MEDITERRANEAN ACTION PLAN
MED POL

UNITED NATIONS ENVIRONMENT PROGRAMME

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

APPLICABILITY OF REMOTE SENSING FOR SURVEY OF WATER QUALITY PARAMETERS IN THE MEDITERRANEAN

Final Report of the Research Project

MAP Technical Reports Series No. 67

UNEP
Athens, 1992

For bibliographic purposes this volume may be cited as:

UNEP/IOC: Applicability of Remote Sensing for Survey of Water Quality Parameters in the Mediterranean. Final Report of the Research Project. MAP Technical Reports Series No. 67, UNEP, Athens, 1992.

Pour des fins bibliographiques, citer le présent volume comme suit:

PNUE/COI: Applicabilité de la télédétection à l'étude des paramètres de la qualité de l'eau en Méditerranée. Rapport final du projet de recherche. MAP Technical Reports Series No. 67, UNEP, Athens, 1992.

This volume is the sixty-seventh issue of the Mediterranean Action Plan Technical Report Series.

This series contains selected reports resulting from the various activities performed within the framework of the components of the Mediterranean Action Plan: Pollution Monitoring and Research Programme (MED POL), Blue Plan, Priority Actions Programme, Specially Protected Areas and Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea.

PREFACE

The Mediterranean Action Plan, a regional programme for the prevention and control of pollution of the Mediterranean Sea was adopted in 1976 at the Intergovernmental Meeting on the Protection of the Mediterranean.

The Mediterranean Action Plan has following three substantive components:

- Integrated planning of the development and management of the resources of the Mediterranean Basin;

- Co-ordinated programme for research, monitoring and exchange of information and assessment of the state of pollution and of protection measures (MED POL); and

- Framework convention (Barcelona Convention) and related protocols with their technical annexes for the protection of the Mediterranean marine environment.

All components of the Mediterranean Action Plan are interdependent and provide a framework for comprehensive action to promote both the protection and the continued development of the Mediterranean region. No component is an end in itself. The Mediterranean Action Plan is intended to assist Mediterranean Governments in formulating their national policies related to the continuous development and protection of the Mediterranean area and to improve their ability to identify various options for alternative patterns of development and to make choices and appropriate allocations of resources.

MED POL, being the environmental assessment component of the Mediterranean Action Plan, was principally designed to help Mediterranean coastal states - Contracting parties to the Barcelona Convention - to participate in a full-scale research and monitoring programme as well as to provide continuous information on pollution in the Mediterranean Sea.

The general objectives of MED POL-Phase I (1976-1980), which evolved through a series of expert and intergovernmental meetings, were:

- to formulate and carry out a co-ordinated pollution monitoring and research programme taking into account the goals of the Mediterranean Action Plan and the capabilities of the Mediterranean research centres;

- to assist national research centres in developing their capabilities to participate in the programme;

- to analyse the sources, amounts, levels, pathways, trends and effects of pollutants in the Mediterranean Sea;

- to provide the scientific-technical information needed by the Mediterranean States and the EEC for negotiation and implementation of the Convention for the Protection of the Mediterranean Sea against Pollution and its related protocols;

- to build up consistent time-series on the sources, pathways, levels and effects of pollutants in the Mediterranean Sea.

MED POL-Phase I initially consisted of seven pilot projects on baseline studies and monitoring of oil, petroleum hydrocarbons and microbial pollution in sea water, heavy metals and chlorinated hydrocarbons in marine organisms as well as research on the effects of pollutants on organisms, populations, communities and ecosystems. In addition, four related projects were also included to broaden the scope of the programme or to provide the ancillary support.

The experience gained in the MED POL-Phase I allowed UNEP to initiate in 1981 MED POL-Phase II with specific objectives to provide, on a continuous basis, the Parties to the Barcelona Convention with:

- information required for the implementation of the Convention and the protocols;

- indicators and evaluation of the effectiveness of the pollution prevention measures taken under the Convention and the protocols;

- scientific information that may lead to eventual revisions and amendments of the relevant provisions of the Convention and the Protocols and for the formulation of additional protocols;

- information that could be used to formulate environmentally sound national, bilateral and multilateral management decisions essential for the continuous socio-economic development of the Mediterranean region on a sustainable basis;

- periodic assessment of the state of pollution of the Mediterranean Sea.

The monitoring of, and research on, pollutants affecting the Mediterranean marine environment reflects primarily the immediate and long-term requirements of the Barcelona Convention and its protocols, but also takes into account factors needed for the understanding of the relationship between the socio-economic development of the region and the pollution of the Mediterranean Sea.

Monitoring and research on the sources, levels and effects of pollutants in the Mediterranean Sea constitute one of the cornerstones of the Mediterranean Action Plan. To date, over 400 research projects have been implemented within the framework of MED POL-Phase II since 1982 by over 150 Mediterranean institutions.

Results gathered through the research component of MED POL have been presented at numerous scientific meetings, and published in a large number of scientific journals and in the MAP Technical Reports Series.

Individual and collective training is provided for scientists and technicians in techniques (methods) required for their effective participation in monitoring and research envisaged in the framework of MED POL - PHASE II. This assistance is in the form of fellowships, experts, workshops, seminars, grants for attendance to meetings, etc., and covers training in analytical and sampling techniques, data processing, interpretation of results and various research topics.

As in MED POL-Phase I, the overall co-ordination and guidance for MED POL-Phase II is provided by UNEP as the secretariat of the Mediterranean Action Plan. Co-operating specialized United Nations Agencies (FAO, UNESCO, WHO, WMO, IAEA, IOC) are responsible for the technical implementation and day-to-day co-ordination of the work of national centres participating in monitoring and research.

This sixty-seventh volume of the MAP Technical Reports Series contains the final report of the Research Project of the Applicability of Remote Sensing for Survey of Water Quality Parameters in the Mediterranean completed in the framework of MED POL.

ACKNOWLEDGEMENTS

This applied research effort was carried out with the support of the United nations Educational, Scientific and Cultural Organisation acting through the Intergovernmental Oceanographic Commission, in the framework of Phase II of the MEDPOL programme of the Mediterranean Action Plan. We would like to express our deepest appreciation for this support, which made the research effort possible.

The project was carried out from March 1990 to May 1992. In December 1990, a progress report was submitted, which included preliminary conclusions on the subject. This report includes the final conclusions of the research effort and proposals for the application of remote sensing in the Mediterranean.

The report was compiled by P. Panagopoulos, Civil Engineer Ph.D. and D. Karavellas, Biologist M.Sc.. We are deeply indebted to P. Geerders, consultant for remote sensing of the marine environment, for his cooperation in the formulation of our conclusions and proposals.

In addition, we would like to thank Dr. E.G. Mitchelson-Jacob of the University of Wales in Bangor, Dr. G. Ferrier of the University of Reading, Dr. E.C. Barrett of the University of Bristol, Mr. J.M. Suijlen of the Tidal Waters Division of the Dutch Rijkswaterstaat, Dr. Aamodt of Oceanor, Norway, and Dr. T. Reilly of Innotech Aviation Ltd., Canada, for their contributions regarding the potential of remote sensing in the marine environment.

Finally, we would like to thank the European Space Agency (ESA) in Germany, the U.S. Earth Observation Satellite Company (EOSAT), the National Environmental Satellite, Data & Information Service of the U.S. National Oceanic and Atmospheric Administration (NOAA), the Remote Sensing Technology Center of Japan, the Canada Centre for Remote Sensing, Radarsat International of Canada and Itres Research Inc. of Canada for their contributions to the operational satellite information presented herein.

TABLE OF CONTENTS

1. INTRODUCTION

The monitoring of sea water quality is normally carried out by in-situ measurement and/or sampling and laboratory testing, which are currently executed with standarised and reliable methodologies and techniques. Each measurement provides the value of a parameter at a certain location and depth and at a certain time; a large number of measurements is thus required for the monitoring of water quality of an area over a reasonable time period. In most cases, budget restrictions impose significant limitations on the monitoring effort.

Thus, the potential application of remote sensing, which appeared in the last decades and especially in the 1980's as an attractive alternative for the efficient monitoring of large areas, has become a subject of much interest.

The main strength of remote sensing is its capability to provide synoptic images of large areas with intervals of a few days, at a reasonable cost; the main weaknesses of the method are (i) that it can only provide information for water quality parameters near the water surface, and (ii) that, as an indirect means for measurement, it can provide only particular kinds of information. The careful assessment of the capabilities of this relatively new technology for the provision of reliable information on water quality has thus become a matter of significance.

The present applied research effort was directed precisely to that end, namely towards the formulation of an objective assessment of the potential of remote sensing techniques for the monitoring of sea water quality. Since the research effort was executed in the framework of the MEDPOL programme, special regard was given to the potential for application in the Mediterranean Sea.

The present report was produced mainly to assist non-specialised scientists and planners in the formulation of monitoring programmes for water quality assessment. To this end:

- Section 2 has been devoted to the explanation of the basic concepts of remote sensing,

- in Sections 3 and 4, the basic facts related to its application, i.e. types of instruments, satellites in orbit etc. are presented,
- on the basis of the above, the potential of remote sensing for monitoring of water quality parameters is evaluated in Section 5, for each type of instrument,
- in Section 6, the major applications of remote sensing for the assessment of the various water quality parameters are presented,
- in Section 7, the potential of remote sensing for monitoring of water quality parameters is evaluated for the aprticular conditions of the Mediterranean Sea, and
- in Section 8, proposals are made for specific areas of implementation of remote sensing in the Mediterranean.

2. CONCEPT OF OPERATION

2.1. Introduction

The surface of the earth emits and reflects electromagnetic radiation in a manner that depends on characteristics of the surface cover. Thus, signals received remotely (e.g. by airplanes, satellites) can be used to efficiently gain information on the surface cover.

2.2. Electromagnetic Waves

Electromagnetic waves transmit energy and are known to vary from less than 10^{-6}µm[1] (cosmic rays) to more than 10^{8}µm (television & radio waves). The electromagnetic spectrum is shown in Fig. 2.1. From this figure, it may be observed that visible electromagnetic waves range from 0.4µm (border of ultraviolet & blue waves) up to 0.7µm (border of red & near infra-red waves). Infra-red (IR) waves include near IR (from 0.7µm to 1.3µm), mid IR (from 1.3µm to 3µm) and thermal infra-red waves, which transfer heat (3µm to 1mm). Microwaves have wavelengths roughly between 1mm and 1m.

It should be noted that for electromagnetic waves, the longer the wavelength, the lower the energy content of the wave. This has important implications for remote sensing in that naturally emitted long wave radiation such as microwave emission from the surface is more difficult to sense than radiation of shorter wavelengths such as emitted thermal IR energy.

2.3. Sources of Electromagnetic Radiation

The sun is the basic source of electromagnetic radiation for remote sensing. However, all matter continuously emits electromagnetic radiation; thus, all terrestrial objects are also continuous sources of radiation.

[1] 1µm = 10^{-6}m

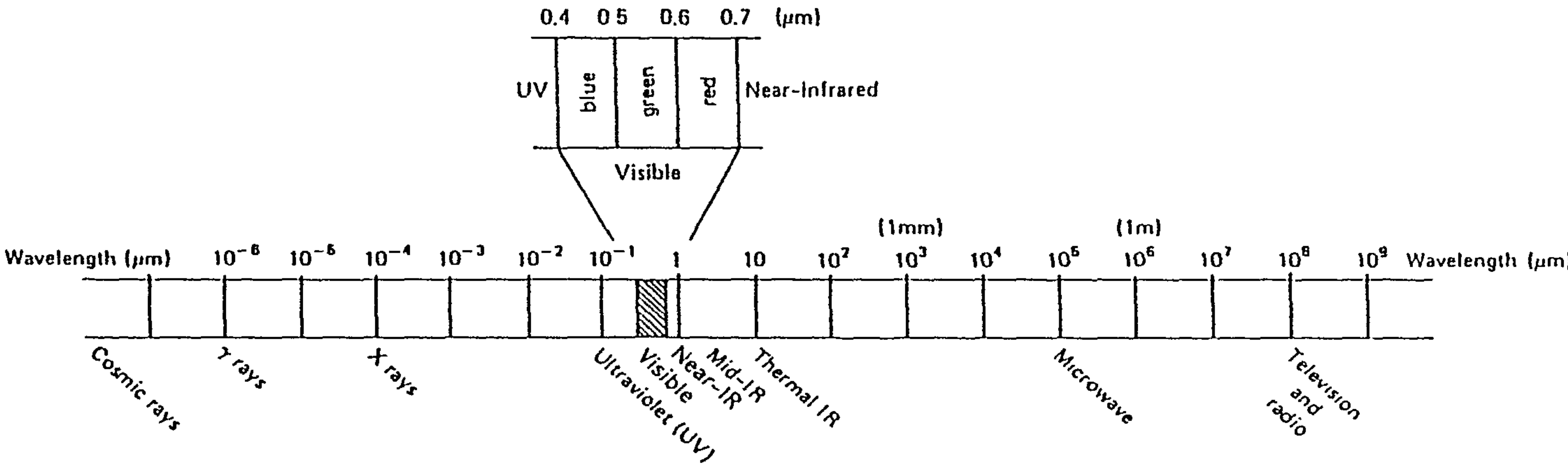

Fig. 2.1. The electromagnetic spectrum [36]

The total energy and spectral composition of radiation (i.e. the distribution of radiation energy at various frequencies) are strongly dependent on the temperature of the object. The spectral composition of electromagnetic waves emitted from the sun & earth are shown in Fig. 2.2. From this figure, it can be observed that, for wavelengths below 8µm, the sun's energy is predominant. The earth's energy is comparable with the sun's energy for wavelengths above 10µm; it is clearly measurable between 8µm and 14µm. In wavelengths above 100µm, the emitted energies of the sun and earth are extremely small.

The total energy and spectral composition of radiation are also dependent on the nature of the object; the emitting ability of materials is characterised by its emissivity, which has values between 0 and 1 and varies with the wavelength. The variation of emissivity with wavelength, i.e. the spectral emissivity of the object, is an intrinsic characteristic of the object.

2.4. Energy Interactions in the Atmosphere

The atmosphere can have a profound effect on the intensity and spectral composition of radiation, through the mechanisms of scattering (i.e. the diffusion of radiation by particles in the atmosphere) and absorption, which results in the effective loss of electromagnetic energy to the atmosphere (mainly by water vapour, carbon dioxide and ozone).

The effect of scattering in most cases strongly decreases with increasing wavelength. The effect of absorption on the other hand is selective, i.e. occurs in specific wavelength ranges. The degree of transmittance of electromagnetic waves of various frequencies through the atmosphere is shown on Fig. 2.3. From this figure, we may observe that certain frequencies are highly transmitted through the atmosphere (including visible light), while others are completely blocked; the following electromagnetic wavelength ranges have a high degree of transmission and are called "atmospheric windows":

- from 0.3µm to 1.2µm, i.e. in the UV, visible and near-IR ranges,
- from 3µm to 5µm (mid-IR range)

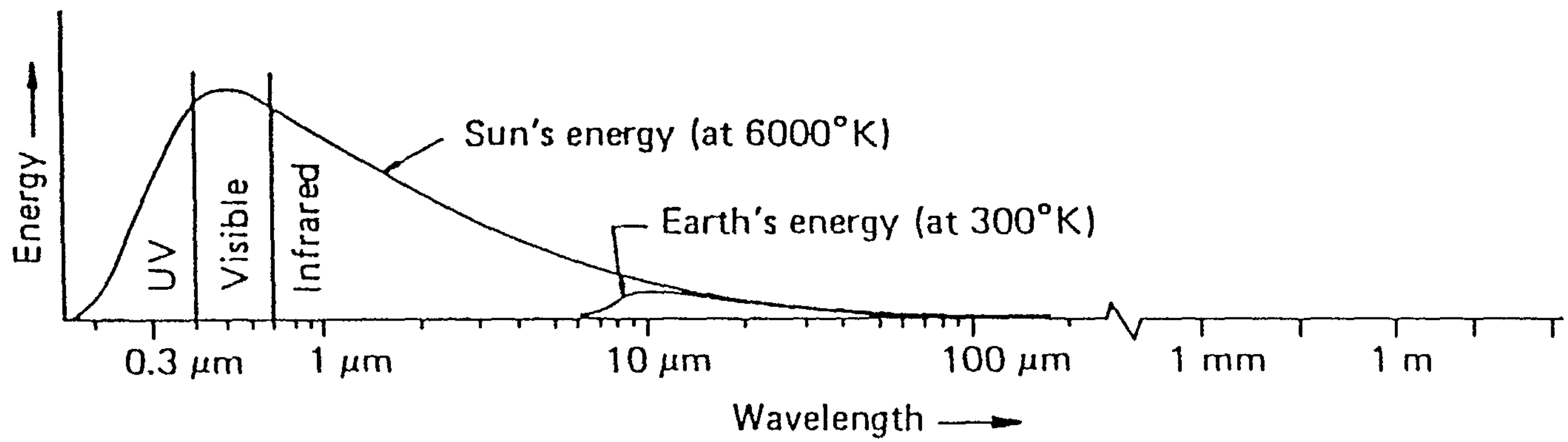

Fig. 2.2. Spectral characterisitcs of electromagnetic radiation emitted from the sun and earth [36]

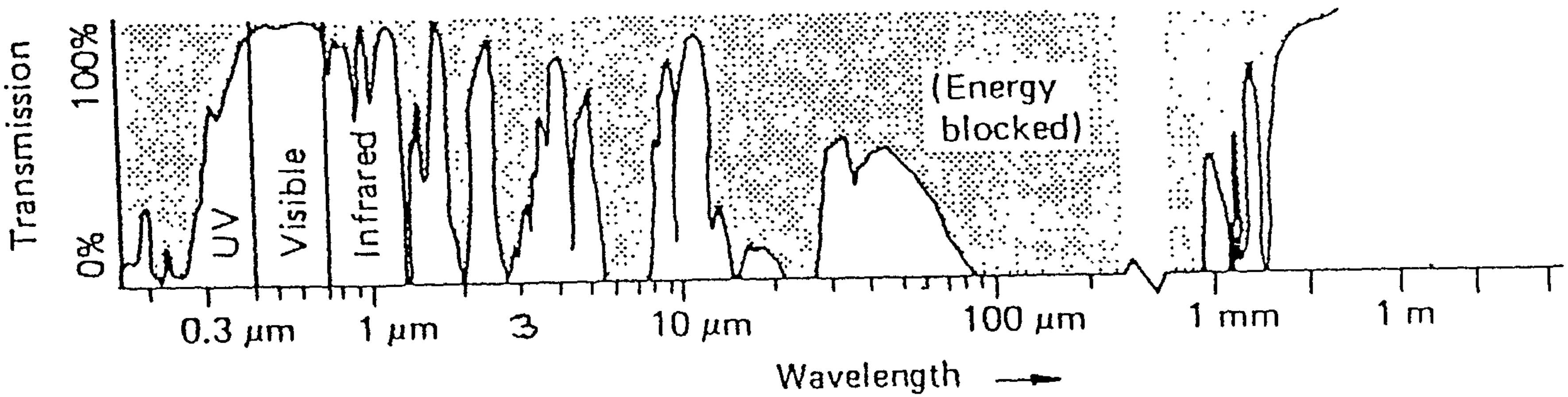

Fig. 2.3. Atmospheric transmittance for various wavelengths of the electromagnatic spectrum [36]

- from 8μm to 14μm (thermal IR range)
- from 1000μm (or 1mm) upwards up to about 1m (microwave range).

2.5. Energy Interactions with Earth's Surface

Electromagnetic energy incident on the surface of the earth is partly reflected, partly absorbed and/or partly transmitted, depending on the characteristics of the surface. Also, the proportion of energy reflected, absorbed and transmitted varies for different wavelengths.

The proportion transmitted is in most cases very small and can be neglected. So, the incident energy is mostly reflected and/or absorbed. Thus, objects that have good reflection properties (such as sheet metal) absorb a relatively small fraction of energy, while objects that have low reflection characteristics (such as water) absorb a relatively high proportion of the incident energy.

The sensors in remote sensing are in most cases not perfectly aligned with the energy source, so the received reflection signal comes from the diffused energy due to surface roughness of the object; surface roughness depends on the height variations of the object compared to the incident energy wavelength. Thus, the reflectance of an object depends strongly on its roughness compared to the incident wavelength.

The proportion of incident energy absorbed is subsequently radiated and is quantified by the spectral emissivity of the object (ref. section 2.3); in Fig. 2.4 spectral emissivities are shown for a blackbody (fictitious body that has zero reflectance), a graybody (fictitious body that has constant emissivity values at all wavelengths) and a selective radiator (realistic body with variable emissivities with wavelength).

The proportion reflected is quantified by the spectral reflectance, i.e. the percentage of incident energy reflected from an object for any particular wavelength; in Fig. 2.5, typical spectral reflectance curves are shown for vegetation, soil and water.

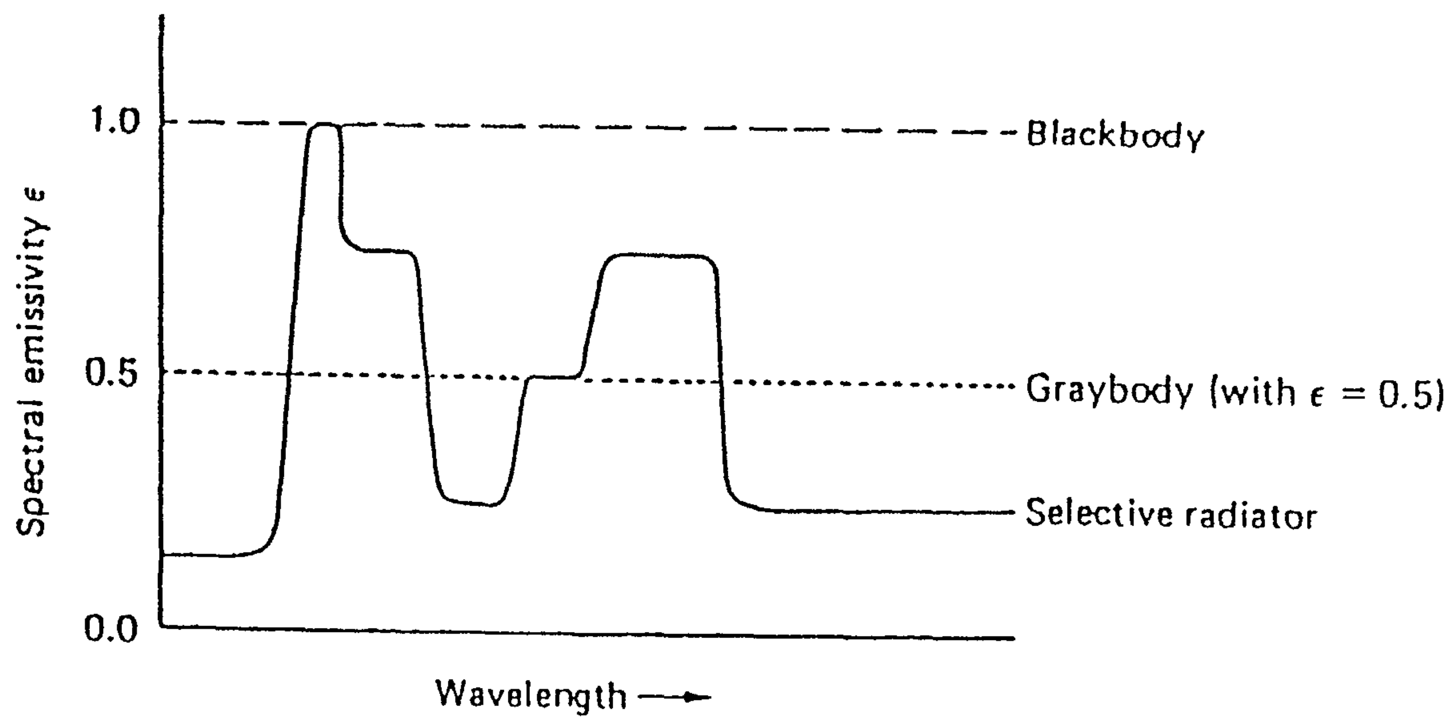

Fig. 2.4. Typical spectral emissivities for various radiators [36]

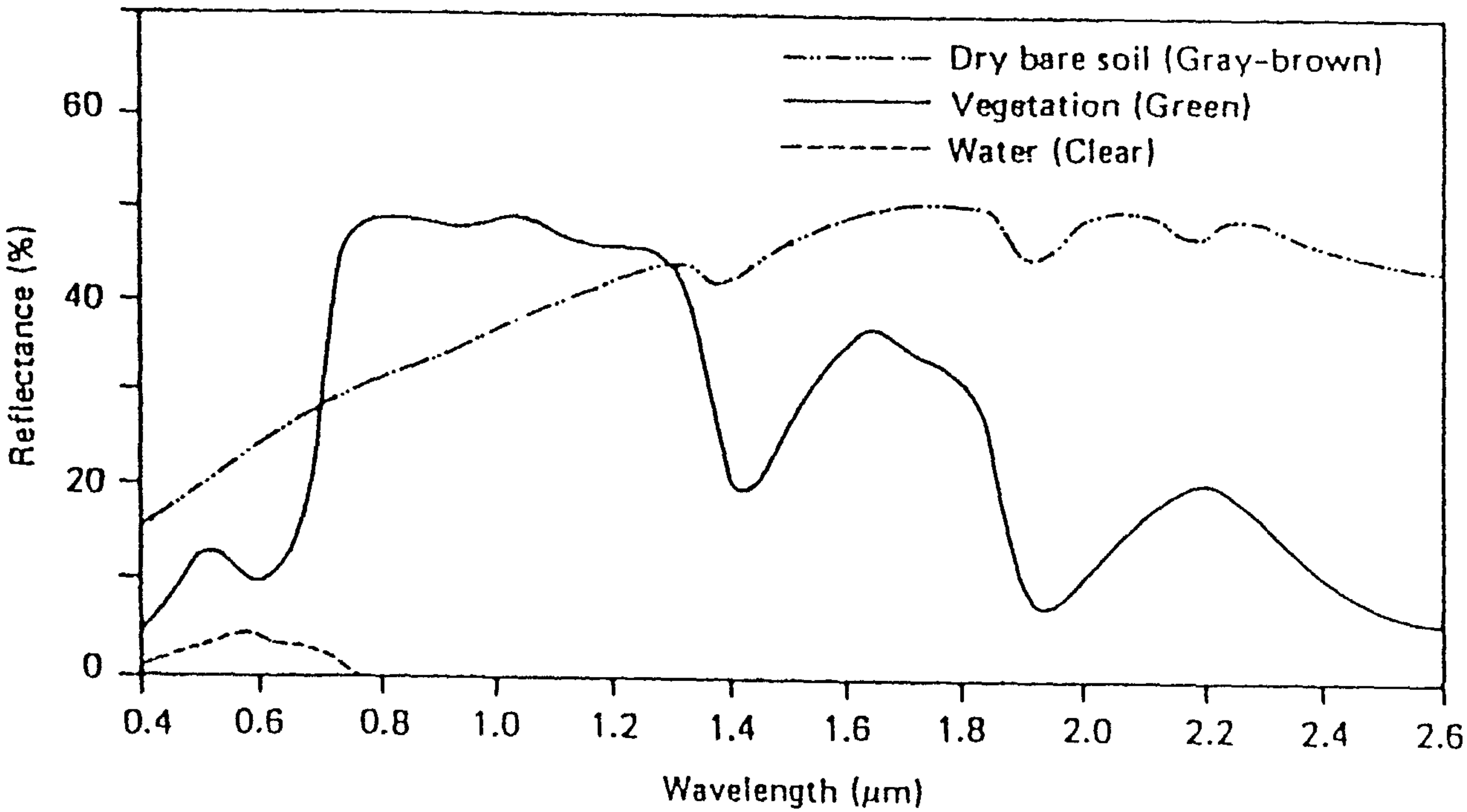

Fig. 2.5. Typical spectral reflectance curves for vegetation, soil and water [36]

The spectral emissivity and/or reflectance curves are intrinsic but non-unique features of surface bodies, i.e. each type of surface feature has certain spectral emissivity and/or reflectance curve characteristics, but very different bodies may have similar spectral curves. Thus, with the use of either the emissivity or the reflectance characteristics (or both), valuable information can be gained on the nature of the surface features of all kinds.

Finally, the phenomenon of fluorescence should be mentioned; it has been observed that some materials have the property of absorbing energy of one wavelength and subsequently re-emitting it in another wavelength; this can be of value for the identification of these materials and their concentrations on the surface.

2.6. Spectral Response Patterns

From the above it may be concluded that each type of surface feature has a certain electromagnetic response pattern (or spectral signature), which is characterised by its spectral composition of emitted radiation and spectral reflectance curve.

The spectral response patterns for any given surface feature depends on the condition of this feature and generally vary spatially (due to variable conditions) and temporally (e.g. variation of vegetation colour with season) within certain ranges. In Fig. 2.6, generalized spectral reflectance envelopes are shown for deciduous (broad-leaved) and coniferous (needle-bearing) trees.

2.7. Operation Concept

On the basis of the above, it can be concluded that information may be acquired from an airplane or satellite platform on characteristics of any given segment of the earth's surface by analysis of the spectral response patterns of radiation emission of the segment and/or reflectance to electromagnetic radiation from the sun or any

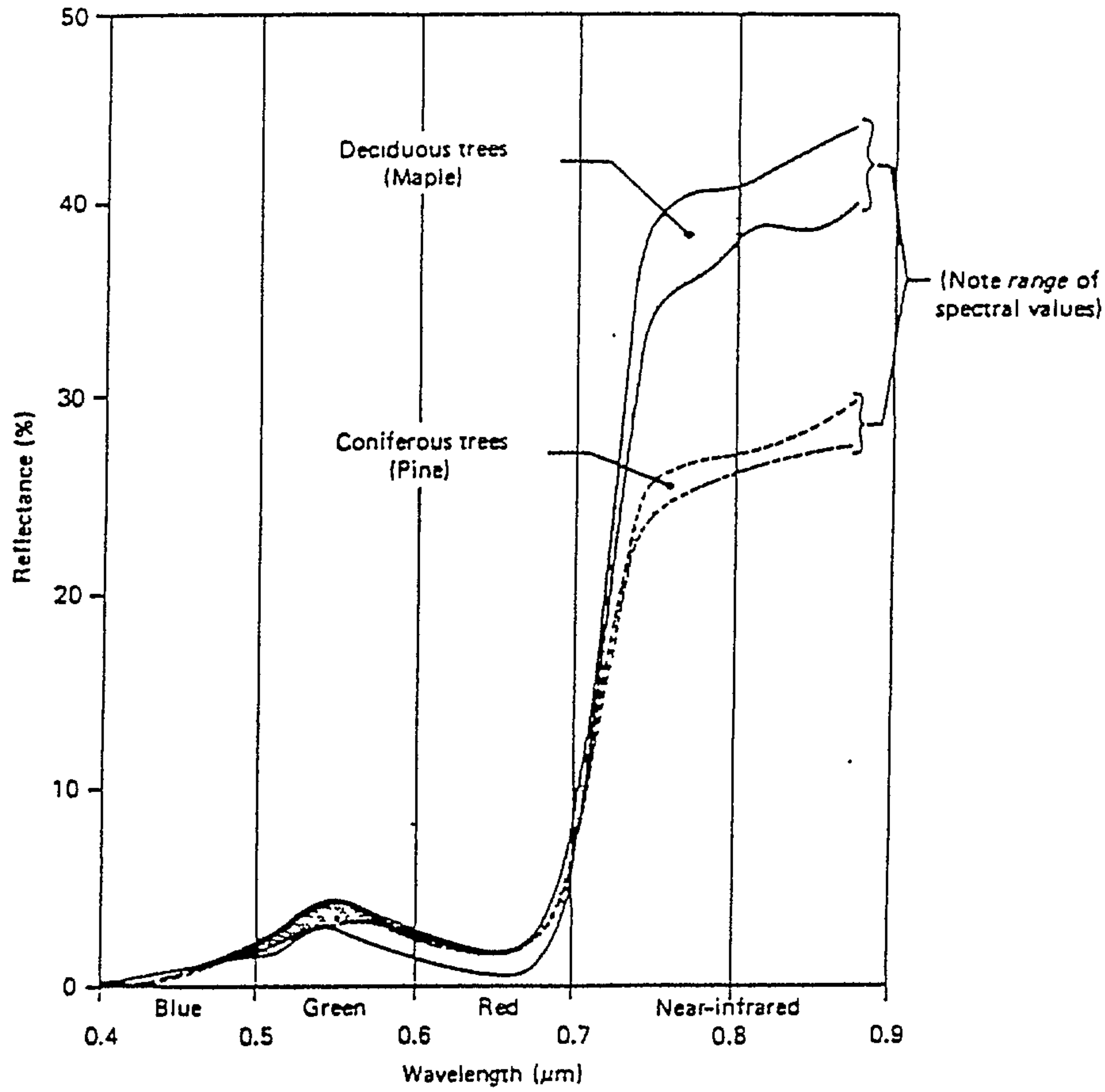

Fig. 2.6. Generalized spectral reflectance envelopes for deciduous and coniferous trees [36]

other artificial source, taking into account of the energy interactions of the atmosphere.

The above constitutes the basic operational concept of remote sensing. Clearly, the method has a significant potential for rapid collection of synoptic information about surface features of the earth. Moreover, repetitive applications can yield the temporal development of these surface features (such as crop production or dispersion of pollution), which is in itself of major significance.

Taking into account the wavelength ranges where the sun's and the earth's energy is emitted (ref. section 2.3), it may be concluded that:

- for wavelength ranges up to 8µm, where the sun's energy is dominant, reflectance of the sun's radiation is mainly detectable[2]
- for wavelengths between 8µm and 14µm, where earth's energy is most intensive, both emitted and reflected energy are recorded; the reflected energy is much less than the emitted energy in that range, so the emitted energy is mainly detected
- for wavelengths above 1000µm, the energies from the sun and earth are very small; practically only emitted energy from the earth is detectable

By combining the above conclusions with the observations on ranges of atmospheric transmittance (ref. section 2.4), it can be concluded that detection of reflected energy from the sun or emitted energy from the earth is most effective in the following ranges of the electromagnetic spectrum:

- the 0.3µm to 1.2µm (UV, visible and near-IR) range, where reflected energy is detectable
- the 3µm to 5µm (mid-IR) range, where reflected energy is detectable
- the 8µm to 14µm (thermal IR) range, where mainly the emitted energy is detectable,
- the 1mm to about 1m (microwave) range, where the emitted extremely low earth radiation is detectable.

[2] Also, the emission of very hot objects on the earth's surface (e.g. lava flows) is detectable.

In addition to monitoring the naturally occuring electromagnetic energy, it is also possible to generate electromagnetic energy of selected wavelengths, direct it to the earth's surface and record the reflectance characteristics; the sensors of this type are called active sensors, as opposed to passive sensors which measure natural electromagnetic energy.

Active sensors can theoretically operate at wavelengths corresponding to all the atmospheric windows, i.e.

- from 0.3μm to 1.2μm, i.e. in the UV, visible and near-IR ranges,
- from 3μm to 5μm (mid-IR range)
- from 8μm to 14μm (thermal IR range)
- from 1000μm (or 1mm) upwards up to about 1m (microwave range).

2.8. Operational Features

The main elements of a remote sensing system thus include:

- a platform of appropriate height above the target area; the most common are airplanes and satellites
- an energy source, natural (e.g. sun, earth) or artificial on the platform and
- one or more sensors to receive the emitted and/or reflected radiation on the platform.

Two principal classes of sensors are distinguished, namely passive and active. Passive sensors are receptive of emitted radiation from the earth or reflected radiation from the sun. Active sensors, on the other hand, include an artificial electromagnetic energy source.

There are various types of sensors, with different spectral sensitivities, i.e. each sensor can receive electromagnetic waves with wavelengths within certain ranges; these are discussed in section 2.2.

Sensor reception is limited by its resolution, i.e. its ability to distinguish small features, which depends on the altitude of operation and the type and characteristics of the sensor; the

theoretical limit to spatial resolution is defined by the ratio of wavelength of the radiation to the aperture of the sensing instrument, i.e. operational wavelength is a determining factor.

Information is collected in an analog manner (e.g. photographs) or in a digital manner; in the latter case, the electromagnetic image of a surface area, for any given frequency, is broken down into a set of discrete segments (i.e. pixels) characterised by the value of radiation recorded for each of them (digital number).

2.9. Interpretation of Images

For information to be gained about features of the surface, the images received remotely require appropriate interpretation. This is where most of the difficulty in application of remote sensing is encountered, because of:

(a) The amount of information to be processed is very large. For each segment, the analysis should be performed on essentially a spectral basis (i.e. considering the response to all frequencies) if any results are to be obtained; spectral emission and reflection ranges should be applied and atmospheric interactions taken into account.

(b) There are no unique spectral characteristics for features of the earth's surface; thus, for each particular application, information has to be obtained at ground level about the spectral characteristics of the features to be remotely sensed.

(c) Spectral characteristics do not uniquely define features or conditions of the earth's surface. i.e. features of very different character may have similar spectral characteristics. Thus, the application of remote sensing requires appropriate selection of sensors and careful calibration/verification of the method.

(d) The interactions of the emitted or reflected electromagnetic waves with the atmosphere are not unique or completely clear; this introduces an additional variance in the results of image interpretation.

From the above it may be concluded that careful and extensive processing of data is required in order to extract reliable information about features on the earth's surface. Thus digital recording of images, which facilitates processing of the image by computer, can substantially improve the accuracy and rate of interpretation.

In any case it should be clarified that the application of remote sensing should always be complemented by reference data, i.e. measurements or observations about the objects, areas and phenomena that are being sensed remotely, in order to aid in the analysis and interpretation of remotely sensed data and to calibrate/validate the information process.

2.10. Conclusions

The electromagnertic reflectance and emission properties of surface features can efficiently provide useful and spatially synoptic information about their characteristics. Sources of electromagnetic energy that can be used for remote sensing are:

- the sun's energy reflected from earth's surface ,
- the energy emitted from the earth, and
- generated energy from active sensors.

Remote sensing operations may be carried from any platform above the earth; airplanes and satellites are most common.

The application of remote sensing should always be complemented by reference data for the analysis and interpretation of remotely sensed data.

3. PRINCIPAL SENSOR TYPES

3.1. General

As was discussed in section 2.7, detection by passive sensors of reflected energy from the sun or emitted energy from the earth is most effective in the following ranges of the electromagnetic spectrum:

- the 0.3μm to 1.2μm (UV, visible and near-IR) range, where reflected energy is detectable
- the 3μm to 5μm (mid-IR) range, where reflected energy is detectable
- the 8μm to 14μm (thermal IR) range, where mainly the emitted energy is detectable,
- the 1mm to about 1m (microwave) range, where the emitted extremely low earth radiation is detectable.

In addition, detection by active sensors of the reflected energy from the earth can be effected at wavelengths corresponding to all the atmospheric windows, i.e.

- from 0.3μm to 1.2μm, i.e. in the UV, visible and near-IR ranges,
- from 3μm to 5μm (mid-IR range)
- from 8μm to 14μm (thermal IR range)
- from 1000μm (or 1mm) upwards up to about 1m (microwave range).

There are various types of sensors for the above ranges, with different spectral sensitivities, i.e. each sensor can receive electromagnetic waves with wavelengths within certain ranges. The principal types of passive and active remote sensing systems are discussed in the next sections.

3.2. Principal Sensor Types

The main types of passive sensors are:

(a) **Photographic Systems and Nonphotographic Cameras**, which are passive sensors in the 0.3μm to 0.9μm (UV, visible and near-IR) range and can detect only reflected energy.

(b) **Thermal Radiometers & Scanners**, which are passive sensors in the 3μm to 14μm (mid-IR and thermal IR) range and can detect reflected energy in the 3μm to 5μm (mid-IR) range and mainly emitted energy in the 8μm to 14μm (thermal IR) range.

(c) **Multispectral Scanners**, which are passive sensors in the 0.3μm to 14μm (UV, visible, near-IR, mid-IR and thermal IR) range and can detect reflected energy in the 0.3μm to 5μm range and emitted energy in the 8μm to 14μm (thermal IR) range.

(d) **Microwave Radiometers & Scanners**, which are passive sensors in the 1mm to 30cm (shorter microwave) range and can detect the extremely low levels of emitted energy from the earth.

The main types of active sensors are:

(a) **Radars** (for Radio Detection and Ranging), which are active sensors in the 1mm to 1m (microwave) range and can detect reflected energy from the surface of the earth.

(b) **Lidars** (for Light Detection and Ranging), which are active sensors in the 0.3μm to 1μm (UV, visible and near-IR) range and can detect reflected energy from the surface of the earth.

In the following sections, the above sensor types are discussed in more detail.

3.3. Photographic Systems and Nonphotographic Cameras

3.3.1. General

The sensitivity of these sensors ranges from 0.3μm to 0.9μm, i.e. from the ultraviolet (UV) band, through the visible band and into the near-infrared (near-IR) section.

3.3.2. Recording Method

3.3.2.1. Photographic systems

Photographic systems are among the most common, versatile and economical forms of remote sensing. The basic recording mechanism is photochemical; the presentation is on a still image (called photograph). There are two principal classes of film, depending on their spectral sensitivity:

(a) Films sensitive to wavelengths up to 0.7μm; this includes black & white panchromatic film and normal colour film.

(b) Films sensitive to wavelengths up to 0.9μm; this includes infrared sensitive black & white film and colour infrared film.

The colour films, consist of a set of layers, each one of which is sensitive to a certain colour (e.g. magenta dye layer that controls green colour, sensitive for wavelengths between 0.45μm and 0.6μm); usually, three colours are used to compose the photographs, namely blue, green and red.

Colour infrared films also have three layers, but the sensitivity of the layers is extended more to cover the increased range, so the correspondence of colour of the image with visible colour becomes weak; the result is a "false-colour" film, which is something like a colour-coded film, in which each of the three main colours of the image represent specific wavelengths in the visible and near-IR ranges (blue images result from objects primarily reflecting green light, green images result from objects primarily reflecting red light and red images result from objects primarily reflecting near-IR electromagnetic waves).

The usefulness of filters should be mentioned; filters can screen out ranges of wavelengths, thus resulting in a clearer view of the remaining wavelengths; this can be especially useful to amplify differences of surface features whose response patterns are similar in part of the range, e.g. in Fig. 3.0.

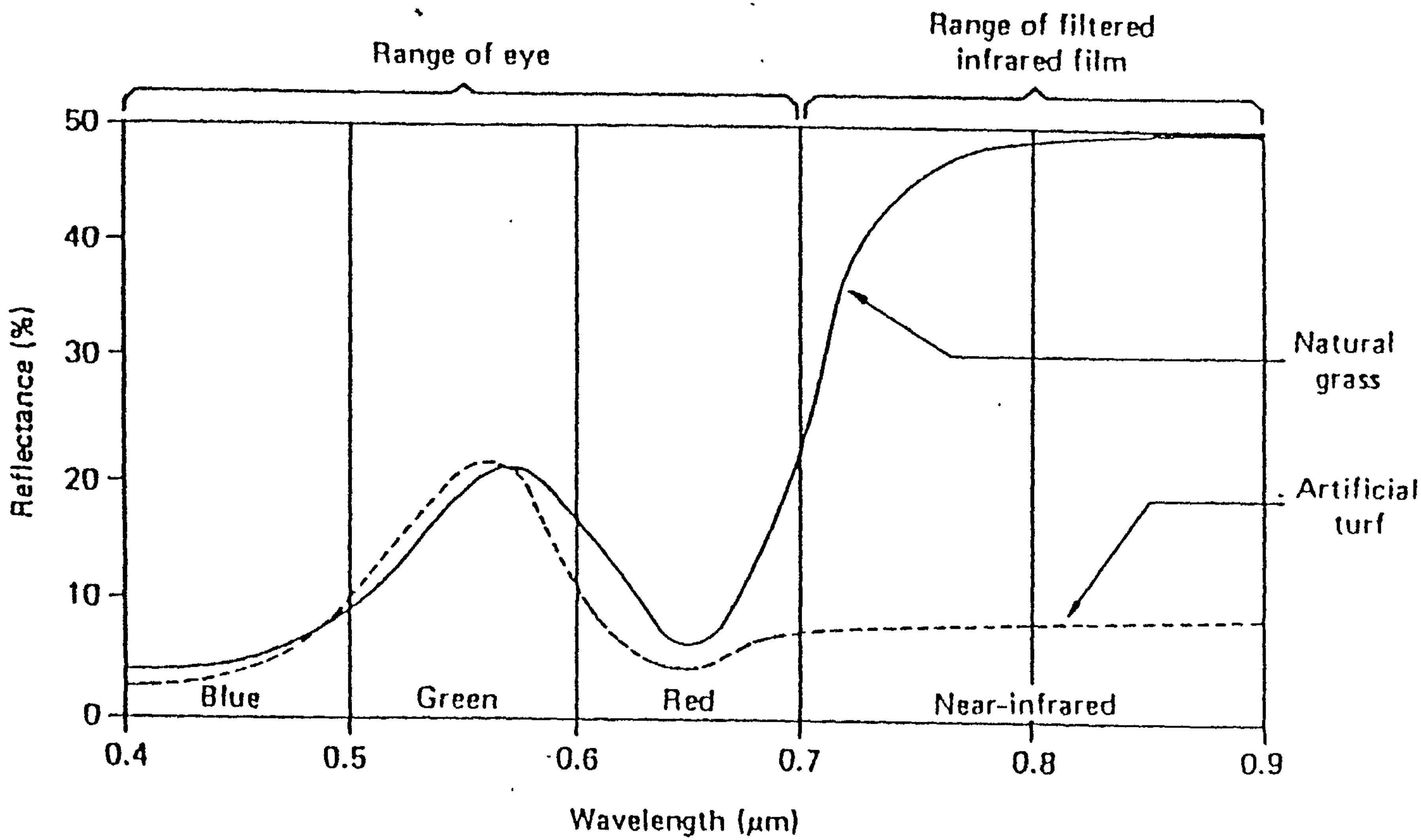

Fig. 3.0. Generalized spectral reflectance curves for natual grass and artificial turf [36]

3.3.2.2. Nonphotographic Cameras

The basic recording mechanism in this case are light-sensitive detectors that generate electrical signals which are stored on a medium other than photographic film (e.g. magnetic tape, computer disk); for visual analysis, the output may be displayed as an image on film. The most common types of sensors are solid-state array cameras and video recorders.

Solid-state array cameras use one dimensional or two dimensional arrays of microelectronic silicon chips that produce charges when light strikes the surface, of magnitude proportional to the light intensity and exposure time; because of their sensitivity, these sensors are capable of recording a wider range of light intensities than photographic film.

One-dimensional arrays consist of a few thousand elements and are moved perpendicular to their axis or rotated to record a two-dimensional images. Two-dimensional array consist of a few hundred to few thousand elements on each side; no movement relative to the image is required. The **High Resolution Visible (HRV)** instruments of the SPOT programme are sensors of this type.

Video cameras use either solid-state array cameras or vidicon (television) cameras and generate standard television signal output. The number of lines per image frame is usually 485 (U.S. and Japan industry standard), with 300 to 600 pixels for each line. Scanning of even-numbered lines and odd-numbered lines is made consecutively so that, if there is significant motion, the quality of the image is retained by half the lines.

The main advantages of video recording are that the image can be viewed while recorded, immediate analysis after recording is possible and the recorded information is amenable to processing by computer. The principal disadvantages of video recording are lower resolution, slower recording (i.e. less image accuracy). Thus, video recording is more suitable to applications where timeliness of data processing is

more important than resolution & accuracy of image, such as crop disease inventory, oil spill propagation etc.

3.3.3. Interpretation

Interpretations may take place at a number of levels of complexity, from the simple recognition of objects on the earth's surface to the derivation of detailed information. A systematic study of aerial photographs usually involves several characteristics of features shown in the photograph, such as:

- shape of objects,
- size of objects,
- pattern (i.e. spatial arrangement of objects),
- tone (i.e. relative brightness or colour),
- texture (i.e. frequency of tonal change on photographic image),
- shadows of objects

The above characteristics can be used for the identification of objects shown in the photographs. The identification of objects in remote sensing photography is usually performed visually without the use of computers, since synthetic judgment is extensively required. Computers are sometimes used to aid visual interpretation: the photograph is viewed through a video camera, which digitizes the information in the process and can communicate it to a computer, which can process the information accordingly, i.e. adapt the scale, enhance the tones. This can be particularly useful for overlaying of images and/or maps of different scales.

The tone of objects/regions in the photograph can however also provide invaluable information for the quantification of ground features, e.g. the extent of dispersion of suspended solids in the sea from a river delta.

For the use of tone for the quantification of ground features, the following are necessary:

(a) accurate measurement of the tonal value of points/areas of the image, and

(b) establishment of a quantitative relationship between the tonal values on the image and the ground intensity of the phenomenon, with due regard for level of illumination (and possible variation across the image), atmospheric interactions etc.

The accurate measurement of the tonal values is performed by densitometers; the tonal values can be manually recorded for particular points or automatically stored in arrays in computers for later processing.

The establishment of a quantitative relationship between the ground intensity and tonal values is possible with the measurement in-situ of the ground intensity at selected points which can be identified on the photograph and correlated with the tonal values obtained at those points. The correlation of these ground intensities with tonal values can then be interpolated/ extrapolated over the whole tonal range, taking into account the film characteristics (exposure-density relationship) and atmospheric interactions.

Computers are extensively used for such applications, since the volume of information is too large to be handled by individuals and since the process requires less synthetic judgement than that for the identification of objects.

3.3.4. Applications

Photographic systems can successfully record reflected electromagnetic waves in the upper UV, visible and near-IR range. Since surface features have discernibly different reflectance characteristics in this range, photographic systems can be very useful in the identification of these features and even intensities of surface phenomena. However, it is clear that photography cannot by its nature be used to detect temperature differences[1].

[1] with the exception of very high temperatures, where some emitted energy can be found in the range of sensitivity of photography

The applications of photographic systems are extensive and include diverse aspects such as:

- topographic mapping
- geologic and soil mapping
- crop type classification, crop condition assessment and crop yield estimation
- tree species identification, tree condition assessment etc.
- urban planning (population estimates, traffic studies, urban change detection etc.)
- water pollution detection and lake eutrophication assessment
- wetland mapping & inventory
- wildlife censusing
- environmental management (sanitary & hazardous waste landfill site selection, emergency response coordination etc.)

Resolution capabilities of such sensors can be very high, in the order of a 15-20m from satellite platforms and much less from airborne sensors (depending on flight altitude). The applicability of photography for the evaluation of water quality parameters will be discussed in the following chapter.

3.4. Thermal Radiometers & Scanners

3.4.1. General

As discussed in section 3.2 above, thermal radiometers & scanners are passive sensors that can detect:

- mainly emitted energy in the 8μm to 14μm (thermal IR) range, and
- reflected energy in the 3μm to 5μm (mid-IR) range.

The principal application of thermal sensors is for detection of the emitted energy in the thermal IR range. Thermal sensors are capable of operating in darkness and are in fact most effective just before dawn, when the thermal emissions are stabilised (during daylight, the effects of solar energy on earth's surface may contaminate the information).

3.4.2. Recording Method

The basic recording mechanism of thermal sensors is electronic and its output can be recorded in a number of ways (e.g. magnetic tape, computer disks). For visual analysis, the output may be displayed as an image on film. Two broad categories of detectors are in use, namely **thermal detectors** (bolometers) and **quantum (or photon) detectors**.

Thermal detectors are devices that change their temperature in response to absorption of incident radiation and whose electrical resistance depends on temperature; thus differences in incident radiation are translated into variations of electrical current intensity. Such detector systems are extremely accurate but have a relatively slow response time.

Quantum detectors operate on the principle of direct interaction of between photons of radiation and the energy levels of electrical charge carriers within the detector material. Their operating temperature is in the order of -200 to -250^{0}c; for operation, the detectors are encased in dewar flasks containing liquid nitrogen or helium. These detectors have very rapid response times.

The most basic thermal detection instrument is the **thermal radiometer**, which measures the thermal radiation from a point on the earth's surface (actually a small area). **Thermal scanners** basically contain a thermal radiometer that scans the earth's surface for the production of two-dimensional thermal images. Data are normally recorded digitally on tape, which later facilitates computer processing.

3.4.3. Interpretation

In the thermal range, where emitted energy is mainly measured, the emissivities of different objects can be considered to be constant, i.e. not wavelength dependent. Thus, by correlation of the emitted

energy with the known emissivity values for various materials in that wavelength, the thermal image can be appropriately interpreted.

Complications may arise from atmospheric effects on the measured energies. Thus, even in the atmospheric window 8μm to 14μm, partial absorption can occur; also, ground signals may be attenuated by scattering in the presence of suspended particles. Finally, gases and suspended particles in the atmosphere may emit a radiation of their own, adding to the radiation sensed. The total result of the above effects will depend on the atmospheric conditions during sensing and can bias the sensor output upwards or downwards by as much as 2^oC. Various methods are used to compensate for these atmospheric effects depending on the prevailing conditions, in order to improve the sensing accuracy.

3.4.4. Applications

As discussed above, thermal sensors mainly detect emitted energy in the 8μm to 14μm thermal range, which can be very useful for identification of surface features and intensities of surface phenomena.

Successful applications of thermal scanning include diverse tasks such as:
- determination of rock type & structure
- location of geologic faults
- mapping soil type and moisture
- locating irrigation canal leaks
- determining thermal characteristics of volcanoes
- evaluation of evapo-transpiration from vegetation
- locating cold water & hot springs
- determining the extent & characteristics of thermal plumes in lakes and rivers
- determining the extent of active forest fires

Resolution capabilities of such sensors are medium, in the order of 80 to 120m from satellite platforms and much less from airborne

sensors (depending on flight altitude). The potential for applications of thermal scanning for the evaluation of water quality parameters is discussed in the following chapter.

3.5. Multispectral Scanning

3.5.1. General

As discussed in section 3.2 above, multispectral scanners (MSS) are passive sensors that can detect:

- reflected energy in the 0.3μm to 5μm (UV, visible, near-IR, mid-IR) range and
- emitted energy in the 8μm to 14μm (thermal IR) range.

From the above it may be observed that multispectral scanners cover the operating range of both the photographic & nonphotographic cameras and the thermal scanners; this is accomplished by the electronic register of the energy in a number of narrow spectral bands that cover the above range simultaneously.

Thus, multispectral scanners are among the most useful remote sensing devices, since they register energy simultaneously over a large range of the electromagnetic spectrum in a uniform & consistent manner, producing digital output that facilitates computer processing. Moreover, the thermal range of multispectral scanners is also operable in night time, as for thermal sensors.

3.5.2. Recording Method

In the multispectral scanners the incoming energy is separated into several spectral components (bands), which are then simultaneously recorded by several independent detectors (usually about 5-10 in number).

The signal separation is achieved either by appropriate filters in front of each detector or by a combination of a dichroic grating and

a prism (diffraction grating). The dichroic grating separates the thermal from the non-thermal wavelengths and disperses the thermal component of the signal into its constituent wavelengths, while the prism splits the non-thermal energy into a continuous range from the UV wavelength, through the visible wavelength and up to the near-IR wavelength; thus, by placing the various detectors in the appropriate positions, the various energy bands can be recorded.

The scanning process thus yields two-dimensional images for each band recorded. The MSS data can be stored either on an analog recorder, if the data analysis is pictorially oriented, or on a high-density digital tape, if the data will be computer processed.

Sensors of this type are:
- the **Landsat MSS** and **Thematic Mapper** of the Landsat programme,
- the **Advanced Very High Resolution Radiometer (AVHRR)** of the NOAA
- the **Multispectral Electro-optical Imaging Spectrometer (MEIS)** developed for the Canada Center for Remote Sensing, which is an airborne pushbroom CCD system, built in 1982, operating in 5 bands with future expansion to 8 bands including infrared,
- the **Compact Airborne Spectrographic Imager (CASI)**, a pushbroom imager developed by Itres Research Ltd., which has the feature of selecting up to 39 equally spaced points across the field of view and then extracting the spectral signature for each selected point in the scene.

The band width of multispectral scanners is usually a few tenths of a µm, e.g. band 7 of the Thematic Mapper has a width of 0.27µm. This band width, narrow though it is, may be too coarse for the detection of some surface features that have diagnostic absorption of reflection characteristics over very narrow wavelength intervals in the order of a few hundredths of a µm. For such applications, **imaging spectrometers** were developed.

Imaging spectrometers are essentially multispectral scanners with many bands (in the order of a few hundred) and very narrow widths (in the order of 0.01µm). Sensors of this type are:

- the **Coastal Zone Colour Scanner (CZCS)** of the NIMBUS programme with 6 channels,
- the **Airborne Imaging Spectrometer (AIS)** with 128 channels,
- the **Airborne Visible-Infrared Imaging Spectrometer (AVIRIS)** with 224 channels,
- the **Shuttle Imaging Spectrometer Experiment (SISEX)** to be deployed in the early 1990's with 128 channels and
- the **High Resolution Imaging Spectrometer (HIRIS)** to be deployed in the mid-1990's in the framework of the Earth Observing System (EOS).

3.5.3. Interpretation

The images obtained in the non-thermal bands are interpreted in the manner described in section 3.3.3 for the photographic systems, while the images in the thermal bands are processed and interpreted in the manner described in section 3.4.3 for the thermal scanners.

The great advantage of multispectral scanners is that the images obtained in the various bands are directly comparable to each other, so all bands can consistently contribute to the interpretation effort.

3.5.4. Applications

The applications of multispectral scanning include the applications of both the photographic systems and the thermal scanners discussed previously, i.e.:
- topographic mapping
- geologic and soil mapping
- location of geologic faults
- locating cold water & hot springs
- determining thermal characteristics of volcanoes
- mapping soil type and moisture
- locating irrigation canal leaks

- crop type classification, crop condition assessment and crop yield estimation
- evaluation of evapo-transpiration from vegetation
- tree species identification, tree condition assessment etc.
- determining the extent of active forest fires
- urban planning (population estimates, traffic studies, urban change detection etc.)
- water pollution detection and lake eutrophication assessment
- wetland mapping & inventory
- wildlife censusing
- environmental management (sanitary & hazardous waste landfill site selection, emergency response coordination etc.)
- determining the extent & characteristics of thermal plumes in lakes and rivers

Resolution capabilities of such sensors can be high to medium (depending on the wavelength of operation), i.e. for satellite platforms in the order of a 20m for the UV, visible and near-IR ranges and 100m for the thermal-IR range; resolutions are much less for airborne sensors, depending on flight altitude. The potential for applications of thermal scanning for the evaluation of water quality parameters is discussed in the following chapter.

3.6. Microwave Radiometers & Scanners

3.6.1. General

Microwaves have the significant feature that they have relatively small atmospheric interaction and can penetrate the atmosphere under virtually all conditions, in day and night. Moreover, since these sensors utilise microwave wavelengths that are a few thousand times larger than those of the visible or thermal ranges, they contribute a drastically different perception of the surface features, which can be a valuable source of information.

Microwave radiometers & scanners are passive sensors in the 1mm to 30cm (shorter microwave) range that can detect the extremely low

levels of energy emitted and reflected from the earth; in addition, energy transmitted to the surface from subsurface features may contribute to the signal. Thus the intensity of the sensed energy depends in general on the emittance, reflectance and transmittance properties of the surface features; these properties are in turn influenced by the electrical, chemical and textural characteristics of the surface feature as well as its size, shape and angle of view.

The electrical characteristics of the surface features, which influence the microwave signals received, are clearly indicative of water or moisture: in the microwave range of the electromagnetic spectrum, water has very different characteristics than the other materials and clearly shows up, even as moisture, in microwave images.

3.6.2. Recording Method

The incoming signal, which normally carries a lot of noise because of its low intensity, is continuously compared to a calibration reference signal by means of a microwave switch which permits rapid alternate sampling between the incoming and reference signal; the difference of the two signals is then amplified and stored.

Microwave radiometers are non-imaging one dimensional recordings, while microwave scanners apply mechanical or electronic scanning or use multiple antenna arrays for the generation of two-dimensional images. Because of the low intensity of the received signal, the beamwidth of the sensor is necessarily broadened, necessarily increasing the width scanned on the surface, i.e. the resolution of the sensor. The **Scanning Multifrequency Microwave radiometer (SMMR)** of the NIMBUS-7 satellite and the **Scatterometer** are sensors of this type.

The microwave range is presently very broad; it has been observed that the response of surface features to microwaves as well as the atmospheric interaction are not uniform over this whole range. For

greater application of this range in the electromagnetic spectrum, multispectral microwave sensing appears to be an attractive approach.

3.6.3. Interpretation

The interpretation of the received signals is more complex than that for the other sensors, because of (i) the variety of possible sources and (ii) the low intensity of the received signals. The phenomena influencing the response of surface features to microwave energy are not very much understood; thus, the application of passive microwave sensors to remote sensing is still in the developmental stage.

However, certain surface characteristics, such as oil pollution on the water surface, presence of water or moisture, subsurface ocean currents etc. can be determined with passive microwave images.

3.6.4. Applications

Passive microwave sensing is most useful in oceanography; indicative applications are:
- monitoring sea ice,
- monitoring currents
- detection of oil slicks

In addition, waterways and soil moisture can be detected because of the sensitivity of this type of sensors to water.

The resolution of the system depends on the distance and beamwidth of the pulse, which in turn is inversely proportional to the length of the antenna. For sensors operating in the microwave region, spatial resolution capabilities are three to four orders of magnitude less than those of sensors operating in the visible region, for the same antenna size. Physical limitations on antenna size thus restrict the resolution capabilities of sensors operating in the microwave region to a few Km for satellite platforms; airborne platforms can achieve much higher resolutions of course, depending on flight altitude.

3.7. Radars

3.7.1. General

As discussed in section 3.2, radars (for Radio Detection and Ranging) are active sensors in the 1mm to 1m (microwave) range and can detect reflected energy from the surface of the earth.

As discussed in the previous section, microwaves have relatively small atmospheric interaction, can penetrate the atmosphere under virtually all conditions in day and night and contribute a vary different perception of the surface features than the photographic systems or the thermal scanners.

3.7.2. Recording Method

These systems use radio waves, which are transmitted in short bursts (or pulses) in the direction of interest and recording the origin and strength of the reflected (echoed) wave.

The most common wavelength bands used in radar pulse transmissions are:

Band K_a: 0.75cm - 1.10cm
Band K : 1.10cm - 1.67cm
Band K_u: 1.67cm - 2.40cm
Band X : 2.40cm - 3.75cm
Band C : 3.75cm - 7.50cm
Band S : 7.50cm - 15.0cm
Band L : 15.0cm - 30.0cm
Band P : 30.0cm - 100.cm

In addition to the wavelength, radar pulses are characterised by their polarisation, i.e. whether the electromagnetic wave is transmitted in one plane or not and which plane (horizontal,H or vertical, V); moreover, sensors are capable of transmitting in one plane and recieving in another.

Radar systems may or may not produce images and may be mounted on aircraft or satellites. Common forms of radar are the **Doppler Radar** used to measure vehicle speeds, which is a non-imaging system and the **Plan Position Indicator (PPI) Radar**, which have circular display screens on which a radial sweep indicates the position and nature of radar echoes and are extensively used in weather forecasting, traffic control and navigation. Most airborne radar remote sensing has been performed with antennas fitted below the aircraft and pointing sideways; these systems are commonly referred to as **Side-Looking Radar (SLR)** or **Side-Looking Airborne Radar (SLAR)**.

The physical limitations on resolution capabilities mentioned in section 3.6.4 above have been overcome by the **Synthetic Aperture Radar (SAR)**, which has the unique capability of superimposing the reflected signals received from a limited-size antenna as it travels along its path, thus operating with an equivalent antenna with a length of hundreds of meters or few kilometers; this results in resolution capabilities in the order of 20 to 30m from satellite platforms, i.e. orders of magnitude below the resolution capabilites of conventional radars.

The **Altimeter** is a radar for the study of ocean topography and for making topographical measurements over ice.

3.7.3. Interpretation

Though the development of data acquisition and processing techniques for radar systems have developed to an adequate level, the interpretation of radar images is still not in an operational level for many applications; for example, the factors influencing radar reflectivity have not as yet been fully clarified.

The signal return times are influenced directly by the distance from the source, while the signal intensities are influenced by incidence angle, roughness of the terrain (compared to the incident wavelength) and electrical characteristics of the surface features; the more

inclined the surface is in relation to the signal and the smoother the surface texture compared to the incident wavelength, the lower will its return echo be. The electrical characteristics of most natural materials in the microwave region are similar, with the exception of water, which has very different characteristics; thus water or moisture can be clearly discerned in radar images.

On the basis of the above it can be concluded that radar systems can be used to effectively detect topographical features, surface roughness (in the order of millimeters to meters) and presence of water or moisture.

3.7.4. Applications

in the previous section it was concluded that radar systems can be used to effectively detect topographical features, surface roughness (in the order of millimeters to meters) and presence of water or moisture. Major applications of radar systems to date include:
- land mapping (incl. surface features)
- study of sea-bottom topography
- mapping of water resources
- soil and geologic mapping
- mapping of geologic structures (faults, joints etc.)
- mapping vegetation types (natural vegetations & crops)
- monitoring of wind, wave and ice conditions

Moreover, it should be noted the radar can be invaluable for sensing of remote areas where cloud cover is permanent or near-permanent and other sensors cannot be effectively employed.

The resolution of conventional active microwave sensors is in the order of few Km; synthetic aperture radars however have much higher resolution capabilities, in the order of a 20 to 30m from satellite platforms, ref. section 3.7.2 above.

3.8. Lidars and laser fluorosensors

3.8.1. General

Lidars (for Light Detection and Ranging) and laser fluorosensors are active sensors in the 0.4μm to 0.7μm (visible) range and can detect reflected energy from the surface of the earth. The energy source is a laser light (i.e. a very narrow and uniform bean of light), which is reflected from the surface.

3.8.2. Recording Method

The outgoing signal is sent in pulses, which reflect on the surface and return. The light sensor of **lidars** can then register the response time, which depends mainly on the distance, and the intensity of the signal, which depends on the reflectance characteristics.

As in the case of other sensors, there are point detectors, which produce a one-dimensional response strip along the flight path and scanners, which scan in a transverse direction to the flight path for the generation of two-dimensional images.

As discussed in section 2.5, some materials have the property of absorbing energy of one wavelength and subsequently re-emitting it in another wavelength, i.e. exhibit fluorescence. The laser-induced (LIF) properties of surface features can be measured with **Laser Fluorosensors**, which employ a single-channel laser source and a multiple channel receivers to record the spectral characteristics of the resulting fluorescense emitted by the objects.

The platforms from which such sensors can be operated for remote sensing of the surface of the earth are airborne, for reasons of signal strength; satellite platforms have been used only for monitoring of phenomena in the atmosphere.

3.8.3. *Interpretation*

The method is still under development; lidars are most commonly used for the measurement of distance, which can be very accurate and whose interpretation is relatively straightforward.

The intensity and response characteristics of laser-induced fluorescence can be effectively used, with in-situ calibration, for the evaluation of concentrations of chlorophyll and pollutants in the top layer of water bodies.

3.8.4. Applications

The main applications to date of lidars relate to distance measurements, such as measurement of tree height in remote areas (as a difference between the distance of the tree canopy and the ground level obtained by chance penetration of some pulses).

Laser fluorosensors have been used to:
- map chlorophyll concentrations,
- detect and classify oil slicks and measure oil thickness, and
- detect other water pollutants in the top layer of water bodies.

Resolution capabilities are in the order of a few meters, for airborne sensors at altitudes of a few hundred meters, and less for higher altitudes.

3.9. Conclusions

A broad range of sophisticated equipment is curently available for the collection & processing of information regarding surface features by remote sensing; the interpretation however of the collected information, which essentially amounts to correlations of colours and tonal values with in-situ concentrations, still lags behind the sophistication of the equipment, especially for microwave sensors.

4. OPERATIONAL PLATFORMS

4.1. General

Current operational platforms include aircraft with flight capacities in various altitudes and satellites, ref. section 2.8.

Operational and research satellite systems are now providing global synoptic measurements of climatic and environmental parameters that relate the major processes of the oceans and atmosphere. Satellite platforms, though necessarily more distant (and thus less detailed) are usually more cost-effective for any given application, since they are permanently in orbit and serve many applications. In fact, the satellite industry is currently entering a commercial maturity phase, with several competitors in the market and application of economic viability criteria for most enterprises.

For needs at higher spectral and spatial resolution, aircraft platforms may be used. These can obtain remotely sensed measurements which are more amenable to coordination with surface measurements under the existing weather or other environmental conditions. Various kind of aircraft can be used ranging from low flying aircraft, which can provide vary clear and detailed images of local areas, to high flying aircraft, which produce more synoptic images with smaller resolutions.

Finally, conventional platforms, such as ships and buoys, may be used in combinations with satellite data-relay systems to transmit data to other locations for analysis and interpretation.

In the following, the available satellite platforms will be discussed in more detail.

4.2. Satellite platform types

Satellites can generally be divided in to two groups according to the type of orbit, namely polar orbiting and geostationary.

(a) Polar Orbiting Satellites

The polar or near polar satellites, which are typically at an altitude between 800 Km and 1,000 Km and take about 105 minutes to circle the earth, pass near both North and South Poles during a single orbit; orbits shift meridians however, in order to cover the full surface of earth. The orbit parameters can be selected in such a way that, within 24 hours, a full circle of meridians has been covered; thus any particular location can be viewed twice every 24 hours, once when the satellite is travelling from north to south and once again when it is travelling from south to north. Most polar orbiting satellites are given a sun synchronous orbit, in which the satellite crosses the equator at the same local solar time at each pass throughout the year, which has the advantages of regularity of data sampling, uniformity of solar irradiation on the earth surface and optimal use of solar panels.

(b) Geostationary Satellites

A geostationary satellite remains stationary relative to the earth and so always views the same area of the earth's surface. This is achieved by putting it into an orbit above the equator at a height such that it takes precisely 24 hours to complete one orbit and so matches exactly the rotation rate of the earth. The necessary height is about 36,000 Km, many times greater than the altitude of the polar orbiting satellites. From its high vantage point, the satellite can view a circular area representing more than a quarter of the earth's surface, although towards the edges of the area the view becomes too oblique to be useful.

Thus, geostationary satellites have limited spatial capabilities, but excellent temporal capabilities, since they are capable of giving a continuous time series of observations at a point. Polar orbiting satellites on the other hand have good spatial capabilites, but with low temporal sampling frequencies; the precise capability depends on the details of the orbit and particularly the repeat of the ground track and the swath width of the sensor.

4.3. Operational Satellite Programmes

4.3.1. General

There are currently a number of satellites in operational status and several others are planned to be deployed in the near future. Most of the satellites are deployed in the framework of particular programmes, which accumulate developments and establish a continuity of the supplied information. The programmes were originally scientific, with strong national support. In the last few years however, a clear commercial trend is developing, with emphasis on customer service and economic viability.

In the following sections, detailed information is presented on the presently operational satellite programmes. This information has been compiled from (i) study of published information on the subject and (ii) replies to a questionnaire which was sent out to all major satellite organisations; organisations that replied include the European Space Agency (ESA), the Earth Observation Satellite Company (EOSAT), the National Environmental Satellite, Data and Information Service of the National Oceanic and Atmospheric Administration (NOAA), the Remote Sensing Technology Center of Japan, the Canada Centre for Remote Sensing, Itres Research Inc. and Radarsat International.

4.3.2. Landsat Programme

The Landsat programme is currently operated by the U.S. Earth Observation Satellite Company (EOSAT). Current operational satelllites are (i) **LANDSAT-4**, placed in orbit in 1982, (ii) **LANDSAT-5**, placed in orbit in 1984 and (iii) **LANDSAT-6**, placed in orbit in 1991; all satellites have been placed in near-polar sun-synchronous orbits at an altitudes of 705Km. Their cycles have duration of about 16 days. The orbits of the two first satellites

have a phase difference of 8 days, in order to achieve an 8-day alternate revisit cycle.

The sensors onboard these satellites include:

(a) the Landsat MSS, on the LANDSAT-4 and LANDSAT-5 satellites, with a resolution of about 80m (which can vary significantly with the reflectance/emission contrast) and 4 channels, which can operate simultaneously:

Band 1: 0.50 - 0.60μm (visible)
Band 2: 0.60 - 0.70μm (visible)
Band 3: 0.70 - 0.80μm (near-IR)
Band 4: 0.80 - 1.10μm (near-IR)

For the MSS carried by Landsat, the images are produced by reflecting the radiance, recorded from 80m wide scan lines on the Earth's surface, to detectors onboard the satellite. The instantaneous field of view of the sensor divides the scan line into units in order to measure radiance for a particular area. As the satellite moves forward quickly, it is necessary to record 6 scan lines at once; 24 detectors are thus required, 6 in each of the 4 channels. The recorded radiance is then converted into a continuous electrical signal by each of the detectors. This is then sampled at fixed time intervals and converted to a 6 bit number, which is either recorded onto a magnetic tape or transmitted to Earth where it is rescaled to a 7 bit number.

The conversion of the electrical signal to a discrete digital number (ie the sampling procedure), is not the same as the scanning rate. As a result, the pixels will correspond to an area of 56m by 80m but the spatial resolution of the image is the 80m by 80m area sampled by the instantaneous field of view of the sensor. The pixels which comprise a Landsat MSS image are consequently rectangular in shape.

The data is available in the form of two-dimensional images at a cost of about $0.03/km^2, for a scale of 1:250.000.

(b) the Thematic Mapper (TM), on the LANDSAT-4 and LANDSAT-5 satellites, which is a highly advanced multispectral scanner, with 7 channels and a resolution of about 30m for all bands except band 6 which has a resolution of 120m. The 7 bands of this sensor, which can operate simultaneously, are:

Band 1: 0.45 - 0.52μm (visible)
Band 2: 0.52 - 0.60μm (visible)
Band 3: 0.63 - 0.69μm (visible)
Band 4: 0.76 - 0.90μm (near-IR)
Band 5: 1.55 - 1.75μm (mid-IR)
Band 6: 10.40 - 12.50μm (thermal IR)
Band 7: 2.08 - 2.35μm (mid-IR)

The recordings are digital, so data are available in the form of two-dimensional images or digital tapes. The cost of the data is about $0.1/km^2 for a standard colour print, for scales of 1:250.000 to 1:1,000,000.

(c) the Enhanced Thematic Mapper (ETM), on the LANDSAT-6, similar to the previous TM's but which will incorporate an additional panchromatic band in the range of 0.50 - 0.90μm with a ground resolution of 15m. The 8 bands of this sensor, which can operate simultaneously, are:

Band 1: 0.45 - 0.52μm (visible)
Band 2: 0.52 - 0.60μm (visible)
Band 3: 0.63 - 0.69μm (visible)
Band 4: 0.76 - 0.90μm (near-IR)
Band 5: 1.55 - 1.75μm (mid-IR)
Band 6: 10.40 - 12.50μm (thermal IR)
Band 7: 2.08 - 2.35μm (mid-IR)
Band P: 0.50 - 0.90μm (visible & near-IR)

The alternative downlink modes for these bands are (i) Bands 1 to 7, or (ii) Bands P,4,5,6 or (iii) Bands P,4,6,7. The recordings are digital, so data are available in the form of two-dimensional

images or digital tapes. The cost of the data from this sensor was not available.

In the near future LANDSAT-7 is planned to be deployed, with the same orbit characteristics; the year of launch and sensor payload have not been finalised yet. The following sensors have been developed however, and could be deployed on this satellite, in addition to a possible MSS and/or ETM sensor:

(a) The **Enhanced Thematic Mapper with Thermal Infrared Option (ETM-TIR)**, with following bands:

0.45 - 0.52μm with 30m resolution
0.52 - 0.60μm with 30m resolution
0.63 - 0.69μm with 30m resolution
0.76 - 0.90μm with 30m resolution
0.50 - 0.90μm with 15m resolution
1.55 - 1.75μm with 30m resolution
2.08 - 2.35μm with 30m resolution
3.53 - 3.93μm with 120m resolution
8.20 - 8.75μm with 60m resolution
8.75 - 9.30μm with 60m resolution
10.2 - 11.0μm with 60m resolution
11.0 - 11.8μm with 60m resolution

Six alternative downlink modes are planned for these bands. The recordings will be digital, so data will be available in the form of two-dimensional images or digital tapes.

(b) The **Sea Wide Field Sensor (SeaWiFS)** is a new imaging spectrometer in development for the detection of ocean colour and temperature data with resolutions of 1.13Km for local area coverage and 4.5Km for global area coverage in the following bands:

Band 1: 0.443 - 0.453μm (visible)
Band 2: 0.490 - 0.510μm (visible)
Band 3: 0.555 - 0.575μm (visible)

Band 4: 0.655 - 0.675μm (visible)
Band 5: 0.745 - 0.785μm (near-IR)
Band 6: 0.843 - 0.887μm (near-IR)
Band 7: 10.5 - 11.5μm (thermal IR)
Band 8: 11.5 - 12.5μm (thermal IR)

(c) Also under consideration is **MSA (ALS)**, a new instrument that will have 32 spectral bands in the visible, near-IR and mid-IR ranges with 20m and 10m spatial resolution and the ability for side viewing that can appreciably decrease revisit times.

4.3.3. SPOT Programme

The SPOT Programme (Systeme Pour l'Observation de la Terre) is operated by the French Centre National d'Etudes Spatiales (CNES). It includes the **SPOT-1** and **SPOT-2** satellites, placed in near-polar sun-synchronous orbit at an altitude of 830 Km in 1986 and 1990 respectively. SPOT-1 was temporarily decomissioned in December 1989 and was reactivated in March 1992. The return cycles for these satellites are 26 days, but sites can be revisited at 3-4 day intervals or less (depending on their location), thanks to a very efficient pointable optical system that permits side viewing; the pointable optical system also facilitates stereoscopic coverage, which can be obtained by viewing one area in successive orbits.

The satellites are equipped with two parallel independently programmable **High Resolution Visible (HRV)** instruments, which are nonphotographic cameras with two alternative operational modes:

(a) Panchromatic (black & white) mode, with a resolution of 10m and an operating range of:

0.51 - 0.73μm (visible)

(b) Multispectral (colour infrared) mode, with a resolution of 20m and following operating ranges:

0.50 - 0.59μm (visible)
0.61 - 0.68μm (visible)
0.79 - 0.89μm (near-IR)

The above information is available in analog and digital form. To become a usable product, the raw SPOT data, as recorded by the receiving stations, must be preprocessed. This operation is performed by the Space Imagery Rectification Centers (CRIS), which carry out radiometric and geometric corrections according to four designated levels. The cost of Spot data ranges from about $\$0.05/Km^2$ for a standard colour print with a scale of 1:100,000 to about $\$0.1/Km^2$ for a similar print of 1:50,000 scale.

Satellites that are planned for deployment in the near future are SPOT-3 (to be launched in mid-1993), SPOT-4 (to be launched in 1995) and SPOT-5 (to be launched around 1999), with similar orbit characterisitcs. SPOT-3 is planned to have an identical payload be as SPOT-1 and SPOT-2, while SPOT-4 and SPOT-5 satellites are planned to have:

- **High Resolution in the Visible and Infrared range (HRVIR)** sensors, i.e. HRV sensors with the range 0.61-0.68μm in the panchromatic mode (instead of the current 0.51-0.73μm) and an additional band in the 1.58 to 1.75μm (mid-IR) range with a resolution of 20m, and

- possibly (to be finalised at a later date) the new wide-view low-resolution instrument **VEGETATION (VGT)**, which will facilitate biomass estimation and estimation of the proportion of a given species in large homogeneous regions; according to available informaiton, this sensor will probably have five ranges including the HRV bands currently used, the mid-IR planned and a blue band at 0.43 to 0.47μm for oceanographic studies; the resolution will be 1Km for regional mode and 4Km for worldwide mode.

4.3.4. NOAA Programme

The NOAA programme of the U.S. National Oceanographic and Atmospheric Administration (NOAA), currently includes the following satellites:

- **NOAA-9**, which was launched 1984 in sun-synchronous orbit at an altidude of at an altitude of 833-870Km and has been on standby status since 1988,
- **NOAA-11**, which was launched in 1988 in sun-synchronous orbit at an altidude of at an altitude of 833-870Km and is operational since then, and
- **NOAA-D** (or NOAA-12), which was launched in 1991 in sun-synchronous orbit at an altidude of at an altitude of 833Km and is operational since then.

The repeat cycle for the first two is 11 days; the repeat cycle for the NOAA-D was not specified, but is expected to be approximately the same.

The programme objective is primarily to collect meteorological information, sea ice monitoring, snow cover mapping, mapping of vegetation & other land features. The satellite payload includes various sensors (SBUV - Solar Backscatter Ultra-Violet Spectrometer, MSU - Mechanical Scanning Unit, SEM - Space Environmental Monitor etc.), most of which are designed for monitoring of the atmosphere; at the time of compilation of this report, detailed information was available only for the AVHRR and HIRS sensors described below.

(a) **Advanced Very High Resolution Radiometer (AVHRR)** sensors, which are essentially multispectral scanners operating with a ground resolution of 1.1Km in the following ranges (for NOAA-9, and NOAA-11):

Channel 1: 0.58 - 0.68μm (visual)
Channel 2: 0.72 - 1.18μm (near-IR)
Channel 3: 3.55 - 3.93μm (thermal IR)
Channel 4: 10.3 - 11.3μm (thermal IR)
Channel 5: 11.5 - 12.5μm (thermal IR)

(b) **High Resolution Infrared Sounder (HIRS):** This is an infrared radiometer with a resolution of 17.4km, operating in the following ranges:

Channels 1-5:	14.95 - 13.97µm
Channels 6-7:	13.64 - 13.35µm
Channel 8:	11.11µm
Channel 9:	9.71µm
Channels 10-12:	8.16 - 6.72µm
Channels 13-17:	4.57 - 4.24µm
Channels 18-20:	4.00 - 0.069µm

Satellites planned for future deployment are NOAA-I for 1992, NOAA-J for 1993, NOAA-K for 1995, NOAA-L for 1996 and NOAA-M for December 1995; these satellites are scheduled to carry essentially the same equipment, with minor variations in channel ranges and minor improvements. For the AVHRR on board the NOAA-K, L and M, operation will be carried out in the following ranges:

Channel 1:	0.58 - 0.68µm
Channel 2:	0.72 - 1.00µm
Channel 3A:	1.58 - 1.64µm
Channel 3B:	3.55 - 3.93µm
Channel 4:	10.3 - 11.3µm
Channel 5:	11.5 - 12.5µm

4.3.5. TIROS-N Programme

The TIROS programme of the U.S. National Oceanographic and Atmospheric Administration (NOAA), operates with the **TIROS-N** satellite, in sun-synchronous orbit at an altitude of about 850Km and a repeat cycle of 11 days. This was launched in 1978 and is presently not operational. The TIROS-N satellite is equipped with an **Advanced Very High Resolution Radiometer (AVHRR)** sensor, a **High Resolution Infrared Sounder (HIRS)** and similar other sensors (MSU, SEM etc.) as described in the previous section.

4.3.6. NIMBUS Programme

The NIMBUS satellite is the principal meteorological research and development satellite operated by NASA. The currently operational satellite is **NIMBUS-7**, which was launched into a sun-synchronous orbit in 1978, with an altitude of 955km and a repeat cycle of 6 days. The satellite is equipped with several sensors mostly related to monitoring of the atmospere (LIMS - Limb Infra-red Monitor of the Stratosphere, SAMS - Stratospheric and Mesospheric Sounder, SAM II - Stratospheric Aerosol Measurement II, SBUV/TOMS - Solar Backscatter Ultra-Violet/ Total Ozone Mapping Spectrometer etr.) and:

(a) **Coastal Zone Colour Scanner (CZCS)**, which has been retired since December 1986, is an imaging spectrometer operating with a resolution of 800m in six bands:

Channel 1: 0.43µm - 0.45µm (visible)
Channel 2: 0.51µm - 0.53µm (visibile)
Channel 3: 0.54µm - 0.56µm (visible)
Channel 4: 0.66µm - 0.68µm (visible)
Channel 5: 0.70µm - 0.80µm (near-IR)
Channel 6: 10.5µm - 12.5µm (thermal IR)

The very narrow visible bands were selected in order to enhance the discrimination of very subtle water colour differences and have been used to map phytoplankton concentrations and inorganic suspended solids (refer to sections 6.2.1. and 6.2.4.). Data was available in photogrphic and digital form.

(b) **Scanning Multifrequency Microwave Radiometer (SMMR)**, shut-down since July 1988, which is a passive microwave sensor operating in the following 5 frequencies:

6.6 GHz with 148 Km resolution
10 GHz with 91 Km resolution
18 GHz with 55 Km resolution
21 GHz with 46 Km resolution
37 GHz with 27 Km resolution

4.3.7. Canadian Radarsat Programme

RADARSAT, due to be launched in 1994, is the first Canadian remote sensing satellite. It is being constructed by the Canadian Space Agency in cooperation with the U.S., Provincial Governments and the private sector. NASA will provide launch services and will operate a data receiving station in Alaska in exchange for radar data for its research programs. RADARSAT is scheduled for a five year life span; the selected orbit is a sun-synchronous, dawn-dusk polar orbit, with a 24 day repeat cycle. The orbital altitude is scheduled to be 793-821km and the inclination to be 98.6^{0}.

The satellite will be equipped with a **Synthetic Aperture Radar (SAR)**; this will operate in the C-band (wavelength of 5.7cm) with a resolution of 28m and with a steering capability of 25 degrees, which will facilitate the creation of stereographic images. This SAR will provide the first stereogeological map of the world.

4.3.8 METEOSAT and MOP Programmes

The METEOSAT programme is operated by the European Space Agency (ESA). The programme commenced in 1977 with the launching of satellite **METEOSAT-1**, which was followed by **METEOSAT-2** in 1981 and **METEOSAT-3** in 1988, all in geostationary orbit with the objective of collecting meteorological information. METEOSAT-1 was decommisioned in 1983 while METEOSAT-2 was planned for decomissioning in December 1991. Thus, the only currently operational satellite is METEOSAT-3, which is planned for decomissioning in 1993.

The METEOSAT satellites were equipped with multispectral scanners operating in the following ranges:

Band 1: 0.4µm - 1.1µm (visible & near IR)
Band 2: 5.7µm - 7.1µm (thermal IR)
Band 3: 10.0µm - 12.5µm (thermal IR)

Of the above, the visible & near-IR band operated with a resolution of 2.5Km and the other two with a resolution of 5Km.

The Meteorological Operational Programme (MOP) will provide operational continuity to the METEOSAT programme until approximately 1995. The first and second of the operational series of satellites, **MOP-1** (or METEOSAT-4) and **MOP-2** were launched in 1989 and 1990 correspondingly with corresponding decomissioning dates of 1994 and 1995 respectively; the **MOP-3** satellite is scheduled for launching at the end of 1993 with a five year life span; all MOP satellites are equipped with multispectral scanners similar to those of the METEOSAT programme.

4.3.9. ERS Programme

The European Remote Sensing (ERS) Programme is operated by the European Space Agency (ESA). The programme commenced in 1991 with the **ERS-1** satellite, placed in sun synchronous orbit at an altidude of about 800Km, with a repeat cycle of 3, 35 and 176 days. A 3 day cycle has been chosen for the commissioning phase on account of the fact that it provides frequent revisiting of calibration sites under constant geometrical and illumination conditions. The limitations of the latter cycle are the restricted global coverage for the imaging SAR and the wide separation of the Radar Altimeter tracks. The advantage of the 35 day cycle is that it provides global SAR imaging,while the 176 day cycle is favoured for measurement of the mean sea surface and ocean geoid due to the very high density of the altimeter tracks. The overall programme objective is to provide high resolution images of coastal zones, land areas and sea surface conditions.

The satellite will be equipped with the following main sensors:

(a) **Active Microwave Instrumentation (AMI)**, which operates in in the C-band (wavelength of 5.6cm) in three different modes, namely:

- Synthetic Aperture Radar (SAR) Image Mode that will obtain strips of high resolution imagery 100km wide to the right of the satellite track. Imagery is built up from the strength of the return signals, which depend mainly on the roughness and dielectric properties of the surface. The mid-swath incidence angle of the radar in normal operation is 23^{o}. However, the satellite has a "roll-tilt" capability which makes it possible to operate at 35º incidence angle on an experimental basis.
- Synthetic Aperture Radar (SAR) Wave Mode produces 5km x 5km images at intervals of 200km along track. It provides a global sampling of wave spectra suitable for the measurement of the wavelengths and directions of the main ocean swell wave systems.
- Wind Scatterometer Mode, a microwave system for measurement of wind velocity over the oceans with a spatial resolution of 50Km and an accuracy of 2m/sec in wind speed and 20 degrees in wind direction. The operation of the wind scatterometer can be interleaved with SAR wave mode for the acquisition of wind/wave data. Data for the whole orbit can be stored on the satellite before downloading to a receiving station.

(b) **Radar Altimeter (RA)**, is a nadir pointing pulse radar designed to measure the echoes from ocean and ice surfaces. In ocean mode (operating wavelength of 2.15 to 2.20cm), it will be used to measure wave height, wind speed and sea-surface elevation. In ice mode (operating wavelength of 2.17 to 2.18cm), the instrument operates with a coarser resolution to determine ice sheet surface topography, ice types and sea/ice boundaries.

(c) **Along Track Scanning Radiometer (ATSR)**, which consists of two principal components, the infrared radiometer with four channels at 1.6μm, 3.7μm, 11μm and 12μm and a spatial resolution of 1Km and the microwave radiometer with two channels at 0.82cm and 1.26cm. The main role of the above instruments is to provide precise orbit determinations for the referencing of height measurements made by the Radar Altimeter.

The sensor is designed to provide sea surface temperature with an accuracy of $0.5^{o}K$ with a spatial resolution of 50Km and in conditions of up to 50% cloud cover, images of surface temperature with 1Km resolution and a relative accuracy of $1^{o}K$ etc.

In addition to the above, the **Precise Range and Range-Rate Equipment (PRARE)**, and a **Laser Retroflector** are deployed for the accurate determination of the satellite position.

Future plans include deployment of ERS-2 in 1993. This will be set in sun-synchronous orbit at an altitude of about 800km with a repeat cycle of 3 days. Its sensor payload will include an AMI (including SAR and Scatterometer), a RA and an ATSR.

4.3.10. JERS Programme

The Japanse Satellite Programme is operated by the National Space Development Agency of Japan (NASDA), which cooperates for processing and interpretation of the data with the Remote Sensing Technology Center (RESTEC). The first satellite, **JERS-1**, is scheduled to be placed in sun-synchronous orbit in early 1992 at an altidude of approximately 570Km, with a recurrent period of 44 days.

The satellite will be equipped with:

(a) a **Synthetic aperture radar (SAR)** that will operate in the L-band (wavelength of 23.5cm) with a resolution of 18m, and

(b) high resolution **Optical Sensors (OPS)** with a spatial resolution of 18 X 24m in 8 bands:

Band 1: 0.52 - 0.60μm (visible)
Band 2: 0.63 - 0.69μm (visible)
Band 3: 0.76 - 0.86μm (visible, nadir viewing)
Band 4: 0.76 - 0.86μm (visible, forward viewing)
Band 5: 1.60 - 1.71μm (visible)

Band 6: 2.01 - 2.12μm (visible)
Band 7: 2.13 - 2.25μm (visible)
Band 8: 2.27 - 2.40μm (visible)

Bands 3 and 4, of the same wavelength, are use to generate stereographic images.

4.3.11. MOS Programme

The Marine Observation Satellite (MOS) Programme of Japan is operated by the National Space Development Agency of Japan (NASDA), which cooperates for processing and interpretation of the data with the Remote Sensing Technology Center (RESTEC). The first satellite, **MOS-1**, was deployed in February 1987, in sun-synchronous orbit at an altitude of 909 km and a repeat cycle of 17 days. This was shortly followed by the second satellite **MOS-1B**, with the same orbit characteristics. Both satellites have a sensor payload including MESSR, VTIR, and MSR, the characterisitcs of which were not available at the time of preparation of this report.

4.3.12. ADEOS Programme

The ADEOS Programme of Japan is also operated by the National Space Development Agency of Japan (NASDA), which cooperates for processing and interpretation of the data with the Remote Sensing Technology Center (RESTEC). The **ADEOS** satellite is scheduled for launching in 1993 in sun-synchronous orbit at an altitude of about 800Km with a repeat cycle of 41 days.

The satellite will be equipped with the following two core sensors, which are presently under development:

(a) **Ocean Colour and Temperature Scanner (OCTS)**, a multispectral scanner, operating under 12 bands with a resolution of 700m and a swath width of 1400km. The detailed band description is shown below (for all bands described, resolution is 700m):

Band No. 1: 0.402 - 0.422μm
Band No. 2: 0.433 - 0.453μm
Band No. 3: 0.480 - 0.500μm
Band No. 4: 0.510 - 0.530μm
Band No. 5: 0.555 - 0.575μm
Band No. 6: 0.655 - 0.675μm
Band No. 7: 0.745 - 0.785μm
Band No. 8: 0.845 - 0.885μm
Band No. 9: 3.550 - 3.850μm
Band No.10: 8.250 - 8.750μm
Band No.11: 10.500 - 11.500μm
Band No.12: 11.500 - 12.500μm

(b) **Advanced Visible and Near-infrared Radiometer (AVNIR)**, which operates under 5 bands with a sensor swath width of 80km and a resolution of 16m for bands 1-4 and 8m for band 5.

Band No. 1: 0.42 - 0.50μm
Band No. 2: 0.52 - 0.60μm
Band No. 3: 0.61 - 0.69μm
Band No. 4: 0.76 - 0.89μm
Band No. 5: 0.52 - 0.69μm (panchromatic)

The sensor will have a tilting capability for bands 1 to 5.

4.3.13. Resurs-O and Resurs-F Programmes

The Resurs Programmes are operated by the USSR Research Centre for Earth Exploration (URCERE), under the State Committee for Hydrometeorology (SCHM).

The first operational Resurs-O satellite was placed in sun synchronous orbit at an altitude of 650Km in April 1988.

This satellite is equipped with:

(a) **Multispectral Electronic Scanning System** with a resolution of 45m and 4 spectral bands:

0.50 - 0.60µm (visible)
0.60 - 0.70µm (visible)
0.70 - 0.80µm (near-IR)
0.80 - 0.90µm (near-IR)

(b) **Multispectral Conical Scanning System,** with two visible bands, two near-IR bands and one thermal IR band:

0.50 - 0.60µm (visible)
0.60 - 0.70µm (visible)
0.70 - 0.80µm (near-IR)
0.80 - 1.10µm (near-IR)
10.5 - 12.5µm (thermal IR)

The resolution for the visible and near-IR bands is 150m and for the mid-IR 600m.

An advanced version of this satellite was scheduled for deployment in 1990; it provides a 22.5m resolution in eight spectral bands.

The objective of the Resurs-F programme is to obtain photographs of the earth's surface. Satellites of this programme are apparently launched consecutively on a continuious basis to altitudes of 260 to 275Km and generally only remain in orbit for fourteen to sixteen days, in order to return the photographs to earth.

The satellites are equipped with a KFA-1000 camera (probably solid state) which is capable of taking multispectral images with resolutions of 5-10m.

4.3.14. Okean Programme

The Okean Programme is operated by the USSR Research Centre for Earth Exploration (URCERE). The first operational **Okean-1** satellite was placed in sun synchronous orbit at an altitude of 650Km in July 1988.

The satellite is equipped with:

(a) **Side-Looking Radar (SLR)**, with an operating wavelength of 3.15cm and a resolution of 1.5Km

(b) ***Scanning Microwave Radiometer (SHF)***, with an operating wavelength of 0.8cm and a resolution of 200m

(c) **Multispectral Medium Resolution Spectrometer (MSU-M)**, which is a multispectral scanner with a resolution of 1500m and 2 spectral bands:

0.55 - 0.70μm (visible)
0.70 - 1.00μm (near-IR)

One or two Okean satellites are scheduled to be launched each year. Future Okean satellites will include, in addition to the above sensors **Multispectral Low Resolution Spectrometers (MSU-L)**, with a resolution of 2Km and 4 spectral bands:

0.50 - 0.60μm (visible)
0.60 - 0.70μm (visible)
0.70 - 0.80μm (near-IR)
0.80 - 1.10μm (near-IR)

and **Multispectral Medium Resolution Corn-Field Scanners (MSU-K)**, with a resolution of 500m and 1 spectral band:

0.55 - 0.80μm (visible & near-IR)

Also, the SLR system of the 1993 Okean will have advanced resolution capabilities, in the order of 50m.

4.3.15. USSR Radarsat Programme

The USSR Radarsat Programme is operated by the USSR Research Centre for Earth Exploration (URCERE). The Radarsat satellite was placed in orbit at an altitude of 250-280Km; the satellite musy be boosted to higher altitude.

The satellite is equipped with a **Synthetic Aperture Radar** capable of 25 to 30m resolution.

4.3.16. Meteor 2 and Meteor 3 Programmes

The Meteor 2 & 3 Programmes are operated by the USSR Research Centre for Earth Exploration (URCERE). The objective of these programmes is to obtain meteorological information. The Meteor-2 programme maintains two or three satellites in orbit at all times in polar orbits and at altitudes of 950Km; the Meteor 3 programme has successfully launched satellite Meteor 3-2 in July 1988 and will eventually maintain two or three satellites in orbit at all times in polar orbits and at altitudes of 1200 to 1250Km.

The satellites are equipped with:

(a) **Scanning Televisions**, with a resolution of 2Km in the visible spectral range.

(b) **Multispectral Scanners** with various bands in the visible, near-IR and possibly thermal IR ranges.

The details of the deployed equipment could not be confirmed at the time of preparation of this report.

4.3.17. SKW Programme

The SKW Programme of China has launched several satellites equipped with remote sensing payloads. Data obtained from these misisons have been successfully used for mineral and petroleum exploration, coastal and ocean measurements, construction of harbours, cartographic and topographic survays, achaeological studies, revision of maps and agricultural surveys.

4.3.18. IRS Programme

The Indian Remote Sensing (IRS) Programme Satellite (IRS-1A) has been deployed in 1988 in a sun-synchronous orbit at an altitude of 904Km, with a repeat cycle of 22 days.

The satellite is equipped with **the Linear Imaging Self Scanning Sensors (LISS-I and LISS-II)**, which are nonphotographic cameras operating with 4 bands in the 0.45µm to 0.86µm spectral range with resolutions of 72.5m and 36.25m respectively.

The IRS-1 series will be continued and a new series, IRS-II, will follow up. Satellites scheduled for deplyment in the near future are:

- IRS-1B, which will be similar to IRS-1A, is scheduled for 1990-1991,
- IRS-1C & IRS-1D, which will be equipped with two multi-spectral cameras with 20m resolution in 3 bands in the visible and 1 in the near-IR range and a panchromatic camera with a resolution better than 10m; additionally, an optional experimental system to study vegetation and ocean-related phenomena using 6 narrow spectral bands. IRS-1C is scheduled to be deployed in 1992-1993 and IRS-1D in 1995-1996
- IRS-1E, an engineering version of the IRS-1 series which in addition to the LISS-I, will carry the Monocular Electro-Optical Stereo Scanner (MEOSS); this scanner will operate in the 0.57µm to 0.72µm spectral range, with a ground resolution of 78.8m square. IRS-1E is scheduled to be deployed in 1991-1992, i.e. after IRS-1B.

The IRS-II series of satellites will have a combination of optical payloads as in IRS-1C and IRS-1D and in addition microwave payloads such as synthetic aperture radar, altimeters, scetterometers and radiometers in a suitable combination to be finalised in the next few years.

4.3.19. SROSS Programme

The Stretched Rohni Satellite Series (SCOSS) of India is essentially of experimental nature; the third satellite of this series, SROSS-3, with the main objective of contributing to the understanding of the mechanisma of the ionosperic region of the atmosphere, is scheduled for launch in the early 1990's. The SROSS-4 satellite experiments will be aimed at studying the time variability and spectral characterisitcs of cosmic X-ray sources.

4.3.20. Earth Observation System (EOS)

This is the most ambitious remote sensing programme, which is international (involving cooperation of the U.S., Canada and Japan) and of multidisciplinary nature (for the collection of atmospheric, ocean and land surface data). It involves four polar platforms, two from NASA, one from the ESA and one from Japan, which will accomodate numerous instruments for simultaneous observations. The first of NASA's platforms is scheduled for launching in 1995, the ESA platform for 1997 and Japan's for 1998.

The sensors to be deployed in this programme are decribed below:

(A) U.S. PLATFORM

(a) **Moderate Resolution Imaging Spectrometer (MODIS),** for measurement of biological and physical processes on a 1Km X 1Km scale for the study of terrestrial, oceanic and atmosperic phenomena, including:
- MODIS-T, with a tilting capability and a 1Km resolution, which will accomodate 65 spectral bands in the 0.4μm to 1.04μm range

- MODIS-N with pixel sizes of 250m, 500m and 1Km. which wil accomodate 40 spectral bands in the ranges 0.47μm to 2.13μm, 3.7μm to 4.56μm and 6.7μm to 14.2μm.

(b) **High Resolution Imaging Spectrometer (HIRIS)**, is an imaging spectrometer providing highly programmable localized measurements of geological, biological & physical processes with a resolution of 30m and appreciable tilting capabilities; it will cover the ranges 0.4μm to 1.0μm and 1.0μm to 2.5μm in almost 200 spectral bands.

(c) **Synthetic Aperture Radar (SAR)**, which will operate on the L, C and X bands with resolutions varying between 20m and 200m, depending on the swath width.

(d) **Geodynamics Laser Ranging System (GLRS)**, which is a laser ranging system for the study of earth crust movements using arrays of reflecting targets on the ground, for the high-resolution altimetric profiling of ice sheets, land and cloud top surfaces. The system consistis of three major subsystems:
- a dual-mode laser ranging/altimetry subsystem,
- a high-speed high-accuracy optical tracking sunsystem, and
- an altitude determination subsystem.

(e) **Laser Atmospheric Wind Sounder (LAWS)**, which is a Doppler lidar system for direct tropospheric wind measurements in a grid spacing of 100Km at a height of 1Km and with an accuracy of 1m/sec.

(f) **Atmospheric Infrared Sounder (AIRS)**, an infrared sounder of atmosperic temperature, in 115 spectral bands in the 3μm to 5μm and 8μm to 17μm ranges, with a horizontal resolution of 50Km for most channels and 15Km for some selectedc channels and an accuracy of 1oK.

(g) **Advanced Microwave Sounding Unit (AMSU)**, which is a microwave radiometer providing measurements of temperature & humidity in twenty channels and is divided into two subsystems:

- AMSU-A, which primarily provides atmosperic temperature measurements from the surface up to 40Km in 12 channels between 0.34cm and 0.6cm (approx.) and in 15 channels between 0.95cm and 1.26cm, with a spatial resolution of 50Km and a temperature resolution of about 1oK, and
- AMSU-B, which primarily provides atmosperic humidity measurements in 3 channels near 0.16cm and 5 channels between 0.18cm and 0.34cm, with a spatial resolution of 50Km and a temperature resolution of about 1oK.

(h) **Advanced Medium Resolution Imaging Radiometer (AMRIR)**, an 11 channel visible/infrared radiometer for global measurement of cloud cover, atmospheric temperature & water vapour, sea surface temperature, snow & ice extent and vegetation cover and characteristics with a spatial resolution of 500m.

(i) **Global Ozone Monitoring Radiometer (GOMR)**, a dual instrument consisting of UV radiometer for total ozone measurement and IR radiometer for measurement of the vertical distribution of temperature and ozone. The UV radiometer will operate in 6 wavelengths between 0.305μm and 0.340μm with a spatial resolution of 43Km; the IR radiometer will operate in at least three channels between 6 and 18μm.

(j) **Space Environment Monitor (SEM)** for the monitoring of:
- the energy of electrons and protons in the 0.05keV to 20keV range,
- the energy of electrons and ions in the range from 30keV up to and exceeding 100keV,
- the ionospheric electric field of the magnetosphere, and
- the total electron content of the ionosphere.

(k) **Altimeter (ALT-1)**, a radar altimeter for the study of ocean topography and for making topographical measurements over ice, operating with a wavelength of 2.2cm.

(l) **Scatterometer (SCATT-1)**, a microwave system for the measurement of wind velocity over the oceans.

(m) **Earth Radiation Budget Instrument (ERBI)**, a multiple channel instrument for the measurement of earth's radiation budget on a regional, zonal and global scale, using selected fields of view; the instrument operates in the 0.2μm to 50μm range with selective filters.

(B) EUROPEAN PLATFORM

(a) **Medium-Resolution Imaging Spectrometer (MERIS)**, an imaging spectrometer primarily for global ocean colour monitoring in 9 bands selectable from a total of 60 bands in the spectral range of 0.4μm to 1.04μm, with a spatial resolution of 500m.

(b) **High-Resolution Imaging Spectrometer (HRIS)**, an imaging spectrometer for land and coastal applications in 10 bands selctable from 100 in the spectral range from 0.4μm to 2.5μm and a resolution of 20 to 50m.

(c) **Atmospheric Lidar (ATLID)**, a lidar for atmospheric research and pre-operational meteorology measuring cloud top height, atmospheric dicontinuities and aerosol layer distribution with a spatial resolution of 10 to 50Km horizontal & 100 to 500m vertical.

(d) **Scatterometer (SCATT-2)**, an active radar instrument for the measurement of syrace winds over the **ocean; the instrument** will probably operate with a wavelength of about 5.7cm with an accuracy for wind speed of about 10%.

(e) **Altimeter (ALT-2)**, which shall operate in two modes, namely:

- a radar altimeter mode, for the study of ocean and ice sheet topography with two operation wavelengths, one of 2.18cm and another to be determined and
- a passive microwave radiometer mode, for humidity correction.

The height resolution will be about 5cm.

(f) **Synthetic Aperture Radar, C-Band (SAR-C)** is a radar operating in the C-Band (i.e. with a wavelength of 5.66cm), for agriculture, forestry, land, ocean and sea ice studies with a spatial resolution of 10 to 200m.

(C) JAPANESE PLATFORM

(a) **Intermediate Thermal Infrared Radiometer (ITIR)**, a radiometer for the global observation of land surface under high resolution for the monitoring of non-reneawable resources, operating with 11 bands in the spectral ranges 0.85μm to 0.92μm, 1.60μm to 2.26μm and 3.53μm to 11.7μm, with a resolution of 15m in the near and short-wavelength IR and 60m in the thermal IR region.

(b) **Advanced Microwave Scanning Radiometer (AMSR)**, a microwave radiometer for the global observation of atmospheric water vapour, sea surface temperature and sea surface wind, operating in the 0.95cm, 1.26cm, 1.60cm, 2.81cm and 4.54cm wavelengths with a spatial resolution of 9 to 28Km and a temperature resolution better than 1^{o}K.

4.4. Conclusions

An appreciable number of remote sensing satellites have been deployed in the last decade; many more will be deployed in the coming decade, as the European Remote Sensing programme gets underway and several other countries such as China, India etc. increase their efforts.

Moreover, there is a clear trend towards commercialisation of the remote sensing programmes, with emphasis on customer service and economic viability of the operating organisations.

5. REMOTE SENSING POTENTIAL IN THE MARINE ENVIRONMENT

5.1. General

In this section, an examination of the effectiveness of remote sensing for assessment of water quality will be made, on the basis of the operational concepts presented in section 2 and the main types of sensors presently operational presented in section 3.

The principal types of sensors discussed in section 3 can be grouped into five major classes insofar as their operational wavelength and operation principle is concerned, namely:

(a) **Passive sensors operating in the ultraviolet, visible, and near-infrared range**, i.e. with wavelengths of 0.3μm to 1.2μm; sensors that operate in these ranges include Photographic Systems and Nonphotographic Cameras, Thermal Radiometers & Scanners and Multispectral Scanners.

(b) **Active sensors operating in the ultraviolet, visible, and near-infrared range**, i.e. with wavelengths of 0.3μm to 1.2μm, mostly by measurement of laser-induced fluorescence; Lidars are sensors of this group.

(c) **Passive sensors operating in the infrared range**, i.e. with wavelengths of 3μm to 14μm; sensors that operate in these ranges include Thermal Radiometers & Scanners and Multispectral Scanners.

(d) **Active sensors operating in the microwave range**, i.e. with wavelengths from 1mm to 1m; radars are such sensors.

(e) **Passive sensors operating in the microwave range**, i.e. with wavelengths from 1mm to 1m; sensors that operate in these ranges include Microwave Radiometers & Scanners.

Active Acoustic sensors or sonars, which operate from the surface of the water with frequencies of 20-200 kHz and can yield useful

information on the concentration of particles in water column, thermal or salinity discontinuities and fish densities, are also remote sensors from an operational point of view. However, from the applicational point of view, the use of acoustic sensors necessitates the deployment of vessels, in which case the "remote" character (i.e. does not apply); moreover, in such cases conventional water quality measurement methods (such as water samplings at various depths, in-situ tests etc.) can usually be applied, so these sensors can be considered as part of the conventional water quality measuring equipment.

5.2. Passive sensors operating in the UV, visible & near-IR range

As mentioned above these sensors operate with wavelengths of 0.3μm to 1.2μm and include Photographic Systems and Nonphotographic Cameras, Thermal Radiometers & Scanners and Multispectral Scanners.

The application of this type of sensor to water quality assessment is based on the difference of reflectance characteristics, i.e. the difference in colour, of clear water and other substances such as suspended solids, chrolophyll, algae, macrophytes etc.

Since colour differences in themselves can be due to various effects, the interpretation of the images generated by remote sensing requires the calibration of image colour density with in-situ concentration measured simultaneously in a limited number of points. As discussed in section 3.3.3, the correlation of colour density with concentration can then be used for the spatial and time-variable interpretation of remote sensing images.

Thus, by measurement of reflectance and scattering from aircraft or satellite, information may be gained on:
- the concentration of suspended solids,
- the concentration of chlorophyll-a and algae,
- macrophyte densities (under certain conditions), and
- oil pollution

The resolution that can be obtained from satellites is on the order of 10-20m and from aircraft much less.

5.3. Active sensors operating in the UV, visible & near-IR range.

As mentioned above these sensors operate with wavelengths of 0.4μm to 0.7μm, mostly by measurement of laser-induced fluorescence; laser fluorosensors and lidars are sensors of this group.

The application of this type of sensor for the evaluation of water quality parameters is based on the property of fluorescence (ref. section 2.5) exhibited by certain substances of interest to water quality assessment such as oil pollution, chrorophyll etc.

This fluorescence, i.e. the emission in certain wavelengths, is visible in the images generated by remote sensing by use of the appropriate spectral bands and can be correlated to the concentration of the substances by calibration of image colour density with in-situ concentration measured simultaneously in a limited number of points; the correlation of colour density with concentration can then be used for the spatial and time-variable interpretation of remote sensing images.

Thus, by measurement mainly of fluorescence, but also reflectance and scattering from aircraft, information may be gained on:

- concentrations of suspended solids,
- the concentrations of chlorophyll-a & phytoplankton, and
- oil pollution

Aircraft platforms are necessary; the resolution that can be obtained from aircraft is in the order of a few meters.

5.4. Passive sensors operating in the infrared range

As mentioned above these sensors operate with wavelengths of 3μm to 14μm and include Thermal Radiometers & Scanners and Multispectral Scanners.

The application of this type of sensor to water quality assessment is based on the thermal emmission of water bodies, which is visible in the thermal images obtained by sensors of this group. The colour density can be correlated with water temperature by calibration with simultaneous in-situ temperature measurements in a limited number of points; the correlation of colour density with concentration can then be used for the spatial and time-variable interpretation of remote sensing images.

Thus, by measurement of emmission from aircraft or satellite, information may be gained on water temperature. The resolution that can be obtained from satellites is in the order of 80 to 120m; much higher resolution can of course be obtained from aircraft. As discussed in the previous chapter, such sensors usually operate in the nightime and best just before dawn.

5.5. Active sensors operating in the microwave range

As mentioned above these sensors, i.e. radars, operate with wavelengths of 1mm to 1m.

The application of this type of sensor to water quality assessment is based on the difference of reflectance characteristics of water bodies with variable substance concentrations such as oil pollution. These variations are manifested as tonal differences in the microwave images.

Since tonal differences in themselves can be due to various effects, the interpretation of the images obtained requires the calibration of image tonal density with in-situ concentration measured simultaneously in a limited number of points; the correlation of tonal density with concentration can then be used for the spatial and time-variable interpretation of the images.

Thus, by measurement of microwave reflectance and scattering from aircraft or satellite, information may be gained on oil pollution.

The resolution that can be obtained from satellites is in the order of a few Km for conventional systems and 20-30m for synthetic aperture radar (SAR) systems; resolution from aircraft is less, depnding on flight altitude.

5.6. Passive sensors operating in the microwave range

As mentioned above, these sensors, operating with wavelengths from 1mm to 1m include Microwave Radiometers & Scanners.

The application of this type of sensor to water quality assessment is based on emission differences of water bodies with variations of physical properties such as salinity or temperature. The variations are manifested as tonal differences in the microwave images.

Since tonal differences in themselves can be due to various effects, the interpretation of the images obtained requires the calibration of image tonal density with in-situ concentration measured simultaneously in a limited number of points; the correlation of tonal density with concentration can then be used for the spatial and time-variable interpretation of the images.

Thus, by measurement of microwave emissions from aircraft or satellite, information may be gained on:
- water temperature
- salinity
- oil pollution

The resolution that can be obtained from satellites is in the order of a few Km; higher resolutins can be obtrained by aircraft.

5.7. Conclusions

The potential for application of remote sensing for water quality assessment is restricted to the surface (or near-surface) values of relatively few parameters, namely water temperature, suspended solids concentrations, chlorophyll & algae concentrations and, under certain

conditons, macrophyte density; remote sensing can also be very useful for the identification and monitoring of oil pollution.

6. REMOTE SENSING APPLICATIONS IN THE MARINE ENVIRONMENT

6.1. General

The following section involves a detailed review of the applications of remote sensing for the measurement of water quality parameters in the marine environment.

The application of remote sensing, whether satellite or airborne, to quantitative water quality monitoring offers significant advantages over direct sampling and in situ monitoring techniques. In a short period of time, the equivalent of a very large number of sample measurements can be taken, covering areas of large spatial extent. This may be significant in view of the considerable costs and complications involved in gathering and analysing a large number of samples by conventional sampling methods which ultimately restrict the sampling frequency and spatial coverage of the area.

The waters of the coastal zone create a remote sensing problem with multivariate dimensions of the highest degree: horizontal and vertical gradients in currents, temperature, salinity, turbidity and biological activity are compounded by point and non-point releases of pollutants, both conservative and non-conservative, of great biochemical variety and complexity, makes the task of measurement more difficult.

Remote sensing has been applied in the marine environment for assessment of particular water quality parameters and for monitoring coastal water pollution. It must however be noted that remote sensing of the water column is also subject to a number of limitations and restrictions.

The depth from which a significant backscattered signal can be detected, represents an obvious first physical limitation of the system. This depth has been arbitrarily defined by Gordon and McCluney (1975) as that above which 90% of the diffusely reflected irradiance (excluding specular irradiance) originates. The same workers have demonstrated that for a homogeneous water column, this

is the depth at which the downwelling inwater irradiance falls to exp(-1) of its surface value. This depth is found to decrease on going from deep ocean water to turbid or polluted waters.

6.1.1. Point-source pollution applications

Point-source pollution in the coastal zone includes plumes from ocean dumping of waste materials, such as sewage sludge, acid and other chemicals. These materials often have unique spectral characteristics that may be used and exploited for remote sensing. In some circumstances there is also a unique spatial signature.

Early literature describes interpretation of aerial photography for plume location, and tracing of plume movement and dispersion. Since the launch of Landsat-1 in 1972, multispectral-spectral scanner imagery from orbit has proven to be useful.

The discrimination between various components contributing to radiance is made possible by the spectral separability of pollutants and their brightness differences from clear water. Plumes in the coastal zone, due to scattering by suspended particles, usually produce higher radiance than emanates from clear water, rendering the identification of such areas practically possible.

6.1.2. Diffuse pollution applications

Substances found in marine and coastal waters have both natural and artificial origins, and may be transported large distances, undergoing mixing, dilution and dispersion. Great effort is involved in discovering points of origin for introduced materials. Those pollutants with dispersed points of origin, termed *non-point* pollution, often play an important part in many environmental issues affecting resources and use of the coastal zone. Their remote sensing is often of interest; however, the problems (unrelated to remote sensing) in discriminating transport pathways and origins have had

the consequence of limiting somewhat the intensity of effort toward development of suitable remote sensing techniques.

Toxic chemicals, nutrient chemicals (as in urban waste and agricultural soil runoff) and inorganic sediments are the principal classes of input pollutants. These affect and give rise to unnatural fluctuations of natural marine substances, producing for example, red tides.

Because chemical solutions are generally colourless and distributed through the water column, they are beyond the application of most optical techniques allowing sensing near the water surface. There may be developments in the future of Raman scattering techniques suitable for some non-point variables. For the present, however, some remote sensing is possible because colourless chemicals as well as bacteria often are absorbed onto surfaces of suspended sediment particles. Chemical concentrations can then be tied to the sediment concentrations measured by remote sensing.

6.1.3. Offshore pollution applications

Of all the chemical materials spilled into the marine environment, oil pollution is among the most notorious and ubiquitous. Other materials have been locally more important in some cases, such as mercury in Minimata Bay, Japan and kepone in the James River, Virginia.

However, concerning remote sensing, oil is the most studied, and only preliminary studies have begun on the great majority of other pollutants. From results of numerous investigations of the potential for remote sensing of spilled materials, a general conclusion is that unattended remote monitoring is not yet possible for any more than a handful of pollutants, and these only in cases where the given pollutant is the only substance whose concentration is varying. On the other hand, sustained effort might yield techniques involving narrow spectral band widths and sophisticated instruments for

monitoring many specific pollutants. The potential cost has thus far precluded such effort for pollutants other than oil.

6.2. Water Quality Assessment

6.2.1 Suspended Solids

Suspended sediment concentrations are easily detected in situ by optical techniques such as the Secchi disk, since through scattering and absorption, they affect the colour and general clarity of water.

Typical inorganic sediments have scattering/absorption coefficient ratios much larger than unity throughout the visible spectrum; hence the input of sediments to a water parcel will increase the volume reflectance, and the water will appear brighter in contrast to clear water. In addition, the optical depth will decrease.

The above suggests two possible approaches to remote sensing of suspended inorganic particles:

(a) measurement of total upwelling radiance either under passive solar or active laser illumination, and

(b) laser backscatter measurement of return signal attenuation with depth.

Both approaches yield data that can be transformed into either a turbidity value or a concentration of particles.

The best wavelengths for passive solar measurement of suspended sediment are between 0.55μm and 0.65μm; shorter wavelengths suffer high absorption by water, restricting data collection to the upper few cm of the water column.

Thus, the measurement of suspended sediment can be accomplished by multispectral scanners from satellite or airborne platforms using band ratios or even with photographs, which have the advantage of being easily obtained; however, numerous steps are required in the photographic data-reduction process, in order to account for variables that affect the measurement accuracy.

Fresh water studies have indicated that Landsat data and Secchi depth readings have correlation coefficients of about 0.9. Lindell et al (1985), took Secchi disk readings all along the Swedish coastline and compared these with Landsat data. Chromaticity analysis was applied in the analysis to allow for Sun angle and atmospheric corrections. The results from this investigation assisted in the determination of the relative solids loading situation along the Swedish coastline, and were subsequently used in environmental planning and coastal zone management.

Although many successes have been reported in the assessment of suspended solids concentration by remote sensing, reservations have also been expressed about the accuracy of such assessments; it appears that, although reasonable correlation coefficients have been obtained from calibration of suspended solids concentration and registered radiance, relatively little effort has been directed in the subsequent validation of the interpretation process.

Airborne Thematic Mapper data from NERC, MSS-82 campaign in Swansea Bay, Bristol Channel were correlated, in linear and multiple regression analyses, with measured water quality parameters: suspended sediment concentration, mean grain size of material in suspension, surface salinity and chlorophyll-a concentrations. It was found that particle size influences the spatial signature of suspended sediment.

Indeed, one of the major sources of error is the inhomogeneity of suspended material; this error is inherent in all types of data collection, whether for single or multiple dates, where surface information and remote sensing data are being compared. The greater the inhomogeneity within the resolution capacity of the instrument, the greater the error. Inhomogeneity has two effects:

(a) the collected sample may not be representative of the "average" particle concentration in the field of view, and
(b) the suspended solids concentration may be underestimated when calculated from an average radiance within the field of view, due to nonlinearity between radiance and concentration.

The magnitude of these effects cannot be evaluated without knowledge of the particular spatial distribution of suspended material under consideration. For the Nimbus 7 Coastal Zone Colour Scanner, this error was found to be in the order of 30% for North Sea Data.

Thus, where numerous types of particles are simultaneously varying, a single band measurement cannot be reduced to particle concentration of any one type; multispectral methods involving numerous narrow bands are required to monitor even a small number of components. Also, the measurement of total particle concentration in such cases may have reduced reliability and even a turbidity value should be viewed with caution.

Also, the coastal environment necessitates that particular attention be paid to atmospheric variations, if data from different dates are to be compared.

In addition to temporal variations in atmospheric conditions, problems may also arise from atmospheric variations even within a given scene at any one time. In situ calibration data for a more dense and detailed network of points would be required in order to allow for this variation. However, a refinement of the network to be sampled would also imply greater fieldwork costs, thus reducing the objective value of remote sensing.

An alternative solution to the problem of atmospheric variation, as suggested by Cracknell and Hayes (1991), is the use of a model atmosphere. In the case of the latter, the details and parameters could be adjusted according to the geographical location and the time of the year. The success of such a model will be greater for instruments with low spatial resolution covering large areas and also for situations in which the size of atmospheric correction is small in relation to the signal from the target area being observed.

The same workers alternatively suggest that atmospheric effects may possibly be eliminated through a multi-look approach whereby a specific target area is viewed from two different directions. If data

from two different satellites is used for this purpose, the differing paths of the two satellites may result in inaccuracies. A solution to this problem is provided by the Along Track Scanning Radiometer (ATSR). The conical scanning technique of this sensor enables the Earth's surface to be viewed at different angles (0^o and 52^o) in two curved swaths. Data from the two swaths are then combined to provide an accurate atmospheric correction.

The use of lasers mentioned above has opened the attractive possibility of measurement of the depth profile of suspended solids concentration, with or without measurement of absolute radiance with depth. The obvious advantage of lasers include their day/night capability, and the monochromatic nature of the radiation involved. The latter simplifies the laboratory work required for appropriate calibration of the technique. Multispectral dye lasers should provide power in resolving multi-particle components. Exton et al (1983) have, on the basis of laboratory measurements, suggested that suspended sediment concentrations can be remotely detected by measuring the concurrent (laser wavelength) Mie backscatter from the water column.

In assessing the spatial distribution of suspended sediments, Wensinjk et al (1989), believe that an ideal product would be a database containing actual information on the concentration of various suspended substances. The same workers stress the drawbacks of individual means of measurement and suggest that an integrated approach be followed, using satellite data and in situ measurements, integrated into numerical transport models.

6.2.2. Temperature

Remote sensing can contribute to the monitoring of the temperature of the sea surface. Sensors operating in the thermal range (i.e. thermal sensors and multispectral scanners) are of course the most suitable equipment and have adequate reliability, but passive radiometers which have all-weather capabilities and provide sea surface temperature by measurement of microwave energy have also been used;

the resolution of passive radiometers is of course substantially less than that of thermal sensors ref. chapter 3).

The work of the Centre de Meteorologie Spatiale (CMS) in France provides a prime example of the application of remote sensing to the measurement of sea surface temperature. As described by Le Bogne et al (1988), the CMS initiated a routine analysis of sea surface thermal structures in 1979. In order to overcome the disrupting effect of cloud cover, the CMS has developed the use of interactive image processing systems and the combined use of the multispectral scanner AVHRR of the NOAA and that of the Meteosat programme. In this way, more precise readings are obtained which may in turn be used to provide real time assistance to fishing vessels or oceanographic ships.

The results of several aircraft programs have demonstrated that water temperature information can be derived from passive microwave measurements with an accuracy that satisfies most user applications. In particular, a remote sensing technique to concurrently measure sea surface temperature and salinity has been demonstrated with a dual-frequency microwave radiometer system; accuracies in temperature of $1^{o}C$ were obtained after correcting for extraterrestrial background radiation, atmospheric emission and attenuation, sea surface roughness and antenna beamwidth. The radiometers, operating at 11.3cm to 21cm, comprise a third generation system using null balancing and feedback noise injection, and were developed specifically for obtaining sea surface temperature and salinity maps of coastal and estuarine areas.

The atmosphere is essentially transparent to electromagnetic radiation at wavelengths of 10cm to 30cm. Extensive work over the years with microwave-signal propagation through the atmosphere has indicated that the influence of clouds is small at these wavelengths except under very severe storm conditions. Also, the background galactic noise tends to decrease substantially for wavelengths below 30cm. Therefore, the wavelength range from 10cm to 30cm is well suited for minimal extraterrestrial background radiation and atmospheric interference. Detailed knowledge and correction of these

effects is required however for accurate surface temperature measurements by airborne radiometers in this microwave region, since their impact on measured brightness temperature of the ocean surface can be in the order of a few ^{o}K.

One potential source of error in the validation of space born sensors of sea surface temperature, is the oceanic skin effect. This may be defined as the difference between the temperature of the oceanic skin, consisting of the first few micrometers of water, and the temperature of the bulk water about 10cm below the surface. It results from the physical processes relating to heat transport across the ocean-atmosphere interface and may be complicated by the physical properties of both the sea water and the air. Within the framework of the ROSSA research project described by Hepplewhite (1989), it was found that for the Atlantic Ocean, the skin of the sea was about $0.30^{o}K$ cooler than the bulk at around 10cm below the surface; the skin was rarely warmer than the bulk temperature and on some occasions the skin was found to be in the order of $1^{o}K$ cooler than the bulk. In climatic studies, where extreme accuracy is essential, this may be regarded as a considerable source of error.

6.2.3. Salinity

Chemical variables of the ocean environment are nearly all beyond present remote sensing capabilities, except for salinity. This important exception is significant for study of density driven features of circulation.

The only direct technique for remote salinity measurement is the use of a microwave radiometer. However, preliminary studies have indicated that a laser Raman detection of sulphate ion in sea water may also yield salinity data indirectly.

The results of several aircraft programs have demonstrated that salinity can be derived from passive microwave measurements with an accuracy that satisfies most user applications. In particular, a remote sensing technique to concurrently measure sea surface

temperature and salinity has been demonstrated with a dual frequency microwave radiometer system; accuracies in salinity of $1^{0}/_{00}$ for salinity greater than $5^{0}/_{00}$ were obtained after correcting for extraterrestrial background radiation , atmospheric emission and attenuation , sea surface roughness, and antenna beamwidth. The radiometers, operating at 11.3cm to 21cm, comprise a third-generation system using null balancing and feedback noise injection, and were developed specifically for obtaining sea surface temperature and salinity maps of coastal and estuarine areas.

6.2.4. Chlorophyll Concentration

The principal biological parameter that can be measured by remote sensing is the chlorophyll bearing phytoplankton, with their unique optical properties; phytoplankton may be widely distributed horizontally and vertically in the water column. Chlorophyll, the primary photosynthetic pigment in phytoplankton particles at the base of the marine food chain, is an important aquatic parameter that has significance for water quality and marine productivity.

In the past few years, the growing problem of eutrophication of water bodies is manifested in the development of algal blooms. Toxins are sometimes produced in association with these blooms, which are poisonous to marine animals and also to unwary swimmers and consumers of contaminated seafood. Remote sensing is of interest for direct investigation of excessive bloom phenomena and for indirect indication of nutrient pollution.

Also, the monitoring of macrophytic vegetation which contains chlorophyll pigments is of interest since the outbursts of such vegetation caused singnificant environmental problems in the Northern Adriatic Sea.

There are two main approaches for passive remote sensing of oceanic phytoplankton (Sathyendranath et al 1989):

(a) Ocean colour technique. Using passive sensors operating in the visible range, this technique is based on the observation of ocean colour, which is affected by chlorophyll concentration. The relationship between ocean colour and chlorophyll concentration, which is non-linear, is directly affected by the physical properties of the phytoplankton population. The technique can be used for the assessment of total column productivity (Platt 1986).

(b) Fluoresence technique. Using active sensors operating in the visible and near-IR range, it is based on the observation of in vivo fluorescence of chlorophyll, also affected by chlorophyll concentration; the connection between fluorescence height and chlorophyll may be described by a linear relationship. Chlorophyll fluorescence characteristics are most affected by the physiological state of the phytoplankton cells (eg. nutrient stress, photoinhibition); the technique has also been used for the assessment of the rate of primary productivity from fluorescence efficiency (Topliss and Platt 1986).

The two methods presented above have a number of technical differences:

(a) The ocean colour technique can be applied from satellite or airborne platforms, while the fluorescence technique can be applied only from aircraft, thus entailing higher application costs

(b) The ocean colour technique is considered more sensitive at low levels of chlorophyll while at high levels, the fluorescence technique is considered more accurate

(c) The required atmospheric corrections are lesser for the fluorescence technique than for the ocean colour technique.

Thus it appears that, for the assessment of low background chlorophyll concentrations, the ocean colour technique applied from satellite platforms is the most appropriate. For the assessment of

chlorophyll concentrations in algal blooms and in macrophytes, it would be preferable to apply both techniques jointly from airborne platforms flown at the time of the blooms; the compilation of information from both techniques will significantly improve the reliability and accuracy of the remote sensing effort.

A number of studies have obtained useful information on blooms with the use of remote sensing. Dupouy et al (1988), used a Nimbus 7 CZCS to detect a large phytoplankton bloom (90,000 km^2), caused by the cyanobacterium Oscillatoria around New Caledonia and the Vanuatu archipelago, east of Australia in the Coral Sea. The CZCS image was used to estimate nitrogen fixation by the bloom - the total nitrogen fixed by the bloom over a 10 day period was found to range between 0.02 and 1.17 billion g N_2. The findings suggest that such a biological event plays a significant effect in the global nitrogen oceanic budget.

From the correlations on data from the MSS-82 campaign with the Airborne Thematic Mapper in Swansea Bay, Bristol Channel (ref. section 6.2.1), it was confirmed that there is a masking effect of high suspended solid concentrations on the spectral reflectance of chlorophyll.

Using Coastal Zone Colour Scanner (CZCS) data from the Adriatic Sea, Tassan and Sturm (1986), developed an algorithm for the retrieval of the sediment content of turbid coastal waters and tested this against experimental values. This experimental exercise resulted in the identification of two water types in the northern basin of the Adriatic Sea, characterized by a substantially different correlation between sediment and chlorophyll and corresponding to coastal zones, with different hydrological conditions.

Thus, in assessing the applicability of remote sensing for the measurement of chlorophyll concentration, the suspended solids concentration must be considered. In this respect, waters have been divided into two types (Sathyendranath et al., 1989): Case 1 waters are waters with low suspended solids concentrations and where phytoplankton may be considered as the only major independent factor

affecting changes in ocean colour. Case 2 waters are waters where suspended solids concentrations are significant, i.e. coastal locations in the vicinity of estuaries, major outfalls etc. where such material may affect ocean colour in a more complex way.

From the above it may be concluded that, while in case 1 waters the application remote sensing for the assessment of chlorophyll concentration is feasible, in case 2 waters, the situation is more difficult; due to the high productivity of such waters and their associated economic value, efforts are being made to develop accurate remote sensing techniques. A possible approach is the use of algorithms which make use of the entire spectrum, including the fluorescence signal. Sathyendranath et al (1989), examined the situation for case 2 waters by simulating ocean reflectance spectra for a wide range of variations in chlorophyll concentration, suspended sediment load and dissolved organic material. The concentrations were then retrieved from the spectra using principal component analysis and multiple regression. Their results showed that, at least in some cases, retrieval from the reflectance spectra was a feasible task. Their results also indicated that due to the non-linear effects in the system, global algorithms that give equal weighing to phytoplankton, non-chlorophyllous particles and dissolved organic matter may be used as a preliminary step, allowing an evaluation of the type of water involved. A second level algorithm may then be carried out, specifically for the predetermined water type.

One of the practical limitations which must be considered when assessing the applicability of remote sensing for the monitoring of algal blooms, is the fact that blooms may develop relatively suddenly and may in some cases persist for a short duration of time. This implies that the operational platform for the observation of such blooms must be in the appropriate position at the appropriate time, and furthermore, in situ measurements must be taken at the same time that the image is being taken for ground correlation, which makes practical application very difficult.

In this context, an interesting approach to in situ measurement has been the development of the algal sensor, "Optisens" by the Oceanographic Company of Norway, "Oceanor". This may be mounted to marine structures or moored buoys and may be used to monitor algal concentrations, thus providing a continuous source of in-situ information. In combination with aerial surveys, this may facilitate the monitoring of all algal blooms.

As regards the assessment of marine macrophytic vegetation with remote sensing, the fluorescence technique is considered the most appropriate, due to its greater sensitivity at high levels of chlorophyll and its capabilities for atmospheric correction.

6.2.5. Oil Pollution

6.2.5.1. General

Emphasis on remote sensing of oil pollution is justified because of the frequent release of oil into the marine environment and the devastating consequences it may have on the aquatic ecosystem. The fact that, at least in the first stages of an oil spill, oil rises to or spreads across the surface of a water body, has contributed to the development of successful techniques applied to surveillance activities and to assessment and cleanup activities. These goals require different capabilities: surveillance aims at small to modest spills where detection and subsequent legal proceedings are most important, while cleanup typically deals with massive spills where detection is easiest and volume measurement and transport are most important.

6.2.5.2. Sensor capabilities

Theoretical and laboratory tests have established the electromagnetic properties of oil films on water. Based on such data, single band and multispectral detection techniques have been designed for the ultraviolet to microwave portions of the spectrum. Dielectric

constants and optical properties, such as a refractive index, absorptivity, fluorescence, and emissivity, have been measured for varieties of petroleum and its products as well as naturally occurring biological oils. Field tests have considered environmental factors such as ambient air and water temperatures, salinity, sea state, and turbidity.

(a) **Visible & UV Spectral Region**

In the visible and ultraviolet region, different oils have unique spectral signatures, yielding sometimes brighter and sometimes darker than background radiances, depending on the wavelengths of illumination and observation, the type of oil and the background water clarity. Thus, colour and brightness contrasts, which are determined for chosen oils overlying turbid mid-latitude waters, may have to be revised for clear tropical waters.

Regarding the selection of appropriate bands:
- The near ultraviolet is seen to be excellent for imaging slick edges and thin regions of various fuel oil slicks.
- The blue band is next best for imaging slick images and thin regions of various fuel oil slicks and satisfactory for measurement of slick areas.
- The green band is best for delineating thick regions.

No band was found to distinguish thick and thin regions for No.2 fuel oil but such oil is distinguishable from Nos. 4 and 6 by lacking negative contrast in the blue and green bands. Fuel oils usually show interference rings at slick edges, up to a depth of a few wavelengths, permitting an estimate of minimum spill volume. Where thick regions are distinguishable by colour contrast, the minimum thickness is in the order of 1mm. Menhaden oil is distinguishable from fuel oils because it remains in small thick lenses surrounded by a colourless microlayer. Narrow band multi-spectral scanners offer all the available spectral capability, except in dim light.

Colour film is an all-purpose record for most situations; quick look records can be obtained from television cameras with high sensitivity in the blue and green regions, while low right-level television extends the capability into periods of darkness.

In the visible and ultraviolet regions of the spectrum, active sensors can detect oils by exploiting oil fluorescence. Fluorescence spectra show that broad classification of oils is feasible with fluorosensors, via type-specific emission peak wavelengths that vary from 0.4µm to 0.6µm. Most results from field work have been more modest at the level of oil detection.

In the field situation, there may be confusion between oil and other targets. Marine waters contain natural materials that also exhibit fluorescence, including Gelbstoff and chlorophyll-a, but the former fluoresces in a larger bandwidth, and the latter has a peak at a longer wavelength (0.685µm for chlorophyll-a in situ): furthermore, spatial gradients and texture patterns of natural materials vary from those of oils.

A specialised fluorosensor, the Fraunhoffer Line Discriminator, operating in an airborne imaging mode, has also detected oil slicks and provided data for slick morphology and volume. Of the wavelengths sensed (0.4861, 0.589 and 0.6563µm), the blue wavelength (0.4861µm) had the greatest sensitivity due to the broad blue peak in the fluorescence emission spectrum. The quantum yield of oil fluorescence varies with the thickness for oils with specific gravities less than approximately 0.875. It should therefore be possible to measure slick thickness in the field using fluorosensors, given knowledge of the specific gravity.

A different approach is a thickness measurement via depression of water Raman backscatter; potential for success with this technique has been reported for thickness between 0.05 and 5µm using an airborne 337nm nitrogen laser.

All visible region passive sensors are, of course, limited to available light and clear weather.

(b) **Thermal Spectral Region**

Scanners with a thermal channel offer, moreover, the capacity for a temperature map of an oil slick, day or night. Such a map however, must be interpreted carefully. First, over water, the 8-14μm thermal band includes atmospheric and surface reflection contributions to the signal received. Other contributions to total radiance, such as path radiance, may be neglected for low altitude surveys.

Proceeding to the thermal signal over an oil slick, an emissivity value for the oil in question is required. Values for specific oils are sparse; evidently, the oil value of 0.972 is too large, and the value to use depends on oil film thickness (for very thin slicks, the remote instrument partially "sees through" the slick to the underlying water). It has been suggested that thermal infrared data might be correlated with oil slick thickness. Such a correlation appears possible via the indicated emissivity/thickness dependence, but the usual surface temperature variations in estuarine waters will introduce ambiguity. Also, emissivity values and their thickness dependencies may be oil specific.

(c) **Microwave Spectral Region**

Greater success has been reported for determination of oil slick thickness using a microwave radiometer, which offers the advantage of being operable in more adverse weather conditions. Also, in the realm of active remote sensing systems, radar is quite effective in detecting oil slicks. Oil smooths surface capillary waves and reduces radar backscatter, especially for viewing angles beyond 20^o. However, slicks caused by spilled oil cannot be discriminated from those caused by wind patterns, thin ice or natural oils. Because the mechanism of detection is indirect - via surface roughness - thickness determination is

necessarily crude and dependent on sea state; for detection per se, seas must be neither very calm nor very rough. However, radar offers many advantages. For example, use of a side looking radar permits slick detection at long range over wide areas. Also, radar provides all weather day/night operations unaffected by clouds or darkness. Finally, radar can be arranged to produce quick look records on dry silver film.

6.2.5.3. Surveillance Systems and Satellite Detection

For surveillance and monitoring of oil pollution, a multi-sensor system is required to achieve all-weather and illumination capability. Several countries have developed airborne surveillance systems for oil spills.

A fleet of at least 10 aircraft are maintained by countries bordering the North Sea for the surveillance of oil and chemical discharges. The UK Marine Pollution Control Unit of the Dept. of Transport has 2 aircraft with Side-Looking Radar (SLAR), Infrared Line Scanner (IRLS) and Ultraviolet Line Scanner (UVLS). Innotech Aviation in Canada, employ a Falcon 20 jet fitted with a multispectral electro-optical imaging system (MEIS), a digital ultraviolet/infra-red imaging system (DS 1260 MSS), and a 230mm format black and white, colour and colour-infra-red film mapping camera (RC 10), for use in surveillance and monitoring. The US Coast Guard initiated a program in 1968, and is currently developing a fourth generation system called AIREYE, the Airborne Remote Instrumentation System. This will be carried on six Falcon 20 jets fitted with an AN/APS-94 SLAR. /targets detected by the SLAR can be overflown and imaged by a three channel infra-red/ultraviolet scanner. An aerial reconnaissance camera, KS-87B, is configured for nadir or 30^{0} depression angle operation. An active gated television (AGTV) has been developed for night-time identification.

Many instances of satellite detection of oil slicks have been investigated. The implications are significant of course, for the future when pointable sensors with high spatial resolution will be on

board operational satellites with global coverage; at present, spatial resolution from geosynchronous satellites is too coarse for surveillance, while polar-orbiting satellites with better spatial resolution have inadequate repeat cycles and data turn-around times for routine use. Other problems include the paucity of spectral channels, their wide bandwidths, variable oil/water radiance contrasts, especially in and out of sunlight regions, and small signal to noise ratios. The noise sources that are particularly troublesome for orbital oil detection include electronic noise, path radiance, and variable particle and plankton loading of the underlying water.

The efficiency of satellite data in operational detection and tracking of oil slicks may be evaluated on the basis of a case study. The Ixtoc 1 oil well blowout which occurred in Campeche Bay in 1979, was detected by five different satellites: GOES, Nimbus 7, TIROS-N, and Landsats 2 and 3. All five satellites presented similar data analysis problems, namely, coarse resolution, sun-angle variations and weather limitations. In terms of oil volume and tracking, the CZCS and similar coarse spatial resolution sensors, are not considered appropriate. The visual imagery derived from TIROS-N and GOES showed the oil as a light grey toned crescent originating at the well site and corresponding to locations determined by aerial reconnaissance.

Spot Image S.A. advertise an oil pollution contingency plan. The specifications of the plan include contrast-enhanced image processing, separation of large thematic areas through photointerpretation, computer aided classification and a priority index incorporating surface area. The work is naturally accompanied by ground truth campaigns in order to confirm classifications. The end product is a map showing environmentally sensitive areas, land cover and sea farming sites.

6.2.6. Thermal Plumes

Some effluents are hotter than receiving waters, making thermal infrared scanner imagery particularly useful for analysis. The latter are preferred over microwave scanners due to the better resolution capabilities of thermal infrared scanners. Thus, thermal imagery is widely used for detailed studies of plumes from low altitude. Overflights provide synoptic information on spatial distributions that are not readily available from surface measurements, and subtidal coverage yields temporal distributions as a function of tidal phase. For regional analysis, orbital imagery from thermal scanner areas subjected to industrial and urban thermal loads is used.

6.2.7. Waste Outfalls

For outfalls discharging waste into waters nearer shore, the background (receiving) waters are more turbid than the clear waters subject to ocean dumping. Greater difficulties in remote sensing of pollutants should be expected as background turbidities increase. There will, however, be some outfalls in clear-enough water to allow plume discrimination from orbit by simple grey-level analysis of single Landsat MSS bands, which can be used to discriminate broad classes of coloured pollutants.

Generally, however, a multispectral technique from aircraft, with its considerable resolution capabilities, will be required. In this way the spectral properties that characterize different parcels of water can be fully exploited for discrimination of the various pollutants and natural water constituents that may be present. Although it will rarely be possible to positively identify individual pollutants, at least points of discharge may be detected, plus direction of flow and rate of dispersion.

Polcyn and Wezernak (1970 - cited in Colwell, 1983), mapped industrial discharges, with the use of a scanner which collected data

in 17 channels. Four of these channels mentioned by Colwell, were able to discriminate broad classes of coloured pollutants.

Davies and Charlton (1986), employed SPOT simulation data to identify and delineate the structure of effluent plumes in a tidal estuary. The identification was achieved without the addition of coloured marking material to the discharge and with the use of contrast enhancement techniques to delineate suspended sediment distributions and to locate discrete sources of discharge. The findings were in agreement with earlier results obtained from multispectral scanner surveys

Many pollutants that discolour water can be detected using colour photography. Even when receiving waters are highly polluted, discharges at/or near the surface are usually visible for at least a short distance from the release point. The use of colour infrared instead of colour photography is recommended when the photographic altitude is above roughly 6000m, in order to minimize the effects of atmospheric haze, or when it is desired to discriminate floating or very shallow vegetation, algal blooms, and shoreline vegetation. The scale of photography should be adequate for detecting and identifying features associated with pollutant outfalls and spills, such as storage tanks, pipelines, sewage treatment plants, raw material and waste holding facilities, and shipping docks. The scale range most suitable for such interpretations is usually 1:5,000 to 1:10,000. Such detailed photography may conveniently follow reconnaissance mapping at smaller scales such as 1:500,000.

The timing and frequency of photographic and scanner coverage depend on the pollution source and the objective of monitoring. Some outfalls discharge only at certain times of day. In other cases tidal action of receiving waters alters pollutant dispersion and hence visibility, requiring selection of appropriate tidal-current phases. In this regard, low tides reduce the depth over submerged outfall nozzles.

Remote sensing of outfalls can be enhanced by the use of dyes the effluent, free releases of dye, and/or dye-releasing markers, which

enhance the flow field in the outfall region. the dye-marker techniques are particularly suited for outfall analysis: dye streams from anchored buoys placed at an outfall site show the direction of tidal flow and indicated dispersal patterns even when an outfall plume itself may be undetectable. Also, dye-emitting floats will reveal currents. Also, elegant photogrammetric methods have been developed for measurement of currents with surface floats and aerial photography. Suijlen (personal comm.), applied simple aerial photography on small scale continuous releases using rhodamine B, a red fluorescing dye. The results, confirmed by in situ fluorometry, showed that the combination of remote sensing and dye markers is excellent for measuring small scale diffusion ranging from a few decimeters up to a few kilometers.

In general however, the benefit from the application of remote sensing for the observation of waste outfalls appears to be marginal, since remote sensing can at best effectively contribute only to the detection of the source and the direction of flow, information which may be known from other sources. The identification of type of pollutant or the assessment of rates of diffusion, which would require expensive airborne platforms, can only be done with considerable in-situ work, which may be adequate for those needs anyway.

6.2.8. Ocean Dumping

For dumps of sewage sludge, laboratory data indicate that single wavelengths (i.e. photographic systems and multi-spectral scanners) would suffice for measurement of suspended-solids concentration; a multispectral multiple regression equation may improve accuracies of measurement.

In the case where multiple pollutants influence ocean spectra, eigenvector analysis may be used to extract the various spectral signatures.

The same conclusions apply to dumping as for the waste outfalls, i.e. the benefit from remote sensing is considered marginal.

6.2.9. Chemical Solutes and Yellow Substance

Colourless chemicals that are present in the water column cannot be detected directly by remote sensors. Situations may occur, however, when concentrations of such chemicals are correlated with suspended particle concentrations. This may result from chemical adsorption on particles, dissolution of absorbed or adsorbed chemicals from particles, or input of both to the water column from a common origin. Remote measurement of turbidity may then be calibrated for chemical concentration.

The well-known coloured solute of nearshore marine waters called yellow substance will interfere with accurate remote measurement of chlorophyll and turbidity, unless corrections are made; yellow substance is in large measure the result of erosion and runoff from the land, i.e. silt in engineering terms. Particles are carried in streams and are deposited. Yellow stuff and its fluorescent by-products are, therefore, dependent upon runoff and salinity and may be used as an indicator of fresh water input. However, yellow substance may also be the result of the degradation of phytoplankton. According to Geerders (personal comm.), the problem lies in the quantitative calibration of the observed ocean colour in terms of yellow substance, closely related to a precise definition of yellow substance and its spectral behaviour. Salinity, temperature, sediment, chlorophyll and yellow substance may be considered as elements in a complex model of interactions, which are only partly understood.

Thus, the applications of remote sensing for the assessment of the above can still be considered as in the refinement stage.

6.3. Future outlook

Remote sensing will play an ever increasing role in investigations of the marine environment, as evidenced by steady increase in the use of combinations of traditional techniques with remote sensing systems. The continuing development of new remote measurement techniques, complementary and parallel development of microcomputer technology, and sensors with improved spatial and temporal measurement\capability are providing exciting new opportunities in marine science. Expanding capabilities in the microwave spectral-region, particularly from satellite and aerial platforms, offer opportunities for synoptic and repetitive measurements on regional and global scales that have not been previously possible. Another significant factor is that instruments are now available that measure, directly of indirectly, the same or interlocking features by one or more techniques in different parts of the spectrum, thus avoiding some previously troublesome environmental constraints, such as cloud cover and other atmospheric effects.

Several emerging techniques may be mentioned as illustrations, without any intention of summarizing or highlighting what may be the most significant:

(a) Determination of oceanic currents and water masses by combined and complementary thermal infrared and passive microwave measurements, in conjunction with precision altimetry.

(b) Measurement of sea surface temperatures by infrared radiometers (a generally accepted technique) and the complementary development of microwave thermal-measurements with calibration using data from nearby spectral bands.

(c) Significant development of multifrequency sonar-sensors and analysis techniques which, in combination with systems such as time-gated laser systems, will provide information on coastal zone and oceanic underwater features more readily than previously available, and in nearly pictorial detail.

A proposal of this research effort is to develop a geographic information system platform suitable for the superposition of images from several types of sensors for the comprehensive assessment of the monitored parameters, especially for fields where the operation of more than one senors is complementary, such as the application of remote sensing for oil pollution assessment, for phytoplankton monitoring etc.

The resulting data should stimulate significant model development. These measurement systems may not be readily available to all investigators of users of the marine environment, due to hardware and data-reduction constraints. However, it is clear that, as the aircraft and satellite experiments continue, there will be opportunities available throughout the marine community to participate and/or subsequently to analyze data from such systems. With repetitive coverage, lines of investigation will open that may not have been considered before.

Although there is much to be learned about the ocean and its processes, especially below the surface where they are less amenable to remote sensing, major strides are obviously being made in measurements associated with surface phenomena and within the euphotic region, which will contribute significantly to the understanding of the marine processes in conjunction with analytical and laboratory models should improve in character, since there will be more opportunity to obtain measurements with which to calibrate and verify these models.

6.4. Conclusions

From the above, it may be concluded that remote sensing has been successfully applied to date for the assessment of:
- suspended solids concentration,
- sea surface temperature,
- salinity,
- chlorophyll concentrations
- oil pollution,

- thermal plumes, and
- effects of waste outfalls and ocean dumping

7. REMOTE SENSING POTENTIAL IN THE MEDITERRANEAN

7.1. General

In this section, the potential of application of remote sensing in the Mediterranean is assessed, taking into account its basic hydrodynamic and water quality characteristics. To this end, the relevant characteristics of the Mediterranean are first presented, followed by a brief review of anthropogenic effects; subsequently, on the basis of the above and the information in the previous chapters, an assessment is carried out of the potential of remote sensing for the survey of water quality parameters in the Mediterranean.

7.2. Principal Characteristics of the Mediterranean

7.2.1. General

The Mediterranean Sea, in the order of three million square kilometres in extent, is significantly shallower than most major oceanic regions. It is a relatively closed sea, having only one small outlet to the Atlantic Ocean, the Strait of Gibraltar.

Continental shelf areas throughout the Mediterranean are extremely narrow, compared to those of major oceans, ref. Fig. 7.1; the only moderately wide shelf areas are found in the Adriatic Sea, in parts of North Africa (Gulf of Gabes etc.) and locally, in the deltas of significant rivers (such as the Nile, the Rhone, the Ebro etc.).

The narrow constriction of the Strait of Sicily effectively divides the Mediterranean seafloor into distinct eastern and western basins. The western basin is characterised by broad, generally smooth abyssal plains, in marked contrast to the eastern basin, which is dominated by the Mediterranean Ridge System, ref. Fig. 7.1.

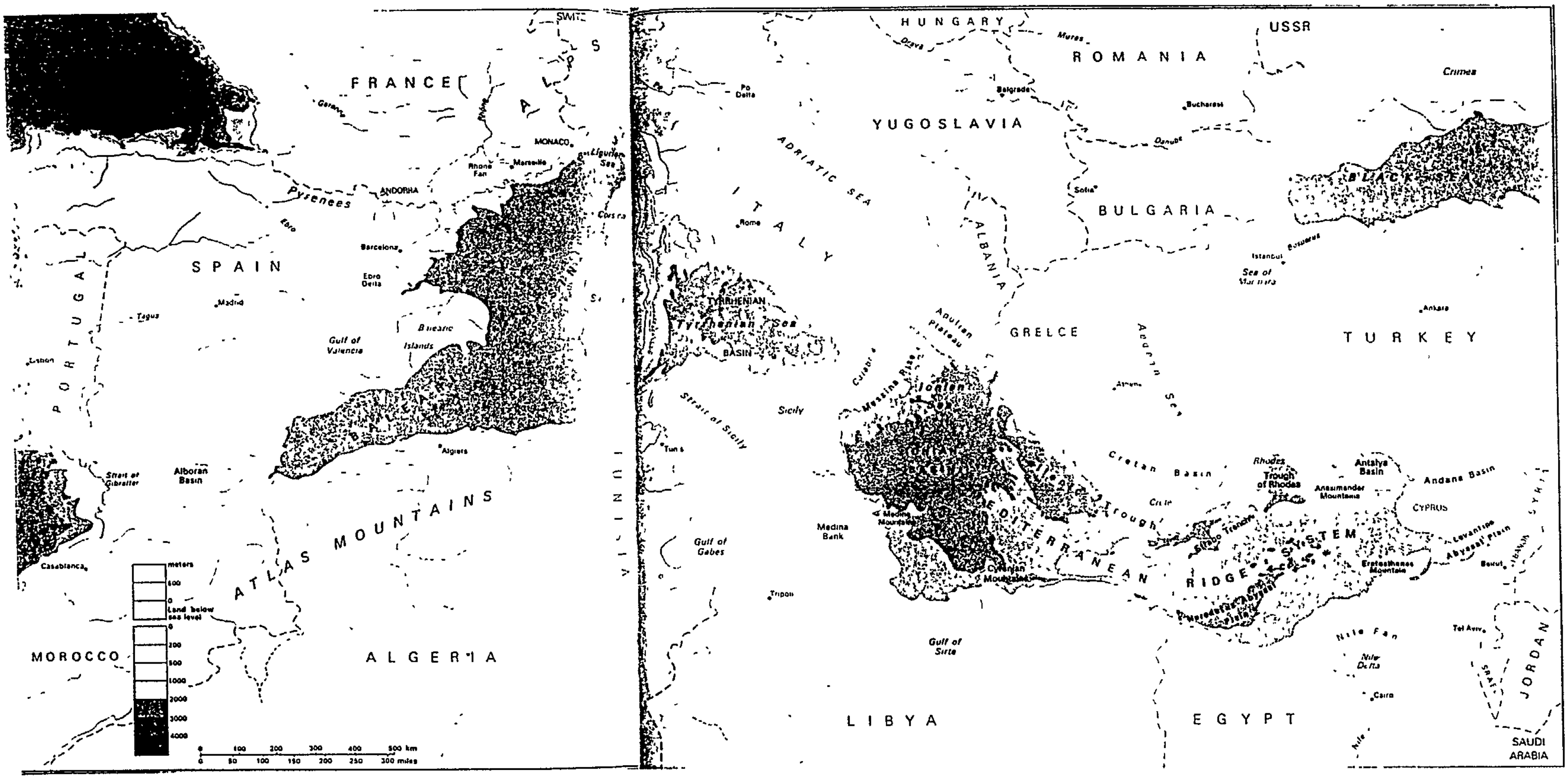

Fig. 7.1. The bathymetry of the Mediterranean Sea [44]

7.2.2. Hydrodynamic characteristics

The water circulation pattern of the Mediterranean Sea, characterised by a delicate and constantly varying response to inflow from the surrounding river systems, evaporation into the atmosphere, seasonal changes in the wind and pressure systems over the sea and a relatively complex bottom topography, is markedly different from most of the major oceans.

The water abstraction by evaporation is three times as much as the inflow from rainfall and runoff and this imbalance is compensated by a constant inflow from the Atlantic Ocean. The incoming water forms a surface current in the upper 75 meters of water, flowing eastward along the coast of North Africa and into the eastern basin, ref. Fig. 7.2; minor branches feed the secondary counter-clockwise circulations in the western basin, the Adriatic and Ionian Seas and the eastern basin. The Mediterranean also receives a modest inflow from the Black Sea as a surface current through the Dardanelles.

As the main surface flow travels to the east it steadily loses momentum and is warmed by the sun. Evaporation causes the salinity to increase and the consequent increase in density causes the water to sink to greater depth. In winter, cold winds from the north cool the surface waters and produce additional sinking of dense water. The denser water of the deeper layers flows steadily back toward the Strait of Gibraltar, where it eventually flows out into the Atlantic. The water flowing from the Mediterranean is considerably more saline than that of the eastern Atlantic and the outflow can be detected as a horizontal tongue of relatively high salinity extending westward at a depth of about 900 meters.

Local stratifications are often observed. In the Aegean Sea at least, thermal, density and salinity stratification is present in spring, summer and fall, with a top layer thickness in the order of a few tens of meters, ref. Fig. 7.3; the distributions of the above parameters with depth become more uniform in winter, ref. Fig. 7.4.

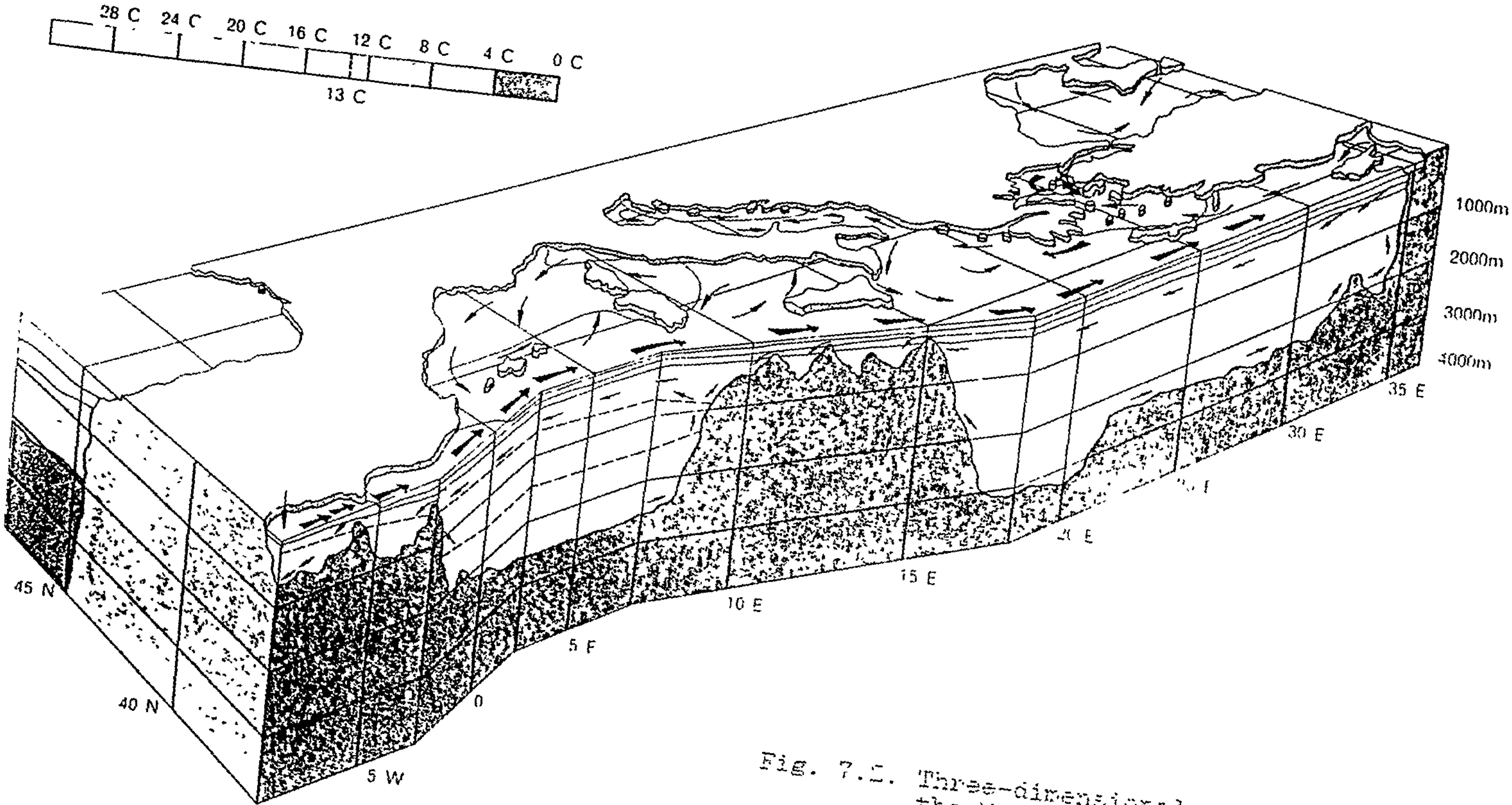

Fig. 7.2. Three-dimensional representation of the Mediterranean water circulation

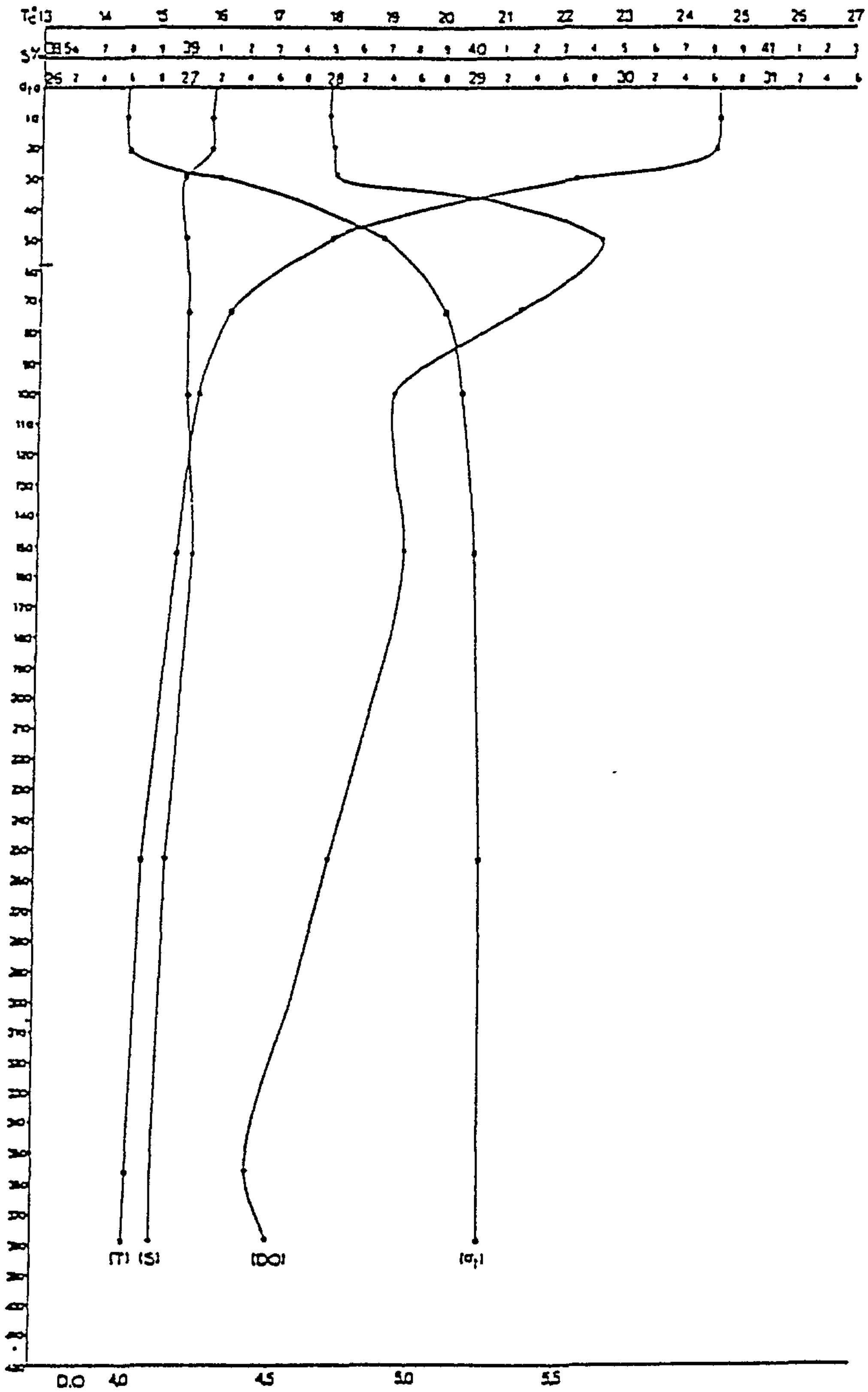

Fig. 7.3. Typical summer vertical distribution of temperature (T), salinity (S), density (σ_t) and dissolved oxygen (DO) in the Aegean Sea [67].

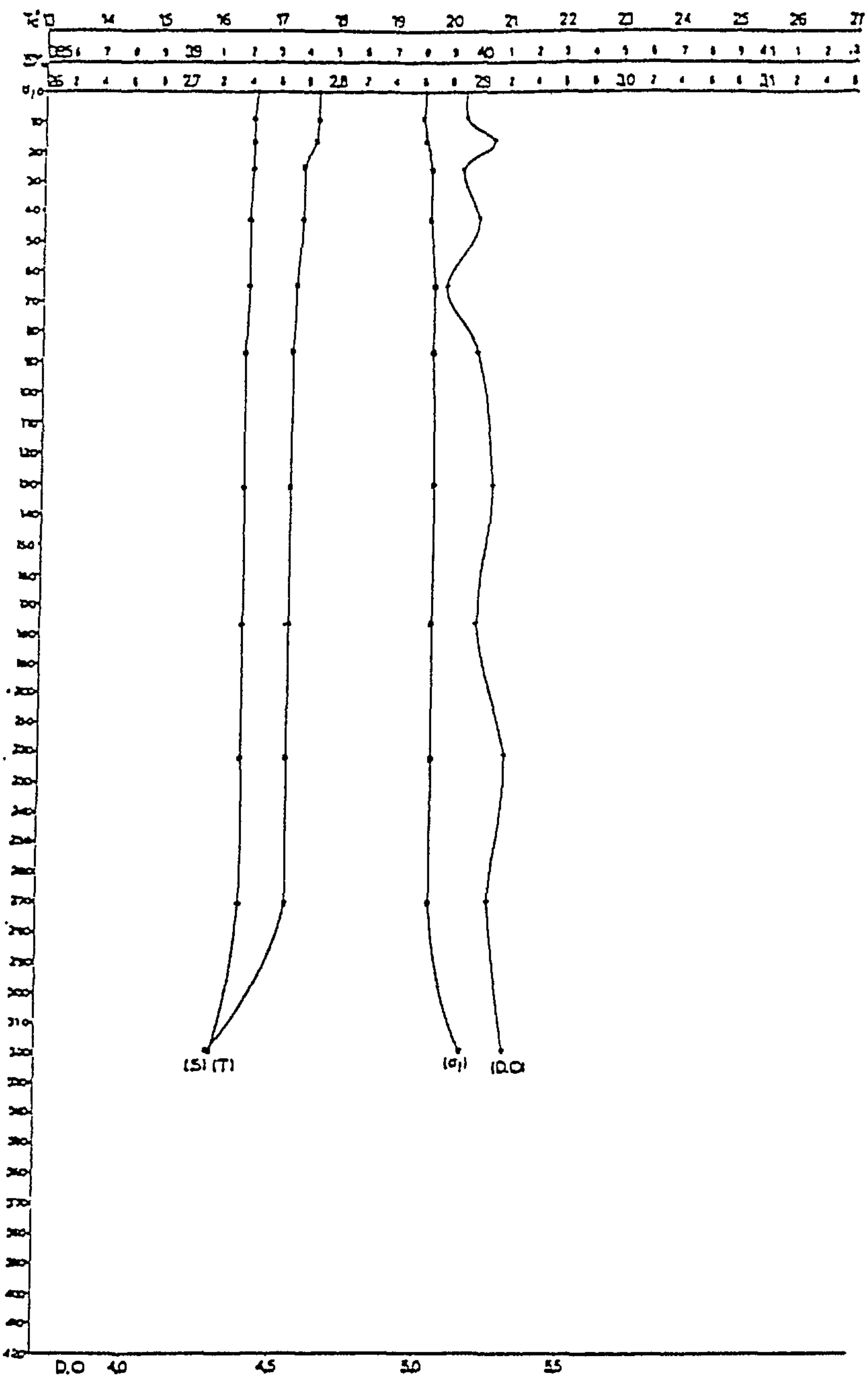

Fig. 7.4. Typical winter vertical distribution of temperature (T), salinity (S), density (σ_t) and dissolved oxygen (DO) in the Aegean Sea [67].

The top layer, which can be observed by remote sensing, is of considerable interest, since:

- it determines the water quality in tidal zones and biotopes,
- it determines the suitability of water for bathing,
- it mostly determines the suitability of water for shellfish production, and
- it partly determines the suitability of water quality for fishing.

The circulation of the Mediterranean Sea is also affected seasonally both by the prevailing winds and by variations in sea level air pressure. Strong winds blowing to east or west may considerably alter the speed of the surface currents, while at times of very high atmospheric pressure, the surface of the Mediterranean may act rather like a diaphragm, forcing water out of the Mediterranean at depth and breathing it in at the surface at an increased rate.

The tides in the Mediterranean are generally small, in the order of 0.3m/sec; thus, there is relatively little flushing of water from bays and inlets. As a result, coastal waters, where most pollution sources are located, tend to become areas of pollution concentration.

7.2.3. Water quality characteristics

Although the Mediterranean Sea is of a semi-enclosed nature, it does not possess a unique water chemistry but is nevertheless considered to have certain characteristic features. In addition to its high salinity and warm water temperatures, the Mediterranean is also typified by low concentrations of biologically important chemical constituents. Due to the absence of deep nutrient-rich Atlantic waters in the Mediterranean circulation, the latter region is also characterised by low nutrient concentrations. As the Mediterranean is only replenished by the upper 150m of Atlantic water, the only increase in the concentration of nutrients is due to river input and agricultural run-off or pollution (Miller 1983).

As a result of the above, the basic biological productivity of the Mediterranean Sea is generally lower than that of most major oceans;

hence, the Mediterranean waters exhibit relatively large values of clarity (or transparency) and a relatively stronger blue colour.

7.2.4. Anthropogenic effects on water quality

7.2.4.1. Changes of flow and quality of river discharges

Estimates of total riverine input of water to the Mediterranean varies between 16,000 m^3/sec and 14,000 m^3/sec (UNEP 1989). The area of the Mediterranean that receives the largest input through river runoff is the Adriatic Sea, followed by the northwest Mediterranean, receiving between them nearly 70% of all the river discharges. These two areas are followed by the Aegean, the Tyrrhenian and the Ionian Seas, with 20%. The North African coast receives less than 10%.

Irrigation and increased evaporation through dam construction may be cited as two forms of human interference which have had marked effects on the water quality of the Mediterranean. The case of the Nile provides a prime example of this interference. At Cairo, the initial natural flow of the Nile was 2,800 m^3/sec. Following the construction of the Aswan dam, this flow was reduced to 1,500 m^3/sec. Due to intensive irrigation activities in the area, much of this does not reach the Mediterranean and hence a major source of fresh water and accompanying nutrients has been lost from the system. This has also occurred in other areas of the Mediterranean where dam construction and diversion of river branches has taken place (eg. Tage-Segura in Spain and Sinni in Italy).

Changes in fresh water input affect water density which in turn may alter the system of currents and mixing conditions. The biological system may also be affected due to changes in nutrient input and suspended matter.

7.2.4.2. Disposal of Urban and Industrial Waste Waters

The Mediterranean Sea acts as a recipient of a variety of liquid waste discharges from urban and industrial sources; in the past few years, both the volume and the composition of such discharges have shown a substantial increase. Agricultural run-off has also been responsible for increased organic and inorganic waste loads.

Waste water disposal into coastal zones has traditionally been effected via marine outfalls without any prior treatment. This system, based on the processes of waste water dilution and dispersion in combination with biochemical mechanisms relating to purification in the sea-water, has resulted in severe ecological impact on many areas. Consequently, there has been an increased trend among Mediterranean countries to install waste water treatment plants in the coastal zones, a measure financed and supported by the EC. Although this may be considered a positive measure, it must nevertheless be noted that the volumes being discharged are still considerable.

According to a study carried out by UNEP (1987), a total of 420 billion m^3/year are discharged from rivers and 2 billion m^3/year and 6 billion m^3/year are discharged from domestic and industrial polluters respectively. Touristic activities in the Mediterranean are considered as yielding 350 million m^3/year. In terms of biochemical oxygen demand, of the 1.5 million tons/year in the coastal areas, 900 thousand tons/year are associated with industrial sources, 500 thousand tons/year are of domestic origin and the other 100 thousand tons/year are associated with agricultural run off. Industrial sources are also responsible for considerable heavy metal discharges, significant for their toxicity and bioaccumulation (UNEP, 1989). Data which has been evaluated for mercury, lead, chromium and zinc, shows that inputs are largely due to river discharges.

7.2.4.3. Disposal of Solid Waste

Sources of municipal solid waste in the Mediterranean are generally related to land use and zoning. The actual quantity of municipal solid waste produced is influenced by a number of factors such as geographical location, season of the year, frequency of collection, and the habits and economic status of the people; marked differences are thus exhibited in the amounts of solid waste produced by different countries of the Mediterranean (UNEP 1987).

Although substantial efforts are being made to reduce the direct disposal of solid wastes into the sea, this is still occurring in various regions of the Mediterranean with detrimental environmental effects (UNEP 1989).

7.2.4.4. Anthropogenic Eutrophication

Eutrophication, in its broadest sense, concerns the situation in which the trophic level is substantially increased beyond the prevailing conditions in a given ecosystem, due to an unusually rich supply of nutrients in the euphotic layer. Natural eutrophication is caused by nutrients originating from upwellings and non-polluted river discharges, while anthropogenic eutrophication is a consequence of pollution mainly by sewage disposal and agricultural runoff containing fertilizers. All future references to eutrophication in the following text refer to anthropogenic eutrophication.

Eutrophication, as reported for embayments and estuaries around the Mediterranean, is mostly associated with the release of untreated domestic and industrial waste water (UNEP 1988b). In the Mediterranean Sea, eutrophication may be considered a local rather than a regional problem. It commonly develops in areas where the rate of input of domestic and industrial waste water exceeds that of the exchange with the open sea. Such areas include: the North Adriatic, Izmir Bay, Elefsis Bay, and the lagoon of Tunis.

The impacts of eutrophication on the marine environment are varied and may range in intensity. The community structure, as regards biomass, specific diversity and dominance of indicator species may be altered. This is often accompanied by algal blooms and 'red tides', triggered by stable stratification, quiet weather and rising temperature. The development of anoxic or azoic conditions are further results of eutrophication.

7.2.4.5. Oil Pollution

Oil pollution of the Mediterranean is substantial and considerable amounts have often been observed. The UNEP/IMO Regional Oil Combating Centre, established in 1976, produces a yearly "List of Alerts and Accidents" which includes information on the date and place of the spill or accident, the source of information, the type and quantity of pollutant, actions taken and consequences of the incident. Between August 1977 and December 1987 a total number of 140 reports were made, consisting of 46 operation discharges and 94 accidents. The four major spills in the Mediterranean, with significant short term and long term impacts on the marine environment, are those of the M/T INDEPENDENTA in the Bosphorus, Turkey (94,600 t in 1979), the M/T IRENES SERENADE in the Bay of Navarino, Greece (40,000 t in 1980), the M/T J.A. LAVALLEJA in Arzew, Algeria (39,000 t in 1980) and the M/T CAVO CAMBANOS off Corsica, France (18,000 t in 1981).

Oil pollution is also generated from deliberate discharge of bilge waters from commercial vessels and ballast waters from tankers. The volumes of oil released at such discharges is much less than that of oil spills, but of much higher frequency; the cumulative effects of such discharges are thus even larger than those from accidental pollution (UNEP 1989) . The control of this type of pollution, which is restricted by the provisions of the MARPOL convention, is very difficult because such discharges can virtually occur anywhere, anytime; continuous surveillance of national and international waters is thus necessary.

Oil spreading as a thin film on water has the effect of interfering with gaseous exchange and hence reducing the rate at which atmospheric oxygen can be adsorbed into deoxygenated water. Most oils have a biochemical oxygen demand related to their mass by a factor of between 0.4 and 0.7; although the direct BOD exerted by oil may be limited, the effect of oil is potentially catastrophic, especially for a partially polluted water body both from the point of view of the retardation of the self-purification process as well as the consequences to marine life.

7.3. Remote sensing potential for the Mediterranean Sea

The potential for remote sensing depends on the particular application and the relevant characteristics of the water body. In the following sections, the potential for each application in the Mediterranean is assessed.

A first general comment is that, since remote sensing observations relate to the top layer, very little can be deduced for the water quality in deeper waters, especially in stratified areas.

(a) **Suspended Solids**

The high water clarity and relatively blue sea colour of the Mediterranean facilitates for the application of remote sensing for the assessment of suspended solids.

In section 6.2.1 it was concluded that the monitoring of suspended solids concentration can be made either by passive sensing in the visible range (preferably at 0.55-0.65μm) from satellites or aircraft or laser backscatter measurement from aircraft.

The assessment of suspended solids concentration is sensitive to the degree of imhomogeneity of suspended particles and spatial and temporal atmospheric variations. Regarding the former, it may be observed that, in the relatively mild wave conditions of the

Mediterranean, suspended particles larger than the clay fraction (i.e. sand and silt) tend to remain in suspension for a few hours or days at the most; thus, with the exception of areas in the vicinity of estuaries and major outfalls, suspended particles will mostly consist of the clay fraction (with diameter below 0.002 mm), i.e. the degree of inhomogeneity will be relatively low. Regarding the latter effect, i.e. that of the spatial and temporal atmospheric variations, it can be expected that the milder meteorological conditions of the Mediterranean also facilitate the application of remote sensing.

The application of laser backscatter for the assessment of suspended solids concentrations has less extensive; more research is required regarding the reliability and accuracy of results obtained by this method.

Thus, the application of remote sensing for the assessment of suspended solids concentrations in the Mediterranean is considered practically feasible with passive sensing in the visible range (preferably at 0.55-0.65μm) from satellite platforms; the technique can yield reliable results for suspended solids concentration in the top layer for most areas, with the exception of the vicinity of estuaries and large waste outfalls, where its application may have reduced accuracy. In-situ observations are of course necessary for calibration and verification of remote sensing observations.

(b) **Temperature**

The observation of the sea surface temperature can be reliably executed with sensors operating in the thermal range or passive radiometers (best in the 10cm to 30cm range), ref. section 6.2.2. The latter have the advantage of all-weather operating ability, but require detailed knowledge for the correction of atmospheric effects; their resolution capabilities are three to four times less than those of multispectral sensors.

On the basis of the above, the use of thermal sensors from satellite platforms appears to be the best approach for the monitoring of sea surface temperature in the Mediterranean, where weather conditions are favourable. Passive radiometers from satellite or airborne platforms, with their lesser resolution capabilities, may also be applied in certain cases where all-weather capability is necessary and for surveying of large areas, where high resolution is not required; in that case attention should be paid however to the necessary corrections.

In-situ observations for calibration and verification of the method are of course necessary, especially if passive radiometers are used.

(c) **Salinity**

The observation of salinity is possible with the use of a passive microwave radiometer; the measurement of salinity with such a technique can be combined with the monitoring of temperature, with the use of a dual-frequency radiometer system. Also, active sensors in the visible & near-IR range, i.e. lasers, may contribute information in this respect, although such an approach cannot be reliably applied on its own.

Satellite platforms should provide adequate resolution for most applications, but the use of airborne sensors may be required in others. In-situ observations for calibration of the method are of course necessary.

(d) **Chlorophyll Concentration**

The oligotrophic character of the Mediterranean, with its associated high water clarity and relatively blue sea colour provides favourable conditions for the application of remote sensing for assessment of chlorophyll and algal concentrations.

As the Mediterranean may generally be classified a "case 1" water type, the ocean colour technique (ref. section 6.2.4.) may be

successfully used from satellite platforms to measure chlorophyll and algal concentrations for most areas. For situations of anthropogenic blooms or excessive growth of macrophytic vegetation, a combination of the ocean colour technique and the fluorescence technique applied from aircraft platforms may be more appropriate, both for resolution and operational requirements (satellites have revisit periods in the order of 10 days, while information may be required on a daily basis during the periods of interest).

In the vicinity of river estuaries and large waste discharges, the presence of suspended solids in appreciable concentrations may render the quantitative assessment of chlorophyll difficult, ref. section 6.2.4. In such waters, referred to as "Case 2" waters, the use of remote sensing for the assessment of chlorophyll concentration is essentially in the experimental stage.

In-situ observations are necessary for calibration and verification of remote sensing observations.

(e) **Oil Pollution**

Remote sensing may be successfully employed to assess the spatial distribution, type and thickness of an oil spill, a subject of much interest in the land-locked Mediterranean. Satellite platforms can be used for larger spills, while airborne systems are necessary for smaller spills due to their greater resolution capabilities.

The equipment which should be deployed includes (ref. section 6.3.1):

- passive sensors operating in the ultraviolet, visible and near-IR range, e.g. photographic systems, nonphotographic cameras and narrow-band multispectral scanners, which are suitable for

the delineation of thick and thin regions of the spill, but are limited to available light & clear weather conditions

- active sensors operating in the visible and near-IR range, e.g. laser fluorosensors , which can assist in the classification of oil spill type, but limited to clear weather conditions

- passive sensors operating in the infrared (thermal) range, e.g. thermal radiometers & scanners, which may assist in delineating oil slick thickness and can operate day or night

- active sensors operating in the microwave range, e.g. radars which can easily detect oil spills and provide information on their thickness, under any weather or light conditions.

The interpretation of the information from each of the above sensors has its restrictions and particularities; for the most complete and reliable result, it is thus advised to operate the sensors jointly. In this context, the development of a geographic information system, in which the information from the various sensors is superimposed, may contribute to the interpretation process.

(f) **Thermal plumes**

As discussed in section 6.2.2., thermal infrared scanner imagery, especially if used from airborne platforms with superior resolution capabilities, may be useful for providing information on the spatial distribution of thermal plumes. The subject of thermal plumes is of relatively less importance in the warm Mediterranean than in other colder seas, but can on occasion become significant in the vicinity of thermal discharges (geothermal plants etc.).

The application of remote sensing would thus contribute to the understanding of the actual spatial distribution of the thermal plume under various meteorological conditions; such information

would be useful for the validation of computer models that predict the plume development.

(g) **Waste Outfalls**

As regards waste outfalls, multispectral scanners from aircraft may be used to detect the point of discharge, to observe the direction of flow and to assess the rate of dispersion of the waste product. In the case of the pollutant causing water discolouration, simple colour photography may also be used; in order to minimize possible atmospheric haze effects, infrared photography is recommended for altitudes above 6,000m.

The correlation of observed spectral signatures with the distribution of pollutants is established on a case-by-case basis and can be of variable reliability; thus, frequent and extensive corroboration with in-situ data is necessary. The application of remote sensing for such phenomena is considered marginal.

(h) **Ocean Dumping**

Ocean dumping from airborne platforms may be detected by photographic systems as well as multispectral scanners. The correlation of observed spectral signatures with the distribution of pollutants is established on a case-by-case basis and can be of variable reliability; thus, frequent and extensive corroboration with in-situ data is necessary.

7.4. Conclusions

On the basis of the above analysis, it may be concluded that the characteristics of the Mediterranean Sea more or less enhance the potential for the application of remote sensing for monitoring of basic water quality parameters.

The most significant application of remote sensing for the Mediterranean is the detection and monitoring of oil spills from

satellite and airborne platforms, including assessment of spill type and thickness. In this context, every effort should be made for the implementation of remote sensing for the detection and coordination of combating of oil pollution incidents.

Another area which may become significant in the near future in certain regions of the Mediterranean is the application of remote sensing for the monitoring and of exceptional algal blooms and macrophyte concentrations; as such, remote sensing may be useful for the coordination of combating efforts from airborne platforms.

Remote sensing may be used for the monitoring of a limited number of water quality parameters in the surface layer from satellite platforms; suspended solids, sea surface temperature, salinity and chlorophyll concentrations can be monitored with satisfactory degrees of accuracy - the latter with the exception of coastal areas with high suspended solids concentrations.

Finally, remote sensing can be applied to observe the effects of point discharges such as thermal plumes, waste discharges and ocean dumping; the reliability of observations is higher for the observation of thermal plumes, where the sea surface temperature is measured, than for the observation of the other discharges, where indirect effects such as sea colour are observed. Airborne platforms are necessary almost in all cases for purposes of adequate resolution.

In all cases examined, it must be stressed that in-situ data of the phenomena observed are essential for calibration and validation of the remote sensing observations.

8. PROPOSALS FOR IMPLEMENTATION

8.1. Introduction

The Mediterranean is a strategic area of joint interest between developed and developing countries and of renewed interest for UNEP, IOC, WMO, UNESCO and the European Community. Within this context and on the basis of information presented in the previous sections of this report, specific proposals can be made relating to the implementation of remote sensing in the Mediterranean Sea for:

- combating of oil pollution
- surveillance for oil pollution
- combating excessive bloom formations
- monitoring of water quality characteristics

As discussed in the previous chapter, the remote sensing of thermal plumes is useful only for study of the relevant diffusion processes; thus no specific proposals for implementation are included for this application.

8.2. Combating Oil Pollution

The most feasible application of remote sensing for the assessment of water quality is the combating of major oil pollution occurrences which are mainly caused by shipping accidents. As mentioned above, remote sensing can provide reliable information about the location, size, oil thickness and pollutant characteristics of oil slicks. Such information, obtained on a daily basis during the combating effort, could be extremely valuable for its good coordination.

The appropriate platform for such applications are aircraft, which can provide daily coverage of the area of interest and have good resolution capabilities. Aircraft for such applications should be fitted with photographic systems or narrow-band multispectral scanners, laser fluorosensors, thermal radiometers & scanners, and radars; the joint operation of these sensors and superposition of information is recommended for the increased effectiveness and reliability of observations. In this context, the development of a

GIS base for superposition of information from several sensors may be useful.

Oil pollution accidents constitute an environmental hazard of major significance which transcends national boundaries; it may thus be justified to pursue an international cooperation for the application of remote sensing in this respect, perhaps under the auspices of the UNEP/IMO Regional Oil Combating Centre in Malta. This international cooperation could include arrangements for existing aircraft of advanced countries fitted with remote sensing equipment to become routinely available to other countries of the Mediterranean for the combating of oil spills. These aircraft would provide the national authorities with daily updates of the pollution situation; running costs for the operation of the aircraft systems would normally be undertaken by the host country.

The contribution of remote sensing to the combating effort could be enhanced with the application of mathematical models for the prediction of the oil spill evolution. Such models could be independently developed under the auspices of UNEP and made available to the authorities of all countries of the Mediterranean. The models are envisioned to have the capability to predict the corresponding evolution of the spill, on the basis of the one-day and five-day weather forecasts by the national meteorological services; in addition, it may be possible to determine at the outset the area that may be probably polluted by the spill, on the basis of historical meteorological information about the region.

8.3. Surveillance for Oil Pollution

The capability of remote sensing to provide reliable information about the location, size, oil thickness and pollutant characteristics of oil slicks can be valuable for the identification of cases of deliberate oil pollution. Such pollution incidents are much smaller in size than those from maritime accidents, but also more frequent; their identification and restriction is thus equally important.

Satellite platforms could be used for spot checks for each area, whenever the satellite is over the area (every 5-10 days); the equipment to be used would primarily include SAR sensors, which have reasonable resolution capabilities and can operate day or night and under almost all weather conditions. An automatic data processing system is envisioned, which would alert its user for potential spill conditions observed. Such a system, which does not entail excessive costs, could be tried on a pilot basis in order to measure its effectiveness.

Alternatively, airborne systems could be considered by for this type of operation. The cost of the monitoring effort, which could focus on the most common shipping routes in the Mediterranean, would nevertheless be considerable: several aircraft would need to be purchased, fitted with the requisite sensors and operated on a continuous basis; revenue could be obtained from the fines imposed on the polluters. However it is clear that the setup of the operation of such a system, which would require multilateral agreement and funding from the countries of the Mediterranean, would be very difficult. Thus, the organisation of an airborne oil pollution system for the Mediterranean, although technically feasible, would have significant implementation difficulties.

8.4. Combating excessive bloom formations

As discussed in section 7.3, remote sensing could be applied for the monitoring of excessive chlorophyll concentrations, such as those occurring in excessive algae blooms or macrophyte concentrations; such occurrences which occur in the warmer months of the year, are of immediate interest because of their potential to significantly damage tourism.

For such applications, satellite or airborne platforms could be used. Satellite platforms equipped with multispectral scanners can efficiently provide the general overview of the affected area; airborne platforms equipped with multispectral scanners and laser fluorometers could, if available, provide more detailed and reliable

information. Since the frequency of such extreme situations is still relatively low in the oligotrophic Mediterranean and the consequences are not as devastating as those from oil pollution, the organisation of airborne platforms for this application alone does not appear to be justified; however, since the sensor payload used by aircraft platforms used for combating of oil pollution is adequate also for the monitoring of chlorophyll, the same aircraft could be used for both applications.

8.5. Monitoring of Inherent Water Quality

Remote sensing may be used for the efficient spatial monitoring of a limited number of water quality parameters in the surface layer from satellite platforms; suspended solids, sea surface temperature, salinity and chlorophyll concentrations can be monitored with satisfactory degrees of accuracy - the latter with the exception of coastal areas with high suspended solids concentrations.

In this context, remote sensing may complement water quality monitoring programmes focused on the above parameters by reducing the number of in-situ observations needed at any particular time. If the monitoring programme is also targeted at other water quality parameters, however, the benefit from remote sensing becomes marginal, since the extensive in-situ work has to be done anyway.

Satellite platforms are most suitable for such activities, which normally would cover large areas and a number of measurements over a period of one or more years; the required sensor payload includes multispectral scanners, for monitoring of suspended solids, sea surface temperature and chlorophyll concentrations, and microwave radiometers, for monitoring of salinity (and temperature).

Depending on the exact nature of the research being carried out and the relevant precision requirements, different sensor types and operational platforms could be used. For example, the Landsat-4 and Landsat-5, which are fitted with an MSS and an alternate repeat cycle of 8 days, may be used to measure sea surface temperature. However,

if more frequent and accurate measurements of sea surface temperature are required, perhaps the ERS 1 which is fitted with an Along Track Scanning Radiometer and a 3 day repeat cycle may be considered more appropriate.

9. CONCLUSIONS

The conclusions of this final report can be summarised as follows:

1. The electromagnetic reflectance and emission properties of surface features can provide useful information on their condition. Remote sensing is a technique for the efficient and synoptic retrieval of such information. Sources of electromagnetic energy that can be used for remote sensing are:
   - the sun's energy reflected from earth's surface,
   - the energy emitted from the earth, and
   - generated energy from active sensors.

2. Remote sensing operations may be carried from any platform above the earth; airplanes and satellites are the most common. The selection of the appropriate platform depends on desired resolution, frequency of observation (satellites have revisit times in the order of 5 to 20 days) and cost (for airborne platforms the full operational cost is covered by the application).

3. A broad range of sophisticated equipment is currently available for the collection & processing of information by remote sensing; the interpretation however of the collected information still lags behind the sophistication of the equipment, especially for microwave sensors.

4. An appreciable number of remote sensing satellites have been deployed in the last decade; many more will be deployed in the coming decade, as the European Remote Sensing programme gets underway and several other countries such as China, India etc. increase their efforts. There is a clear trend towards commercialisation of the remote sensing programmes, with emphasis on customer service and economic viability of the operating organisations, particularly in Europe, Japan and the U.S.

5. The application of remote sensing should always be complemented by reference data obtained in-situ for the analysis and

interpretation of remotely sensed data. On the basis of this reference data, the images obtained by remote sensing images can be appropriately interpreted.

6. The potential for application of remote sensing for water quality assessment is restricted to the surface (or near-surface) values of relatively few parameters. Remote sensing can be successfully applied for the observation and assessment of:
   - detection and monitoring of oil pollution,
   - monitoring of exceptional algal blooms,
   - monitoring of suspended solids concentration
   - monitoring of sea surface temperature
   - monitoring of salinity
   - monitoring of phytoplankton concentration,
   - observation of the effects of thermal plumes, and
   - observation of the effects of waste outfalls and ocean dumping.

7. The Mediterranean is characterised by low nutrient concentrations, warm waters, low tidal flows and local seasonal stratifications, which are favourable for the application of remote sensing for assessment of water quality.

8. The Mediterranean is burdened by significant urban, industrial and agricultural pollution from land and oil pollution at sea; moreover, as a land-locked area with an abundance of biotopes and increasing tourism, it is sensitive to pollution. Thus, the contribution of remote sensing to the monitoring of water quality in the Mediterranean can be very valuable.

9. It is proposed that remote sensing be used in the Mediterranean for the following applications:
   (a) combating of oil pollution, with airborne platforms which could be coordinated by the UNEP/IMO Regional Oil Combating Centre in Malta
   (b) surveillance for oil pollution, from satellite platforms with automatic data processing facilities; for the present, the execution of a pilot programme for the assessment of the feasibility of this application is recommended.

(c) combating excessive bloom formations, from satellites or with the same airborne equipment as that used for oil pollution combating

(d) as a supplement to in-situ monitoring efforts of water quality characteristics such as suspended solids, sea surface temperature, salinity and chlorophyll concentrations (the latter with the exception of coastal areas with high suspended solids concentrations).

10. The contribution of remote sensing to the combating effort could be enhanced with the application of mathematical models for the prediction of the oil spill evolution. Such models could be independently developed under the auspices of UNEP and made available to the authorities of all countries of the Mediterranean.

10. REFERENCES

[1] American Society of Photogrammetry (1983) "Manual of Remote Sensing", Editor in Chief R.N. Colwell.

[2] Alpers W. & H. Huehnerfuss (1987), "Radar signatures of oil films floating on the sea surface", Proceedings of IGARSS'87 Symposium, Ann Arbor

[3] Bagheri S. & R.A. Dios, "Chlorophyll-a estimation in New Jersey's coastal waters using Thematic Mapper data", Int. J. Remote Sensing, Vol.11, No.2

[4] Ben Moussa H. et al (1989), "Teledetection des algues macrophytes de l'Archipel de Molene (France). Radiometrie de terrain et application aux donnees du satellite SPOT", Int. J. Remote Sensing, Vol.10, No.1

[5] Bowker D.E. & S.R. LeCroy (1985), "Bright spot analysis of ocean-dump plumes using LANDSAT MSS", Int. J. Remote Sensing, Vol.6, No.5

[6] Bristow M.P.F. et al ((1985), "Airborne laser fluorosensor survey of the Columbia and Snake rivers: simultaneous measurements of chlorophyll, dissolved organics and optical attentuation", Int. J. Remote Sensing, Vol.6, No.11

[7] Bukata R.P. et al (1988), "Particulate concentrations in Lake St. Clair as recorded by a shipborne multispectral optical monitoring system", Remote Sensing of Environment 25, Elsevier Science Publishing Co., Inc.

[8] Catts G.P. et al (1985), "Remote Sensing of tidal chlorophyll-a variations in estuaries", Int. J. Remote Sensing, Vol.6, No.11

[9] Chen Y-W & R.S. Berkowitz (1987), "Inverse synthetic aperture radar imaging techniques for sea-surface targets", Proceedings of IGARSS'87 Symposium, Ann Arbor

[10] Cracknell A., L. Hayes & H.Wei Gen (1990), "Remote Sensing Yearbook 1990", Taylor & Francis

[11] Cracknell A.P. & W.G. Huang (1988), "Surface currents off the west coast of Ireland studied from satellite images", Int. J. Remote Sensing, Vol.9, No.3

[12] Cracknell A.P., Ibrahim M. (1988), "Bathymetry studies on the coastal waters (Red Sea) of Jeddah, Saudi Arabia, using Shuttle MOMS-01 data", International Journal of Remote Sensing, Vol. 9, No. 6.

[13] Curran P.J. & W.B. Wilkinson (1985), "Mapping the concentration and dispersion of dye from a long sea outfall using digitized aerial photography", Int. J. Remote Sensing, Vol.6, No.11

[14] Curran P.J. et al (1987), "Multispectral remote sensing of nearshore suspended sediments: a pilot study", Int. J. Remote Sensing, Vol.8, No.1

[15] Davies P.A. & J.A. Charlton (1986), "Remote sensing of coastal discharge sites using SPOT-simulation data", Int. J. Remote Sensing, Vol.7, No.6

[16] De Chateau-Thierry P. (1987), "Poseidon radar altimeter oceanographic remote sensing", Proceedings of IGARSS'87 Symposium, Ann Arbor

[17] Drenth, F. - Wijsmuller Engineering b.v.and Wensink G.J.& Boer S. - Delft Hydraulics (1989) "Remote Sensing for Marine Activities", BCRS Report No. WENG 87.081/2.

[18] Dupouy C. et al (1988), "Satellite detected cyanobacteria bloom in the southwestern tropical Pacific. Implication for oceanic nitrogen fixation", Int. J. Remote Sensing, Vol.9, No.3

[19] Dwivedi R.M. & A. Narain (1987), "Remote Sensing Letters: Remote sensing of phytoplankton. An attempt from the Landsat Thematic Mapper", Int. J. Remote Sensing, Vol.8, No.10

[20] Esaias W.E. (1987), "Use of satellite ocean color observations for basin and global scale studies of biochemical cycles", Proceedings of IGARSS'87 Symposium, Ann Arbor

[21] Exton R.J. et al (1983), "Laboratory analysis of techniques for remote sensing of estuarine parameters using laser excitation", Appl. Optics, Vol.22, 54

[22] Finley R.J. & R.W. Baumgardner (1980), "Interpretation of surface-water circulation, Aransas Pass, Texas, using Landsat imagery", Remote Sensing of Environment 10, Elsevier Science Publishing Co., Inc.

[23] Fischer J. (1985), "On the information content of multispectral radiance measurements over an ocean", Int. J. Remote Sensing, Vol.6, No.5

[24] Gagliardini D.A., H. Karszenbaum, R. Legeckis & V. Klemas (1984), "Application of Landsat MSS, NOAA/TIROS AVHRR, and Nimbus CZCS to Study the La Plata River and Its Interaction with the Ocean", Remote Sensing of Environment 15:21, Elsevier Science Publishing Co., Inc.

[25] Gordon H.R. and McCluney W.R. (1975), "Estimation of the depth of sunlight penetration in the sea for remote sensing", Appl. Optics Vol.22, 20

[26] Gower J.F.R & G.A. Borstad (1990), "Mapping of phytoplankton by solar-stimulated fluoroscence using and imaging spectrometer", Int. J. Remote Sensing, Vol.11, No.2

[27] Hepplewhite C.L. (1989), "Remote observation of the sea surface and atmosphere", Int. J. Remote Sensing, Vol.10, Nos. 4 & 5

[28] Hong J-K & J. Iisaka (1982), "Coastal environment change analysis by Landsat MSS data", Remote Sensing of Environment 12, Elsevier Science Publishing Co., Inc.

[29] Hord R.M.(1986), "Remote Sensing: Methods and Applications", John Wiley & Sons

[30] Houghton W.M. et al (1983), "Field investigation of techniques for remote laser sensing of oceanographic parameters", Remote Sensing of Environment 13, Elsevier Science Publishing Co., Inc.

[31] Jobson D.J. et al (1980), Remote sensing of benthic microalgal biomass with a tower-mounted multispectral scanner", Remote Sensing of Environment 9, Elsevier Science Publishing Co., Inc.

[32] Johannessen J. et al (1989), "Remote sensing and model simulation studies of the Norwegian coastal current during the algal bloom in May 1988", Int. J. Remote Sensing, Vol.10, No.12

[33] Karidis M., Georgopoulos D., Ignatiadou L., Nikolaidou A., Papathanasiou E., Siokou-Fragou I. (1988) "Ecological and Oceanographical Study of the Rhodes Marine Area - Technical Report", National Centre for Marine Research, Hydrobiological Station of Rhodes.

[34] Kim B-G (1987), "Surface water velocity measurements on Delavan Lake using aerial photographs", Photogrammetric Engineering and Remote Sensing, Vol.53, No.6, American Society for Photogrammetry and Remote Sensing

[35] Koepke P. (1985), "The reflectance factors of a rough ocean with foam-comment on 'Remote sensing of the sea state using the 0.8-1.1μm spectral band' by L. Wald and J.M. Monget", Int. J. Remote Sensing, Vol.6, No.5

[36] Kozu T. et al (1987), "Observations of oil slicks on the ocean by X-band slar", Proceedings of IGARSS'87 Symposium, Ann Arbor

[37] Lasker R. et al (1981), "The use of satellite infrared imagery for describing ocean processes in relation to spawning of the

northern anchovy (engraulis mordax)", Remote Sensing of Environment 11, Elsevier Science Publishing Co., Inc.

[38] Lathrop R.G. & T.M. Lillesand (1989), "Monitoring water quality and river plume transport in Green Bay, Lake Michigan with SPOT-1 imagery", Photogrammetric Engineering and Remote Sensing, Vol.55, No.3, American Society for Photogrammetry and Remote Sensing

[39] Le Borgne P. et al (1988), "Sea surface parameters inferred from meteorological satellite data at CMS, Lannion. New products and projects", Int. J. Remote Sensing, Vol.9, Nos. 10 & 11

[40] Lillesand T.M., Kiefer R.W. (1987), "Remote Sensing and Image Interpretation", J. Wiley & Sons.

[41] Lindell L.T. et al (1985), "Mapping of coastal-water turbidity using LANDSAT imagery", Int. J. Remote Sensing, Vol.6, No.5

[42] Lopez Garcia M.J. & V. Caselles (1990), "A multi-temporal study of chlorophyll-a concentration in the Albufera lagoon of Valencia, Spain, using Thematic Mapper data", Int. J. Remote Sensing, Vol.11, No.2

[43] Meulstee C. et al (1988), "Aerial photography for biomass assessment in the intertidal zone", Int. J. Remote Sensing, Vol.9, Nos. 10 & 11

[44] Miller A. (1983), "The Mediteranean Sea, A. Physical Aspects. In: B.H. Ketchum (Ed.), "Estuaries and Enclosed Seas", Elsevier, pp 219-238

[45] Miller R.K. & T.C. Walker (1989), "Survey on Remote Sensing", Survey Report 81, Future Technology Surveys, Inc.

[46] Nelepo B.A. & G.A. Grishin (1988), "Ocean dynamics observed from space using Salyut, Cosmos and Meteor satellites", Int. J. Remote Sensing, Vol.9, No.6

[47] Platt A. (1986), "Primary production of the ocean water column as a function of surface light intensity: algorithms for remote sensing", Deep Sea Research Vol. 33, 149-163

[48] Prangsma G.J. & J.N. Roozekrans (1989), "Using NOAA AVHRR imagery in assessing water quality parameters", Int. J. Remote Sensing, Vol.10, Nos 4 & 5

[49] Rand McNally Atlas of the Oceans (1979), Rand McNally & Co.

[50] Rimmer J.C et al (1987), "Mapping of water quality in coastal waters using Airborne Thematic Mapper data", Int. J. Remote Sensing, Vol.8, No.1

[51] Ritchie J.C. & C.M. Cooper (1987), "Comparison of Landsat MSS pixel array sizes for estimating water quality", Photogrammetric Engineering and Remote Sensing, Vol.53, No.11, American Society for Photogrammetry and Remote Sensing

[52] Sabins F.F. (1987), "Remote Sensing: Principles and interpretation", W.H. Freeman & Company

[53] Sathyendranath S. et al (1989), "A three-component model of ocean colour and its application to remote sensing of phytoplankton pigments in coastal waters", Int. J. Remote Sensing, Vol.10, No.8

[54] Sgavetti M. & C. Ferrari (1988), "The use of TM data for the study of a modern deltaic depositional system", Int. J. Remote Sensing, Vol.9, Nos. 10 & 11

[55] Sheres D. & K.E. Kenyon (1990), "An eddy, coastal jets and incoming swell all interacting near Pt Conception, California", Int. J. Remote Sensing, Vol.11, No.1

[56] Shimoda H., M. Etaya, T. Sakata, L. Goda & K. Stelczer (1986), "Water quality monitoring of Lake Balaton using LANDSAT MSS data", Symposium on Remote Sensing for Resources Development and Environmental Management

[57] Singh S.M et al (1985), "Evaluation of sensitivity decay of Coastal Zone Colour Scanner (CZCS) detectors by comparison with in situ near-surface radiance measurements", Int. J. Remote Sensing, Vol.6, No.5

[58] Spitzer D & R.W.J. Dirks (1987), "Bottom influence on the reflectance of the sea", Int. J. Remote Sensing, Vol.8, No.3

[59] Szekielda K-H., D. McGinnis, B. Ambroziak, P. McPlain & D. Clark (1988), "Satellite Observations over the North Sea, Mitt. Geol.-Palaeont. Inst. Univ. hamburg, S.1-33

[60] Tassan S. & B. Sturm (1986), "An algorithm for the retrieval of sediment content in turbid coastal waters from CZCS data", Int. J. Remote Sensing, Vol.7, No.5

[61] Thie J. & C. Wachmann (1974), "Remote sensing for environmental monitoring and impact assessment", International Society for Photogrammetry, Proceedings of Symposium on Remote Sensing and Photo Interpretation,, Vol.1

[62] Topliss B.J. and Platt T. (1986), "Passive fluorescence and photosynthesis in the ocean: implications for remote sensing", Deep Sea Research Vol.33, 849-864

[63] Tyler M.A. & R.P. Stumpf (1989), "Feasibility of using satellites for detection of kinetics of small phytoplankton blooms in estuaries: tidal and migrational effects", Remote Sensing of Environment 27, Elsevier Science Publishing Co., Inc.

[64] United Nations Environment Programme, (1987) "Preliminary report on Blue Plan Scenarios" (UNEP/W6.171/3), Blue Plan, Sophia, Antipolis

[65] United Nations Environment Programme, (1988) "Mediterranean Action PLan: The Blue Plan - Executive Summary and Suggestions for Action".

[66] United Nations Environment Programme, (1988), "Statistics concerning marine oil pollution in the Mediterranean", Regional Oil Combating Centre, Malta

[67] United Nations Environment Programme, (1988), "Eutrophication in the Mediterranean Sea: Receiving Capacity and Monitoring of Long Term Effects", MAP Technical Reports Series No.21

[68] United Nations Environment Programme, (1989), "State of the Mediterranean Marine Environment", MAP Technical Reports Series No.28

[69] Vodacek A. (1989), Synchronous fluoroscence spectroscopy of dissolved organic matter in surface waters: Application to airborne remote sensing", Remote Sensing of Environment 30, Elsevier Science Publishing Co., Inc.

[70] Wadsworth A. & P. Piau (1987), "Spot, a satellite for oceanography", Proceedings of IGARSS'87 Symposium, Ann Arbor

[71] Wagle B.G. (1985), "Distribution and dispersion of turbid waters on the western continental shelf of India - An interpretation of LANDSAT images", Int. J. Remote Sensing, Vol.6, No.11

[72] Welch R. et al (1988), "Remote sensing and geographic information system techniques for aquatic resource evaluation", Photogrammetric Engineering and Remote Sensing, Vol.54, No.2, American Society for Photogrammetry and Remote Sensing

[73] Wensink G.J. et al (1989), "Remote Sensing for Marine Activities", Delft Hydraulics ECRS rapport no:WENG 87.081/2 November 1989

[74] Wyatt L.R. (1988), "Significant waveheight measurement with h.f. radar", Int. J. Remote Sensing, Vol.9, No.6

[75] Yokota T. et al (1987), "Simultaneous estimation of the distribution of radiation absorbers and sea surface temperature from

infrared 3-band images", Proceedings of IGARSS'87 Symposium, Ann Arbor

[76] Zheng Q. et al (1984), "Dynamics of the slope water off New England and its influence on the Gulf Stream as inferred from satellite IRR data", Remote Sensing of Environment 15, Elsevier Science Publishing Co., Inc.

[77] Zibordi G. et al. (1990), "Ocean colour analysis in coastal waters by airborne sensors", Int. J. Remote Sensing, Vol.11, No.5

PUBLICATIONS OF THE MAP TECHNICAL REPORTS SERIES

1. UNEP/IOC/WMO: Baseline studies and monitoring of oil and petroleum hydrocarbons in marine waters (MED POL I). MAP Technical Reports Series No. 1. UNEP, Athens, 1986 (96 pages) (parts in English, French or Spanish only).

2. UNEP/FAO: Baseline studies and monitoring of metals, particularly mercury and cadmium, in marine organisms (MED POL II). MAP Technical Reports Series No. 2. UNEP, Athens, 1986 (220 pages) (parts in English, French or Spanish only).

3. UNEP/FAO: Baseline studies and monitoring of DDT, PCBs and other chlorinated hydrocarbons in marine organisms (MED POL III). MAP Technical Reports Series No. 3. UNEP, Athens, 1986 (128 pages) (parts in English, French or Spanish only).

4. UNEP/FAO: Research on the effects of pollutants on marine organisms and their populations (MED POL IV). MAP Technical Reports Series No. 4. UNEP, Athens, 1986 (118 pages) (parts in English, French or Spanish only).

5. UNEP/FAO: Research on the effects of pollutants on marine communities and ecosystems (MED POL V). MAP Technical Reports Series No. 5. UNEP, Athens, 1986 (146 pages) (parts in English or French only).

6. UNEP/IOC: Problems of coastal transport of pollutants (MED POL VI). MAP Technical Reports Series No. 6. UNEP, Athens, 1986 (100 pages) (English only).

7. UNEP/WHO: Coastal water quality control (MED POL VII). MAP Technical Reports Series No. 7. UNEP, Athens, 1986 (426 pages) (parts in English or French only).

8. UNEP/IAEA/IOC: Biogeochemical studies of selected pollutants in the open waters of the Mediterranean (MED POL VIII). MAP Technical Reports Series No. 8. UNEP, Athens, 1986 (42 pages) (parts in English or French only).

8\. Add. UNEP: Biogeochemical studies of selected pollutants in the open waters of the Mediterranean MED POL VIII). Addendum, Greek Oceanographic Cruise 1980. MAP Technical Reports Series No. 8, Addendum. UNEP, Athens, 1986 (66 pages) (English only).

9. UNEP: Co-ordinated Mediterranean pollution monitoring and research programme (MED POL - PHASE I). Final report, 1975-1980. MAP Technical Reports Series No. 9. UNEP, Athens, 1986 (276 pages) (English only).

10. UNEP: Research on the toxicity, persistence, bioaccumulation, carcinogenicity and mutagenicity of selected substances (Activity G). Final reports on projects dealing with toxicity (1983-85). MAP Technical Reports Series No. 10. UNEP, Athens, 1987 (118 pages) (English only).

11. UNEP: Rehabilitation and reconstruction of Mediterranean historic settlements. Documents produced in the first stage of the Priority Action (1984-1985). MAP Technical Reports Series No. 11. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1986 (158 pages) (parts in English or French only).

12. UNEP: Water resources development of small Mediterranean islands and isolated coastal areas. Documents produced in the first stage of the Priority Action (1984-1985). MAP Technical Reports Series No. 12. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (162 pages) (parts in English or French only).

13. UNEP: Specific topics related to water resources development of large Mediterranean islands. Documents produced in the second phase of the Priority Action (1985-1986). MAP Technical Reports Series No. 13. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (162 pages) (parts in English or French only).

14. UNEP: Experience of Mediterranean historic towns in the integrated process of rehabilitation of urban and architectural heritage. Documents produced in the second phase of the Priority Action (1986). MAP Technical Reports Series No. 14. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (500 pages) (parts in English or French only).

15. UNEP: Environmental aspects of aquaculture development in the Mediterranean region. Documents produced in the period 1985-1987. MAP Technical Reports Series No. 15. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (101 pages) (English only).

16. UNEP: Promotion of soil protection as an essential component of environmental protection in Mediterranean coastal zones. Selected documents (1985-1987). MAP Technical Reports Series No. 16. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (424 pages) (parts in English or French only).

17. UNEP: Seismic risk reduction in the Mediterranean region. Selected studies and documents (1985-1987). MAP Technical Reports Series No. 17. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (247 pages) (parts in English or French only).

18. UNEP/FAO/WHO: Assessment of the state of pollution of the Mediterranean Sea by mercury and mercury compounds. MAP Technical Reports Series No. 18. UNEP, Athens, 1987 (354 pages) (English and French).

19. UNEP/IOC: Assessment of the state of pollution of the Mediterranean Sea by petroleum hydrocarbons. MAP Technical Reports Series No. 19. UNEP, Athens, 1988 (130 pages) (English and French).

20. UNEP/WHO: Epidemiological studies related to environmental quality criteria for bathing waters, shellfish-growing waters and edible marine organisms (Activity D). Final report on project on relationship between microbial quality of coastal seawater and health effects (1983-86). MAP Technical Reports Series No. 20. UNEP, Athens, 1988 (156 pages) (English only).

21. UNEP/UNESCO/FAO: Eutrophication in the Mediterranean Sea: Receiving capacity and monitoring of long-term effects. MAP Technical Reports Series No. 21. UNEP, Athens, 1988 (200 pages) (parts in English or French only).

22. UNEP/FAO: Study of ecosystem modifications in areas influenced by pollutants (Activity I). MAP Technical Reports Series No. 22. UNEP, Athens, 1988 (146 pages) (parts in English or French only).

23. UNEP: National monitoring programme of Yugoslavia, Report for 1983-1986. MAP Technical Reports Series No. 23. UNEP, Athens, 1988 (223 pages) (English only).

24. UNEP/FAO: Toxicity, persistence and bioaccumulation of selected substances to marine organisms (Activity G). MAP Technical Reports Series No. 24. UNEP, Athens, 1988 (122 pages) (parts in English or French only).

25. UNEP: The Mediterranean Action Plan in a functional perspective: A quest for law and policy. MAP Technical Reports Series No. 25. UNEP, Athens, 1988 (105 pages) (English only).

26. UNEP/IUCN: Directory of marine and coastal protected areas in the Mediterranean Region. Part I - Sites of biological and ecological value. MAP Technical Reports Series No. 26. UNEP, Athens, 1989 (196 pages) (English only).

27. UNEP: Implications of expected climate changes in the Mediterranean Region: An overview. MAP Technical Reports Series No. 27. UNEP, Athens, 1989 (52 pages) (English only).

28. UNEP: State of the Mediterranean marine environment. MAP Technical Reports Series No. 28. UNEP, Athens, 1989 (225 pages) (English only).

29. UNEP: Bibliography on effects of climatic change and related topics. MAP Technical Reports Series No. 29. UNEP, Athens, 1989 (143 pages) (English only).

30. UNEP: Meteorological and climatological data from surface and upper measurements for the assessment of atmospheric transport and deposition of pollutants in the Mediterranean Basin: A review. MAP Technical Reports Series No. 30. UNEP, Athens, 1989 (137 pages) (English only).

31. UNEP/WMO: Airborne pollution of the Mediterranean Sea. Report and proceedings of a WMO/UNEP Workshop. MAP Technical Reports Series No. 31. UNEP, Athens, 1989 (247 pages) (parts in English or French only).

32. UNEP/FAO: Biogeochemical cycles of specific pollutants (Activity K). MAP Technical Reports Series No. 32. UNEP, Athens, 1989 (139 pages) (parts in English or French only).

33. UNEP/FAO/WHO/IAEA: Assessment of organotin compounds as marine pollutants in the Mediterranean. MAP Technical Reports Series No. 33. UNEP, Athens, 1989 (185 pages) (English and French).

34. UNEP/FAO/WHO: Assessment of the state of pollution of the Mediterranean Sea by cadmium and cadmium compounds. MAP Technical Reports Series No. 34. UNEP, Athens, 1989 (175 pages) (English and French).

35. UNEP: Bibliography on marine pollution by organotin compounds. MAP Technical Reports Series No. 35. UNEP, Athens, 1989 (92 pages) (English only).

36. UNEP/IUCN: Directory of marine and coastal protected areas in the Mediterranean region. Part I - Sites of biological and ecological value. MAP Technical Reports Series No. 36. UNEP, Athens, 1990 (198 pages) (French only).

37. UNEP/FAO: Final reports on research projects dealing with eutrophication and plankton blooms (Activity H). MAP Technical Reports Series No. 37. UNEP, Athens, 1990 (74 pages) (parts in English or French only).

38. UNEP: Common measures adopted by the Contracting Parties to the Convention for the Protection of the Mediterranean Sea against pollution. MAP Technical Reports Series No. 38. UNEP, Athens, 1990 (100 pages) (English, French, Spanish and Arabic).

39. UNEP/FAO/WHO/IAEA: Assessment of the state of pollution of the Mediterranean Sea by organohalogen compounds. MAP Technical Reports Series No. 39. UNEP, Athens, 1990 (224 pages) (English and French).

40. UNEP/FAO: Final reports on research projects (Activities H,I and J). MAP Technical Reports Series No. 40. UNEP, Athens, 1990 (125 pages) (English and French).

41. UNEP: Wastewater reuse for irrigation in the Mediterranean region. MAP Technical Reports Series No. 41. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1990 (330 pages) (English and French).

42. UNEP/IUCN: Report on the status of Mediterranean marine turtles. MAP Technical Reports Series No. 42. UNEP, Athens, 1990 (204 pages) (English and French).

43. UNEP/IUCN/GIS Posidonia: Red Book "Gérard Vuignier", marine plants, populations and landscapes threatened in the Mediterranean. MAP Technical Reports Series No. 43. UNEP, Athens, 1990 (250 pages) (French only).

44. UNEP: Bibliography on aquatic pollution by organophosphorus compounds. MAP Technical Reports Series No. 44. UNEP, Athens, 1990 (98 pages) (English only).

45. UNEP/IAEA: Transport of pollutants by sedimentation: Collected papers from the first Mediterranean Workshop (Villefranche-sur-Mer, France, 10-12 December 1987). MAP Technical Reports Series No. 45. UNEP, Athens, 1990 (302 pages) (English only).

46. UNEP/WHO: Epidemiological studies related to environmental quality criteria for bathing waters, shellfish-growing waters and edible marine organisms (Activity D). Final report on project on relationship between microbial quality of coastal seawater and rotarus-induced gastroenterities among bathers (1986-88). MAP Technical Reports Series No.46, UNEP, Athens, 1991 (64 pages) (English only).

47. UNEP: Jellyfish blooms in the Mediterranean. Proceedings of the II workshop on jellyfish in the Mediterranean Sea. MAP Technical Reports Series No.47. UNEP, Athens, 1991 (320 pages) (parts in English or French only).

48. UNEP/FAO: Final reports on research projects (Activity G). MAP Technical Reports Series No. 48. UNEP, Athens, 1991 (126 pages) (parts in English or French only).

49. UNEP/WHO: Biogeochemical cycles of specific pollutants. Survival of pathogens. Final reports on research projects (Activity K). MAP Technical Reports Series No. 49. UNEP, Athens, 1991 (71 pages) (parts in English or French only).

50. UNEP: Bibliography on marine litter. MAP Technical Reports Series No. 50. UNEP, Athens, 1991 (62 pages) (English only).

51. UNEP/FAO: Final reports on research projects dealing with mercury, toxicity and analytical techniques. MAP Technical Reports Series No. 51. UNEP, Athens, 1991 (166 pages) (parts in English or French only).

52. UNEP/FAO: Final reports on research projects dealing with bioaccumulation and toxicity of chemical pollutants. MAP Technical Reports Series No. 52. UNEP, Athens, 1991 (86 pages) (parts in English or French only).

53. UNEP/WHO: Epidemiological studies related to environmental quality criteria for bathing waters, shellfish-growing waters and edible marine organisms (Activity D). Final report on epidemiological study on bathers from selected beaches in Malaga, Spain (1988-1989). MAP Technical Reports Series No. 53. UNEP, Athens, 1991 (127 pages) (English only).

54. UNEP/WHO: Development and testing of sampling and analytical techniques for monitoring of marine pollutants (Activity A): Final reports on selected microbiological projects. MAP Technical Reports Series No. 54. UNEP, Athens, 1991 (83 pages) (English only).

55. UNEP/WHO: Biogeochemical cycles of specific pollutants (Activity K): Final report on project on survival of pathogenic organisms in seawater. MAP Technical Reports Series No. 55. UNEP, Athens, 1991 (95 pages) (English only).

56. UNEP/IOC/FAO: Assessment of the state of pollution of the Mediterranean Sea by persistent synthetic materials which may float, sink or remain in suspension. MAP Technical Reports Series No. 56. UNEP, Athens, 1991 (113 pages) (English and French).

57. UNEP/WHO: Research on the toxicity, persistence, bioaccumulation, carcinogenicity and mutagenicity of selected substances (Activity G): Final reports on projects dealing with carcinogenicity and mutagenicity. MAP Technical Reports Series No. 57. UNEP, Athens, 1991 (59 pages) (English only).

58. UNEP/FAO/WHO/IAEA: Assessment of the state of pollution of the Mediterranean Sea by organophosphorus compounds. MAP Technical Reports Series No. 58. UNEP, Athens, 1991 (122 pages) (English and French).

59. UNEP/FAO/IAEA: Proceedings of the FAO/UNEP/IAEA Consultation Meeting on the Accumulation and Transformation of Chemical contaminants by Biotic and Abiotic Processes in the Marine Environment (La Spezia, Italy, 24-28 September 1990), edited by G.P. Gabrielides. MAP Technical Reports Series No. 59. UNEP, Athens, 1991 (392 pages) (English only).

60. UNEP/WHO: Development and testing of sampling and analytical techniques for monitoring of marine pollutants (Activity A): Final reports on selected microbiological projects (1987-1990). MAP Technical Reports Series No. 60. UNEP, Athens, 1991 (76 pages) (parts in English or French only).

61. UNEP: Integrated Planning and Management of the Mediterranean Coastal Zones. Documents produced in the first and second stage of the Priority Action (1985-1986). MAP Technical Reports Series No. 61. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1991 (437 pages) (parts in English or French only).

62. UNEP/IAEA: Assessment of the State of Pollution of the Mediterranean Sea by Radioactive Substances. MAP Technical Reports Series No. 62, UNEP, Athens, 1992 (133 pages) (English and French).

63. UNEP/WHO: Biogeochimical cycles of specific pollutants (Activity K) - Survival of Pathogens - Final reports on Research Projects (1989-1991). MAP Technical Reports Series No. 63, UNEP, Athens, 1992 (86 pages) (French only).

64. UNEP/WMO: Airborne Pollution of the Mediterranean Sea. Report and Proceedings of the Second WMO/UNEP Workshop. MAP Technical Reports Series No. 64, UNEP, Athens, 1992 (246 pages) (English only).

65. UNEP: Directory of Mediterranean Marine Environmental Centres. MAP Technical Reports Series No. 65, UNEP, Athens, 1992 (351 pages) (English and French).

66. UNEP/CRU: Regional Changes in Climate in the Mediterranean Basin Due to Global Greenhouse Gas Warming. MAP Technical Reports Series No. 66, UNEP, Athens, 1992 (172 pages) (English only).

PUBLICATIONS "MAP TECHNICAL REPORTS SERIES"

1. PNUE/COI/OMM: Etudes de base et surveillance continue du pétrole et des hydrocarbures contenus dans les eaux de la mer (MED POL I). MAP Technical Reports Series No. 1. UNEP, Athens, 1986 (96 pages) (parties en anglais, français ou espagnol seulement).

2. PNUE/FAO: Etudes de base et surveillance continue des métaux, notamment du mercure et du cadmium, dans les organismes marins (MED POL II). MAP Technical Reports Series No. 2. UNEP, Athens, 1986 (220 pages) (parties en anglais, français ou espagnol seulement).

3. PNUE/FAO: Etudes de base et surveillance continue du DDT, des PCB et des autres hydrocarbures chlorés contenus dans les organismes marins (MED POL III). MAP Technical Reports Series No. 3. UNEP, Athens, 1986 (128 pages) (parties en anglais, français ou espagnol seulement).

4. PNUE/FAO: Recherche sur les effets des polluants sur les organismes marins et leurs peuplements (MED POL IV). MAP Technical Reports Series No. 4. UNEP, Athens, 1986 (118 pages) (parties en anglais, français ou espagnol seulement).

5. PNUE/FAO: Recherche sur les effets des polluants sur les communautés et écosystèmes marins (MED POL V). MAP Technical Reports Series No. 5. UNEP, Athens, 1986 (146 pages) (parties en anglais ou français seulement).

6. PNUE/COI: Problèmes du transfert des polluants le long des côtes (MED POL VI). MAP Technical Reports Series No. 6. UNEP, Athens, 1986 (100 pages) (anglais seulement).

7. PNUE/OMS: Contrôle de la qualité des eaux côtières (MED POL VII). MAP Technical Reports Series No. 7. UNEP, Athens, 1986 (426 pages) (parties en anglais ou français seulement).

8. PNUE/AIEA/COI: Etudes biogéochimiques de certains polluants au large de la Méditerranée (MED POL VIII). MAP Technical Reports Series No. 8. UNEP, Athens, 1986 (42 pages) (parties en anglais ou français seulement).

8. Add. PNUE: Etudes biogéochimiques de certains polluants au large de la Méditerranée (MED POL VIII). Addendum, Croisière Océanographique de la Grèce 1980. MAP Technical Reports Series No. 8, Addendum. UNEP, Athens, 1986 (66 pages) (anglais seulement).

9. PNUE: Programme coordonné de surveillance continue et de recherche en matière de pollution dans la Méditerranée (MED POL -PHASE I). Rapport final, 1975-1980. MAP Technical Reports Series No. 9. UNEP, Athens, 1986 (276 pages) (anglais seulement).

10. PNUE: Recherches sur la toxicité, la persistance, la bioaccumulation, la cancérogénicité et la mutagénicité de certaines substances (Activité G). Rapports finaux sur les projets ayant trait à la toxicité (1983-85). MAP Technical Reports Series No. 10. UNEP, Athens, 1987 (118 pages) (anglais seulement).

11. PNUE: Réhabilitation et reconstruction des établissements historiques méditerranéens. Textes rédigés au cours de la première phase de l'action prioritaire (1984-1985). MAP Technical Reports Series No. 11. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1986 (158 pages) (parties en anglais ou français seulement).

12. PNUE: Développement des ressources en eau des petites îles et des zones côtières isolées méditerranéennes. Textes rédigés au cours de la première phase de l'action prioritaire (1984-1985). MAP Technical Reports Series No. 12. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (162 pages) (parties en anglais ou français seulement).

13. PNUE: Thèmes spécifiques concernant le développement des ressources en eau des grandes îles méditerranéennes. Textes rédigés au cours de la deuxième phase de l'action prioritaire (1985-1986). MAP Technical Reports Series No. 13. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (162 pages) (parties en anglais ou français seulement).

14. PNUE: L'expérience des villes historiques de la Méditerranée dans le processus intégré de réhabilitation du patrimoine urbain et architectural. Documents établis lors de la seconde phase de l'Action prioritaire (1986). MAP Technical Reports Series No. 14. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (500 pages) (parties en anglais ou français seulement).

15. PNUE: Aspects environnementaux du développement de l'aquaculture dans la région méditerranéenne. Documents établis pendant la période 1985-1987. MAP Technical Reports Series No. 15. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (101 pages) (anglais seulement).

16. PNUE: Promotion de la protection des sols comme élément essentiel de la protection de l'environnement dans les zones côtières méditerranéennes. Documents sélectionnés (1985-1987). MAP Technical Reports Series No. 16. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (424 pages) (parties en anglais ou français seulement).

17. PNUE: Réduction des risques sismiques dans la région méditerranéenne. Documents et études sélectionnés (1985-1987). MAP Technical Reports Series No. 17. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1987 (247 pages) (parties en anglais ou français seulement).

18. PNUE/FAO/OMS: Evaluation de l'état de la pollution de la mer Méditerranée par le mercure et les composés mercuriels. MAP Technical Reports Series No. 18. UNEP, Athens, 1987 (354 pages) (anglais et français).

19. PNUE/COI: Evaluation de l'état de la pollution de la mer Méditerranée par les hydrocarbures de pétrole. MAP Technical Reports Series No. 19. UNEP, Athens, 1988 (130 pages) (anglais et français).

20. PNUE/OMS: Etudes épidémiologiques relatives aux critères de la qualité de l'environnement pour les eaux servant à la baignade, à la culture de coquillages et à l'élevage d'autres organismes marins comestibles (Activité D). Rapport final sur le projet sur la relation entre la qualité microbienne des eaux marines côtières et les effets sur la santé (1983-86). MAP Technical Reports Series No. 20. UNEP, Athens, 1988 (156 pages) (anglais seulement).

21. PNUE/UNESCO/FAO: Eutrophisation dans la mer Méditerranée: capacité réceptrice et surveillance continue des effets à long terme. MAP Technical Reports Series No. 21. UNEP, Athens, 1988 (200 pages) (parties en anglais ou français seulement).

22. PNUE/FAO: Etude des modifications de l'écosystème dans les zones soumises à l'influence des polluants (Activité I). MAP Technical Reports Series No. 22. UNEP, Athens, 1988 (146 pages) (parties en anglais ou français seulement).

23. PNUE: Programme national de surveillance continue pour la Yougoslavie, Rapport pour 1983-1986. MAP Technical Reports Series No. 23. UNEP, Athens, 1988 (223 pages) (anglais seulement).

24. PNUE/FAO: Toxicité, persistance et bioaccumulation de certaines substances vis-à-vis des organismes marins (Activité G). MAP Technical Reports Series No. 24. UNEP, Athens, 1988 (122 pages) (parties en anglais ou français seulement).

25. PNUE: Le Plan d'action pour la Méditerranée, perspective fonctionnelle; une recherche juridique et politique. MAP Technical Reports Series No. 25. UNEP, Athens, 1988 (105 pages) (anglais seulement).

26. PNUE/UICN: Répertoire des aires marines et côtières protégées de la Méditerranée. Première partie - Sites d'importance biologique et écologique. MAP Technical Reports Series No. 26. UNEP, Athens, 1989 (196 pages) (anglais seulement).

27. PNUE: Implications des modifications climatiques prévues dans la région méditerranéenne: une vue d'ensemble. MAP Technical Reports Series No. 27. UNEP, Athens, 1989 (52 pages) (anglais seulement).

28. PNUE: Etat du milieu marin en Méditerranée. MAP Technical Reports Series No. 28. UNEP, Athens, 1989 (225 pages) (anglais seulement).

29. PNUE: Bibliographie sur les effets des modifications climatiques et sujets connexes. MAP Technical Reports Series No. 29. UNEP, Athens, 1989 (143 pages) (anglais seulement).

30. PNUE: Données météorologiques et climatologiques provenant de mesures effectuées dans l'air en surface et en altitude en vue de l'évaluation du transfert et du dépôt atmosphériques des polluants dans le bassin méditerranéen: un compte rendu. MAP Technical Reports Series No. 30. UNEP, Athens, 1989 (137 pages) (anglais seulement).

31. PNUE/OMM: Pollution par voie atmosphérique de la mer Méditerranée. Rapport et actes des Journées d'étude OMM/PNUE. MAP Technical Reports Series No. 31. UNEP, Athens, 1989 (247 pages) (parties en anglais ou français seulement).

32. PNUE/FAO: Cycles biogéochimiques de polluants spécifiques (Activité K). MAP Technical Reports Series No. 32. UNEP, Athens, 1989 (139 pages) (parties en anglais ou français seulement).

33. PNUE/FAO/OMS/AIEA: Evaluation des composés organostanniques en tant que polluants du milieu marin en Méditerranée. MAP Technical Reports Series No. 33. UNEP, Athens, 1989 (185 pages) (anglais et français).

34. PNUE/FAO/OMS: Evaluation de l'état de la pollution de la mer Méditerranée par le cadmium et les composés de cadmium. MAP Technical Reports Seri es No. 34. UNEP, Athens, 1989 (175 pages) (anglais et français).

35. PNUE: Bibliographie sur la pollution marine par les composés organostanniques. MAP Technical Reports Series No. 35. UNEP, Athens, 1989 (92 pages) (anglais seulement).

36. PNUE/UICN: Répertoire des aires marines et côtières protégées de la Méditerranée. Première partie - Sites d'importance biologique et écologique. MAP Technical Reports Series No. 36. UNEP, Athens, 1990 (198 pages) (français seulement).

37. PNUE/FAO: Rapports finaux sur les projets de recherche consacrés à l'eutrophisation et aux efflorescences de plancton (Activité H). MAP Technical Reports Series No. 37. UNEP, Athens, 1990 (74 pages) (parties en anglais ou français seulement).

38. PNUE: Mesures communes adoptées par les Parties Contractantes à la Convention pour la protection de la mer Méditerranée contre la pollution. MAP Technical Reports Series No. 38. UNEP, Athens, 1990 (100 pages) (anglains, français, espagnol et arabe).

39. PNUE/FAO/OMS/AIEA: Evaluation de l'état de la pollution par les composés organohalogénés. MAP Technical Reports Series No. 39. UNEP, Athens, 1990 (224 pages) (anglais et français).

40. PNUE/FAO: Rapports finaux sur les projets de recherche (Activités H, I et J). MAP Technical Reports Series No. 40. UNEP, Athens, 1990 (125 pages) (anglais et français).

41. PNUE: Réutilisation agricole des eaux usées dans la région méditerranéenne. MAP Technical Reports Series No. 41. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1990 (330 pages) (anglais et français).

42. PNUE/UICN: Rapport sur le statut des tortues marines de Méditerranée. MAP Technical Reports Series No. 42. UNEP, Athens, 1990 (204 pages) (anglais et français).

43. PNUE/UICN/GIS Posidonie: Livre rouge "Gérard Vuignier" des végétaux, peuplements et paysages marins menacés de Méditerranée. MAP Technical Reports Series No. 43. UNEP, Athens, 1990 (250 pages) (français seulement).

44. PNUE: Bibliographie sur la pollution aquatique par les composés organophosphorés. MAP Technical Reports Series No. 44. UNEP, Athens, 1990 (98 pages) (anglais seulement).

45. PNUE/AIEA: Transfert des polluants par sédimentation: Recueil des communications présentées aux premières journées d'études méditerranéennes (Villefranche-sur- Mer, France, 10-12 décembre 1987). MAP Technical Reports Series No. 45. UNEP, Athens, 1990 (302 pages) (anglais seulement).

46. PNUE/OMS: Etudes épidémiologiques relatives aux critères de la qualité de l'environnement pour les eaux servant à la baignade, à la culture de coquillages et à l'élevage d'autres organismes marins comestibles (Activité D). Rapport final sur le projet sur la relation entre la qualité microbienne des eaux marines côtières et la gastroentérite provoquée par le rotavirus entre les baigneurs (1986-88). MAP Technical Reports Series No.46. UNEP, Athens, 1991 (64 pages) (anglais seulement).

47. PNUE: Les proliférations de méduses en Méditerannée. Actes des IIèmes journées d'étude sur les méduses en mer Méditerranée. MAP Technical Reports Series No.47. UNEP, Athens, 1991 (320 pages) (parties en anglais ou français seulement).

48. PNUE/FAO: Rapports finaux sur les projets de recherche (Activité G). MAP Technical Reports Series No. 48. UNEP, Athens, 1991 (126 pages) (parties en anglais ou français seulement).

49. PNUE/OMS: Cycles biogéochimiques de polluants spécifiques. Survie des Pathogènes. Rapports finaux sur les projets de recherche (activité K). MAP Technical Reports Series No. 49. UNEP, Athens, 1991 (71 pages) (parties en anglais ou français seulement).

50. PNUE: Bibliographie sur les déchets marins. MAP Technical Reports Series No. 50. UNEP, Athens, 1991 (62 pages) (anglais seulement).

51. PNUE/FAO: Rapports finaux sur les projets de recherche traitant du mercure, de la toxicité et des techniques analytiques. MAP Technical Reports Series No. 51. UNEP, Athens, 1991 (166 pages) (parties en anglais ou français seulement).

52. PNUE/FAO: Rapports finaux sur les projets de recherche traitant de la bioaccumulation et de la toxicité des polluants chimiques. MAP Technical Reports Series No. 52. UNEP, Athens, 1991 (86 pages) (parties en anglais ou français seulement).

53. PNUE/OMS: Etudes épidémiologiques relatives aux critères de la qualité de l'environnement pour les eaux servant à la baignade, à la culture de coquillages et à l'élevage d'autres organismes marins comestibles (Activité D). Rapport final sur l'étude épidémiologique menée parmi les baigneurs de certaines plages à Malaga, Espagne (1988-1989). MAP Technical Reports Series No. 53. UNEP, Athens, 1991 (127 pages) (anglais seulement).

54. PNUE/OMS: Mise au point et essai des techniques d'échantillonnage et d'analyse pour la surveillance continue des polluants marins (Activité A): Rapports finaux sur certains projets de nature microbiologique. MAP Technical Reports Series No. 54. UNEP, Athens, 1991 (83 pages) (anglais seulement).

55. PNUE/OMS: Cycles biogéochimiques de polluants spécifiques (Activité K): Rapport final sur le projet sur la survie des microorganismes pathogènes dans l'eau de mer. MAP Technical Reports Series No. 55. UNEP, Athens, 1991 (95 pages) (anglais seulement).

56. PNUE/COI/FAO: Evaluation de l'état de la pollution de la mer Méditerranée par les matières synthétiques persistantes qui peuvent flotter, couler ou rester en suspension. MAP Technical Reports Series No. 56. UNEP, Athens, 1991 (113 pages) (anglais et français).

57. PNUE/OMS: Recherches sur la toxicité, la persistance, la bioaccumulation, la cancérogénicité et la mutagénicité de certaines substances (Activité G). Rapports finaux sur les projets ayant trait à la cancérogénicité et la mutagénicité. MAP Technical Reports Series No. 57. UNEP, Athens, 1991 (59 pages) (anglais seulement).

58. PNUE/FAO/OMS/AIEA: Evaluation de l'état de la pollution de la mer Méditerranée par les composés organophosphorés. MAP Technical Reports Series No. 58. UNEP, Athens, 1991 (122 pages) (anglais et français).

59. PNUE/FAO/AIEA: Actes de la réunion consultative FAO/PNUE/AIEA sur l'accumulation et la transformation des contaminants chimiques par les processus biotiques et abiotiques dans le milieu marin (La Spezia, Italie, 24-28 septembre 1990), publié sous la direction de G.P. Gabrielides. MAP Technical Reports Series No. 59. UNEP, Athens, 1991 (392 pages) (anglais seulement).

60. PNUE/OMS: Mise au point et essai des techniques d'échantillonnage et d'analyse pour la surveillance continue des polluants marins (Activité A): Rapports finaux sur certains projets de nature microbiologique (1987-1990). MAP Technical Reports Series No. 60. UNEP, Athens, 1991 (76 pages) (parties en anglais ou français seulement).

61. PNUE: Planification intégrée et gestion des zones côtières méditerranéennes. Textes rédigés au cours de la première et de la deuxième phase de l'action prioritaire (1985-1986). MAP Technical Reports Series No. 61. UNEP, Priority Actions Programme, Regional Activity Centre, Split, 1991 (437 pages) (parties en anglais ou français seulement).

62. PNUE/AIEA: Evaluation de l'état de la pollution de la mer Méditerranée par les substances radioactives. MAP Technical Reports Series No. 62, UNEP, Athens, 1992 (133 pages) (anglais et français).

63. PNUE/OMS: Cycles biogéochimiques de polluants spécifiques (Activité K) - Survie des pathogènes - Rapports finaux sur les projets de recherche (1989-1991). MAP Technical Reports Series No. 63, UNEP, Athens, 1992 (86 pages) (français seulement).

64. PNUE/OMM: Pollution par voie atmosphérique de la mer Méditerranée. Rapport et actes des deuxièmes journées d'études OMM/PNUE. MAP Technical Reports Series No. 64, UNEP, Athens, 1992 (246 pages) (anglais seulement).

65. PNUE: Répertoire des centres relatifs au milieu marin en Méditerranée. MAP Technical Reports Series No. 65, UNEP, Athens, 1992 (351 pages) (anglais et français).

66. PNUE/CRU: Modifications régionales du climat dans le bassin méditerranéen résultant du réchauffement global dû aux gaz à effet de serre. MAP Technical Reports Series No. 66, UNEP, Athens, 1992 (172 pages) (anglais seulement).

Issued and printed by:

Mediterranean Action Plan
United Nations Environment Programme

Additional copies of this and other publications issued by
the Mediterranean Action Plan of UNEP can be obtained from:

Co-ordinating Unit for the Mediterranean Action Plan
United Nations Environment Programme
Leoforos Vassileos Konstantinou, 48
P.O.Box 18019
11610 Athens
GREECE

Publié et imprimé par:

Plan d'action pour la Méditerranée
Programme des Nations Unies pour l'Environnement

Des exemplaires de ce document ainsi que d'autres
publication de Plan d'action pour la Méditerranée
de PNUE peuvent être obtenus de:

Unité de coordination du Plan d'action pour la Méditerranée
Programme des Nations Unies pour l'Environnement
Leoforos Vassileos Konstantinou, 48
B.P. 18019
11610 Athènes
GRECE