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MERIS

The Medium Resolution Imaging Spectrometer

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Report of the MERIS Scientific Advisory Group,
March 1995

Parts A and B

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FOREWORD

The increasing relevance of Earth observation as a tool for understanding and managing our planetary ecosystem has long been recognised in the scientific and political communities. The European Space Agency (ESA) has been steadily developing its plans to contribute to the realisation of a global environmental monitoring system in space by the end of this decade. In particular, an early commitment was made by ESA to provide the international Earth sciences community with an instrument dedicated to the study of biological phenomena and processes in the upper ocean — which dominates three quarters of the planetary surface and plays a crucial role in shaping its climate and ecology — as well as to investigations of terrestrial and atmospheric processes.

To formulate the requirements for a system to observe the visible and near-infrared region of the spectrum with a high resolution instrument, ESA called for the cooperation of a group of scientists, recognised as experts in the field of environmental remote sensing. The group was instructed to review the current situation from the point of view of both potential applications and instrument developments, and to advise ESA on the design and use of this new instrument. The aim was to compile an exhaustive report, which would lay the foundations for both the scientific and technical performance of MERIS.

Valuable inputs were received during a two-day workshop organised by ESA in 1991, which was attended by about fifty international experts. The findings of this workshop are compiled in a brief report, attached in Annex X-I.

The Science Advisory Group was asked to bear in mind the long-term objectives and global aspects underlying the concept of an observation system such as MERIS. Further, the Science Advisory Group was asked to make recommendations on scientific requirements and priorities, in the light of possibilities offered by European technology. The outcome of this work is presented in this report. This four-part report, which describes the end-to-end concept of MERIS, has evolved over a considerable time span. It should be borne in mind that the scientific aspects, as well as many of the technical aspects, have changed and undergone further development in the meantime.

Michael Rast,
Convenor of the MERIS Science Advisory
Group.

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PREFACE

The medium resolution imaging spectrometer, MERIS, forms part of the core instrument payload of ESA's environmental research satellite Envisat–1. MERIS is funded by ESA. The Report of the MERIS Science Advisory Group comprises of four parts describing the end-to-end concept of the MERIS system as part of the Envisat–1 system. These are:

Part A	Scientific Objectives and Requirements;
Part B	Instrument Concept and Mission Constraints;
Part C	Data Products and Processing within the Envisat–1 Ground Segment;
Part D	Calibration and Validation of the MERIS Data Products.

Parts A and B of this report are the first of four Parts which describe the complete MERIS system, starting from the mission objectives and scientific requirements, through to the elements of the ground segment of the MERIS mission and the validation of the MERIS data products.

Part A describes the mission objectives and scientific requirements. It also addresses the priorities resulting from our current understanding of the problems, as well as the algorithms and analysis tools which will be used to generate the data products needed to address these issues. Part B describes the MERIS instrument design and the specifications enabling it to deliver the required data at the appropriate resolutions and accuracies.

Part C gives an overview of the MERIS data products, their different levels of processing, and descriptions of the algorithms implemented to derive those geophysical products. Part C will also contain a general outline of the MERIS ground segment.

Part D describes the in-orbit calibration of MERIS, including the on-board instrument calibration as well as the vicarious calibration philosophy. This Part also focuses on techniques of validating the different data products derived from raw MERIS data.

Parts A and B share a single binding. Parts C and D will be published at a later date.

Past and present members of the MERIS Science Advisory Group are given in the table on the facing page.

Part A: Scientific Objectives and Requirements

PART A

CONTENTS

INTRODUCTION

Recent developments in the Earth sciences have revealed the overwhelming complexity of our planetary ecosystem. This view of the Earth has led to the derivation of a number of theoretical and/or empirical models, aimed at describing the various ecosystem components and their interactions. In particular, the biosphere has attracted a great deal of attention due to its role in the energy, water and carbon cycles. The models relating to this subject make use of the long term environmental data bases acquired so far, including those referring to climate dynamics, in order to forecast the evolution of the terrestrial ecosystem.

It is unfortunate that when dealing with the fluid components of our habitat, namely the atmosphere and the oceans, the available data bases are generally inadequate. Important interactions take place in both the atmosphere and the oceans over a wide range of space and time scales, which can be assessed only through repeated observations at appropriate levels of detail. Given the difficulty of performing adequate measurements to monitor long term trends, it is imperative to use environmental monitoring tools capable of sensing on a planetary scale, without neglecting the fine structure of many events. This justifies the need for sensors providing wide spatial coverage with a relatively high spatial resolution. In addition these tools must be capable of repeating their assessment over short time periods, ranging from hours to days in some cases, but also for longer periods stretching out to years or even decades.

The era of remote sensing of ocean colour from space began in 1978 with the successful launch of the coastal zone colour scanner (CZCS) on board the Unites States' Nimbus-7 spacecraft. This mission, designed as a proof-of-concept, was intended to last only one year, but the sensor continued to transmit data over selected oceanic test sites until early 1986, ultimately generating a valuable time series of data on the optical properties of the marine surface layers for most of the world's oceans.

Researchers all over the world have been working for more than a decade on the analysis of the CZCS data set, thus gaining a better understanding of the bio-geochemical patterns of the sea and their driving mechanisms. The results of the CZCS experiment, which are still being interpreted today, have shown the great potential of ocean colour observations for the detection of planktonic algae, their biomass and possibly their photosynthetic potential. Other marine variables include dissolved organic materials and total suspended load (sediments of terrigenous nature from coastal runoff, river discharges or bottom resuspension). Applications have been documented in the assessment of phytoplankton concentration and patchiness, blooms, eutrophication events, the correlation of these events with run-off or pollution sources, with weather patterns, even with the exploitation of marine resources (i.e. tourism or fisheries). In addition, the monitoring of freshwater flows, possible discharges of pollutants, areas of environmental risk, sediment transport and near coastal erosion patterns can also be addressed by analysing these observations.

It is now apparent that the specific contribution of the remote sensing of ocean colour lies in monitoring the marine environment. The discipline of bio-optical oceanography, devoted to the assessment of surface optical properties and water constituents and leading to phytoplankton biomass and productivity via the measurement of the concentration of various pigments, has developed significantly over the past decade. The impact of its findings on the understanding of global climate is also becoming increasingly evident. In fact, the marine component of the carbon cycle plays an important role in shaping the climatic variability of the Earth which is a subject of growing concern.

The demands of the European scientific community for a global environmental monitoring system, whose technical characteristics enable the extraction of quantitative information from ocean colour data, as well as for documentation of the state and evolution of the atmosphere and land surfaces, led to the conception of MERIS. The design of MERIS is driven by the radiometric, spectral and spatial requirements of ocean colour observations. The oceanographic mission is radiometrically the most demanding in terms of low radiance levels and their associated high signal-to-noise ratios. The oceanographic requirements will satisfy the signal-to-noise ratio requirements of the land and cloud science communities, for which radiance levels are higher. The instrument, therefore, will be capable of detecting the low levels of radiation emerging from the ocean (linked to the water constituents by the processes of absorption and scattering), in addition to acquiring information about the atmospheric medium through which the observation is made as well as terrestrial environments. The characteristics of MERIS will also be of great value for the retrieval of information on land surfaces, in particular that of global biomass. Given the high scientific and operational priority that MERIS observations will have in the coming years, and given the fact that the international scientific community has lacked remotely sensed information about the global ocean colour since 1986, the ESA adopted, as one of its goals, the deployment of MERIS during the Envisat-1 mission. The Envisat-1 platform is currently scheduled for launch in 1999, when it will carry in orbit a suite of complementary instruments for the global monitoring of the Earth's environment.

The primary task of MERIS is to monitor the marine biophysical and biochemical variables over a large area at a very high spectral resolution. Because the signal measured in space over the oceans comes primarily from the atmosphere, this objective requires a very accurate characterisation of the state of the atmosphere. The second task of MERIS is therefore to provide accurate, reliable information on specific atmospheric constituents, such as water vapour, aerosols and cloud properties. The third task of this sensor is to support terrestrial observations, which can take advantage of the spatial and spectral resolution of this advanced sensor to address scientific issues at a scale or resolution hitherto unattainable.

Specifically, it is envisaged that studies based on MERIS data will make significant contributions in the following areas:

(i) *bio-optical oceanography*:
assessment of surface optical properties and water constituents, leading to phytoplankton biomass and productivity via the estimate of various pigment concentrations and suspended matter;

(ii) *atmospheric properties*:
investigation of the nature and amount of various atmospheric constituents, especially column water vapour, cloud and aerosol properties, to provide both accurate atmospheric corrections for surface studies and an improved characterisation of the atmosphere;

(iii) *land surface processes*:
characterisation of biosphere properties, terrestrial production, and the monitoring of environmental change.

The foundations of the plan to build an imaging spectrometer were initially laid down in 1984 by ESA's Ocean Colour Working Group, which specified the requirements for an ocean colour sensor together with the ESA Scientific Advisory Group for MERIS, created in 1988. These requirements have been refined and extended to cover the broader mission described above, while keeping in mind the constraints imposed by the polar orbiting platform and the capabilities of an imaging spectrometer.

A.1 SCIENTIFIC BACKGROUND, OBJECTIVES AND APPLICATIONS

A.1.1 BACKGROUND

Throughout history, man has sought to adapt or modify the environment. As the human population has grown, his activities have produced significant perturbations to the natural processes of the environment and have provided some of the forces shaping the evolution of that environment.

Cumulative changes over the last few centuries, and present rates of change in the chemical composition of the atmosphere, ground water and soils and the ecological balance of many ecosystems, have now been documented (see for example: National Aeronautics and Space Administration (NASA) 1988 and National Research Council (NRC) 1986 and 1988). An increasing awareness of these issues and the fear of serious consequences for humanity has prompted the scientific community to set up major international efforts to understand the causes and implications of these changes. These include the World Climate Research Programme (WCRP) and the Intergovernmental Panel on Climatic Change (IPCC), the International Geosphere Biosphere Programme (IGBP) and the Human Aspects of Global Change (HAGC), as well as a host of more focused research projects and field campaigns. These various programmes are now collectively referred to as global change investigations.

Whilst there are no doubts about the reality of the global increase in atmospheric carbon dioxide concentration, the thinning of the protective ozone layer in the stratosphere, or the destruction of forests and other ecosystems, there is a vigorous debate in the scientific community on the nature and extent of the implications of these changes over the long term. There remain major uncertainties in the amount of carbon stored in the oceans and in the biosphere, and in the fluxes between these reservoirs and the atmosphere. The presence of other mechanisms involving, for example, the hydrological cycle — specifically the global cloud cover, which could compensate at least in part the impact of increased carbon dioxide (CO_2) — and fundamental uncertainties about other aspects of the functioning of the Earth as an integrated system have slowed or stalled attempts to avoid or remedy these impacts.

An improved understanding of the processes at work and the capability to accurately and reliably predict the consequences of these events, based on an accurate assessment of the current situation and of its evolution in the recent past, would be useful to chart a course of action either to prevent those changes, to avoid their consequences, or to mitigate their impact. As governments enforce new regulations and implement political, social and technological changes to this effect, there will be a need to further evaluate the efficiency of these decisions and actions. This implies the conduct of scientific research which will provide the required understanding, as well as the development of the observational means to monitor relevant environmental variables.

The MERIS instrument was designed and implemented by ESA to address some of the most pressing issues outlined above. Specifically, the data produced by this sensor will permit a detailed description of the spatial distribution of biological activity in the upper ocean and its temporal variability. This will, in turn, provide a better and long overdue assessment of the role of the oceans in the carbon cycle and their interaction with the atmosphere, both so essential to the functioning of the Earth system. Because of its high spectral resolution, MERIS will also permit new investigations of the atmosphere itself, for example through the observation of clouds or the measurement of water vapour or aerosol concentrations. MERIS will also significantly improve our present capability to monitor terrestrial environments by combining a much finer spatial resolution with higher spectral resolution, both of which exceed the performance of the instruments currently available for studies on a continental to global scale. The repetitive acquisition of such measurements will allow a much improved description of the dynamics of these ecosystems, and provide more reliable answers to crucial questions such as their primary productivity (i.e. the phytoplanktonic biomass produced through photosynthetic processes) or the location and strength of the terrestrial carbon sinks.

A.1.2 OCEAN APPLICATIONS

A.1.2.1 Open ocean

'The remote measurement which has caused the greatest interest within JGOFS (Joint Global Ocean Flux Study) is the estimation of basin and global-scale variability in the concentration of chlorophyll in the upper ocean. The images of the global distribution of these pigments, derived from data taken by CZCS, have revolutionised the way biological oceanographers view the oceans. For the first time, the blooming of the ocean basins in the spring has been observed, as has the extent of the enriched areas associated with the coastal ocean. There is now no satellite ocean colour sensor in orbit. JGOFS crucially needs the new ocean colour sensors.' (International Geosphere-Biosphere Programme (IGBP) *A Study of Global Change*, Report No 12, 1990).

Since the set up of JGOFS and IGBP, the above recommendation has been repeatedly expressed. JGOFS is a major internationally coordinated effort, designed to increase our understanding of the ocean carbon cycle, the regulation of the atmosphere-ocean CO_2 balance, and the possible changes within the coupled system. Two main objectives have been assigned:

— to determine and understand, on a global scale, the processes controlling the time varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries;

— to develop a capability to predict on a global scale the response of oceanic bio-geochemical processes to anthropogenic perturbations, in particular, those related to climate change (see the work of the Scientific Committee Ocean Research (SCOR) and International Committee of Scientific Unions (ICSU) published in the JGOFS Report, 1987).

JGOFS is a core project of the IGBP, which has been initiated and is organised by SCOR. A core project of the IGBP, the Global Ocean Euphotic Zone Study (GOEZS) is also considered for implementation when the field activities of the World Ocean Climate Experiment (WOCE) and JGOFS are almost completed in the late 1990s. This project will require the deployment of advanced instrumentation for remote and automated measurement of the upper ocean characteristics and will focus on, and analyse the evolution of, the biological and physical properties within the euphotic layer and the mixed layer.

The rationale for the above recommendation lies in the importance of the oceanic phytoplanktonic biomass in fixing CO_2 through photosynthesis. This bio-geochemical role can be assessed on the appropriate time- and space-scales from ocean colour data, acquired from space and used as a proxy for the algal pigment distribution.

The size of the algal reservoir, namely the instantaneous phytoplanktonic biomass in the world ocean, is poorly known (estimates range from 1 to $5x10^{15}$ gC). More important, the amount of inorganic carbon photosynthetically fixed by phytoplanktonic algae remains an open question. According to various estimates, the carbon flux entering the marine biosphere would be between 25 and $45x10^{15}$ gC per year. With such values, the 'biological pump' appears to be almost as efficient as the 'thermodynamic pump', which is the dissolving of CO_2 in cooled waters and its subsequent sinking. These pumps also work in opposition: the deep waters, when upwelled, release CO_2 during warming; much of the photosynthetically produced organic matter is quickly consumed and recycled back to CO_2, through respiration and various oxidations (Bolin 1983).

For an ocean in equilibrium, or in very slow natural evolution, the entering and exiting carbon fluxes are equal. The ocean-atmosphere system is now out of its natural equilibrium. It is generally believed that a sizeable part of the anthropogenic input of CO_2 originating from fossil-carbon burning and changes in land use, that is not found in the atmosphere, could have been sequestered inside the ocean. In the present time, with a human emission of about $7x10^{15}$ gC per year, a rate of increase in the atmosphere of about $4x10^{15}$ gC per year, the corresponding rate of absorption by the ocean might be about $3x10^{15}$ gC per year. This is an important amount from a geochemical viewpoint; however, it is a small number when compared to the uncertainty affecting the estimate of the 'unperturbed' flux itself, from 25 up to $45x10^{15}$ gC per year, as recalled above. That fraction of the primary production which escapes from fast consumption and thus is able to reach the ocean interior is a potential sink and could be responsible for the absorption of the missing carbon.

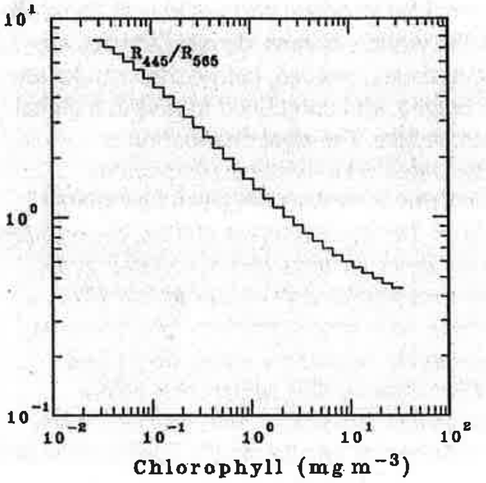
In addition, the efficiency of the thermodynamic pump, which is regulated by the difference in partial CO_2 pressure (the ΔpCO_2 between ocean and atmosphere), is greatly influenced by the biological activity. Photosynthesis in the upper ocean often results in driving the partial pressure in surface waters far from its thermodynamic equilibrium and therefore speeds up the CO_2 dissolution rate. Algal abundance, as a proxy of photosynthesis capability and CO_2 fixation, is again involved, and synoptic, permanent, measurements are needed.

Progress in understanding the processes involving oceanic carbon, particularly in quantifying the various carbon fluxes and the balanced or unbalanced budget between the entering and exiting fluxes, requires an extensive programme of satellite observations (colour, sea surface temperature, wind field) and a data continuity guaranteed over an extended period of time. Comprehensive computational analyses, data assimilation and modelling efforts are also needed and must appear as major activities in the plans of IGBP and IGOFS. They are inseparable complements to the development of oceanography from space.

Even if the problem addressed is at the scale of the world's oceans, detailed studies are nevertheless needed, before their results are averaged, and cumulated for use in a global perspective. The algal distribution is associated with dynamic phenomena occurring at various temporal and spatial scales. The equatorial circulation, the western boundaries currents and associated gyres, the circumpolar drift and other currents delimit wide biogeographical provinces. At mesoscale, meanders, cores, fronts and eddies often exhibit remarkable colour signatures, associated with specific trophic conditions; at smaller scales, complicated and fast evolving patterns, as well as various optical signatures, are typical of coastal waters. All these studies certainly would benefit from permanent ocean colour monitoring with the appropriate MERIS spatial resolution.

If, for obvious reasons, emphasis is put on the impact of the phytoplankton upon the cycle of matter in the biosphere-geosphere system, the role of the primary producers within the food webs remains a major question in biological oceanography. The dynamics of the phytoplanktonic population are governed by the availability of the nutrients (N, P), combined with the light level and vertical turbulence or stability. To a great extent, these chemical and physical environmental conditions are dependent on meteorological forcing, from the general atmospheric circulation (trade winds, westerlies) and the latitude-dependent heat budget, to local and transient impulses. A comprehensive study of the primary production, in a biological or bio-geochemical perspective, requires a combined use of satellite data (wind, irradiation, sea surface temperature), in addition to the ocean colour information used as a proxy of the algal concentration. The aim of reducing the uncertainties in carbon flux estimates is demanding in terms of ocean data quality. In the upper layer of the open ocean, the chlorophyll concentration is the most convenient index for the phytoplankton abundance. Considering that it may vary from less than 0.03 $mg\ m^{-3}$, in oligotrophic waters, (i.e. waters poor in nutrients and therefore in phytoplankton), up to about 30 $mg\ m^{-3}$ in eutrophic waters (i.e. in nutrient rich waters, supporting high biomass), the achievement of an accurate assessment could be seen as ambitious. To this chlorophyll

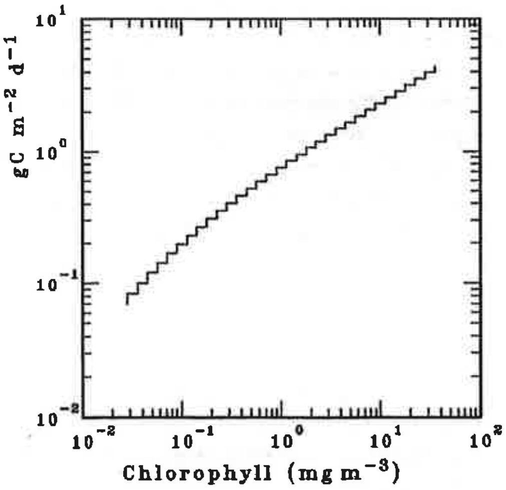
Figure A.1–1. Ratio of the ocean reflectances at the wavelengths 445 and 565 nm as a function of the chlorophyll concentration and for oceanic case 1 waters. The curve corresponds to ten equal increments per decade in chlorophyll concentration. The mean value for the world ocean is about 0.3 mg m^{-3}, and that most of the oceanic waters (90%) exhibit chlorophyll concentrations within the range 0.03 to 1.00 mg m^{-3}. Higher values are temporarily observed during the bloom periods and more steadily in upwelling areas.



content variation, which spans over three orders of magnitude, the ocean colour responds in a non-linear way. It is conveniently depicted and quantified by a ratio of blue to green radiation back-scattered by the ocean. According to the absorption spectrum of algae, the ratio which is the most sensitive to the algal concentration is that comprising wavelengths of 445 and 565 nm (Figure A.1–1). It varies within a range of one to twenty for the types of pigments considered and decreases, almost linearly, with the logarithm of the concentration.

A reasonable goal for an advanced instrument should be one whose radiometric performance can be adjusted in such a way that, over three orders of magnitude, thirty classes of pigment concentration may be discriminated (30 dB). The classes would be of equal width on a logarithmic scale, with a constant factor of 1.26 ($1.26^{10} = 10$) between the nominal values of two consecutive classes. This requirement is close to the limit for retrieving chlorophyll concentration from optical data taken at sea level. A natural variability actually exists in oceanic Case I waters so that the relationships between phytoplankton abundance and optical properties are not rigorous; when inverted, these relationships cannot produce a concentration with an accuracy better than about 20%. Therefore the goal of a resolution of ten classes per decade seems reasonable. In terms of primary production, as computed from the pigment concentration, this resolution of thirty categories, is appropriate and consistent with the accuracy of ^{14}C determinations of the primary production as performed at sea (Figure A.1–2). These user requirements directly govern the specifications of the sensor, in terms of radiometric sensitivity and of changes in noise equivalent radiance (NEΔL).

Figure A.1–2. Primary production within the euphotic layer (expressed as gC m^{-2} day^{-1}) computed in a case study (vernal equinox, latitude of the Tropic of Cancer, clear sky, chlorophyll uniformly distributed inside the euphotic layer). The mean chlorophyll concentration is varied as in Figure A.1–1 and the curve is similarly stepped. For the values of the carbon fluxes entering the marine phytosphere, given in the text as 25 to 45x10^{15} gC yr^{-1}) the corresponding average daily fixation rates would be 0.24 and 0.42 gC m^{-2} d^{-1}, respectively.



Note that the primary production spans over one and a half orders of magnitude, whereas the chlorophyll concentration within the productive layer varies within three orders of magnitude. This is due to the regularly decreasing thickness of the productive, sufficiently lit (euphotic) layer, when the biomass increases.

The radiances, L, to be recorded at the satellite level in the various channels within the visible domain are largely dominated by the atmospheric signal caused by Rayleigh and aerosol scattering. The contribution of the water-leaving radiance to the signal at the top of the atmosphere amounts to a few percent in most cases (Table A.1–1). It may only exceed 10% in the exceptionally favourable condition of an extremely clear atmosphere. Consequently the pigment concentration is never a crucial variable in sizing the dynamics of the sensor. For given orbit characteristics (altitude, equator crossing time) and swath capability, the minimal and maximal radiances to be detected over the ocean are essentially determined by the aerosol load.

Even with a relatively high aerosol load (equivalent to a visibility of about 5 km) the ocean can still be observed by the sensor, in spite of the strong atmospheric component in the recorded signal. Over other targets, such as land, snow and clouds, the relative contribution of the atmosphere is decreased as these surfaces have reflectances well above that of the ocean. For instance, a 100% reflectance scene (such as a cloud) will generate radiances at the satellite level that are 10 times (in the blue part of the spectrum), or even 100 times (in the red), more intense than those expected over the ocean at the same wavelengths. Therefore the dynamic range, from the darkest ocean to the brightest cloud (L_{max}), is strikingly different over each band. The critical design driver is to simultaneously accommodate the requirements of low NEΔL needed in ocean observation, and the capacity to measure L_{max}.

For the near infrared channels the signals originate entirely from the atmosphere (Table A.1–2). This does not mean that for these wavelengths the radiometric requirements (in terms of NEΔL) can be relaxed with respect to those recommended for the visible channels. The atmospheric correction procedure, namely the removal of the atmospheric effects from the visible channels, is based firstly on the estimate of the atmospheric signal in several infrared (IR) channels, and then on an extrapolation of this estimate toward the shorter wavelengths. This extrapolated atmospheric contribution is then subtracted from the total signal recorded by the sensor to obtain the marine signal. It is conceivable that such a correction, which actually involves the removal of more than 90% of the total signal, must be made with a high resolution to preserve the quality of the retrieved marine signal. The basic information in the infrared region of the spectrum must be acquired with a radiometric resolution compatible with the correction scheme and the accuracy required in the final product, i.e. the water-leaving radiance.

This requirement also holds true for the aerosol studies. The above mentioned correction, which includes an estimate of the radiances originating from the presence of aerosols, is valuable information to the extent that over the open ocean (which appears as a black target in the near infrared domain), the aerosol load can be reliably estimated. Information about its nature and granulometry can, in principle, be derived from its spectral scattering properties. Such systematic observations are of fundamental importance for both geochemical and climatological studies such as aeolian transport of materials, and the Earth radiation budget.

Channel (nm)	L_{max} $Wm^{-2}sr^{-1}\mu m^{-1}$	L_{max} Ocean Contrib.	L_{min} $Wm^{-2}sr^{-1}\mu m^{-1}$	L_{min} Ocean Contrib.
410	39.4	2.2 %	114.6	4.5 %
445	33.2	3.1 %	98.4	6.0 %
490	23.6	4.3 %	72.8	8.1 %
520	17.3	3.4 %	55.1	6.3 %
565	11.8	2.8 %	41.0	5.2 %
665	7.3	0.8 %	23.9	1.3 %

Table A.1–1. Radiances at the satellite level computed for an ocean with a chlorophyll concentration of 0.3 mg m^{-3}, a clear sky with a visibility of 23 km (maritime aerosol) and on the day of the vernal equinox. The mean altitude of the satellite is 780 km. The equator crossing time (descending track) is 10:00 a.m. The two radiance values correspond to the minimum and maximum radiances found within a swath of 82° and for any point in the orbit where the zenith-Sun angle is less than 60°. The precentages in the right hand column represent the oceanic contribution to the radiance reaching the sensor.

A.1.2.2 Coastal waters

Coastal waters cover less than 1% of the world ocean surface, but they are highly important with respect to photosynthetically produced organic matter. Although coastal waters have been observed over recent decades, we have only a poor knowledge of the horizontal distribution and temporal variation of the constituents of coastal waters. The distribution of the water constituents is sensitive to the bio-geochemical cycle which, in turn, depends on dynamic forcing. The heterogeneous topography of the bottom of the ocean, combined with a shallow water circulation and meteorological forcing, is responsible for producing mesoscale features, such as gyres and fronts, which are highly variable in space and time.

The coastal regions are the most populated areas in the changing world and coastal waters are highly affected by man's activities.

Channel (nm)	V = 7 km L_{min}	V = 7 km L_{max}	V = 23 km L_{min}	V = 23 km L_{max}	No aerosol L_{min}	No aerosol L_{max}
710	7.7	33.8	5.3	19.6	2.4	7.8
755	5.6	24.0	3.7	13.5	1.5	4.7
880	4.9	20.3	2.8	10.4	0.8	2.4
1020	3.1	13.1	1.6	6.2	0.3	1.0

Table A.1–2. As in Table A.1–1, but for channels in the near infrared. Only the minimum and maximum radiances are given, as the marine contribution is zero. Two visibilities (V) are considered as well as pure rayleigh atmosphere (no aerosol).

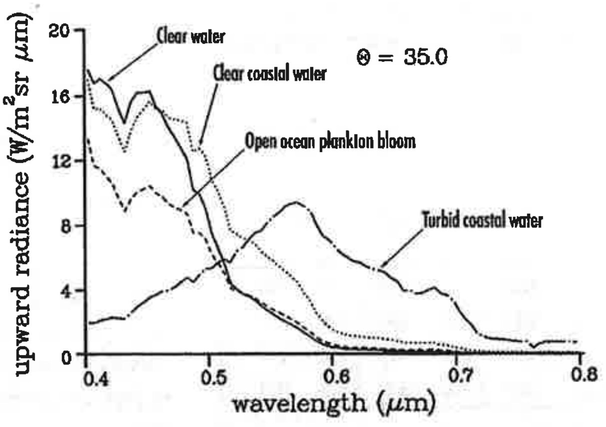
These marine ecosystems are subject to bio-geochemical forcing due to the influx into the coastal seas of pollutants from rivers and the atmosphere which inhibit or stimulate marine productivity to the point of causing eutrophication (Martin and Barth 1991). In addition, large amounts of agricultural and industrial pollutants and sewage are discharged into these waters.

Continuous and long term observation of coastal waters, which cover an area of more than three million square kilometres, is most important for climate impact studies and for environmental monitoring. Remote sensing measurements from satellite are the only available means for providing us with a synoptic view of such large areas of water.

Although the CZCS on board the United States' Nimbus 7 satellite successfully monitored the ocean colour from 1978 (Gordon and Morel, 1983) to 1986, significant improvements in future sensors are envisaged. Additional channels for atmospheric correction in the near infrared, as well as a channel to measure the Sun-stimulated chlorophyll fluorescence, will improve the interpretation of ocean colour measurements above coastal waters.

Figure A.1–3. Simulated multispectral radiances for a spectral resolution of 5 nm just below the water surface for:

- *clear water;*
- *open ocean plankton bloom* $\rho_p = 1\ mg\ m^{-3}$;
- *clear coastal water* $\rho_p = 1\ mg\ m^{-3} + \rho_s = 1\ mg\ l^{-1}$;
- *turbid coastal water* $\rho_p = 20\ mg\ m^{-3} + \rho_s = 1\ mg\ l^{-1}\ a^{YS}_{(\lambda=380nm)} = 2\ m^{-1}$.



The major water constituents, which determine the marine and estuarine ecology and the bio-geochemical budget and whose concentration and distribution can be determined by optical remote sensing, are suspended matter, phytoplankton and yellow substance (gelbstoff). Suspended matter is defined as a combination of:

- inorganic particles and detritus, present due to re-sedimentation and advection processes;
- atmospheric inputs;
- dead material of plankton.

Gelbstoff consists of various highly polymerised dissolved organic molecules which are formed by the degradation products of organisms. These originate in brackish and underground water as well as in extraordinary plankton blooms. All these constituents have different optical properties, but there is a similarity in their spectral scattering and absorption coefficients.

The upward radiance at any visible wavelength is composed of contributions from all these substances. Figure A.1–3 shows simulated multispectral radiances for different ocean waters. A plankton bloom in the open ocean has pigment concentrations up to $\rho_p = 1\ mg\ m^{-3}$. In the Elbe river plume typical values for the pigment concentration of $\rho_p = 20\ mg\ m^{-3}$, for suspended matter of $\rho_s = 10\ mg\ l^{-1}$ and for the absorption coefficient of gelbstoff of $a^{YS}_{(\lambda=380nm)} = 2\ m^{-1}$ are found. Suspended matter usually enhances the upward radiances through reflection within the visible spectrum, while gelbstoff reduces the radiances mainly in the blue.

To analyse whether these properties are detectable from remote sensing measurements, eigenvector and factor analysis were applied to measured and simulated multispectral radiances. The results predict that three properties are retrievable which are related to chlorophyll, suspended matter and gelbstoff (Fischer *et al.*, 1986). Commonly used techniques, such as simple colour ratios, are not sufficient for the evaluation of several water substances. Consequently, for their retrieval a more advanced interpretation method is needed. The inverse modelling technique is an adequate method for the detection and separation of different substances from multichannel measurements. The most sensitive part of such a technique is the model for the simulation of the radiative transfer model. The radiative transfer model, which is adjusted to the results of a complete radiative transfer model of a combined atmosphere ocean system, has led to a successful interpretation of CZCS measurements (Doerffer and Fischer, 1994).

The horizontal distribution of pigment and suspended matter concentrations and the yellow substance absorption in the North Sea were estimated. To convert from the optical properties of the water constituents, used in the radiative transfer model, to concentration units, the relationships between both have to be known. Since this procedure is also sensitive to errors in atmospheric correction, the inability of a channel to provide a more accurate estimate of the atmospheric influence and to measure the chlorophyll fluorescence limits the application to a few CZCS images.

An improvement of the evaluation of the coastal water substances will also be realised by measuring the Sun-stimulated chlorophyll fluorescence, which has been found to be a specific spectral feature for phytoplankton within the ocean-leaving spectral range (Gower, 1980). The desired spectral resolution is about $\Delta\lambda = 5$ to 10 nm and the radiometric resolution is found to be 0.03 Wm^{-2} sr^{-1} µm^{-1} at a wavelength of 682.5 nm for a discrimination of 1 mg m^{-3} pigment concentration (Fischer and Kronfeld, 1990). The chlorophyll fluorescence signal, although small, is detectable from space with MERIS (Figure A.1–4).

The accuracy of derived oceanic properties depends significantly on the precision of the atmospheric correction procedure. As mentioned above, the atmospheric correction will benefit from the increased radiometric sensitivity MERIS and the channels selected for aerosol detection.

The development of inverse modelling techniques for the interpretation of MERIS measurements is not complete, but is an ongoing process. For monitoring coastal regions world wide, precise multispectral radiance with contemporary optical and concentration measurements of the water constituents is needed.

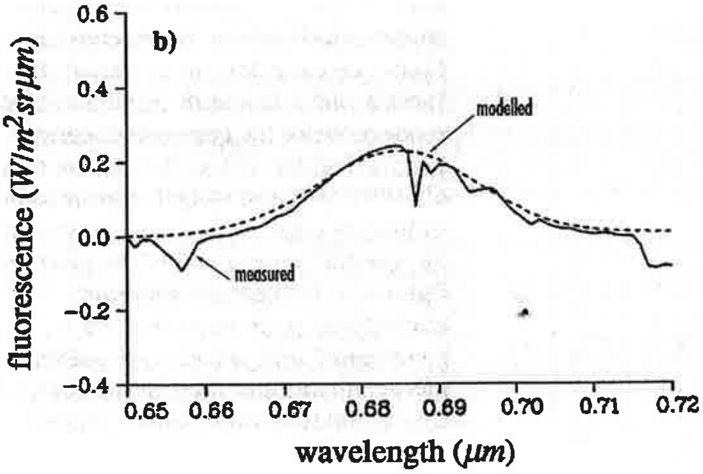


Figure A.1–4. The measured fluorescence F_0 and modelled fluorescence signals just above the water surface for wavelengths between 650 to 720 nm and a solar zenith angle θ_s = 50.7° and chlorophyll concentration ρ_p = 10 mg m^{-3}.

The international programmes for global measurements, such as JGOFS and regional investigations, will benefit highly from MERIS measurements.

A.1.3 ATMOSPHERIC APPLICATIONS

The prediction of variations in the Earth's climate system has been recognised by the international scientific community as requiring improved understanding of interactions between the atmosphere, land surface, and oceans. The water and energy budgets are most important to the climate system, but they are inadequately understood on regional and global scales. These deficiencies have led to the establishment of the Global Energy and Water Cycle Experiment (Gewex) which has been a core component of the World Climate Research Programme (WCRP) since 1987. The ultimate goal of Gewex is to improve, by an order of magnitude, the ability to model global precipitation and evaporation and to provide an accurate assessment of the sensibility of atmospheric radiation and clouds, as well as the response of the hydrological cycle and water resources to climate change (Chahine, 1992). A global inventory of the relevant atmospheric properties is needed on a long term basis.

ESA has decided to launch a series of satellites for global observation of the Earth in the late 1990s. The instruments on board the satellites will monitor essential atmospheric properties and complement existing operational meteorological observations. The selected key physical entities which have to be observed are clouds, aerosols and water vapour. The spectral and radiometric resolution of MERIS is adequate for the detection of narrow spectral features in the atmosphere (Rast *et al.*, 1991). The atmospheric transmission features of water vapour and oxygen within the spectral range of MERIS are given in Figure A.1–5. The most important atmospheric parameters that will be investigated using MERIS-type satellite measurements and these include aerosols, clouds and total water vapour content.

1.3.1. Aerosols

The impact of aerosols on the radiation budget is both direct, through scattering and absorption, and indirect through the modification of cloud properties. The magnitude of the influence of aerosols on the Earth's climate is difficult to assess, because they are present in different size distributions, shape, chemical composition and vary by orders of magnitude in space and time (Grassl, 1991). There is however a specific wavelength dependence of the extinction coefficients within the visible and near infrared which can be used to distinguish different aerosol types.

Although algorithms already exist for estimating aerosol optical thickness, new algorithms have to be developed to exploit multispectral measurements made by MERIS. MERIS will have the capacity to evaluate aerosol properties, such as aerosol path radiance, optical thickness, type and concentration. The desired and predicted accuracies are for the optical thickness $\Delta\delta = 0.01$ and for the Ångström exponent $\alpha = 0.05$. Since more than two channels are provided for aerosol detection, deviations of the assumed linear wavelength dependence of the aerosol extinction will be included in the evaluation process of aerosol properties. Additional surface pressure estimates from measurements within the oxygen A–band improve the evaluation of molecular scattering and thus the retrieval of the aerosol properties. A discrimination of boundary layer and stratospheric aerosols is likely after volcanic activity from multispectral measurements within the oxygen A–band.

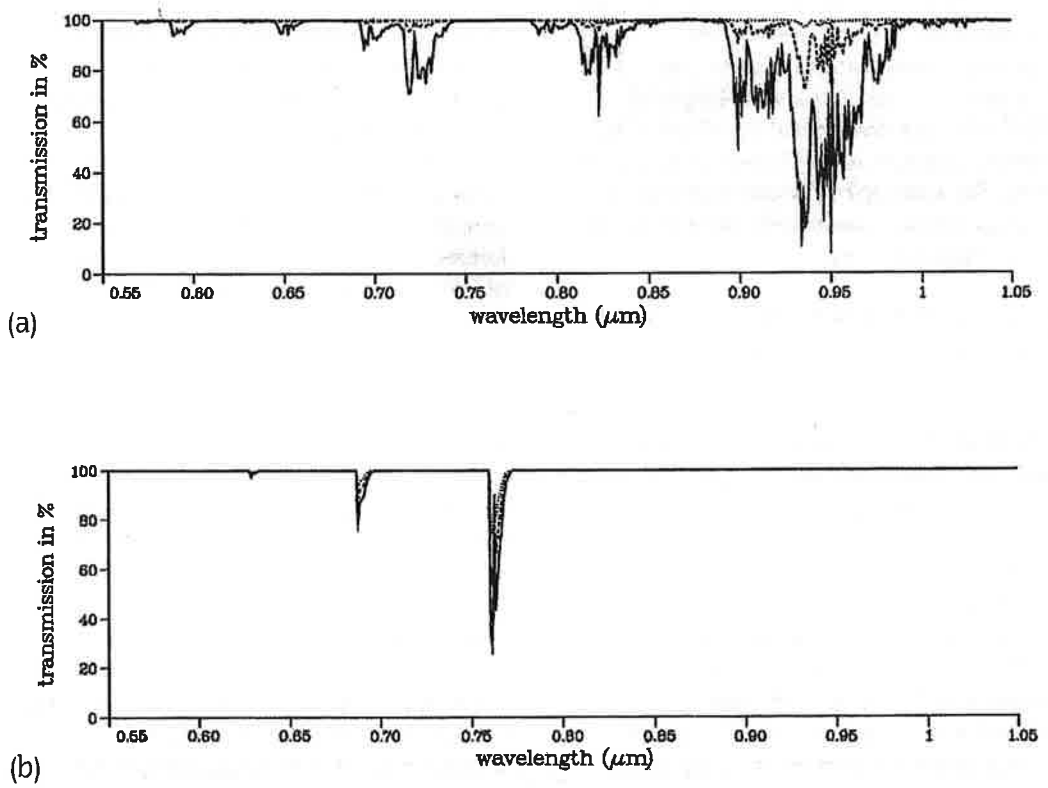


Figure A.1–5. Atmospheric transmission averaged over 1 nm intervals within the wavelength region 550 nm to 1050 nm for different absorber masses from the top of the atmosphere to heights of
z = 10 km, ...
z = 5 km, ----
and z = 0 km, ——
for a mid-latitude summer atmosphere: (a) H_2O and (b) O_2.

The derivation of the atmospheric correction for ocean colour observations will benefit from the improved retrieval of aerosols. This results directly in a more accurate estimation of water substances.

1.3.2. Clouds

Clouds have a strong modulating influence on the global energy budget. They determine the amount of solar radiation scattered back into space and block the terrestrial radiation from the Earth's surface into space. There is a general agreement that the annual global mean effect of clouds is to cool the climate system, but there is significant disagreement on the magnitude, which exceeds 10 W m^{-2} (Arking, 1990). To improve such estimates, the cloud cover, cloud type, and cloud top height have to be known more accurately. For example, an increase in cloud top height of 1 km results in a 1.2 K increase in surface temperature (Ohring and Adler, 1978). Furthermore, a 1 % change in cloud cover is estimated to have more than twice the effect of a CO_2 doubling (Ramanathan *et al.*, 1989). The most important cloud properties with respect to global climate change are cloud amount, cloud-top height, cloud optical thickness, and size distribution of cloud droplets.

The most precise method for estimating cloud top heights from present infrared satellite measurements is called the 'CO_2 slicing technique'. The accuracy of derived cloud-top heights is approximately ±500 m. For climate studies, and also for the improvement in the retrieval of vertical temperature profiles, an accuracy of ±100 m is desired.

The estimation of cloud-top heights from reflected solar radiation is based on radiance measurements within and outside the oxygen (O_2) absorption A-band. Early aircraft campaigns did not show a real advantage in using this method for the retrieval of cloud-top heights. However, recent promising measurements showed that cloud top heights of all types of clouds could be determined to within ±200 m (Fischer *et al.*, 1991). The estimation of cloud-top heights of a stratus cloud field agreed to within 50 m, when derived from lidar and back scattered solar radiance aircraft measurements (Figure A.1–6).

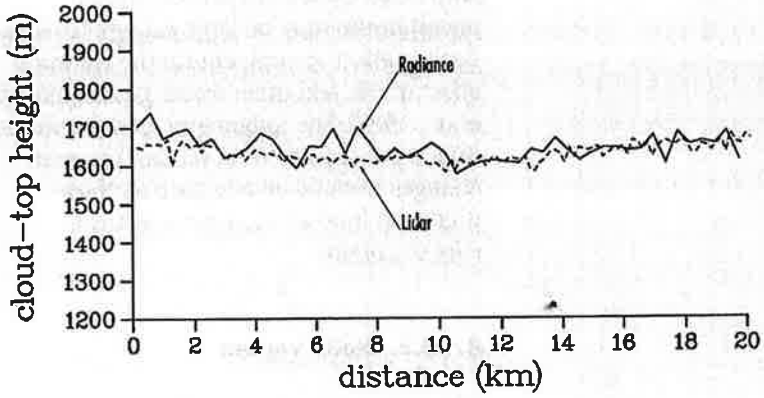


Figure A.1–6. Cloud top heights derived from radiance and lidar measurements along a 20 km track.

During ESA's European Lidar airborne campaign, ELAC'90, a further evaluation of this remote sensing technique was realised. Using a multivariable analysis, three independent quantities for the cloud-top height retrieval have been extracted from 160 000 multispectral radiance measurements within the O_2 A-band, taken above different types of clouds over Europe (Kollewe and Fischer, 1992). The proposed three MERIS channels, two within and one outside of the absorption band, were selected to account for the photon penetration in the cloud top evaluation process. The development of appropriate algorithms for the retrieval of cloud-top heights and cloud optical thicknesses from multispectral MERIS measurements is under way. The application of inverse modelling techniques promises to be successful (Fischer and Grassl, 1991). However, further validation campaigns using aircraft, which include multispectral radiance measurements and active lidar back scattering measurements, are necessary to establish a method for the retrieval of cloud top heights from future MERIS measurements.

Even small changes in the cloud albedo affect significantly the Earth's climate. The cloud albedo depends primarily on cloud optical thickness and this varies with liquid water content and size distribution of the cloud droplets. A small increase in the number of cloud droplets, due to an increase in aerosols (which serve as cloud condensation nuclei) combined with a decrease in mean droplet size, will increase the cloud albedo and thus may reduce the greenhouse effect of the trace gases. There are considerable uncertainties in the processes of linking man-made and natural emissions of sulphur dioxide (SO_2)

with cloud optical properties. These uncertainties may be large enough to cause a cooling effect to compensate the warming effect of CO_2 and other traces gases (Charlson *et al.*, 1987). The radiometric performances of MERIS are capable of observing the small changes in cloud albedo such as those predicted from an increase in aerosol concentrations.

A.1.3.3. Water vapour

Water vapour is the most important atmospheric gas with respect to the radiation budget, cloud amount, precipitation and evaporation rates. Since our basic knowledge of global water vapour content is limited, efforts are being made to establish a climatology of integrated water vapour (WMO, 1992). A detailed global view of the spatial and temporal distribution of the total atmospheric water vapour content is needed.

Using existing infrared sounders, the total amount of precipitable water can be estimated to within an accuracy of 25%. Over oceans the total water vapour amount can be determined with an error of 10% from satellite microwave measurements (Prabhakara *et al.*, 1982). Successful application of such measurements over land surfaces fails due to the variability in emissivity at microwave frequencies. Frequently the apparent surface temperature, which depends on skin temperature and surface emissivity, is close to the average temperature of the boundary layer, This reduces the variations in infrared and microwave measurements due to variations in boundary water vapour. Although it is expected that water vapour profiles, in steps of 2 km, will be retrieved to within 10% from future satellite sensors, the absorption of solar radiation by water vapour seems to be more sensitive in the near infrared (King *et al.*, 1992).

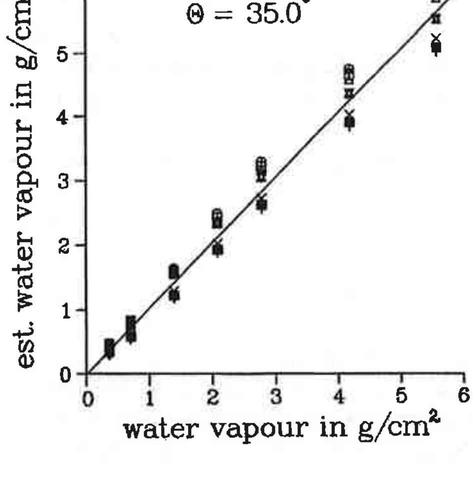


Figure A.1–7. Total atmospheric water vapour from upward radiance estimated in g cm^{-2} versus the actual value at 880 and 900 nm over different surfaces (barley, blue grass, basalt, limestone, pines, sunflower, snow and water). Solar zenith angle is 35°.

For the remote sensing of the total water vapour content, radiance measurements within the H_2O $\rho\delta\tau$ absorption band are suitable (Kaufmann and Gao, 1992). The ratio of reflected radiances at λ = 900 nm and λ = 880 nm can be used as an indicator for the total amount of atmospheric water vapour (Fischer, 1988). Although these radiances depend strongly on the surface albedo, the observed spectral range and the aerosols, the accuracy of estimation of the total atmospheric water vapour is expected to be within 10% for measurements above land and water surfaces (Figure A.1–7).

Further aircraft validation campaigns, including multispectral radiance measurements and measurements of active water vapour using Dial (differential absorption lidar), are necessary to establish the best method for the retrieval of the total water vapour content from future MERIS measurements.

A.1.4 TERRESTRIAL APPLICATIONS

A.1.4.1 The importance of continental surfaces and scientific issues

Terrestrial environments play a crucial role in the global Earth system. First of all, they carry over 99% of the biosphere (Ajtay *et al.*, 1979). Vegetation supports the bulk of animal and human life; it contributes to the formation of soils, reduces soil erosion, and largely controls the exchanges of water and carbon between the continents and the atmosphere (Bolin *et al.*, 1986). Terrestrial and oceanic surfaces significantly affect the atmosphere because most of the solar radiation that drives the climate system is first absorbed at the surface. This energy may be temporarily stored, re-emitted as thermal infrared radiation, or released as sensible and latent heat. The geographic distribution and orography of the land masses, together with the thermal contrast produced by the very different specific heats of the continents and oceans, induce systematic weather and climatic patterns (e.g., Gates, 1981). The continents host the entire human population as well as the bulk of its economic activities, concentrated along the coastal regions. Hence, most of the pollution sources are located on land.

One of the major scientific issues currently being debated in the framework of global change is the cycling of carbon in the Earth system (e.g., Bolin *et al.*, 1986). It is well known that CO_2 contributes to the greenhouse effect and that its concentration has varied in geological times, together with the global average surface temperature (see for example Schneider and Londer, 1984). However, over the last few centuries, increased human activity and especially the burning of fossil fuels and deforestation have resulted in an increase in the release of this trace gas in the atmosphere (e.g., Schneider, 1989). A sizeable fraction of the CO_2 emitted through these agricultural and industrial activities cannot currently be accounted for by the observed CO_2 increase in the atmosphere, or its dissolution into the upper ocean surface.

Convincing arguments have been proposed to suggest that the missing carbon sink will be found in the terrestrial biosphere. This cannot be verified yet, in part because the size and location of the major carbon pools locked in live vegetation or as dead organic materials in soils are poorly known (Curran and Foody 1994). This is particularly unfortunate because the composition of the air has already been modified on a global basis, and the cumulative effect of these practices may result in significant perturbations of the hydrological cycle (IPCC, 1990). This could have consequences for the distribution and availability of fresh water. A more accurate evaluation of the stocks and exchanges of carbon in the land biosphere could provide much needed information on this topic and help identify the location and size of the missing carbon sink.

Other environmental issues are continually being raised as a result of the growth of the human population and its activities (Ehrlich and Ehrlich, 1990). The production of increasingly large quantities of food and fibre results in the progressive destruction of habitats and the loss of biodiversity (Wilson, 1988), the erosion of topsoil (Brown and Wolf, 1984), deforestation (Hecht and Cockburn, 1989), and desertification (United Nations Conference on Desertification (UNCOD), 1977). Similarly, expansion of industrial activities and the exploitation of natural resources have often resulted in pollution of the air, water and soils. Some of these forms of environmental degradation are directly affected by climatic conditions, and also further impact on the climate system through significant modifications of the properties of the surface or its exchanges with the atmosphere.

Beyond the understanding of the fundamental role of terrestrial surfaces in climatic processes and the investigation of environmental crises, a number of human activities benefit from repetitive monitoring. These include the management of agriculture and other natural resources, land use planning, and the prevention of, or recovery from, natural disasters. In other cases, the surveillance of certain processes may yield information on associated activities; for instance, monitoring biomass burning not only helps estimate the release of gases and smoke into the atmosphere, but also provides information on the location and type of human activity in progress (e.g., Grégoire *et al.*, 1993).

It can be seen that the state of the vegetation provides crucial information for a number of these applications, either because the plant cover is the object of direct interest, or because its state and evolution provide indirect evidence on the processes at work. It should therefore be no surprise that assessing the distribution in space and time of the type, amount, productivity and health of vegetation should constitute a major scientific objective and a priority in the monitoring of terrestrial regions (Foody and Curran, 1994).

A.1.4.2 Scientific algorithms and data needs

Providing relevant information on the processes and activities described above on the basis of data collected from space is not trivial. First of all, the sensors on satellite platforms can only measure the characteristics of the radiation that enters the instrument, rather than the climatic or environmental properties of interest. The analysis and interpretation of the remotely sensed data therefore relies on a series of mathematical tools, from empirical relations to physically-based models, to extract the relevant information from measured radiation. A range of tools and models has been developed so far to address the large number of terrestrial applications. This is necessarily based on the exploitation of the variability of the measured signals with respect to the independent variables of space and time and also the spectral and directional signatures of the surface (Verstraete *et al.* 1994).

Various objects can be distinguished and identified by their specific spectral reflectance patterns, or signatures. Ignoring the problem of atmospheric contamination for the moment, the nature of the surface corresponding to an observed pixel can be derived from the spectral signature associated with that location. Numerous land applications have been based on spectral measurements in two or more spectral bands. As far as terrestrial vegetation studies are concerned, interest has been largely focused on the high contrast between the low reflectance around 670 nm, due to the strong absorption by chlorophyll and the high reflectance beyond 700 nm, due to the intense scattering of light by cellular structures within leaves (Curran, 1985). Traditionally, vegetation indices have been designed to enhance this spectral contrast and help identify the presence of vegetation in the scene. These indices are simple mathematical formulae which are designed to take on large values when the spectral contrast around this 700 nm threshold is present, and low or negative values elsewhere.

Field and laboratory studies have shown that the position and slope of this reflectance gradient around 700 nm may provide useful information on the physiological status of the plants under observation. The exploitation of this feature will therefore require a better characterisation of what is called the 'red edge'. Similarly, additional bands in the visible and infrared spectral regions should yield improved information on the amount of vegetation under observation. For instance, the leaf area index (the total one-sided area of leaf material per unit ground area) has been found to be an indispensable variable for describing the growth of plants and in particular their gaseous exchanges with the atmosphere, and can be estimated, within certain limits, from the value of vegetation indices (Pinty *et al.*, 1993).

These algorithms require as minimum, spectral data on both sides of the 700 nm threshold. One spectral band should be located in the region of maximum chlorophyll absorption, typically around 660 nm, while another should be positioned beyond 700 nm. Because of the sharp reflectance gradients in that region, and the presence of atmospheric water vapour absorption bands near 730 nm, this latter band should be positioned around 710 nm, and both bands should have a bandwidth not exceeding 10 nm. Studies on the position and slope of the red edge would require at least one additional band, for example near 682 nm, and to be useful, that band should be even narrower. A width of 5 nm is recommended. Clearly, the spatial resolution of the measurements should be sufficient to monitor the highly heterogeneous terrestrial surfaces. Current experience with the advanced very high resolution radiometer (AVHRR), flown by the United States National Oceanographic and Atmospheric Administration (NOAA), the Landsat thematic mapper (TM) and the high resolution visible instrument (HRV) flown on the French satellite SPOT (système pour observation de la terre), shows that there is considerable spatial variance over a wide range of scales (Vogt, 1992), but a spatial resolution of the order of a few hundred meters would go a long way to address the limitations of the current data. Finally, the co-registration of these bands must be assured to a high degree of accuracy for the vegetation index methods to be useful.

New approaches are being investigated in parallel with these empirical vegetation index studies. Physically-based models describing the reflectance of light by plant canopies and soils are being constructed and validated (Verstraete et al., 1990; Pinty *et al.*, 1990). The inversion of these models against remote sensing data will provide accurate and reliable data about the surface, as well as a verifiable description of the surface (Pinty and Verstraete, 1992). This strategy must be applied separately in each spectral band and it entails somewhat different requirements. Since all natural surfaces are anisotropic, the sensor should ideally provide a characterisation of the bi-directional reflectance distribution function (BRDF) of the surface. This would require either a pointable instrument, to observe the same surface from different view points, or multiple instruments, either on the same or on different platforms. MERIS has no fore- or aft-looking capability and so the anisotropy of the surface will have to be characterised by repetitive monitoring over time, and by combining MERIS measurements with observations made by other instruments on different platforms.

Two major requirements result from this strategy to extract surface information from remote sensing data. The first one is an accurate knowledge of the illumination and viewing geometry at the time of observation. An accuracy of the order of a fraction of degree is needed. The second requirement is for an accurate radiometric performance, since the presence of noise in the measurements significantly degrades the reliability of the inversion procedure (Rahman *et al.*, 1993(a) and 1993(b)). Nevertheless, it appears that the radiometric requirements are more stringent for ocean applications than for terrestrial studies.

Other scientific issues need to be dealt with in conjunction with the estimation of surface properties. As is the case for the oceans, terrestrial surfaces are observed through the atmosphere. The presence of the latter can induce significant perturbations in observations made from space, because of the absorption and scattering of light by molecules and aerosols. Providing adequate atmospheric corrections over land surfaces is much more difficult than over the oceans, because of the wide differences in surface properties and the interactions (e.g. through multiple scattering) between these surfaces and the atmosphere. However, the contribution of the surface to the total reflectance is also often much higher than that of water surfaces, although the case of deep forests in the visible range constitutes a notable exception.

The effects of making observations in spectral absorption bands, caused by atmospheric constituents such as water vapour, can be circumvented almost entirely by selecting narrow bands which are positioned outside of the affected regions. The effects of aerosols, however, cannot be so simply avoided, as these are seen over a very wide range in the spectrum. Improved vegetation indices have been proposed, either to incorporate an automatic atmospheric correction based on the same two visible and near-infrared channels (Pinty and Verstraete, 1992), or to exploit the differential sensitivity of different bands to the presence of aerosols (Kaufmann and Tanré, 1992). New indices will most likely follow this trend.

The state of the art in physically-based models is in the inversion of coupled surface-atmosphere models, which will allow the simultaneous retrieval of information on both the surface and the atmosphere (Rahman *et al.*, 1993(a) and 1993(b)). Here again, the availability of a variety of measurement bands for which the atmospheric effects are clearly different, should improve our capability to characterise the atmosphere at the same time as the surface.

A.1.5 CONCLUSION

From the discussions above it can be seen that although MERIS was initially conceived as an oceanic mission it will be of considerable benefit to other disciplines in the atmospheric and terrestrial sciences. A number of supporting studies has been carried to gain a fuller understanding of the suitability of MERIS for applications other than case I water observations. The findings of these studies have, amongst others, helped maintain the flexibility of the MERIS instrument to meet a variety of mission requirements. These studies have also contributed to the design of many algorithms which will ensure the retrieval of important geophysical parameters outside the confines of ocean colour monitoring.

A.2 OBSERVATIONAL AND MISSION REQUIREMENTS

A.2.1 SUMMARY

This Chapter describes how the instrument and mission requirements for MERIS have been derived from the data needs described in Chapter A.1.

MERIS is a powerful instrument, designed to satisfy a range of data needs, important to a variety of global change issues. This is achieved with both a high spatial and spectral resolution, as well as by making the carefully calibrated instrument fully programmable in the spectral domain. It will be shown in Part B that MERIS is also designed to have programmable gain, so that the full dynamic range of the digitising electronics can be tailored to meet the expected range of useful radiance values.

A.2.2 SPATIAL REQUIREMENTS

The selection of the two spatial characteristics of the MERIS sensor, swath width and spatial resolution, is the result of a compromise between the capability to describe the surface in great detail and the requirement to provide global Earth coverage within a relatively small period of time. The choice of these characteristics must of course also take into account the limitations and engineering constraints of the polar-orbiting Envisat–1 platform on which MERIS will fly.

The scientific issues described in Chapter A.1 clearly call for a mission capable of acquiring data on a global scale. For oceanic and especially atmospheric applications, measurements should be made frequently, because of the inherent temporal variability of the targets under study. When combined with a field of view of about 34 degrees on either side of nadir, the characteristics of the Envisat-1 platform orbit will provide full, repetitive, global coverage of the Earth with a period of three days at the most. Given the nominal altitude of 800 km for the Envisat–1 platform, this corresponds to a swath width of the order of 1150 km.

Previous experience with CZCS and AVHRR has shown that patterns of ocean productivity, as evidenced by changes in ocean colour, can be usefully monitored at a spatial resolution of up to a few square km. The spatial resolution decreases with the viewing angle from nadir, and this imposes a minimum spatial resolution of 2 km on the extreme end of the swath, implying a linear resolution of approximately 1 km at sub-satellite point. This resolution is too crude for coastal zones and continental surfaces, where the spatial variability of the environment is much higher. Estuaries and land ecosystems, as well as agriculture and topography, normally exhibit significant variability when observed on scales of the order of a few hundred metres. To observe these ecosystems, a much better spatial resolution is desirable.

The MERIS instrument has accordingly been designed with a spatial resolution of 300 m at the sub-satellite point. Since this strategy would far exceed the data needs of the oceanic applications and would needlessly increase the data rate over large regions, the sensor will be operated in two modes. The full-resolution mode is intended for use over continental land masses and coastal areas, while the reduced resolution mode, which has a spatial resolution of 1.2 km at sub-satellite point, is suitable for global observations. These modes of operation are further detailed in Part B and the corresponding data products are described in Part C of this series. Most atmospheric investigations will not require such a high resolution, but the availability of observations at the 300 m spatial resolution over land will permit the definition of reliable cloud flags.

In addition to swath width and spatial resolution, there is also a need for precise geographical referencing of the acquired data. This requires an accurate knowledge of the position of the satellite in space at all times, so that reliable latitude and longitude coordinates can be assigned to individual observations. Requirements are more critical over land than above the sea, but the existence of landmarks, and the availability of accurate orbit restitution are expected to provide accurate registration of the data sets. Over the oceans and far from the coastlines, registration is essentially impossible to improve *post priori*, because of the absence of any recognisable surface features. However, the greater uniformity of the oceanic patterns imposes less severe requirements. As a result, an absolute registration accuracy of about 2 km over the oceans and 600 m over land at the sub-satellite point (two pixels in each case) is considered adequate.

A.2.3 TEMPORAL REQUIREMENTS

The basic temporal requirement to provide global coverage within three days at the most for oceanic and atmospheric applications has already been mentioned. This observation frequency is adequate for most terrestrial applications, although a significant reduction in the amount of useful observations should be expected as a result of the frequent cloud cover.

The sparsest coverage will occur over Equatorial regions, because the characteristics of the Envisat–1 orbit will produce the largest gaps between orbits around the Equator, and because these regions are frequently cloud covered. However, all areas poleward of 50 degrees latitude will be observed at least once every two days by MERIS with the field-of-view given above. Additional details on the orbital parameters and the coverage of the instrument will be found in Part B of this series.

A.2.4 SPECTRAL REQUIREMENTS

The MERIS instrument has been conceived as a flexible programmable imaging spectrometer. Specifically, MERIS has the capability to observe the Earth at a resolution of 2.5 nm over the entire spectral range from 390 to 1040 nm. As will be seen in Part B of this series, up to 15 spectral bands within this range can be transmitted to ground, and these spectral bands can be selected and changed in flight, both in position and in width, subject to minor additional technical constraints. It must be emphasised however, that a nominal configuration for an operational ocean colour mission will be maintained. Thus ESA does not foresee frequent changes in the band configuration throughout the MERIS mission.

The Scientific Advisory Group has defined a set of nominal spectral bands, and these are summarised in Table A.2–1 (inside the back cover). This particular band set has been selected to support the various applications described above, and also to permit specific feasibility and design studies needed, for example, to size the instrument and evaluate its performance. The final fifteen-band configuration with which MERIS will be flown, will be determined during the course of the algorithm development phase but this configuration may be modified further during the commissioning phase.

The width of each spectral band given in Table A.2–1 has been chosen to match the features to be observed. Over the oceans, a bandwidth of 10 nm has been found sufficient. A narrower band around 681.5 nm, only 7.5 nm wide, is proposed to detect chlorophyll fluorescence in the open sea, predominantly in the coastal zones. It may also be needed to characterise the sharp increase in reflectance of green plants known as the red edge.

For many applications, the desired information will be obtained from an analysis of two or more spectral bands pertaining to the same location. It is therefore crucial that these bands do in fact refer to the same place at the surface of the Earth, and an additional requirement has been identified, namely that the co-registration of the spectral bands should be within 0.2 pixel.

A.2.5 RADIOMETRIC REQUIREMENTS

In the visible part of the solar spectrum, the reflectance of natural surfaces spans the range from very dark oceans and dense forests to very bright surfaces such as snow, ice and clouds. Particularly high reflectances should also be expected in Sun glint areas. A high radiometric performance, together with an accurate calibration procedure, will be essential for MERIS to deliver its promised contribution to the various climatic and environmental issues previously identified.

In the visible part of the spectral range covered by MERIS, the most demanding applications will be the monitoring of the ocean colour, because of the very low contribution of the sea surface to the total observable radiance in this spectral region. Figures A.2–1 (a), (b) and (c) show the maximum values of the noise equivalent spectral reflectance (NEΔR) at sea level required to be able to differentiate ten, five, or three classes within each of the three orders of magnitude of pigment concentration; curves are given for three different proposed algorithms. An algorithm based on the ratio of the reflectances at 445 and 565 nm appears to be the most sensitive one for determining average chlorophyll concentrations in the open ocean of (0.3 mg m^{-3}).

Since these requirements exceed those of atmospheric applications in this spectral

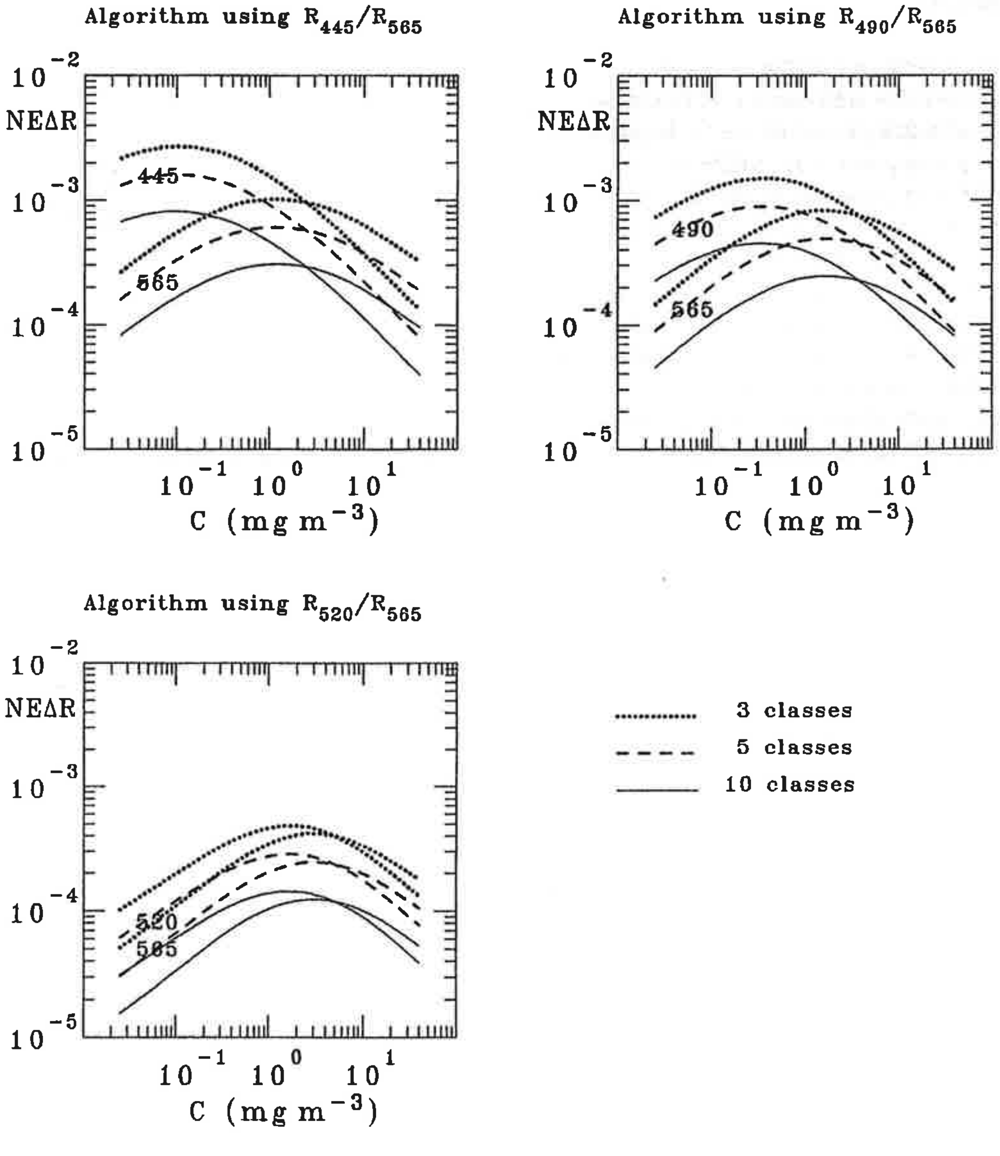


Figure A.2–1. Maximum values of NEΔR (noise equivalent difference in reflectance) required to be able to detect ten classes (solid), five classes (dashed) or three classes (dotted) within each order of magnitude in pigment concentration. The values of NEΔR vary according to the range of pigment values. The three panels show results obtained with three algorithms, each using the three ratios of spectral reflectances. Note that there is a common channel at 565 nm in each of the algorithms; the NEΔRs for this wavelength however, are not the same according to the algorithm which is envisaged. The worst-case situation is the smallest and most stringent NEΔR at 565 nm, which is encountered when the R(520)/R(565) algorithm is used. (LPCM, (1991)) region, the corresponding specifications of MERIS are driven by ocean colour monitoring in the visible spectral region. The contrary occurs in the near-infrared region, where the contribution of the oceanic surface is negligible compared to that of the atmosphere and terrestrial surfaces (Tables A.1–1 and A.1–2). In this case, the radiometric requirements are derived from the need to correctly characterise the state of the atmosphere for performing very accurate atmospheric corrections. These provide useful data for oceanic and terrestrial applications. Indeed, the atmospheric corrections required to monitor the ocean colour will be based primarily on an assessment of the radiance in near infrared channels. The feasibility of estimating pigment concentrations at the expected resolution and accuracy will depend entirely on the quality of these atmospheric corrections.

As far as terrestrial applications are concerned, it is well known that existing spectral indices are sensitive to the presence of the atmosphere. Poor radiometry results in unreliable estimates of vegetation characteristics. Furthermore, preliminary results from the inversion of coupled surface-atmosphere models have shown the importance of high quality data (Rahman *et al.*, 1993a and 1993b). However the stringent radiometric resolution requirements of the oceanic applications have been shown to be sufficient for terrestrial applications.

A.2.6 POLARISATION REQUIREMENTS

At short wavelengths, primarily in the blue region, the radiation reflected by the atmosphere may be highly polarised. Since this radiation interacts with various surfaces in the optical module before being detected in the sensor, the signal may be contaminated if the polarisation induced by the instrument itself is not parallel to that of the incoming radiation. To reduce this effect, which could severely limit the capability of the system to effectively observe oceanic pigment concentrations, the instrument-induced polarisation error must not exceed 1 % of the signal in any 5 nm bandwidth. Since corrections will nevertheless have to be applied, it would be desirable to know the polarisation characteristics of the instrument to an accuracy of 0.1 %.

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Part B: Instrument Concept and Mission Constraints

PART B

CONTENTS

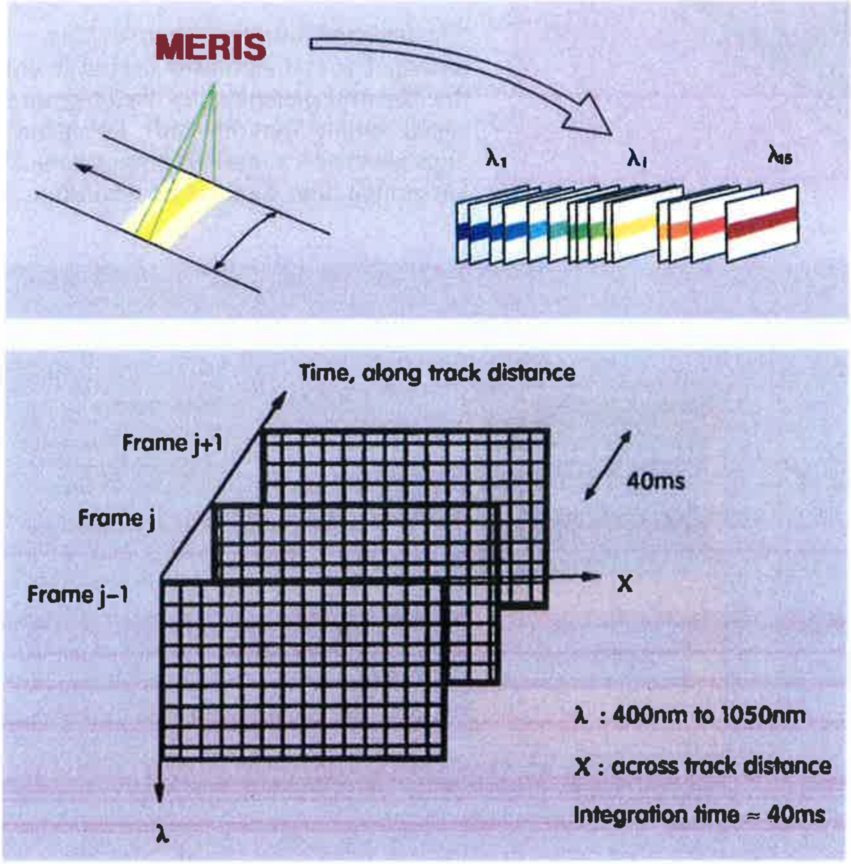
B.1 MERIS INSTRUMENT CONCEPT

In this Chapter, the MERIS instrument concept is briefly described.

B.1.1 FUNCTIONAL DESCRIPTION

MERIS is a programmable, high spectral-resolution, imaging spectrometer, which makes observations at wavelengths in the 390 to 1040 nm region of the electromagnetic spectrum. Up to fifteen spectral bands can be selected by telecommand from the ground. Band positions are programmable and resolution can be set equal to, or in multiples of, 2.5 nm. A nominal bandset has been chosen, but this can be modified before launch and, later, in-flight. Table A.2–1 shows position, bandwidth and application of the nominal bands. Ongoing research will serve to refine the spectral band positions further and consequently, the set of bands which is programmed at launch may well be different.

Figure B.1–1. MERIS Data Organisation Principle.



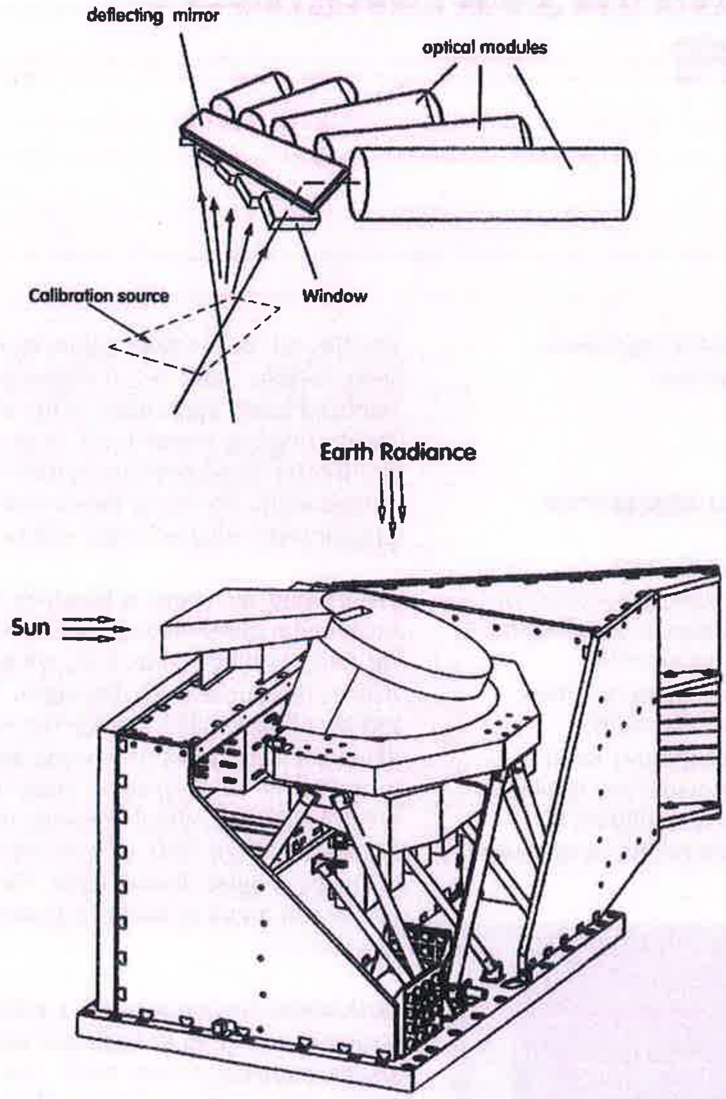
The imaging technique is based on the pushbroom observation principle. A strip on the Earth is imaged onto a slit whose length defines the across track dimension. The motion of the satellite sweeps the narrow slit along-track and gives the second dimension in space. The whole spectral range of the scene is projected simultaneously through a dispersive system onto a frame transfer array of charge coupled devices (CCD). The pushbroom mode of MERIS is illustrated in Figure B.1–1.

Earth scenes are imaged with a spatial resolution of 300 m at nadir and with regular angular sampling across- track. Over open oceans, the spatial resolution will be reduced to 1200 m, by combining together, on board, four adjacent pixels across-track and four consecutive lines along-track. Over coastal zones and land, it will also be possible to transmit data with the full spatial resolution of 300 m.

MERIS is designed so that it can routinely acquire data over the whole of the Earth's surface. With a 68° field-of-view centred about nadir, covering a swath width of 1150 km from a circular, Sun-synchronous, polar orbit at an altitude of 800 km, MERIS is capable of covering the entire Earth surface within three days.

B.1.2 OPTICS

The large field of view of the instrument is divided between five identical optical



modules, each having a field-of-view of 14° The modules are arranged in a fan configuration in which the fields-of-view overlap slightly (Figure B.1–2). In this desig the calibration subsystem hardware is plac at the entrance port of MERIS. The Earth viewing windows are polarization scrambl designed to reduce the sensitivity of the instrument to incoming polarised light.

An off-axis catadioptric system images the Earth onto the entrance slit of the spectrometer. The design of the spectrome incorporates a concave diffraction grating, refractive element and a blocking filter to eliminate the grating's second order spectrum.

The design of the optics offers excellent inherent registration between spectral ban A concave grating has been demonstrated be ideally suited for imaging applications o CCD-based spectrometer applications. A modular concept has been selected as this facilitates the control of the instrument polarization and spectral co-registration.

B.1.3 DETECTORS

The detectors are silicon matrix CCDs, arranged as frame transfer devices in whicl the electrons generated by the integrated signal coming from the Earth, are shifted a high speed into a masked storage area. The integration time during data acquisition is

Figure B.1–2. Arrangement of optical modules, deflecting mirror and Earth viewing windows and mechanical layout of the MERIS system.

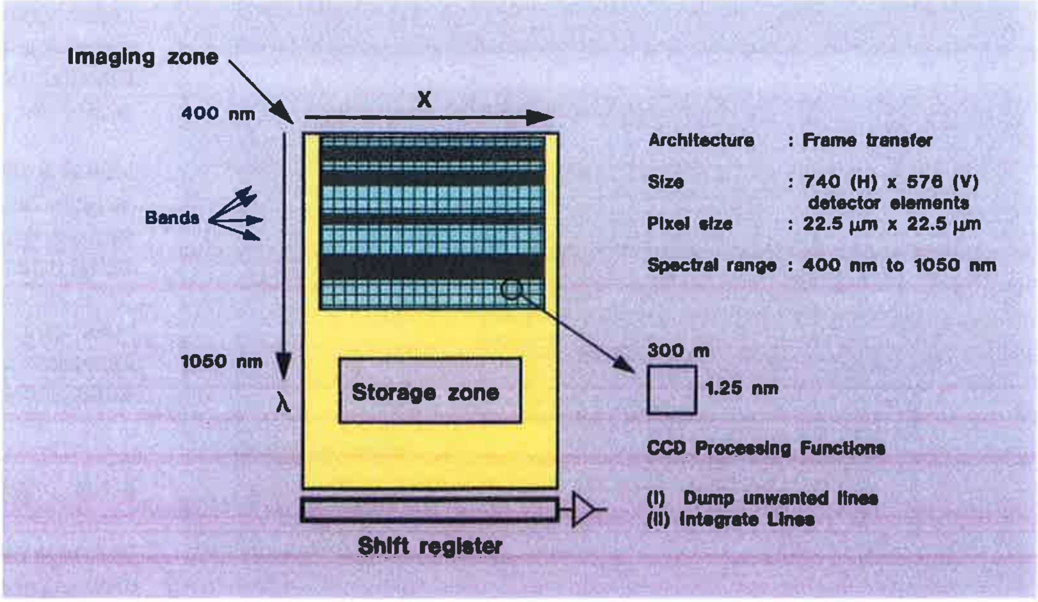


Figure B.1–3. Architecture of the CCD sensor.

about 44 ms. The stored charges, can be read out of the storage area while the next frame is being integrated in the imaging zone.

The entire spectrum in the range 390 to 1040 nm, emanating from each pixel within the swath, is recorded along a CCD column, while a line across the CCD records the across track image of a strip on the Earth (Figure B.1–3). The data not contained within the fifteen chosen spectral bands are discarded at the frame transfer stage.

Back-illuminated, thinned, CCDs have been selected to provide the high signal-to-noise ratio in the visible part of the spectrum required for oceanographic applications. To achieve this performance, the CCD focal plane assembly is cooled to –25 °C.

The CCD design is optimized to provide the best compromise between responsitivity in the blue region of the spectrum, modulation transfer function in the near infrared region, storage capacity, and mechanical strength.

B.1.4 ENCODING

One of the major difficulties in designing MERIS is to accurately detect the low water radiances, which form part of larger signals arising from radiation backscattered by the atmosphere. This must be achieved in addition to the dynamic range needed to observe bright targets such as land surfaces and clouds. This requires an analogue-to-digital converter with 12-bit resolution whose speed is high enough to convert the large amounts of analogue data generated by the CCD. These two exacting requirements have been eased by preliminary on-chip signal processing which reduces the required conversion rate.

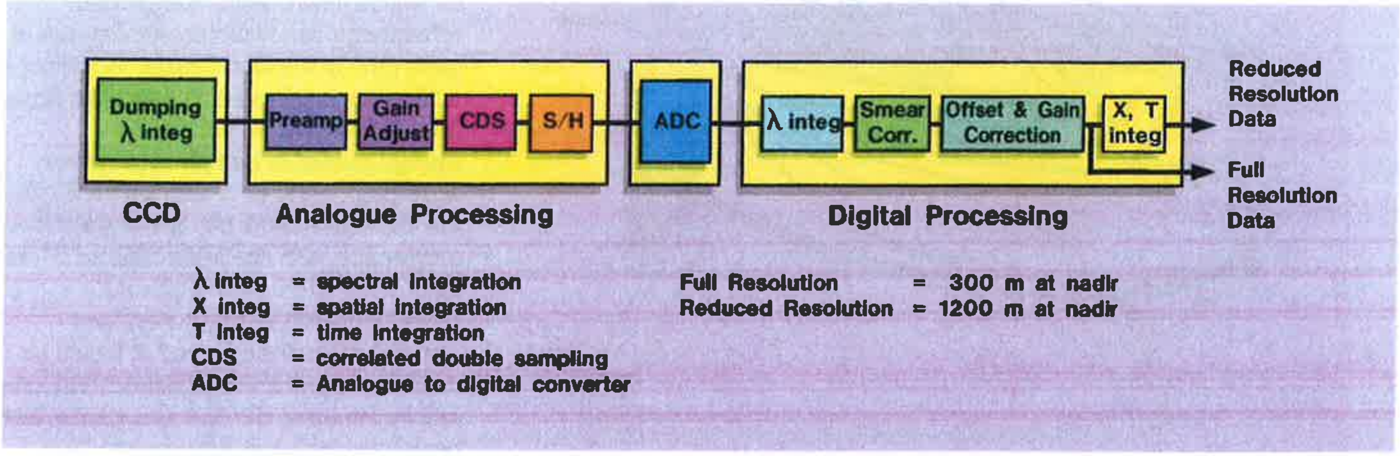
MERIS is designed to operate over a dynamic range extending from the instrument noise level to the maximum signal scattered by a bright cloud, which is assumed to be a 100% Lambertian reflectance target located at the top of the atmosphere and illuminated under the smallest zenith angle encountered in the field-of-view of MERIS. This is known as the L4 condition. To maintain the radiometric resolution requirement for open ocean, whilst retaining the dynamic range, the gain associated with each spectral channel of MERIS is programmable and selectable to provide sufficient flexibility in the adjustment of the saturation limit. The gain chosen for each band can be changed during the lifetime of MERIS. A single gain can be assigned to more than one band.

B.1.5 SIGNAL CONDITIONING

The CCD readout signals go through several processing steps to attain the required image quality requirements. The on-board signal management tasks are divided into three main processing areas, the CCD, the analogue electronics and the digital electronics. (Figure B.1–4).

The CCD processor tasks involve discarding the unwanted spectrum information (typically 75% of the full spectrum) and integrates the CCD lines to 2.5 nm wide spectral bands over the spectral range of the instrument. The analogue electronics provides basic functions such as pre-amplification of the CCD signals,

Figure B.1–4. MERIS signal processing chain.



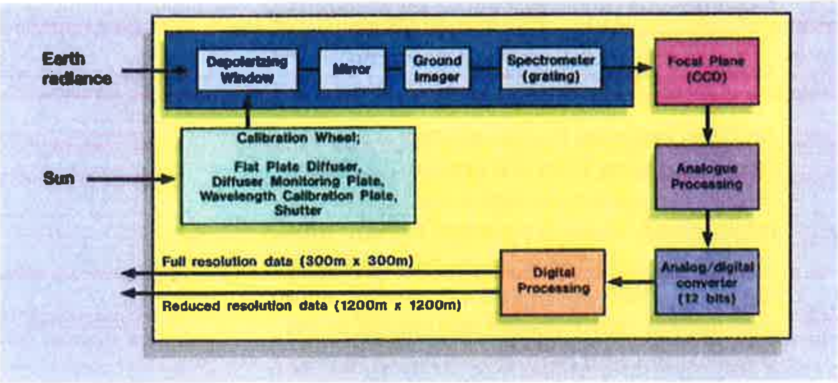


Figure B.1–5. Functional block diagram of the MERIS signal chain.

correlated double sampling and gain adjustments before digitization. The digital electronics has three functions. Firstly it must complete spectral integration in order to achieve the required width for the transmitted bands, secondly it must perform the smearing, offset, and gain corrections and thirdly it must combine full resolution pixels to produce reduced resolution pixels whenever required. Figure B.1–5 summarises the MERIS signal chain.

B.1.6 CALIBRATION

One of the most severe requirements on MERIS is posed by calibration. A very accurate band-to-band calibration, relative to the solar spectral irradiance, is required for ocean colour applications. The imaging principle of MERIS imposes, in addition, a need for the detector elements to be accurately normalised.

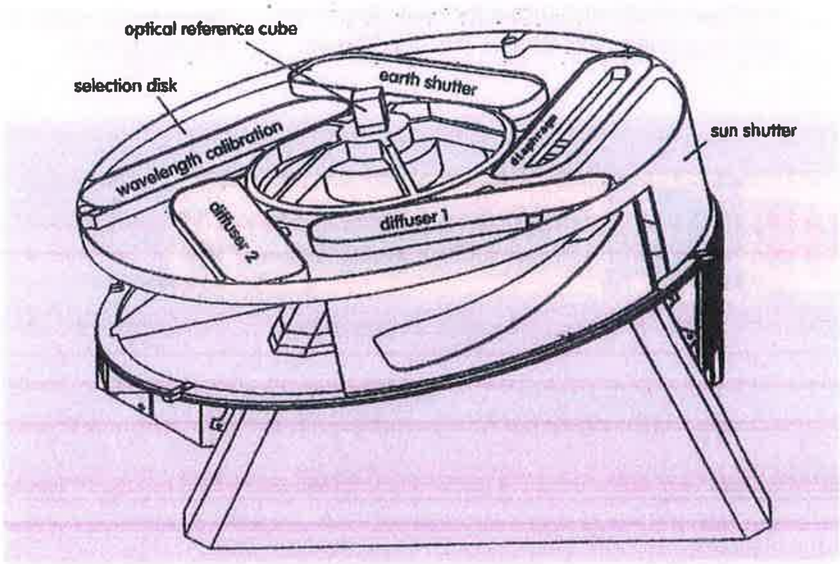


Figure B.1–6. MERIS on-board calibration wheel.

The basic hardware requirements for an on-board calibration system offering both uniform reference signal over a large field-of-view and a stable absolute spectral reference signal have led to the preferred solution which utilizes three separate on board reference sources (Figure B.1–6). Th sources are diffuser plates mounted on a calibration wheel which can insert any one these plates into the cross over point of th MERIS field-of-view. The wheel contains fiv sectors. One sector contains an aperture u for normal Earth viewing, another sector h a shutter for dark calibration and protectin the optics during launch, and the remainin three hold diffuser plates. The first plate D1 used for routine calibration, the second pla D2, is used to monitor any changes in the behaviour of the D1 plate. The third plate i doped with a rare Earth element to produc well known, wavelength-dependant, signal which can be used for wavelength calibrati of the CCD assembly.

For the absolute calibration, a well characterized flat plate diffuser D1, is inser into the field-of-view of MERIS. This diffuse illuminated by the Sun and provides a reflectance standard across the entire spectral range and field-of-view. In this wa full-aperture, end-to-end, instrument calibration which follows the same optical path as used the Earth viewing mode, is realised. This single plate also provides for relative spectral calibration. The uniform Spectralon diffuser may degrade over time due to illumination by ultraviolet (UV) radiation. Over the lifetime of MERIS, it is expected that the diffuser will yellow by u 2% in reflectance of the shorter wavelengt regions. To monitor the potential degradation, a second identical diffuser pla D2 will be flown which will be used infrequently and will thus not degrade at t same rate as the first diffuser. Wavelength calibration is achieved by using the doped diffuser plate D3. MERIS will be reprogrammed to sample appropriate absorption features. It also seems feasible use the solar Fraunhofer line absorptions i conjunction with the white diffuser D1 as a alternative. Extensive on-ground characterisation at component and instrument level is required. It would be desirable to perform a prelaunch instrume calibration using the Sun as a source, as h been done for other instruments. Dark current calibration will be obtained by obscuring the optical modules with the shutter and by monitoring masked pixels on the CCD detector.

Calibration will be carried out when the spacecraft flies over the South orbital pole and the Sun illuminates the instrument in a direction orthogonal to nadir. MERIS may be calibrated an average of once per day throughout its life. However once the stability of the instrument has been verified, the time between successive calibrations will be increased to minimise any further degradation of the diffuser plates.

B.1.7 INSTRUMENT SPECIFICATION

From the scientific requirements detailed in Part A, the instrument specification given in Table B.1–1 have been derived. A radiometric specification, in terms of NEΔL (noise equivalent change in radiance) for certain radiation levels, *L*, has been given to industry. To do this ESA took the NEΔR (noise equivalent change in reflectance) requirements given in Section A.2.5 as a starting point and translated these into an instrument specification in terms of NEΔL. The translation was done by simulating the radiances and NEΔLs for a 'standard ocean' in three positions of the MERIS swath. The model radiometric conditions were :

L_1 = standard ocean in a position in the MERIS swath for which radiance is a minimum;
L_2 = standard ocean in a position in the MERIS swath which requires the smallest value of NEΔL;
L_3 = standard ocean in a position in the MERIS swath for which radiance is a maximum.

The parameters, which define a standard ocean, are listed in Table B.1–2. The specifications and performance of the MERIS instrument within its swath are given in Part C of this series. Dynamic ranges can be selected for each band individually by using the range of pre-set of gains that are available (see Section B.1.4 on signal encoding). Although the performance parameters of MERIS have been derived for a solar zenith angle of less than 60°, MERIS will capture data at solar zenith angles of up to 80°.

System Characteristics

Lifetime		> 4 years
Data rate:	- reduced spatial resolution mode - full spatial resolution mode	0.9 Mbits/s 14.2 Mbits/

(Data rates are for raw data and do not include header information.)

Geometric specifications

Instrument field-of-view		68 degrees centred about nadir
Swath width:		1150 km
Spatial resolution:	- reduced spatial resolution mode - full spatial resolution mode	1200 m 300 m

(The Envisat orbit meets these requirements. Angular sampling accross-track is regular.)

Spectral specifications

Spectral range	400 nm to 1050 nm
Spectral sampling interval	< 1.25 nm
Band transmission capability	15 spectral bands
Spectral bandwidth	from 2.5 nm to 30 nm
Registration between bands	< 0.2 IFOV
Band centre knowledge	< 1 nm

(Some band combinations are not possible due to technical restrictions, but these are unlikely to be needed during the Meris mission.)

Radiometric specifications

Polarisation sensitivity	< 1% over the full spectral range
Radiometric accuracy (relative to the Sun)	400-900 nm < 2% 900-1050 nm < 5%
Band to band accuracy	< 0.1%
Pixel to pixel accuracy (across swath)	< 2 x NEΔL
Dynamic range	From NEΔL to cloud (L_4)

(The dynamic range of each band is variable.)

Table B.1–1. The main performance parameters of MERIS.

Table B.1–2. Parameters needed to derive a standard ocean case.

Day of the year	80
Ozone	350 DU
Precipitable water	2 cm
Aerosols	maritime
Visibility	23 km
Water type	open ocean Case I
Chlorophyll pigment	0.3 mg m^{-3}
Pixel position	within Meris swath, solar zenith angle less than 60 degrees.

B.2 MISSION CONSTRAINTS

The area of the Earth's surface that can be observed with an optical instrument is limited by many environmental constraints such as inadequate solar illumination, the presence of clouds, the radiometric and geometric resolution required for different mission applications. The capability of MERIS in the face of some of these constraints is assessed in this section.

B.2.1 THE ENVISAT–1 ORBIT

MERIS is planned to fly on board ESA's Envisat–1 satellite, which will placed in a Sun-synchronous orbit, having the following characteristics:

Semi major axis:	7159.5 km
Mean orbital altitude:	799.8 km
Eccentricity:	0.001165
Argument of perigee:	90°
Inclination:	98.549°
Period:	100.47 min.
Local Equator nodal crossing time:	10:00 hrs.
Repeat Cycle:	35 days

The pointing of the axes of the Envisat–1 satellite will be controlled to compensate for the effect of the Earth's rotation on the sub-satellite geocentric point and to keep the satellite's yaw axis pointing towards the local Earth normal. This orbit was selected as a compromise between the needs of the various payload components and their missions.

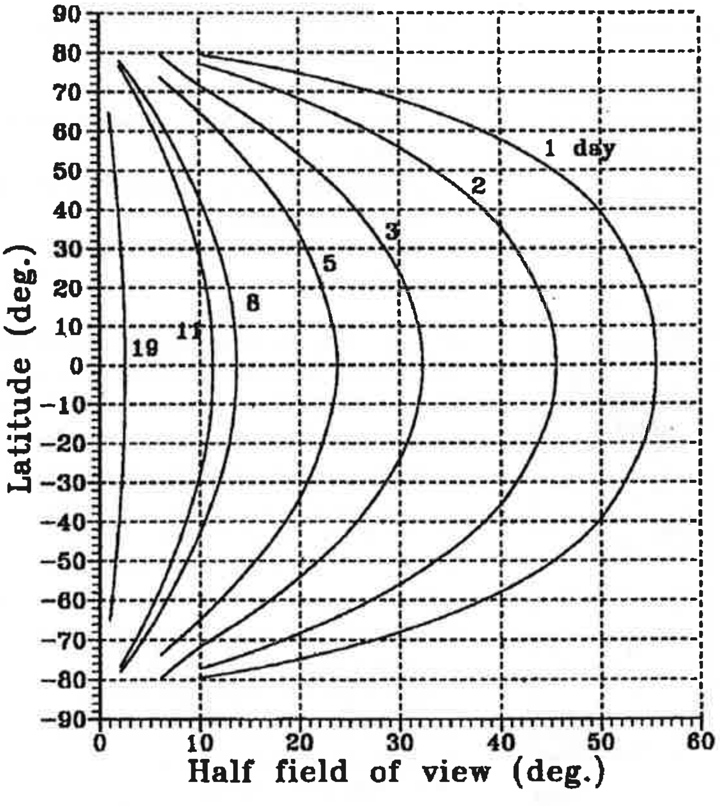


Figure B.2–1. Earth coverage for the instruments on-board Envisat–1.

B.2.2 IMAGING CHARACTERISTICS

The MERIS field-of-view is driven by the requirement to provide global Earth coverage over a three day period. Figure B.2–1 shows the latitudes beyond which the Earth is entirely covered within a given number of days as a function of half of field-of-view of an instrument in the Envisat–1 orbit.

With the present baseline of a half field of view of 34°, MERIS will achieve a total Earth coverage within 3 days. For parts of the earth above latitude 50°, total coverage will be achieved within 2 days, and for areas above latitude 65°, total coverage will be achieved in one day.

As described in Section B.1, the spatial imaging function will operate in pushbroom mode, which implies that the resulting pixel dimensions will be determined by the dynamics of the system (satellite velocity, instrument integration time).

The pixel dimensions along-track (PAL) and across-track (PAC) will vary with position along the instrument swath and with the satellite position in orbit. The across-track pixel size will depend only on the pointing direction in the instrument field of view. However, the along-track pixel size will depend on the apparent velocity of the satellite over ground and on the instrument integration time. Table B.2–1 gives the mean pixel sizes (in metres) in full and reduced resolution modes, for the total MERIS instrument field of view during one descending swath.

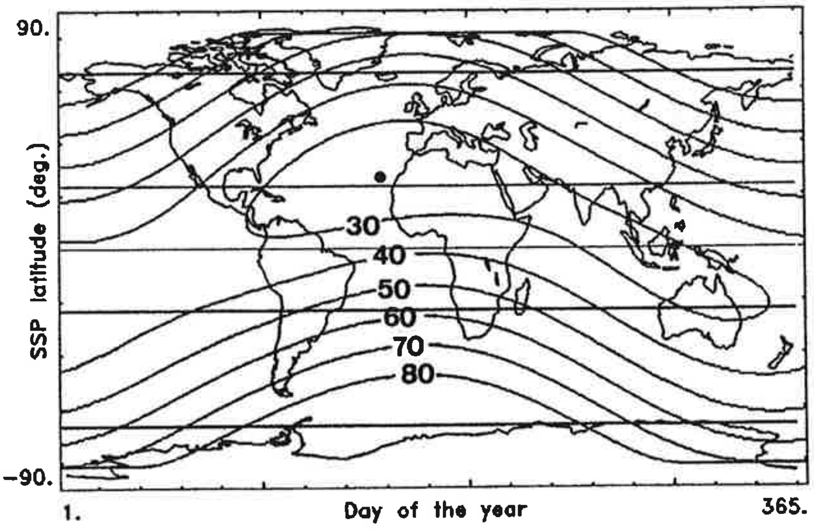
Table B.2–1. Spatial resolution characteristics of MERIS.

Angle in FoV	Reduced resolution		Full resolution	
	PALmax (m)	PACmax (m)	PALmax (m)	PACmax (m)
34	1192	1648	297	412
20	1189	1205	297	301
0	1184	1015	296	254
-20	1184	1204	296	301
-34	1186	1644	296	411

B.2.3 ILLUMINATION CONDITIONS

MERIS can only acquire satisfactory data if the target area is properly illuminated. The following sections outline some of the problems encountered in obtaining satisfactory results.

Figure B.2–2. Envisat–1 contours of solar illumination angle at the sub-satellite point for latitude and day of the year.



B.2.3.1 Sun illumination conditions

The radiometric quality of the data acquired by MERIS will depend on the illumination of the scene. The solar zenith angle varies with the day of the year, the angular position in the instrument's field-of-view and the nodal crossing time of the Sun-synchronous orbit of Envisat-1. The latter changes during the year due to the elliptical trajectory of the Earth around the Sun. In Figure B.2–2, the solar zenith angle is plotted against latitude at sub-satellite point for each day of the year.

Solar zenith angle contours are given at ten-degree intervals. The black dot indicates the position of the minimum zenith angle (23.6°). In the Figure, a map of the Earth has been superimposed to aid comprehension and the nodal crossing time has been set to 09:55 a.m. on 1 January, so that its variations during the year are symmetrically distributed around the nominal value of 10:00 a.m.

B.2.3.2 Sun glint

One of the factors influencing the temporal and spatial coverage of MERIS over the ocean is Sun glint (specular reflection of sunlight into the instrument's field-of-view).

The signal detected by MERIS is composed of three parts:

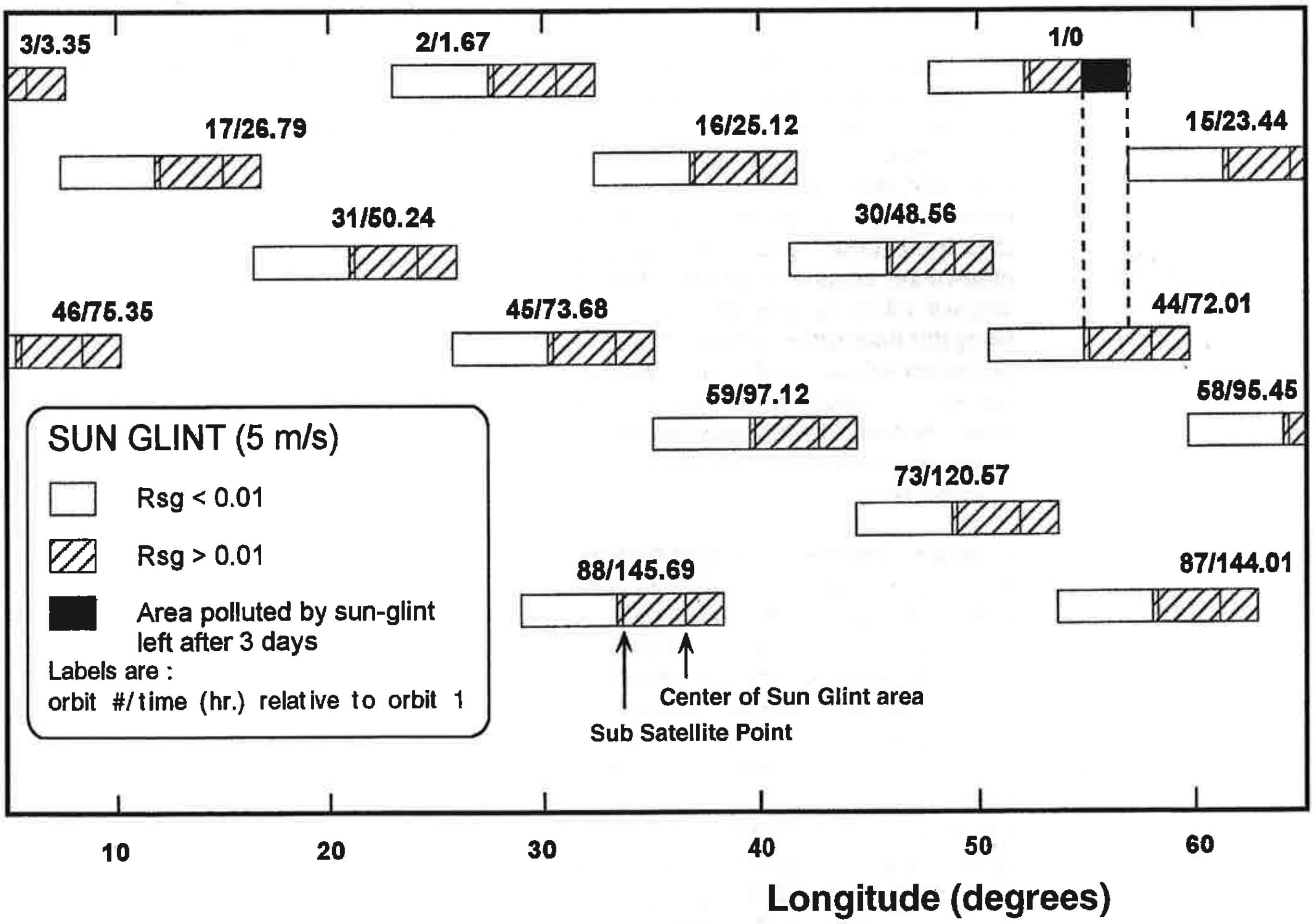
- photons backscattered by the atmosphere, chiefly by aerosols and water vapour;
- photons specularly reflected by the sea surface (Sun glint);
- photons emitted by the surface of the water.

Of these, only the latter signal has suffered any interaction with the constituents of the water and therefore contains a useful signal for ocean studies. The other two components constitute background signals, which have to be correctly subtracted from the signal sensed at the top of the atmosphere. In the absence of Sun glint, the atmospheric radiance is predominant and can comprise as much as 90% of the total signal over water. Alternatively, the glint signal will predominate for areas with certain combinations of solar illumination and viewing geometries, making the exploitation of the data very difficult. These images are usually discarded.

The theoretical maximum Sun glint will occur over the sea on a windless day when it will exhibit the behaviour of a perfect mirror-like reflector. In such cases the Sun glint will be up to a thousand times stronger than the signal returned by a 100% diffuse reflector. In practice the sea surface is not flat, even at very low wind speeds, and this theoretical maximum is not reached. Instead, only some individual facets of the rough ocean surface are in the Sun-glint orientation, thus lowering and spreading the total signal over a wider area. The detectors of MERIS will saturate over high Sun glint regions, but this will be confined to one of the five MERIS cameras and recovery within five seconds is guaranteed.

The occurrence of Sun glint over a specific region of the ocean does not mean that it will never be imaged without Sun glint. Due to the phasing and the swath overlaps of the MERIS orbit, data pertaining to the geographical zone affected by Sun glint along a specific satellite track can be recovered within the next three days from other satellite tracks as depicted in Figure B.2–3. For this simulation, an average wind speed of 5 m s^{-1} was assumed, using the Cox and Munk model as a basis for the calculation, (Cox and Munk, 1954). In this figure, instrument swaths at the equator are shown for several different orbit tracks. The Sun glint zone always occurs in the same angular part of the instrument's field-of-view, at an angle of 20 to 25 degrees from nadir. Overlapping tracks have been separated for the sake of clarity. The amplitude of the glint signal is indicated by the ratio between the radiance observed in the instrument instantaneous field-of-view and the radiance observed over a 100% diffusing Lambertian scene under the same conditions. This radiance ratio is noted Rsg (radiative ratio of Sun glint). The Sun glint zone is defined by the area on the Earth, giving a Sun glint signal comparable to the useful signal (water leaving radiance), i.e., the Earth area with a radiance ratio Rsg ≥ 0.01.

Figure B.2–3. MERIS coverage at the equator for a three day period with the sun glint zone indicated by the hatched area.



B.2.4 CLOUD OCCURRENCE

The successful achievement of the objectives for the application of MERIS to open ocean, coastal water and land surface investigations requires at least one observation of the entire field-of-view without cloud obscuration after a requested time period. This period will be application specific. Using cloud coverage models, it is possible to derive the probability that an observed area will be clear of cloud at a given time. These models can also be used to calculate the number of passes required to achieve a certain probability of viewing the Earth's surface.

Table B.2–2. Percentage of sea surface area exhibiting certain atmospheric transmission factors after different observation periods, for the Mediterranean Sea.

Operation Period	Image quality		
	T > 0.75	0.75 > T > 0.65	0.65 > T
3 days	87%	5%	7%
5 days	93%	2%	5%
8 days	95%	2%	3%
12 days	98%	1%	1%

Simulations involving the superposition of global Earth cloud maps, extracted from the International Satellite Cloud Climatology Project (ISCCP), on the MERIS swath coverage, show that after three days, only 50% of the ocean and 78% of the land can be expected to be free of clouds. Even after 10 days of observation, about 17% of ocean and 4% of land will still not be seen without clouds. Using this information, a trade-off was performed between field-of-view and the probability of cloud-free acquisition. As a result, the MERIS field-of-view has been set at ± 34° which will allow complete Earth coverage within three days.

To obtain a regional cloud climatological model suitable for the simulation of cloud interactions with regional MERIS data requires a more sophisticated approach than the use of statistical models of global cloud coverage referred to above. These regional climatological models should not only predict the presence of clouds but should also enable the most important optical properties of the atmosphere to be determined. As an example, the coverage of the Western part of the Mediterranean Sea during a spring chlorophyll bloom has been assessed.

Meteosat radiometer images from 1984 have been used to compute the representative atmospheric transmission factor T. The percentage of the Mediterranean sea surface providing values of

$T > 0.75$,
$0.75 > T > 0.65$, and
$0.65 > T$,

are presented in Table B.2–2.

From these statistics it can be seen that, in the absence of clouds, the potentially lower transmission factors will not generally inhibit the routine recovery of ocean colour products for the Mediterranean Sea.

It should be noted that this local performance over the Mediterranean Sea would not be maintained over areas of persistent low clouds such as the Eastern South Atlantic Ocean.

B.2.5 FUTURE ACTIVITIES

To support phase C-D of the development programme of MERIS, a range of mission and science support studies have been initiated. Further studies will be initiated which address mission operations and ground segment support issues. Studies concerning scientific requirements and the exploitation of MERIS data are addressed in Parts A and C of this series respectively.

ANNEX X.I

Results of the MERIS Workshop

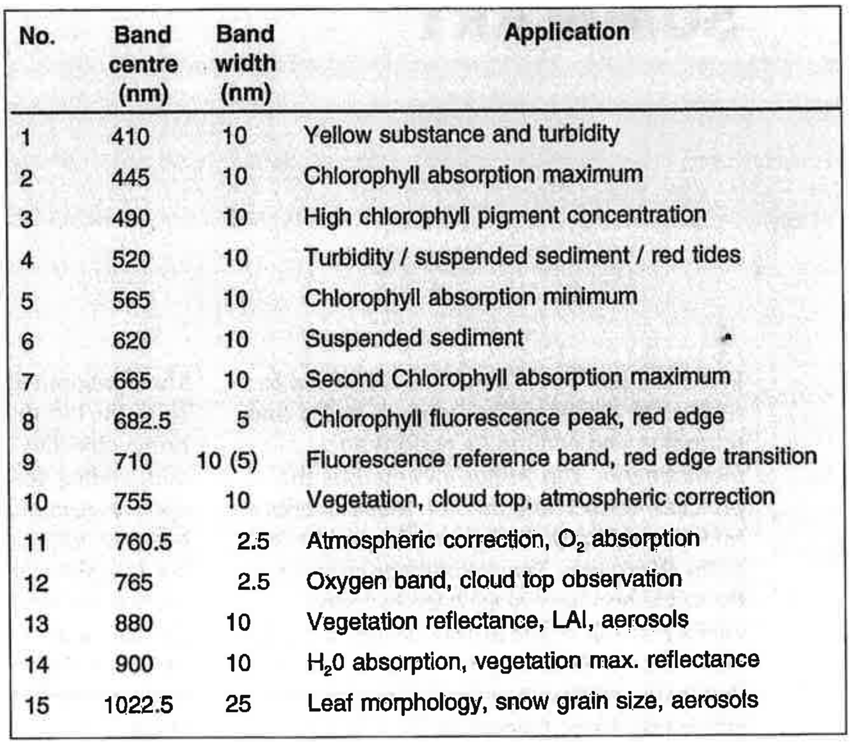
CONTENTS

SUMMARY

In November 1991, ESA held a workshop to review the development status of MERIS and to update and confirm its performance requirements. This Annex summarises the principal science and mission requirements of MERIS updated in the light of the conclusions of the Workshop. The recommendations of the workshop have since been included where possible in the further design of MERIS. This Annex is thus in some ways an historical document, containing assumptions on MERIS which may have changed in the subsequent development of the instrument. For instance, the provisional MERIS band, set at the time of the Workshop, is shown in Table X.I–1; this has now evolved to the bandset shown in Table A.2–1.

The development of MERIS has been pursued since the termination of CZCS operations. The prime objective is to design a mission capable of providing ocean colour data with high spectral resolution on a repetitive and global basis. In addition environmental processes like biosphere-atmosphere interactions are suitable for investigation by MERIS. The determination of uptake and fixation of carbon in the oceans requires high precision measurements of global plankton and these high precision measurements can only be performed by a spectrometer. Marine observations will be highly influenced by atmospheric attenuation, which degrades the quantitative assessment of the marine signal component. MERIS is so far the only space borne sensor designed to provide a bandwidth that allows an accurate determination of this influence. During the workshop, discipline-related panels reviewed the requirements for MERIS. Their findings are described in the panel reports which follow.

Table X.I–1. Science bandset at time of Workshop held in November 1991.



No.	Band centre (nm)	Band width (nm)	Application
1	410	10	Yellow substance and turbidity
2	445	10	Chlorophyll absorption maximum
3	490	10	High chlorophyll pigment concentration
4	520	10	Turbidity / suspended sediment / red tides
5	565	10	Chlorophyll absorption minimum
6	620	10	Suspended sediment
7	665	10	Second Chlorophyll absorption maximum
8	682.5	5	Chlorophyll fluorescence peak, red edge
9	710	10 (5)	Fluorescence reference band, red edge transition
10	755	10	Vegetation, cloud top, atmospheric correction
11	760.5	2.5	Atmospheric correction, O_2 absorption
12	765	2.5	Oxygen band, cloud top observation
13	880	10	Vegetation reflectance, LAI, aerosols
14	900	10	H_20 absorption, vegetation max. reflectance
15	1022.5	25	Leaf morphology, snow grain size, aerosols

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The 15 selected MERIS bands are the following:

Band Nr.	Band centre (nm)	Bandwidth (nm)	Potential Applications
1	412.5	10	Yellow substance, Turbidity
2	442.5	10	Chlorophyll absorption maximum
3	490	10	Chlorophyll, other pigments
4	510	10	Turbidity, Suspended sediment, Red tides
5	560	10	Chlorophyll reference, Suspended sediment
6	620	10	Suspended sediment
7	665	10	Chlorophyll absorption
8	681.25	7.5	Chlorophyll fluorescence
9	705	10	Atmospheric correction, Red Edge
10	753.75	7.5	Oxygen absorption reference
11	760	2.5	Oxygen absorption R-branch
12	775	15	Aerosols, vegetation
13	865	20	Aerosols corrections over ocean
14	890	10	Water Vapour Absorption Reference
15	900	10	Water Vapour Absorption

X.I.1 REPORT OF THE OCEAN PANEL

X.I.1.1 Introduction

The use of optical remote sensing for assessing the marine environment has been steadily growing in recent years, both in the amount and scale of applications as well as in the refinement of methods and techniques. This is due to the great potential of ocean colour data for providing novel information on a suite of biological, geochemical and physical processes of the sea. Such capabilities contributed to the success of the CZCS experiment, which collected a unique data set over a period beginning in late 1978 and continuing through to early 1986. Even though the exploitation of CZCS data is still far from being complete, a growing demand for real time data and for a longer time series of data has, in recent times, fostered the planning of new ocean colour missions. Examples are the sea-viewing wide-field-of-view sensor (Seawifs), originally scheduled by NASA for launch in 1993, the ocean colour and temperature scanner (OCTS), planned by Japanese space agency NASDA for launch in 1995, and MERIS, planned by ESA for service at the end of this decade. Within this framework, the international scientific community was invited to contribute to the definition of the next generation of ocean colour sensors and of MERIS in particular. The main perspectives, and recommendations, provided by the community on the requirements for a mission whose main objective is marine applications will be summarised in this Annex.

X.I.1.2 Spectral considerations

The goal of the discussion on the spectral bands of MERIS was to recommend a nominal set of measurement bands that could be used as a basis for instrument development and for the experiments and field activities to be carried out before the launch of the instrument. This set was intended to facilitate the elaboration of robust multi-spectral algorithms for the retrieval of radiance values and of other derived variables, as detailed below. To this end, a provisional set of fifteen channels, identified in the early phase of MERIS-related studies, was discussed in detail.
In general, there was a substantial agreement on the current list of spectral bands, and Table X.I–1 shows the band positions agreed at the end of the workshop. It cannot be ruled out that changes in some of the centre wavelengths may be found desirable in the future. For example, a comparison of the spectral bands of MERIS and Seawifs shows that the channel centred at 565 nm in MERIS is placed at 555 nm in Seawifs to avoid a water vapour absorption band.

The MERIS instrument has an independent capability to estimate water vapour content, therefore the signal in the 565 nm channel may be corrected accordingly. Nevertheless, to permit cross-referencing between ocean colour sensors, shifting this channel to 555 nm would appear to be desirable. Furthermore, the latest selection of bands for Seawifs shows that the channel at 520 nm has been moved to 510 nm, and those at 665 nm to 670 nm, even though these changes do not appear to be critical. Besides these possible minor adjustments, the overall band selection for MERIS appears to be appropriate, both in the visible channels, devoted directly to ocean colour observations, and the near infrared channels, used specifically for atmospheric observations and corrections.

Regarding the bandwidth of the channels, it emerged from the discussion that an increase in the bandwidth of the spectral bands from 10 to 15 nm may be tolerated if this is needed to improve the radiometric accuracy of the sensor. As will be seen later, limiting the dynamic range of some bands could also be considered as a way to increase radiometric performance.

Obviously, a band configuration, capable of satisfying every potential user, will not be achieved. Even when considering marine applications only, the requirements on band selections needed for different water masses or environment conditions (inland waters or coastal waters, versus open ocean waters) may vary considerably, and lead to a request for conflicting sensor characteristics. However, the flexibility of MERIS will still accommodate the needs of most users, since band selections can be programmed within certain limits. One critical point which should be kept in mind when planning possible spectral adjustments, is that of continuity with other instruments (CZCS, Seawifs, OCTS). In the light of the need for data to construct a long time series of data, it is advisable to freeze a preferred band selection throughout the lifetime of the sensor, and allocate the remaining bands for experimental algorithms, which require their spectral width and position to be reprogrammed.

Finally, it should be noted that, given a proper selection of channels, well distributed in the visible and near infrared range, it may be possible to reconstruct the entire spectral signature of marine targets. As the scientific community acquires more experience of this over the next few years, there may be new applications requiring new band configurations, which MERIS will be able to fulfil by exploiting ESA's programmable design. A high degree of co-ordination with groups dealing with other ocean colour sensors is strongly recommended (see also Section X.I.1.7).

X.I.1.3 Radiometric resolution and dynamics

The radiometric resolution of MERIS will be a critical factor for the success of its oceanographic mission. The maintenance of requirements on radiometric resolution is a top priority.

If the system requirement for the observation of both marine and non-marine targets can not be met, then the radiometric dynamic range should be restricted to just above the maximum radiance values of the marine surface, in all spectral bands used for the assessment of ocean colour. Similarly the dynamic range of the infrared bands used for atmospheric correction will be sized solely for this purpose at the expense of the atmospheric applications themselves. Since ocean colour is the recognised primary objective of the MERIS mission, the sensor should be optimised for the detection of the oceanic signal. This includes the signal originating from turbid case II waters and an atmosphere with a visibility of 7 km. Such optimisation should be sought even at the expense of accepting a poorer performance over land targets and clouds.

It has been recognised that the radiometric resolution for the oceanic mission is similar to that required for the atmospheric mission. The difference between the requirements expressed by both the ocean and atmosphere science communities lies mainly in the dynamic range.

X.I.1.4 Calibration and radiometric accuracy

The MERIS calibration philosophy puts emphasis on relative calibration with respect to the Sun's emission. Current user requirements would indicate a need for relative calibration with respect to the Sun's irradiance with an accuracy of 1 % throughout the visible and near infrared range of the spectrum. Radiometric accuracy is expressed in terms of reflectance, which is the parameter of interest.

Furthermore, stable performance between calibrations is considered to be of paramount importance. The frequency of calibration needs to be optimised to ensure a stable and well calibrated instrument.

X.I.1.5 Variables and algorithms

The aim of developing algorithms specially fo MERIS is the accurate retrieval of radiance values and other derived variables, such as the Rayleigh, aerosol and water-leaving components of the radiance (seen at all wavelengths) versus the concentration and distribution of various water constituents. These should be valid over all, or at least most, of the ocean areas surveyed by the sensor.

Considerable experience already exists for CZCS-type algorithms and variables. Similar algorithms will be adopted for Seawifs and later the ocean colour and temperature scanner, OCTS, in order to obtain compatible variables which contribute to the historical time series of ocean colour data currently available. Thus, to maintain continuity, the same kind of algorithms should be used for the derivation of compatible variables also in the case of MERIS. Advanced algorithms, which exploit the improved spectral performance of MERIS by making use of several near infrared channels to perform atmospheric corrections and several visible channels to compute radiance values, still need to be developed. Also, specific algorithms need to be developed, under the responsibility of specialised user groups, for particular marine and other applications to permit the computation of derived variables, such as pigments, optical properties, dynamic and/or ecological patterns.

Note that ancillary parameters such as total ozone content, atmospheric pressure, and winds, will also be needed for accurate processing of MERIS data on an operational basis by any kind of algorithm, whether of CZCS-type or advanced. Further, the merging of MERIS data products with other complementary parameters should be considered. It is stressed, in particular, that concurrent assessments of sea surface temperature are needed, if possible, on an operational basis.

Finally, disagreement was expressed during the discussion on the efficiency of CZCS-type, two-band, ratio algorithms for open ocean regions. If the CZCS-type value-added data are of limited value, what would be the point of ensuring continuity of the historical time series? This question has not been further clarified, and some elements of the international scientific community have given ample proof of placing intrinsic values on historical CZCS data. On the other hand, most kinds of algorithms, even those of CZCS-type, are still evolving today, for example on a regional basis. A recommendation was made to continue studies of the available time series of ocean data, as well as simulations using data from airborne campaigns, in order to improve the classical algorithms and to derive new advanced algorithms. The role of ESA in sponsoring these developments and in delivering value-added data of geophysical interest (for which operations such as atmospheric correction should be considered as pre-processing) should also be assessed.

X.I.1.6 Data products and operational capabilities

Even though MERIS will be a highly flexible instrument, due in part to its programmability in orbit, it is clear that the operational profile of the sensor should be frozen, after the commissioning phase. It is also recognised that an early, careful assessment of the MERIS operational requirements is crucial for the success of the mission, in that it will drive the definition of an appropriate ground segment. Providing recommendations on such issues, therefore, is of prime importance at the current stage of the development of MERIS.

Concerning the operational potential, two main kinds of data products should be considered. The standard MERIS data products should be of general nature, providing basic geophysical variables. Radiances, at all wavelengths, with all major components identified, have been recognised as the basic variables, while other variables are derived from them. The basic products should be delivered on an operational basis within 72 hours, in digital form and referenced to a standard geographical grid. All other derived products could be produced and made available to the general user, together with the processing history and algorithms. At the local and regional levels, basic and/or derived variables, could then be used within specific algorithms for local and regional goals. In addition, the generation of fast delivery products, within six hours of data collection, should also be considered. This category should include not only water-leaving radiances, mapped onto a standard geographical grid, but also derived products such as a plankton index or an index of turbidity, total suspended matter and dissolved organic material, or the optical properties such as K_λ (the diffuse attenuation coefficient, at a specific wavelength). The fast delivery products should be sent to local agencies where the data flows could be exploited over the short term, or could be reserved for special requests and particular users, for example to assist in directing a cruise campaign.

Finally, it must be noted that although the observations considered here as operational are generally needed on a continuous and regular basis, most environmental applications of ocean colour data can be carried out successfully even if data is collected at intervals of two to three days. More important for some applications, is the availability of time series and statistical data, as these provide the background for the analysis of all other data products. It is recommended therefore, that provision be made in the MERIS ground segment for the implementation of such capabilities, particularly the cataloguing, archiving and retrieval system to be used for long term, climatological and geochemical studies.

X.I.1.7 Supporting activities

There is a strong need for activities to support the development of advanced algorithms and the assessment of specific issues, for example fluorescence techniques, and yellow substance determination in case II waters. Therefore, the participation in planned future programmes, such as Seawifs, and later OCTS, is seen as imperative for the preparation of the MERIS mission.

It is recommended that careful consideration be given to the development of an optical and bio-optical data base, considering that:

- the definition and the adoption of standards is required for optical measurements as recommended by JGOFS;
- the 'global' mission objectives imply the consideration of all water types and all regions in the world's oceans for in-water measurements;
- atmospheric measurements in the oceanic environment are also needed.

Such a programme should support work *in situ*, aimed at assessing both calibration and validation issues. The continuous monitoring of blue waters by permanent moored instruments, has already been incorporated into the Seawifs scheme. It should lead to the exploitation of ocean colour data and concurrent data such as sea surface temperature and roughness, from complementary space missions. Thus the programme would contribute greatly to large data systems being developed for regional and global environmental monitoring.

Airborne campaigns using instruments such as AVIRIS (airborne visible infrared imaging spectrometer), Polder (polarisation and directionality reflectometer), and CASI (compact airborne spectrographic imager), over zones where ships are deployed in the context of other programmes also have to be considered. Studies concerning data products of high interest might be promoted. The MERIS science groups should be open, to allow the exchange of information, personnel, calibration data and processing experience, from one mission to the next, particularly within the scientific community, from CZCS, Seawifs and OCTS to MERIS. Calibration between successive sensors is also a fundamental problem which should be approached along the same route.

X.I.1.8 Long-term programmes

Long-term programmes, such as JGOFS and the IGBP, have been instrumental in augmenting the current interest in ocean colour, primarily through their requirements in terms of such data. Consequently, the MERIS mission will provide a stable long-term continuity of global data.

The long-term perspective of MERIS may be summarised as follows. First, the mission should provide continuity of classical observations, contributing to bio-optical data on the marine environment. Second it should foster progress in the elaboration of improved ocean colour techniques and new data products, promoting their use in advanced applications. And third, it should establish a clear data policy, develop a network of facilities, and support scientific groups to ensure the full exploitation of its information potential.

X.I.2 REPORT OF THE ATMOSPHERE PANEL

X.I.2.1 The overall contribution of MERIS

To the atmospheric scientist, MERIS offers the opportunity to investigate some questions of fundamental importance to climatological and ecological research since its data will provide significant inputs into the following:

- the variation of cloud concentration (i.e. cloud and albedo) with aerosol load, of special importance in metropolitan areas and in remote oceanic locations;
- the dependence of the Earth's radiation budget on cloud height;
- the transfer of minerals and fertilisers to oceans.

In addition, the availability of MERIS data should improve the quality of meteorological analyses by providing cloud-top pressures and total water vapour column contents over all surfaces.

It is clear that MERIS data will be of value to both the Global Energy and Water Cycle Experiment (Gewex) of the World Climate Research Programme (WCRP) and the IGBP (JGOFS), as well as providing valuable inputs to the general atmospheric data sets.

X.I.2.2 Specific atmospheric variables

In considering lists of variables that might be derived from MERIS data and be of interest to atmospheric scientists, it is necessary to investigate their feasibility. This is reflected in the division of products into two classes, class A and class B. Class A are products likely to be available from the onset of the MERIS mission, whereas class B products are those which might eventually be retrieved from radiance measurements made by MERIS.

The question of accuracy must also be addressed since, to meet user requirements, the derived variables will have to meet certain minimum specifications. These are indicated where known.

Class A variables:

(i) *Aerosol optical thickness and aerosol type:*
This is represented by the Ångström exponent and derived from data collected above water surfaces for bands centred on 665, 755, 880 and 1022.5 nm:
- desired accuracies:
    - optical thickness 0.01;
    - Ångström exponent 0.05;
- achievable accuracies as above

(ii) *Cloud reflectance (albedo, optical thickness):*
This is derived from bands centred on 665, 800 and 1022.5 nm. The 755 nm band may be used in place of the 1022.5 nm band. For all clouds:
- desired accuracy ±0.01;
- achievable accuracy ±0.01.

(iii) *Cloud-top pressure (height):*
This is derived from the 755, 760.5 and 765 nm bands, near to and within the O_2 absorption band at 760 nm for optically thick clouds:
- desired accuracy ±100 m;
- present status ±500 m;
- achievable accuracy of ± 200 m or better over oceans.

The results will be less accurate over land due to pixel size, cloud type and sun elevation.

(iv) *Water vapour column content:*
This is derived from the 880 and 900 (665) nm bands for cloudless regions and above the clouds:
- desired accuracy ±1 kg m^{-2};
- achievable accuracy ±1 kg m^{-2}.

Both shadowing and the presence of broken clouds will reduce the accuracy.

Class B variables:

(i) *Aerosol scale height:*
This is derived from the 755, 760.5 and 765 nm bands during periods of high turbidity such as desert dust storms, volcanic eruptions, planetary boundary layer pollution or forest fires:

– desired accuracy	± 500 m;
– achievable accuracy	unknown.

(ii) *Cloud liquid water content:*
This is derived from the 755, 760.5 and 765 nm bands using the temperature dependence of absorption in the O_2A–band:

– desired accuracy	± 0.05 g m^{-3};
– achievable accuracy	unknown.

(iii) *Foam reflectance:*
This is derived over the 710 to 1022.5 nm bands using the enhanced absorption in the O_2 A–band which occurs in cases when foam is present.

(iv) *Integrated reflected radiance:*
This is derived by combining the outputs from all the individual MERIS channels to give a measurement of the shortwave radiation budget at the top of the atmosphere (TOA). Accuracy is mainly dependant on calibration with respect to the sun.

(v) *Snow cover:*
This is derived from the 665, 710, 755, 760.5 and 765 nm (plus 880 and 1022.5 nm) bands exploiting the capability of cloud/snow separation using the 760.5 and 765 nm bands.

(vi) *Snow crystal size:*
This is derived from near infrared (NIR) window in the 710, 755, 880 and 1022.5 nm bands plus one visible channel, using the albedo reduction in the NIR, as a function of crystal size.

(vii) *Surface pressure:*
This is derived from data collected in the 755, 760.5 and 765 nm bands over the ocean:

– desired accuracy	± 2 hPa
– achievable accuracy	unknown

X.I.2.3. Status of the extraction algorithms

As a general rule the development of the extraction algorithms for the retrieval of atmospheric variables is in a preliminary state though the structure of most of the basic algorithms is known.

Class A variables
The following variables are considered:

(i) *Aerosol optical thickness and aerosol type:*
There already exist some algorithms for estimating aerosol optical thickness but new ones will have to be developed to exploit the MERIS bands. The essentially linear wavelength dependence of aerosol extinction should also be exploited since, as well as being necessary for the derivation of the atmospheric correction for ocean colour observations, this is a good indicator of aerosol type. The 665, 755, 880 and 1022.5 nm bands should be used.

(ii) *Cloud reflectance:*
Various algorithms for estimating cloud optical thickness from radiance measurements exist but these will have to be adapted for the MERIS channels. Furthermore, the influence of surface albedo has to be evaluated. Formulae also exist for converting upward radiance measurements into cloud reflectance using standard solar irradiance measurements for given solar zenith angle. The 665, 775, 880 and 1022.5 nm bands are candidates for this algorithm.

(iii) *Cloud-top pressures:*
There already exists an algorithm which is capable of providing cloud-top heights above stratus clouds. It needs data from only two of the MERIS channels; one inside and one outside the O_2 A–band. Multichannel radiance measurements taken from the upper surfaces of various cloud types have already shown that three channels are needed to estimate the cloud-top heights. An algorithm for cloud-top height determination, applicable to different cloud types, is under development. Data from the 775, 760.5, and 765 nm bands will be used, but the locations and bandwidths of the 760.5

and 765 nm bands are currently under discussion.

(iv) *Water vapour column content:*
The structure of the algorithm and its expected accuracy are known from numerical simulations, which exploit radiative transfer models; validation by aircraft campaign has not yet been carried out. The 665, 880 and 900 nm bands will be used though the exact location of the latter band may have to be changed slightly.

Class B variables

(i) *Aerosol scale height:*
There are indications that the aerosol scale height can be retrieved from observations of absorption within the O_2 A–band. However, although the general structure of the algorithm is known, its sensitivity has not been studied. Radiation transfer calculations, as well as airborne measurements, are needed. The 755, 760.5, and 765 nm bands should be used.

(ii) *Cloud liquid water content:*
Knowledge of the retrieval of liquid water content is quite limited and it is likely that the use of data from two different spectral regions will have to be considered including possibly that from the O_2 A–band. This means that the basic structure of the retrieval method is open but the 755, 760.5 and 765 nm bands and possibly the 1055.5 nm band may all be used.

For the other class B variables the situation is open.

X.I.2.4 Evaluation of operational and semi-operational capabilities

Operational products have to meet three quite specific types of requirements, namely:
- delivery schedule, including fast delivery products;
- continuity of data flow;
- reliability of data products.

Other products obey less stringent requirements but may still have to be viewed as being quasi-operational.

The main candidates for MERIS operational products are:
- cloud-top pressure;
- water vapour column content;
- snow cover.

It is believed the provision of these data on an operational basis would prove of great benefit to both operational meteorology and climatology.

Possibilities for semi-operational products include:
- aerosol variables such as loading, type, scale height;
- information on aerosol distributions during special events such as volcanic eruptions.

The former would find their main application in climate research programmes such as JGOFS, while the latter would have to become a fast delivery product during these events.

X.I.2.5 Validation of data and products

Validation was defined as the post-launch activities designed to confirm the validity of geophysical variables derived from MERIS data. Validation would involve comparisons between MERIS data products and those derived from other instruments and campaigns. In addition, further insight into the quality of some MERIS products should emerge from their assimilation into numerical models. These would validate MERIS data not only against data from other sources, but also against model predictions (i.e. objective analyses).

It was noted that Sciamachy (scanning imaging absorption spectrometer for atmospheric cartography) covered the whole of the MERIS spectral range although its spatial resolution was much lower. However, in many instances it should be possible to directly compare the two sets of data, thus providing the means for direct validation of radiance measured by each MERIS channel. Thus, cloud-top pressures could be compared with similar data derived from Sciamachy and with observations from lidars, either ground-based or airborne. These data could, in addition, be checked by assimilation into numerical meteorological models, as could data relating to liquid water and water vapour content. Water vapour content could also be directly validated against radio-sonde data and ground-based observations of the transmission of solar radiation.

Aerosol properties should be validated against ground-based observations made by passive and active instrumentation supplemented by back-scatter lidar observations made during aircraft campaigns. Cloud optical thickness could also be obtained from aircraft campaigns and also from surface observations of incoming radiation, coupled with corresponding TOA satellite data and a knowledge of relevant atmospheric profiles.

Snow data could be checked against other satellite data such as high resolution optical and surface observations.

A by-product of many of these validation activities would be an appreciation of the validity of the atmospheric corrections applied to ocean colour observations. This makes it desirable to continue many validation activities, at varying levels of intensity, throughout the life time of the MERIS, covering not only the main types of cloud and aerosol but also different synoptic conditions. A validation plan should be compiled.

X.I.2.6 Recommendations for calibration

Requirements on the main atmospheric class A variables are likely to be as follows:

(i) *aerosol optical thickness and type:*
A band-to-band calibration accuracy of 1-2% will be required for a NEΔL 5×10^{-4} W m^{-2} sr^{-1} nm^{-1}.

(ii) *Cloud reflectance:*
Again, calibration relative to the Sun is needed, with band-to-band accuracy of 0.2% for all channels involved.

(iii) *Cloud-top pressure:*
Calibration relative to the sun will be necessary, with a band-to-band accuracy 0.2% over the range 755 to 764 nm.

(iv) *Water vapour column content:*
A band-to-band accuracy of 0.2% will be required between the 880 and 900 nm bands.

Requirements on the class B variables are likely to be met by relative calibration to about 0.1% to 0.2% accuracy. For the determination of cloud properties, it is important that no saturation occurs below an apparent albedo value of 1.1. However, other atmospheric applications could tolerate or even gain from a lower saturation level.

X.I.2.7 Supporting activities

Three types of supporting activities have been discussed, namely modelling, simulations and campaigns, it being understood that modelling refers to the study of specific processes, while simulations indicate studies of the whole system. These activities should all be initiated well before launch, although some will continue after that event, and will ultimately merge with validation activities.

Since the Panel could not identify any specific gaps in current knowledge of the physics of the atmosphere that could undermine the simulations, it was agreed that there was no urgent requirement to initiate any modelling activities. However, the situation should be reviewed from time to time in the light of findings emerging from simulations and campaigns.

The converse was true of simulations, since a quantitative appreciation of the MERIS performance was a high priority. Furthermore, these simulations will have to be comprehensive, covering all known atmospheric processes and should consider various types of cloud and aerosol.

Simulations must cover not only the prime atmospheric variables (cloud-top pressure, water vapour column content, cloud optical thickness, and aerosol type and optical thickness) but also the atmospheric correction for ocean colour observations, cloud liquid water content, surface pressure and foam reflectance. The atmospheric correction of ocean colour observations was a high priority for the mission, viewed overall.

To support these simulation studies, a programme of campaigns should be initiated, preferably based on an instrument mounted in an aircraft and capable of simulating the MERIS performance over the spectral range 660 to 1022 nm (i.e. the 665, 755, 760.5, 765, 880, 900, and 1022.5 nm bands). The data should be supported by lidar observations of clouds and aerosol, *in-situ* observations of aerosol and cloud structure and ground-based observations of the relevant geophysical variables. If possible these observations should include observation of industrial aerosols, dust storms and sea spray plus the main types of cloud. They should build on the ELAC '90 campaign but extend it to include all the geophysical variables being simulated.

One further source of relevant data would be GOME (global ozone measuring experiment) scheduled to be flown on ERS–2, since this instrument covers the whole of the spectral range of MERIS. The GOME validation campaigns could help assess the potential of MERIS for atmospheric observations. This possibility should be investigated.

X.I.2.8. Synergism with the other instruments

Other instruments with MERIS:

With the current scenario, other instruments on polar missions will provide total ozone contents (relative accuracy less than 5%), aerosol content and wind speed (approximately 2.5 m s^{-1}) all of which will provide useful supplements to the MERIS data. These very important variables are used to derive accurate atmospheric corrections for ocean colour observations made by MERIS, as well as to retrieve aerosol properties.

MERIS with other instruments:

MERIS can provide many valuable data to support the evaluation of data collected by other instruments. Good examples are cloud layer properties, fractional cloud cover, cloud thickness and albedo, and cloud-top height for experiments such as the infrared sounder used to retrieve atmospheric temperature profiles, or for the observation of tropospheric gases by Sciamachy.

A good example of synergism is the analysis of cloud properties using MERIS derived cloud variables in connection with the surface and cloud-top temperature measured by the AATSR (advanced along-track scanning radiometer).

X.I.3 REPORT OF THE LAND PANEL

X.I.3.1 Introduction

MERIS is an oceanographic instrument which has been optimised for monitoring ocean colour. As this instrument will acquire data on global basis, it could also support a variety of land applications. The User Group expressed great interest in the high resolution provided by the instrument over the entire spectrum between 400 and 1050 nm which will be observed with a spectral resolution of 1.25 nm; but the User Group expressed its disappointment at the limitations imposed by the data transfer technology employed which limits the data rate, i.e. the number of spectral bands whose data can be transmitted to ground stations is restricted to fifteen.

Remote sensing from instruments on space-borne platforms, such MERIS on ESA's Envisat–1, are expected to be useful, particularly for the detection and monitoring of significant changes in terrestrial ecosystems, for the assessment of the impact of these changes, and for the evaluation of the availability and rate of use of renewable and non-renewable resources. Global climate and environmental change, and in particular the issues of environmental degradation and resource exploitation, therefore provide the framework in which to cast the scientific problems that could be addressed with observations from satellite sensors.

Various categories of users have been identified for these observations. Their objectives range from detection of events or identification of targets (probably on a local or regional scale) and the estimation of biophysical variables for planners and researchers involved in process studies, to the initialisation, forcing or validation of global circulation models of the atmosphere in climate studies. The study of the energy, water, carbon and other bio-geochemical cycles on a global and repetitive basis was considered a priority research item with multiple applications in various fields of science and engineering.

The discussions of the group can be summarised as follows. Recognising that remote sensing from satellite sensors provides the only, currently available, means for making truly global and repetitive observations, and that radiation measurements are the only observations that can be made by satellite sensors, the participants agreed to underscore the need for quantitative models to support the interpretation of these radiation measurements in terms of the variables of interest, such as the nature and distribution of vegetation, primary productivity and carbon fixation at the surface, monitoring of the hydrological cycle or biomass burning.

X.I.3.2 MERIS land observation variables

In the optical spectral range covered by MERIS, radiance measurements are often converted to reflectance (R) by normalising these measurements with respect to the incoming solar radiation. The reflectance of a pixel over typical land surfaces was reviewed, and it was noted that over simple homogeneous surfaces, this reflectance could be expressed as a function of four independent variables and a set of physical parameters:

$$R = R\,(x, t, \lambda, \theta;\ \omega, P(g), \kappa, S, \sigma\ \dots)$$

where:

x	is the coordinates in latitude and longitude of the location of the point under observation;
t	is the time of observation;
λ	denotes a particular spectral band;

θ represents the set of angles defining the geometry of illumination and observation at the time of the measurement.

The physical variables shown here are:

ω the single scattering albedo of the scatterers;

$P(g)$ the phase function of the scatterers;

κ the orientation of the scatterers;

S a structural variable that accounts for the spatial distribution of these scatterers;

σ the fractional cover occupied by each surface type within the pixel.

The nature and possible use of the variance in the data was reviewed. In general, the spatial variability in the data is interpreted in terms of the spatial distribution of the objects of interest, while the temporal variations are used to document the dynamic evolution of these objects. The spectral variability is used to distinguish the various targets at the Earth's surface (or in the atmosphere). The angular variability therefore constitutes the main source of information to retrieve physical information about the structure and properties of the surface.

The Land Working Group (LWG) spent a considerable amount of time discussing the extraction of useful information from the data. The discussion was structured around the partial derivatives of the physical variables with respect to the independent variables:

$$\frac{\partial \alpha_i}{\partial \beta_i}$$

where:

α_i refers to any one of the variables $(\omega, P(g), \ldots)$;

β_i stands for any one of the independent variables (x, t, λ, θ).

A coherent strategy for the exploitation of these data was then suggested, which led to the following definition of a hierarchy of potential products. Primary products will result from an inversion of physically-based reflectance models against the calibrated data sets to yield the physical variables mentioned above. Secondary products will then be obtained through additional modelling effort and will include items such as albedo, pigment concentration, absorbed photosynthetically-active radiation, gaps and stress in plant canopies. Tertiary products will be derived from further analysis of the results of the first and second steps, and processed with significant inputs from other data bases (remote sensing data and field or airborne sensor data), to yield estimates of biomass, leaf area index, evapotranspiration, net primary productivity, land cover, and surface roughness.

To the extent that MERIS is to be used for land applications, it is important to discuss its relative strengths and weaknesses with respect to other satellite based instruments. The majority of remotely sensed data used for terrestrial studies are taken from the Landsat multi spectral scanner (MSS), the Landsat TM and the SPOT HRV, and are directed at local to regional scale studies. The principal sensor used for terrestrial studies on a global scale is the AVHRR on-board the NOAA series of platforms.

In its GAC (global area coverage) mode, AVHRR has a resolution of 4 km. There is also a discontinuous, but significant, local area coverage (LAC) archive available with 1 km resolution. AVHRR only provides two relatively broad bands in the visible and near infrared regions of the spectrum. The main disadvantage of the AVHRR is the lack of an on-board calibration mechanism and the difficulty in applying meaningful atmospheric corrections. In comparison, MERIS will provide global coverage over fifteen spectral bands with a resolution of 1 km. A higher spatial resolution of 250 m will be locally available. The 250 m resolution lies in between the high spatial resolution of sensors, such as SPOT, HRV or Landsat TM, and the coarser resolution of NOAA's AVHRR. The calibration of the instrument will be more accurate than is usual for terrestrial studies, because of the severe constraints provided by the monitoring of oceanic surfaces.

The potential for applying adequate atmospheric corrections is also large, especially above water, because the narrow bands can be chosen to be intrinsically less sensitive to absorption by atmospheric constituents, and because some of the bands will be used to retrieve information about the atmosphere itself. The LWG was particularly interested in the possible synergy between

MERIS and some of the other sensors due to fly on the Envisat–1 platform. Significant progress should be achievable by combining observations made by MERIS with those made by other sensors in the thermal and microwave regions of the spectrum.

Although specific studies have been carried out to investigate the feasibility of retrieving useful information from MERIS data over the oceans, no comparable research has yet been conducted for land applications in general. This point led to one of the main recommendations of the LWG, which did not feel comfortable in describing, in great detail, the nature and characteristics of the expected land data products that could be derived from MERIS data.

X.I.3.3 MERIS data products for land application

The Working Group adopted the following minimal, but definite, set of simple products which will now be described.

(i) calibrated instantaneous bidirectional reflectance observations in each of the fifteen spectral bands, at full spatial resolution (250 m at nadir);
(ii) simple combination of these calibrated measurements, as, for example, vegetation indices;
(iii) useful empirical relations between these indices and desirable variables.

The LWG realised that this minimal set does not go beyond the products currently derived from the AVHRR data, but felt that new or more accurate products based on MERIS data should result from exhaustive studies which need to be carried out.

These studies should address three broad categories of issues. First are those specific to the instrument, such as accuracy requirements for navigation and resampling, pixel co-registration, or in-flight monitoring of instrument drift (calibration), which must be better specified. Second, are the mission-related issues such as the synergy in the use of data from other instruments, in particular with the sensors on Envisat-1 and the length of the observation period required to acquire a cloud-free data set at different latitudes and seasons. The third category of issues is related to the production of operational and research products.

X.I.3.4. Recommendations and future activities

Concerning the issues mentioned above, the LWG underlined the need to assess the constraints on product generation resulting from the instrument, the orbit, and the availability of models and inversion procedures. The following aims were specifically identified:

(i) determine the required accuracy and the acceptable channel saturation levels;
(ii) develop physical models of reflectance for realistic natural surfaces that can be inverted against satellite sensor data, to derive primary physical variables;
(iii) determine the relationship between the detectability of key spectral features (e.g. the red edge) and spatial resolution;
(iv) improve the quality and reliability of inversion procedures;
(v) develop biological, chemical, ecological models to derive secondary and tertiary products;
(vi) improve the algorithms for atmospheric corrections over land areas, in particular to more accurately account for the effect of aerosols;
(vii) design and implement new products for specific applications such as the monitoring of fires or biomass burning, taking full advantage of the finer spatial resolution and possible synergy with other instruments;
(viii) investigate the feasibility of retrieving the liquid water content of leaves at 960 nm, if an instrument band is located there;
(ix) investigate how the NOAA AVHRR, Landsat MSS, Landsat TM, SPOT HRV and MERIS records could be combined so that the historical perspective allowed by the former can optimally complement the spatial and spectral resolution of the latter.

These are nine among the many issues that should be addressed, and the LWG recommends a vigorous application of human and financial support to ensure the comprehensive use of MERIS data for land applications.

X.I.3.5 Conclusions

The LWG had few technical comments on the instrument design, but did make the following suggestions. In terms of the spectral band location, it is suggested that shifting the 880 nm band to 860 nm, will permit better determination the position of the maximum of near infrared reflectance of vegetation, and that the 665 nm band be displaced slightly to 670 nm, to better sample the red edge. The group also expressed interest in acquiring data at 960 nm to be able to observe the presence of liquid water on the Earth's surface, in particular in the vegetation canopy, even though this would require an additional channel.

The LWG did not feel enough information was available to make definite recommendations on localisation accuracy (navigation, registration, resampling), but included this item as one of the research areas requiring further attention. It was also noted that decreasing the saturation level to values somewhat less than 100% in reflectance would severely hamper the study of snow and ice on land, clouds in the atmosphere and sea ice in polar regions, and that reducing the dynamic range to those reflectance values actually observed over the oceans would preclude all land applications. The proposal to reduce saturation level should be strongly discouraged.

Finally, the LWG recognised the importance of an airborne simulator, which would contribute to a better definition of the instrument and improve our degree of confidence and readiness in analysing MERIS data over terrestrial areas.

X.I.4 WORKSHOP RECOMMENDATIONS AND CONCLUSIONS

During the development phase of MERIS, scientific and mission studies will have to be carried out to support the mission (strategy) planning, and later, the data handling and exploitation of the sensor data.

Some of the studies proposed as a matter of more immediate importance are:

(i) The accurate evaluation of the various components (including their coupling) of the radiance to be recorded at the top of the atmosphere above ocean targets;

(ii) The development of a general scheme for atmospheric corrections, involving all of the visible and near infrared channels, which should be studied in the perspective of algorithm selection and implementation;

(iii) The use of inverse modelling of radiative transfer to derive the concentration of different water constituents and different types of pigments in case II waters;

(iv) The use of Sun-induced fluorescence (around the 682.5 nm band) for estimating the quantum efficiency of photosynthesis, a calculation by inverse modelling;

(v) The detection and quantification of exceptional plankton blooms;

(vi) The MERIS mission calibration plan and its in- flight calibration strategies;

(vii) A simulation of the detection and quantification of atmospheric variables observed by MERIS;

(viii) Ground measurements, their coordination and planning variables for the calibration of MERIS data by external organisations;

(ix) A simulation of the MERIS band set for land applications on the basis of data collected by airborne imaging spectrometry.

LIST OF ACRONYMS ABBREVIATIONS AND PRINCIPAL SYMBOLS

ANNEX X.II

Acronyms and abbreviations

AATSR	advanced along-track scanning radiometer
AVHRR	advanced very high resolution radiometer
AVIRIS	airborne visible and infrared imaging spectrometer
BRDF	bi-directional reflectance distribution function
CASI	compact airborne spectrographic imager
CCD	charge coupled device
CZCS	coastal zone colour scanner
dB	decibel
DU	Dobson unit
Dial	differential absorption lidar
ELAC'90	European Lidar Airborne Campaign
ENVISAT	environmental research satellite (of ESA)
ERS	European remote sensing satellite (of ESA)
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre (at Noordwijk).
FOV	field-of-view
GAC	global area coverage
gC	grams of carbon
Gewex	Global Energy Water Cycle Experiment
GOEZS	Global Ocean Euphotic Zone Study
GOME	Global ozone monitoring experiment
hPa	hectopascal
HAGC	Human Aspects of Global Change (Programme)
HRV	high resolution visible instrument
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Programme
IPCC	Inter-Governmental Panel on Climate Change
IR	infrared
ISCCP	International Satellite Cloud Climatology Project
JGOFS	Joint Global Ocean Flux Study
K	kelvin
kg	kilogram
km	kilometre
LAC	local area coverage
Landsat	land observing satellite (of NASA)
LIDAR	laser ranger
LWG	Land Working Group
m	metre
MERIS	medium resolution imaging spectrometer system
mg	milligram
MSS	multi-spectral scanner
µm	micron
N	nitrogen
NASA	National Aeronautics and Space Administration (of the United States).

NASDA	Space Development Agency (of Japan).
NIR	near infrared
NRC	National Research Council (of the United States)
nm	nanometre
NOAA	National Oceanographic and Atmospheric Administration (of the United States)
OCTS	ocean colour and temperature scanner
OCWG	Ocean Colour Working Group
Pa	pascal
PAL	pixel dimensions along-track
PAC	pixel dimensions across-track
PBL	planetary boundary layer
Polder	polarisation and directionality reflectometer
POEM	polar orbiting Earth observation mission
SAG	Scientific Advisory Group
Sciamachy	scanning imaging absorption spectrometer for atmospheric cartography
SCOR	Scientific Committee on Oceanic Research
Seawifs	sea-viewing wide field-of-view sensor
SPOT	system pour observation de la terre (French spacecraft)
sr	steradian
TM	thematic mapper
TOA	top of atmosphere
UNCOD	United Nations Conference on Desertification
USC	Union of Scientific Councils
UV	ultraviolet
W	watt
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment

Principal symbols

α	Ångström's coefficient
$\Delta\delta$	optical thickness
$\Delta\lambda$	bandwidth of a MERIS detection band
ΔpCO_2	partial pressure of carbon dioxide
λ	wavelength
ρ_p	pigment concentration
ρ_s	concentration of suspended matter
a^{YS}	absorption coefficient of yellow substance
CO_2	carbon dioxide
H_2O	water
K_λ	diffuse attenuation coefficient
L_{max}	maximum radiance
$NE\Delta L$	noise equivalent radiance
$NE\Delta R$	noise equivalent reflectance
O	oxygen
P	phosphorous
R	reflectance
Rsg	radiative ratio of Sun-glint to water-leaving radiance
SO_2	sulphur dioxide
T	atmospheric transmission factor

No.	Band centre (nm)	Band width (nm)	Application
1	412.5	10	Yellow substance and turbidity
1	442.5	10	Chlorophyll absorption maximum
3	490	10	Chlorophyll and other pigments
4	510	10	Turbidity, suspended sediment and red tides
5	560	10	Chlorophyll, suspended sediment
6	620	10	Suspended sediment
7	665	10	Chlorophyll absorption
8	681.25	7.5	Chlorophyll fluorescence, red edge
9	705	10	Aerosol type, red edge transition, atmospheric correction
10	753.75	7.5	Oxygen absorption reference band, (vegetation)
11	760	2.5	O_2 absorption R-branch
12	765	5	O_2 absorption P-branch
13	775	15	Aerosol over ocean, optical thickness, vegetation
15	865	10 (20)	Aerosol optical thickness, vegetation, water vapour reference over the ocean
15	890	10	Water vapour over land
16	900	10	Water vapour, vegetation

Table A.2–1. Sixteen potential spectral bands of MERIS as identified by the Science Advisory Group in the summer of 1995. Evolution of this bandset has followed the evolution of the science base which supports MERIS. This evolution can be seen by comparing this Table with the bandset derived from the MERIS Workshop of 1991 and which is given in Table X.I–1. The final choice of the fifteen bands to be used by MERIS in-flight will be determined during the course of the algorithm development phase.