.4-1.0µm
Spatial resolution (across track)	512 pixels
Spatial resolution (along track)	Limited only by storage
IFOV	1.2 mrad (along track)
GSD	0.5-10m
Operating modes	Spatial: <19 wavebands, 512 pixels Spectral: 288 wavebands, <39 pixels Hyperspectral: 288 wavebands, <101 pixels Full frame: all spatial and spectral information
Aperture	F/2.8 to f/11.0
Dynamic range	12 bits
SNR	420 (peak)
Radiometric accuracy	±2.0% (0.47-0.8µm) ±5.0% (0.43-0.87µm)
Data throughput	420-840 kbytes/s
Readout time	8 ms
Integration time	10ms
Frame rate	56 frames/sec

The Environment Agency has an operational CASI and a second UK CASI instrument is owned by NERC. DERA is in the process of undertaking some trials work, using the Environment Agency's CASI in support of one of it military assignments.

DAIS 7915

The Digital Airborne Imaging Spectrometer (DAIS 7915) is a joint programme between the European Union and DLR to produce a sensor to cover the spectral region from the visible to LWIR at spatial resolutions of 3 to 20m.

DAIS operates in a pushbroom mode, a rotating cubic mirror scans the ground across track, the motion of the aircraft enables an image to be built up along track. The up welling radiation is reflected by the scanning mirror onto a flat mirror and is then directed onto a beam splitter and split into two parallel beams, further beamsplitters then direct the energy into five grating spectrometers each dealing with a specific wavelength range.

The main characteristics of the sensor are given in Table 3.30 and details of the five spectrometers are given in Table 3.31

Table 3.30 DAIS 7915 characteristics

IFOV	2.5 or 5.0 mrad
Swath angle	$\pm 39^o$
Spatial pixels	512
Dynamic range	15 bit
Sensitivity	NESR <10 $\mu W\ cm^{-2}\ Sr^{-1}\ \mu m^{-1}$ (VIS/NIR) NESR <5 $\mu W\ cm^{-2}\ Sr^{-1}\ \mu m^{-1}$ (SWIR) NEΔT<0.1K (MWIR/LWIR)

Table 3.31 DAIS 7915 spectrometers.

Spectrometer	Spectral range	Spectral bands	Bandwidth	Detector technology
1	0.4-1.0	32	16nm	Si
2	1.5-1.8	8	36nm	InSb
3	2.0-2.5	32	15nm	InSb
4	3.0-5.0	1	2μm	MCT
5	8.7-12.3	6	0.6μm	MCT

GER

GER designs and manufactures a range of airborne hyperspectral sensors. There are three basic EPS Series scanners, with different aperture sizes. The baseline band configuration for each series is given in Table 3.32. Systems can also be tailored to specific customer requirements with configuration options and band substitutions available for all spectral regions.

GER provide aerial surveys with their imaging spectrometers, which are adaptable for a range of aircraft and can also generally be fitted to user-supplied aircraft. Ground resolutions vary between 2 and 20m. All survey data is GPS encoded.

Table 3.32 Nominal spectral bands of GER airborne hyperspectral sensors

Imaging System:	EPS-M Series	EPS-A Series	EPS-H Series
Collection Aperture (cm^2)	28 Number of bands	115 Number of bands	460 Number of bands
300 –1000nm	2	28	76
1000-2000nm	1	32	-
2000-2500nm	1	28	-
8 - 12μm	1	1	12

MIVIS (Multiple Infrared and Visible Imaging Spectrometer)

MIVIS is a simultaneous multispectral imaging system that operates in the wide range from visible to thermal-IR regions of the spectrum. A Daedalus AA5000 MIVIS sensor has been acquired by CNR (Italian National Research Council). The instrument is composed by 4 spectrometers that use a common Field Stop allowing the pixel alignment for all the channels. MIVIS is designed to provide a fine quantization of spectral information to permit the accurate definition of absorption features from a variety of materials, allowing the extraction of chemical and physical information.

MIVIS is a modular instrument constituted by 102 spectral channels that use independent optical sensors simultaneously sampled and recorded. MIVIS, with 4 spectrometers designed to collect radiation from the earth's surface in the Visible (20 channels), Near-IR (8 channels), Mid-IR (64 channels), and Thermal-IR (10 channels), represents a second generation imaging spectrometer developed for its use in Environmental Remote Sensing studies across a broad spectrum of scientific disciplines.

CNR established an airborne hyperspectral imaging laboratory, devoted to environmental problems, in1994 and offer surveys with the MIVIS sensor.

The primary characteristics of the MIVIS sensor [Bianchi, 1995] are given in Table 3.33.

Table 3.33 Primary characteristics of MIVIS airborne sensor

Bands	Lower edge	Upper edge	Bandwidth
#	µm	µm	µm
1-20	0.43	0.83	0.02
21-28	1.15	1.55	0.05
29-92	1.983	2.478	0.009
93-102	8.18	12.7	0.34-0.54

102 spectral bands: simultaneously sampled and recorded
Two built in reference sources thermally controlled in the range 15°C below and 45°C above ambient temperature
Field of view : Instantaneous 2.0 mrad, Total 71.059°
Sample rate (angular step): 1.64 mrad
12 bits data quantization
Pixels per scan line: 755
Scan rotational speeds: 25, 16.7, 12.5, 8.3 and 6.25 scans/sec
Computer aided data quality check for all 102 channels in real time
Thermally compensated optical-mechanical design
Thermally compensated optical-mechanical design
Large dynamic range: 1200°C maximum scene temperature
Computer interfaced data recording system. VHS cassette media (10.2 Gbytes capacity)
Built in aircraft Position and Attitude Sensor (PAS) using a GPS receiver, a roll/pitch gyro and a flux gate compass for aircraft heading sensor.
Real time aircraft roll correction: ±15°

3.4.4 Applications of hyperspectral data

Introduction

The availability of high spectral resolution data can be expected to lead to a greatly enhanced ability to classify land-surface and sea features. The limited number of spectral bands available for example from the Landsat multispectral sensor, allow only a few broad classes of classification. With data from many fine spectral bands the possibility of distinguishing fine classes of vegetation or water quality exists.

A number of core issues are the focus of much research to realise the full potential of hyperspectral sensors and are briefly outlined below.

Spectral characterisation: The accurate interpretation of remote sensed hyperspectral data requires a sound understanding of the expected spectral characteristics of the imaged surface. A knowledge of the expected reflective of emissive spectral features, an understanding of the variation of the spectrum with viewing angle (BRDF effects), multiple scattering effects (eg within a vegetative canopy) and how this influences the spectrum. In many cases spectral ground truth data will be collected at the time of data acquisition to substitute for full knowledge of the above. However, this is not likely to be a viable method for large-scale classification.

At sensor signal and atmospheric correction: The signal recovered from the sensor is composed of the reflective (or emissive) spectral characteristics of the images surface convoluted with the atmospheric absorption, path radiance and sensor characteristics. The sensor characteristics will be known but the atmospheric effects are more difficult to quantify. Standard atmospheric modelling packages, such as MODTRAN, exist but sufficiently detailed information about the local atmospheric parameters, to allow the recovery of the reflectance spectrum is not generally available. Current research effort in the area is investigating the possibility of recovering atmospheric information from the hyperspectral data itself. Accurate atmospheric removal will be crucial to the utilisation of data from space-based hyperspectral sensors for classification tasks.

Data processing: Ultimately the usefulness of hyperspectral data is limited by the ability of the data processing algorithms to retrieve the required information. The development and evaluation of hyperspectral processing techniques is a very active area of research and progress here can be expected to significantly enhance the usefulness of hyperspectral imagery.

Band selection and trade-offs: The optimum sensor characteristics and performance will depend on the application. The most appropriate spectral range, the number and width of spectral bands, signal to noise ratio (SNR), radiometric calibration accuracy and spatial resolution will all depend on the application and inevitably trade-offs will need to be made. In general, for a given platform, it is necessary to reduce spatial resolution in order to gain high spectral resolution with sufficient SNR. Sensors designed for specific applications, such as ARIES for mining applications will be optimised for that task. However, in general the choice of sensor or specification of a new sensor would need to be based on a consideration of the above. With some sensors, such as the airborne CASI sensor, it is possible to pre-select a choice of wavebands.

Application areas

The following sections address the potential for hyperspectral imaging to contribute to the environmental applications which have been identified as of relevance to the Environment Agency. Current research efforts related each application are discussed.

Vegetation information

Knowledge of the vegetation-type is of interest for a number of applications. Water management and flood modelling (via run-off), land-use and land-cover and biodiversity. The vegetation-type and its health may also be indicators of pollution, soil contamination, soil water content, crop irrigation, etc.

The reflectance spectra of living vegetation tend to be rather similar. The visible region exhibits low reflectance due to the strong absorption of chlorophyll. There is slightly higher reflectance in the green region, which gives plants their green appearance. At about 700nm the reflectance dips and then rises sharply in the near infra-red. This sharp rise, known as the 'red-edge' is caused by the sharp cut off of chlorophyll absorption. In the infra-red the reflective properties are primarily determined by the cellulose structure of the vegetation. Strong water absorption features will also be found at 1.4 and 2.0μm. In the LWIR the reflectance is only a few percent.

Most species-specific spectral properties of plants are to be found in the near infra-red region of the spectrum. Here the unique cell structure determines the spectral properties. Spectral information on the red-edge at around 700nm and reflectance in the near infra-red is therefore the most important region for vegetation-type classification. The red-edge, in particular, is also a good indicator of plant stress due to drought or contamination. The received spectral signature will depend on the structure of the vegetation canopy, due to multiple reflections, on reflective components from the underlying soil, wooded plant structure and shadow regions. This combined signature will also depend on the sun and sensor positions.

Determination of vegetation type

Numerous studies involving the collection and analysis of airborne hyperspectral data, to assess the accuracy of vegetation-type determination have been performed. Lelong *et al*. [1998] studied MIVIS data (20 bands, visible and NIR, 10m ground resolution) of wheat parcels in France with a particular interest in tracing crop evolution. With relatively unsophisticated analysis tools, namely linear spectral mixture modelling and principal component analysis they were able to separate out wheat spectral features from soil and shadow, distinguish the leaf area index (LAI), indicative of the crops development stage and distinguish irrigated crops from un-irrigated ones.

A study of coastal wetlands in Florida [Neuenschwander *et al. 1998*] using AVIRIS data (224 bands 400-2500nm, 18m spatial resolution) investigated a number of classification method for distinguishing wetland and upland vegetation types. The method has been used to monitor the response to wetland management practices. Table 3.34, taken from Neuenschwander *et al. 1998*, gives the classifier success rates, for a number of species and three classifiers. It is reproduced here to give a quantitative indication of the accuracy of such methods in distinguishing vegetation types.

Table 3.34 Classifier success rates

Vegetation type	Classifier: 1	2	3
	%	%	%
Scrub	95.3	84.8	97.2
Willow swamp	93.8	90.5	96.3
Cabbage Palm Hammock	87.1	87.9	88.2
CP/Oak Hammock	63.1	63.1	91.7
Slash Pine	62.3	67.1	83.0
Oak/Broadleaf Hammock	46.0	47.2	90.8
Hardwood swamp	88.6	94.3	100.0
Overall uplands	76.6	76.4	92.5
Graminoid Marsh	74.8	74.2	98.6
Spartina Marsh	87.3	89.6	90.8
Cattail Marsh	83.6	90.8	94.8
Salt marsh	97.1	96.9	99.3
Mud Flats	92.8	73.6	83.8
Overall Wetlands	87.1	85.0	93.5

Bach and Mauser [1997], have compared the information obtainable from hyperspectral data compared with multispectral data. AVIRIS, CASI and GER data have been used. The usual approach of NDVI characterisation is compared with the hyperspectral parameterisation of red edge position and water absorption features. The following conclusions were made: that in comparison to the NDVI the red edge position is more sensitive to biomass changes, that hyperspectral data is required to determine the red-edge position, that modelling of the water absorption allows the extraction of information on plant water content, that the relations between NDVI and the water absorption feature are species dependent, that the absorption features of cellulose in the SWIR can be connected with different maturing stages of vegetation.

A number of studies investigating the spectral properties of vegetation and canopies have been undertaken [Xiang *et al*. 1998, Blackburn 1998].

Canopy structure and angular signatures.

Studies characterising the spectral and directional effects of canopies have been undertaken. Such information is important for two main reasons. Firstly the canopy properties affect the spectral signature of the vegetation, due to multiple scattering and the degrees of shadow in the canopy, and secondly information on the spectral/directional properties may be exploited to assist in the identification of vegetation-type. The directional reflectance properties are described by the bidirectional reflectance distribution function (BRDF).

Sandmeier and Deering [1999] have developed a methodology to derive vegetative canopy structural characteristics from the hyperspectral BRDF. Data have been acquired with the Advanced Solid-State Array Spectroradiometer (ASAS) over the Canandian boreal forests (BOREAS campaign). Canopy structural details have been shown to be derivable from the spectral variability of the BRDF effects. Including both BRDF data and hyperspectral data significantly improved the classification accuracy in some cases, However, the classification accuracy was significantly degraded for certain species. A number of other workers are investigating the utility of BRDF data for determining canopy structures see for example, [Ni 1999, Qin, *et al* 1999 and Gerstl *et al*. 1999]

Stress and contamination indicators

In the near infra-red part of the spectrum, including the characteristic red-edge, where reflectance is dominated by the plant cell structure, evidence of plant stress may be seen in the spectrum. This stress may be due to lack of water, disease or soil contamination. Sommer *et al*. [1998] demonstrated a clear correlation between spectral anomalies of agricultural vegetation (rape, rye, maize) grown on the area of a former waste site, and heavy metal anomalies. Data was collected with an airborne GER 63-band imaging spectrometer. Soil tests found increased concentrations of lead (500-3250 ppm), Zinc (1500-2500 ppm) and copper (500-1000ppm). In the plants only Zinc was concentrated to a critical level (140-170 ppm of dry substance). The results suggest the potential of hyperspectral imaging to identify and map areas of soil contamination using vegetative indicators.

Applicable Sensors

A number of airborne hyperspectral sensors, eg CASI, HyMap, are currently available with appropriate spectral range and resolution for characterisation of vegetation type. Such airborne sensors can offer high spatial resolution but map relatively small area.

A number of space-borne hyperspectral sensors will be launched over the next few years. The highest ground resolution is likely to be the Orbview 4 hyperspectral sensor with 24m (degraded from 8m) resolution. However, co-registered 1m panchromatic imagery will enhance the usefulness of this data. Such a sensor would allow determination of single crop type within fields for example. Although the satellite revisit time is about 1-5 days, the probability of a cloud-free line-of-sight on each occasion is only about 15-20%. This should however be sufficient to allow imagery to be taken in each season, for each site of interest in the UK.

A number of the planned hyperspectral space sensors have significant off-axis viewing capabilities, which will allow BRDF effects to be further studied and utilised. In particular the UK CHRIS sensor, due for launch this year, should provide important BRDF data for the future interpretation of satellite imagery.

Summary

Detailed information on the vegetation cover will be of relevance to the Environment Agency in a number of areas which are briefly summarised below.

Flood defence: Vegetation type (including bare fields) can be fed into predictive flood models, the impact of flood damage can also be assessed eg damage to crops.
Inland water quality: The likelihood of contamination, such as agricultural run-off (eg nitrates) can be assessed if crop type is identified. This may influence the choice of river monitoring location.

Contamination of land: The identification of crops associated with high levels of nitrate and phosphate run-off is one clear application area. An area, which is likely to be of interest in the future, is the use of vegetation as an indicator of land contamination via spectral stress indicators.

Climate change: Close monitoring of species and their location and indicators of drought stress, etc. will be important for monitoring the effects of climate change on the environment.

Biodiversity: Determination of vegetation type and changes in vegetation type are expected to be one of the key tools for assessing the diversity of species and habitats.

Irrigation: Water stress monitoring may allow detection of illegal irrigation.

Air quality and gas detection

Hyperspectral systems of sufficiently high spectral resolution are able to reveal information about the gas make up of the atmosphere in their viewing path. However, little work appears to have been done to assess the suitability for monitoring air quality. The detection requirement for most airborne pollutants (~100ppb) may be too stringent for such systems. However, it may be possible to detect higher concentrations such as those of methane emitted from landfill sites or perhaps accidental emissions to air; section 4.6 describes a new multispectral sensor for this application.

Laboratory spectral analysis of gases is carried out in the 2-14µm 'fingerprint' region of the spectrum. For remote sensing applications the spectral region would be further limited to the atmospheric transmission windows of 8-12µm and 3-5µm.

A number of satellite multispectral sensors offer aerosol products and presumably hyperspectral sensors could provide such information. For MODIS an operational algorithm will be applied to derive the aerosol optical thickness over land. The method will use measured radiances in two channels [Centre for Earth Observation 1999].

Water quality

Multispectral sensors are in current use for determination of some aspects of water quality and this has been discussed in section 3.3. The derivation of water quality information from the remotely sensed data involves the deconvolution of a number of parameters. Consequently the additional spectral bands available to hyperspectral sensors might be expected to enhance the extractability and accuracy of such information.

Significant research activity, to characterise the performance of hyperspectral sensors for water quality applications, has been reported in the literature. Some examples of current research, dealing with algae, algal blooms and sediment content are described below.

Keller and Bostater [1997] have measured absorption spectra in-situ, using a portable absorption tube system connected to a moving ship. The absorption spectra have been correlated with laboratory measurements of water quality collected at the same time. The long-path cuvette system is capable of measuring important water quality parameters such as Chlorophyll-a, seston or total suspended matter, tannins, humics, fulvic acids or dissolved organic matter. This work is intended to support the interpretation of hyperspectral reflectance data, which should be obtained simultaneously.

Schalles *et al,* [1997] have performed laboratory experiments with a hyperspectral radiometer to examine reflectances of algal blooms and suspended kaolin white clay. The reflectance spectra of suspended kaolin and algae in isolation have been determined and the interplay of scattering and absorption when both components are present was investigated. It was found that in solutions containing a mixture of clay and algae the fundamental algae signatures (670nm chlorophyll maximum absorbance and near 700nm scattering peak between strong pigment and absorbance features) were preserved but that algal pigments strongly attenuated clay reflectance in a dose dependent manner. The mixed solutions changed the overall albedo so significantly that chlorophyll algorithms for broad-band sensors would be highly compromised. The authors concluded that high spectral resolution at diagnostic wavelengths was important for determination of water parameters in turbid water.

New modelling and analysis methods will need to be developed and improved to fully exploit the benefit of hyperspectral data for determining water quality parameters. Methods employed with multispectral data, will in general, not be applicable to hyperspectral data due to the strong band-to-band dependencies in hyperspectral data, see for example [Philpot *et al*. 1997, Kruse *et al*. 1997]

Malthus *et al,* [1997] have worked on a Monte Carlo modelling approach for the characterisation of reflectance for different bloom-forming marine phytoplankton species. The investigation looked at four species and a range of chlorophyll concentrations. They found that there were prominent differences in the reflectance spectra for the four different species (from four different algal groups) allowing successful discrimination. A number of wavelengths were identified which yielded near perfect classification success: 481, 535, 586, 626 and 649nm. The classification success using the wavebands available on space sensors, SeaWiFS, MERIS and MODIS was also investigated and high classification rates were obtained. The authors comment that the presence of varying amounts of dissolved humid substances influenced the ability to identify species. Further work was also needed to investigate the effect of suspended sediments on classification and to address the identification of mixed species blooms.

Pollution incidents

Hyperspectral sensors can be expected to find application in the detection and monitoring of pollution incidents, where the degree of pollution, either on land in water, is sufficient to affect the reflective properties. An example is the detection and monitoring of oil spills. Infrared and UV channels are used together to identify the entire extent of the slick (UV channels) and its thickness (IR channels). Analysis of the hyperspectral images allows regions where the oil is sufficiently thick to be recovered, to be identified [Fingus and Brown 1997c]. The identification of oil in the UV spectral region can be difficult with possible confusion with wind slicks, sun glints and biogenic materials. However, because these interferences are often different for the IR spectral region the scope for confusion is limited with a hyperspectral instrument. Recent work by GER INTRADAN, for the Danish Ministry of Environment, has shown that the extent of a thin oil sheen could be detected with a combination of two blue channels thereby making the UV channels redundant. This result opens up the possibility of using more general hyperspectral instruments for oil spill monitoring, rather that requiring a specialist instrument [Flanders *et al*. 1997].

Significant, pollution discharges to rivers or spills on land may well be detectable with hyperspectral sensor. It may not be possible to identify the pollutants but information on the source and dispersion characteristics may be evident.

3.5 Thermal IR

3.5.1 Introduction

The emissive or thermal infrared portion of the spectrum generally extends from 7 to 18μm. An obvious advantage of thermal sensors is their night-time use (eg, by surveillance forces). They also have applications for such measurements as cooling water outflows and can be used to identify materials through differences in emissivity or other thermal properties. Remote sensing in this part of the spectrum uses a family of imaging devices that differ greatly from the cameras and films used in the visible and near-infrared. Detectors sensitive in the thermal portion of the spectrum use materials such as Indium Antimonide (InSb) and Mercury-doped Germanium (GeHg) [Rees 1999]. In the design of thermal sensors it is usually important that the detector array is maintained at a sufficiently cold temperature, requiring the use of dewars with cryogenic coolants or (especially in space) mechanical coolers.

In general, the data produced by these detectors requires a number of processing steps to obtain reliable estimates of the subject temperature or of the radiance for specific acquisition conditions. The atmosphere has a significant effect on the intensity and spectral composition of the energy recorded by a thermal system. The atmosphere intervening between the thermal sensor and the ground can increase or decrease the apparent level of radiation coming from the ground. Gases and suspended particles in the atmosphere may absorb radiation emitted from ground objects, resulting in a decrease in the energy reaching a thermal sensor. Ground signals can also be attenuated by scattering in the presence of suspended particles. On the other hand, gases and suspended particles in the atmosphere may emit radiation of their own, adding to the radiation sensed. Hence, atmospheric scattering tend to make the signals from ground objects appear colder than they are, and atmospheric emission tends to make ground objects appear warmer than they are. Depending on the atmospheric conditions that exist during image acquisition, one of these effects will outweigh the other. Both of the effects are directly related to atmospheric path length, or the distance through which the radiation is sensed.

There are three main methods for the correction of atmospheric effects on thermal data;

i) *The LOWTRAN atmospheric correction model* [Mather 1999].
LOWTRAN (LOW resolution TRANsmittance) is a computer model of the radiative transfer equation in the Earth's atmosphere. It requires the input of an atmospheric profile of pressure, temperature and humidity. In order to accurately model atmospheric water vapour variations this atmospheric profile should be obtained from either radiosonde data or a satellite-flown instrument such as TOVS.

ii) *Split-level windows* [Richter 1998].
Split-level windows can be used to eliminate atmospheric effects between two channels of nearby but different wavelength ranges. The brightness temperature (T_{bi}, i=1,2) that is equivalent to the blackbody temperature of the radiation reaching the sensor in each of the two wavebands is calculated using calibration data. The equivalent blackbody temperature for the radiation leaving the surface of the Earth (T_0) is then determined as a linear combination of these two brightness temperatures;

$$\text{ie., } T_0 = A_0 + A_1 T_{b1} + A_2 T_{b2}$$

- where coefficients A_0, A_1, A_2 have been determined empirically.

iii) *Two-look method* [Richter 1998].
The two-look method, e.g. by conical scanning system such as that used in the Along Track Scanning Radiometer (ATSR), can be used to correct for atmospheric effects in thermal imagery. Again two brightness temperatures are determined for the two views of a given area on the surface of the Earth and a similar relation to that in (ii) is used to determine T_0, but with its own set of values of A_0, A_1, A_2.

In thermal remote sensing we are normally only interested in the radiation which is self emitted from terrain features. However, the radiation entering the sensor will also include solar radiation at these wavelengths which has been reflected from the terrain. Therefore it is necessary to distinguish between the amount of radiation emitted from the ground surface and the amount of solar reflected radiation that is also present in thermal data.

There are a number of techniques available for performing this correction, for example, the simulated reflectance technique of Liu *et al.*, [1997]. This is based on a simplified energy conservation model of solar radiation incident on a land surface. It uses a weighted summation of thermal and spectral reflectance data to derive simulated reflectance, and therefore emittance, from the relationship between irradiance, thermal emittance, spectral reflectance and albedo.

Calibration of thermal sensors is an important topic and is frequently solved by including constant temperature black body sources in the sensor design.

3.5.2 Satellite thermal IR sensors

Because of the longer wavelength, it is difficult to obtain spatial resolutions using satellite borne thermal IR sensors which are comparable with visible/near IR sensors. In any case, many of the applications require large area coverage (eg, for sea surface temperature measurement) and hence several sensors have quite coarse resolutions, typically around 1km. The following table (Table 3.35) lists a number of thermal IR sensors which are currently in use or planned and spans a complete range of resolutions. Note that some sensors will already have been mentioned in section 3.3 (Visible and near IR sensing) since the same instrument may collect radiation in both visible and thermal bands.

Table 3.35 Thermal Infra-red satellite sensors

Sensor	Resolution (m)	Wavelength range μm	No of Thermal IR bands	Swath (km)	Satellite	Launch date
AVHRR	1100	3.55 – 12.3	3	3000	NOAA/10/12/14	1986/91/94
AVHRR/3	1090	3.55 – 12.5	3	3000	NOAA/K/L/M/N & METOP	1998/00/01/03 & 2003
ATSR &AATSR	1000	1.6, 3.7, 10.85 & 12.0 (Centre freqs)	4	500	ERS-1/2, ENVISAT	1991/4, 2001
Thematic mapper	30 and 60	2.09 –2.35, 10.4 – 12.5	2	185	LANDSAT7	1999
MODIS	1000	3.66 – 14.285	15	2330	Terra EOS AM/PM1/PM 2	1999/01/06
ASTER	90	1.6 – 11.65	11	60	Terra EOS AM	1999
COSMO SWIR	35	8.0 – 12.0	1	40	Cosmo - Skymed	TBC
MWIR	30 – 38[1]	3.7 – 5.2	1[2]	16 – 19[1]	STRV-2	2000

Notes: 1: The resolutions and swaths are given for perigee – the satellite orbit is elliptical.
2: The wavelength range can be selected by filter wheel – 3 options are available.

Landsat TM [http://geo.arc.nasa.gov/sge/landsat/landsat.html]
The general features of the Landsat TM instrument have been dealt with in section 3.3 and will not be repeated here. The thermal band 6 covers the portion of the spectrum between 10.4 – 12.5 micrometers on both Landsat 5 and Landsat 7. The spatial resolution of this detector is much coarser than that of the spectral reflective bands. On Landsat 5 band 6 has a spatial resolution of 120 metres, whilst on Landsat 7 this has been reduced to 60 metres. A number of studies have been carried out to investigate different methods of improving the spatial resolution without altering the thermal spectral information contained within the spectral data. Liu, *et al* [1997] have developed a technique called Pixel Block Intensity Modulation or PBIM. PBIM uses the 30m resolution reflective spectral bands to modulate the band 6 image on the basis of its 120-m resolution pixel blocks. Topographic detail in each 120m resolution block of the band 6 image is thus recovered, without altering the average thermal digital number level of the block, by the spatial information recorded in the reflective spectral bands. It has been found that the presence of high frequency texture, such as that from buildings and building shadows, produces pseudo edges in the resulting images. In these instances an alternative technique must be used such as the Smooth Filter based Intensity Modulation or SFIM. The SFIM is an example of a Spectral Preserve Image Fusion technique. It is based on a solar radiation and land surface reflection model and uses a ratio between the high resolution image and its low pass filtered image to modulate spatial detail to a co-registered lower resolution image. The advantage of this technique is that it processes continuously and is not based on pixel block structure, like the PBIM technique. Both the SFIM and PBIM techniques enhance the spatial resolution of the thermal band data to 30 metres, the resolution of the multispectral bands on Landsat 5 and 7. However, if the panchromatic band on Landsat 7 is used it may be possible to improve the spatial resolution of the thermal band to 15 metres.

ASTER [http://asterweb.jpl.nasa.gov]
The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was launched on the Terra platform on December 18th 1999, reaching its final orbit on February 23rd 2000. The objective of the mission is to provide high resolution multispectral data from visible to thermal wavebands in order to enable the estimation of surface kinetic temperatures. ASTER has been placed in a sun-synchronous near-Earth orbit at an altitude of 705km. It has a 60km swath width and a 60km along track. The spatial resolution of the three visible and near infrared bands is 15 metres. The spatial resolution of the short-wave infrared bands has a spatial resolution of 30 metres. The five thermal infrared bands have a spatial resolution of 90 metres. It may be possible to improve the resolution of the thermal imagery in a similar way to that outlined for Landsat TM data. ASTER will revisit any place on the Earth at least every 16 days. However, because of a limited duty cycle (ASTER can only acquire 750 scenes a day) it will be scheduled to acquire data over areas specified by researchers and scientists (i.e. non-commercial) and to obtain one-time coverage of the entire Earth's surface.

ATSR
The Along Track Scanning Radiometer was provided by the UK (Rutherford Appleton Laboratory) as addition to the core payload of the ESA ERS-1 satellite. It is intended for precise measurement of sea surface temperature but actually consists of an IR radiometer and a microwave sounder. The latter is also used to compensate for water vapour in the atmosphere as an input to correcting the path length delay of the ERS-1 radar altimeter. A novel feature of the radiometer is that two measurements of the same area of sea are made one vertically and one slightly inclined. This allows the correction for the atmosphere to be more accurately made; sea temperatures accurate to 0.5°K can be obtained.

MWIR
The Medium Wave Infra Red instrument was developed by DERA and launched on a small US satellite – STRV-2. The instrument was intended to demonstrate the detection of aircraft from space. To do this a novel frame differencing technique is used in which two images are acquired (using two separate detector arrays) and these are subtracted. Stationary features (eg, the ground) are cancelled but moving targets such as aircraft may be detected.

3.5.3 Airborne thermal Infra-red sensors

Airborne thermal infra-red sensors are widely used by defence forces and also by the police and by the coastguard. In addition, they are used to measure heat loss from buildings and to detect buried waste. Some sensors are used to develop techniques which would later be used with satellite sensors. The current state of technology in this area is illustrated by the following examples:

TIMS
The Thermal Infrared Multispectral Scanner or TIMS is an airborne multispectral scanner that supports NASA's Airborne Science and Applications Programme. The instrument consists of a scan head with thermal reference sources, a motor controller, a six-channel spectrometer, a system control console (inside the aircraft) and a digitiser. It provides six-channel spectral data in the thermal infrared portion of the spectrum using a six-element mercury cadmium telluride array detector. TIMS has a channel sensitivity of approximately 0.1°C and is used whenever an accurate measure of spectral radiance or brightness temperature of the earth's surface is needed.

Spectral range (μm)

Band 1	8.2 – 8.6
Band 2	8.6 – 9.0
Band 3	9.0 – 9.4
Band 4	9.4 – 10.2
Band 5	10.2 – 11.2
Band 6	11.2 – 12.2

Extent of coverage

The TIMS sensor has a selectable scan rate (7.3, 8.7, 12 or 25 scans per second) with 698 pixels per scan. The swath width is dependent on the altitude at which the aircraft flies. With an Instantaneous Field of View of 76.56 degrees the swath width at 10 000 feet is 4.8 kilometres.

Spatial resolution

At an altitude of 10 000 feet the spatial resolution of the TIMS data is 7.6 metres.

Temporal coverage

Aircraft can be flown repeatedly over the same site as many times as required, weather permitting. Therefore the temporal coverage can be as sporadic or as intensive as the application or funding dictates.

STAIRS-C

The STAIRS-C (Sensor Technology for Affordable IR Systems) is a UK MOD programme to develop a new thermal imaging system for a variety of equipment (land vehicles and aircraft). It is being developed by Marconi Electronics and uses a Cadmium Mercury Telluride diode array as the detector. Typical performance details are given below for the STAIRS detector as part of the Pilkington Optronics EPIC infrared camera:

Spectral bands: 8 – 9.4 μm
Detector: 768 x 8 CMT array
Optics: 110mm telescope (FOV 5 x 3 degrees)
Cooling: Long life linear Stirling engine
Weight: 20kg.

IRIS

The IRIS system is developed by BAE systems for a variety of applications. It is similar to the STAIRS in using CMT detectors, in this case 8 element detectors are used. Typical details are:

Spectral range: 8 – 12 μm
Detector: 8 element CMT
Optics: Various systems, typically from FOV of 1x 2 deg to 15 x 30 deg
Cooling: Split cycle Stirling engine
Weight: from 16.7kg to 28.7kg depending IRIS version.

3.5.4 Applications

Air quality

Tropospheric ozone can be obtained using thermal emission spectra from Fourier transform infrared (FTIR) emission spectrometry. The technique, developed by Puckrin (Evans and Puckrin, [1999]), measures the downward thermal radiation from tropospheric ozone.

The instrument required is a ground-based Magna 550 FTIR spectrometer (Nicolet instrument) which is equipped with a liquid-nitrogen-cooled MCT detector.

Measurements have been made for both cloudy skies and hazy, polluted conditions. For the former, the thermal radiation from ozone is measured against background blackbody emission from the cloud; the cloud effectively forms a barrier against the detection of ozone in the upper atmosphere. In the case of hazy, polluted conditions, thermal emission spectra of the atmosphere have been measured at a large zenith angle to enhance the detection of tropospheric ozone near the surface. Simulations of the background atmospheric emission are performed in order to extract the ozone emission band, from which ozone amounts are determined.

The amounts of ozone derived from this technique have been found to agree well with in-situ measurements reported at a 440m high tower near to a test site. The ozone amounts measured are of the order of 75 – 80 ppbv.

Waste

A study has been carried out with the US Department of Energy (DOE) to examine the use of thermal remote sensing for the detection and geolocation of buried waste trenches (Irvine *et al.*, [1997]). Considerable cost savings are demonstrated to accrue from the application of remote sensing techniques at buried waste sites. This study uses historical photographs for reference and analyses the signatures observed on thermal imagery, together with ground truth data, for areas corresponding to known trench locations.

The thermal data used in this study was high-resolution multispectral data from the Daedalus 1268 Multispectral Scanner (a similar airborne system to TIMS). It has a spatial resolution of 5 metres on the ground. Data was collected during both daylight hours and during the night.

The thermal signatures recorded correspond to temperature and soil moisture differences observed at the site through ground measurements. On average the trench areas were 0.4 – 0.75°C cooler than the non-trench areas. The clearest temperature difference is apparent in the night-time imagery. Therefore, to insure that the most accurate identification of trenches is achieved a composite of repeated night-time imagery is ideal.

Marine and coastal water quality – oil spills

Grierson [1998] of The University of Adelaide, Australia, designed a research project to field test an airborne video platform incorporating a low-cost thermal imager (LCII). The aim was to locate and monitor the controlled release of two different oil spill residues (paraffinic lubricating oil and automotive diesel oil) close to a shoreline and during darkness hours.

Current methods for the detection and monitoring of oil spills, such as tracking beacons and aerial surveillance in the visible part of the spectrum have inherent disadvantages and inaccuracies, especially where oil spills are close to shorelines. Traditional optical aerial surveillance also has the disadvantage that it is unable to monitor such spills during the night.

The aim of the project was to construct a system that was cheap to build and operate and made up of components that were readily available commercially. The video system comprised of two Sony CCD cameras and a Panasonic SVHS video recorder, operating in the 0.4-0.7 µm and 0.7 –1.0 µm parts of the spectrum. The thermal imager operates in the 8 – 12 µm band and uses a circular scanning mechanism. It has a 40-degree swath angle mode which, at an altitude of 300m metres, results in a 250-m wide swath of ocean at approximately 50cm resolution. The ‘temperature resolution’ of the thermal imager is 0.05ºC.

The thermal imagery obtained shows two distinct slicks due to the oil spills. The different types of oil have substantially different viscosities and chemical properties and, therefore, display different emissivities and area characteristics. The paraffinic lubricating oil produces a darker, more compact slick and shows a strong negative contrast against the sea surface (i.e. it has a lower temperature). The diesel oil produces a slick that is much more dispersed and only shows a slight negative contrast against the sea surface.

The airborne thermal imager clearly showed the extent of both spills, its location and an indication of the thickness of the oil residue spilt. The one problem that has been identified with this technique is the narrow swath width of the instrument used (LCII) which would require a large number of flight passes to locate an oil spill. This could be overcome by flying at a higher altitude with perhaps a loss of spatial resolution.

3.6 Fluorescence

3.6.1 Introduction

Fluorescence is the re-emission of absorbed radiation at a different (usually lower) frequency, without first converting the absorbed energy to heat, by electronic transitions in the atoms or molecules of the fluorescent material.

3.6.2 Sensors

The instruments used for fluorescence-based remote sensing techniques are based around the same principle. They have an emitter head that emits radiation to stimulate the surface being imaged and a detector to record the resulting fluorescence. The type of radiation used to stimulate fluorescence, however, varies.

Natural fluorescence

The Integrating Natural Fluorometer (INF) System, [http://www.biospherical.com/products /inf300.html] produced by Biospherical Instruments Inc., is an example of a natural fluorescence instrument. It is a self-contained field instrument that is optimised for operation at unattended sites. Powered by only 4 "D" size batteries, the instrument measures upwelling natural fluorescence, scalar irradiance (photosynthetically active radiation (PAR)), temperature, pressure, and battery voltage for periods up to several months. Natural fluorescence is the fluorescent flux from a surface that is stimulated by available sunlight. Research conducted throughout the oceans of the world has shown that this measurement is related to photosynthetic rates and chlorophyll concentrations. Unlike strobe fluorometers, a natural fluorometer measures fluorescence emitted under the ambient light conditions that are driving photosynthesis *in situ*.

Laser induced fluorescence

Laser induced fluorescence instruments use laser energy to stimulate fluorescence. The Laser Environmental Active Fluorosensor or LEAF instrument, [http://adam.frw.uva.nl/MFII /leaf.html] is developed for remote sensing of laser induced chlorophyll fluorescence under field conditions. The field instrument consists of a detection head, a power and laser control unit and a power generator. A laptop computer is used to control the leaf instrument. In the detection head of the LEAF instrument two optical units are mounted together. The excitation unit of the instrument uses a frequency doubled Nd:YAG laser (532 nm) providing a 10 nsec, 20 mJ pulse. The intensity of the laser pulse is monitored by deviating a small fraction of the pulse to a photodiode. The laser beam is adjustable (5-50 mrad) and matched to the field of view of the detection optics. The detection unit is able to detect radiation with or without the presence of the laser pulse. Radiation is collected by a telescope and deviated to four photomultipliers by means of beam splitters. Each photomultiplier has its own optical colour band filter. Using these filters the maxima at 680 nm and 730 nm of the chlorophyll fluorescence spectrum are covered. During a typical measurement the radiance of the observed scene is measured once without (passively) and once in presence of the laser pulse (actively). The passive measurement reflects thus the ambient light conditions and is used to separate between the laser-induced fluorescence and the ambient light. Passive and active measurements are done in different time windows depending on the distance to the measured object. The position of the time window is determined automatically by focussing the instrument optically. After correction for time window length and transmission characteristics of the optical system the measured values are stored for later analysis.

The Laser Induced Fluorescence Imager or LIFI,[http://www.nv.doe.gov/business/capabilities /Lifi/Default.html] is a similar type of system to LEAF operated by the United States' Department of Energy. The instrument is usually mounted on an aircraft.

Ultra-violet fluorescence

Ultra-violet fluorescence instruments use ultra-violet radiation to stimulate fluorescence. The ALF instrument [http://www.agso.gov.au/marine/products/petpros.html], operated by World Geoscience Corporation Ltd., is an airborne system that scans and records fluorescence emission using 266nm ultra-violet stimulation.

3.6.3 Applications

Inland water quality : Chlorophyll-a

Fluorescence techniques can be used for water quality assessment because they are able to detect algal pigments, coloured dissolved organic matter cyanobacteria and ammonium concentrations. Fluorescence techniques, together with tracers, can also be used to measure and map flow rates and leaks.

Algal pigments.
Phytoplankton populations are typically estimated by measuring chlorophyll-a, the principle photosynthetic pigment present in all forms of algae. Chlorophyll-a naturally absorbs blue light and emits red light. Fluorometers can detect chlorophyll by transmitting an excitation beam of light in the 440nm (blue) range and by detecting light emitted in the 680nm (red) range of the spectrum [http://luminometer.com/applications/enviroscience.html]. Generally, the amount of light emitted is directly proportional to the concentration of the material in question.

Coloured Dissolved Organic Matter (CDOM).
Monitoring chromorphic or coloured fraction of dissolved matter in natural waters is also possible with fluorescence techniques. CDOM has a fluorescent property and absorbs UV light and fluoresces blue light.

Cyanobacteria.
Cyanobacteria has been found to be a numerically abundant faction of the phytoplankton community. Fluorescence techniques can be refined to detect this portion of the phytoplankton family. Marine cyanobacteria species, such as *Synechococcus spp*., have a dominant accessory pigment, phycoerythrin. Narrow band interference filters are used for excitation and this pigment produces emission wavelengths of 544 nm and 577 nm. In contrast, fresh water taxa such as *Anabaena, Microcystis,* and *Spirulina*, are rich in phycocyanin. For detection of this pigment narrow band interference filters that utilise excitation and emission wavelengths of 630 nm and 660 nm are used.

Ammonium.
Fluorescence techniques are also good at detecting the amount of ammonium in water. A fluorometric technique is particularly useful for work in oligotrophic systems, where natural ammonium concentrations are commonly in the submicromolar range.

Water flow.
Fluorescence techniques and tracers can be used to measure water flows, model surface and ground water systems, trace contaminants and detect leaks. A tracer is usually a non-toxic, stable salt or dye, an example of which is Rhodamine WT. Rhodamine WT is a highly fluorescent material with the unique ability to absorb green light and emit red light.

Marine and coastal water quality : petroleum and oil seepage

The Department of Energy in the United States has developed an airborne Laser Induced Fluorescence Imager or LIFI [http://www.nv.doe.gov/business/capabilities/Lifi/Default.html]. This stimulates UV fluorescence with a laser, which illuminates a line perpendicular to the direction of flight of the aircraft. This technology has been evaluated for the detection of spilled oil and oil products on shore, in wetlands and on ice. Five materials were tested; background materials without oil, diesel oil, kerosene, Santa Barbara crude oil and aviation fuel. The fluorescence characteristics of the oils were found to be distinct from the background materials in most instances. One exception was the low contrast between the heavy Santa Barbara crude oil and straw. For all of the oils tested the level of fluorescence produced decreased with time. However, after a period of three weeks there was still sufficient magnitude for detection in most cases.

The Australian Geological Survey or AGSO [Balick 1997] has been conducting pilot studies into the use of ultra-violet fluorescence signatures as a means of detecting, mapping and typing hydrocarbon seeps. AGSO has complied a database of ultra-violet fluorescence spectra by scanning the 250-500nm emission response of oils using 266nm (i.e. UV) excitation.

Contaminated land

The US department of Energy is also investigating the use of the LIFI system to effectively pinpoint areas contaminated by uranium during nuclear materials production

3.7 Spectroscopy

3.7.1 Introduction

The spectrum of radiation emitted by a hot (glowing) body reveals a pattern of spectral lines which are characteristic of the elements in the solid. In a similar way, radiation passing through a gas or vapour can become absorbed by molecules and these absorption spectra can be used to identify the constituents in the gas. The detection accuracy is dependent on the spectral coverage, spectral resolution, and signal-to-noise of the spectrometer, the abundance of the material and the strength of absorption features for that material in the wavelength region measured [http://www.scimedia.com/chem-ed/spec/vib/ir.html].

The application of spectroscopic techniques to imaging systems is addressed in section 3.4 – Hyper Spectral Sensors. In this section the use of spectroscopy for the measurement of pollutant gases in air is considered and the two relevant techniques are: Infrared Spectroscopy and Differential Optical Absorption Spectroscopy or DOAS.

3.7.2 Sensors

Infrared Spectroscopy

Infrared spectroscopy is the measurement of the wavelength and intensity of the absorption of mid-infrared radiation by gases or vapours. Mid-infrared radiation is energetic enough to excite molecular vibrations to higher energy levels and the wavelength of the infrared absorption bands are characteristic of specific types of chemical bonds in the material being imaged. This section describes dispersive and Fourier-transform spectrometers that are used in infrared absorption spectroscopy.

Dispersive infrared spectrometers use tungsten lamps, Nernst glowers or glowbars as light sources [http://www.scimedia.com/chem-ed/spec/vib/ir-instr.html]. They use a grating monochromator to select the wavelengths of interest and they are commonly used when the detection uses single absorption wavelengths. Figure 3.6 shows a schematic diagram of a dispersive infrared spectrometer.

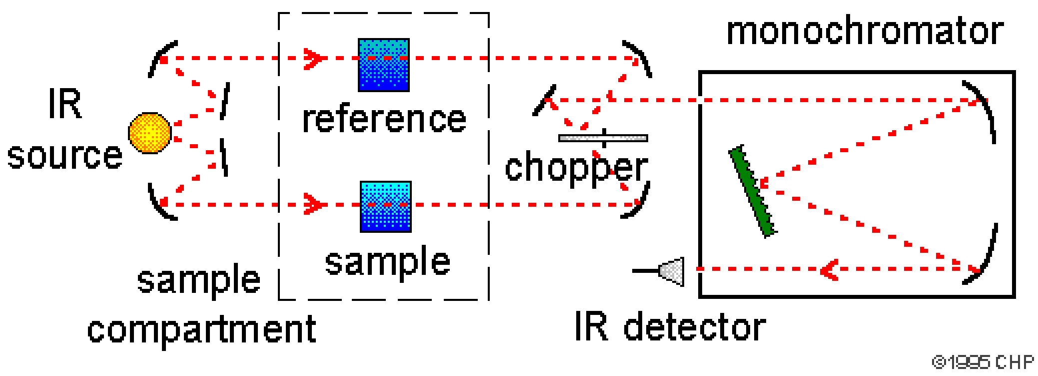


Figure 3.6 Dispersive infrared spectrometer [http://www.scimedia.com/chem-ed/spec/vib/ir-instr.htm]

In practice, Fourier-transform infrared spectrometers are more commonly used and a common version is that based on the Michelson interferometer, see Figure 3.7.

A Michelson interferometer is advantageous because radiation can be admitted to the system through much larger apertures than the slits required for scanning instruments. Incoming radiation is split into two beams which travel separate paths through the instrument and are then recombined. If the length of one path is varied with respect to the other, the various wavelengths of radiation contained in the recombined beam will go in and out of phase as a function of the wavelengths themselves and of the path difference. If the recombined beam is then focussed on a detector and sampled at the proper intervals, a signal (effectively an interferogram) is produced which can be transformed to yield the amount of radiation contained in the original beam as a function of wavelength.

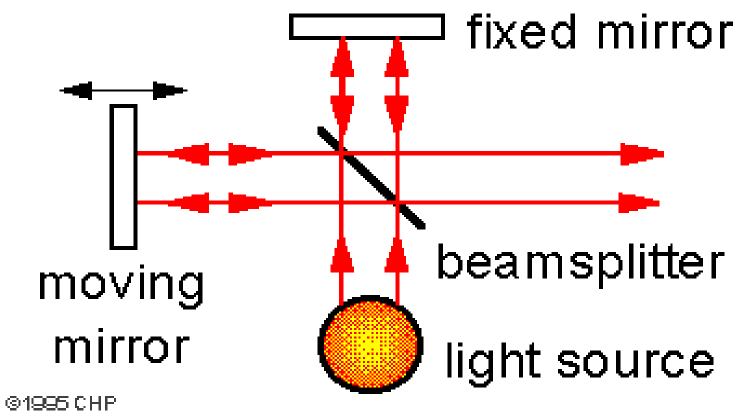


Figure 3.7 Michelson interferometer used in Fourier-transform spectrometry [Rees 1999]

The ATMOS instrument (Atmospheric Trace Molecule Spectroscopy) [ATMOS website: http://remus.jpl.nasa.gov] operated by NASA on board a space shuttle is an example of a Fourier-transform Michelson interferometer. Although the concepts involved in interferometry are straightforward, the instrument itself must work in the realm of fractions of wavelengths of the radiation being measured and thus severe demands are placed on the fidelity of the optics and the precision and accuracy of the sampling intervals. It is the advent of high stability single-frequency lasers, ultra-fast electronic components, and modern optical polishing techniques, which has enabled the construction of the ATMOS. The instrument uses optical components polished flat to within a twentieth of the shortest wavelength of the radiation being measured, and generates an interferogram containing 400,000 sample points (the intervals between which are precisely controlled using a reference laser) every second

The ATMOS instrument has flown four times on the Space Shuttle since 1985. The predecessor to ATMOS, flown on aircraft and high altitude balloon platforms, was born in the early 1970s out of concern for the effects of Super Sonic Transport exhaust products on the ozone layer. The experiment was redesigned for the Space Shuttle when the potential for ozone destruction by man-made chlorofluorocarbons was discovered and the need for global measurements became crucial. The investigation is conducted by JPL under the sponsorship of the Upper Atmospheric Office at NASA.

The four-laser airborne infrared instrument or FLAIR [Roths *et al*. 1996] is a tuneable diode laser absorption spectrometer, which is designed for high-sensitivity in situ measurements of four atmospheric trace gases in the troposphere.

Differential Optical Absorption Spectroscopy (DOAS)

In the DOAS (Differential Optical Absorption Spectroscopy) system, the spectrum of an artificial light source within a given bandwidth is measured after passing through the open atmosphere over ranges between 100m and 20km. After the removal of the emission spectrum of the light source the remaining differential absorption features are compared with the absorption cross sections of known materials (usually trace gases). This allows a qualitative and quantitative determination of their concentration in the light path. Clearly, these systems are usually designed for fixed installation in areas where pollution or contamination is suspected.

Below is an example (Rees 1999) of a DOAS system, the Hoffmann DOAS system [http://www.optran.de/doas1.html]. The basic configuration incorporates a compact coaxial transmitter-receiver unit at one end of the range and a rectroreflector at the other end. This system can detect the following trace gases at different concentrations within the atmosphere (Table 3.35):

Table 3.35 Detection performance of the Hoffman DOAS system

Species	**Chemical symbol**	**Spectral Region (nm)**	**Detection Limit (ppt : 10^{12})**
Sulphur dioxide	SO_2	290 – 310	17
Carbon disulfide	CS_2	320 – 340	500
Nitrogen dioxide	NO_2	330 – 500	80
Nitrate ion	NO_3	600 – 670	2
Nitric acid	HNO_3	330 – 380	40
Ozone	O_3	300 – 330	4000
Formaldehyde	CH_2O	300 – 360	400

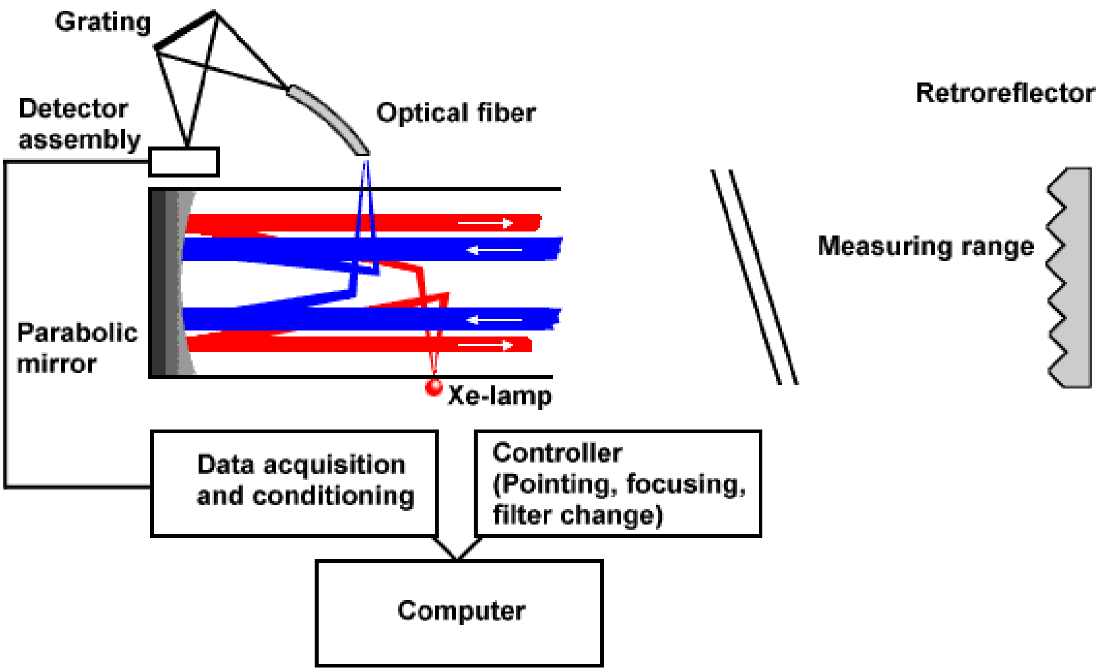


Figure 3.8 Differential Optical Absorption Spectrometer

3.7.3 Applications

Infrared Spectroscopy

The ATMOS Fourier transform spectrometer, flown on the ATLAS 3 (Atmospheric Laboratory for Applications and Science) shuttle flight 3rd – 12th November 1994, was used to measure vertical mixing profiles of four relatively long-life gases; hydrogen cyanide (HCN), Ethyne or Acetylene (C_2H_2), carbon monoxide (CO) and ethane (C_2H_6). The positive correlations obtained between the simultaneously measured mixing ratios suggest that the levels of these gases are the result of biomass burning or urban industrial activities. (Rinsland *et al.*, [1998]). The FLAIR (four-laser airborne infrared) instrument was employed during a large-scale airborne campaign on tropospheric ozone (TROPOZ II) in 1991 [Roths *et al.* 1996]. It was used to measure carbon monoxide (CO), hydrogen peroxide (H_2O_2), formaldehyde (CH_2O), and nitrogen dioxide (NO_2) in the free troposphere. Detection limits below 100 parts in 10 by volume were achieved.

DOAS

The New Zealand Ministry for Research, Science and Technology have conducted a study to investigate the use of a DOAS system for the measurement of four trace gases; nitrous oxide (NO), nitrogen dioxide (NO_2), ozone (O_3) and sulphur dioxide (SO_2) [http://www.aquila.infn.it/o3symp/paper_01/reisinger.html]. The technique used employs a conventional scanning monochromator and a beam splitter to record and subsequently remove the influence of atmospheric turbulence and an arc lamp flicker from recorded spectra. On a 220m optical path the system reaches detection limits well below the typical concentrations of the trace gases, even in an urban environment, with a time resolution of 20 minutes for all four gases. The system, therefore, allows a continuous and low cost monitoring of important trace gases and investigation into the dynamics and photochemistry on their ambient concentrations.

3.8 Radiation

3.8.1 Introduction

The scope of this section is to identify the current status and likely future capabilities for the detection of radioactive contaminants by remote techniques. The McGraw-Hill Encyclopedia of Science & Technology [McGraw-Hill 6th Edition] defines 'Remote Sensing' as 'the gathering and recording of information about terrain and ocean surfaces without actual contact with the object or area being investigated'. Applying this strict definition to radiation survey it is evident that all non-invasive surface monitoring techniques may be technically included. It is therefore appropriate to include walk over and vehicle mounted monitoring systems in this discussion, in addition to aerial surveys and the use of satellite systems.

Radioactive materials are discharged to the environment by the nuclear and other industries, by universities and by hospitals. These discharges are controlled and have been continually reduced in recent years. Within the UK, requirements relating to the disposal of radioactive waste are detailed in the Radioactive Substances Act 1993 (RSA93) and specific Exemption Orders are provided in relation to the disposal of radioactive materials and wastes from certain specified processes. In England and Wales, licences for radioactive waste accumulation and disposal are granted by the Environment Agency.

The doses to members of the public, resulting from environmental discharges of radioactive materials, are generally small in comparison to the radiation doses received as a result of exposure to natural sources of radiation and the use of radiation in medicine. The average annual radiation dose to the UK population is approximately 2600 microSieverts (μSv) overall [NRPB, 1994]. Of this dose, approximately 50% results from the inhalation of radon and thoron gases emitted by uranium and thorium deposits occurring naturally in the ground. Additionally, approximately 14% of the dose results from exposure to gamma rays emitted from the ground and building materials, approximately 12% results from naturally occurring radionuclides in food and drink and 10% results from exposure to cosmic radiation from extraterrestrial sources. The remaining 14% of average annual public exposure results from medical uses of radiation, such as the use of X-rays to diagnose and treat disease. The average dose to members of the public from discharges of radioactive materials is approximately 0.4 μSv or less than 0.1% of the average dose from all sources.

3.8.2 Discharges of radioactive material to the environment

Radioactive materials, which may be discharged to the environment under the authorisation of the Environment Agency or which may be inadvertently released as a result of accidents, may enter the environment via a number of pathways. The primary routes are as follows:

- Aerial discharge of particulate or gaseous radioactive material via a stack or chimney;
- Disposal of liquid effluent to sewers, water courses, estuaries or the sea; and
- Leakage of solid radioactive material from underground disposal sites.

Following the airborne release of radioactive material, material will be carried downwind as a plume with dispersion characteristics dependant on the height of the release point and prevailing weather conditions such as wind speed and air temperature. The deposition of particulate material onto the ground at a given position is dependent on the time integrated air concentration of radioactive material at that position and other factors such as the type and rate of any precipitation. The radiological consequences of inhalation from the plume can be determined either by collection and analysis or air samples, or retrospectively by analysis of the extent of ground contamination. Analysis can also be undertaken to determine the radiological consequences associated with the deposited contamination (eg. radiation doses due to direct irradiation from the deposited material, inhalation of resuspended material, ingestion of contaminated foodstuffs etc.).

The discharge of organic or inorganic liquids containing radioactive material will result in contamination of the water-courses or environments into which the discharge is made. Radioactive materials will be carried in the direction of flow or tide although concentrations are lively to progressively decrease as a result of dilution. Where discharges are into rivers or water-courses, radioactive residues may collect on the river banks and on the surface of any pipes or channels through which the material flows. Deposition is likely to be greatest where flow is restricted in some way, such as at corners, bends or 'bottle-necks'. Where discharges are into the sea, deposition onto the sea-bed and at the shore-line will occur. Radiological monitoring is of use for determination of the radiological consequences of direct irradiation from the deposits and ingestion of contaminated fish, seafood, water and vegetation.

Within the UK there is currently no disposal facility or disposal route for 'High Level' and 'Intermediate Level' solid radioactive wastes. Such wastes must therefore be stored, either to allow the material to reduce in activity through radioactive decay, or until such a time as a suitable storage facility for such waste becomes available. The disposal of solid waste categorised as 'Low Level' may only be executed at BNFL's licensed facility at Drigg, Cumbria. Waste categorised as 'Very Low Level' may be disposed of at authorised landfill sites under certain 'special precautions'.

Prior to the Radioactive Substances Act 1960, the disposal of radioactive materials was less tightly regulated. Consequently, there are a number of UK sites at which low level radioactive materials have been disposed of by a means considered appropriate at the time, for example radium luminising residues have been buried at a number of Ministry of Defence (MoD) sites. There is often an absence of documentary evidence relating to such historic disposals and, in some circumstances, sites have been identified only during land quality assessments executed prior to sale and/or change of site use.

Radioactive material may be carried from underground disposal sites to the wider environment by mechanisms such as degradation or weathering and the influence of aquifers. Environmental dispersion is likely to be highly dependent on the chemical solubility of the radioactive material. As is the case for aerial and water borne discharges, determination of the consequences of the dispersion of radioactive contaminants from disposal sites can be achieved by a combination of surface measurement and sampling.

3.8.3 Radiation types and detection

The extent to which remote sensing techniques can be utilised for the measurement of environmental radioactivity is dependent on the nature of the radiation emissions from the contaminants which require study and, in particular, the attenuation properties of the media through which these radiations must pass prior to detection.

The three main types of radiation emitted by radioactive materials are known as alpha particles, beta particles and gamma rays. The property common to these radiation types is that each causes ionisation (or charge imbalance) within the atomic structure of the materials through which they pass prior to total absorption or attenuation. It is this ionisation property which may directly or indirectly result in damage to living tissue potentially leading to stochastic or non-stochastic biological effects. Stochastic, or probability effects, may occur at low and high radiation exposures and include effects such as the incidence of cancers. Non-stochastic effects, which only occur at very high levels of exposure, include effects such as skin beta burns and radiation sickness.

Environmental radioactive contamination is detected by the direct or indirect measurement of the ionisation produced when specific types of radiation emitted by the radioactive contamination pass through matter (ie. the material incorporated within the detector probe or sensor).

Alpha (α) radiation is predominantly emitted by the actinides (including isotopes of uranium, americium, plutonium, thorium and radium). Alpha radiation is attenuated very readily, a few centimetres of air or a single sheet of paper being sufficient to provide complete attenuation. In circumstances where the detection of alpha emissions from surface contamination is required, dedicated α contamination probes are used, which have very thin end-windows fabricated using materials such as mylar, and the probes must he held within a few centimetres of the surface under investigation. Alpha monitoring therefore tends to be a slow and laborious process. The alpha radiations associated with radioactive contamination below the ground surface are not generally measurable using remote, or non-invasive, techniques as the radiation is likely to be attenuated prior to reaching the probe or sensor. Fortunately, many alpha emitters, including the uranium isotopes, have progeny which emit readily detectable beta and gamma radiations.

Beta (β) radiations are emitted by many of the 'fission products', including the caesium isotopes Cs-134 and Cs-137, the radioactive iodines I-129, I-131 etc, Sr-90 etc., which are directly produced during nuclear fission reactions. They are additionally emitted by materials which become radioactive when exposed to the neutron radiation associated with nuclear fission. These 'activation' products include isotopes such as Co-60, H-3, Ni-63 etc).

Beta radiations are less easily attenuated than alpha particles, and generally have a range of the order of 1 to 10 metres in air or up to a few millimetres in aluminium, depending on the energy of the radiation. Beta emissions from radioactive contaminants below ground are therefore generally measurable using remote techniques provided the contaminant is close to the surface and the probe or sensor is located no more than a few metres from that surface. The ease of detection of a beta emitting substance will depend strongly on the energy associated with the radiation emitted. Some beta emitting radionuclides, such as tritium (H-3), which emit only very low energy beta radiations, are extremely difficult to detect as the radiation is often attenuated before passing through the end window or outer protective cover of the sensor or probe. Beta radiations are normally measured using specialised beta sensitive contamination probes. As is the case for many alpha emitters, beta decay is frequently accompanied by gamma emission.

Gamma (γ) radiation, which may be emitted simultaneously with alpha or beta radiation or may sometimes be emitted in the absence of any other radiation type, is the radiation type most readily applied to remote sensing techniques. This radiation type is characterised by its considerable range in most substances. For example, 0.85 MeV gamma radiation requires a

thickness of approximately 1 cm of lead or 20 cms of soil to reduce the intensity by a factor of two.
As is the case with beta radiation, the precise attenuation characteristics of gamma radiation will depend on the energy associated with it. As gamma radiation is much less easily attenuated than alpha and beta radiations, it is much more often difficult to eliminate gamma radiation exposures in the workplace. Workplace radiation surveys therefore tend to be dominated by measurements of gamma radiation levels using gamma sensitive instruments scaled in exposure or 'dose rate' units.

The majority of manmade and natural radionuclides emit gamma radiation, or have progeny which emit gamma radiation. Gamma radiation measurement is therefore appropriate for most applications where assessment of environmental radioactive contamination is required. Common radionuclides for which gamma monitoring is not appropriate include H-3 (tritium), C-14, Ni-63 and Pu-239. Where radioactive material is located at depths greater than approximately 0.5 metres in soil, or similar depths in water, gamma emissions become attenuated to such an extent that non-invasive monitoring techniques become inappropriate. Additionally, where contamination is introduced to large volumes of water, mixing and dilution may be such that surface emissions rapidly become negligible.

3.8.4 Baseline surveys

In order to assess the impact of any major environmental release of radioactive material, it is useful to have a baseline survey indicating the spatial distribution of radiation levels at a specific reference time. In Great Britain, only one such extensive study has been undertaken to date. This study was undertaken by the National Radiological Protection Board (NRPB) prior to July 1988 and included all of England, Wales and Scotland [Green, 1989].

In the NRPB study, terrestrial gamma-ray dose-rates were measured out of doors using energy-compensated Geiger-Muller probes calibrated at the Board's own calibration facility. The intention of the survey was to make at least one measurement within every accessible 10km square of the Ordnance Survey grid. The results were presented in tabular, graphical and cartographical form and presented with consideration of influences such as underlying geology. The main factor influencing the observed radiation dose rate was found to be the geology of the site. Higher levels were found in areas of igneous rocks, which have relatively high uranium and thorium contents, whilst lower levels were found to be typical of clay and chalk areas. Gamma dose rate can be influenced by height above sea-level (for the cosmic component) and climatic effects, eg. heavy rain, can cause increased levels of gamma dose rate owing to the wash-out of radioactive daughter products from the decay of naturally-occurring radon.

Whilst the only significant radiological baseline survey of the entire UK mainland undertaken at the time of writing has been the NRPB study, it should be noted that the British Geological Survey is carrying out an extensive aerial survey during 2000 (see section 3.8.9). Other extensive aerial surveys have been undertaken by agencies such as the Scottish Universities Research and Reactor Centre (SURRC) (section 3.8.9).

3.8.5 Gamma remote sensing techniques for detection of environmental radioactivity

For the reasons outlined in the preceding sections, the majority of radiological remote sensing applications to date have involved the measurement of gamma radiation emissions. Measurements may be restricted to gross counting of gamma interactions or measurement of the gamma dose rate and, for such applications, scintillation detectors (eg. plastic scintillators or NaI(Tl) scintillators) or Geiger-Muller detectors are normally chosen. Where qualitative information relating to the proportions of specific radionuclides associated with contamination is required, gamma ray spectroscopy may be undertaken. Gamma spectroscopy is of particular use where the emissions from man-made contaminants must be distinguished from, often much more intense, natural radiation emissions. For gross counting or dose-rate measurement applications,

In gamma spectroscopy at energies above several hundred keV, there are, at present, only two detector categories of major importance [Knoll 1989]: inorganic scintillators, of which NaI(Tl) is the most popular, and germanium semiconductor detectors. Although there are many other potential factors, the choice in terrestrial applications most often revolves about a trade-off between counting efficiency and energy resolution. Sodium iodide scintillators have the advantage of availability in large sizes (tens of litres), which together with the high density of the material can result in very high interaction probabilities for gamma rays. The energy resolution of scintillators is, however poor. Good germanium systems will have a typical energy resolution of a few tenths of a percent compared with 5-10% for sodium iodide.

The disadvantages of germanium type systems, in relation to remote sensing applications, are that the detector and ancillary equipment are bulky, they are sensitive to shock and vibration and, most importantly, the detectors must be cooled to a constant temperature of approximately 77K (-196 °C). Cooling is normally achieved using an insulated dewar in which a reservoir of liquid nitrogen is kept in thermal contact with the detector. There are often flight safety implications and other practical difficulties relating to the use of such systems in aircraft. In recent years, technological developments have led to the commercial availability of electrical cooling systems which obviate the requirement for nitrogen dewars. Such systems are now in use at sites where liquid nitrogen supplies are unavailable or unreliable. Notwithstanding the above, scintillation based systems are likely to remain the most practical option for aerial gamma spectroscopy remote sensing applications in the foreseeable future.

Traditionally, photomultipliers are used in conjunction with scintillators to produce the electric pulses and current which are compatible with counting and measurement equipment. However, recent advances in the development of semiconductor photodiodes have led to the substitution of newly available solid state devices for photomultiplier tubes in some applications [Knoll 1989]. In general, photodiodes can provide better energy resolution, lower power consumption, and are more compact and rugged than photomultipliers. It is likely that within a timescale of 5-10 years such systems will become increasingly utilised in remote monitoring systems and as a result sensitivities may become enhanced to some extent.

Whilst, as stated above, it is in general only gamma radiation that can be measured using remote techniques, some research has been carried out in relation to the measurement of radiation by measuring the effect it has on the air near its source. Moss et al [1999] found the remote sensing optical techniques could be used to detect new molecular species that are formed during chemical reactions resulting directly from the ionising effect of radiation. It was, however, concluded that even for moderately intense sources of gamma rays and neutrons, currently available techniques are not sensitive for this application.

3.8.6 Installed monitoring systems

Radioactive Incident Monitoring Network (RIMNET)

Following the Chernobyl reactor accident in 1986, RIMNET, the nuclear radiation monitoring and nuclear emergency response system, was installed in 1988 to monitor the consequences to the UK of nuclear incidents abroad [www.environment.detr.gov.uk/des20/chapter5/5.htm] Radiation dose rate readings (gamma plus cosmic) from 91 sites within the UK are collected every hour and checked by a computer at the Department of the Environment, Transport and the Regions (DETR) in London for any indication of abnormal increase. Any evidence of a nuclear incident of radiological significance for the UK would result in a national alert being raised.

RIMNET data recorded up to 1997 has indicated that background radiation continues to be the main component of observed levels of gamma radiation. The observed UK annual radiation dose rate at the RIMNET sites has been found to range from 0.5 mSv to 0.9 mSv with an average of 0.7 mSv.

Perimeter monitoring systems

At nuclear installations there are detectors at the boundary of the site which detect and measure site radiation emissions and radioactive materials leaving the site. For example, within the Ministry of Defence (MoD) Perimeter Monitoring Systems (PMSs) are installed at the Devonport, Clyde and Rosyth Dockyards as part of a post reactor accident monitoring capability. In the case of the MoD capability, each system comprises 15 to 25 stations on, or close to, the site perimeter and detectors are positioned such that detection of airborne activity can be achieved with any prevailing wind direction.

3.8.7 Ground-Based Mobile Survey Techniques

The established method of undertaking land quality radiological assessments is by 'walk-over' or vehicle mounted gamma survey combined with soil sampling as appropriate. The use of vehicles allows coverage of larger areas within a given time but this is normally only achieved at the expense of loss of positional sensitivity (which may be of importance when attempting to locate small areas of contaminated ground). There is a wide variety of instrumentation available for radiological survey and it is beyond the scope of this study to provide in depth information in respect of the detection equipment available. As stated above the principal detector types used are scintillation and Geiger-Muller probes.

Ground-based surveys vary in cost between approximately £1,000 and £5,000 per Ha. The cost of the survey largely depends of the exact coverage required and the extent to which ancillary work such as trial pit excavation, sample collection and radiochemical analysis is undertaken. Surveys can normally detect surface contamination of common radionuclides such as Co-60, Cs-137 and Ra-226 (when progeny are present) at surface activities below 0.4 Bq/cm^2 (4 kBq/m^2) averaged over an area of 300 cm^2 (0.03 m^2) or more.

In recent years there been considerable developments in Global Positioning System (GPS) technology and in mapping software which, when combined with GPS data and the data from radiation survey instrumentation, can be applied successfully in radiological survey.

The GPS system is essentially a network of satellites; the positions and trajectories of which are known to a very high degree of accuracy. The satellites transmit position information which can be received by commercially available instrumentation on the ground yielding precise latitude, longitude and altitude information updated every second. For security reasons, positional information is encrypted to some extent such that commercial GPS receivers only achieve an accuracy of the order of 40 metres. It is, however, possible to obtain position data to an accuracy of within 1m using a freely available technique known as differential correction.

The use of GPS means that manual, and relatively inaccurate, triangulation survey methods are no longer required and significant time savings are therefore possible. Additionally, it is a simple matter to incorporate computer software such that positional information, and monitoring data, can be automatically logged and subsequently printed or plotted.

Within the UK a GPS based radiation mapping service known as ‘Groundhog’ is provided by AEA Technology [www.aeat.co.uk/nuceng/products/groundhog.htm]. The ‘Groundhog’ system incorporates gamma monitoring instrumentation which can be fitted into a specially designed back-pack or onto a vehicle. Similar systems are known to be under development by other organisations including DERA Radiation Protection Services (a business group of the Defence Evaluation and Research Agency).

It is likely that the increased availability of low-cost GPS technology and mapping software will lead to increased use of this technology in ground-based surveys in the future. In particular, it is likely that the encryption built in to the GPS signal will be removed by the US military within a timescale of a few years. This will lead to a dramatic reduction in the cost of obtaining accurate GPS information.

There are many organisations within the UK and overseas with the capability to undertake ‘walk-over’ or vehicle based radiological surveys. Reference [Sakamota and Tsutsumi 1999] provides an example of some work in relation to a ‘carborne’ gamma survey system.

3.8.8 Airborne survey techniques

Penetrating radiations emitted by terrestrial radioactive materials may be detected by instrumentation carried on aircraft and such surveys are particularly valuable where surface terrain or topology makes ground-based survey impractical or where rapid analysis of extended areas is required. More rapid spatial coverage (in comparison with ground based survey) is achieved at the expense of loss of spatial resolution and higher minimum detection threshold. Where spatial resolution is of primary importance, helicopters tend to be used as a result of their capability to travel at low speed in comparison with fixed wing aircraft.

The speed at which aerial surveys are undertaken is determined primarily by the aircraft speed and the fight line separation. Typically, coverage rates of 10-50 square km per hour are achieved. The cost of aerial surveys is dominated by the cost of hiring aircraft and aircrew for the task. Typically, the cost of hiring a helicopter and pilot is of the order of £500 to

£1,000 per hour and the cost of a 1-2 day survey and subsequent provision of a report is £5,000-20,000.

The attenuation of gamma radiation in the atmosphere reduces the scope for high altitude survey of environmental radiation levels. For this reason aerial surveys are usually undertaken at altitudes of below approximately 500 ft (150 m). At greater altitudes cosmic radiation tends to progressively dominate gamma exposures [Wilson *et al*. 1994] and the spatial accuracy of surveys is reduced. In the case of cosmic radiation, exposures increase with both altitude and latitude and these effects must therefore be compensated for in aerial monitoring applications. Other factors, such as the shielding and scattering effect of precipitation, must also be taken into account. Where flight altitude is limited as detailed above, detection thresholds of the order of 4-10 kBq/m^2 for typical gamma emitters (such as Cs-137 and Co-60) can normally be achieved.

A selection of airborne radiation monitoring capabilities, which are offered or have been used in English speaking countries, is provided in the subsequent sections of this report. Information relating to these capabilities was collected from the World Wide Web (www) using the search engine 'Google' and literature searches using the DERA 'Web of Science' and aerospace and NTIS databases.

Scottish Universities' Research & Reactor Centre (SURRC) (UK)

Within the UK a helicopter borne radiation monitoring capability is offered by the Scottish Universities' Research & Reactor Centre (SURRC), East Kilbride [www.gla.ac.uk/R-E/leading_edge/4/chernobyl.html].

Following the April 1986 accident at Chernobyl nuclear power station in the Ukraine, the European Commission launched an extensive collaborative research programme. Sixteen projects were funded to study health and environmental issues including emergency response procedures and long term management. One of these projects led to the publication of an atlas graphically illustrating the deposition levels of radioactive material, and in particular Caesium- 137. The SURRC team, led by Dr David Sanderson of the University of Glasgow, provided data for the atlas using their Airborne Gamma-Ray Spectrometry technique (AGS). The technique is based on high efficiency gamma-ray spectrometers operated from low-flying aircraft, usually helicopters, in conjunction with suitable navigation and altimetry equipment, and, it is claimed, area sampling rates 106-107 times greater than associated with ground based methods can be achieved.

The UK section of the atlas incorporated observations made by the SURRC team from during surveys undertaken in Scotland and parts of England and North Wales. In addition to the work outlined above, SURRC has carried out other surveys in the SW of Scotland, Cumbria, the Ribble Estuary, North Wales and at the locations of many nuclear sites within the UK.

SURRC has also undertaken aerial monitoring in Finland for an airborne monitoring exercise involving teams from Europe and Canada [Sanderson, 1995]. The RESUME 95 (Rapid Environmental Surveying Using Mobile Equipment) exercise had the objective of cross comparison of various aerial monitoring techniques.

The British Geological Survey (BGS)

The British Geological Survey (BGS) has recently launched a collaborative project with industry to fly a series of detailed airborne surveys over Britain to collect new environmental and geological data [www.bgs.ac.uk/press/archive/airborne.html]. The project is known as Hi-RES, which is an acronym of High-resolution airborne Resource and Environmental Survey. The first survey (Hi-RES-1) is being carried out in partnership with World Geoscience (UK) Ltd and will cover an area of around 14,000 km^2 over central England. The data are being collected from a fixed wing aircraft flying at low altitude along survey lines 400m apart. The instrument package on the aircraft includes a gamma spectrometer and the stated aims of the project include the following:

- Mapping areas of above background radioactivity which may indicate radioactive industrial waste related to industrial activity.
- Identifying areas which may be prone to high radon levels.
- Measuring baseline levels of natural radioactivity against which any future radioactive contamination may be assessed.

Oak Ridge National Laboratory (ORNL) (US)

The US Oak Ridge National Laboratory (ORNL) conducts gamma radiological surveys (primarily at the Oak Ridge Reservation) to provide data for the characterisation and long-term monitoring of contaminated sites, for which many of the radioactive materials of interest are direct gamma radiation emitters or have gamma emitting progeny [www.ornl.gov/~ept/rs/gam.html]. High resolution gamma radiation surveys have been typically conducted at altitudes of 150 ft (46 m) and have utilised a helicopter outfitted with one or two detector pods, a computer- based data acquisition system, and an accurate navigational positioning system for relating acquired data to ground location.

ORNL has found that the highest gamma sensitivities are achieved when data is acquired in areas where soils contain low water content. The favoured times for undertaking surveys are therefore late summer and early autumn. ORNL's sensors have measured the ground-level gamma energy spectrum in the 38 to 3,026 KeV range.

U.S. Geological Survey

Aerial gamma-ray data has been used by the US Geological Survey to quantify and describe the radioactivity of rocks and soils. The US Geological Survey used gamma-ray detectors mounted in aircraft flown at a typical altitude of 120-150 m (400-500 ft). The majority of the gamma-ray signal was found to be derived from the upper 20-25 cm of superficial material (ie. near surface layers of rock or soil) [www.cr.usgs.gov:8080/radon/dd5-9.html].

The primary sources for aerial radiometric data in the United States are the reports of the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program of the 1970s and early 1980s. Data have been integrated into contour maps of equivalent uranium, thorium, potassium, and total gamma radioactivity exposure for the conterminous United States.

Bechtel Nevada (US)

Bechtel Nevada, a sister company of Bechtel Hanford Inc, have undertaken helicopter surveys for gamma radiation at the Hanford nuclear facility. Two helicopters were used in these surveys, with flights at an altitude of 200 feet and with flight lines separated by a distance of 400 feet. Radionuclides of interest in these surveys included Caesium-137, Cobalt-60, and isotopes of uranium, radium and potassium [www.tri-cityherald.com/doe/1996/march6.html].

The Bechtel Navada corporation have also carried out radiological surveys of US nuclear power facilities at Prairie Island, Point Beach, Monticello and Kewaunee. Reference [Feimster 1996] presents the results of the Prairie Island survey.

Picodas Environmental Systems

The Picodas Group Inc., based in Richmond Hill, Toronto, Canada, is a commercial organisation, which offers technologies in support of the 'airborne geophysical industry' [www.picodas.com/env/htm].

Picodas offers an 'Airborne Environmental Monitoring System-Integrated Gamma Ray Spectrometer' which, it is claimed, is a gamma ray spectrometer for fast and accurate airborne monitoring of natural and man-made radiation levels. The integrated system combines real-time navigation with gamma ray spectrometry and a digital map database. Specialist software provides 'measurements in physical units for immediate emergency evaluation'. Picodas market their system as appropriate for use in nuclear surveillance, man-made radiation monitoring to build-up radiation history of areas surrounding nuclear reactors, uranium mines, processing plants, etc., security and search applications, environmental studies.

3.8.9 Terrestrial radiation monitoring from satellites

Internet and literature searches yielded no available capabilities for the monitoring of terrestrial ionising radiation using satellites. As stated previously, the practicalities of such monitoring are likely to be severely effected by factors such as the attenuation and scattering of gamma radiation in the Earth's atmosphere and limitations to the positional sensitivities that could be achieved by such systems.

3.8.10 Summary

As a result of the penetrative nature of gamma emissions, it is detection of this type of radiation, which is of primary use in remote sensing applications relating to radioactive contaminants. The majority of radioactive contaminants of interest to the Environment Agency emit gamma radiation, or have progeny which emit gamma radiation. Certain radionuclides, such as H-3 and C-14, are unlikely ever to be detectable by remote sensing applications.

A 'base-line' radiation survey of the UK was undertaken by the National Radiological Protection Board (NRPB) in the 1980's. A more detailed aerial survey is currently being undertaken by the British Geological Survey (BGS).

'Walk-over' and vehicle based surveys are typically carried out using scintillation or Geiger-Muller detectors. Global Positioning System (GPS) technology is being increasingly applied in such surveys.

Airborne gamma counting and spectroscopy systems provide a rapid method of surveying extensive areas although flight altitude must be limited to avoid effects such as the elevated contribution of cosmic radiation and the attenuation of terrestrial gamma radiation in air. Instrumentation typically consists of large volume NaI scintillators in conjunction with photomultipliers. Developments in photodiode technologies are likely to enhance capabilities within a timescale of approximately 5-10 years.

The use of satellite technology for radiological remote sensing is not practical owing to the attenuation properties of the Earth's atmosphere. No evidence of capabilities or research in this area was found.

3.9 Magnetometry

3.9.1 Introductory remarks

The magnetic environment at the earth's surface is composed of three main contributions. The largest of these is the earth's own field, approximately 50 μT (10^{-4} Tesla), which is fairly uniform over small distances but varies by several μT over the U.K [Jacobs 1987]. The U.K. has three permanent magnetic observatories that constantly monitor the earth's field [http://ub.nmh.ac.uk]. These are networked with the global array of such observatories so the overall behaviour of the earth's field is recorded for examination.

Secondly, there are geomagnetic sources due to iron deposits within the geology of bedrock. The main effect of these is to cause anomalies in the earth's field. These have been mapped by aeromagnetic surveys, which show Scotland as having the highest concentrations of anomalies. ('Magnetic mountains' in Scotland are well known to wayfarers for unreliable compass readings.) The '*Smoothed Aeromagnetic Map of Great Britain and N. Ireland*' [Dunham 1970] indicates the largest geomagnetic anomalies to be of order 0.5 μT i.e. 1% of the earth's field.

Thirdly there are man-made magnetic sources, usually iron or steel constructions. Although these can have a large magnetic influence in their immediate vicinity, the magnetic fields from these sources tend to decay very rapidly with distance. Large cities, where the highest concentrations of iron and steel are expected, do not register as magnetic anomalies in high altitude aeromagnetic surveys such as that cited above. Even with low altitude survey it is very difficult to see cities by their magnetic influence.

Because of the rapid fall-off of magnetic strength with distance for man-made objects, magnetometry can not be used for long range remote detection of such targets. Although magnetometers are mounted in satellites for monitoring the '*magnetosphere'* and in some aircraft for detecting iron-ore deposits, man-made objects are magnetically located by land-based survey either with hand held or vehicle mounted sensors. Remote sensing is impractical at ranges pertinent to airborne survey.

Magnetic measuring instruments fall into two classes, passive and active. Passive instruments monitor the environmental magnetic fields that are incident upon them whilst active instruments induce magnetisation in metals and receive just the induced signals. In this respect active instruments, their main manifestation being the metal detector, are insensitive to the natural magnetic environment. This can be a significant advantage for many applications because small, nearby 'targets' are not then masked by the earth's field. In addition they are sensitive to all metals, not just the ferromagnetic ones. Passive sensors are mainly used to look for small perturbations on top of the comparatively massive earth's field. For many ferromagnetic targets, passive sensing offers longer range than active.

3.9.2 Passive magnetic sensing

Although there are three main 'types' of magnetism, *diamagnetism*, *paramagnetism* and *ferromagnetism*, only the latter is of relevance to this study because it is a strong enough effect to be measurable outside laboratory conditions. Magnetic measurements are confined to materials that have significant ferromagnetic content. The most abundant of such material is iron, although cobalt and nickel are also common. Ferromagnets are characterised by having a '*magnetic susceptibility,* χ_m' that is greater than zero. Many of the substances of interest to the Environment Agency have χ_m at or very close to zero and cannot therefore be detected by magnetic means. Below is a list of some of these.

- Sea water.
- River water.
- Air.
- Air pollutants.
- Greenhouse gasses.
- Sewage sludge.
- Biologicals.
- Bio-degradable waste.
- Most domestic waste.

From this, one may quickly conclude that passive magnetometry is not appropriate for the main application areas of interest to the Environment Agency. However, for completeness we now discuss some specialist applications where this technique is very important.

One application is locating underground ferrous (i.e. steel and iron) objects, in particular unexploded ordnance (UXO) and buried industrial waste. The UXO application has a far higher importance placed on it in continental Europe than in the U.K. – due to there being far larger quantities of buried UXO left over from the two world wars. In Germany all new sites for development are magnetically surveyed beforehand. The technology to perform such surveys is relatively mature and available, but in our opinion still has considerable room for improvement. A recent description of UXO location technology is given by Rose-Pehrsson [1998]. Location of industrial waste is also more common outside the U.K. In the U.S., for example, magnetometry is used to locate abandoned oil wells and environmental monitoring wells with steel covers that have become buried [Crosby 1997]. Magnetometers for these applications operate at 1-20 m ranges depending on the size of the target material.

Another important application is non-destructive ground survey, usually for archaeological purposes. Soil and rocks are usually weakly magnetic to various extents. Archaeologists take advantage this to non-destructively map underground stone-works and filled ditches, usually in and around buried settlements [Aitken 1974]. Because of the weak nature of the magnetism, the sensor needs to be scanned directly over the ground, which makes the process slow. However, this is a powerful technique for determining soil disturbances like filled ditches or pits, and buried walls. For example, the U.K. company STS have used magnetometers to locate disused mine-works and underground cavities prior to building construction or to investigate land slippage [http://www.stsltd.co.uk]. The instrumentation for this application is essentially identical to that used for UXO location.

3.9.3 Active magnetic sensing

In the context of this study active magnetic detection is synonymous with metal detection. Metal detectors are fundamentally short-ranged instruments, typically less than one metre for small targets although larger special types can be sensitive to bigger targets further out. They have certain advantages over passive magnetometers that render them more useful in several cases. In particular metal detectors are easier to use, less expensive, and are sensitive to all metals – not just ferrous ones. The most advanced can even discriminate between different types of metal. In general, metal detectors are insensitive to the substances listed in the preceding section with the exception of seawater (which is conducting).

Due to the short detection range available, metal detectors would also need to be operated in the context of hand held or vehicle mounted ground surveys. The main non-military applications for metal detectors are for underground cable and pipe location, as well as for general ground survey and treasure seeking. As far as we are aware, the use of metal detection for determining the extent of landfill disposal sites has not been researched in detail.

3.9.4 Instrumentation

The instruments for both passive and active magnetic detection are relatively mature, reliable, inexpensive and easily available. There are several U.K. companies who provide a ground survey service using these and other techniques. For example ground penetrating radar, GPR, is an up-and-coming technology that essentially images the shallow underground environment and is highly complementary to magnetic sensors. To improve discrimination a thorough survey would use metal detectors, or magnetometers as well as GPR. As a rough guide a magnetometer would cost between one and ten thousand pounds, while a good metal detector costs between one and three thousand pounds. However, because these require dedicated operators to perform the surveys, the real cost of these techniques lies in the manpower.

Passive magnetometers are available as two types. The optically pumped 'scalar' magnetometers measure the field dependent atomic splitting of electron energy levels in a gas cell. This method can be highly accurate and is the favoured technique for aeromagnetic anomaly mapping. Scalar magnetometers measure the total magnetic field incident upon the gas cell. As such, magnetic anomalies therefore present very small perturbations on the large earth's field. The alternative type is the fluxgate gradiometer. These consist of two fluxgate magnetometers, separated by a short distance, which are subtracted from each other to back off the large ambient earth's field. This is necessary because unlike the scalar magnetometers, fluxgates are sensitive to the magnetic field's direction as well as magnitude. The earth's field must be accurately backed off otherwise the wanted signals would be swamped by the movement of the sensor in the full earth field. Fluxgates work by measuring changes in the field dependent magnetic properties of a sample magnetic material. They are more suitable for close-in detailed examination of an area whereas the scalar magnetometers are preferred for more general survey work. Although there are several other methods for measuring fields, the scalar magnetometer and the fluxgate gradiometer represent the majority of available models.

Metal detectors are also available in two types; *pulse-induction* and *continuous wave*. Pulse induction detectors output a pulse of magnetic energy into the ground. If a metal is present it will magnetically 'ring' for a time after the energising pulse has finished. This signal is then received using a galvanic coil. Continuous wave detectors emit continuous sinusoidal magnetic fields into the ground. If a metal is present it will oscillate sympathetically with this signal and re-radiate a *secondary* field that is received with coils. In practice there is little to choose between these two techniques, although the more advanced Continuous wave detectors are able to discriminate between different types of metals by using dual frequencies and measuring the phase of the returning signals.

3.9.5 Future developments

Unfortunately there are no foreseeable scientific advances that would extend the range of magnetometers to that suitable for true remote detection applications. Additionally, the physics dictates that they will never become sensitive to some of the environmental materials of interest. There are, however, several advances being made in the instrumentation to improve the functionality of both passive and active magnetometers within a five-year time-scale. For fluxgate gradiometers, new data processing techniques are being pioneered to improve performance and usability whilst reducing sensor cost. New metal detectors are also being researched that could perform pinpoint location of metals as well as a crude tomography capability to determine shape. Each of these advances is being actively researched at DERA.

3.9.6 Summary

Magnetometry is essentially a short-range (<10 m) technique for locating metals as well as host materials with magnetic contamination e.g. soil, rock etc. It is, however, insensitive to most of the environmental materials that the Environment Agency is primarily interested in monitoring. As such, these techniques would be unsuitable for the remote monitoring of environmental features. However, magnetometry techniques provide a very powerful tool-set for the close examination of limited areas to determine underground structures or to seek metals. The instrumentation is relatively mature, available and inexpensive.

4 REVIEW OF APPLICATION AREAS

4.1 Introduction

This section considers each of the application areas identified in section 2.2 and the effectiveness of the remote sensing techniques (considered in section 3) in addressing these applications. For each application the potential sensors are tabulated and assessed against the physical measurements which are needed to satisfy the application. Some of the issues involved with the use of the sensors for the relevant application are discussed and for each application, some remarks on practical considerations are given.

4.2 Flood Defence

In order to develop a strategy for Flood Defence in a particular region it will generally be necessary to predict the likelihood of flooding. This is an area of continuing research but the approach to flood prediction involves the construction of numerical hydraulic models for the region concerned and running the model with different water or river flow rates. (measurement of river flow using in-situ flow meters also enables the model to be used to generate flood warnings.) The model requires an accurate knowledge of the topography of the region and of the vegetation cover. The vegetation is important since it will provide a resistance to flood water flow which will generally exacerbate flooding further upstream. To provide accurate models the topography has to be known to the order of 10cm and this requirement can only be approached at present using airborne LiDAR. It is understood that the Environment Agency already use their airborne LiDAR for this purpose but that bias errors limit the overall accuracy obtained from track to track. The LiDAR may also used to measure vegetation height and from this derive an estimate of the resistance to flow [Mason *et al*. (to be published)]. Other information required to produce the model (eg, of hedgerows, buildings, etc) may be obtained from optical sensors and hyperspectral sensors can be used to assist in classifying vegetation. The remote sensing instruments which can contribute to flood modelling (and hence, flood defence) are shown in Table 4.1:

Table 4.1 Sensors with potential to contribute to flood defence.

Sensor	Terrain slope	Land cover	Vegetation height
LiDAR (airborne)	Yes, but some bias errors.	No	Yes
Hyperspectral (airborne or satellite)	No	Yes in principle, more research needed.	No
Optical/NIR (airborne or satellite	No, stereo would not be detailed enough	Yes	No
SAR (airborne or satellite)	Accuracy not yet demonstrated with SAR interferometry.	Yes – broad classifications only.	May be possible using polarisation techniques

The SAR is included here because it may eventually have the capability for fine vertical height measurement though single pass interferometry. The SAR can also be used for classifying land cover type (although not for species identification) and current research indicates a potential for vegetation height measurement using polarimetry. An important use of SAR is to validate hydraulic models by measuring the actual flood extent for comparison with the predicted extent. However, one of the difficulties in doing this is the delineation of the water/land boundary, especially when vegetation is partly submerged. For height measurement the airborne LiDAR seems currently to be the best sensor but further developments in satellite interferometry may eventually yield topographic measurements to the order of accuracy required.

Practical issues:
At present, airborne LiDARS seem to be the only effective tool for measuring topography, although further work is needed to remove bias. It is not known whether the existing Environment Agency LiDAR aircraft can also be equipped with optical imaging instruments (eg, CASI) but this would be a way of simultaneously classifying vegetation type and land cover at reduced cost. Satellite Electro-Optic sensors (particularly the high resolution and hyperspectral sensors) would be an alternative method of classifying land cover and might be a more cost effective approach to updating land cover maps and features for hydraulic models.

The use of satellite SAR for validation of models is limited by their individual repeat times. However, the expected increase in the number of satellite SAR systems in orbit could, in principle, overcome this problem were it not for the delay in placing image requests, typically of the order of one week. Airborne SAR systems could be used for flood extent measurement but at present, the airborne SAR systems accessible to the Environment Agency are used mainly for research and would probably not be available for continuous routine use.

4.3 Flood Monitoring

In this application there are two principal requirements, the delineation of the flood water/land boundary (and hence the extent of a flood) when flooding is taking place, in order to assess immediate risk and to support emergency activities. The second is the measurement of the extent of damaged areas (when flood has receded). This is understood to be needed for damage assessment and for planning of flood defences. In the first case timing is critical, to within hours, whereas the second requirement needs to be met within days of a flood receding. Table 4.2 shows the sensors which could be used in this application:

Table 4.2 Sensors for flood monitoring

Sensor	Flood extent	Damaged area
SAR	Yes, aircraft better for timeliness.	Yes, through change detection techniques but research needed.
Optical/NIR	Yes, subject to visibility (cloud, rain)	Yes.
Hyperspectral	May permit automatic flood mapping	Possibly, but research needed to quantify results
Thermal	Yes, subject to visibility.	No

Note, SAR has been used extensively for flood mapping; its particular advantage is that it is an all weather sensor and can also be used at night. There is sometimes a problem in delineating the water/land boundary, especially for partly submerged areas; however, current research on the applications of multipolarisation SAR may eventually mitigate this problem.
The recent work on the use of interferometric SAR for coherent change detection has shown that the *maximum extent* of flood may be obtained through demarcation of the area changed as a result of the flood [Geudtner 1996]. The advantage of this technique is that the measurement

is not so time critical – it is not necessary to image at the time of maximum flood extent, but a disadvantage is that changes in image coherence due to flood damage may also be confused with changes caused by wind movement (for example).

Practical issues
The advantage of satellite SAR for these applications is that they can image large areas easily and reliably; the disadvantage is the poor timeliness, but this would be less critical for measuring the maximum flood extent using change detection techniques. Use of other sensors (visible and IR) would be handicapped by poor visibility which in conditions prevailing at the time of flooding can generally be assumed to be poor. Airborne SAR is clearly an effective way of providing imagery rapidly and overcomes some of the timeliness problems of satellites. However, existing airborne SAR facilities tend to be used for research rather than to support operational applications although a number of demonstration activities have been conducted with the DERA airborne SAR [White, private communication].

4.4 Inland Water Quality

In this application it is important to measure dissolved oxygen, ammonia and various nitrates, nitrites and metals. In addition, water clarity (algae), turbidity and oil contamination need to be measured. Table 4.3 shows which sensors may contribute to these measurements:

Table 4.3 Sensors for Inland Water Quality measurements

Sensor	Chemical content, pH	Algae	Chlorophyll	Turbidity	Oil contamination	Flow rate
LiDAR	No	Possibly, research needed	Yes	Yes	Yes	Yes
Optical/ NIR	No	Yes, using multispectral	Yes, using multispectral	Yes	Yes, using multispectral.	No
SAR	No	No	No	No	Yes, if oil is in slicks	Possibly, using interfero-metric SAR
Fluor escence	Yes (for ammonium)	Yes	Yes	No	Yes	Y (with dye tracer)
Hyper spectral	No	Yes	Yes	Yes	Yes	No

The literature contains a large number of references to research in the use of visible/near IR and hyperspectral sensors for water quality measurements (see sections 3.3 and 3.4). It is seems evident that there is considerable potential in the use of remote sensing for water quality but it is noted that chemical content will still require in-situ measurements. SAR has been demonstrated for oil slick detection and this should be applicable to inland water but the analysis of images may be complicated by wind shadow effects (for example). SAR also has potential for flow measurement using along track interferometric techniques.

Practical issues
The majority of inland water quality measurements will need to be made at a number of positions along the water course and will generally involve fine resolutions (of the order of 1m or less). This kind of measurement generally favours the use of airborne sensors, particularly where hyperspectral sensors are concerned (because of the current relatively coarse resolution). It is believed that the Agency have made some hyperspectral

measurements with their airborne CASI sensor; this system would clearly be suitable to support further research on this application.
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4.5 Radioactive Materials

In this application the aim is to detect the presence of radioactive deposits or of leakage of radioactive materials from waste dumps by measurement of γ radiation emissions. Several measurements are needed:

- discrimination of the emissions from background radiation,
- identification of source type,
- measurement of the level of radiation.

Table 4.4 shows the effectiveness of two sensors in making these measurements:

Table 4.4 Sensors for radiation measurements

Sensor type	Radiation level	Source type	Discrimination
Counters (ie, scintillation detectors, Geiger-Muller detectors)	Yes	No	No
Gamma spectrometers (inorganic scintillators or Germanium detectors)	Yes	Yes	Yes

Note, α and β emissions cannot normally be detected by remote sensing because of their short range in air. Airborne sensing with these devices is feasible (see section 3.8) but some nuclides may not be detected with these γ sensors, eg, H-3, C-14, and Pu-239. Satellite sensors are generally unsuitable for radiation measurements.

Practical issues
The practical aspects of radiation measurement have been addressed in detail in section 3.8.

4.6 Air Quality

In this application there are three basic measurement requirements;

- chemicals such as ozone, benzene, etc,
- aerosols
- airborne particulate matter

Table 4.5 shows the sensors which can contribute to this application:

Table 4.5 Sensors suitable for Air Quality measurements.

Sensor	Chemicals (ozone, etc)	Aerosols	Airborne particulate matter
LiDAR	Yes, using DIAL	Yes, using DIAL	Yes, using DIAL
Spectroscopy	Yes, using DOAS	No	No
Hyperspectral	Possibly, but research needed.	Yes	No
Thermal IR	Yes,using spectral IR for tropospheric ozone (ground based)	No	No
Spectroscopy	Yes, both air and satellite based	No	No
Visible/near IR	No	Yes, using multispectral sensors	No

Measurement of air quality needs to be considered in the context of global, regional or local air quality. It is assumed that the Agency is primarily concerned with local air quality, particularly in industrial areas. The most important techniques are LiDAR (using DIAL) and Spectroscopy, using DOAS; however, some other sensors (visible, hyperspectral, thermal) may have contribute to measurement of some parameters.

Practical issues
DIAL is already used operationally from both ground and airborne platforms (see section 3.3) primarily for local and regional scale measurements. Satellite LiDAR has been used for measurement of atmospheric constituents. The particular advantage of DIAL is that it can measure backscattered radiation and hence does not require a remote source (unlike DOAS). DOAS is also used operationally, especially with ground based sensors. Airborne DOAS has been demonstrated [http://www.aquila.infn.it/o3symp/paper_01/reisinger.html] where the radiation source is on the ground. A satellite DOAS system such as GOME [http://www.earth.esa.int/symposia//papers/data/callies] uses the sun as a remote source for ozone and nitrogen dioxide measurements. The choice of DIAL and DOAS has to be made in regard to specific circumstances and in regard to the contaminants which are to be measured.

It should be noted that Spectra-Map [Hunt, personal communication] are developing a hand-held but highly sensitive, IR multispectral imaging spectrometer, through the integration of new-generation MIR and LWIR infrared camera technology and an electronically tunable optical filter. Such a novel but relatively simple improvement to imaging spectrometer design will for the first time allow the rapid ‘stand-off’ (ground or airborne) sensing of most greenhouse gases.

The ability to obtain a real time regional picture of the distribution of gases like methane and CO_2 has proved impossible with the current point sampling (non-imaging) and laboratory-bound instruments used hitherto. However, Spectra-Map’s new instrument should have a major impact on the efficacy of future environmental monitoring procedures. It is expected, for example that methane concentrations of less than 100ppm.m (over landfills, petro-chemical sites, etc) could be detected and viewed in real time.

4.7 Land Cover

In this application it is necessary to identify the principal classes of land cover and the subdivisions within these classes. Characterisation of land cover does not in itself identify threats to the environment but it does allow areas at risk to be identified, eg, waste sites, chemical run off from fields, industrial development. Several sensors are considered effective at the initial classification but more research is needed for the subdivisions: Table 4.6 below shows applicability to principal classes and subdivisions.

Table 4.6 Sensors suitable for land cover mapping

Sensor	Classification	Urban	Water	Vegetation	Infrastructure
SAR	Principal classes	Yes	Yes	Yes	Yes
	Subdivisions	Research needed	NA	Research needed	Yes
Visible/NIR	Principal classes	Yes	Yes	Yes	Yes
	Subdivisions	Yes	NA	Yes	Yes
LiDAR	Principal classes	No	No	Yes (height)	No
	Subdivisions	No	NA	Limited	No
Hyper-spectral	Principal classes	Yes	Yes	Yes	Yes
	Subdivisions	Research needed	NA	Yes	Yes

Note, many sensor types are effective at identifying the principal classes of land cover but have varying degrees of effectiveness with the subdivisions. For example, SAR can be used reliably for broad land use classification but may be unable to identify species in a woodland. This, however, is an area where Hyperspectral sensors may be particularly effective.

Practical issues.
It should be noted that the Institute of Terrestial Ecology (ITE) have already produced a land cover data base for the UK which is derived from the LANDSAT visible/NIR sensors. This database was produced in the early 1990's and it is now in the process of being updated with more recent imagery from LANDSAT. The data base is readily accessible within NERC and academic institutes. It is understood that there is an initiative within DETR to set up a national land use data base which would utilise the ITE data base and the Ordnance Survey digital map data base. Currently, trials are in place to determine the most effective means of updating this national data base and the sources of data to be used (aircraft, satellite, etc.). It is assumed that the Environment Agency are already involved in this activity.

4.8 Pollution Incidents

These incidents refer mainly to oil pollution in the immediate vicinity of the coast and on shore. Note that river contamination by chemicals and oil is considered under Inland Water Quality. Table 4.7 shows the sensors effective for this application:

Table 4.7 Sensors for detecting pollution incidents

Sensor	Oil detection(on coast)	Oil slicks (on sea, vicinity of coast)
Hyperspectral	Yes (also oil thickness)	Yes
Thermal	No	Yes, including night time slick detection
LiDAR	Yes	No
Fluorescence	Yes (also oil type)	Yes
SAR	Limited, depending on resolution	Yes, subject to break up by surf
Passive microwave	Limited	N

Note, the ability of SAR to detect oil is affected by sea state and by breaking waves or surf.

Practical considerations
In order to contain any risk the detection of slicks on the sea requires a remote sensing system with virtually instant response. Airborne systems are suitable and the Marine and Coastguard Agency (MCA) already use an airborne SLAR (Side Looking Airborne Radar) for oil pollution detection. Satellite systems are, however, being used to provide the MCA and DTI with a wide area 'first alert' warning of pollution. This makes use of the DERA satellite ground station to provide rapid access to satellite data and to provide coverage of almost all the European coastline.

The detection of oil on the shore is less time critical and the fine resolution required would tend to suggest the use of airborne sensors. With improvements spatial resolution the new generation of satellite SAR sensors (eg, RADARSAT, TerraSAR) should become effective for this application and provide regular coverage.

4.9 Waste

This application is concerned with the characterisation of waste material, the estimation of the volume of waste deposits (in land fill sites), the detection of gaseous emissions from waste (eg, methane) and the detection of underground pollution from waste sites. Table 4.8 shows the sensors which can support this application.

Table 4.8 Sensors for detecting waste.

Sensor	Waste material	Land fill volume	Gas emission (methane)	Underground pollution
LiDAR	No	Yes	Yes, using DIAL	No
SAR	No, or very limited.	Possibly, using interferometry	No	No (except through coherent change detection of subsidence)
Hyperspectral and Visible/NIR	No, except for particular substances	Yes, using high resolution stereoscopic techniques.	Possibly using IR wavelengths	Research needed; detection of pollution induced stress in vegetation.
Spectroscopy	No	No	Yes, possibly with DOAS	No
Thermal	Yes, used for buried waste	No	No	No, other than stress induced effects.

Practical issues
The detection and sizing of waste tips could be done effectively with visible/NIR sensors, either on aircraft or satellites. The volumes can be estimated using the same sensors using steroscopic techniques, or the use of LiDAR. Characterisation of waste material may be possible with hyperspectral sensors, particularly if certain substances are to be identified. DIAL or DOAS would be needed for gas emission detection, but these might be most effective if ground based. Underground pollution may only be detected through its effect on vegetation or through subsidence, possibly detected using coherent change techniques and SAR. The latter may also be effective for fly tip detection, ie, for the detection of changes caused by the illegal dumping of waste. In this case satellite sensors may be effective through provision of wide area coverage. Airborne magnetometry may be useful for detecting quantities of metal deposits buried beneath other waste.

4.10 Contamination of Land

This application is concerned with the detection of chemicals or metals in soil with consequent impact on subsequent land use. The substances to be detected include: build up of heavy metals, presence of nitrates or phosphates from over fertilisation and buried waste (including old industrial sites). Table 4.9 shows the relevant sensors:

Table 4.9 Sensors for measuring land contamination

Sensor	Heavy metal build up	Nitrates and phosphates	Buried waste
SAR	No	No (but run off estimated from slopes determined with interferometry)	Possibly, using very low frequency sensors
LiDAR	No	No, but estimate run off from slopes	No
Hyperspectral	Possibly, from plant stress. Research needed.	Possibly, from plant stress.	No
Optical/NIR	No	Yes, from detection of agricultural practices	No
Magnetometry	No	No	Yes (if in quantity)

Note, the existence of nitrates and phosphates may be inferred from knowledge of crop types and hence likelihood of fertilisation. SAR and LiDAR could be used to estimate slopes and hence possible concentrations of chemicals from runoff.

Practical issues
Remote sensing can be used to identify features which suggest that there is a risk of land contamination. However, this would need to be backed up by in-situ measurements or by taking samples for analysis. It is considered that this application could form a specific sub set of the more general land cover application (see 4.7).

4.11 Marine and Coastal Water Quality

The parameters to be measured here include algal blooms, algae on mud flats, salt marsh vegetation and salt marsh extent. Sensors effective for this application are shown in Table 4.10:

Table 4.10 Sensors for marine and coastal water quality

Sensor	Algal blooms	Algae on mudflats	Saltmarsh extent	Saltmarsh vegetation
Optical/NIR	Yes, using multispectral	No	Yes	Yes, using multispectral
Hyperspectral	Yes	Yes	Yes	Yes
Fluorescence	Yes	Yes	No	No

Note, the SeaWIFs sensor (an optical/NIR sensor) is already being used to characterise algal blooms along coasts and on mudflats. This is an application in which considerable research is in progress using both airborne and satellite sensors.

Practical issues

This is an application which can (and is) well served by a number of remote sensing techniques. With the improvement in spatial resolution of satellite sensors and the increase in provision of multispectral/hyperspectral capabilities, satellite sensors are becoming well placed to regularly cover large areas of coast. Airborne sensors should continue to be used to develop analytical techniques and to provide coverage of local areas.

4.12 Biodiversity

Biodiversity is a qualitative measure relating to the range of species (both animal and vegetation) which exists in a particular region. Changes in this measure are unlikely to be measured directly by remote sensing techniques but may be inferred from the detection of other parameters which impact on biodiversity. These parameters are listed below in Table 4.11 together with the sensors considered most relevant.

Table 4.11 Biodiversity indicators and relevant sensors.

Biodiversity indicators	**Relevant sensors**
Land-use, land cover and changes in these indicators	Optical/NIR, Hyperspectral, SAR, LiDAR
Changes in natural vegetation species	Hyperspectral
Vegetation stress	Hyperspectral
Changes in hedgerows	Optical/NIR, SAR
Changes to land cultivation	Optical/NIR
Response to pollutants (through plant stress)	Hyperspectral

Practical issues

In this application remote sensing can be used to indicate changes in land cover from which changes in biodiversity may be inferred. It follows that sensors and techniques already identified for land cover applications (see 4.7) should be used here. This application might be considered to form a sub set of the land cover application, although there would be more emphasis on measuring the subtle changes which impact on biodiversity. The use of a regularly updated national land cover map might be particularly useful in this case.

4.13 Climate Change

In this application measurements are required which allow the direct impact of climate change to be assessed, eg, flooding, changes in natural vegetation, coastal erosion. In addition, those factors which contribute to climate change need to be monitored, eg, greenhouse gas emissions. Some of these factors have already been considered, Table 4.12 below identifies those additional measurements which might be required:

Table 4.12 Indicators of climate change and the relevant sensors.

Indicator of climate change	Sensor
Sea level rise, coastal erosion and topography	LiDAR, SAR
Species migration	Hyperspectral
Greenhouse gases (infer from urban developments, traffic use, etc)	Optical/NIR (for urban development), spectroscopy, LiDAR.
Flooding	SAR
Storm damage	SAR, Optical/NIR

Note, the general estimation of greenhouse gases in the atmosphere is considered to be the province of other agencies (eg, Meteorological Office). However the estimation of some of the sources contributing to greenhouse gases may be a responsibility of the Environment Agency. The use of remote sensing to identify and quantify such sources is indicated above.

Practical issues.
Some factors contributing to climate change may be considered to have been addressed in other applications, eg, greenhouse gas emissions in measurements of air quality (4.6). The impact of climate change may be deduced from land cover maps such as those discussed in section 4.7. As with biodiversity, the analysis of such (land cover) data would need to take into account the specific factors being sought, eg, storm damage, erosion, etc. However, it is possible that the timescales for land cover map updates would not satisfy this application and the Agency may need to provide more frequent updates of areas which are of concern.

4.14 Summary

The study has shown that while remote sensing could be used to address most of the Agency's applications, in general, a range of different sensors would be needed to fully cover all applications. In many cases, a number of different sensors would be needed to address a single application. It should also be noted that the specification of any sensor may be different for different applications; for example a SAR used for flood monitoring will not generally have the same specification as one intended for land cover monitoring. In most cases there is potential for the application to be solved but more research is needed to allow quantifiable measurements to be made; this is particularly true in the case of SAR and hyperspectral sensors. It is also noted that the hyperspectral sensor is considered to be the most effective sensor in that it can be used over the widest range of applications; this observation is reinforced by the current use by the Environment Agency of the CASI sensor. It is also noted that use of remote sensing to serve the land cover application may also provide a means of addressing other applications which depend on land cover to some degree, ie, contamination of land, biodiversity and climate change. A common land use data base would form a starting point for these applications together with additional remote sensing updates of particular regions as required.

5 CONCLUSIONS

The study has shown that remote sensing has the potential to contribute to all the applications of concern to the Environment Agency. However there are a number of instances where in-situ measurement are needed in order to quantify the environmental risk, ie.

- Inland water quality – chemical content,
- Contamination of land – metals, nitrates, etc,
- Classification of waste (and underground pollution).

In other areas, particularly Land cover, Marine and Coastal water quality, Biodiversity and Climate change, airborne or satellite sensors are an effective means of providing regular coverage; however, more research is needed to quantify the level of risk (or change), particularly for hyperspectral sensors. For the more time critical applications (Flood monitoring, Pollution incidents) remote sensing is highly effective provided that the response times can be met – this is currently an area in which satellites are at present limited.

The study has shown that there are widespread developments in remote sensing techniques aimed generally at improving spatial resolution, particularly for satellites, and information content (through increase in spectral bands or use of polarimetry).

The data base search has revealed an extensive amount of research in progress in areas related to Environment Agency interests. In particular, research in SAR, LiDAR and Hyperspectral sensors is expected to yield results which should be of benefit to the Agency in a number of areas, eg, models for flood prediction (SAR, LiDAR), discrimination of land cover categories (Hyperspectral). It is also note that the Agency has already equipped itself with facilities to support further research using the airborne CASI and LiDAR and it is considered that the Agency should take advantage of other remote sensing facilities to develop additional techniques which might later become operational. In particular, access to airborne or satellite multipolarisation SAR and satellite hyperspectral systems should be considered (see section 3.1 and 3.4). In the measurement of air quality it is considered that airborne DOAS systems should be considered as an alternative to ground based systems.

One of the aims of the study was to identify remote sensing techniques which are capable of being developed into operational status within a five year timeframe. Given the very wide range of both applications and techniques, it was not possible to define a priority list of techniques which should be considered by the Agency. However, the following list identifies a number of sensors and techniques which should be considered for operational use or for further development:

- Development of a land cover data base using satellite high resolution visible/NIR and hyperspectral sensors, with the aim of providing up dates of specific regions as required using airborne or satellite imagery. This would help the land cover, land contamination, biodiversity and climate change applications.
- Set up a GIS system which would allow different data sets (from remote sensing or other measurements) to be incorporated with the land cover data base – this would allow data to be more effectively used across a number of applications.
- Investigate the use of satellite and/or airborne multipolarisation SAR for flood monitoring and pollution monitoring (and flood defence).

- Investigate the use of interferometric SAR for change detection (and land use) and for illegal dumping and waste site monitoring.
- Investigate the use of airborne sensors (DIAL and DOAS) for more effective air quality measurements (in locations not served by ground based sensors.
- Investigate the use of hyperspectral sensors, particularly for land cover classification (and biodiversity) and inland and coastal water quality.
- Extend the use of the existing airborne CASI and LiDAR systems to support research on flood modelling, water quality measurement and vegetation classification.

6 RECOMMENDATIONS

The list given in the preceding section (section 5) indicates the remote sensing techniques which could be considered by the Agency as a basis for further work. The selection of techniques from this list will depend on the Agency's priorities and on the specific requirements for each of the Agency's applications. It is recommended that these priorities and requirements should be reviewed with the aim of identifying those applications which urgently need attention. This short list should then be used as a basis for a more detailed review of the relevant sensing techniques, leading to development of sensor technologies and/or analyis procedures.

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