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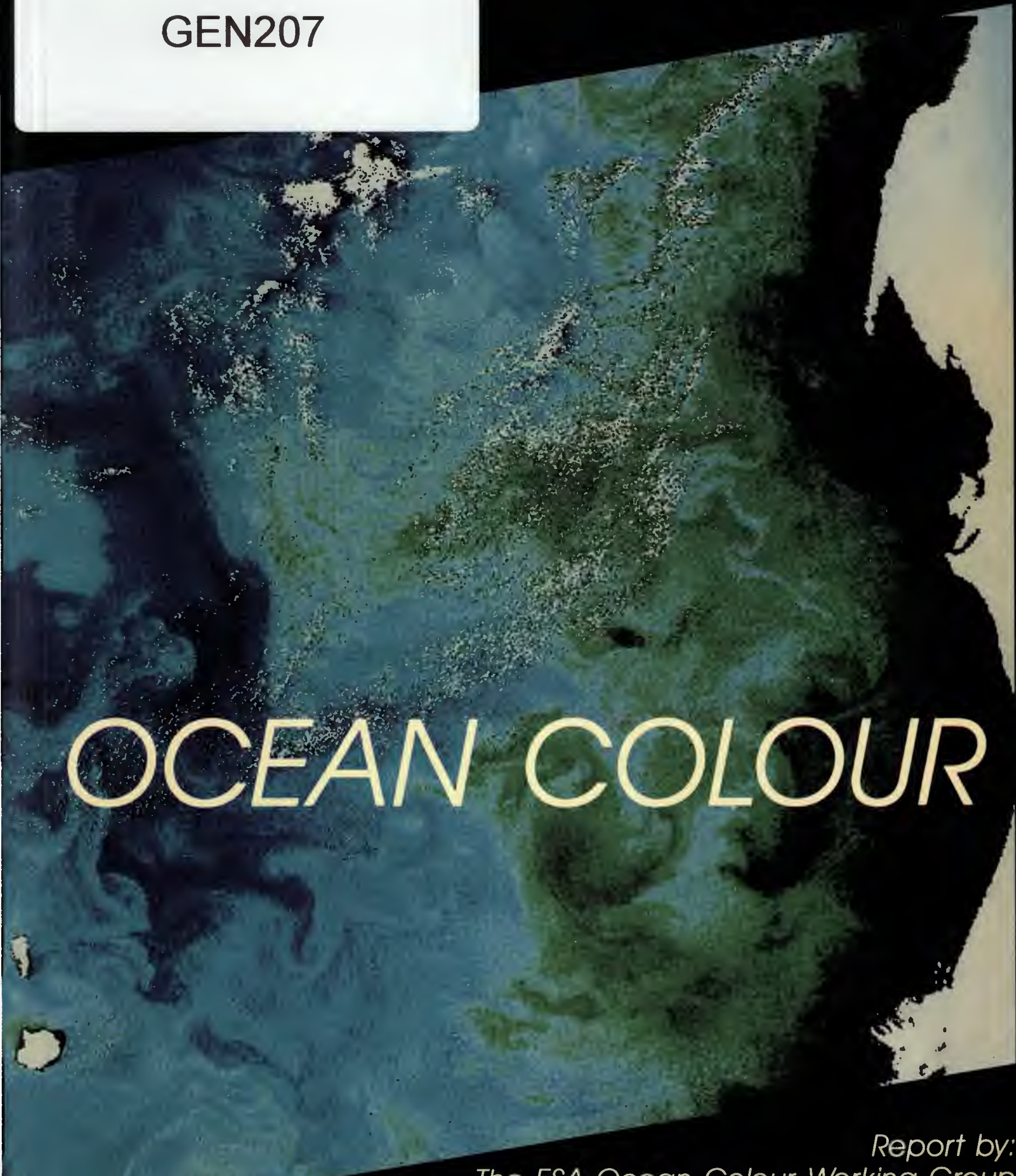

OCEAN COLOUR

Report by:
The ESA Ocean Colour Working Group
Villefranche-sur-Mer, November 1986

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Contents

INTRODUCTION: WORKSHOP'S OBJECTIVES 5
G. Duchossois, Earth Observation & Microgravity Directorate, ESA, Paris

EUROPE'S POSITION CONCERNING OCEAN COLOUR ACTIVITIES 7
G. Duchossois, ESA, Paris

OVERVIEW OF ESA'S ACTIVITIES IN OCEAN COLOUR REMOTE SENSING 9
M. Rast & M. Reynolds, Earth Observation Dept., ESA/ESTEC, Noordwijk, The Netherlands

UPDATE OF NASA'S OCEAN COLOUR ACTIVITIES 13
J.A. Yoder, NASA Oceanic Processes Branch, Washington, USA

Panel Reports & Conclusions

PANEL 1:Studies of Biological Productivity & Biochemical Cycles 19
Rapporteurs: P.M. Holligan & A. Morel

PANEL 2:Applications in Ocean Dynamics & Coastal Processes 23
Rapporteurs: I.S. Robinson & D. Spitzer

PANEL 3: Technical Aspects of Future Ocean Colour Remote Sensing 27
Rapporteur: M. Rast, ESA

National Reports

JRC's WORK ON THE APPLICATION OF OCEAN COLOUR MONITORING FROM SPACE 35
B. Sturm &al, CEC/JRC, Ispra, Italy

CANADA's ACTIVITIES IN REMOTE SENSING OF OCEAN COLOUR & FLUORESCENCE 41
J.F.R. Gower, Institute of Ocean Sciences, Sidney, Canada

RESEARCH IN SWITZERLAND ON OCEAN & INLAND-WATER COLOUR MONITORING 49
J.-M. Jaquet, GTA, Geology Dept., Geneva University, Switzerland

GERMANY's ACTIVITIES IN REMOTE SENSING OF OCEAN COLOUR & FLUORESCENCE 53
H. van der Piepen, Institut für Optoelektronik, Oberpfaffenhofen, FR Germany

FRENCH ACTIVITIES IN OCEAN COLOUR OBSERVATIONS 59
J.-L. Fellous, CNES, Paris & A. Morel, LPCM, Villefranche-sur-Mer, France

ITALIAN ACTIVITIES IN OCEAN COLOUR REMOTE SENSING 71
R. Frassetto, ISDGM-CNR, Venice & L. Pantani, IROE-CNR, Florence, Italy

REMOTE SENSING ACTIVITIES IN IRELAND 79
E. O'Mongain, Physics Dept. University College, Dublin, Ireland

OCEAN COLOUR MONITORING IN NORWAY 81
K. Kloster &al, CMI etc., Norway

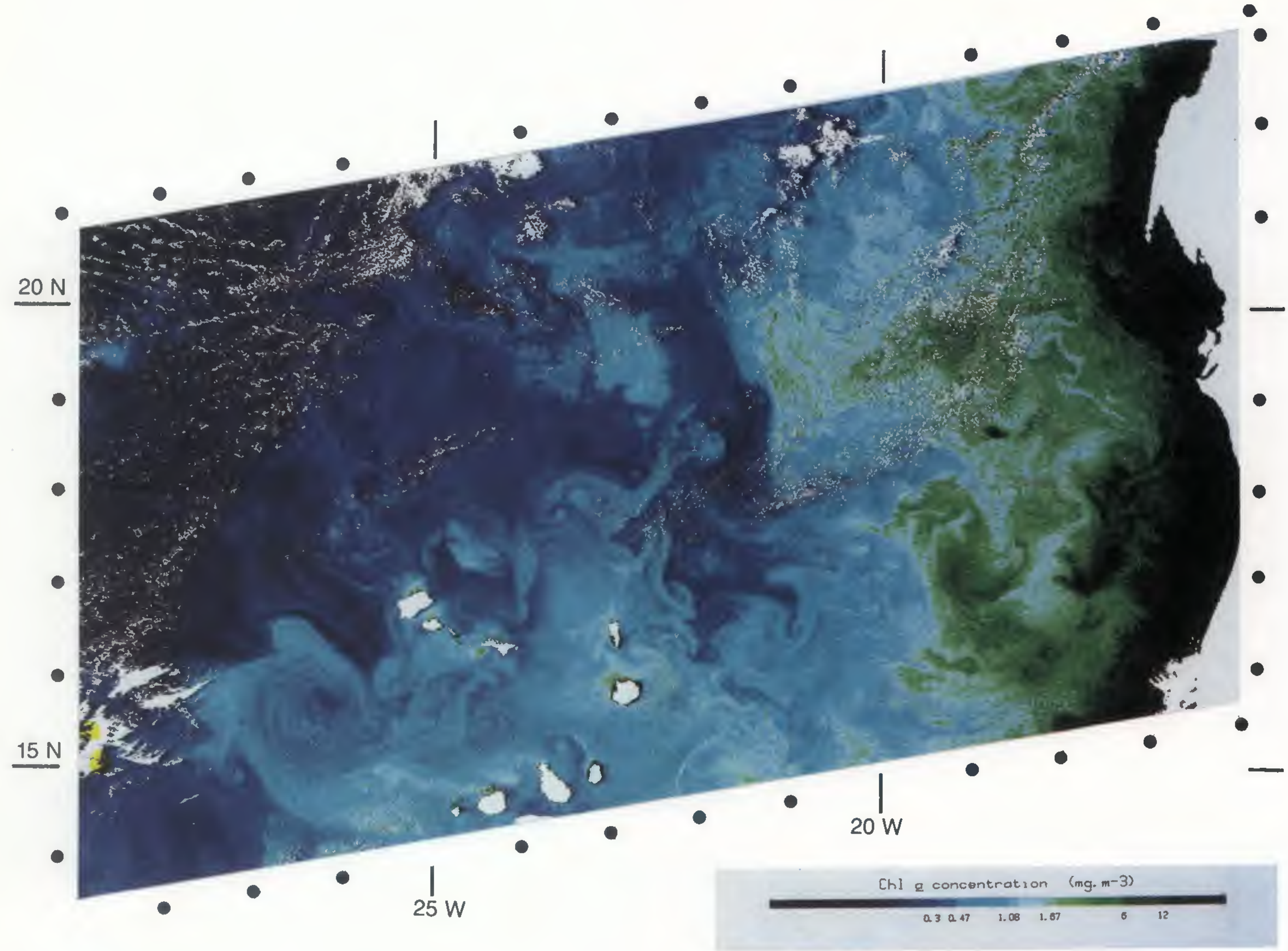
THE NETHERLANDS's REMOTE SENSING PROGRAMME (NRSP) 83
D. Spitzer, Ministry of Transport & Public Works, The Hague, The Netherlands

DEVELOPMENTS IN OCEAN COLOUR RESEARCH IN THE UK 91
I.S. Robinson, Univ. Southampton & P.M. Holligan, Marine Biological Assoc., Plymouth, UK

Recent Research Activities supported by ESA

USE OF CHLOROPHYLL FLUORESCENCE MEASUREMENTS FROM SPACE FOR SEPARATING CONSTITUENTS OF SEA WATER 103
H. Grassl, GKSS-Forschungszentrum Geesthacht GmbH, FR Germany

INFLUENCE OF YELLOW SUBSTANCES ON SEA-WATER CONSTITUENTS 111
H. Grassl, GKSS, Geesthacht, FR Germany



Cover: *This image shows the chlorophyll-pigment concentration in the upper layer of the ocean, as computed from a CZCS scene taken on 8 February 1983. The N-S and E-W dimensions of the image, remapped on a Marcator grid, are respectively 800 and 1450 km. The Mauritanian and Senegalese coasts (right side) and the Cape Verde islands (bottom, middle) are represented in white, as are the scattered clouds. The different concentrations of phytoplankton chlorophyll are shown in a range of colours from dark blue to dark green which correspond to increasing value (in mg/m^3) as shown along the colour-scale. The black colour along the coast is used to mask the turbid waters for which the computation of the pigment content is impossible or at least dubious. This turbidity is mainly due to sediment resuspension.*

At this season, the NE-tradewinds induce an intense upwelling all along the African coast. The nutrient-rich upwelled waters support an actively growing algal population. Compared to the previous knowledge acquired through ship-board observations, a surprising fact revealed by such images is the huge extension of the area influenced by the upwelling event. This certainly will lead to a reassessment of the oceanic primary production. The amount of CO_2 fixed through the photosynthesis process carried out by the microscopic algae can be derived from a dense spatial and temporal coverage provided by the space sensor combined with an adequate parametrisation of the physiological capacity of algae to photosynthesise organic matter.

A somewhat unexpected gift made by the algal community when seen from space is their fine-scale display of the turbulent structures and eddies.

Image processed by Laboratoire de Physique & Chimie Marines (LPCM), Villefranche-sur-Mer, France.

INTRODUCTION
WORKSHOP'S OBJECTIVES

G. Duchossois

ERS-1 Mission Manager
Earth Observation & Microgravity Directorate, ESA, Paris

The utilisation of airborne and spaceborne remote sensing techniques for the study of ocean colour has seen a growing interest over the past ten years. In Europe, both at national and integrated European levels, a particular effort has been dedicated to the analysis of data from the Nimbus-7 Coastal Zone Colour Scanner (CZCS), in particular by the biological oceanographers interested in the quantitative monitoring of primary productivity. An Ocean Colour Monitor instrument was considered and studied in depth within the frame of the ERS-1 programme but unfortunately not retained in the final payload configuration. With the advent of the Polar Platform element of the international Space Station programme, there is a unique opportunity to fly an advanced ocean colour sensor with the aim of providing data to both the scientific and application user communities. This is the reason why the European Space Agency has decided to organise a workshop on the subject of ocean colour monitoring from space, to discuss prospects for the 1990's.

The specific objectives of the workshop have been defined as follows:
- to review the progress status in ocean colour remote sensing, in particular in terms of modelling, algorithms and scientific applications, and to identify priorities for further work;
- to review and, if necessary, update national interests, priority activities and objectives for ocean colour monitoring in ESA Member States in relation to on-going and planned national and international oceanographic programmes;
- to review current and planned ESA and US activities in this field and opportunities to fly ocean colour sensors;
- to identify possibilities for cooperation or coordination between Space Station partners (USA, ESA, Canada and Japan) for the provision of ocean colour sensors on the Polar Platforms;
- to inform user communities about the preparation and issue of an ESA Announcement of Opportunity (in close coordination with NASA and Japan) with the aim of obtaining instrumentation proposals for the Polar Platform;
- to obtain clear recommendations and inputs to be used for activities within the Earth Observation Preparatory Programme and related to the preparation of the Polar Platform mission;
- to discuss and obtain recommendations for an in-depth involvement of users in both pre-launch and post-launch activities (e.g. campaigns).

Following a plenary session providing general background and information to the participants, the Workshop has been structured in such a way as to allow detailed discussions on three major topics:
- Global geochemical fluxes and biogeochemical processes
- Ocean and coastal dynamics
- Ocean colour instrumentation performance requirements.

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

EUROPE'S POSITION CONCERNING OCEAN COLOUR ACTIVITIES

G. Duchossois

ESA, Paris

1. INTRODUCTION

Activities related to ocean colour monitoring using airborne and spaceborne remote sensing techniques started in Europe in the 1970's with the preparation for the Coastal Zone Colour Scanner (CZCS) on Nimbus-7, launched in October 1978. In cooperation with specialised institutes in Europe, a proposal prepared by the Joint Research Centre (JRC) of the European Economic Communities (EEC) was accepted by NASA in December 1975; as a consequence, JRC became a member of the Nimbus Experimental Team (NET). To prepare for the utilisation of CZCS data, an Ocean Colour Scanner (OCS) experiment was carried out in the North Sea in 1977, combining the OCS flight together with sea-truth data collection.

One of the tasks of the ESA's Earthnet Programme Office was to receive, preprocess, archive and distribute CZCS data to users. Two ground stations were upgraded for these activities, one at Maspalomas in the Canary Islands, the other at Lannion in France.

In the period 1979–81, the Agency conducted in-depth studies of an Ocean Colour Monitor (OCM) instrument as a candidate to fly on the first ESA Remote Sensing satellite (ERS-1) due to be launched in early 1990. Pre-development of critical technology items (e.g. bearings, focal plane arrangements, detectors...) was also performed. Unfortunately, the OCM was not retained in the final payload configuration, but activities related to analysis and interpretation of CZCS data were pursued in order to fully understand and demonstrate the capabilities of ocean colour remote sensing for both scientific research and application demonstrations (e.g. aid to fish resources management).

With the advent of the International Space Station, alternative scenarios for realising future earth observation missions from a polar orbit are developing from the present expendable satellite approach to include serviceable platforms. The Polar Platform element under study in the Agency's Columbus Preparatory Programme is, in principle, a serviceable platform which should offer new opportunities to the user community and a new approach for earth observation in:
- satisfying multidisciplinary mission objective;
- encouraging development of multidisciplinary payloads;
- developing international cooperation and coordination for the provision of instrumentation and for the utilisation of the data;
- providing a quasi-permanent observation capability (not necessarily with the same platform) which is essential for earth observation.

It was in this context that ESA undertook a wide consultation of the user community to identify or update user requirements, priorities and content of missions to be flown on the Polar Platform(s).

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

2. EUROPE'S POSITION

One of the various activities organised by ESA to identify user requirements in the 1990's was the 'ESPOIR' symposium (European Symposium on Polar Platform Opportunities & Instrumentation for Remote Sensing) which took place in Avignon (France) from 16 to 18 June 1986 where, in particular, the overall multidisciplinary requirements for earth observation were reviewed, as well as the instrumentation requirements.

The Ocean Panel of the Workshop identified a number of key objectives in this field including, in particular, ocean colour monitoring for which the main recommendations were as follows:

- The Polar Platform mission should fulfil commercial, operational and longer term research objectives.
- Data continuity should be guaranteed over long periods of time (say, decades).
- New sensor concept should be investigated taking into account the results from CZCS.
- An attractive concept to be studied is the multi-purpose imaging spectrometer, primarily for ocean and atmosphere objectives, characterised by a large number of selectable, narrow bandwidth spectral channels in the visible and infrared (not necessarily combined into a single instrument).
- Two different instruments should be considered to satisfy conflicting requirements in terms of coverage, temporal repetitivity and spatial resolution:
    - a high spatial resolution (e.g. 30 m $\times$ 30 m) sensor for local, coastal monitoring;
    - a medium spatial resolution (e.g. 500 m $\times$ 500 m) large swath (similar to AVHRR swath) instrument for continuous and global monitoring on a daily basis;
- Proper attention should be given to calibration problems, atmospheric corrections, higher signal-to-noise ratios and more digitisation level than for past instruments.
- Systematic processing and analysis of CZCS data should be pursued to improve scientific understanding of ocean colour data and for algorithm tuning.
- Campaigns should be organised to collect data to further develop user expertise and applications.

In view of this strong support for ocean colour, ESA is investigating a new sensor type based on the imaging spectrometry concept as a major European facility instrument to fly on the Polar Platform. An Expert Group is being set up by ESA to define instrument performance requirements prior to the industrial definition of a new generation of ocean colour sensors for the 1990's.

OVERVIEW OF ESA'S ACTIVITIES IN OCEAN COLOUR REMOTE SENSING

M. Rast & M. Reynolds

ESA/ESTEC, Noordwijk, The Netherlands

ESA's activities in Ocean Colour Remote Sensing started in 1978 after the launch of the American NIMBUS 7 spacecraft. This Earth Observation platform was carrying the CZCS - Coastal Zone Colour Scanner - as the first Ocean colour observation instrument.

The acquisition, pre-processing, archiving and distribution to ESA Member States users of CZCS data from the NIMBUS 7 spacecraft was one of the EARTHNET activities. This data is still used by the European Scientific community. It has demonstrated the usefulness of space acquired data for coastal waters monitoring.

The EARTHNET data processing package is based on a NASA package run at Goddard Space Flight Centre. Quick looks have been produced and sent weekly to NASA for the selection of scenes to be processed. Up to 1986 about 5000 orbits have been acquired and NASA has been provided with more than 1000 scenes with a level one processing. All CZCS acquired and processed data have been made available to the users community and are contained in an EARTHNET centralised catalogue system for easier user access.

At the end of the 70's an Ocean Colour Monitor (OCM) was considered as a possible part of the core payload of Europe's first polar orbiting Remote Sensing Satellite ERS-1 and has been studied by industry under ESA contract as a Phase A study.

This instrument study was supported by modelling of the expected signatures. Two major studies were made by P.Y. Deschamps et al. in 1979 and 1980, titled:

- "Critical Evaluation Study of the Radiometric Measurement Requirements for an OCM"

and

- "Definition of a Practical Earth/Atmosphere Signal Model".

This was followed by an investigation: "Study of the interpretation of Ocean Colour Data with Special Emphasis on the OCM", carried out by A. Morel et al. in 1981.

COMPARISON OF TECHNICAL SOLUTIONS

	MECHANICAL SCANNING	ELECTRONIC SCANNING
SPECTRAL COVERAGE (MICRONS)	0.39 TO 12.5	0.39 TO 1.05
SPATIAL RESOLUTION (METERS)	APPROX. 800	APPROX. 250
FOV	± 40°	± 40°
CALIBRATION	SPACE-DIFFUSER-BLACKBOOK (USING THE MECHANICAL SCAN HEAD)	SPACE-DIFFUSER (USING ADDED MECHANISM)
OPTICS	SINGLE, NARROW FIELD REFLECTING TELESCOPS	MULTIPLE, WIDE FIELD REFRACTING TELESCOPS
DETECTOR ELECTRONICS	CLASSICAL - NO PROBLEMS	DYNAMIC RANGE CAPACITY TO BE DEMONSTRATED
GENERAL FEASIBILITY	STATE-OF-THE-ART	SOME TECHNOLOGY DEVELOPMENTS REQUIRED

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The OCM was originally conceived as a mechanical scanner with a swath width of 1300km and an instantaneous field of view of 800m. It was designed as an imaging spectrometer covering 13 spectral bands from 0.4 to 12.5 micrometers.

In the beginning of the 1980's the OCM was dropped from the ERS-1 platform scenario and postponed for a possible inclusion in the ERS-2 payload.

In the meantime technology has been driven towards a new imaging technique - the pusbroom approach.

In 1982 new contracts were issued to study an "Advanced OCM" with this CCD imaging technology. Three industrial companies studied such camera concepts.The most promising advanced design was again an imaging spectrometer concept with a ground pixel size of 300m, swath width of 1017km and eight spectral bands reaching from 0.4 to 1 micrometer. A comparison both of the technical solutions and a view of the general assemblies is given above.

Detailed technology studies and investigations have also been made in support of the instrument studies, as listed in Table 1.

INSTRUMENT DEFINITION ACTIVITIES

SUPPORTING ACTIVITIES:

- SCANNING HEAD TECHNOLOGY DEFINITION STUDIES AND TECHNOLOGY EVALUATION
- IMAGE DATA PROCESSING STUDIES
- OCM FOCAL PLANE OPTICS DESIGN STUDY
- OCM IMAGING ELECTRONICS BREADBOARDING
- PASSIVE COOLER BREADBOARDING
- VISIBLE AND IR DETECTOR EVALUATION STUDIES AND BREADBOARDING
- EVALUATION OF "BLUE" SENSITIVE CCD ARRAYS
- STUDY OF CALIBRATION TECHNIQUES

In 1982 the ad hoc Ocean Colour Working Group (OCWG) has been created by ESA as a sub-committee of the Earth Observation Advisory Group, EOAC. The OCWG consists of 6 international scientists and 1 ESA Executive.

The specific tasks of this group are:

1) The report on Ocean Colour ongoing and planned activities

2) The identification of updated technology of sensing the Ocean Colour for science and application

3) The identification of further scientific investigation in the Ocean Colour and indication of needed experiments

4) The recommendation of further technological development.

The members of this group were selected to fill the required range of experience in atmospheric physics, marine biology, the application of ocean colour in physical and biological oceanography, pollution monitoring and other experimental work.

At the end of 1983 a report of the working group on Ocean Colour has been published (ESA-BR 20) to summarize the state of the art in Ocean Colour physics, monitoring and use, and provided a progress report on the subject.

In the field of chlorophyll fluorescence and yellow substance monitoring two contracts have been issued in 1984 titled:

- "The Use of Chlorophyll Fluorescence Measurements from Space for Separating Constituents from Sea Water"

and

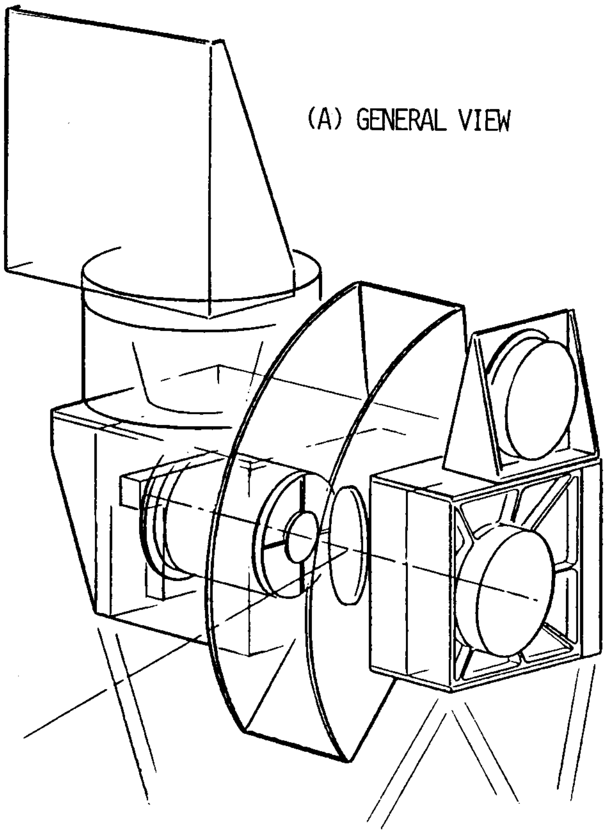
- "The Influence of Yellow Substance on Remote Sensing of Sea Water Constituents from Space."

These studies addressed questions concerning, among others, the relation of ground and spaceborne measurements, the influence of diurnal variation on fluorescence efficiency, atmospheric influence, albedo relations, signal influence by yellow substance, and algorithms.

The results of these contracts will be compiled together with the general conclusions of the Workshop in Villefranche sur Mer published in ESA's second report on Ocean Colour Remote Sensing.

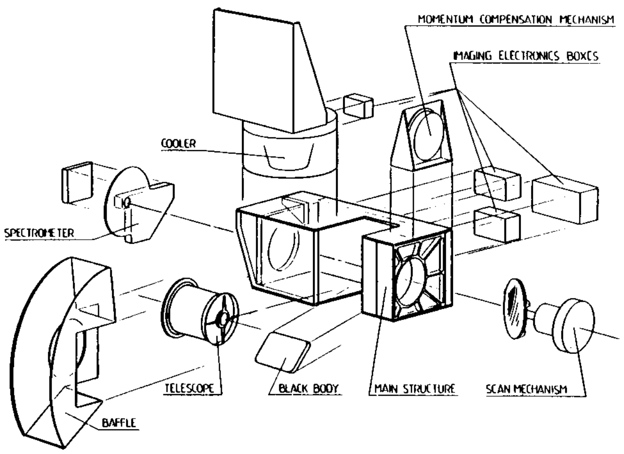
ESA's activities in the future will pursue the definition of an optimum technical solution for an OC sensing instrument and the determination of parameter standards and model algorithms.

OCEAN COLOUR MONITOR (OCM)

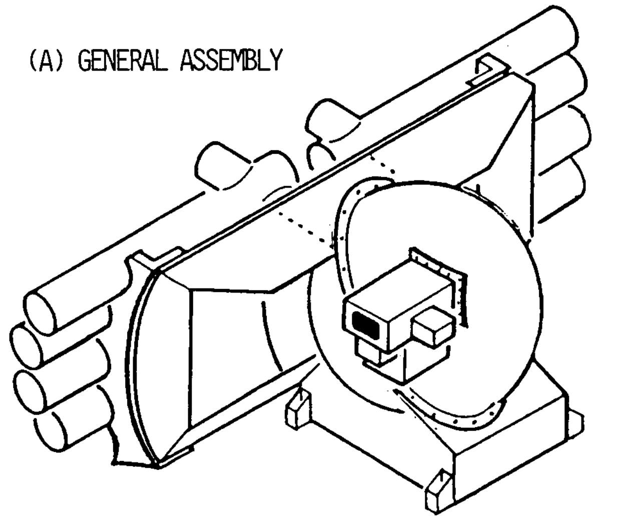


(A) GENERAL VIEW

(B) EXPLODED VIEW

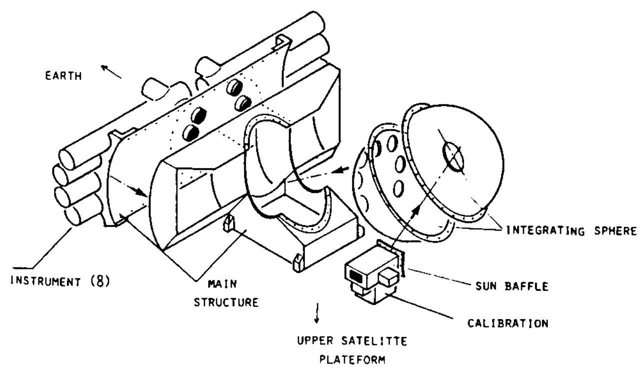


ADVANCED OCM



(A) GENERAL ASSEMBLY

(B) EXPLODED VIEW



UPDATE OF NASA'S OCEAN COLOUR ACTIVITIES

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ABSTRACT

Recent developments in NASA's ocean color program are: the Coastal Zone Color Scanner (CZCS) is probably dead but a final attempt to re-start it will be made in December, 1986; NASA/Goddard is re-processing all CZCS data and will establish a new archive; and NASA Headquarters is trying to get approval for a new ocean color instrument for the early 1990's.

1. CZCS STATUS

The Coastal Zone Color Scanner (CZCS) on the Nimbus 7 satellite has been off since summer 1986. In December 1986, NASA will attempt to re-start the instrument, but the engineers do not feel that this effort will be successful. We anticipate that the CZCS will be pronounced "dead" by the end of December 1986. However, if the engineers successfully start the CZCS and if it operates properly, the Oceanic Processes Branch will argue strongly to keep the instrument kept on for as long as possible, but since CZCS operation interferes with other projects on the Nimbus 7 satellite, we would not be able to keep the instrument on indefinitely. We will keep ESA and the ESA Ocean Color Working Group informed on CZCS status.

2. CZCS PROCESSING

Goddard Space Flight Center has embarked on an ambitious project to re-process all CZCS data and to build an archive of Level 1 and derived products including basin-scale composite chlorophyll images (see Figure). As of December 1986, the Goddard project team was completing the purchase and installation of computer hardware and software that will give the project team the capability to rapidly process CZCS data. The North Atlantic Basin composite image illustrated in the figure is a prototype of the major products that will result from the Goddard project. Bi-weekly, monthly, and seasonal composites of basin-scale CZCS imagery will be very useful to the U.S. Global Ocean Flux Study and to other projects that study the role of the ocean in global cycles of carbon, nitrogen and other elements. A unique feature of the data archive to be developed at Goddard will be a video disc "browse" file of both single scenes and composite images. Video disk readers are relatively inexpensive, and we hope that this medium will help us widely distribute CZCS chlorophyll images and other derived products. Level 1 and derived products will also be available on magnetic tape for those who have access to image processing systems. The Goddard project is exploring the possibility of also archiving products on digital optical disks. Data products will be made available to interested scientists for the cost of the transfer medium (i.e. tape, disk, etc.). The North Atlantic Basin (see Figure) is the top priority of this project and all CZCS imagery from this region should be processed and archived by the end of 1987. For additional information, contact Dr. Wayne Esaias, Dr. Charles McClain, Dr. Jane Elrod (all at Code 670), or Dr. Gene Feldman (Code 630), NASA/Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA.

3. FUTURE U.S. OCEAN COLOR INSTRUMENTS

3.1 NASA-X or NASA-STP.

During summer 1986, Goddard Space Flight Center proposed a major Earth Sciences mission (NASA-X) for launch in 1988-90 that would have included a modified CZCS, an ozone mapper (TOMS) and a carbon monoxide mapper (MAPS). As a cost-saving measure, the Goddard group promoting this mission established a partnership with the Space Test Program (STP) of the U.S. military, who also have an interest in flying their own unclassified environmental sensors. Unfortunately, NASA Headquarters could not afford the cost of this

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mission, and it is now very unlikely that this project will develop any further.

3.2 Ocean Color on Landsat 6 and 7.

EOSAT, a partnership between RCA and Hughes Aircraft, is responsible for Landsat operations as well as the marketing of Landsat products. On May 30, 1986, EOSAT announced plans to place a wide-field ocean color sensor on Landsat 6 and 7, to be launched in 1989 and 1992, respectively. The specifications for the Landsat 7 ocean color instrument, WIFS, are very similar to those of MODIS-T (see below). WIFS will be an imaging spectrometer with 64 bands in the range 400-1030 nm. Band spacing is 10 nm with 15-30 nm bandwidth. Data would be digitized with 12-bit accuracy. The satellite would have dual altitude capability (705 and 850 km) and would have a 2-day revisit (1500 km swath). EOSAT has not yet finalized their plans for Landsat 6, but the proposed instrument for this mission is a less-sophisticated version of WIFS. EOSAT will announce their plans for Landsat 6 in early 1987.

EOSAT'S interest in commercial applications for ocean color greatly complicates NASA'S ability to develop ocean color sensors for research purposes. EOSAT realizes that a true commercial market for ocean color will not exist for many years, and thus their main customers for the near-future will be NASA, the U.S. Navy, and the National Science Foundation. Under these circumstances, it is very unlikely that NASA will proceed with an ocean color mission independent of EOSAT. The situation is also complicated by EOSAT's uncertain financial situation. EOSAT can only exist with a U.S. government subsidy, and the future of this subsidy is very difficult to predict. IF EOSAT loses the federal subsidy, the future of Landsat 6 and 7, including the proposed ocean color instruments, will be in jeopardy.

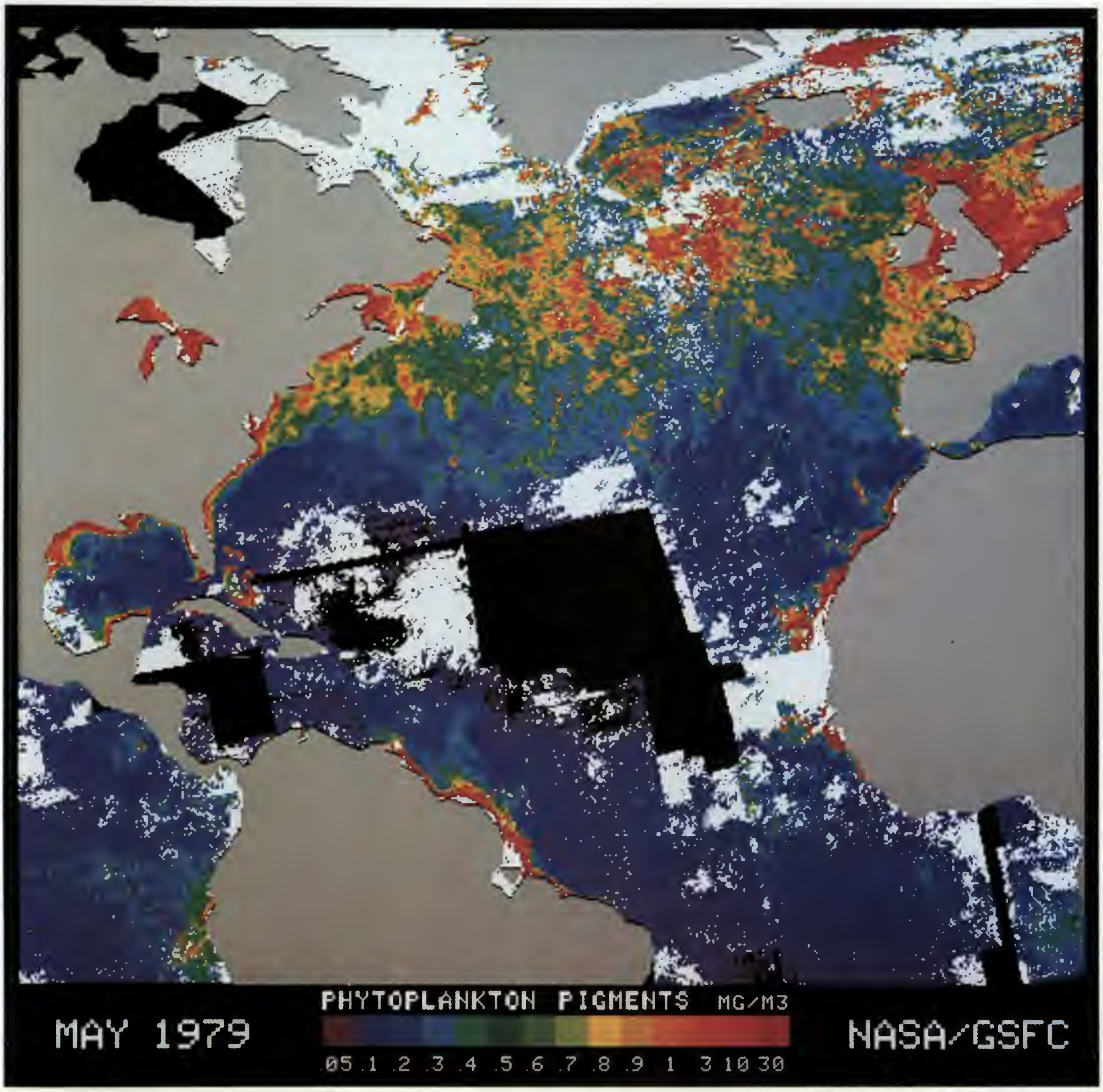
The position of the Oceanic Processes Branch at NASA is to consider EOSAT a partner in ocean color. We are trying to work out an arrangement for research users of ocean color, and our goal is to acquire global coverage for research use at no charge to the principal investigators. Many obstacles need to be overcome, but if EOSAT stays in business, we are hopeful that NASA can provide the research community with global ocean color data by the early 1990's.

3.3 MODIS-T.

MODIS-T is an imaging spectrometer proposed for the Polar Platform of the Space Station. MODIS-T has the following design parameters:

1. System configuration - Wiskbroom imaging spectrometer
2. Spectral range - 0.4 to 1.04 microns
3. Spectral resolution - 10 nm
4. Spectral bands - 64
5. Spatial resolution - 1.0 km (from 824 km altitude)
6. Footprint (along track) - 64 km
7. Scan (across track) - 1500 km (84 degrees)
8. Fore/aft tilt angle - +-50 degrees
9. Optics diameter - 7.6 cm
10. Dynamic range - 50% Earth radiance (max.)
11. S/N ratio - 800/1 (mid band)
12. Scan configuration - 360 degree rotation (2-sided mirror)
13. Operation life - 10 years continuous
14. Data rate - 26 MB/sec (64 bands)
    7 MB/sec (17 bands)

If EOSAT develops the WIFS instrument described above, NASA will not develop MODIS-T. However, a joint NASA/EOSAT development of a U.S. instrument for the Polar Platform meeting MODIS-T specifications is an option presently being explored. At the present time, the EOSAT situation is so volatile that accurate long-range predictions for U.S. ocean color instruments are impossible.



CZCS-chlorophyll composite image derived from all CZCS data collected over the North Atlantic during May 1979. Data from cloud-free areas are averaged over 5 X 5 km grids, and colors representing different chlorophyll concentrations are defined in the legend. Black areas indicate no observations during the month, and white regions are areas where clouds or sea ice were present in every image.

Panel Reports & Conclusions

PANEL 1

Remote sensing of ocean colour for studies of biological productivity and biochemical cycles

Rapporteurs: P M Holligan & A Morel

1. The use of ocean colour for biological studies

The need for information on phytoplankton distributions over larger spatial and temporal scales than can be described from ships has long been recognised. In continental shelf waters, upwelling regions and the oligotrophic oceans, an understanding of photosynthetic processes (primary production) is required to assess the marine biological resources of the globe, including pelagic and demersal fisheries, shellfish and even organic sedimentary deposits.

Data from the Coastal Zone Colour Scanner (CZCS) satellite in 1978, has demonstrated unambiguously the value of remote sensing in this context. For the first time, biological features of ocean basin gyre systems, oceanic fronts, mesoscale eddies and shelf-ocean boundaries have been observed in a synoptic mode. This allows much more objective criteria to be used in the development of ideas on the functioning and management of ocean ecosystems.

Recent work with ocean colour imagery has been largely concerned with establishing reliable algorithms for determining the concentrations of photosynthesic pigments and the rates of photosynthetic carbon fixation in the surface euphotic layer. These will lead to improved estimates of primary production in the ocean, both at a global level and in relation to variability at regional and local scales. Such information is needed urgently for studies on a range of ecological and biogeochemical problems.

2. Primary productivity

Imagery from the CZCS, supplemented to varying degrees by data from broad band visible sensors on other satellites (eg. Landsat, NOAA and now SPOT) and from visible scanners on aircraft, has been used to investigate phytoplankton distributions in selected areas (eg. coastal waters off E and W North America, South Africa and NW Europe, the North Pacific, the Mediterranean) and recently the first composite image of chlorophyll distribution in the whole North Atlantic has been produced. Specific studies of phytoplankton growth in response to upwelling, frontal dynamics, island mixing etc. have been made, and the bio-optical characteristics of blooms of different species measured.

Procedures for the quantitative evaluation of ocean colour imagery in terms of the biomass and productivity of the phytoplankton are now well established both on observational and theoretical

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grounds. Single biomass or productivity algorithms cannot be applied on a global basis. However, variations in the relationships between ocean reflectance at different wavebands and phytoplankton biomass/productivity appear to be largely attributable to a number of factors that can be independently assessed such as latitudinal differences in solar irradiance, the depth of the surface mixed layer, and the reflectance/absorbance characteristics of the main algal groups. Methods for dealing with the special problems of coastal waters (yellow substances, suspended particulate matter) are also being developed.

In order to allow a more complete analysis of satellite data on phytoplankton distributions, methods to obtain compatible information on the main parameters controlling photosynthetic rates, light and nutrients, are now being examined. Visible band sensors, including the CZCS, can be used to quantify sea-surface irradiance from data on atmospheric aerosols and clouds. Algorithms for estimating light attenuation in surface waters from CZCS data are available. Finally inputs of new nutrients (i.e. phosphate, nitrate) through vertical exchange processes (upwelling, wind mixing) can be assessed indirectly from satellite temperature and wind stress measurements. Nutrient inputs from land are generally only of local importance and may be derived from information on fresh water drainage.

Global information on geographical and seasonal variations in primary production will allow a more complete assessment of secondary production processes in the oceans. Already efforts to understand the factors controlling the feeding and survival of larval fish, the distribution of commercially-important adult fish, and the formation of organic material in upwelling and frontal regions have received a new impetus from satellite ocean colour imagery.

3. Biogeochemical cycles

Since the first issue of the OCWG report (ESA BR-20) in 1984, the most rapid conceptual advances in the application of ocean colour data have concerned the importance of the oceans in the global cycles of important elements such as C, D, N, S and P. This has led to proposals for several large-scale observation programmes (eg. GOFS in the US, BOFS in the UK, and other programmes in France and in W-Germany) for which global data on ocean colour is a fundamental requisite. In general the main attention is being given to the carbon cycle and the role of the oceans in determining atmospheric CO_2 levels. Other elements are important either due to their intimate geochemical association with carbon or due to separate environmental problems.

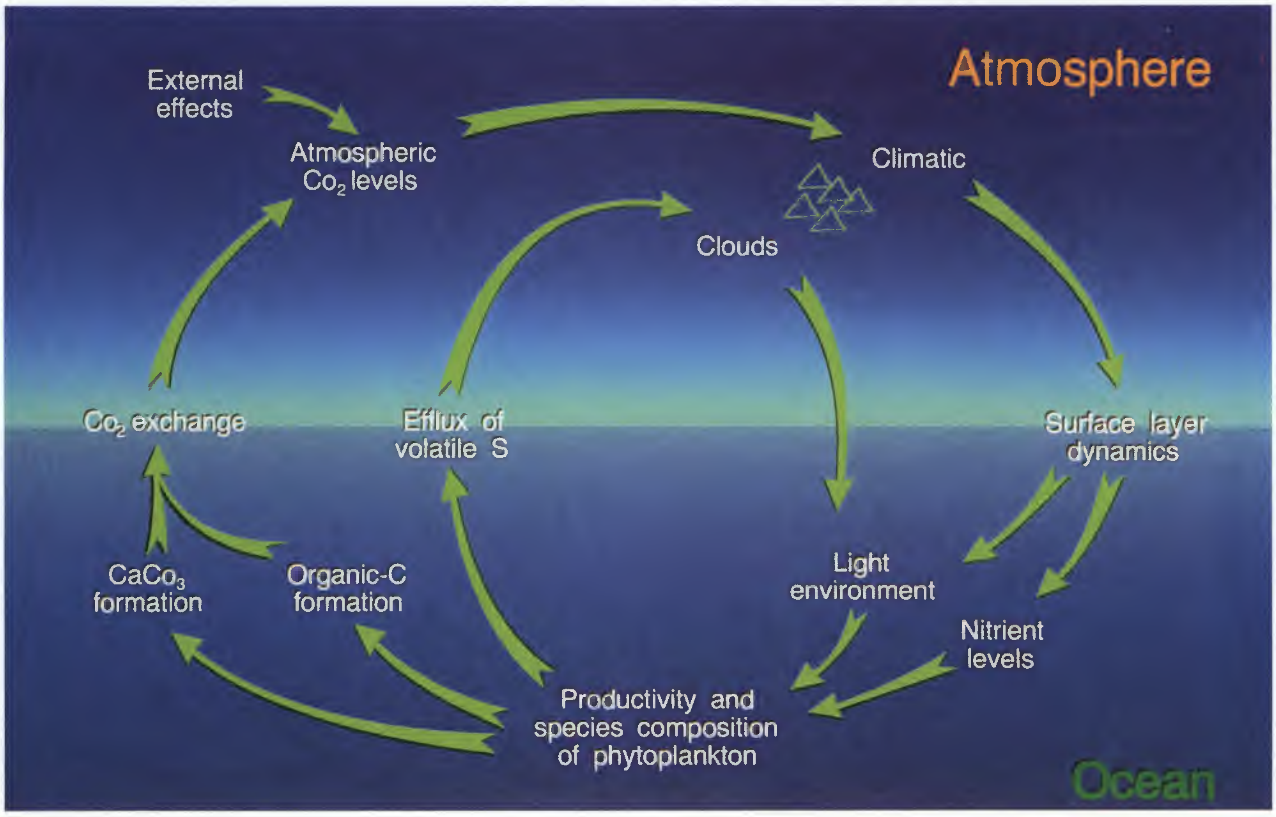
Exchanges of CO_2 between the atmosphere and the oceans are caused by a combination of physical effects, resulting from the influence of temperature on the solubility of CO_2 in water, and of biological effects which lead to a net transfer of carbon from the atmosphere to marine sediments. Together these influence the carbon cycle over a range of time scales determined by rates of mixing and advection, ocean ventilation, sinking of biogenic particles, oxidation of organic carbon and dissolution of calcium carbonate. It is estimated that as much as half of the excess CO_2 released by the burning of fossil fuels and forests has already been taken up by the oceans, but the precise mechanisms remain obscure.

Thus, one of the main objectives of large scale biogeochemical programmes is to relate satellite ocean colour data on phytoplankton to the various processes in the oceans that drive the carbon cycle. Information is needed on seasonal changes in pCO_2 for the surface mixed layer, on the relative productivity of particulate organic C, dissolved organic C and $CaCO_3^-C$, and on the relationship between total primary production and the downward flux of C through the permanent thermocline. Studies on the relative importance of regenerated *versus* new inputs of inorganic nutrients and on trace metal distributions are likely to provide important new information about vertical fluxes. In this context a better understanding of the dynamics of deep water formation in the North Atlantic and Southern Ocean is also vital.

Predictions of the ocean's capacity to remove CO_2 from the atmosphere are urgently required for forecasting changes in climate and sea level over time periods ranging from tens to hundreds of years. Both short-term effects, such as the response to the burning of fossil fuels, and long-term ones shown by glacial-to-interglacial increase in atmospheric CO_2 will need to be considered in the development of predictive models of C fluxes. A key process appears to be the effect of calcium carbonate formation/dissolution in the oceans on air-sea exchanges of CO_2. Global monitoring of ocean colour to show regions of active $CaCO_3$ formation should therefore be given high priority.

Recent work on the role of the oceans in the sulphur cycle illustrates not only the environmental significance of elements other than carbon, but also the probability of synergistic effects involving marine phytoplankton which could lead to rapid changes in rates of biogeochemical cycling.

It is now thought that the volatile sulphur compound, dimethyl sulphide (DMS), produced in the euphotic layers of the oceans by phytoplankton both accounts for a flux of sulphur from the sea to the atmosphere that is equivalent to that from anthropogenic (industrial) sources, and is of primary importance in the formation of cloud condensation nuclei. Thus, photosynthetic activity by DMS-producing species probably makes an important contribution to acid precipitation, and also gives rise to powerful feedback effects involving the effects of clouds on solar radiation reaching the sea surface (see diagram). The global implications of these are not yet understood, but are of sufficient significance to warrent careful study. This cannot be done without satellite sensors to measure ocean colour and cloud cover.



4. Aerosol and sediment studies

Other new applications of narrow band visible scanners such as the CZCS include studies on atmosphere-water and water-sediment exchanges of materials.

A by-product of the atmospheric correction procedures developed for ocean colour work is information on the load and nature of aerosols which is of fundamental importance for both geochemical and climatological (ie. radiation budget) studies. Sporadic dust outbreaks from terrestrial arid zones represent a major contribution to the tropospheric aerosol load. Unlike stratospheric aerosols which show relatively homogenous spatial distributions and long residence times, the sources, extent and life-times of tropospheric aerosols can only be characterised by continuous monitoring. This material which can be clearly identified in marine sediments, is thought to have an important influence on biogeochemical cycles in the oceans. With an advanced ocean colour sensor having several near infrared channels, it will be possible to investigate the size distribution and chemical composition of these tropospheric aerosols.

For well-mixed continental shelf waters, ocean colour imagery shows variations in the load of suspended particulate material. Information about both bottom mixing conditions and transport processes is provided by sequences of images. For surface waters close to shelf edge these are indicative of exchanges of particulate matter between ocean and shelf waters which could also be important for adsorbed dissolved organic material. The general implications in terms of slope sedimentation have yet to be investigated.

5. Recommendations

The CZCS mission has demonstrated the value of ocean colour imagery for various applications in ocean biology and biogeochemistry. Indeed any large scale study on problems of this type is thought only to be viable if a new, improved ocean colour scanner is flown. The main scientific objective will be prediction of global environmental change, particularly with respect to ocean-atmosphere interactions and climate, so that the need for ocean colour imagery with daily coverage of the globe is urgent.

To make full use of such data, the following steps would need to be taken:

a) Further sea-truth measurements simultaneous to satellite or aircraft overpasses should be made to validate ocean colour signatures, particularly with respect to the influence of accessory pigments, fluorescence effects, coccoliths, suspended matter, yellow substances *etc.* on chlorophyll absorption properties.
b) With improved satellite sensors and sea-truth information, the accuracy and general applicability of phytoplankton biomass/productivity must continue to be rigorously tested.
c) Procedures for analysing ocean colour imagery in relation to remote sensing data for other properties such as surface temperature, wind stress and currents must be developed. Important applications concern assessing the role of phytoplankton in air-sea gas and heat exchanges, and their use as tracers of surface mixing processes (see Panel 2).
d) Processing of the CZCS archive (1979–1986) should be completed both to allow greater access to corrected images, and to ensure that preparations for new satellite ocean colour sensors are optimised both from the technical and application standpoints.

PANEL 2

Ocean colour applications in ocean dynamics and coastal processes

Rapporteurs: I S Robinson & D Spitzer

1. The use of ocean colour in dynamical studies

Ocean colour observations from space are already established as making a valuable new contribution to descriptive physical oceanography. Hitherto there has been a tendency to assume that the contribution of ocean colour data to dynamical studies is little more than descriptive, in contrast to the quantitative measurements made using infrared and microwave remote sensing techniques. Such a view fails to perceive the full potential of ocean colour sensors. The workshop identified two areas in which ocean colour observations from space are now a fundamental requirement of national and international programmes in dynamical oceanography and which demand a similar continuity and reliability of service as that provided by the infrared SST measurements from the meteorological satellites. These are the use of colour as a tracer, in both ocean dynamics and coastal processes, and the contributions of colour scanner data to climate studies. In addition, high-resolution colour data also have useful applications in problems of coastal mapping and bathymetry.

(a) Ocean colour used as a tracer

It is the spatial distribution of ocean colour, and its long-term variability, which are of particular concern to the study of dynamical processes, rather than a complete understanding of the processes controlling the colour. Of course, if the colour can be interpreted quantitatively in terms of a particular tracer (eg. suspended sediment, chlorophyll pigments or yellow substance) then the opportunities for extracting dynamical information are maximised. Nonetheless even without a complete quantitative calibration the spatial distribution of colour revealed by satellite image data provides unique spatial information about dynamical features. Thus for example the shape, size, orientation and movement of ocean eddies, or the meandering of frontal structures, is measurable from colour images. Such observations are sometimes of features which do not have an infrared signature and, even if they do, the colour information is complementary rather than redundant.

In the deep ocean and in shallow seas, the tracer revealed by colour images can provide a means of measuring transport processes. Thus for example suspended sediment movement in estuaries and nearshore zones is readily deduced from image data at appropriate scales. Furthermore, the very patterns of colour distribution, revealing streakiness and patchiness, contain spatial information about dispersion and mixing processes. Colour images used in collaboration with models of tracer transport can explore, for example, the anisotropy of dispersion coefficients in tidally driven seas, although care must be exercised when the colour signature is related to non-conservative tracers. In shelf seas, yellow substance can serve as a conservative tracer for fresh water river discharges, if the ocean colour images can be calibrated in terms of yellow substance.

(b) Climate studies

i. Light penetration in the upper ocean
One of the primary tasks being addressed by dynamical oceanographers is the understanding of ocean/atmosphere interaction on the global scale, and particularly the role played by the ocean as a reservoir of heat. It is becoming clear that central to this undertanding is an appreciation of processes of heat transfer in the upper mixed layer of the ocean. Models of upper ocean heating have not adequately parameterised the depth distribution of solar heating because of a lack of ocean optical data. This can be rather important in those cases where solar radiation is able to penetrate through the mixed layer and into the thermocline. Ocean colour data from space are capable of providing accurate estimates of optical attenuation coefficients and light penetration depths, in the form of instantaneous spatial distributions or, given an operational satellite programme, climatological averages. Such datasets are required by ocean modellers with the same urgency as global datasets of sea surface temperature, surface winds, or sea surface topography.

ii. Albedo of the ocean
Independently of any interpretation (in terms of pigment or sediment content) the measurement of the reflectance properties of the ocean in the whole solar spectrum (visible & near IR) is in itself highly valuable information. The ocean diffuse reflectance, added to the specular reflectance at the air-water interface, forms the ocean albedo which is needed in climate modelling along with the thickness of the heated layer.

iii. Atmospheric aerosol
The measurement of atmospheric aerosol load is a by-product of the atmospheric correction algorithms for ocean colour data. The aerosol load affects the value of the planetary albedo and hence the amount of radiative energy available at the ground level. A general aerosol climatology is needed to properly understand the regional and global climate changes. Stratospheric aerosols will continue to be monitored by specific techniques (e.g. SAGE) as well as by a ground-based lidar station network, so that a monitoring of the total load, allowing the contribution of tropospheric aerosols to be evaluated, is of increased interest.

(c) Coastal bathymetry
High-resolution colour image data also has a valuable contribution to make to coastal mapping and charting. Near IR wavebands provide a clear indication of the land-sea boundary. At lower wavelengths the depth penetration of the light enables bottom depth (and possibly bottom material) to be measured. Whilst the accuracies achievable are unlikely to make the technique competitive with conventional surveying in European waters, it does offer the potential for a valuable service to European coastal engineers working in more remote parts of the world, where existing maps and charts are inadequate and conventional surveying could be prohibitively expensive.

2. Length and Time Scales Required

The following scales were identified as the ideal sampling intervals necessary for an adequate analysis of a particular feature.

Processes	*Spatial Resolution*	*Temporal Resolution*
Ocean Basin Circulation	10 km	5−10 days
Mesoscale (Oceanic fronts & eddies)	1 km	1 day
Shelf Sea processes	500 m	3 hr−1 day (sub-tidal time scale)
Coastal & beach processes	25 m	1−3 hr
Estuarine dynamics	25 m	1−3 hr

These provide guidelines for the design of remote sensing instruments, but it is apparent that the temporal resolution is too demanding to be completely satisfied by satellite ocean colour monitors. Cloud cover would prevent such frequent sampling even if a remote sensing system could be designed to achieve these requirements. In practice, the most important capability of the remote sensing system is its spatial sampling, since it is inevitable that the temporal sampling of dynamical processes must continue to be performed by conventional ship and buoy techniques. Even the occasional cloud-free image at high spatial resolution offers a wealth of unique information, particularly if long period variability can be examined from the analysis of images over several years or decades.

3. Recommendations

The recommendations of the workshop, based on the ideal requirements but bearing in mind the practical sampling constraints were:

(a) For ocean, mesoscale and shelf-sea dynamical processes, a sensor (or series of sensors on seperate satellites) are required which can provide colour data having a spatial resolution of 500 m at nadir, and capable of whole earth coverage in one day. The spectral requirements for dynamical applications are less demanding, the specification of the ESA OCM being acceptable. There would be considerable benefit for improved temporal sampling if at least two polar orbiting satellites carried an ocean colour sensor with a swath wide enough to achieve daily global coverage.

In addition attention should be paid to the possibility of making medium resolution (500−1000 m) colour measurements at coarse spectral resolution at 30 min sampling intervals from the geostationary meteorological satellites. Such a capability would offer the ideal time resolution (during cloud-free periods) for tracking tidal movements, and the broadband measurements could be interpreted using the one sample each day from the spectrally sensitive polar orbiting sensor.

(b) For coastal and estuarine dynamics, a sensor is required which can resolve a length scale of 25 m. Since such a sensor will inevitably have a swath width of no more than a few hundred kilometres, the normal sampling interval for a nadir pointing instrument on a single polar-orbiting satellite would be many days. To improve on this it is worth investigating the scientific and technical feasibility of a pointable sensor which could provide daily sampling of a limited area for a limited time span. Given the variety of tracers to be found in coastal waters (e.g. yellow substance can act as a tracer for fresh water dispersion) more importance attaches to this high-resolution sensor having high spectral resolution, if possible, to be able to detect fluorescence peaks.

(c) Whilst ocean dynamical studies can benefit from spatial patterns alone, it is nonetheless desirable to improve interpretation of ocean colour data in terms of suspended sediment or pigment in order to derive quantitative information about dispersion and transport processes. To this end programmes of field measurements including shipborne optical and airborne remote sensing observations should be encouraged, and continued as sensor validation exercises once a satellite colour instrument is flying.

(d) Theoretical research should be encouraged to develop tracer transport modelling studies which can enable ocean colour data to be interpreted in terms of dynamical processes, and in relation to other remotely sensed ocean measurements. The spatial detail in the colour data provides an ideal means for validating the predictions from tracer models.

4. Summary of priority requirements

(a) In terms of new instruments, the priority is for the medium-resolution ocean colour instrument to be developed for applications in oceanic, mesoscale and shelf sea dynamics. Such sensors should be available to fly alongside other sensors on the Space Station Polar Platform so that modelling studies of ocean dynamics can be provided with inputs of ocean colour data as well as sea surface temperature, surface winds and surface topography.

(b) If the need for a high-resolution colour sensor for coastal and estuarine studies is to be served by a high-resolution land-application instrument, then at the very least it must be suitably adapted to cope with the high spectral and radiometric sensitivity requirements of the marine applications, and a pointing capability would be desirable.

PANEL 3

Technical Aspects of Future Ocean Colour Remote Sensing

Rapporteur: M Rast, ESA

The main task of this panel was to propose performance requirements for a new ocean colour sensor to be studied within ESA's Earth Observation Preparatory Programme (EOPP).

The general consensus stated that a future OC sensor could also contribute to land, atmospheric and climatological application since ocean colour remote sensing imposes most stringent requirements on a monitoring instrument.

1. The properties and merits of a mechanical scanning and opto-electronic imaging device were discussed and taking into account the need for a moderately high ground resolution, the opto-electronic imaging approach was preferred to the mechanical scanning principle.

2. The importance of the combination of VIS/NIR and thermal infrared bands for application purposes has been underlined. To overcome the detector problem in an imaging spectrometer, an instrument split has been suggested where VIS/NIR and TIR acquisition parts are separated in two instruments simultaneously operated on the same platform with an identical swath.

3. The use of a fluorescence laser from space, conceived as an extrapolation from aircraft to spacecraft, has been considered as premature because of the technical complexity and the energy needed for the laser.

4. The following sensor parameters have been suggested for a future mission (these take into consideration application objectives and results from CZCS):

Spatial resolution:	0.5×0.5 km
Swath width:	Not less than 1500 km
Spectral bandwidth:	10 nm (nominal) / 5 nm (goal)
Radiometric resolution:	Possibly 12 bit
Number of spectral bands:	Minimum 9 in the VIS/NIR (see OCWG recommendations)
Band selection capability:	Programmable for additional bands to the nominal 9 spectral channels
Coverage:	A global daily coverage needed which can be achieved by operating the instrument on each Polar Platform
Tilt mode:	Strongly recommended to avoid sunlight

Sensitivity:	To be sufficient for low reflecting targets (e.g. ocean surface at high latitude) in order to get data at low solar illumination conditions
Polarisation:	It is essential that the sensor is unsensitive to polarisation conditions of scattered light.

The above requirements and their interrelationships (global coverage, wide swath, spatial resolution, equator crossing times of the Polar Platform and thus the local times of sampling presently envisaged give preference to the northern hemisphere. For similar conditions at the southern hemisphere either a scenario with additional satellites or a reconfiguration of the orbits would be necessary. Under assumption of the present configuration a significantly high sensibility seems to be the only solution.

5. The above requirements will provide compatibility of ocean colour data with previous observation (CZCS) whilst making improvements in the specifications.

6. It has been recommended to design the instrument as an 'intelligent sensor' with an on-board pre-processing facility.

7. The desire has been expressed for the implementation on an additional band relevant for ocean colour on geostationary meteorological satellite (i.e. Meteosat 2nd Generation). A suggestion for the desired spectral band is 0.43 to 0.47 μm.

WORKSHOP CONCLUSIONS

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Re-examined by and discussed during an OCWG meeting on January 8, 1987, at the ESA Headquarters, the results of the November Villefranche Workshop can be summarized as follow:

The national interests in Ocean Colour for science and applications cover the entire spectrum of visible and IR sensor capability. Most of this interest is based on demonstrations of ocean mechanisms and processes by few experts as shown in the cover figure and in some figures of the national reports, i.e.

- interannual and seasonal variability: Italian Report, Figs. 1,2,3.
- large space scale composite (North Atlantic): U.S. NASA Report, Fig. 1.
- carbon cycle - the coccolithosphore role: U.K. Report, Fig. 3; Canadian Report, Fig. 4.
- upwelling: Cover figure (by Morel).
- ocean dynamics: French Report, Fig. 1.
- shallow water bathymetry: Canadian Report, Figs. 11,12.

It is the lack of standard software packages for CZCS and an uncoordinated Archive and Data Bank system that prevented a large range of users to employ more widely the CZCS data.

NASA has provided the support to reappraise and make available the entire CZCS data set of several years and solicited all possible scientific analysis of data to provide the needed background for planning new satellite ocean colour sensors (particularly for the Polar Platforms).

European scientists could profit from still unprocessed data from Maspalomas, Lannion and Dundee if reorganized and made available in a set with the U.S. data. The investment in such an action could bring ESA and European users the most outstanding return in the interim period in which ocean colour satellite sensing is missing. The following points illustrate the need of enhanced research related to this action, including the use of data from different satellites.

a) A systematic and extensive exploitation of the existing ocean colour data from CZCS is needed. This exploitation should result in the production of time series, of mosaics and of time-averaged images with a geophysical/geochemical significance. Such a systematic exploitation, at least for selected zones (for instance European waters, East Atlantic waters) can contribute to the Global Ocean Flux Studies or to process-oriented field studies; it is also the best way of being experienced and prepared in view of an optimal use of future ocean colour sensors.

b) Synergism: There is a need for a combined exploitation of various sensors, especially CZCS, AVHRR and Meteosat. The relationships which exist between sea surface temperature and algal biomass are easily evidenced through CZCS data, but poorly quantified, mainly because of the lack of accuracy in the SST retrieval from the single IR channel of CZCS. A better work can be achieved by comparing the visible imagery with the SST maps derived from AVHRR. There are good reasons to think that the "new" production (which originates from a new flux of nutrients associated with the cold upwelled waters) could be, at least in principle, estimated from the intensity and extension of the cold plumes. The impinging solar radiation, which can be monitored from geostationary meteorological satellites, forms an input parameter to be introduced in productivity studies (for instance blooms in high latitudes).

c) Use of non ocean dedicated sensors: TM/Landsat/HRV/SPOT/MESSR/MOS data should be further used in studying restricted (and coastal) zones. In spite of obvious radiometric limitations, useful information can be obtained from this kind of sensors at least in three directions: i) sediment transport and distribution; ii) description of the 2-D turbulent field with a high geometric resolution; iii) spectral behaviour of the aerosol scattering in the near IR. Beside the actual result of such studies, any experience acquired when processing and interpreting these data will be beneficial in view of a comprehensive use of future ocean dedicated or multipurpose spatial instrumentation.

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

d)Technological research: There is a need for a sensor with improved perfomances (compared to those of CZCS), i.e. an imaging spectrometer with a medium spatial resolution (0.5 x 0.5 km^2, possibly operating in GAC mode above the open ocean), with high radiometric resolution (=10 nm) for the spectral channels in the visible and several (wider) channels in the near-IR. An OCM-type sensor appears an optimal compromise, with some fine tuning concerning the nominal wavelengths.

A new instrument should be able to provide a daily, or near-daily global coverage (at the Equator). This is an essential requirement for global geochemical studies and monitoring of our planet, but would not satisfy coastal/estuarine small scale application. For such applications, high spectral resolution, high spatial resolution and high temporal rate are simultaneously needed. A distinct instrument would be preferable as, for example, a high resolution spectrometer, currently considered for land applications, with appropriate (selectable) channels for ocean colour and with a depointing system.

Another and complementary approach which could satisfy the severe temporal rate requirement (in the case of tidal motions, for instance) consists of envisaging the possible use of geostationary meteorological satellites (new generation) implemented with adequate extra channels (one or two). Investigation of this possibility and feasibility is recommended, even if the high latitudes are not viewed as favourable conditions from a geostationary position.

RECOMMENDATIONS

A number of biophysical and biochemical processes which have emerged with greater evidence with the first global and local scale satellite observations remain to be understood.

The OCWG strongly recommended the support of active research on a few topics which have a priority also for the development of future sensors. The following general recommendations are in addition to those made by Panels 1 and 2.

a) Biophysical studies on phytoplankton productivity including studies of the light harvesting capabilities of algae in relation to their size and pigment concentration/composition and studies of the quantum yield which governs the conversion of absorbed energy into chemical energy stored in the photosynthesized organic molecules.

A better knowledge of these parameters is essential for an adequate parametrization of the relationship between the algae. biomass (as remotely sensed) and its potential production (in terms of CO2 fixation); or in other words, for being able to reliably transform a "chlorophyll map" into a "production map".

b) Biophysical studies on phytoplankton fluorescence in relation to the pigment content (chlorophyll and phycobilins), the light and nutrient availability and the photosynthetic activity. Both in situ and in vitro studies must be envisaged as well as both natural sun-induced and artificial (laser) induced fluorescence have to be encouraged. The active fluorescence techniques, already developed, could be usefully re-examined in the light of fundamental research to be undertaken.

c) Field optical studies of the aerosols in the whole spectrum of the visible and near infra-red: For the next generation of sensors it is planned to dispose of several channels in the near IR, allowing the spectral dependence of the aerosol scattering to be accurately determined in this domain (the Angstrom exponent). This dependence is thereafter extended towards the visible part of the spectrum to provide the atmospheric correction for the visible channels. A systematic study, with the aim of evaluating the accuracy of such an extrarelation, remains to be done, both for marine and continental (including desertic) aerosols. It is a preliminary condition for an implementation of adequate atmospheric corrections in the future.

d) Optical data assimilation in models should be extensively studied. Related questions are:

i) How can the ocean colour information be introduced in ocean dynamics model, in the same way as SST or altimetric data are presently used? (A first attempt has been demonstrated on the Adriatic model by Bergamasco, Italian Report).

ii) How can the mixed layer models be fed with the satellite derived optical properties which rule the heating rate?

iii) How can the detailed information provided by the optical tracers about the turbulent field and the eddy-like structures be extracted and meaningfully interpreted?

FINAL REMARKS

The Workshop has demonstrated the scientific and potential commercial interest in ocean colour sensing. A maximum deffort should be made to embark an ocean colour sensor on the polar platform(s) and possibly on other (European or non-European) platforms of opportunity.

Basic research as specified in the recommendations should be nationally and internationally supported.

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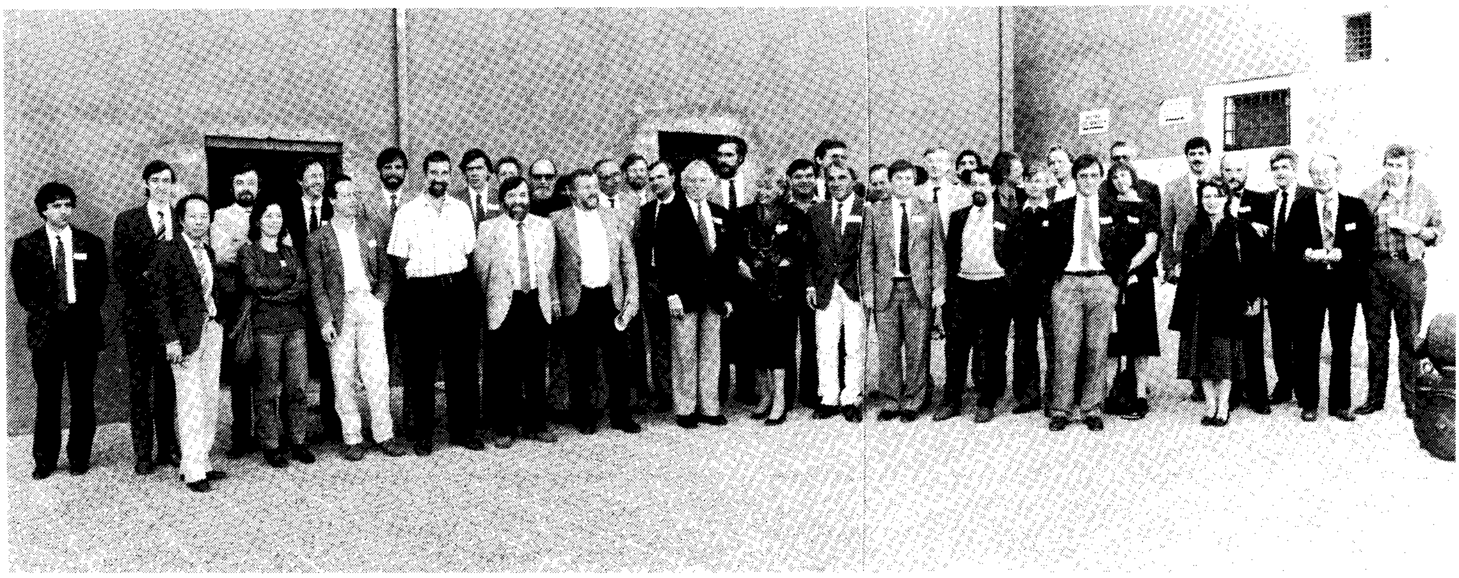

Photo G. Pressenda, *'Nice-Matin'*, 5.11.1986.

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National Reports

STATUS AND PROSPECTS OF THE JRC WORK ON THE APPLICATION OF OCEAN COLOUR MONITORING FROM SPACE

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ABSTRACT

A historical review and a status report of JRC's activity on ocean color analysis is given. The main achievements are an operational software package for the evaluation of CZCS data and site specific interpretation algorithms for case 2-type water of the Northern Adriatic Sea which allow the elaboration of geometrically corrected maps of pigment and total suspended matter concentrations and of diffuse attenuation coefficient. Applying these techniques to an extensive archive of CZCS data from the Adriatic Sea, the ultimate goal is:

- to assess remote sensing of antropogenic pollutants;
- to develop a methodology to predict the movement and dispersion of pollutants in estuarine and coastal zones.

1. INTRODUCTION

1.1 The Eurasep Experiment (1975-1980)

In cooperation with specialized institutes in Europe, a proposal of using NIMBUS-7/CZCS data was accepted in December 1975. The JRC was invited to become a member of the NIMBUS experimental team (NET). Contacts with European organizations and agencies resulted in an organizational and management structure for an experiment comprising 19 test-sites.

The most important of the pre-launch measurement operations was the North Sea Ocean Color Scanner (OCS) experiment, which was carried out in 1977 in preparation of the NIMBUS-7 data utilization (Refs.1,2). Data was collected by the airborne OCS and a large number of scientific teams acquired sea-truth. With the launch of the satellite in October 1978 research was focused on the development of algorithms aimed at the determination of concentrations of chlorophyll-like pigment and total suspended matter (TSM). As test-area the Northern Adriatic Basin, with its particular features due to the Po estuary and Venice lagoon, was chosen. In the meantime some thousand CZCS computer compatible tapes (CCT) from European coastal waters were collected at the JRC. Only those from the Mediterranean area are stored at Ispra; the remaining part is archived at ESRIN-Frascati.

1.2 Coastal Transport of Pollutants (1980-1986)

First results from Ocean Color interpretation and derived products mapping from CZCS data (Ref.3) confirmed the need to develop a data processing and evaluation procedure to allow the transformation of CZCS data into geo-referenced maps of pigment, TSM, diffuse attenuation coefficient and sea surface temperature (SST). With this, the possibility of following the evolution and dispersion of coastal pollution became realistic. A package of CZCS processing programs was developed. The effort was concentrated to improve the CZCS data interpretation algorithms especially for case 2 (near-shore) waters. This was achieved through the analysis of bio-optical and atmospheric, extensive data base, gathered from a number of consecutive multi-annual (from 1981 to 1986) series of sea campaigns (Ref.4).

When applying remote sensing to water bodies, an evaluation of the magnitude of the various error sources which may affect the retrieval procedure is of extreme importance. From 1980 this evaluation was performed by a sensitivity analysis, made by a numerical simulation of the actual phenomena (Ref.5). Several pigment and TSM algorithms have been tested in order to develop algorithms characterized by high sensitivity of the retrieved substance, low sensitivity to other matter contained in the water and low sensitivity to the uncertainties of the atmospheric corrections (Ref.6).

When the sensor degradation of the CZCS reached significant values, it became necessary to correct for its effects on the retrieval process. The evaluation of correction factors consisted in comparing measured total radiances and predicted "true" radiances for clear water zones. Therefore, in addition to the normal CZCS data evaluation, an evaluation of sensitivity deterioration had to be performed since about 1983 when CZCS data from orbits greater than about 10000 became available. By 1985, correction of the sensor degradation has been evaluated using a catalogue of more than 500 clear water pixels from about 53 orbits (Ref.7).

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1.3 Current Motivations and Objectives of the Ocean Color Activity

The feasibility of using remote sensing (RS) to monitor coastal pollution movements is one of the research objectives of the JRC. This project constitutes a support to the policy being developed by the Commission of the European Communities (CEC) in matters of environmental protection and is a voluntary contribution to the UNEP Medpol programme set up as a consequence of the Barcelona convention. The specific goals of this project are:

- to assess how main anthropogenic pollutants into the sea can be remotely sensed;
- to develop a methodology to map and predict the movement and the dispersion of sea pollutants in estuarine and coastal zones.

A secondary objective is to demonstrate the ability of remote sensing to contribute to the understanding of basic physical and biological phenomena in upwelling areas, as an aid to fish resources management.

2. REMOTE MEASUREMENTS OF CHLOROPHYLL-LIKE PIGMENT, SUSPENDED MATTER, DIFFUSE ATTENUATION COEFFICIENT AND PRODUCTIVITY

The evaluation of Coastal Zone Color Scanner (CZCS) data consists in computing from the measured total spectral radiance at satellite altitude the water-leaving contribution which has interacted with water and the dissolved and suspended matter. This is done by the atmospheric correction (Refs.8,9,10). The resulting water-leaving spectral radiance $L_w(\lambda)$ in the first three bands of the CZCS is then used to evaluate the derived products: chlorophyll-like pigment concentration C (mg/m^3), total suspended matter (TSM) S (mg/l) and the diffuse attenuation coefficient K (l/m) at a given wavelength from empirical algorithms (Refs.11,12,13,14,15). The pigment and TSM concentration determined from satellite by this method are representative only for the upper layer (l/K meters) of the ocean. However, as shown by Smith and Baker (Ref.16), the average pigment concentration in the euphotic zone is well correlated with this "satellite measured" concentration. From the knowledge of this correlation and the satellite determined diffuse attenuation coefficient K, it is possible to estimate the euphotic depth and hence the standing phytoplankton stock and then from its evolution in time the productivity (Refs.17,18). An example of CZCS data processing at JRC is given in Fig. 1.

2.1 Atmospheric correction

The atmospheric correction algorithm processes the CZCS imagery pixel-by-pixel into imagery of derived products. In order to keep the computer time within reasonable limits - less than 1/2 hour on a VAX 785 - the algorithms is based on a simple optical model for atmosphere and ocean. The method, as described first by Gordon (Ref.8) is based on the assumptions that

- the aerosol optical thickness $\tau_a(\lambda)$ is small so that the upwelling light undergoes on the average only one scattering collision before it reaches the sensor (single scattering approximation);
- the ratio $\varepsilon(\lambda,670) = \tau_a(\lambda)/\tau_a(670)$ is constant over the scene;
- water-leaving radiance is zero at channel 4 (670 nm).

Due to the particular situation of European coastal waters (turbid water in northern coastal zones, hazy atmosphere over the Mediterranean), some of the simplifications resulting from these assumptions have been modified in the JRC software for CZCS processing:

- transmittance terms are introduced in the calculation of the Rayleigh sky-glitter and Rayleigh diffuse sun-glitter (Ref.9);
- aerosol optical thickness is not assumed equal to zero, but is calculated from the channel 4 path radiance of the same pixel area which is used to evaluate $\varepsilon(\lambda,670)$;
- an iteration technique similar to that proposed by Smith and Wilson (Ref.10) is used on turbid water pixels to correct for non-zero water-leaving radiance in channel 4.

However, the main limitations of the method still remain the single scattering approach and the assumption of scene constant $\varepsilon(\lambda,670)$ and aerosol optical thickness. Improvement of the last two assumptions is possible, but would increase the computer time.

2.2 Evaluation of Derived Products

The general form of the derived product algorithms is based on the observation that the chlorophyll-like pigments have a pronounced absorption maximum at about 440 nm, the first spectral band of CZCS, and that increasing total suspended matter increases the subsurface reflectance in channels 2 and 3 (520 and 550 nm). Therefore, the algorithm for pigment uses band ratios of radiance or reflectance while the algorithm for TSM utilizes ratios and absolute reflectance values.

2.2.1 Algorithms for case 1 waters. Case 1 waters (Ref.12) are defined those waters in which the TSM is the result of the photosynthesis of phytoplankton and the successive formation of detrital matter due to natural death and grazing by zooplankton. Case 1 includes waters ranging from highly oligotrophic waters (Sargasso sea, Guinea dome) to productive upwelling areas (south-west and north-west Africa, Peru, California). The TSM and the diffuse attenuation coefficient in these waters are strongly correlated with the pigment concentration which remains, therefore, the only non-redundant quantity of this type of water.

Pigment algorithms for case 1 water have been proposed by several investigators: Morel (Ref.12) (from in-situ reflectance and pigment concentration measurements), Smith and Baker (Ref.16) (from in-situ pigment concentration measurements and atmospherically corrected CZCS radiances), Gordon et al. (Ref.14) (from in-situ pigment concentration and underwater radiance measurements). Comparisons of these algorithms show that for a typical case 1 water (upwelling front offshore Marocco) they agree within 0.5 of log C in the C-range 0.03 to 3 mg/m (Ref.17).

2.2.2 Algorithms for case 2 waters. Case 2 waters can simply be defined as non-case 1 water. Their water-optical properties are complicated by the presence of non-biogenic suspended matter and relatively high amounts of yellow substance.

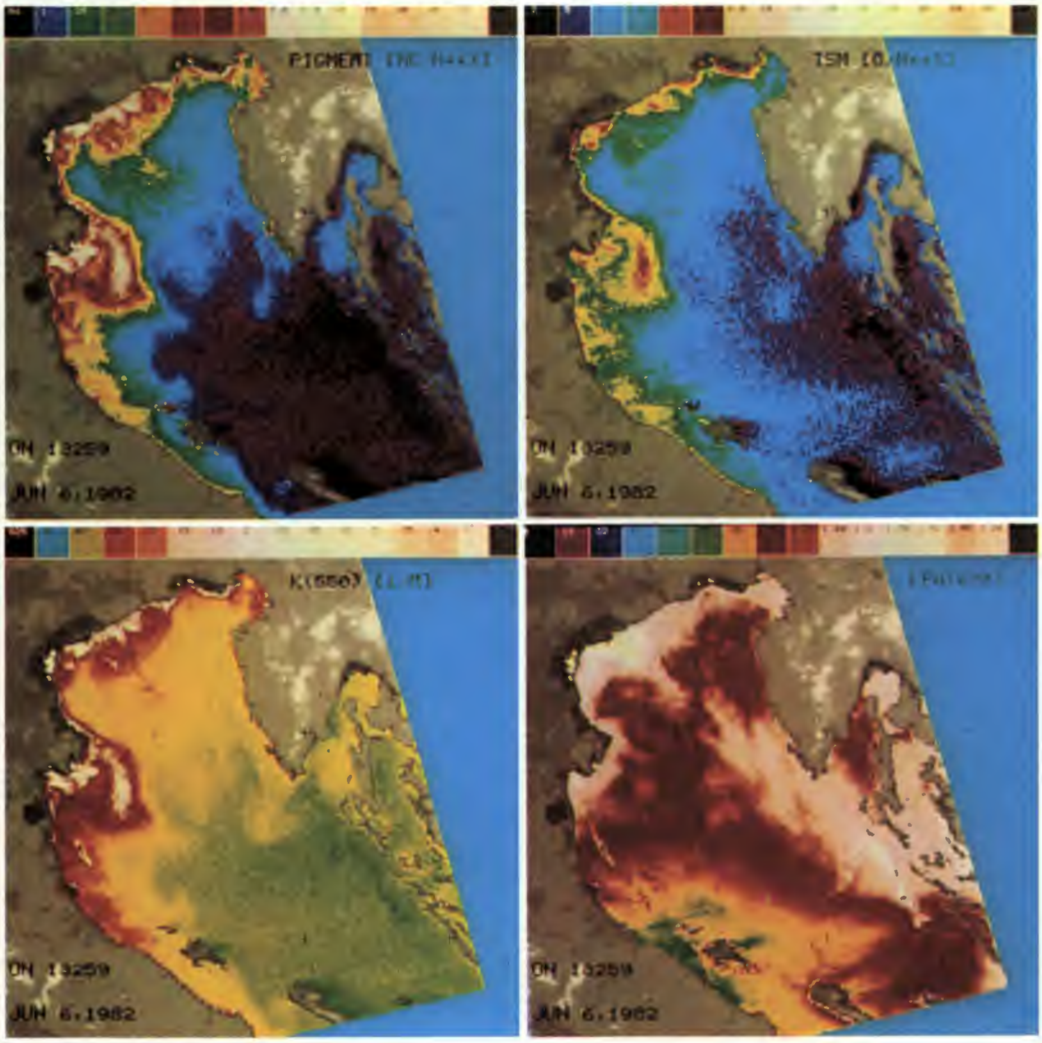

Fig. 1 - Example of maps of derived products from CZCS data evaluation: (a) pigment concentration (mg/m^3); (b) total suspended matter (mg/l); (c) diffuse attenuation coefficient (m^{-1}); (d) aerosol path radiance ($mW/cm^2 sr_\mu$). The maps are geometrically corrected to a Mercator projection. Orbit No. 13259, 6 June 1982, North Adriatic Sea.

They are mainly restricted to the near coastal zones of oceans and marginal seas.

Though one would expect that in case 2 water, pigment and TSM do not correlate, it is found from in-situ measurements that still a significant correlation exists, but with much higher TSM levels.

The work on case 2 algorithms is still in progress, a tentative summary from measurements in different coastal waters around Europe has been given by Viollier and Sturm (Ref.15). First results from the Adria 84 campaign (Ref.4) have been reported by Sturm (Ref.18).

The characteristic difference between a case 2 and a case 1 pigment algorithm is that at equal radiance or reflectance ratio, the case 2 algorithm predicts a much lower pigment concentration due to the presence of yellow substance. The high amount of TSM in case 2 water has the effect of making the radiance or reflectance ratio less sensitive to changes in pigment concentration which makes the retrieval more sensitive to errors in the atmospheric correction procedure. If one takes into consideration also the uncertainties due to the sensor degradation (see Annex 1), it seems impossible to determine from CZCS data in case 2 water the pigment concentration better than a factor of 2.

3. PROJECTS IN PROGRESS

3.1 Coastal Transport of Pollutants

The long-term objective of this project is to contribute to the development of an operational system which should constitute an aid to the control of pollution (origin tracing, transformation and impact) and the management of marine resources (recreational resources, marine productivity, waste disposal). Furthermore, the system will be a very useful tool for further scientific investigation into the marine environment.

The operational system is thought of as an on-line or near on-line data acquisition system connected to a computer run circulation model. The model will be essentially driven by RS data, with a minimum amount of topical in-situ data. Furthermore, the model will realy - whenever possible - on digested topical data from other systems, in particular on meteorological data. The main test site of the activity is the Northern Adriatic Sea. The present CTP activity will be continued for the year 1987, after which it might be reoriented according to new requirements and new sensor availability. The activity is executed in close collaboration with many national institutes of the EC member states. The objective is pursued along three approach lines:

a) RS measurements, essentially from space and associated image processing and interpretation. Up to now the main effort was centered around the visible part of the spectrum (CZCS, TM), and to a lesser extent around the thermal IR part (AVHRR). It is envisaged to extend the research effort to the microwave range, but a sensor in the visible, being the only one to give information on the inside of the upper ocean layer, certainly will be strongly missed.

b) In-situ measurements, normally executed only during campaigns, and the associated data elaboration and interpretation. During the major campaigns, airborne sensors will be used (Daedalus scanner and laser fluorosensors). The in-situ measurements serve for development, calibration and verification of existing and nex RS techniques and of the model. Furthermore, they serve for the development and refinement of new in-situ measurement techniques and instruments (underwater radiometer, laser fluorosensor).

c) Development of a 3-dimensional circulation model. The model should simulate transient and residual circulation and the dynamics of passive and active constituents in the marine environments.

3.2 Study of the North-West African Upwelling Area

The coastal upwelling is a process whereby cold, nutrient-rich water is brought from deeper layers to the surface of the ocean under the influence of the wind and the rotation of the Earth. When the nutrients enter the euphotic zone, they become available for photosynthesis and coastal upwelling are, therefore, characterized by high productivity and normally also high concentrations of fish. In fact, the coastal upwelling areas cover less than 1% of the World ocean area but supply more than 50% of the World's sea food.

The JRC is carrying out a study in the North-West African upwelling area in collaboration with l'Institut Scientifique des Pèches Maritimes, Casablanca, and the University of Copenhagen. The aim of the study is to find out how remotely sensed data can contribute to the understanding of the physical and biological processes going on in the coastal upwelling area. Specifically, the study concentrates on explaining the phytoplankton pigment patterns visible in CZCS images in terms of the mechanisms that control the distribution of phytoplankton in time and space. These mechanisms may regulate the growth and abundance of phytoplankton or they may be responsible for horizontal and vertical transport.

As a result of this study, 30 CZCS scenes in the period 1981-1984 have been processed into geometrically corrected pigment concentration maps using the CZCS elaboration software described in the previous sections. Other data involved in the study, as support for the interpretation of CZCS images, include wind data, locally as well as synoptically in-situ measurements of sea surface temperatures and fish data. In short, the features observed in the processed images can be grouped into three classes:

a) features which are observed in several images and which are believed to be seasonally persistent such as:
   - the phytoplankton pigment patterns off Cap Ghir;
   - the relatively high pigment concentration south of 25 degree north where upwelling is known to persist throughout the year;
   - the dispersion patterns south of 25 degree north.

b) other mesoscale features observed only once, the most clear example being the phytoplankton pigment pattern extending from Cap Bojador to the Canary Islands appearing on the image of May 13, 1983.

c) a myriad of local phenomena varying in time and space.

A more detailed interpretation of the images may be found in Ref. 19.

Future activities concerning remotely sensed data will include the processing of AVHRR IR-imagery specifically to analyse the spatial relationship between sea surface temperature and phytoplankton pigment distribution.

4. USE OF THEMATIC MAPPER AND AVHRR

The CZCS, having already been in operation for more than the scheduled time, is due to reach the end of its lifetime shortly. For the immediate future, there are no provisions to orbit a color scanner specifically designed to sense water bodies. Thus, it is of considerable interest to investigate whether the data produced by existing color sensors designed for other purposes, such as the Thematic Mapper (TM) orbiting aboard Landsat-5, can be satisfactorily used to retrieve characteristic water quality parameters. The potential of the TM for chlorophyll and suspended matter determination in the sea has been investigated with reference to the performance of the CZCS (Ref.20).

In the derivation of information from ocean color imagery, the analysis of simultaneously taken SST is of great importance, especially in the study of river effluents and upwelling areas. The CZCS is equipped with a thermal IR channel which, however, exhibits some problems due to heating of the radiation cooler by the sun and is, therefore, operating only during parts of the year. Because it has only one spectral band (10.5 - 12.5 μ), the accuracy of the sea surface temperature determination is affected rather strongly by water-vapour content of the atmosphere and can, therefore, not be better than several degrees absolute. The relative accuracy is about 0.4 K.

AVHRR has comparable spatial resolution but much better SST determination accuracy due to the split window technique; therefore, its combination with CZCS remains an attractive option for the users. The achievements of the JRC in the field SST mapping by AVHRR are given here briefly. In collaboration with the "Istituto di Fisica della Atmosfera" (CNR), Roma, and based on the Lowtran 5 model (Ref.21), a software package has been developed to elaborate the AVHRR split window data as received from NOAA 7, to derive Sea Surface Temperature. Although only limited calibration and testing has been performed up to now, a precision of 0.3 K seems obtainable. A major difficulty for calibration is the acquisition of reliable in-situ measurements, which can be compared with the RS data.

5. CONCLUSIONS AND RECOMMENDATIONS

The analysis of ocean color as performed with the CZCS permits to have a good synoptic visualization of suspended matter plumes in estuaries or coastal areas, of chlorophyll contents in productive or eutrophicated waters and of their dynamics. The spatial resolution of the CZCS, its repetitivity, its radiometric quality and good dynamic range due to an excellent S/N are appropriate for studies on coastal pollution.and upwelling.

Its limitations are the low number of spectral channels and the sensitivity degradation which reduces the accuracy of the atmospheric correction and its performance in turbid coastal water. Nevertheless, the determination accuracy for phytoplankton pigment concentration in case 1 water is better than a factor of 2 and in case 2 water a comparable accuracy can be achieved using site specific algorithms.

Between the shut-off of the CZCS and the forthcoming ocean color sensor (SPOT, NOAA or EOS), a time lapse of 6 to 10 years will exist. Therefore, among the activities of JRC on ocean color, the utilization of the archived CZCS data for following research items is considered:

- improvement of atmospheric correction algorithms (actually: scene constant aerosol optical thickness and Angström exponent and single scattering);
- elaboration of time sequences of CZCS data in order to individuate special events (plankton blooms, river plume evolutions, etc.) that can be used to assist the development of the 3-dimentional circulation model of the North Adriatic sea.

However, it seems difficult to maintain large active teams in this field, working only on substitution activities such as TM, airborne simulation flights. So, as a general recommendation to the ocean color groups actually active in Europe, we believe that a particular effort should be dedicated to a more systematic analysis of the extensive amount of archived CZCS data of which only a negligible part has yet been processed. To begin with, the available CZCS scenes from the coastal waters of Europe should be processed. Such an activity would be of interest not only for oceanography but also for meteorology and climatology because it would provide useful quantitative information on aerosol concentration and its dynamics over the ocean areas.

Another item that needs development is the data processing capacity necessary for future ocean color missions. The CZCS history has clearly shown that only those laboratories where an operational atmospheric correction software existed were able to draw full advantage from this experiment. Faster and "automatized" atmospheric correction procedures would be needed in the future; the CZCS archived data could be used as "training samples".

Future applications are existing on which the "ocean color technology" can have high economic impact but the users are not well informed and/or convinced of the operationality that could be achieved in the 1990s. An additional effort in this direction is required.

Finally, since the current state of the art permits to well establish the specifications of a future OCI, as for example proposed by the Ocean Color Working Group (Ref.22), we strongly recommend ESA to embark as soon as possible on such a project.

6. REFERENCES

1. Sturm B 1978, Preliminary results from EURASEP activities, EARSeL 2nd General Assembly, Munich (FRG), 27-28 April 1978.
2. Sturm B, Lundgren B, Maracci G & Mehl W 1978, Some results from the EURASEP OCS experiment in 1977, IUCRM Colloquium, Sidney BC, Canada, 14-21 June 1978.
3. Sturm B 1981, Ocean Color remote sensing and quantitative retrieval of surface chlorophyll in coastal waters using Nimbus CZCS data, in: Oceanography from Space (J F R Go ed.), Plenum Press 1981, pp.267-279.
4. Schlittenhardt P 1986, Adria 84 - data catalog, Commission of the European Communities, SA I.05.E2.85.23.
5. Tassan S, Sturm B & Diana E 1979, A sensitivity analysis for the retrieval of chlorophyll concentration from remotely measured radiances, Proc. 13th Int. Symp. on Remote Sensing of the Environment, Ann Arbor, Mich., USA.
6. Tassan S & Sturm B 1986, An algorithm for the retrieval of sediment content in turbid coastal waters from CZCS data, Int. J. Rem. Sensing, Vol.5, No.3, pp.553-560.
7. Sturm B 1986, Correction of the sensor degradation of the Coastal Zone Color Scanner on Nimbus-7, ESA/EARSeL Symp. on Europe from Space, Lyngby, Denmark, 25-28 June 1986.
8. Gordon H R 1978, Removal of atmospheric effects from satellite imagery of the oceans, Appl. Opt. 17, No.10, pp.1631-1636.
9. Sturm B 1981, The atmospheric correction of remotely sensed data and the quantitative determination of suspended matter in marine water surface layers, in: Remote Sensing in Meteorology, Oceanography and Hydrology (A P Cracknell, ed.), Ellis Horwood Ltd., pp.163-197.
10. Smith R C & Wilson W H 1981, Ship and satellite bio-optical research in the Californian Bight, in: Oceanography from Space (J F R Grower, ed.), Plenum Press, pp.281-294.

11. Clark D K 1981, Phytoplankton pigment algorithms for the Nimbus-7 CZCS, Oceanography from Space, J F R Gower, ed., Plenum Press, New York, pp.227-237.

12. Morel A 1980, In-water and remote measurements of ocean color, Boundary-Layer Meteorology, 18, pp.177-201.

13. Austin R W and Petzold T J 1980, The determination of the diffuse attenuation coefficient of sea water using the Coastal Zone Color Scanner, Oceanography from Space, J.F.R. Grower, ed., Plenum Press, New York, pp.239-256.

14. Gordon H R, Clark D K, Brown J W, Brown O B, Evans R H and Broenkow W W 1983, Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates, Appl. Opt. 22, pp. 20-36.

15. Viollier M and Sturm B 1984, CZCS data analysis in turbid coastal water, J. Geophys. Res. 89, No. D4, pp.4977-4985.

16. Smith R R and Baker K S 1982, Oceanic chlorophyll concentrations as determined by satellite (Nimbus-7 Coastal Zone Color Scanner), Mar. Biology 66, pp.269-279.

17. Brown O G, Evans R H, Gordon H R, Smith R C and Baker K S 1985, Phytoplankton blooming of the US coast: a satellite description, Science 229, pp.163-167.

18. Sturm B 1986, Application of CZCS data to productivity and water quality studies in the northern Adriatic Sea, COSPAR XXVI Plenary Meeting, Toulouse (France), 30 June - 12 July, 1986.

19. Nykjaer L, van Camp L, Schlittenhardt P and Refk R 1986, CZCS images and ocean dynamics - application to the North West African upwelling area, ESA SP-258.

20. Tassan S 1986, Evaluation of the potential of the Thematic Mapper for marine applications, ESA/EARSEL Symp. on Europe from Space, Lyngby, Denmark, June 25-28, 1986.

21. Kneizys F W, Shettle E P, Gallery W O, Chetwin J H Jr, Abreu L H, Selby J E A, Fenn R W and McClatchey R A 1980, Atmospheric transmittance/radiance: computer code LOWTRAN 5, AFGL-TR-80-0067, Air Force Geophysics Laboratory, Bedford, Mass.

CANADIAN ACTIVITIES AND GOALS IN REMOTE SENSING OF OCEAN COLOUR AND FLUORESCENCE FROM SPACE

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ABSTRACT

Uses in Canada of ocean colour remote sensing are described, with examples. These uses include oceanography, fisheries research and management, coastal zone mapping and bathymetry. The importance of this work, and the development of an airborne phytoplankton mapping technique based on solar-stimulated chlorophyll fluorescence, has led to development of an imaging spectrometer (the FLI) as a prototype satellite sensor. Results from this instrument are shown. Examples of airborne hydrography with passive and active sensors are also presented.

Keywords: satellite remote sensing, ocean colour, fluorescence, bathymetry, imaging spectrometry, lidar.

1. INTRODUCTION

Canada has long coastlines on 3 oceans (Atlantic, Pacific and Arctic), and major activities and ship traffic on many rivers (including the St. Lawrence and Mackenzie) and on the Great Lakes. Offshore, coastal and fresh water fisheries play an important economic role, as do new and growing aquaculture industries.

Both airborne and satellite remote sensing techniques have been applied to monitoring environmental conditions relevant to these activities, often over large and inaccessible areas. Mapping of water colour is a relatively new development which has the attraction of directly measuring suspended and dissolved constituents of the water, showing the distribution of phytoplankton and, nearer shore, the distribution of suspended sediment. In shallow water, reflection of light from the sea bottom allows estimates of water depth and bottom type.

Various airborne programs have grown from experience with commercial and experimental sensors, leading to development of imaging scanners in Canada, particularly the multilinear array pushbroom scanner "MEIS", and the CCD-based imaging spectrometer "FLI". On a larger scale CZCS data has been used for chlorophyll mapping in all 3 oceans and in the Great Lakes. The importance of this type of data for fisheries biology and management, has led to a cooperation between Canada and Germany to promote launch of an improved satellite sensor.

2. IOS SPECTROMETER

A program of research in aerial optical remote sensing of the ocean was begun at the Institute of Ocean Sciences, Sidney B.C. on the west coast of Canada in 1974, with the construction of the IOS spectrometer (Refs 1,2). This is a sensitive, compact, multichannel instrument with digital recording, designed for airborne work. It can be used to map phytoplankton by measuring chlorophyll absorption effects at blue wavelengths near 440nm. However, its high sen-

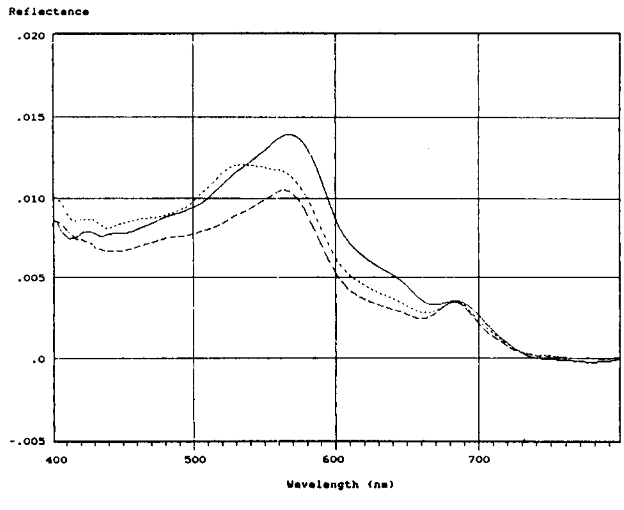

Figure 1 Spectra recorded with the IOS spectrometer in the Baltic Sea (solid line) and on the Canadian west coast, showing the small increases in radiance at 685nm due to chlorophyll fluorescence.

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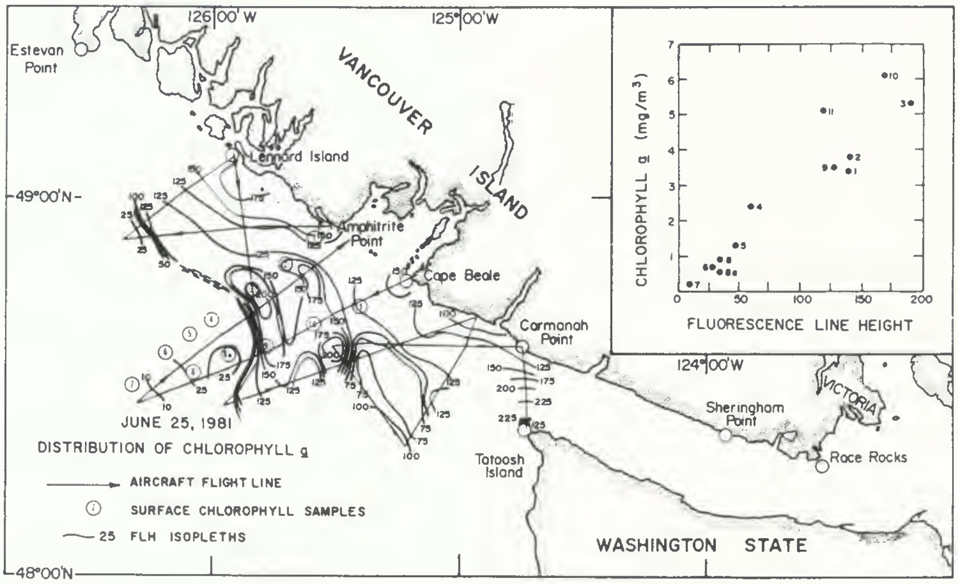

Figure 2. The distribution of near-surface chlorophyll a off the west coast of Vancouver Island, from airborne measurements of naturally stimulated fluorescence. The inset shows a comparison of airborne and ship measurements.

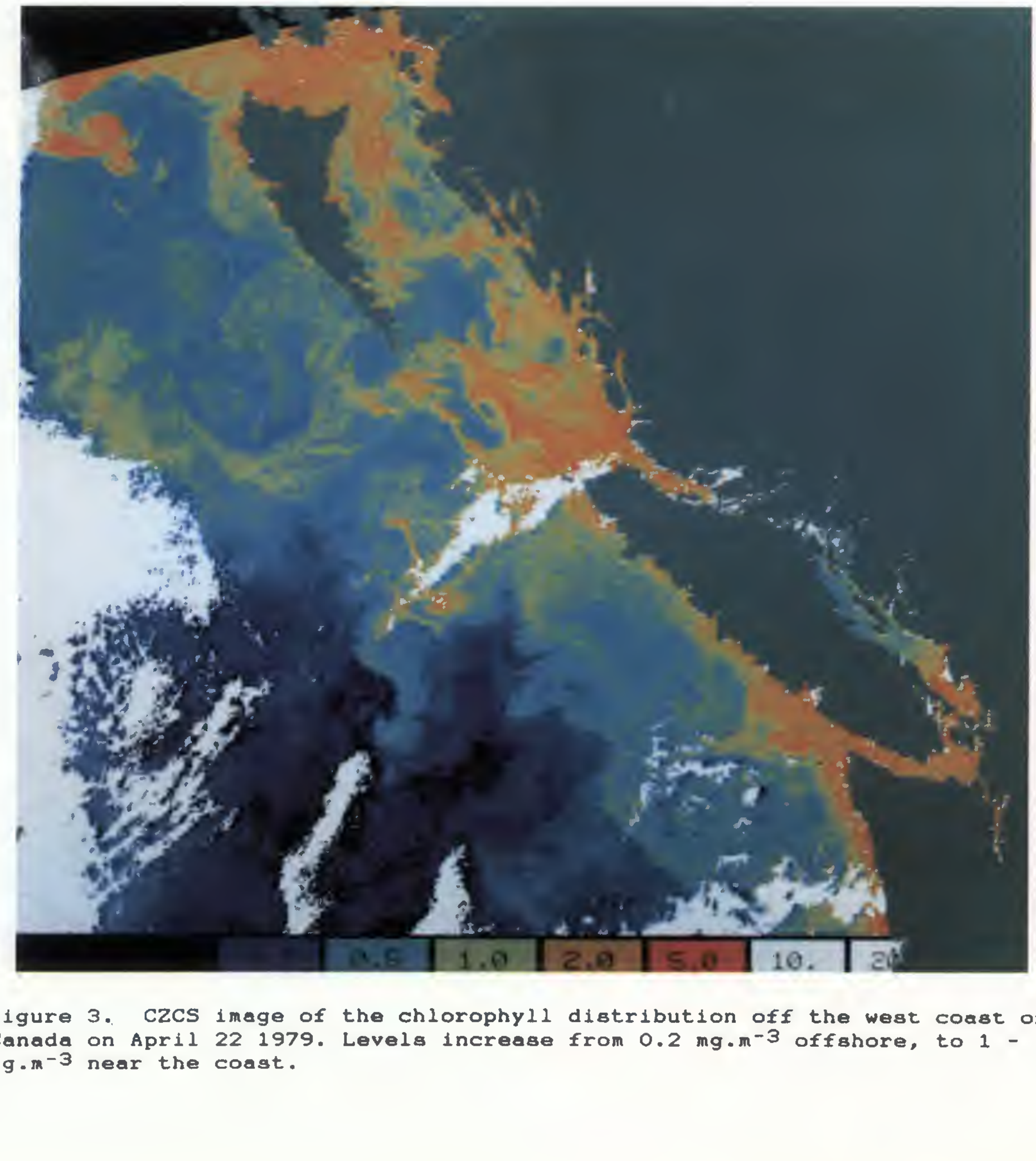

Figure 3. CZCS image of the chlorophyll distribution off the west coast of Canada on April 22 1979. Levels increase from 0.2 $mg.m^{-3}$ offshore, to 1 - 10 $mg.m^{-3}$ near the coast.

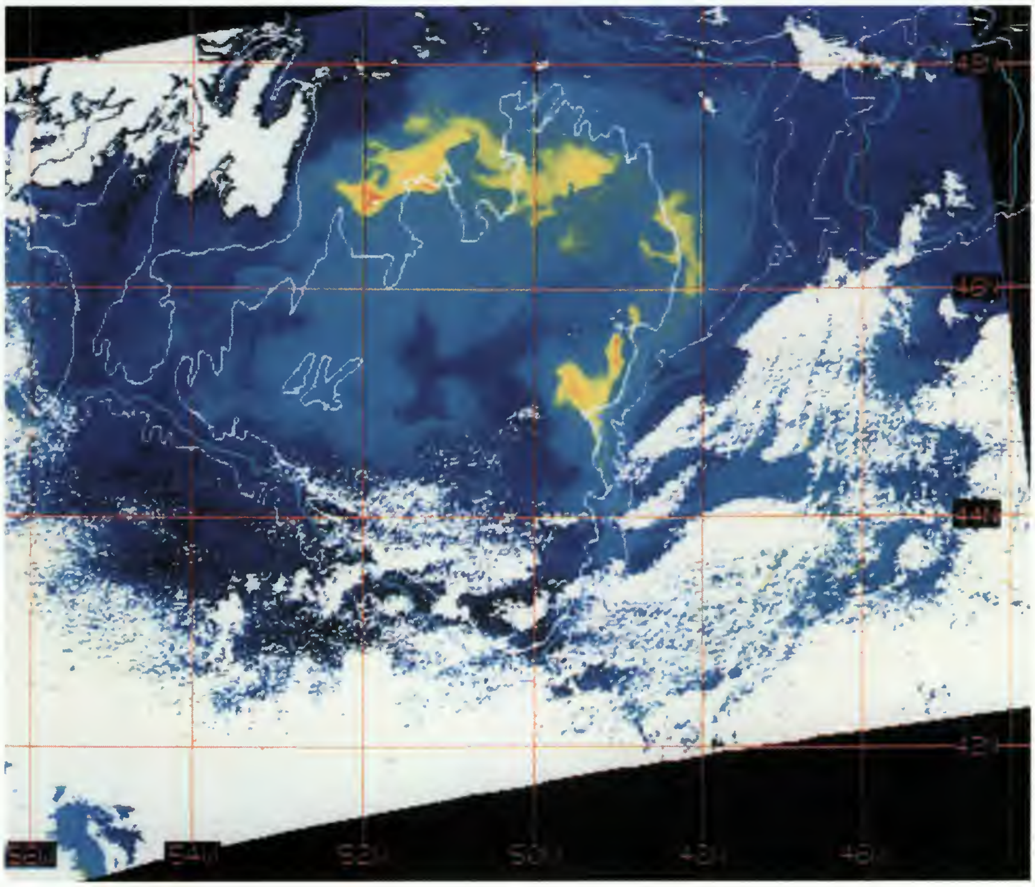

Figure 4. CZCS image of radiance patterns in band 3 (green) off the east coast of Canada on Sept 19 1980, showing coccolithophorid blooms round the Grand Banks of Newfoundland.

sitivity at red wavelengths and its resolution of about 14nm allows detection and mapping of the fluorescence, stimulated by ambient sun- and sky-light, from phytoplankton chlorophyll a at a wavelength of 685nm (Figure 1). Airborne mapping of this signal (Refs 3,4) was found to provide good results even in adverse weather conditions (Figure 2), and led to the proposal for a satellite-borne imaging sensor (see below).

The IOS spectrometer was the main Canadian sensor used in the joint Canada-France experiment CFOX, and the Canada-German experiment FLUREX, and has recently been used in the U.S. and Canadian Arctic for water colour surveys in support of whale habitat studies by Borstad Associates Ltd.

3. CZCS IMAGES

Satellite remote sensing of ocean colour has been carried out using sensors intended for other applications, (Ref 5), but the launch of the Coastal Zone Color Scanner (CZCS), on Nimbus 7 by the U.S. in 1978, demonstrated the value of an instrument designed specifically for this purpose. Figure 3 shows a geometrically rectified image of the chlorophyll distribution along the west coast of Canada on April 22 1979 (Ref 6), near the expected time for the peak of the spring plankton bloom. Concentrations are deduced from chlorophyll absorption effects measured in water-leaving radiances in blue and green light after correction for atmospheric contributions. The image shows the chlorophyll in nutrient-laden water that extends offshore from the continental shelf, and the eddies and jets traced by the surface colour patterns (Ref 7). The absorption method is however, poorly adapted for measuring the higher levels closer to shore.

Figure 4 shows a CZCS green band (3) image of a coccolithophorid bloom around the edge of the Grand Banks off the east coast of Canada on September 19 1980 (Ref 8). Ship sampling showed that coccolithphorids constituted more than 50% of the phytoplankton biomass at this time. The image is part of an atlas produced at IOS in a cooperative program between S. Akenhead (DFO Newfoundland) and Borstad Associates Ltd of Sidney B.C. Similar blooms have been seen in other parts of the North Atlantic. The CZCS detects and maps them, but their calcareous structure causes abnormally high backscatter of light, which interferes with the absorption method used in the CZCS for estimating chlorophyll concentrations.

Images from the CZCS have demonstrated the potential benefits of satellite remote

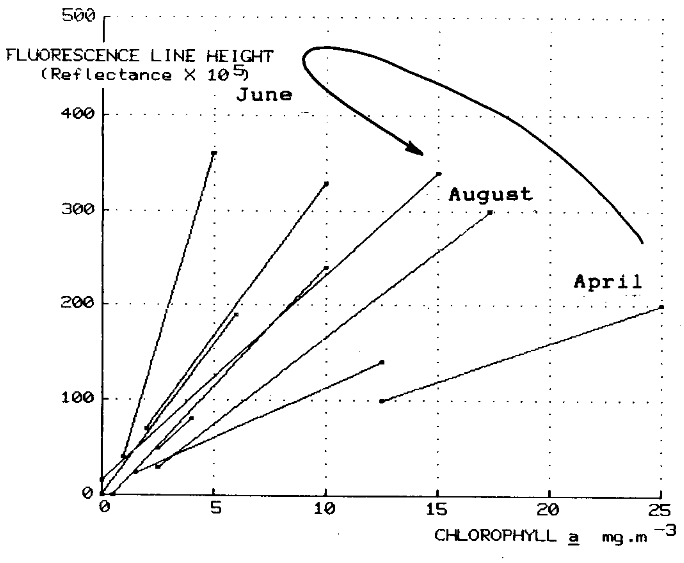

Figure 5. Mean relations between fluorescence and chlorophyll concentration observed on 9 occasions in Canadian and European coastal waters. The slopes vary during the seasonal growth cycle, as indicated by the curved arrow at the top.

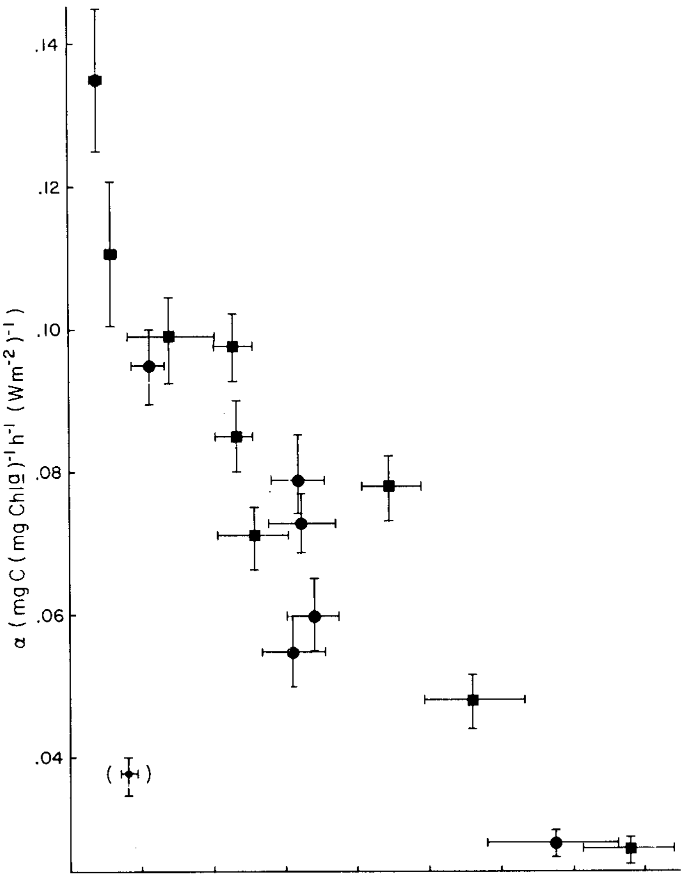

Figure 6 Inverse correlation between photosynthetic and fluorescence efficiencies observed in subsurface observations off the east coast of North America.

sensing to ocean and fisheries studies in Canada. Canada has supported efforts to provide a successor to the CZCS, preferably with improved capability.

4. PASSIVE FLUORESCENCE REMOTE SENSING

Remote sensing of solar stimulated chlorophyll a fluorescence offers a method of improving the accuracy of chlorophyll mapping, and of allowing remote measurement of phytoplankton productivity as well as biomass. The technique uses the emission at 685nm as a more specific indicator of near surface chlorophyll (Refs 9,10), which should allow measurements at higher concentrations, and be less affected by the presence of other confusing materials in the water. Variable fluorescence yield from different phytoplankton species under different conditions, complicates the analysis, but also provides the information on the productivity of the biomass present.

The relation between fluorescence emission and chlorophyll has been studied in a series of remote sensing experiments undertaken at IOS (Ref 11). Linear relations with good correlations are found. The slopes of the relations vary (Figure 5) in a manner that appears related to the seasonal growth cycle.

An inverse correlation between fluorescence yield and productivity has been demonstrated in a series of related experiments undertaken at the Bedford Institute of Oceanography, Dartmouth, N.S. (Figure 6, Ref 12). This confirms the possibility of combining fluorescence and absorption remote sensing measurements to determine the phytoplankton productivity.

5. THE FLI IMAGING SPECTROMETER

The successes of the IOS spectrometer and the CZCS satellite sensor suggest the possibility of imaging chlorophyll fluorescence patterns from space. Following the positive conclusions of studies undertaken by the Canadian Corporation for University Space Science in 1981, a contract was let to Moniteq of Toronto, with Itres Research as subcontractor, to build a 5 CCD camera, imaging spectrometer as an airborne prototype.

This instrument (Ref 13) has 1925 columns of detector elements arranged to form pushbroom images over a swath 70° wide. Each column consists of 288 elements, imaging the same target at a different wavelength so as to give continuous spectral coverage from 430nm to 805nm with a resolution of 2.5nm. This resolution is designed to allow imaging of the fluorescence signal, between the strong atmospheric absorption features due to oxygen and water vapour that occur in the same wavelength region of the spectrum. Data is recorded either as high resolution images in 8 spectral bands whose configuration can be changed under software control (spatial mode), or as low resolution images with full spectral coverage (spectral mode).

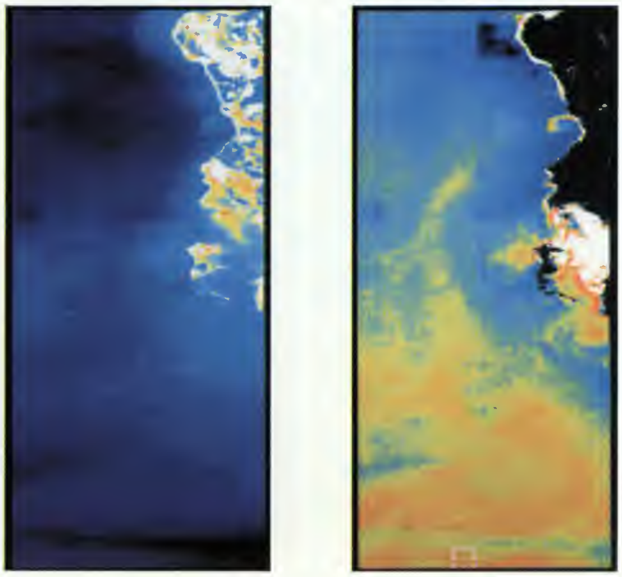

Figure 7 FLI images in Chesapeake Bay on December 14 1984, from 23,000ft altitude. 7a (left) shows the distribution of radiance at 670nm. 7b (right) shows the distribution of chlorophyll fluorescence emission at 684 nm.

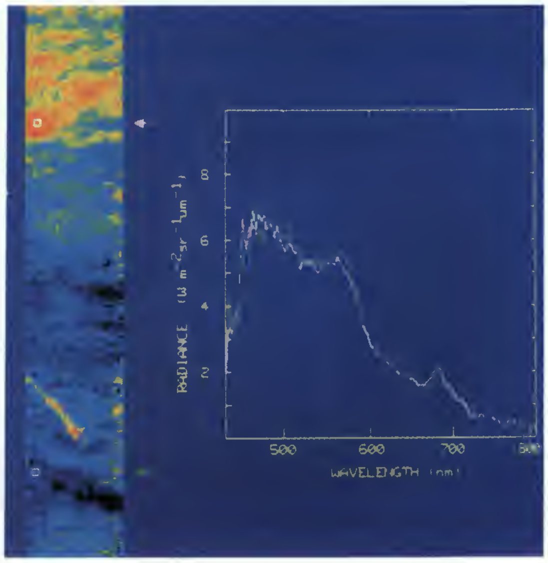

Figure 8 FLI spectral mode data showing a low resolution image of the area round the CSS Hudson on July 31 1985, and spectra at the locations of the white squares, showing different heights of the observed peak at 684nm.

Figure 9. A FLI (spatial mode) image showing the plume of the Humber River as it flows into Lake Ontario in Toronto. This is 1/5 of the width of a full scene.

Figures 7 and 8 demonstrate the imaging of chlorophyll fluorescence patterns with the FLI. Figure 7a shows a spatial mode image of water colour patterns in Chesapeake Bay, in December 1984, in a narrow spectral band near 670nm. These patterns are largely a result of increased back-scatter caused by suspended inorganic material. Figure 7b shows the image formed from the excess radiance at 684nm above a weighted average of the radiance at 670nm (Figure 7a), and the radiance at 711nm. This excess is due to naturally stimulated fluorescence from chlorophyll a.

Figure 8 shows the spectral form of this excess, using the spectral mode of the FLI. The low resolution image strip on the left has the same spectral properties as Figure 7b, and shows the distribution of the fluorescence signal. The wake of the Canadian Survey Ship Hudson crosses the image diagonally near the bottom. The two spectra shown on the right, correspond to the positions on the image indicated by white squares, having high (pink), and low (green) fluorescence. The spectra are very similar at other wavelengths.

Figure 9 demonstrates the imaging capability of the FLI, showing the output from a single camera, out of the 5 that cover a full swath. The image shows suspended sediment patterns at the mouth of the Humber River in Lake Ontario, near Toronto.

The FLI is currently being operated commercially by Moniteq Ltd. Data is still being evaluated from the various flight missions. A proposal to build a satellite instrument based on the FLI design and experience, is the subject of discussions between Canada and Germany, within the framework of ESA.

6. AERIAL HYDROGRAPHY AND BENTHIC VEGETATION MAPPING

The additional radiance component observed by an optical sensor from bottom reflectance in shallow water gives information on both the bottom type or vegetation cover, and the water depth.

FLI imagery has been evaluated by Mouchot and Sharp (Ref 14) for benthic vegetation mapping in shallow water, using spectral bands selected specifically for the water properties expected. In Figure 10, the different vegetation boundaries round St. John's Ledge, Nova Scotia, Canada have been colour coded. The FLI accurately described the outer limit of kelp distribution at a depth of about 10m, with depth penetration superior to aerial photos, thus allowing recognition of 60% more area covered by kelp.

Moniteq Ltd has carried out many experiments on water depth mapping from airborne imagery. Figure 11 shows an image from the FLI sensor taken over the Bruce Peninsular in Lake Huron (Ref 15). The image has been corrected to a geographical grid using position and attitude information from an inertial navigation unit. Depths (superposed

Figure 10. A small area (800m across) of a colour coded map of benthic vegetation types round St John's Ledge, off the south-east coast of Nova Scotia in July 1985. Black, exposed intertidal zone; pink, Chondrus Crispus; red, mixed; blue, kelp.

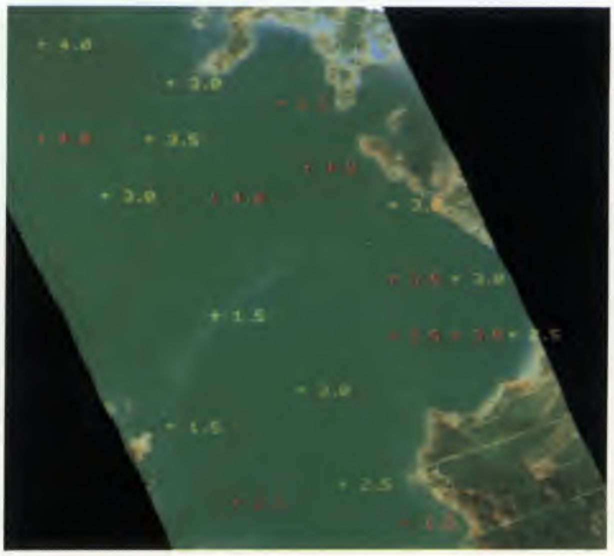

Figure 11 A bathymetry image deduced from FLI spatial mode data of a shallow water area near the Bruce Peninsular in Lake Huron.

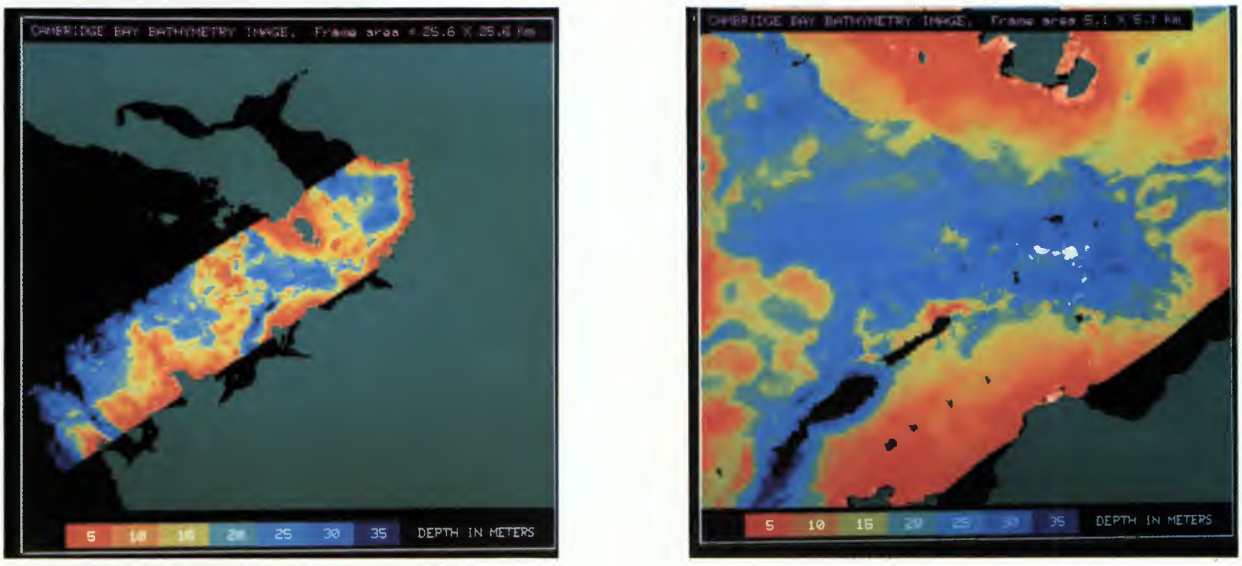

Figure 12. Images of colour-coded depth output from the LARSEN lidar aerial hydrography mapping system, August 1985, Cambridge Bay, NWT, Canada. (Left) The survey area, covered by 20 parallel flight swaths. (Right) The central 5Km square of the survey, enlarged.

numbers, here displayed only at selected positions) are estimated by fitting model spectra computed for 0.5 meter depth increments, with different bottom types, to the measured radiances.

7. LARSEN AERIAL BATHYMETRIC LIDAR

Although lidar bathymetry uses active optics in a system that is at present limited to airborne operation, it is included here as an example of a related and rapidly developing technology. Lidar systems can suppress the effects of the atmosphere, and give depth-resolved information in the water to greater depths than passive measurements can penetrate. Charting of shallow waters has considerable economic benefits, and is one of the first of many potential lidar applications to be developed.

An airborne lidar bathymeter "Larsen 500" was developed for the Canadian Hydrographic Service by Optech Ltd of Toronto in 1984 (Ref 16). The system is based on a two frequency lidar giving range information to the water surface at 1060nm wavelength, and to the bottom, up to about 30m deep, at 530nm. It is designed to be flown at 500m altitude scanning over a swath 265m wide. An operational trial of the Larsen was carried out in the Canadian Arctic in the summer of 1985 by Terra Surveys Ltd. Colour coded depth images from this data are shown in Figure 12.

8. CONCLUSIONS

Water colour remote sensing has been applied in a variety of studies in Canada. The success of the results has led to development of specialized sensors designed to improve the techniques further.

Plans for a cooperative program within ESA are being formulated for an advanced satellite instrument.

9. REFERENCES

1. Walker, G.A.H., V.L. Buchholz, D.Camp, B. Isherwood, J. Glaspey, R. Coutts, A. Condal, and J.F.R. Gower, 1974, "A compact multichannel spectrometer for field use", Rev. Sci. Instrum., 45, 1349-1352.

2. Walker, G.A.H., V.L. Buchholz, D.Camp, B. Isherwood and J.F.R. Gower, 1974, "A silicon diode array spectrometer for ocean colour monitoring", Canadian Journal of Remote Sensing, 1, 26-30.

3. Borstad, G.A., and J.F.R. Gower, 1984, "Phytoplankton chlorophyll distribution in the eastern Canadian Arctic", Arctic, 37, 224-233

4. Borstad, G.A., R.M. Brown and J.F.R. Gower, 1981, "Airborne remote sensing of sea surface chlorophyll and temperature along the outer British Columbia coast", Proceedings of the 6th Canadian Symposium on Remote Sensing, Halifax, N.S. pp 541-547.

5. Gower, J.F.R., K.L. Denman and R.J. Holyer, 1980, "Phytoplankton patchiness indicates the fluctuation spectrum of mesoscale ocean structure", Nature, 288, 157-159.

6. Pan, D., J.F.R. Gower and G.A. Borstad, "Seasonal variation of the surface chlorophyll distribution along the B.C. coast as shown by CZCS imagery", in preparation.

7. Thomson, R.E. and J.F.R. Gower, 1985, "A wind-induced mesoscale eddy over the Vancouver Island continental slope", J. Geophys. Res., 90, 8981-8993.

8. Borstad Associates Ltd., 1986, "An atlas of 1980 CZCS imagery of the Grand Banks, Newfoundland", Contract Report to DFO (Newfoundland).

9. Neville, R.A., and J.F.R Gower, 1977, "Passive remote sensing of phytoplankton via chlorophyll a fluorescence", J. Geophys. Res. 82, 3487-3493.

10. Gower, J.F.R., S. Lin and G.A. Borstad, 1984, "The information content of different spectral ranges for remote chlorophyll estimation in coastal waters", Int. J. Remote Sensing, 5, 349-364.

11. Gower, J.F.R. and G.A. Borstad, 1986, "Remote sensing of ocean chlorophyll fluorescence", Canada-Germany workshop on imaging spectrometry, Ottawa, Oct 14-16.

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

13. Borstad, G.A., H.R. Edel, J.F.R. Gower, and A.B. Hollinger, 1985, "Analysis of test and flight data from the Fluorescence Line Imager", Canadian Special Publication of Fisheries and Aquatic Sciences, 83, 38pp.

14. Mouchot, M.C., Sharp, G and E. Lambert, 1986,"Thematic cartography of submerged marine plants using the Fluorescence Line Imager", Canada-Germany workshop on imaging spectrometry, Ottawa, Oct 14-16.

15. O'Neill, N.T., A.R. Kalinauskas, J.D. Dunlop, A.B. Hollinger, H.Edel, M.Casey, J.Gibson, 1986, "Bathymetric analysis of geometrically corrected imagery data collected using a two dimensional imager", Proceedings of the Society of Photo-Optical Instrumentation Engineers.

16. Casey, M.J., 1984, "Deploying the lidar on hydrographic surveys", Proceedings of the 9th Canadian Symposium on Remote Sensing, Canadian Aeronautics and Space Institute, 165-175.

RESEARCH IN SWITZERLAND ON OCEAN AND INLAND-WATER COLOUR MONITORING

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ABSTRACT

Present research activities undertaken in Switzerland in the field of water colour monitoring are briefly reviewed. Future projects will focus on the development of algorithms adressing the complexity of inland waters.

Keywords: Remote sensing, water colour, inland waters, limnology, TM, CZCS, Switzerland.

1. INTRODUCTION

Being a landlocked country, Switzerland has, so far, contributed relatively little to oceanographic research. It has, however, a rich tradition in limnology of small and large lakes. Much data has been, and still is, collected on these water bodies, thus producing a rich corpus of ground-truth information, which could be used in conjunction with satellite measurements.

Research along these lines has recently started in some Swiss academic institutions. It is focused on lake and estuarine water optical properties and their relationship to environmental parameters, and is based on MSS, TM and CZCS data.

2. PRESENT FIELDS OF RESEARCH

2.1. Optical measurements in lake water

The optical properties of lake Geneva (Léman) waters have been studied originally by transmissometry and nephelometry (Ref. 1) coordinated with Suspended Solid Concentration measurements (Ref. 2). More recently, Balvay et al. (Ref. 3, p. 284) have correlated Secchi depth (Y) to chlorophyll concentration (X) by means of the relationship $Y = 13.1\ X^{-0.42}$ with $r = -0.84$. Work is in progress by GTA (see Appendix) on the relationships between underwater spectral irradiance, PAR, chlorophyll and mineral suspensoid concentration, Secchi depth and spectral reflectance above water (Ref. 4).

Similar investigations have been conducted in lake Zürich by Schanz (Ref. 5-6), which show the light spectra patterns to be typical for water low in Gelbstoffe. On the other hand, the vertical attenuation coefficient (PAR) is mostly influenced by chlorophyll a, although inorganic suspensoids may be of importance during periods of low productivity.

In Lac de Neuchâtel, characterized by abundant $CaCO_3$ precipitation, Bapst and Kübler (Ref. 7) have undertaken extensive turbidity measurements using a scatterance meter (2-5° forward scattering, Ref. 8).

With the exception of Ref. 4, these optical measurements were not conducted in coordination with satellite overpasses. Their use in calibrating retrieval algorithms is therefore limited, and more work of a co-ordinated nature is planned in the future.

2.2. Water colour monitoring of large subalpine lakes

Based on historical Landsat MSS data and in situ measurements co-ordinated with TM overpasses, this program strives to establish usable correlations between satellite-sensed water color and water quality (mineral and organic turbidity, chlorophyll, Gelbstoff, surface films, submerged vegetation). Lake Geneva (Léman) has been chosen as a "training area", and the study is planned to include other lakes of different trophic state (Lac de Neuchâtel, de Morat, d'Annecy et du Bourget).

To date, special emphasis has been put on sewage plume identification and bottom sediment, and vegetation classification (fig. 1 and Ref. 4).

On a broader scale, water masses can be identified on the basis of their colour or turbidity, leading to a trophic classification, such as shown on fig. 2: lac du Bourget water is of type 1 or 2, corresponding to the eutrophic state of this water body. Water of lower reflectance (type 3, meso-oligotrophic) is visible in Lac d'Annecy and Léman).

2.3. Water quality evaluation for aquaculture development

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

The Fishery Resources and Environment Division of FAO is currently engaged in a programme of aquaculture site selection (Ref. 9). Within this framework, a water quality evaluation of Golfo de Nicoya (Costa Rica) has been conducted in collaboration with UNEP/GRID.

Based on Landsat TM and ground-truth data, water masses have been classified in this estuary (fig. 3), and turbidity evaluated by chromaticity analysis (Ref. 10): fig. 4 shows the turbidity gradient in the upper reaches of the Golfo (Ref. 11).

2.4. Trophic state of East African lakes

A feasibility study on remote sensing of trophic state of large lakes in East Africa has been undertaken in collaboration with GEMS (UNEP, WHO, etc.). Preliminary work done on CZCS imagery of Lake Malawi indicates well-developped color patterns. Deciphering of these patterns will depend on the availability and quality of ground-truth data, which is at present being gathered.

3. FUTURE ACTIVITIES

Swiss lakes show a variety of trophic levels, they are rather well studied and also easily accessible. As such, they represent an ideal training material for inland water colour studies, both in situ and from the air.

It is planned, therefore, to develop research in Switzerland along the following axes:

1. Full exploitation of MSS, TM and CZCS archives, as agreed upon at this workshop. This implies an "a posteriori calibration" of the images based on whatever ground data available. Two geographic areas are considered: Switzerland (subalpine lakes) and Africa (lakes of the Rift Valley).

2. Development of algorithms to relate inland-water colour, as seen by satellite, to the following water or sediment descriptors: mineral turbidity (autochtonous $CaCO_3$, allochtonous detritus), organic turbidity (chlorophyll, seston, sewage), Gelbstoffe, bottom-type and underwater vegetation. All this information will be synthesized as trophic indexes. For the time being, ground-truthing campaigns are planned in connection with Landsat TM overpasses and are restricted to large subalpine lakes.

3. Investigations into the application of other methods to inland water colour studies: airborne, SPOT, future sensors.

4. Promote international contacts and collaboration between practicioners of Remote sensing applied to inland waters (Ref. 12-13).

4. APPENDIX

The Groupe de Télédétection Aquatique (GTA) gathers scientists from University of Geneva (Earth Science and Aquatic Biology), Federal Institute of Technology (Lausanne), Institut de Limnologie (University Paris VI) and UNEP/GRID (Geneva).

5. REFERENCES

1. Jaquet J M 1977, Etude hydrologique du Léman: les sédiments en suspension. Final report, SNF Grant 2.606-0.76, Institut Forel, Univ. Geneva.
2. Jaquet J M et al 1983, Premières données sur la matière en suspension dans le Léman. Publ. Institut Forel, Univ. Geneva, 83 p.
3. Balvay G et al 1984, Plancton. In "Le Léman, synthèse 1957-1982", CIPEL publ., Lausanne, Switzerland, 650 p.
4. Jaquet J M, Pelletier J & Orand A 1987, Caractéristiques bio-optiques de l'eau du Léman, in preparation.
5. Schanz F 1985, Vertical light attenuation and phytoplankton development in Lake Zürich, Limnol. Oceanogr., 30(2), 299-310.
6. Schanz F 1986, Depth distribution of phytoplankton and associated spectral changes in downward irradiance in Lake Zürich (1980/81), Hydrobiologia, 134, 183-192.
7. Bapst A and Kübler B 1987, Evolution estivale de la turbidité dans le lac de Neuchâtel, Swiss Jour. Hydrol, 49(1).
8. Nyffeler F and Godet C H 1986, The structural parameters of the benthic nepheloid layer in the northeast Atlantic, Deep-Sea Res., 33(2), 195-207.
9. Kapetsky J M 1987, A Geographic Information System to plan for aquaculture development in the Gulf of Nicoya, Costa Rica: a FAO Fisheries/UNEP-GRID cooperative activity. To be published in FAO Fisheries Technical Papers.
10. Munday J C et al 1979, Bay of Fundy verification of a system for multidate Landsat measurement of suspended sediment, Satellite Hydrology, Am. Wat. Res. Ass., 622-640.
11. Jaquet J M 1986, Remote-sensing evaluation of water quality in Golfo de Nicoya (Costa Rica). Report for FAO+UNEP/GRID Aquaculture Site Selection, GTA, Univ. Geneva, 32 p.
12. McGarrigle M L & Reardon B C 1986, National survey of lakes by remote sensing. Preliminary rept., WR/L13, An Foras Forbartha, Dublin, 31 p.
13. Lillesand T M et al 1983, Use of Landsat data to predict the trophic status of Minnesota lakes, Phot. Eng. Rem. Sens., 49, 219-229.

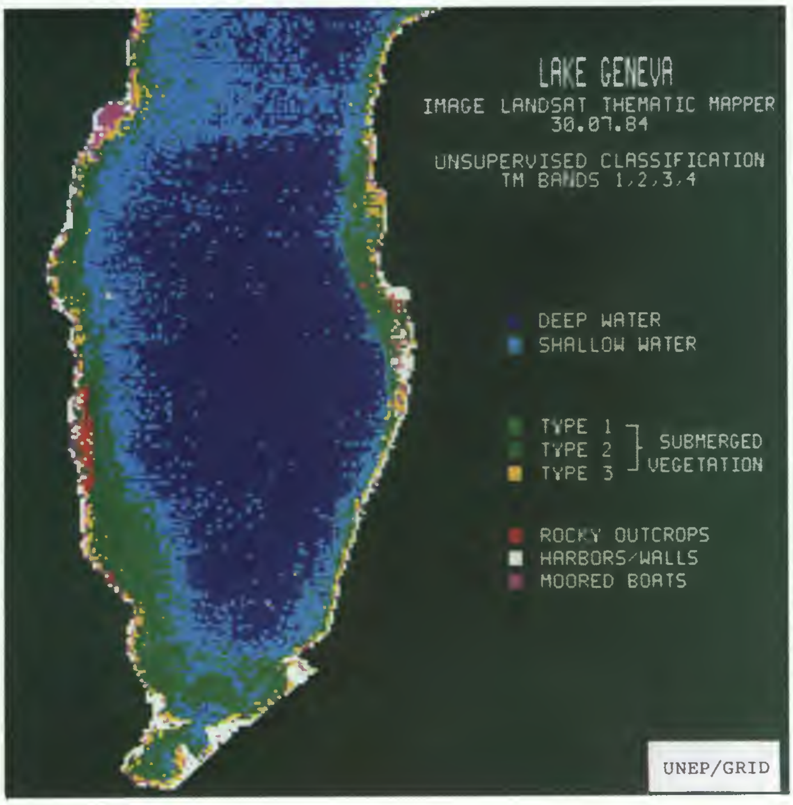

Figure 1. Unsupervised classification of southern part of Lake Geneva showing water and bottom types based on TM 1-4 bands (false colours). City of Geneva is at southernmost tip of lake.

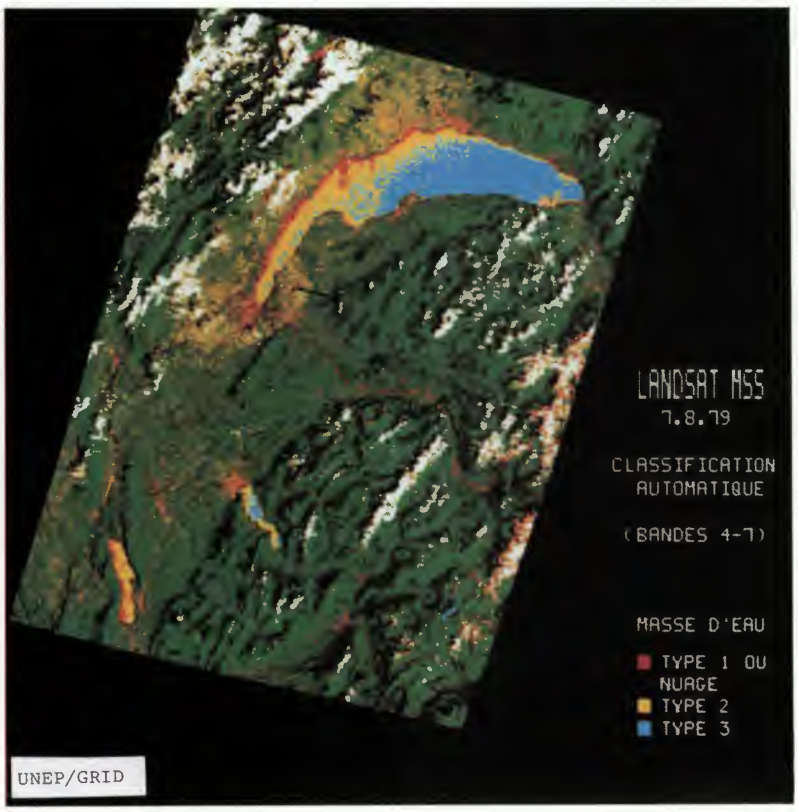

Figure 2. Unsupervised classification of Geneva area (Switzerland and France), showing water mass types based on MSS 4-7 bands (false colours). Turbidity decreases from red to blue.

Figure 3. Unsupervised classification of Golfo de Nicoya (Costa Rica) area Date: 15.04.1985. Water classes are numbered 47 to 59 (false colours). Blue and green: ocean water; yellow: turbid; purple: submerged mud flats; red: very turbid or haze. For detailed interpretation, see Ref. 11.

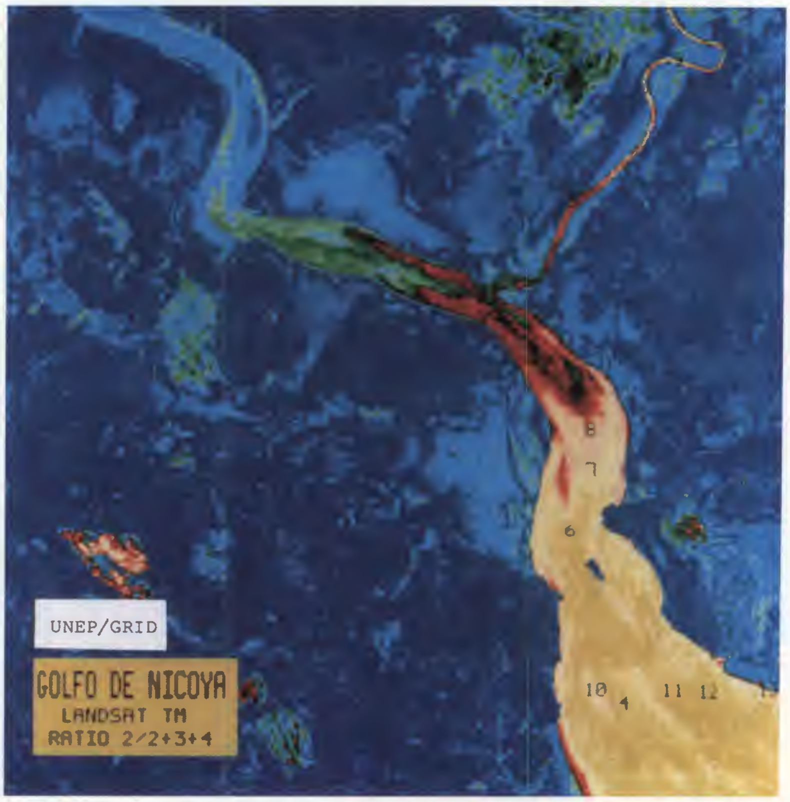

Figure 4. Chromaticity component X (ratio TM bands 2/2+3+4) variations in Upper Golfo de Nicoya (false colours). Blue X $\simeq$. 30; red X $\simeq$. 35; beige X $\simeq$. 45. Turbidity decreases from blue to beige (see Ref. 11, fig. 7).

FEDERAL REPUBLIC OF GERMANY'S INTERESTS, ACTIVITIES AND GOALS IN REMOTE SENSING OF OCEAN COLOUR/FLUORESCENCE FROM SPACE

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ABSTRACT

The interests, activities and goals of the FRG in the remote sensing of ocean color/fluorescence are outlined and discussed. Emphasis is placed on the ongoing scientific research and technical developments concerning natural fluorescence in context with an Advanced Ocean Color Monitor as payload element on the polar platforms of the Columbus programme.

Keywords: Remote Sensing, Ocean Color, Ocean Color Monitor, Chlorophyll, Fluorescence

1. OCEAN COLOR RELATED RESEARCH

1.1 History

Activities in context with optical oceanography and remote sensing of ocean color in the FRG date back till 1976. Based on laboratory and ship investigations, they started first at near-shore research institutes, but spread soon to other organizations, especially in context with atmospheric modelling, aircraft monitoring (Fig. 1) and digital data processing. Joint experiments, first on a national, later on international level (e.g., FMP, FLEX, MARSEN, OSTA-1/OCE, FLUREX) supported strongly the formation of an active user community within the FRG and Europe (Ref. 1, 2,7,8,9,11,14).
Government-funded agencies as for instance the GKSS Research Centre in Geesthacht and the DFVLR Research Centre in Oberpfaffenhofen became directly involved in these activities with their respective technical and research facilities. Within the FRG both Organizations have nowadays become a nucleus for ocean color/fluorescence work and relevant future planning.

Figure 1. Combined aircraft (DFVLR: DO 28) and ship (IfM Kiel: R/V Alkor) operations during the experiment FLUREX 82 in the Baltic Sea

1.2 Present Activities

1.2.1 Science. As a result of the shipborne, airborne and spaceborne data analysis in the past, the request for improved mapping of water constituents in coastal zones lead to the present emphasis of investigating the natural fluorescence (Fig. 2) as an alternative to the "classical" absorption method (Ref. 10). This essentially takes place within the so-called FLUREX-Group, this is a group of scientists, which first began to conduct relevant investigations jointly during the FLUREX Experiment in 1982 (Fig. 3). It also includes investigations with airborne laser systems. Furthermore, the modelling of the radiative transfer in the water and in the atmosphere has become an essential part of present investigations (Ref. 7,8).

1.2.2 Technological developments. Technical developments during the past concentrated on shipborne radiometers on the one hand, and airborne radiometers and multispectral scanners on the other hand. The latter were basically of the mechanically scanning types (Fig. 4).

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

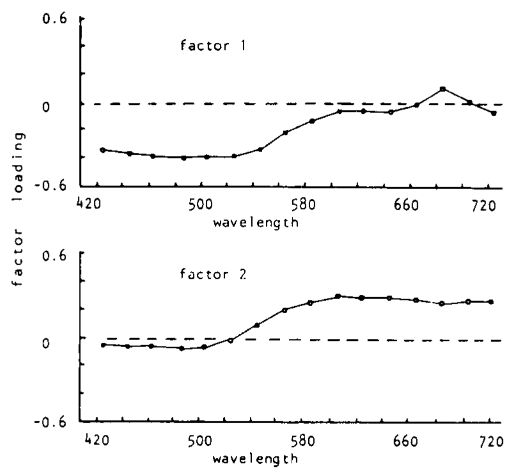

Figure 2. Application of a factor analysis to radiance spectra from a radiometer (GKSS). After an eigenvalue analysis the graphs show 2 extracted factors and their correlation with the 16 spectral channels. The upper graph indicates the presence of phytoplankton, while the lower graph indicates the presence of suspended matter in general (increasing correlation towards the red part of the spectrum).

The present development of airborne sensors concentrates on the implementation of pushbroom-type detectors into the sensor system (Ref. 3-6). After the successful conduct of a (BMFT-sponsored) study (Ref. 4) of a spaceborne color/fluorescence scanner based on an imaging spectrometer with a matrix CCD detector (Fig. 5), the research organizations GKSS, DFVLR and the company MBB/ERNO started with the joint development of an aircraft prototype which will permit not only a thorough test of the feasibility of the instrument concept for water color/fluorescence monitoring, but also will open new applications (including land and atmosphere) because of the narrow spectral bands and the programmable channel selection foreseen.

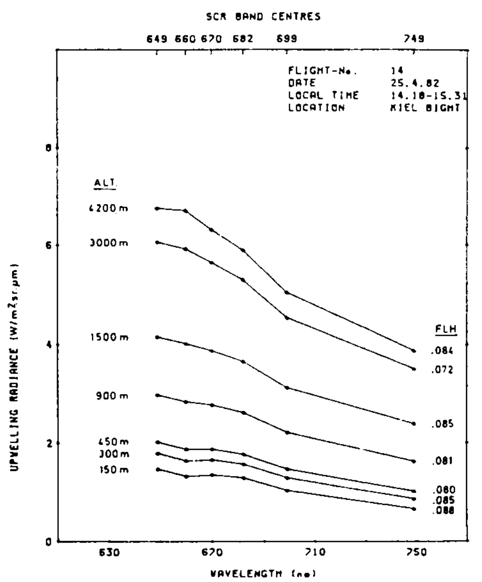

Figure 3. Upwelling radiance spectra at different altitudes collected by the SCR (DFVLR) during the experiment FLUREX 82 above the Kiel Bight. The spectra indicate a weak fluorescence peak around 685 nm (Ref. 10)

Furthermore, DFVLR operates and applies a high resolution spectrometer incorporating a linear CCD-type detector array for wavelength scans (Fig. 6). Sofar this instrument has been used on ships, however, it is planned to incorporate it together with the ROSIS prototype into a DFVLR aircraft.

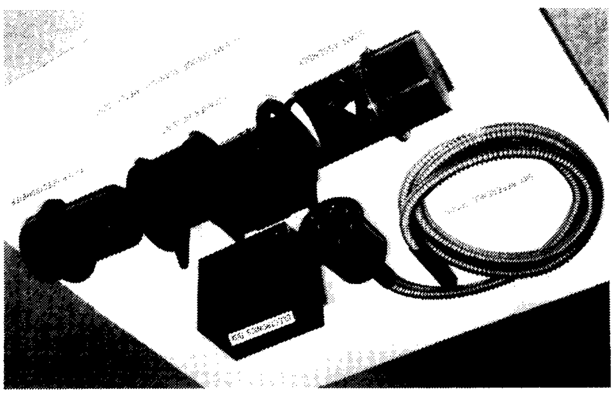

Figure 4. Ocean Color Radiometer (OCR) developed at DFVLR for airborne water color/fluorescence investigations

1.3 Application Programmes

The basic research and technological developments and the verification of new interpretation methods by means of sea truth, have been combined with more application-oriented tasks and projects supported by different sections of the government. Typical examples are:

- o Investigations of frontal systems in the North Sea
- o Baltic Sea monitoring programme (Fig. 7)
- o Eutriphication of rivers, lakes and estuaries
- o Warm water eddies in the North Atlantic
- o Climatology-related processes in the atmosphere, hydrosphere and cryosphere
- o Elbe monitoring programme (Fig. 8)
- o Adria monitoring programme
- o EUREKA/EUROMAR.

This indicates that the remote sensing activities in the FRG are a combination of scientific research, technological developments and applications.

1.4 Scientific and User Communities

From the described situation it is evident that the user communities in the FRG, as in other countries, is rather complex and basically consists of:

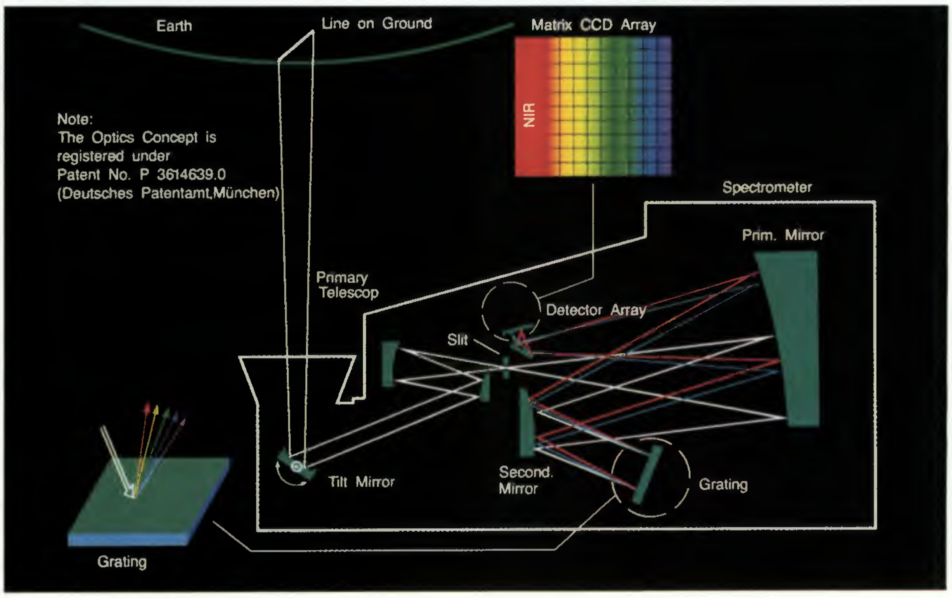

Figure 5. Operation principle of the Reflective Optics System Imaging Spectrometer (ROSIS), which is a potential contribution to ESA's Advanced Ocean Color Monitor (Refs. 3-6)

- o Scientific users. These are at universities, other research institutes and government-funded agencies. They are mainly involved in modelling and in the development, test and verification of water color/fluorescence methods and processing algorithms.
- o Applied science users. These are also at universities, other research institutes and government-funded agencies, but are involved in research programmes which need the derived products (e.g., chlorophyll maps, sediment sinks, carbon fixation numbers etc.) as an input to their investigations.
- o Users. These are mainly federal and provincial government ministries, public services and commercial enterprises which need a processed end product on an operational base.

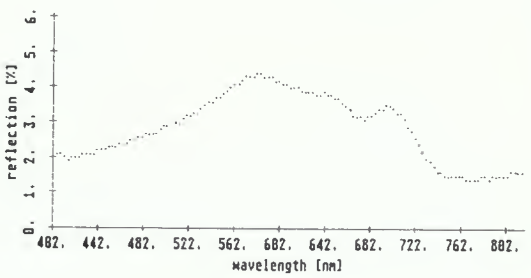

Figure 6. Reflectance spectrum collected by the High Resolution Spectrometer (DFVLR) above mixed water of the Elbe river plume. The spectrum shows clearly a fluorescence peak near 685 nm.

2. GOVERNMENT ACTIVITIES

2.1 General

The German Government supports oceanographic research and associated remote sensing activities on different levels and through different programmes (see also section 1.3).

The responsibility of the Ministry for Research and Technology (BMFT) lies in general in the pre-operational support of scientific research and technological developments on national and (bilateral) international levels, in the support of government-funded agencies (e.g., DFVLR, GKSS, AWI) and in the support of ESA programmes as one of the member countries. The German Research Foundation (DFG) sponsors special sectors of interdisciplinary research at universities mainly in the field of basic research.

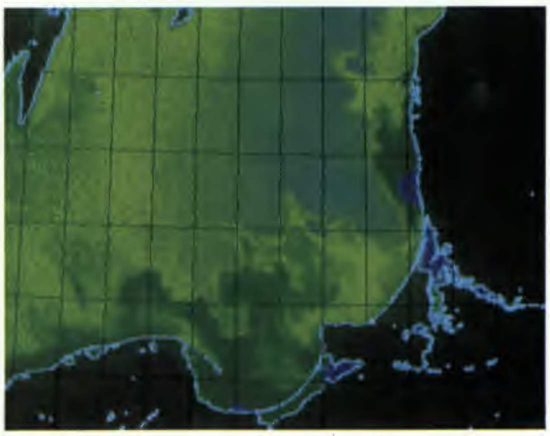

Figure 7. Distribution of pigments/suspended matter in the Danzig Bight (Baltic Sea) as derived by processing Nimbus-7/CZCS data (green=high, yellow=medium, blue=low concentration) (Ref. 11)

Contrary, the operational use and practical application of remote sensing involves partially other ministries and public services with special tasks, as e.g., environmental monitoring, pollution control, fish stock estimates, dumping etc.), but also commercial enterprises.

2.2 User Requirements

The user requirements in regard to a spaceborne ocean color/fluorescence monitoring system can be summarized as follows:

2.2.1 Short-term requirements. There is a strong interest to continue the global data collection as has been obtained from the Nimbus-7/CZCS for a period of 8 years. The emphasis here lies on large and medium scale monitoring.

Further, there is a growing interest to provide an advanced research tool for both, new sciences and new technologies, in particular for investigations of the potential of sun-stimulated fluorescence for the mapping of natural and man-made water constituents. The emphasis here lies on medium and small scale monitoring, in particular of coastal zones.

2.2.2 Long-term requirements. Long-term interests require an operational system which is suitable to respond to the user requirements on all scales, in open ocean areas and coastal zones, especially for the monitoring of biomass, pollution and climatology-related topics like e.g., carbon fixation throgh photosynthesis.

2.3 Potential of German Industry.

Based on the technological facilities and many years of experience in space activities, German industry has a high potential in participating in any ocean color/fluorescence space project. In context with this topic and in accordance with the EOPP procurement plan (Ref. 13), this applies especially to the fiels of

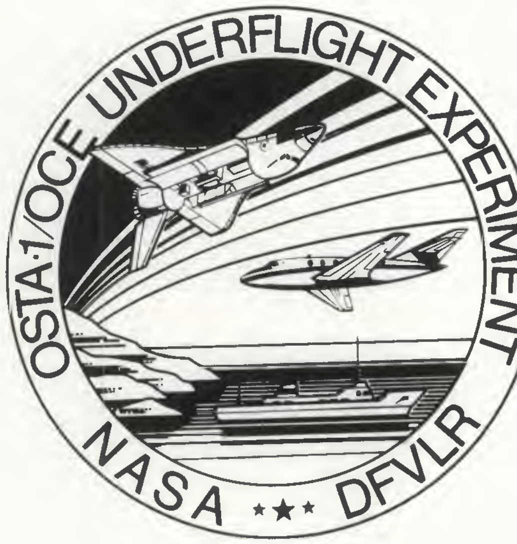

Figure 9. Participation in NASA's Ocean Color Experiment (OCE) on the OSTA-1 mission of the Space Shuttle in 1981 (Ref. 14)

- o optical instrument development
- o mechanical structures
- o electrical and data handling
- o ground segments.

German industry in many cases is supported by research institutes and by government-funded agencies in the fields of

- o modelling
- o laboratory and aircraft tests of detectors and sensors
- o measurement campaigns including ground truth
- o data processing in general
- o verification of methods and algorithms.

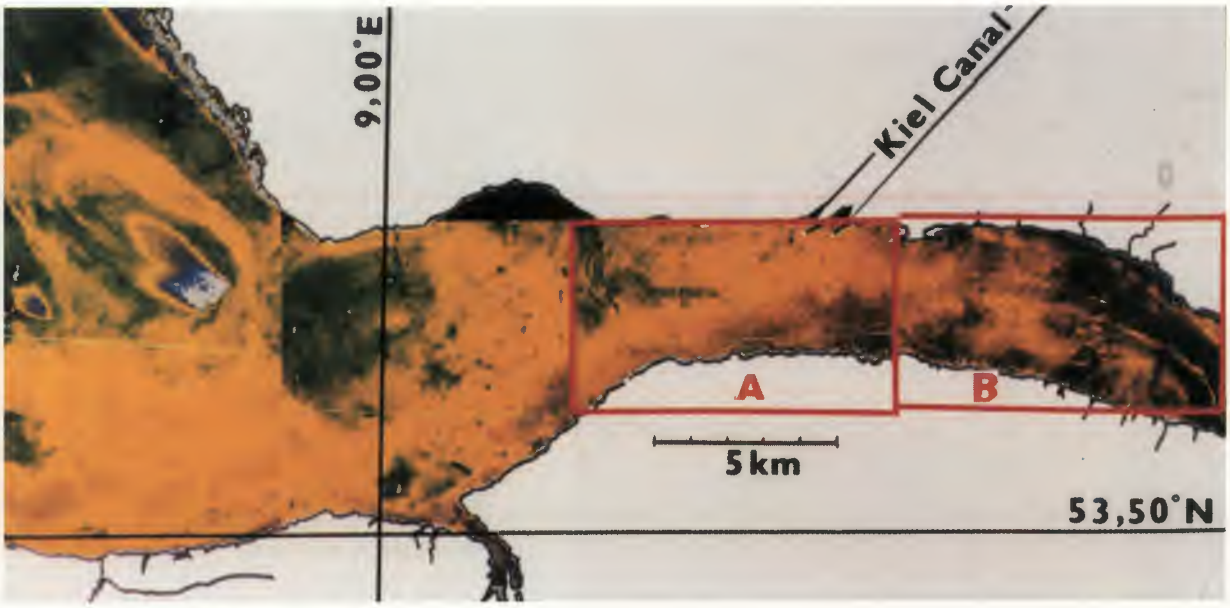

Figure 8. Fluorescence image of the Elbe river derived by processing airborne Ocean Color Scanner (OCS) data. In the image different flight tracks have been merged. Fluorescence intensity is indicated as green (high signal), yellow (medium signal) and blue (weak signal).

Besides this general experience, specific experience has been developed during the past from the handling of many studies and projects like e. g., MOMS, AOCM, ROSIS and others.

In view of the ongoing activities and the abovementioned potential, the various organizations have a strong foothold in this field and are interested to participate further in related ESA activities.

2.4 Participation in the Earth Observation Program

Besides the various national activities (compare section 1), the German participation in future spaceborne ocean color/fluorescence sensor systems is essentially based on the ESA Earth Observation Program (EOP). The objectives of this program which is also supported by the BMFT are to

- o prepare operational systems in polar orbits tailored to the needs of ocean, ice coastal zones and meteorological applications,
- o provide research tools for scientific and user communities,
- o prepare potential future missions by advanced systems and instrument studies and by dedicated instrument developments.

The program elements of the EOP include ERS-I/II (1990-1995) and the polar platform missions.

As part of the EOP the FRG and other member countries signed recently the Earth Observation Preparatory Program (EOPP). One key element in the EOPP is the preparation of an Advanced Ocean/Ice Mission which could make use of the polar orbiting platforms of Columbus. The payload of such a mission is not only based on instruments derived from ERS-I, but also on those which had to be deleted from this mission (e.g., OCM, IMR). Furthermore, the platform will provide space for a set of research/science-oriented sensors. Thus there is a strong possibility that a suitable ocean color/fluorescence sensor will be integrated into this mission. The FRG will support this.
Because of the earlier mentioned potential and interest of various organizations within the FRG, it is expected that these will participate in special tasks of the EOPP such as

- o mission concept and system studies
- o instrument and feasibility studies
- o measurement campaigns involving aircraft and ships
- o pre-development of critical technologies
- o other related topics.

2.5 Bi-Lateral Cooperations

Besides the participation in the ESA program, the FRG has a number of bi-lateral cooperation agreements with other countries (including ESA member or associated member countries).
In the field of remote sensing, the German interests are properly reflected by the ESA program; national programs are closely related to these or complementary. Typical examples are the cooperation with Canada (DFO, CCRS), Spain (INTA) and with Indonesia (LAPAN). This cooperation has also been the base for a participation in international experiments as for instance with NASA (Fig. 9) during the second flight of the Space Shuttle as part of the OSTA-1/OCE mission (U.S.A., Spain), the Alboran Sea Experiment (Spain, U.S.A. and others), the SNELLIUS II Expedition (Indonesia, The Netherlands) and FLUREX (Canada).

3. REFERENCES

1. van der Piepen H, Amann V, Fiedler R, Dörffer R & Fischer J 1986, Erkundung und Interpretation der Meeresfarbe, BMFT Statusseminar: Die Nutzung der Fernerkundung in der BRD, Garmisch Partenkirchen. DGLR Bericht 8-01, 503-516.

2. ESA 1984, Progress report of the Ocean Color Working Group to the Earth Observation Advisoy Committee, ESA BR-20.

3. MBB 1983, Feasibility study of advanced optical techniques for ocean color measurements, ESA contract5235/82/F/OG/SC.

4. MBB 1986, Chlorophyll mapping of the ocean by means of detector array sensors, BMFT contract R4298-3500R.

5. Dörffer R, Fischer J, Graßl H, Fiedler R, & van der Piepen H 1986, Ocean color/fluorescence sensors - analysis of present systems and requirements for the future, Proc. Intern. Symp. on Progress in Imaging Sensors,Stuttgart 1-5 Sept. 1986.

6. Kunkel B, Blechinger R, Buschner R, Lutz R & Winkenbach H 1986, Advanced imaging spectrometer for ocean color/fluorescence measurements and further applications, Proc. Intern. Symp. on Progress in Imaging Sensors, Stuttgart 1-5 Sept. 1986.

7. Quenzel H & Kästner M 1980, Optical properties of the atmosphere: calculated variability and application to satellite remote sensing of phytoplankton, Appl. Opt. 19(8), 1338-1344.

8. Fischer J & Graßl H 1984, Radiative transfer in an atmosphere-ocean system: an azimuthally dependent matrix operator approach, GKSS Report 84/E/28, 1032-1039.

9. Fischer J, Dörffer R & Graßl H 1985, Factor analysis of multispectral radiance over coastal and open ocean water based on radiative transfer calculations, Appl. Opt. 25(3), 448-456.

10. GKSS 1986, The use of chlorophyll fluorescence measurements from space for separating constituents in water, ESA contract, RFQ-5059/84/NL/MD.

11. Horstmann H, van der Piepen H & Barrot K W 1986, The influence of river water on the southeastern Baltic Sea as observed by Nimbus-7/CZCS imagery, Ambio, 15(5), 286-289.

12. Barnes W L, Ostrow H & Salomonson V V 1986, Preliminary system concepts for MODIS: a moderate resolution imaging spectrometer for EOS, Techn. Symp. on Optics and Optoelectronics, Orlando 31 March - 4 April 1986.

13. ESA 1986, Earth observation procurement plan, ESA PB-RS(86)31.

14. van der Piepen H, Kim H H, Hart W D, Amann V, Helbig H, Fiuza A F G, Viollier M & Dörffer R 1983, The Ocean Color Experiment (OCE) on the second orbital flight test of the Space Shuttle (OSTA-I), IEEE Trans. on Geoscience and Remote Sensing Vol GE-21(3), 350-357.

4. LIST OF ACRONYMS

AWI ..... Alfred Wegener Institut f. Polarforschung
AOCM .... Advanced Ocean Color Monitor
BMFT .... Bundesministreium f. Forschung & Techn.
CZCS .... Coastal Zone Color Scanner
DFG ..... Deutsche Forschungsgemeinschaft
EOP ..... Earth Observation Program
EOPP .... Earth Observation Preparatory Program
EOS ..... Earth Observation System
ERS ..... ESA Remote Sensing Satellite
EURECA .. European Retrievable Carrier
FLEX .... Fladenground Experiment
FLUREX .. Fluorescence Experiment
FMP ..... Flugzeugmeßprogramm
GKSS .... GKSS Forschungszentrum Geesthacht
IMR ..... Imaging Microwave Radiometer
MARSEN .. Marine Rem. Sens. Exp. North Sea
MODIS ... Moderate Res. Imaging Spectrometer
MOMS .... Modular Optoelectr. Multispectr. Scanner
OCWG .... Ocean Color Working Group
OCI ..... Ocean Color Imager
OCM ..... Ocean Color Monitor
OCS ..... Ocean Color Scanner
ROSIS ... Reflect. Opt. Syst. Imaging Spectrometer

FRENCH ACTIVITIES IN OCEAN COLOUR OBSERVATIONS

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ABSTRACT

French activities related to ocean color observations are described with respect to the main scientific objectives and space projects in preparation. The French oceanographic community has acquired a strong expertise throughout the use of CZCS data as well as AVHRR or high resolution Landsat-TM or SPOT imagery. Main research programs and experiments are coordinated with international efforts such as TOGA, WOCE and GOFS. Based on the strong interest in this field, CNES is planning to fly a large-swath visible and near IR sensor named VEGETATION on the remote sensing satellite SPOT-4 (mid-1992) for vegetation and ocean color monitoring.

I. SCIENCE OBJECTIVES

The french oceanographic community has planned its activity for at least the next ten years in the framework or nationally coordinated programs and of international programs for which a french participation is already decided. The main national agencies providing support and manpower are essentially :

- Centre National de la Recherche Scientifique (CNRS-TOAE/INSU) ;
- Centre National d'Etudes Spatiales (CNES) ;
- Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) ;
- Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) ;
- Terres Australes et Antarctiques Françaises (TAAF) ;
- Direction de la Météorologie Nationale (DMN) .

Inter-Agency committees have been set up in view of coordinating scientific goals and tools, funding, ship-time, data management and processing.

Table I.A.

French oceanographic programs or participation to international programs including OC/SST imagery	
Global/ large scale	. TOGA . WOCE . GOFS → FMO → Medatlant (1988) Eumeli (1989..) Antares (1990..)
From large (basin) scale to regional scale	. MIZEX/GSP . ECOMARGE (Médit. et Biscaye) . EROS 2000 (EEC) . AEROCE . DYFAMED (sub-FMO program) . FRONTAL
From regional to coastal zones and small scale	. PNDR . Aquaculture . Coastal management

In table I.A., a list is given of the programs which, to various extents, include the use of ocean color imagery (past, present and future), mostly in conjunction with sea-surface temperature mapping. These programs are ordered according to the space/time scale involved ; the adequate OC sensors are accordingly different (e.g. CZCS type-GAC mode-sensor for global to basin scales or, conversely a TM-SPOT type for small scale and coastal studies). Table I.B. provides some information about the content of each program, in particular the french specific programs.

If all the programs listed in Table 1 plan to make use of the ocean color imagery (if available), generally associated with thermal imagery, the benefits which are expected may differ with respect to the main objectives of the programs themselves. These various benefits, or, in other words, the main objectives, of an ocean color experiment have been reviewed in a French Report (Ref. 1). This document

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

Table 1.B.

Acronyms and key-words
TOGA : Tropical Ocean and Global Atmosphere
WOCE : World Ocean Circulation Experiment.
GOFS : Global Ocean Fluxes Study.
FMO : Flux de Matière dans l'Océan (the french GOF program).
MEDATLANT : Geochemical impact of the Mediterranean outflow upon NE Atlantic ; Starting 1988 ; 1 (or 2) cruises from Gibraltar.
EUMELI : Upper layer primary production, CO_2 fluxes, particulates in the water column, benthic activity, bio-geochemistry of elements coupled with C fluxes in three situations (eu-, meso- and oligotrophic situations) ; location : off Marocco ; several cruises 1989-1990.
ANTARES : GOF main objectives in South indian Antarctic with special emphasis on Silicium budget and opale formation / deposition (1990 ...)
MIZEX/GSP : Marginal ice zone experiment/Greenland Sea Project.
ECOMARGE : Benthic ecology and dynamics over the shelf (Gulf of Lions and Biscaye).
EROS : European rivers outflow studies (1987 if approved by EEC).
AEROCE : Aerosols study in the North-Atlantic.
DYFAMED : Aerosol (Saharian dust) impact on Mediterranean Sea ; bio-geochemical cycle of trace-elements, production in the surface layer, sediment traps experiment, air/rain chemistry at permanent stations (Corsica and Riviera) ; started in 1986.
FRONTAL : Front structures description and dynamics (ligurian current and Ushant front).
PNDR : National program for the dynamics of the recruitment.

was elaborated by the french "ocean-color community" in support of the former OCI/SPOT project (now abandoned, see Section 2). This community included all potential users of an Ocean Color experiment and was not restricted to the people experienced in ocean color data processing (mainly in CZCS data and to a lesser extent Landsat data ; see Table 2). The rationales analyzed in detail in the above mentioned document are summarized in Table 3.

A special emphasis wat put on the complementarity and the synergism which could result from the simultaneous presence in orbit of various kind of sensors supposedly launched in the early 90's (when WOCE will start). For instance, color data can be helpful in evidencing ageostrophic motion (e.g. Ekman drift and thus can complement the picture provided by radar altimetry. In general, with the advantage of a wide swath, an ocean color sensor enlarges and details the vision acquired from a profiler instrument such as a radar. Conversely the wind field and wind-stress as well as data about the incoming radiation (and cloudiness) are the relevant information for a comprehensive study of the upwelling activity and its zonal migration.

Table 2.

Expertise in Ocean Color (Data processing and interpretation)*
- ORSTOM at Lannion, Paris, Dakar (Centre de Recherche de Dakar-Thiaroe)
- IFREMER and Station Biologique de Roscoff
- Ecole Normale Supérieure (Géographie, Montrouge)
- Lab. de Physique et Chimie Marines (Villefranche sur Mer)
- Lab. d'Optique Atmosphérique (Lille)
- Lab. d'Etudes et de Recherches en Télédétection Spatiale (Toulouse)
- Centre Océanologique de Marseille and Centre de Télédétection Appliquée aux Milieux Naturels, Sophia-Antipolis
* including CZCS, TM/SPOT, and AVHRR data ; See also Annex for bibliography.

Table 3.

Objectives of an ocean color experiment *
- Algal biomass monitoring in the global ocean : seasonal variations ; blooms, upwelling activity and extension.
- Primary production (CO_2 fixation) by a combination of pigment mapping/evolution, incoming radiation and cloudiness, and biophysical models.
- Biogeochemical cycles and fluxes related to primary production : calcite, opale, particulates, trace-metals, nutrients, regenerated production.
- Upper layer production, sedimentation and benthic life.
- Ocean dynamics and structures/motions visualization : currents, eddies, fronts, 2-D turbulence, Ekman drift.
- Climatology and modeling : heat transfer, heated layer, albedo in the visible part of the spectrum.
- Sediment transport in coastal zones ; river plumes : extension and variability, impact upon algal development (eutrophication).
- Aerosol climatology : load and nature, geochemical influence on ocean.
- Halieutic research and management.
* from the document "ROMEO"

The obvious complementarity of SST and color is widely accepted and it was assumed that an OC sensor should include a 2-channel IR sensor, or at least that an IR sensor (AVHRR-type) should fly on the same platform (in order to ensure that both imageries are acquired in the same meteorological conditions).

Table 4.

Needs and Recommendations for SUPPORTING WORK
1) Demonstrate the usefulness of the O.C. imagery, essentially by an intensive use of the CZCS archive, more precisely - by producing composite-mosaics images for wide zones and by computing time-averaged maps having a bio-geochemical significance (biological activity, carbon fixation...) - by processing dense time series of CZCS data over selected areas in view of studying the temporal evolution of . specific dynamical/hydrological features (such as eddies, meanders, coastal upwellings ...) . or sediment movement (resuspension, river plumes extent ...) - by interpreting the "by-product" of the atmospheric correction in terms of aerosol load and variability.
2) Reinforce the biophysical/biochemical studies of the marine photosynthesis with the aims of - deriving an adequate parameterization of the relationships between available radiant energy, pigment concentration and carbon fixation capability ; such a parameterization is needed when transcribing color imagery in terms of geochemical fluxes. - re-assessing the role of picoplankton in the production by the oligotrophic areas, understanding the optical properties of these cells and measuring (in vitro) their actual production (growth rates, quantum yield, action spectrum ...).
3) Reinforce the biophysical studies of the fluorescence by algae, particularly in the domains of - sun-induced fluorescence variability and factors responsible for it, - "package-effect" for the exciting and re-emitted radiations ; yield and kinetics of the fluorescence process ; fluorescence and photosynthesis as mutually exclusive processes. - laser-induced fluorescence ; chlorophyll, phycobilins, pheopigments responses.
4) Study the spectral dependence of the scattering properties of diverse types of aerosols (nature and size distribution function) within the entire visible and near IR region. Such a study is a proviso for developing algorithms to be used with future sensors which will include several near-IR channels.
5) Re-examine the methodology concerning the "Sea-truth" measurements : pigment concentration and composition, fluorescence measurements, significance of primary production measurements (contamination), yellow substance, and suspended matter quantification.
See also the Report of SCOR/WG 70 (Réf. 3).

Table 5.

OCI Spectral Regions

Channel	Spectral range (nm)	Minimum S/N	Function
1	433-453	370	low chlorophyll, gelbstoffe
2	490-510	360	other pigments
3	555-575	360	Baseline chlorophyll
4	655-675	340	Subsurface scattering
5	745-785 *	290	Atmospheric correction
6	844-890	290	Atmospheric correction
7	10.5 μm	0.08K **	Sea surface temperatures
8	11.5 μm	0.11K **	Sea surface temperatures

* Blocked between 759 and 770 to avoid oxigen band.

** These quoted walues in S/N column are Noise Equivalent Temperature Difference (NETD) at 300°K.

In preparation to a futur ocean color mission, and in the perspective of an "advanced" instrument to be developed, it has been recognized that more scientific work is needed. With regard to the experience in several scientific groups and to parallel activities already planned some realistic recommendations have been put forward (see Table 4) which could be added to, or incorporated within, those listed by the ocean color european community.

II. SPACE PROJECTS RELATED TO OCEAN COLOR OBSERVATIONS

The strong interest of the French scientific community with respect to studies using ocean color observations from spaceborne sensors has led CNES to investigate the possibility to implement such a program. An announcement of opportunity was released in 1984 in which CNES invited proposals to embark scientific experiments as piggy-back passengers onto the SPOT-3 remote sensing satellite. Following this A.O. CNES and NASA agreed to undertake a joint definition study of a collaborative experiment named ROMEO, consisting of a NASA-provided Ocean Color Imager (OCI) flying on SPOT-3 and of NASA-CNES cooperation in OCI data processing and scientific exploitation. The study was concluded in February 1985 with a recommendation to proceed with the ROMEO project which was recognized feasible and of high interest (Ref. 2). Table 5 gives the spectral characteristics of the OCI instrument as defined by the French-US Ocean Color Science Working Group. However the OCI/SPOT 3 project schedule required a FY-86 new start within NASA which was not obtained, and the project was abandoned in mid-1985.

Taking into account the absence of CZCS follow-up and the risk that no ocean color sensor be available before the advent of the polar platform elements of the International Space Station, CNES considered the possibility to add a "blue channel" onto another candidate instrument devoted to vege-

Table 6.

Satellite	SPOT-1	SPOT-2	SPOT-3	SPOT-4	SPOT-5
Design	-	identical to SPOT-1	identical to SPOT-2	new design	identical to SPOT-4
Ready-to-launch date	launched 2/21/86	mid-87	mid-89	mid-92	mid-93

Table 7.

. Spectral Bands		
B_0	0.43 - 0.47 μm	
B_1	0.51 - 0.59 μm	
B_2	0.61 - 0.69 μm	
B_3	0.78 - 0.89 μm	
MIR	1.58 - 1.75 μm	
. NE$\Delta\rho$:	1 to 3 x 10^{-3}	
. Pixel size : 1.15 km	Pixel grouping : 4.6 km	
. Viewing angle : I 50° (2200 km swath)		
. Registration : 0.5 pixel		
. Localisation : 2.5 km		
. Digitization : 10 bits		
. Recording : magnetic memory 256 Mbits		

tation monitoring on SPOT-3. The study conducted in 1985/86 showed off the feasability and usefulness of this solution, which has now been adopted. Recent reassessment of the SPOT program planning has led to postpone improvements and passenger accomodation until SPOT-4. Present SPOT planning is given in Table 6.

The improvements on SPOT-4 will include : the addition of a new middle infrared band at 1.6μm, the registration of the 10 m and 20 m sampled channels, the inclusion of the new payload named VEGETATION, the extension of the ground segment ; and an extension of the mission lifetime to 4 years.

The VEGETATION instrument is a 5-channel radiometer providing large swath imagery at medium resolution ($\sim$ 1 km) in the same spectral bands B_1, B_2, B_3 and MIR as the HRVIR (High Resolution Visible and Infra-Red) instruments of SPOT-4, plus the B_0 "blue" band at 0.45μm. The main characteristics of the VEGETATION instrument are given in Table 7.

The SPOT-4 orbit (circular, sun synchronous, 830 km, 10 H 30 at descending node, 26-day repeat) will allow global coverage every 1.2 day.

On board data storage on a large capacity magnetic bubble memory will allow daily global acquisition at 4 km sampling at Toulouse central receiving station.

Direct transmission of 1 km sampling data will also be available using ciphered X-band data link. Data received in Toulouse (local area at 1 km, global area at 4 km) will be systematically processed. Level I data (system-corrected reflectances in the five spectral bands plus computed vegetation, chlorophyll and aerosol indexes at 1 and 4 km sampling) will be available within one day of data reception, level II products (weekly-produced global maps of level I data) within 3 days of the last acquisition. Data distribution will be made by Spot-Image.

The VEGETATION mission objectives will be primarily to provide world wide operational monitoring of the continental vegetation for applications purposes such as agriculture forecast, environmental studies, evolution survey, etc... The ocean observations permitted by the instrument will allow scientific studies in marine biology (cartography of space-time variations of phytoplankton distribution, quantitative estimate of the global ocean primary production, climatological research related to carbon fixation and CO_2 cycle, mesoscale circulation, help to fisheries, ...) and sedimentology (sediment transport, river plumes, surface water circulation, ...) through the use of B_0, B_1 and B_2 channels for derivation fo the pigment concentration, B_3 and MIR for atmospheric corrections.

Though it is not designed for ocean observation, the high resolution visible imagery now available from SPOT-1 proves very useful for ocean studies and applications, such as wave and swell study, bathymetry, coastal management, etc... The addition of the VEGETATION payload will highly enhance the SPOT mission for the oceanographers.

*

On the longer term, CNES recognizes the need for advanced ocean color imaging facilities on board the Polar Platforms. Satellite-measured ocean chlorophyll concentration data will be an essential parameter for the continuous monitoring of the global state of the Earth and the understanding of the causes and effects of global change.

REFERENCES

1. ROMEO, Objectifs Scientifiques d'une Expérience de Radiométrie Optique Multispectrale pour l'Etude des Océans, CNES, Oct. 1985 (Second edition in preparation).
2. Ocean Color Instrument on SPOT-3, NASA/CNES Phase A Study Report, Feb. 1985.
3. Opportunities and problems in Satellite measurements of the sea. Report of the SCOR/WG 70. UNESCO technical papers in marine science, N° 46, 1986.

ANNEX

The orderly bibliography below intends, via the titles of the quoted papers, to provide an overview of the french research concerning both the

ocean color itself and the bio-geochemical or dynamical studies which could benefit from an ocean color experiment. The referenced works include significant papers, in particular those written in last few years by members of the community aggregated in view of the former OCI/-SPOT project. This list, however, is not claimed to be exhaustive, but is thought to form a sort of summary of the current research.

1) General papers concerning ocean color, its interpretation and its remote measurement from space ; papers making use of CZCS data.

MOREL A. et L. PRIEUR, 1977, Analysis of variations in ocean color. Limnology and Oceanography, 22, 709-722.

P. CASTAING, G.P. ALLEN, M. HOUDART, Y. MOING (1979), Etude par télédétection de la dispersion en mer des eaux estuariennes issues de la Gironde et du Pertuis de Maumusson, Oceanologica Acta, Paris, vol 2, n° 4, 459-468.

MOREL A., 1980. In-water and remote measurements of ocean color. Boundary layer Meteorology, 18 : 177-201.

MOREL A., GORDON H.R., 1980. Passive radiometry of the ocean. Boundary layer Meteorology, 18 : 343-355.

VIOLLIER M., TANRE D., DESCHAMPS P.Y., 1980 : An algorithm for remote sensing of water color from space. Boundary-Layer Meteorology, 18, 247-267.

BRICAUD A. and S. SATHYENDRANATH, 1981. Spectral signatures of substances responsible for the change in ocean color. In : Signatures spectrales d'objets en télédétection ; G. GUYOT et M. VERBRUGGHE édit., INRA, pp. 41-55.

MOREL A., GORDON H.R., 1981. Remote assessment and interpretation of ocean color, the state of the art (COSPAR) Advanced Space Research, 1 : 160-164.

MOREL A. and BRICAUD A., 1981 a. Theoretical results concerning the optics of phytoplankton, with special reference to remote sensing applications, In : "Oceanography from Space", (ed.) JFR Gower, Mar. Sci., Plenum Press (NY), Vol. 13, 313 - 328

HOLLIGAN P.M., VIOLLIER M., SMITH R.C., EPPLEY R.W., BAKER K.S., 1982. Correlation of primary production as measured aboard ship in Southern California coastal waters and as estimated from satellite chlorophyll images. Mar. Biol., 66 : 281-288.

VIOLLIER M., 1982 : Radiometric calibration of the coastal zone color scanner on Nimbus-7 : a proposed adjustement. Applied Optics, 21, 1142-1145.

GORDON, HR and AY MOREL, 1983. Remote assessment of ocean color for interpretation of satellite visible imagery : a review, Lecture notes in Coastal et Estuarine Studies series, Springer-Verlag, NY (4, pp. 114).

HOLLIGAN P.M., VIOLLIER M., DUPOUY C., AIKEN J., 1983. Satellite studies on the distribution of chlorophyll and dinoflagellate blooms in the western English Channel. Continental Shelf Res., 2 : 81-96.

HOLLIGAN P.M., VIOLLIER M., HARBOUR D.S., CAMUS P., CHAMPAGNE-PHILIPPE M., 1983. Satellite and ship studies of coccolithophore production along a continental shelf edge. Nature, 304 : 339-342.

SATHYENDRANATH S. and MOREL A., 1983. Light emerging from the sea : interpretation and uses in remote sensing, In : "Remote Sensing Applications in Marine Science and Technology", AP Cracknell (ed), D. Reidel Publ. Co., Ch. 16, 323-357.

THOMAS Y.F. (1984), Télédétection des structures turbides en Manche, L'espace Géographique, 3, 273-276.

VIOLLIER M., STURM B., 1984 : CZCS data analysis in turbid coastal water. J. Geophys. Res. 89, D4, 4977-4985.

BRICAUD A. and MOREL A., 1987 : Atmospheric corrections and interpretation of marine radiances in CZCS imagery : use of a reflectance model. To be published in Oceanologic Acta.

BRICAUD A., MOREL A. and ANDRE J.M., 1977 : Spatial/Temporal variability of algal biomass and potential productivity in the mauritanian upwelling zone, as estimated from CZCS data. To be published in Advances in Space Research.

DESCHAMPS P.Y. and VIOLLIER M., (1987). Algorithms for ocean color from space and application to CZCS data. To be published in Advances in Space Research.

SATHYENDRANATH S., PRIEUR L., MOREL A., 1987. An evaluation of the problems of chlorophyll retrieval from ocean color for "case 2" waters. To be published in : Advances in Space Research.

2) Papers on atmospheric correction and atmospheric modeling in the visible or near infrared ; papers on the incident solar radiation at the sea level

MOREL A. and R.C. SMITH. 1974. Relation between total quanta and total energy for Aquatic photosynthesis. Limnol. Oceanogr. 19 : 591-600

TANRE D., M. HERMAN, P.Y. DESCHAMPS and A. de LEFFE. 1979. Atmospheric Modelling for Space Measurements of Ground Reflectances, Including Bidirectional Properties. Appl. Opt. 18 : 3587-3594.

GAUTIER C., G. DIAK and S. MASSE, 1980. A Simple Physical Model to Estimate Incident Solar Radiation at the Surface from GOES Satellite Data. J. Appl. Meteor, 19, 1005-1012

GAUTIER C., 1981. Daily short-wave energy budget over the ocean from geostationary satellite measurements. Oceanography from Space, 201-206. Plenum Press, New York.

DIAK G., C. GAUTIER and S. MASSE, 1982 : An Operational System for Mapping Insolation from GOES data. Solar Energy, 28, 371-376.

GAUTIER C., 1982, Mesoscale Insolation Variability Derived from Satellite Data. J. Appl. Meteord., 21, 51-58.

DESCHAMPS P.Y., M. HERMAN, D. TANRE, 1983 : Modeling of the atmospheric effects and its application to the remote sensing of ocean color. Appl. Opt. 22, 3751-3758.

TANRE D., HERMAN M., DESCHAMPS P.Y. (1983) "Influence of the atmosphere on space measurements of directional properties" Appl. Opt. 22, 733-741.

TANRE D., C. DEROO, P. DUHAUT, M. HERMAN, J.J. MORCRETTE, J. PERBOS and P.Y. DESCHAMPS, 1985. Effets Atmosphériques en Télédétection. Logiciel de Simulation du Signal Satellitaire dans le Spectre Solaire. Proc. 3rd Int. Coll. on Spectral Signatures of Objects in Remote Sensing, les Arcs, France, Déc. 1985, 315-319.

DEDIEU G., P.Y. DESCHAMPS and Y.H. KERR (1987). Satellite estimate of Solar irradiance at the surface of the earth and of surface albedo using a physical model applied to Meteosat Data. To be published in : J. Clim. Appl. Meteorol.

3) Sea surface temperature mapping from space, heat storage and dynamics

MERLE J. (1980). Seasonal heat-budget in the Equatorial Atlantic Ocean. J. Phys. Oceanogr. 10 (3).

DESCHAMPS P.Y., FROUIN R. and WALD D. (1981). Satellite determination of the mesoscale variability of the surface temperature. Phys. Oceanogr. 11, 864-870.

LESIEUR M. and SADOURNY R. (1981). Satellite-sensed turbulent ocean structure. Nature, 294, p. 674.

MILLOT C. and M. CREPON (1981). Inertial oscillations on the continental shelf of the Gulf of Lions. Observations and theory. J. Phys. Oceanogr. 11, 5, 639-657.

PRIEUR L., BETHOUX J.P., ALBUISSON M., WALD L., MONGET J.M., 1981. A comparison between infra-red satellite images and sea truth measurements. pp. 159-167, in : Oceanography from space, J.F.R. Gower ed., Plenum Press.

CREPON M., L. WALD and J.M. MONGET (1982). Low frequency waves in the Ligurian Sea during December 1977. J. Geophys. Res. 87, C1. 595-600.

FRANKIGNOUL C. and REYNOLDS R.W., 1983. Testing a dynamical-model for mid-latitude sea surface temperature anomalies. Journal Phys. Oceanogr., vol. 13, n° 7, 1131-1145.

DESCHAMPS P.Y., R. FROUIN and M. CREPON (1984). Sea surface temperature of the coastal zones of France observed by the HCMM satellite. J. Geophys. Res. 89, C1. 8123-8140

HANNOSCHOCK G. and FRANKIGNOUL C., 1985. Multivariate statistical analysis of a sea surface temperature anomaly experiment with the GISS general circulation model I. J. Atmos. Sci. 42.

LE TREUT H., J.Y. SIMONOT, M. CREPON : A model for the sea-surface temperature and heat content in the North Atlantic Ocean, in Ocean Hydrodynamics. "Coupled atmosphere-ocean models", J. NIHOUL Ed., Elsevier, pp. 439-445, 1985.

MILLOT C. (1985). Some features of the Algerian Current, J. Geophys. Res. 90-C4 - pp. 7169-7776.

HASTENRATH S. and J. MERLE (1986). The annual march of heat storage and export in the tropical Atlantic oçean. J. Phys. Oceanogr. 16 (4), 694-708.

HÔ D., A. ASEM and P.Y. DESCHAMPS (1986). Atmospheric correction for the sea surface temperature using NOAA-7/AVHRR and Meteosat 2 infrared data. Int. J. of Rem. Sens., vol. 7, 10, 1323-1333.

SIMONOT J.Y. and H. LE TREUT (1986) : A climatological field of mean optical properties of the World Ocean, J. Geophys. Res., Vol. 91 C5, pp; 6642-6646.

4) Bio-optical properties of ocean waters ; optical properties of phytoplanktonic cells and derivatives.

BRICAUD A., A. MOREL and L. PRIEUR, 1981; Absorption of dissolved organic matter of the sea ("yellow substance") in the UV and visible domains. Limnology and Oceanography, 26, 43-53.

MOREL A. and A. BRICAUD, 1981 b. Theoretical results concerning light absorption in a discrete medium and application to the specific absorption of phytoplankton, Deep Sea Res., 28 A, 11, 1357-1393.

PRIEUR L. and S. SATHYENDRANATH, 1981. An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter and other particulate materials, Limnology and Oceanography, 26 (4), 671-689

BRICAUD A., A. MOREL and L. PRIEUR, 1983. Optical efficiency factors of some phytoplankters, Limnology and Oceanography, 28 (5), 816-832.

BRICAUD A. and MOREL A., 1986. Light attenuation and scattering by phytoplanktonic cells : a theoretical modeling. Applied Optics, 25, 571-580.

NEVEUX J., De BILLY G., 1986. Spectrofluorimetric determination of chorophylls and phaeophytins. Their distribution in the western part of the Indian Ocean. (July-August, 1979). Deep-Sea Res., 33 (1A), 1-14.

MOREL A., 1987. Chlorophyll-specific scattering coefficient of phytoplankton ; a simplified theoretical approach. To be published in Deep-Sea Res.

MOREL A., BRICAUD A., 1987. Inherent optical properties of algal cells including picoplankton : theoretical and experimental results, (review paper). To be published in Canadian Bulletin of Fisheries and Aquatic Sciences.

5) Oceanic primary production, nutrients, nitrogen uptake and carbon dioxyde cycle and photosynthetic fixation.

MOREL A., 1978. Available, usable and stored radiant energy in relation to marine photosynthesis. Deep-Sea Res. 25, 673-688.

HERBLAND A., VOITURIEZ B., 1979. Hydrological structure analysis for estimating the primary production in the tropical Atlantic ocean. J. mar. Res., 37 : 87-101.

SLAWYK G., 1979. ^{13}C and ^{15}N uptake by phytoplankton in the Antarctic upwelling area : Results from the Antiprod I cruise in the Indian Ocean Sector. Aust. J. Mar. Freshwater Res., 30 : 431-448.

COLLOS Y., SLAWIK G., 1980. Nitrogen uptake and assimilation by marine phytoplankton pp. 195-211 in : Primary productivity in the Sea. P. FALKOWSKI édit., Plenum Press, N.Y.

NEVEUX J., JUPIN H., 1981. Une approche vers l'estimation de la production potentielle du phytoplancton par analyse des cinétiques d'induction de fluorescence. Marine Biology, 63 : 13-21.

DANDONNEAU Y., 1982. A method for the rapid determination of chlorophyll plus phaeopigments in samples collected by merchant ships, Deep-Sea Res., Vol 29, 5A, 647-654.

MINAS H.J., PACKARD T.T., MINAS M., COSTE B., 1982. An analysis of the production-regeneration system in the coastal upwelling area off N.W. Africa based on oxygen, nitrate and ammonium. J. mar. Res., 40 : 615-641.

MINAS H.J., CODISPOTI L.A., DUGDALE R.C., 1982b. Nutrients and primary production in the upwelling region off Northwest Africa. Rapp. P.v. Réunions du Conseil International pour l'Exploration de la Mer, 180 : 148-183.

MINAS H.J., PACKARD T.T., MINAS M., COSTE B., 1982c. An analysis of the production-regeneration system in the coastal upwelling area off N.W.-Africa based on oxygen, nitrate and ammonium distributions. Journal of Marine Research, 40 : 615-641.

MOREL A., 1982. Optical properties and radiant energy in the waters of Guinea Dome of Mauritanian upwelling area. Relationship to primary production. Rapp. P.v. Réunions du Conseil International pour l'Exploration de la Mer, 180 : 87-100.

COPIN-MONTEGUT C. and COPIN-MONTEGUT G., 1983. Stoichiometry of carbon, nitrogen and phosporus in marine particulate matter. Deep-Sea Res., 30 (1) : 31-46.

LE CORRE P., MINAS J.H., 1983. Distribution et évolution des éléments nutritifs dans le secteur indien de l'océan Antarctique en fin de période estivale. Oceanol. Acta, 6 : 365-381.

OUDOT R., 1983. Variations of the CO_2 gradient at the ocean-atmosphere interface in the tropical Atlantic. Tropical Ocean-atmosphere newsletter, 22 : 9-10.

COLLOS Y. and SLAWYK G., 1984. ^{13}C and ^{15}N uptake by marine phytoplankton. III. Interactions in euphotic zone profiles of stratified oceanic areas. Mar. Ecol. Prog. Ser., 19 : 223-231.

KLEIN P., COSTE B., 1984. Effects of wind-stress variability on nutrient transport into the mixed layer. Deep-Sea Res., 31 : 21-37.

RAIMBAULT P., 1984. Influence of temperature on the transient response in nitrate uptake and reduction by four marine diatoms. J. exp. mar. Biol. Ecol., 84 : 37-53.

SLAWYK G., MINAS M., COLLOS Y., LEGENDRE L. and ROY S., 1984. Comparison of radioactive and stable isotope tracer techniques for measuring photosynthesis : ^{13}C and ^{14}C uptake by marine phytoplankton. J. Plankton Res., 6 (2) : 249-257.

VOITURIEZ B., HERBLAND A., 1984. Signification de la relation nitrate/température dans l'upwelling équatorial du Golfe de Guinée. Oceanol. Acta, 7 : 169-174.

COPIN-MONTEGUT C., 1985. A method for the continuous determination of the partial pressure of carbon dioxide in the upper ocean. Mar. Chem., 17.

HERBLAND A., LE BOUTEILLER A. and RAIMBAULT P., 1985. Size structure of phytoplankton biomass in the equatorial Atlantic Ocean. Deep-Sea Res., 29 (8) : 953-956.

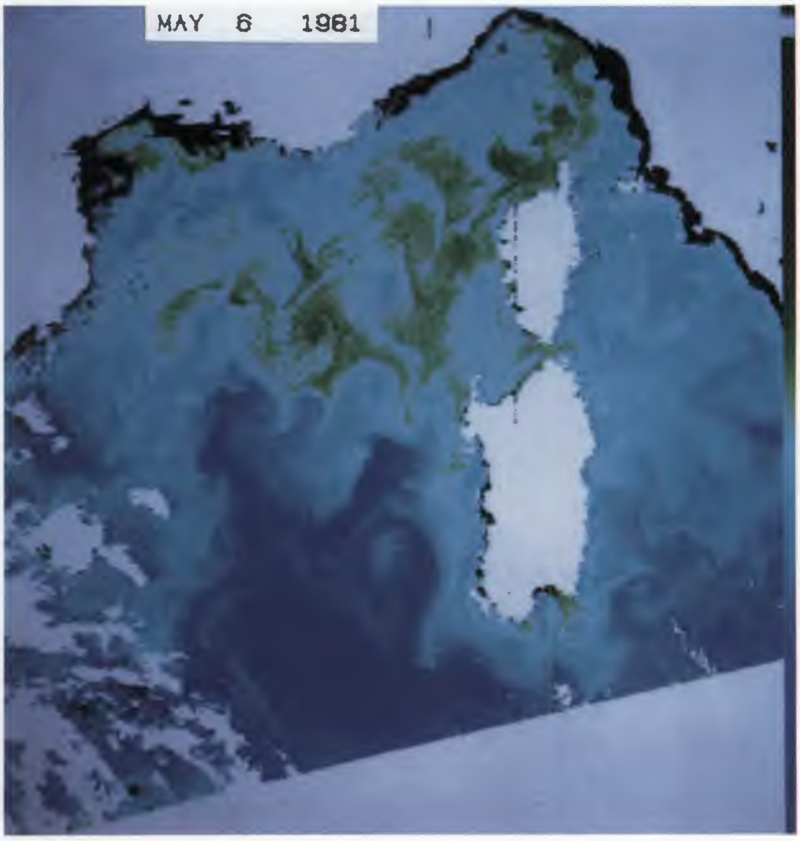
BETHOUX J.P. and G. COPIN, 1986. Biological fixation of atmospheric nitrogen in the Mediterranean Sea. Limnol. and Oceanogr. 31, 1353-1358.

PAPAUD A. and POISSON A., 1986. Distribution of dissolved CO_2 in the Red Sea and correlation with other geochemical tracers. Journal of Marine Research, 44, 385-402.

CHEN C.T.A., POISSON A. and GOYET C., 1987. Comparison of summer-winter carbonate and nutrient data in the southwestern Indian Ocean. To be published in Tellus.

MOREL A., LAZZARA L. and GOSTAN J., 1987. Growth rate and quantum yield time-response for a diatom to changing irradiance (Energy and color) to be published in Limnol. and Oceanogr.

POISSON A. and CHEN C.T.A., 1987. Why is there little anthropogenic CO_2 in the antarctic bottom water. To be published in Deep-Sea Res.



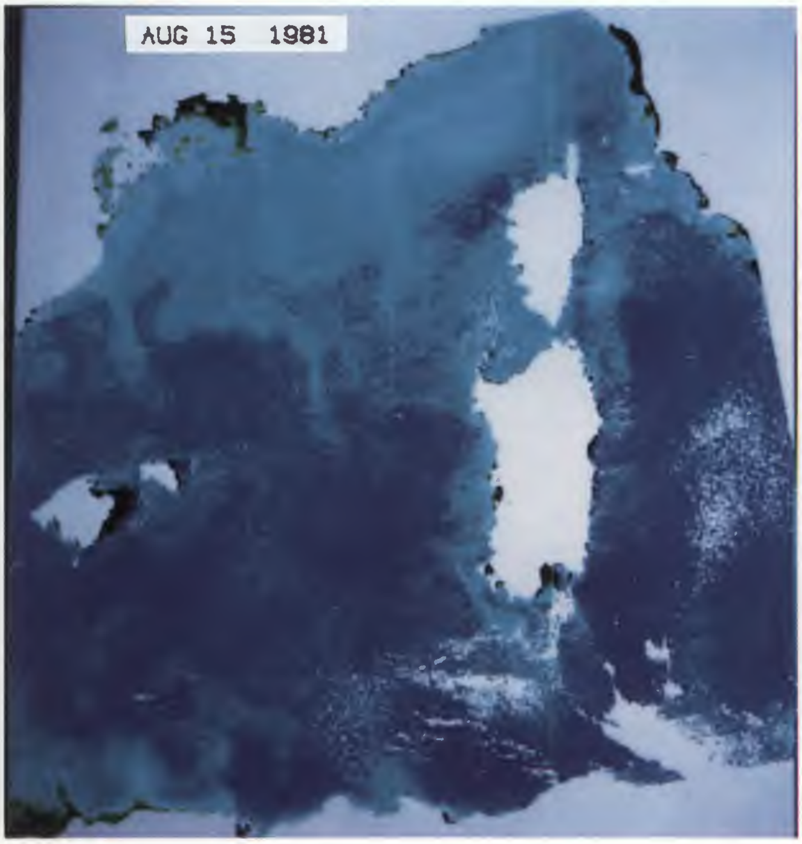
Selected CZCS scenes of the western Mediterranean Sea are shown as typical examples of the phytoplancton distribution for the four seasons in 1981. The pigment concentration (mg/m^3) increases from dark blue, then light blue and green and finally to dark green; the colour scales are adjusted in view of enhancing the spatial structures and therefore differ from an image to another.

6 May	*dark blue: <0.15*	*dark green: >3.0*
15 August	*,, : <0.10*	*,, : >1.0*
16 October	*,, : <0.25*	*,, : >3.0*
15 March	*,, : <0.20*	*,, : >2.0*

For all images, lands and clouds are in white and turbid coastal waters in black.

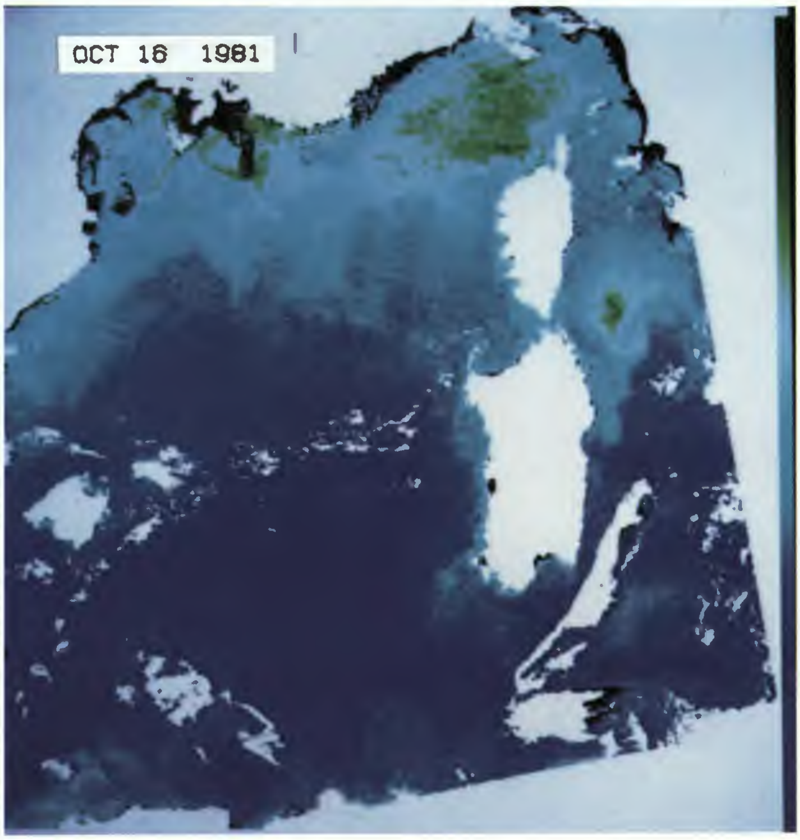
The southern central part of the basin as well as the Tyrrhenian Sea remain oligotrophic throughout the year (less than 0.2 mg Chl a/m^3), with little variability, except along the Algerian coast, where the algal biomass production appears to be associated with the meanders and eddies of the Atlantic entering current. Conversely the northern part of the basin is more variable and, in general, more productive.

1A

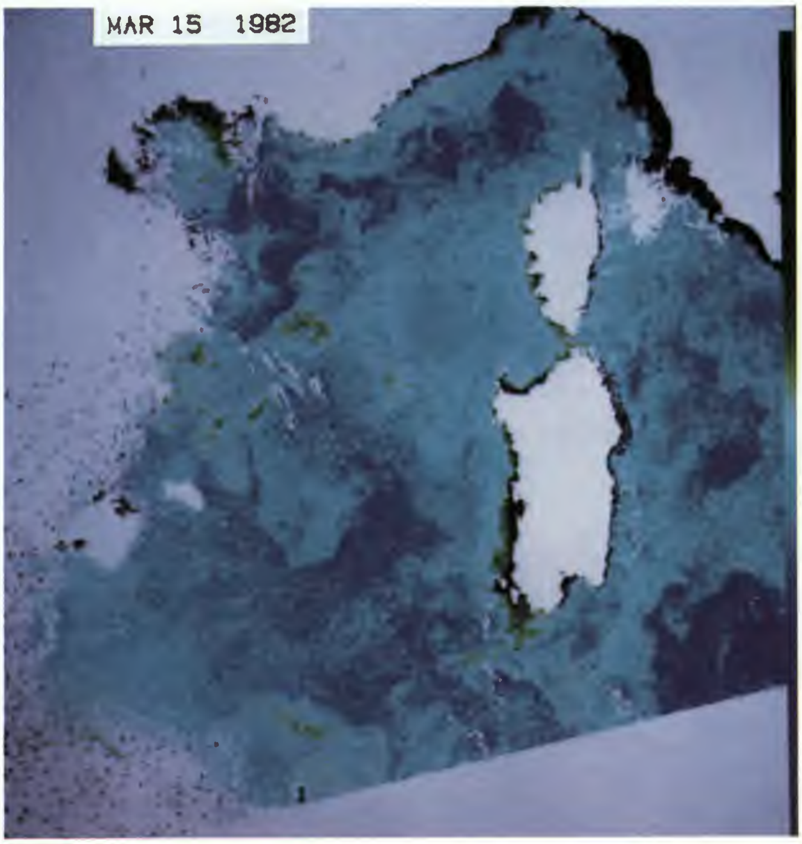


1B

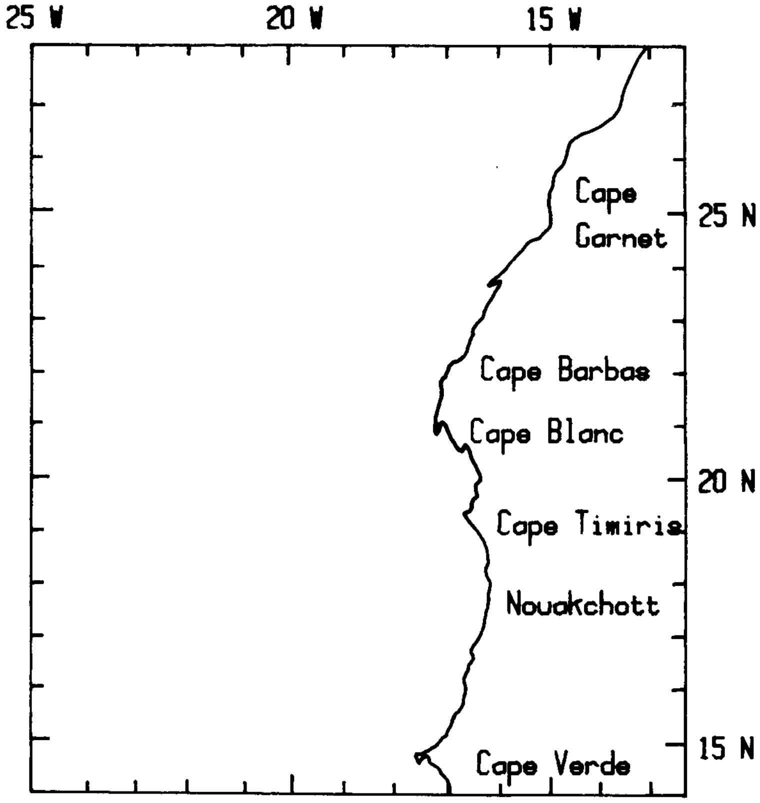
In spring, when stabilised by the solar heating, the nutrient-rich waters, which originate from the winter vertical mixing, support an active algal bloom (1A). In summer (1B) the whole northern sea becomes homogeneous with a relatively low pigment content in the surface layer (about 0.30 mg Chl a/m^3). When climatic forcings deepen the thermocline and re-introduce nutrients in the lighted layer, the 'autumnal bloom' occurs with pigment concentration about 1.5 mg/m^3 and locally up to 3 mg/m^3 (1C). The cooling is maximal in March, and deep water formation takes place in the central Ligurian Sea till the Gulf of Lions; this zone is characterised by clear, low-chlorophyll waters (1D), those waters which, one month later, will become the most productive in the zone.



1C



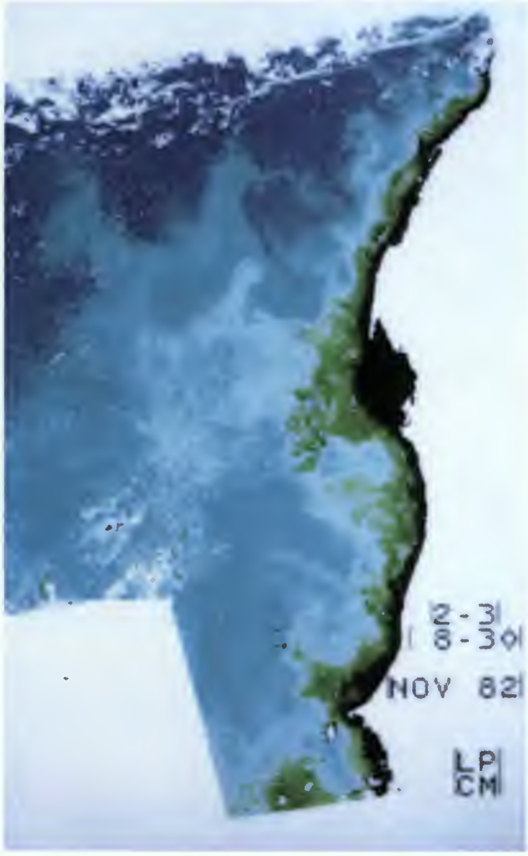
1D



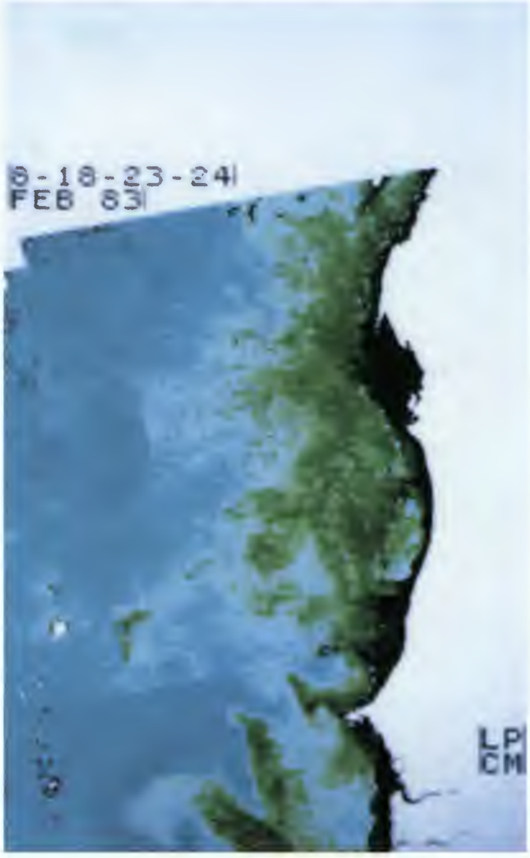
Composite images of the surface pigment concentration, obtained from CZCS data, which show the spatial/temporal evolution of the upwelling off NW Africa, along the coasts of Morocco, Mauritania and Senegal. The composition is obtained by averaging the pigment concentrations computed for several individual scenes acquired over a period of one month (the dates are given on each image). The dimension of the images is approximately 840 km (EW) × 1260 km (NS) and the resolution is 2.5×2.5 km^2. Land and clouds are masked in white, turbid coastal waters in black. In oceanic ('Case 1') waters, the pigment concentrations increase according to a logarithmic scale, from dark blue (<0.2 mg Chl **a***/m^3) to mean blue (0.2 – 1 mg/m^3), light blue (1 – 3 mg/m^3), light green (3 – 5 mg/m^3) and dark green (>5 mg/m^3).*

These images correspond to typical situations in the annual upwelling cycle, which is mainly controlled by the NE tradewinds. The southern limit of the tradewind influence oscillates between 10°N in February-March and 21°N in September-October. The upwelling is therefore more or less permanent north of Cape Blanc, with however, some seasonal fluctuations; the eutrophic zone extends offshore south-west of Cape Blanc, whilst it is confined to a coastal band north of Cape Barbas, with large-scale eddy-like structures in November 82 and 83. South of Cape Blanc, the seasonal variations are more pronounced: in November, the tradewinds progress southwards; in February, they are blowing till south of Cape Verde, and the high algal biomass area extends in front of the Casamance river mouth and far offshore. The image on the cover (8 Febr. 1983) also shows the geographical extension of the zone influenced by the coastal upwelling. In March-April, the tradewinds and the upwelling activity regress northwards. Interannual variations in the upwelling regime also exist, as demonstrated by the images of November 1982 and 1983.

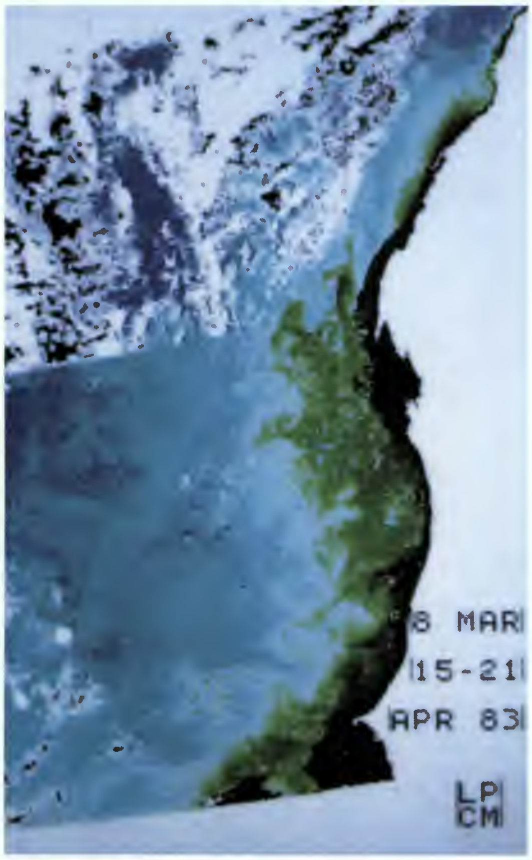
The monthly averages of the surface pigment content, combined with climatic data on daily irradiation, can be transformed into monthly potential primary production per unit area. The global mass of carbon photosynthetically fixed per year can therefore be computed over a given zone; from 15 to 25°N and from the coast to 24°W, it amounts to approximately 276 megatons carbon per year (see Bricaud, Morel & André, Advances in Space Research, *in press).*


2-3
8-30
NOV 82
LP
CM

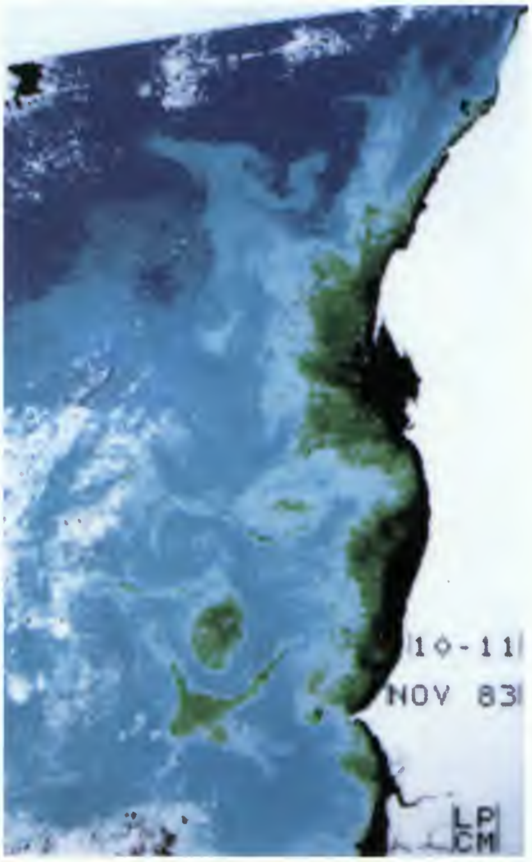
2a


8-18-23-24
FEB 83
LP
CM

2b


8 MAR
15-21
APR 83
LP
CM

2c


10-11
NOV 83
LP
CM

2d

ITALIAN ACTIVITIES IN OCEAN COLOUR REMOTE SENSING

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ABSTRACT

The potentials of Ocean Colour Remote Sensing over coastal and offshore areas of Italy in providing valuable informations for planning and decision making of public administrative agencies has been demonstrated. Their principal interest is in pollution monitoring including the thermal pollution near shore and in possible forecast of eutrophication. Scientific research for this demonstration has been focused in critical zones, some of which are of international interest. Technological research has been so far directed to the development of instruments for in-situ or airborne measurements in air and water. Italian users activity and interests in ocean colour is described.

Keywords: Ocean Colour, Marine Pollution, Chlorophyll Monitoring, Atmospheric Noise

1. INTRODUCTION

With its 8000 km of coastline, few major rivers (the Po, Tevere, Arno) and a great number of minor rivers and canal discharges, Italy provides more than one-third of the runoff water of the Mediterranean Sea. Out of the 537 thousand tons of nitrogen components input per yeaer in the Mediterranean Sea, 290 are estimated to come from the Adriatic Sea. Of the 28 thousand tons of phosphorous components estimated per year in the Adriatic Sea, 1,100 are coming from the Po, the major northern Italian river. Along the coasts an intense population activity takes place with ship traffic, commerce, industries, tourisms, amenities and fishery.

Water pollution is therefore considered the most important problem for several Departments such as Environment, Health, Scientific Research, Public Works, Merchant Marine and Defense. Regional authorities are involved also in the protection of beaches and historical centers such as Venice and several fishing villages, and in planning a control of river discharges.

It is through the effort of few scientific research institutes, who organized also several national and international meetings, among which the "Oceanography from Space" in Venice, 1980, that the interest of the regional and governmental administrations in the earth and ocean observations from satellite (including optical and IR sensors) was raised. Properly corrected image series and statistics are the product which is most requested by users for planning and decision making. The role of science is to provide the methodology and technique to secure the best possible information on the quality, the variability and the dynamics of coastal and offshore waters over the longest possible periods of time. Oceanographers are involved in modelling ocean mechansisms and processes with the objective to study possible forecasting models. The present and future research includes objective analysis to provide the proper synoptic input to the models together with the traditional in situ observation networks. The Adriatic, a critical sea, is so far the best studied.

Biologists and optical oceanographers are involved in basic research concerning primary production, bacteria, anthropic hazards, fishery in the Tyrrhenian and Ligurian seas and in the Adriatic. This involves the development of algorithms for different water masses of case 2 waters.

The interaction of nearcoast waters (from a few metres to a few kilometres) and offshore waters, the mixing and transport mechanisms in connection with seasonal variability and atmospheric forcing are the main topics of present research, connected however with limited financial support from the CNR and PSN (Piano Spaziale Nazionale).

The PSN, a National Space Plan, which is preparing the grounds for the development of an Italian Space Agency which, since a few years has been under consideration by the Senate and the Chamber, is now primarily stimulating the industrial involvement in space and in ground segment

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development. The support to software development and to scientific studies to reach the optimal use of earth observation (in this case of ocean) satellite data is only at its onset as it is now to a large extent on the research institutes budgets.

Scientists of the various institutes of CNR (Consiglio Nazionale delle Ricerche) and university laboratories have created working groups to join forces and means to reach the best possible results in terms of cost and benefit. A cooperation has also taken place with the JRC of Ispra in the scientific use of optical sensors in studies of water dynamics and quality.

2. SCIENTIFIC ACTIVITY AND PROGRESS

The two major areas of Italy for which optical remote sensing has been more actively studied are the polluted waters of the Venice Lagoon and the northern Adriatic Sea, and the polluted air of the largely industrialized Po Valley.

These two problem areas are responsible for the major interdisciplinary scientific research and in-situ observations since the sixties. Remote sensing from aircrafts and satellites became later an indispensable tool to provide, with synoptic observations, the in-situ measurements (networks of stations and campaigns) with more complete observations.

2.1 Optical sensing of water conditions

Early tests on ocean colour were made with the OCS (1977) and later with the CZCS of Nimbus, but for several years these data were lacking calibration and proper software to be of practical use.

In the absence of CZCS images several attempts have been made to use Landsat images and, more recently the TM. The main problem is the cost of the TM images, which is prohibitive for research institutes. The paucity of available images have been therefore the cause of insufficient studies. TM images, however, prevent any discrimination of parameters and give only information on turbidity distributions.

One successful demonstration of CZCS images, properly analyzed, and studied with few repeated in-situ verifications is shown by the series of 14 images (7 per year) of the Adriatic Sea (Barale et al., 1986). Each image shows the monthly mean of phytoplankton pigment concentration from less than 0.30 mg/m^3 (blue) to more than 3.4 mg/m^3 (red) in 10 unit increments. Temporal variability from month to month and yearly averages for 1979 and 1980 are clearly evident (Figs. 1,2,3).

Recent numerical modelling and laboratory experiments allow a rationalization of results. With large discharges of the Po River, the runoff penetrates deeply into the interior of the Adriatic and partly turns northward. With the small Po discharges, the runoff is primarily entrained northward contributing to a well defined western coastal surface layer of low salinity, rich in plankton. In some occasions both optical and IR sensors have been used to obtain a more frequent observation.

The planktonic environment is deeply affected by the river runoff variability as a result of the amount of nutrient influx.

Statistical significance of this analysis must be improved by extending the data set to include all of the CZCS imagery of the period 1978-1985. By extending the analysis to the entire Adriatic and Ionian seas the results may be significant in the perspective of the entire eastern Mediterranean dynamical and biological interaction mechanisms, patterns and variability. This detailed study included a careful study of algorithm for atmospheric corrections and the collection of all the available atmospheric and oceanographic data.

The atmospheric influence of the interannual variability is appearing from the yearly averages, indicating for 1979 a smaller spreading of chlorophyll, as compared to the 1980 average. Most probably this is connected to a relatively dryer summer and therefore to a smaller runoff.

The wind field effects, while they can be noticeable in short time spans (hours - days) in the monthly and annual averages seem to be rather ineffective in modifying pigment distribution. In many occasions, wind gusts such as the bora, which blows over short periods of time, have prevented the development of eutrophication blooms (with its catastrophic effect of dead fish for anoxia) by creating active mixing and forcing the currents southwards.

The series of Landsat images have been analyzed to map suspended matter in the Venice Lagoon as Fig. 4 shows.

Several bio-optical studies have been undertaken in few institutes to better understand the bio-geochemical processes explaining the indicated signals, their distribution and variability.

2.2 Optical sensing of atmospheric parameters

While the atmosphere poses serious problems for ocean colour remote sensing, creating a high noise over the sea surface signals, this noise represents an interesting signal for the study and monitoring of some atmospheric parameters.

Air pollution chemistry and dispersion, its modelling and monitoring is the subject of research by a few institutes of Northern and Central Italy, where the impact of anthropogenic emissions of air pollutants leading to regional haze and acid deposition is a serious concern.

Aerosol studies have been made with optical and IR remote sensing, for quality and quantity analysis in the vertical atmospheric column and atmosperhic turbidity and water vapour have been measured for corrections in sea surface observations.

For aerosol monitoring and analysis two narrow (<10 nm) band centered at 610 and 868 nm would greatly increase the capability of an ESA 13-channel OC sensor as proposed in the OCWG first publication (ESA BR-20 June 1984, Table 9).

In general, it is felt that for clouds, mountain snow and aerosols, the OCM channels, implemented with the two mentioned channels would become a multi-purpose observation system.

2.3 Development of optical sensors

In Italy a particular interest has been the development of fluorescence lidars and spectrometers for discrimination of sea-surface parameters such as yellow substance, chlorophyll, oil slicks or surfactants. These instruments are developed for air and ship-borne applications.

One of these has been called FLIDAR-IROE-2 which couples the characteristics of a passive high resolution spectrometer and a high resolution fluorescence lidar. It covers the spectrum from UV to near-IR by means of a laser pumped by a XeCl excimer laser. The receiver is a telescope provided with a grating spectrometer, the output of which is ready by a gatable detector array (512 channels) (see Fig. 4).

For the measurement of atmospheric parameters such as water vapour, particulate, diffuse and global spectral solar radiations, in the proposed satellite bands, a spectroradiometer with rotating band has been developed and used extensively, intercalibration workshops have been organized in mountain locations for solar radiation instruments intercomparison and the establishment of a standard. The data from the spectroradiometer are used in the analysis of data from the NOAA, AVHRR, SPOT and LANDSAT.

An idea is being considered to provide with such radiometers most ferry boats regularly crossing the Italian seas and possibly, the Mediterranean. This could provide a space-time coverage of the Mediterranean atmospheric-oceanographic research and application.

Italy is the leading country of EUROMAR Working Group on Remote Sensing which is concerned with the development of new instruments and techniques (including software) of ocean and related atmospheric measurements from space as well as from aircrafts, ships, buoys, coastal stations. The program of this international activity, starting in 1987, is being elaborated through a series of planned meetings. EUROMAR is part of the European Community's EURECA programme.

3. APPLICATION ACTIVITY

The responsibility of environmental control in Italy is of each regional administration, while the general national directives are given by the Department of the Environment created in 1985 and residing in Rome. An intensive activity of young government employees is taking place in these agencies to obtain the basic information for juridical and operational decision making. As a consequence there is a considerable interest for the potentials of remote sensing as a source of information for the dynamics, the evolution and monitoring of environmental conditions. Few research institutes, by means of contracts, have been given the task to provide the technology for a practical use also of Ocean Colour from future satellites as part of a long range program.

A decade ago the Region of Emilia-Romagna has organized yearly symposia on coastal and offshore pollution and eutrophication which represents a major threat to the seasonally populated beaches in the northern Adriatic Sea. In each occasion there was a particular session on remote sensing.

The first requirement is the creation of standards and reasonable thresholds and tolerances for air and water pollution. The second requirement is the routine monitoring for control and enforcement of reappraised regulations.

In Genoa, on the other side of Italy, international meetings have been taken place to discuss programs for the second Mediterranean Decade of research for the protection of the common sea.

The topics:

a) application of environmental impact assessment as a tool to ensure "clean" coastal development activites.

b) Safety of maritime navigation - reduction of sea transports of toxic substances.

c) Disposal of liquid and solid wates in the sea.

d) Protection of coastal historical sites of common interest.

e) Reduction of the danger of acid rains.

Rational planning and coastal zone monitoring have been discussed in the PAP (Priority Action Plan). This includes surveys of trends of population influx to the coastal strip, impact of large cities, industries, seasonal tourism,erosion, inadequate use and preservation of historical cores, sewage disposal facilities.

All these factors depend on the capacity of the sea to treat wastes and on the dynamic and chemical interaction of the sea with the coastal properties.

In the Veneto Region (facing the northern Adriatic Sea), satellite images and remote sensing information are being used for a variety of routine land, river and sea observations. With Yugoslavia the ASCOP program is formulated by an intergovernmental commission. Italy is contributing monthly measurements from 12 coastal observation stations.

One of the problems of the industrialized Venetian area is the dumping of wastes in the sea (among which calcium phosphates with traces of heavy metals and polluted muds).

4. CONCLUSIONS

In Italy OC monitoring on a routine basis would provide one of the most important sources of water quality and dynamics information for scientific and real time applications. The availability of high space resolution on special requests is desirable.

Two more narrow band (less than 5 nm) channels could provide more information on atmospheric parameters (water vapour and aerosols).

The users request satellite data together with a related software for the analysis and description of specific water quality conditions.

The Italian regional administrations are interested in establishing adjourned standards and regulations for ocean and air pollution. The study of variabilities and trends depend on the capability of satellites to furnish the necessary information with time-space data.

5. REFERENCES

Barale, V., C.R. McClain & P. Malanotte-Rizzoli, 1986. Space and time variability of the surface color field in the northern Adriatic Sea, JGR, Vol. 91, No. C11, 12957-12974.

6. SELECTED BIBLIOGRAPHY

Alberotanza, L., V. Barale and A. Bergamasco, 1985. Nimbus 7 CZCS images as inputs in circulation modelling of the North Adriatic Sea, Il Nuovo Cimento, Vol. 8C, No. 6, Nov.-Dec., 1985, 621-630.

Alberotanza, L. and A. Zandonella, 1980. Landsat imagery of the Venetian Lagoon: a multitemporal analysis, In: "Oceanography from Space", J.F. Gower (ed.), Marine Science, Vol. 13, 421-428.

Burlamacchi, P., G. Cecchi, P. Mazzinghi and L. Pantani, 1983. Performance evaluation of UV sources for Lidar fluorosensing of oil spills, Appl. Opt., 22, 48.

Castagnoli, F., G. Cecchi, L. Pantani, I. Pippi, E. Radicati, C. Susini, P. Mazzinghi and A. Barbaro, 1985. Remote sensing of oil on the sea: Lidar and passive IR experiments, In: Proc. EARSeL/ESA Symp.: "European Remote Sensing Opportunities", ESA SP 233, 121, ESA, Paris.

Castagnoli, F., G. Cecchi, L. Pantani, I. Pippi, B. Radicati and P. Mazzinghi, 1986. A fluorescence Lidar for land and sea remote sensing, In: "Laser Radar Technology and Applications", SPIE 663, 212, Bellingham.

R. Guzzi, R. Rizzi and G. Zibordi, 1987. Atmospheric correction of data measured by a flying platform over the sea: elements of a model and its experimental validation, Appl. Opt. (in press).

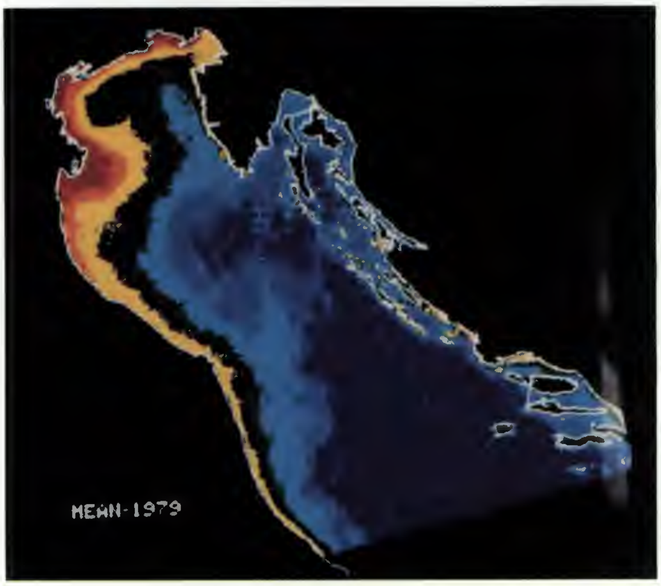
Guzzi, R., G. Maracci, R. Rizzi and A. Siccardi, 1985. A spectroradiometer for ground based atmospheric measurements related to remote sensing in the visible from satellite, Appl. Opt., Vol. 25, 2859.

Rizzi, R., R. Guzzi and R. Legnani, 1982. Aerosol size spectra from extinction data: the use of a linear inversion method, Appl. Opt., Vol. 21, No. 9, 1578-1587.

Van Stokkom, H.T.C. and R. Guzzi, 1984. Atmospheric spectral attenuation of airborne remote sensing data. Comparison betzeen experimental and theoretical approach, Intern. J. of Remote Sensing, Vol. 5, 925-938.

7. FIGURES

1. Barale - Interannual variability.
2. Barale - Seasonal variability 1979.
3. Barale - Seasonal variability 1980.
4. Alberotanza - MSS analysis of the Venice Lagoon.
5. Pantani - Flidar.



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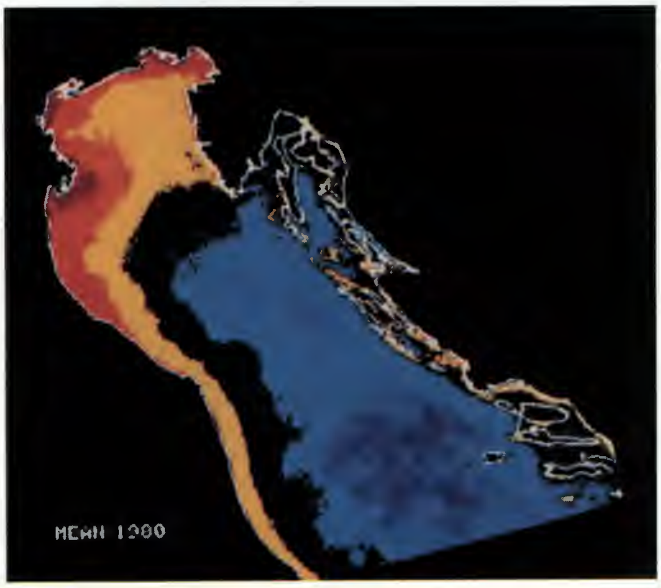

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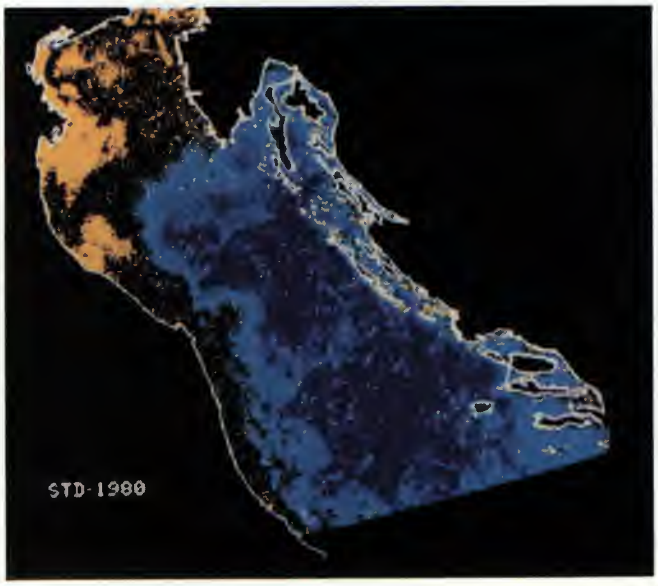

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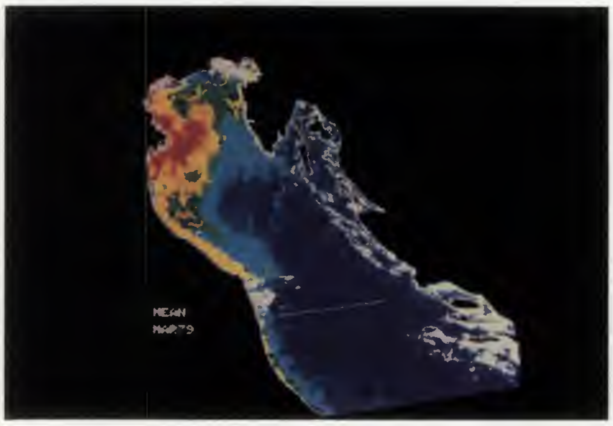
Figure 1. *(Barale &al.)* Interannual Variability: Average conditions of the surface colour field in the northern Adriatic Sea: 1979 yearly mean (a) and standard (b) deviation of phytoplankton pigment concentration and 1980 yearly mean (c) and standard (d) deviation of pigment concentration. The colour coding ranges from blue <0.30 mg/m^3 to red >3.4 mg/m^3. Imagery selection and processing were carried out at NASA/GSFC. Sea truth data collected by CNR Venice fluorometer campaigns provided 69 out of 110 images atmospherically corrected (Gordon &al.). The discarded images are those excessively affected by clouds, aerosols and low solar elevation.



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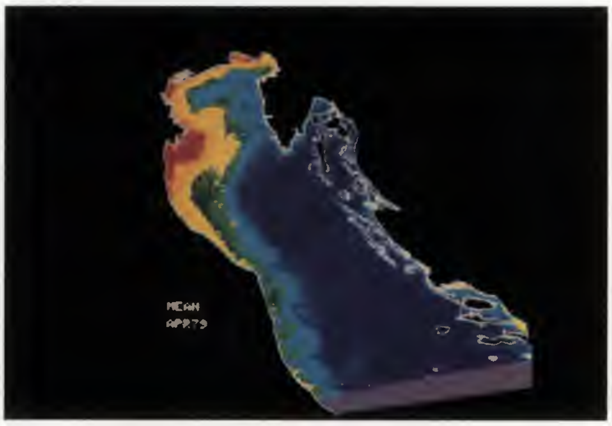

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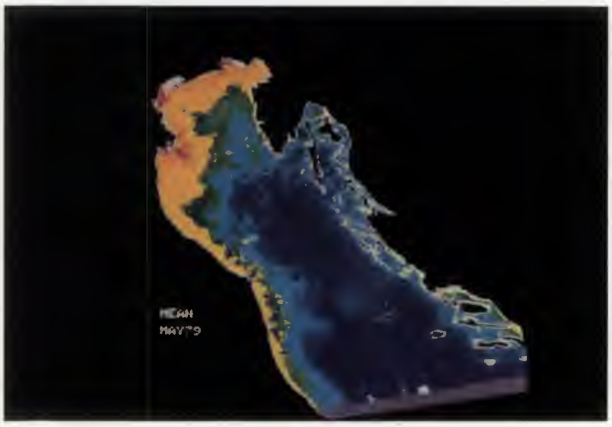

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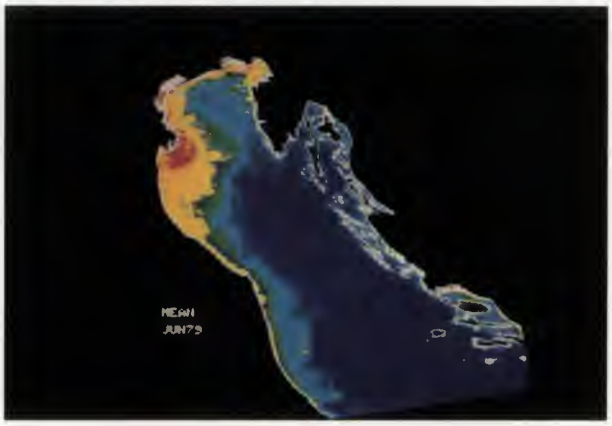

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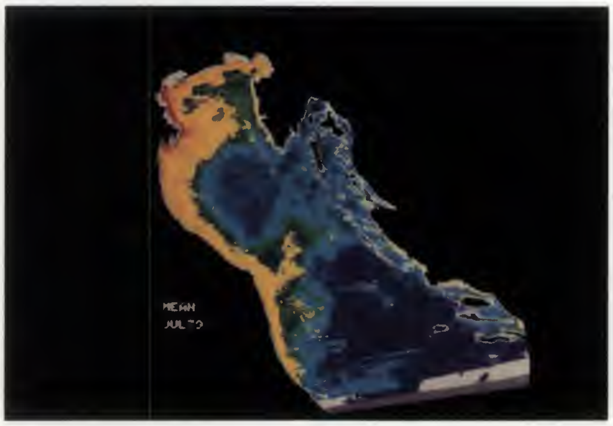

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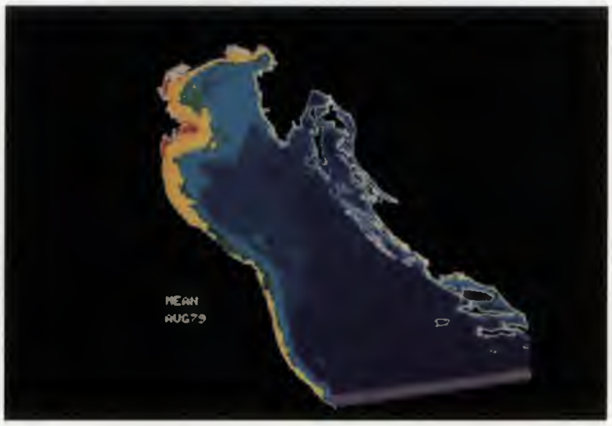

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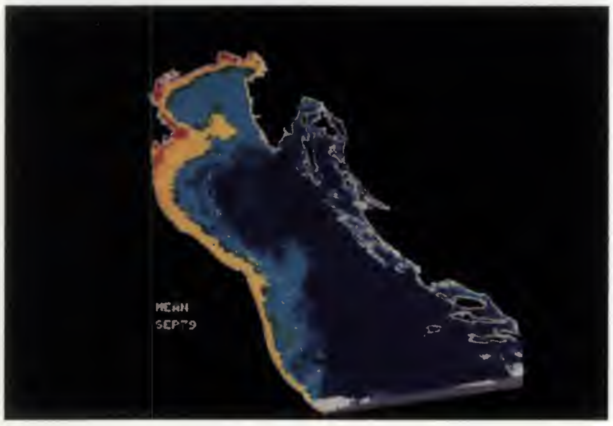

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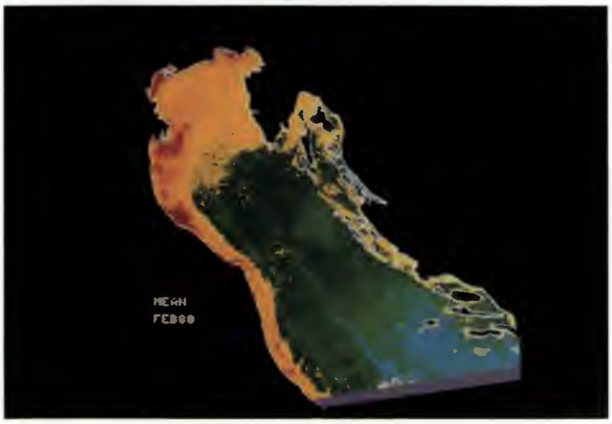
Figure 2. *(Barale &al.)* Seasonal development of the surface colour field in the northern Adriatic Sea for 1979. Monthly mean images of phytoplankton pigment concentration: (a) March, (b) April, (c) May, (d) June, (e) July, (f) August, and (g) September. Same colour coding as for Figure 1.



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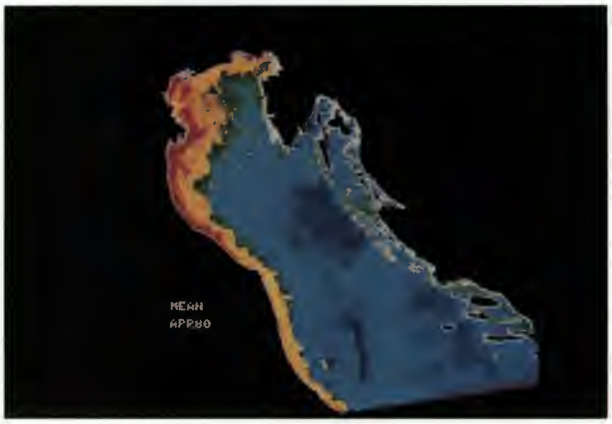

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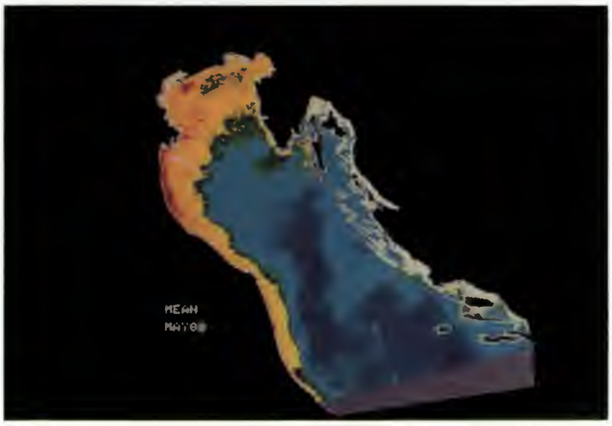

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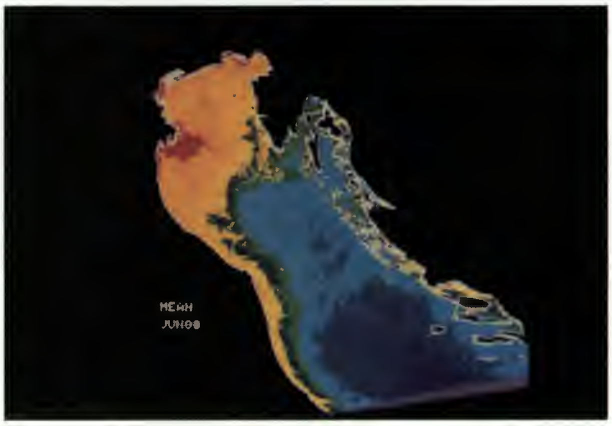

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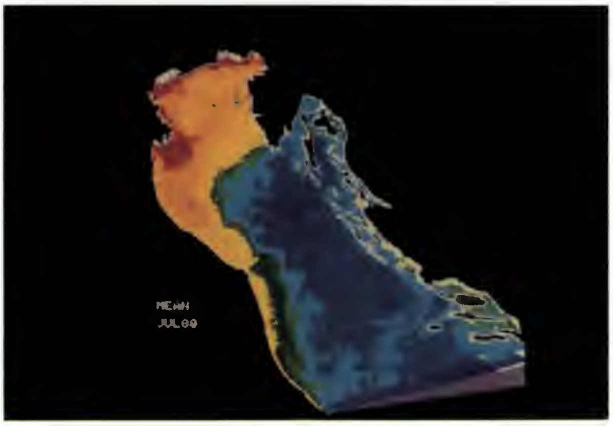

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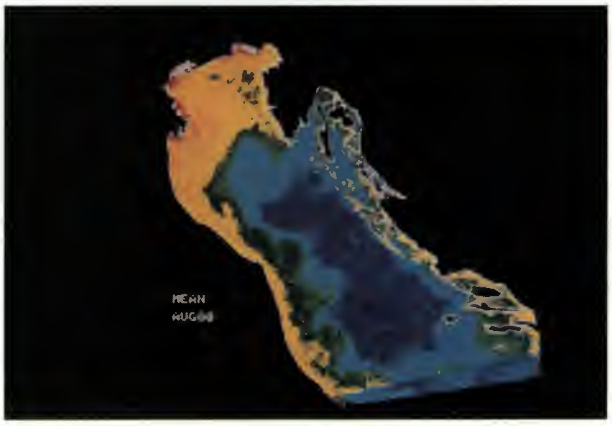

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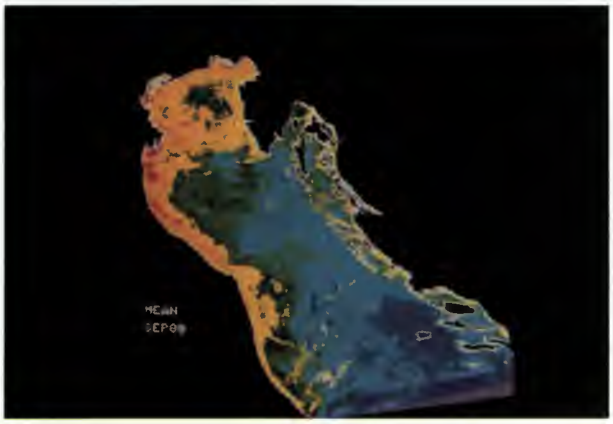

Figure 3. *(Barale &al.)* Seasonal development of the surface colour field in the northern Adriatic Sea for 1980. Montly mean images of phytoplankton pigment concentration: (a) February, (b) April, (c) May, (d) June, (e) July, (f) August, and (g) September. Same colour coding as for Figure 1.

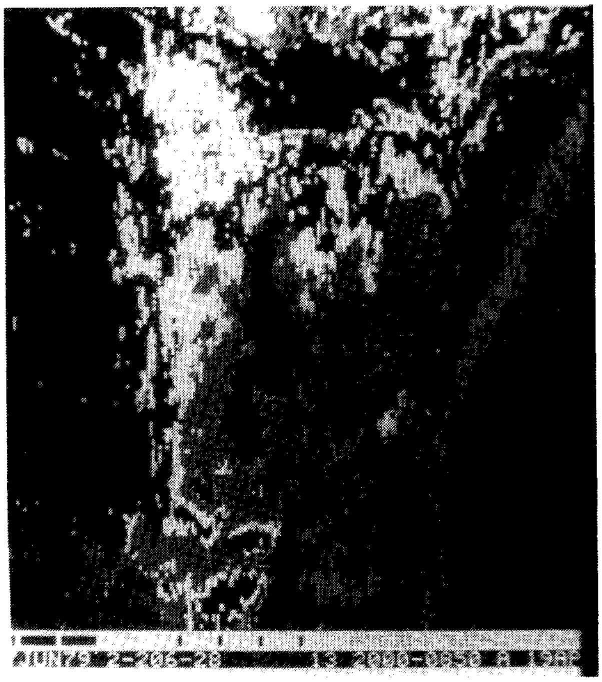

Figure 4. Venice Lagoon, suspended matter of different origins (industrial, agricultural etc.) mapped by means of Landsat-2 MSS images. (*Courtesy Dr. L. Alberotanza, ISDGM*).

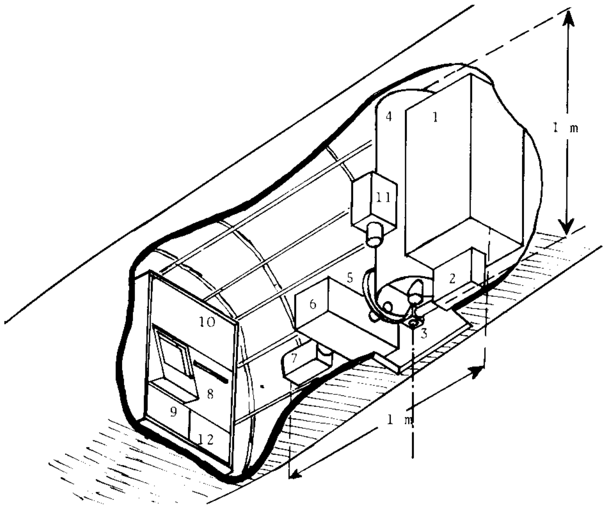

Figure 5. Sketch of the FLIDAR IROE-2 inside a small aircraft. 1: Excimer laser. 2: Dye laser. 3: Mirror. 4: Telescope. 5: Output optics. 6: Monochromator. 7: Detector. 8: Control console. 9: Cooler. 10: Inverter. 11: TV camera. 12: TV recorder. The TV system is used as a reference for the instrument data; the synchronisation is given by the console clock.

REMOTE SENSING ACTIVITIES IN IRELAND

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ABSTRACT

Interest in applying Remote Sensing techniques to quantify chlorophyll levels in Irish waters is developing. Techniques are being developed to monitor Irish lakes.

Keywords: Lakes, Ireland, Chlorophyll, Remote-sensing.

Irelands interest in monitoring its water resources arises from its extensive coastline (3000Km) and large area of jurisdiction which extends to about five times its landmass or about 18% of European jurisdiction waters. In addition Ireland has over 4000 inland water lakes whose trophic conditions it requires to monitor under its lake water quality management program. (Table 1).

It is perhaps because of the relatively low levels of pollution in its coastal waters, that both policy and resources for coastal zone management receive low national priority. The develoment of a European Community Marine Science and Technology program in Coastal Processes could have an important impact on national activity in this area.

By contrast, the level of pollution in a small number of inland waters has led to the investigation of the use of remote sensing to monitor the level of planktonic algal production in Ireland's inland waters. This investigation succeeded in developing a usefull relationship between chlorophyll values and Landsat MSS Band 4 and Band 5 data. (The relationship took the form ($Chl = aL_4 - bL_5 + c$) where L_4 and L_5 are the band 4 and 5 corrected radiances.) However the difficulties of making atmospheric corrections, and of the limited coverage due to clouds, constrain the development of an operational lake monitoring programme based exclusively on Landsat data.

Following a preliminary report (1) by An Foras Forbartha (the Irish National Planning and Physical Institute) a research program involving collaboration with University College Dublin has commenced. This involves the construction of a spectral signature measurement system which will be used in a low altitude airborne campaign along with a ground truth monitoring program in order to investigate the relationships between chlorophyll levels and reflectances under the differing lake turbidity and suspended solid conditions which occur. It is intended that this research activity will be extended in the future to estuarine research. There are also research proposals for the application of remote sensing to the Shannon estuary involving collab-oration between the GKSS (Geesthacht) and An Foras Forbartha.

2. REFERENCES

(1) McGarrigle, M.L., and Reardon, B.C., "National Survey of Lakes by Remote Sensing", Preliminary Report, An Foras Forbartha, St. Martins House, Waterloo Road, Dublin 4. July 1986.

	Quantity	Remote Sensing activity
Inland Waters	4000 lakes	ongoing
Estuaries	1 major + ~6 others	proposed
Ocean Zone	$>4x10^5$ Sq.Km jurisdiction	none

Table 1.

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

OCEAN COLOUR MONITORING IN NORWAY

K. Kloster, O.M. Johannessen, F. Rey & K. Sørensen

CMI Fantoft, Nansen Senteret Solheimsvik,
IMR Bergen & NIVA Oslo, Norway

Ocean colour monitoring activities in Norway are only of recent date and yet at a preliminary phase. Some work has been done in getting and processing tapes from Nimbus-7 Coastal Zone Colour Scanner (CZCS) in order to obtain support for two Norwegian oceanographic projects NORSEX and NORMARSEN. Also some calibration attempts have been done for measuring chlorophyll in coastal areas off the Western coast of Norway and similar work is planned to be carried out in the near future for the Barents Sea and coastal waters off Northern Norway.

Until today the following institutions are getting involved in ocean colour monitoring.

Christian Michelsen Institute (CMI), Bergen

CMI is mainly concerned with the implementation of algorithms for an image processing system CMI-BILD. Work being done at CMI includes:

- tape reading with geometric correction for tilt of sensors, earth rotation and panoramic distortion;
- empirical correction of sensor degradation;
- substraction of Rayleigh scattered radiation and Mie scattered radiation by the method of zero water radiance in channel 4 (CZCS);
- display of CZCS images showing colour index (channel 1/channel 3).

Nansen Centre for Remote Sensing and Oceanography, Bergen

This Centre works in close cooperation with the Geophysical Department of the University of Bergen and has plans for utilising ocean colour monitoring as support for several climatologic/oceanographic projects, both at national and international levels. Its main interest is concentrated in the northern Norwegian Sea and Arctic Ocean.

Institute of Marine Research Directorate of Fisheries, Bergen

The main activities of this Institute is fisheries and marine environmental research. Remote sensing activities here have increased considerably in the past few years and a lot of interest has arisen by the possibility of using ocean colour monitoring techniques for mapping chlorophyll in oceanic waters. Some of the research programmes that include OCM in their plans are:

- distribution of fish egg and larvae along the Norwegian coast;
- marine ecological investigations in the Barents Sea, a part of the national Programme on Marine Arctic Ecology (PROMARE);
- monitoring red tides in Norwegian fjords and coastal waters, as part of a warning system for aquaculture activities.

Norwegian Institute for Water Research (NIVA), Oslo

This Institute is mainly concerned with inshore waters and fjord activities. Its interest on OCM stems from the following research activities:

- monitoring of oil pollution in Norwegian fjords and coastal waters;
- eutrophication in Norwegian fjords and coastal waters;
- mapping of spatial and temporal variations in algae biomasses; red tides;
- spreading of fresh water outflows into coastal areas in Southern Norway;
- mapping of benthic algae in the tidal zone;
- comparison and relationship of large-scale phenomena in coastal waters with small-scale phenomena in fjords.

The majority of the programmes outlined above include also an extensive field work at sea which gives an

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

outstanding opportunity to carry out the necessary calibration of the OCM sensors with true data. The contact persons for these activities who are also responsible for the present summary report are:

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- Ola M. Johannessen, Nansen Senteret, Edvard Griegsvei 3a, N-5037 Solheimsvik, Norway
- Francisco Rey, IMR, Postboks 1870, N-5011 Bergen-Nordnes, Norway
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NATIONAL REMOTE SENSING PROGRAMME (NRSP) OF THE NETHERLANDS

D. Spitzer

Ministry of Transport & Public Works
Tidal Waters Division, The Hague, The Netherlands

ABSTRACT

Structure and organization of the remote sensing are outlined. Priorities and projects are mentioned with respect to operationalization, commercialization, applied and fundamental research, technology development and infrastructure. Progress in remote sensing of ocean colour is enlighted. Ongoing and planned programmes are described. Future applications of the newly developed pushbroom airborne scanner CAESAR having spectral characteristic similar to the OCM, including the fluorescence channels, are emphasized. Underwater and low altitude radiometers were developed allowing an improved interpretation of the remotely sensed imagery.

Keywords: Ocean colour workshop, Netherlands remote sensing program, airborne scanner, underwater measurements.

1. INTRODUCTION

Remote sensing activities in the Netherlands are coordinated and stimulated by the recently reestablished Remote Sensing Program Board.
The objectives can be summarized as follows:

- Promoting of operationalization of the applications.
- Commercialization of the operational applications and services.
- Stimulation of the applied research.
- Reinforcement of necessary fundamental research.
- Promoting of technological developments.
- Improvement of infrastructure.

The program is scheduled and its financing is planned for five years (1986-1990).
The NRSP is based on the know-how and experience attained during past decades. The importance of further development and particularly of the operational applications is emphasized. This appears to be now achieveble due to the most recent (technological) developments in the field of the earth observations.

Within the framework of the program, following activities are being planned for the marine remote sensing.

1.1. Operationalization

- Available ground-based HF and microwave radar-systems will be tested and their potential for supplying of wave and current data will be evaluated.
- From the ERS 1 data-assimilation research, preparations will be done for the exploitation of the ERS 1 data for regional wave and wind forecasting models.
- Preparations will be done also for the global wave models and mid-term forecasting using the ERS 1 data.
- Application of the thermal imagery from the NOAA and ERS 1 satellites for coastal dynamics will be investigated.

1.2. Commercialization

- Marketing of the remote sensing products will be stimulated.
- Possibilities for the distribution of the remote sensing data on commercial basis will be studied.

1.3. Applied research

- A pilot study will be performed concerning the satellite radar-altimetry for climatology, global current and seastate measurements.
- Prior to the operationalization, the ERS 1 data assimilation for global and regional wind and wave forecasting models must be studied.
- Laser airborne bathymetry and waterquality monitoring methods will be investigated.
- Interpretation of the data from the passive optical remote sensing instruments in terms of the bottom composition and depth will be studied.

1.4. Fundamental research

- Laboratory measurements, modelling and algorithm development will be done in order to improve the accuracy of the ERS 1 wind scatterometer measurements.
- Study of interaction mechanisms behind the SAR and SLAR image formation for waves and bottom topography will receive also priority.
- For the interpretation of the optical remote sensing data, optimal algorithms for the suspended and dissolved materials concentration de-

termination will be further investigated.
- Study on the radiative transfer in (coastal) waters will be continued.
- Prior to the applications to the passive optical airborne and satellite imagery and to the active optical techniques, also the algorithms for the bottom depth and composition must be refined and attuned.
- Study on the radiative transfer between the waterbody and the remote sensor (atmosphere) will be performed.
- Emphasis will be put into the research concerning the interpretation of airborne multispectral imagery with respect to the newly developed airborne scanner CAESAR with spectrum characteristic similar to the one as proposed for the OMC, including the fluorescence channels.

1.5. Technology development

- Resulting from previously gained experience and available expertise, a C-band multipolarization SAR is to be developed.
- Further development of active airborne optical and TIR instruments in addition to the CAESAR is being considered.
- Advanced data processing methods will be developed.

1.6. Infrastructure

- Data distribution of present (Landsat, SPOT) and future (ERS 1) satellites must be optimalized.
- Relevant information on the remote sensing potentials and applications must be widely distributed and provided to all users.
- An instrument pool will be organized.
- Education on the remote sensing principles and applications will be supported.

2. PROGRAMMES

Passive optical techniques are of interest for monitoring and management of the Netherlands coastal regions. Projects are performed and being planned by the Rijkswaterstaat of the Ministry of Transport and Public Works in cooperation with the Royal Netherlands Meteorological Institute, the Netherlands Institute for Sea Research, and universities of Amsterdam and Delft.
These projects concern studies on radiative transfer in the water and in the atmosphere, digital image processing, research on the spectral properties of the various aquatic dissolved and suspended materials and the algorithm development.
Fundamental research on the optical remote sensing of water is coordinated by a special working group of the Remote Sensing Program Board.
Recent achievements include results of theoretical and experimental studies, both in laboratory and during campaignes in Dutch and Indonesian (Snellius II expedition) coastal waters.
Influence of the yellow substance fluorescence and absorptian properties was treated (Refs. 1,2).
Chlorophyll fluorescence effects were investigated with respect to its potential for remote sensing (Ref.3)
Algorithms for remote sensing of the bottom depth and composition in shallow waters were predicted and tested (Ref. 4), based on an extensive radiative transfer model treatment (Ref. 5) including the fluorescence and stratification effects.

2.1. Interpretation of optical remote sensing data above coastal waters

Objectives:
a) Development of (local) algorithms from radiative transfer modelling in combination with the sea truth concerning the sediment load, pigment concentration, primary production, pollution, bottom depth and composition.
b) Testing of these algorithms using the in situ and low altitude radiometric measurements.
c) Quantitative interpretation of available satellite and airborne imagery.

Timescale: 1987 - 1991

Activities:
a) Model study and calculations.
b) Regular recalibration of the underwater and airborne optical instruments.
c) Data processing, determination of spectral signatures and algorithms.
d) Image processing.
e) Presentation of the results, publication.

2.2. Theory of radiative transfer in the sea including fluorescence, stratification, bottom and surface effects.

Objectives:
a) Development of useful models describing the in and above water optical processes.
b) Development of inverse models for interpretation of the optical remote measurements.
c) Evaluation of the maximum achievable accuracy of the remote optical measurements.

Timescale: 1985 - 1989

Activities:
a) Analytical and numerical solutions of the radiative transfer problem in terms of spectral (ir)radiance.
b) Introduction of the input parameters like the water column and bottom composition, including their variability.
c) Inverse computations using both, experimental data and solutions.
d) Presentation and publication of the results.

2.3. Processing of Landsat TM imagery for mapping of the bottom depth and composition in Dutch coastal regions.

Objectives:
a) Interpretation of the available TM imagery in terms of bottom depth and composition using the appropriate algorithms developed.
b) Evaluation of the mapping accuracy and horizontal and vertical resolution.

Timescale: 1986 - 1988

Activities:
a) Image selection and processing including the atmospheric corrections.
b) Attuning of the algorithms.
c) Production charts from the imagery.

2.4. IMERSE: Indonesian Marine Environment Remote Sensing Experiments, in cooperation with German (DFVLR) and Indonesian (LAPAN) institutions.

Objectives:
a) Investigations on the feasibility of the application of the RS techniques for the observation and description of the coastal dynamics and marine biological processes in the humid tropical regions.
b) Development of appropriate algorithms for the satellite and airborne remote measurements of the concentrations of the suspended and dissolved materials in the investigated areas of the sea.
c) Study on the pollution distribution retrieval from the remote measurements.
d) Supply of the relevant synoptic data supporting the discrete measurements (sampling) performed from the research vessels.
e) Correct interpretation of the available satellite imagery with respect to the present and future applications concerning the marine environment.

Timescale: 1984 - 1988

Activities:
a) Campaigns including airborne and shipborne operations and sampling within the framework of the Snellius II expedition.
b) Processing, analysis and joint interpretation of the in situ, airborne and satellite data.
c) Presentation of the results at workshops and symposium.

2.5. Development of integrated LIDAR system for remote sensing of coastal regions.

Objectives:
a) Development of an airborne active optical scanner for bathymetry purposes in West European coastal regions.
b) Specification of possibilities and accuracy of determination of watercolumn and seasurface parameters by such a system.
c) Proposal of an operational system.

Timescale: 1986 - 1989

Activities:
a) Feasibility studies concerning the laser transmitter and detector technology.
b) Radiative transfer study.
c) Laboratory and in situ experiments.
d) Design proposal of the system.

2.6. Investigation of optical properties of surface waters.

Objectives:
a) Evaluation of non-linear effects influencing the interpretation of remote sensing data.
b) Evaluation of variability of the measurements.
c) Optimalisation of the sea truth measurements.

Timescale: 1987 - 1990

Activities:
a) Spectroscopic, flowcytometric and scattering measurements on selected water samples.
b) Laboratory simulation of remote sensing procedures.
c) Field experiments.
d) Presentation of results.

2.7. Optical Radiative Transfer Water and Air.

Objective:
a) Improvement of the radiative transfer modelling through the atmosphere in relation to the remote sensing.

Timescale: 1986 - 1990

Activities:
a) Study of the radiative transfer theory and its numerical solutions.
b) Study on the optimal airborne and satellite observation methods in relation to solar conditions, wavelength, direction and polarization.
c) Presentation of results.

3. INSTRUMENTS

3.1. CAESAR: CCD Airborne Experimental Scanner for Applications in Remote Sensing

In the framework of the National Remote Sensing Programme of the Netherlands, a CCD Airborne Experimental Scanner for Application in Remote Sensing, called CAESAR has been built. The project has been executed by the National Aerospace Laboratory NLR. The TNO Institute for Applied Physics TPD has been subcontracted for the development of the sensor part of the system. The project was financed by the Ministry of Education and Sciences. The definition phase has been started in October 1981. The final tests were completed in 1986.

User requirements

The CAESAR scanner should be configured both for land observation (in particular vegetation) and for observation of (sea)water colour. The technical constraints were that only one CCD detector would be available for each spectral channel, that only commercially available CCD's would be used and that standard object-lenses would be applied as imaging optics.

As a result of background research programmes for land observation three spectral bands have been selected positioned at center wavelength values of 550, 670 and 870 nm respectively. The optical system should be dimensioned in such a way, that corresponding with the integration time required to obtain a ground resolution in flight direction of 0.5 m at nominal flight altitude, a radiometric resolution of a noise equivalent value for a reflectance difference of 0,5% would be achieved during the growth season between 10 a.m. and 4 p.m. local time.

For the detection of the spectral distribution of the upwelling radiance from (sea)water, the user requirements differ considerably. Instead of three spectral bands, eight bands within the range between 400 and 1100 nm are required. Averaging over consecutive pixels and a longer integration time are needed in order to reduce signal variation due to local variations of specular diffuse sky reflectance caused by the moving water surface. The dynamic range of the radiance contribution from the water is relatively small compared to the case of land observation. In order to detect small intensity differences, a noise equivalent value for the reflectance difference of 0.05% is required.
It was decided to select the same set of spectral bands within the available spectral region as defined for the Ocean Colour Monitor, a candidate optical instrument for a future ESA remote sensing satellite.
In particular for sea observation absolute calibration of the sensor output signals is required. By using two spectral bands in the near infrared part,

the radiance contribution due to atmospheric path radiance and surface sky glint is measured for each pixel.
The spectral bands in the visible part of the spectrum are positioned in such a way that an improved discrimination may be achieved between chlorophyll present in phytoplankton, the so-called yellow stuff and other anorganic matter and pollutants. The scan plane should also be tiltable up to an off-nadir angle between 10° and 20° in order to avoid detection of direct sunglint.
The user requirements for land and sea observation are summarized in the table.

Sea observation	Land observation
Band 1: 400-420 nm	Band 1: 535-565 nm
Band 2: 435-455 nm	Band 2: 655-685 nm
Band 3: 510-530 nm	Band 3: 845-895 nm
Band 4: 555-575 nm	
Band 5: 620-640 nm	Instead of three discrete
Band 6: 675-695 nm	bands, spectral correla-
Band 7: 770-800 nm	lation filters for soil,
Band 8: 990-1050 nm	green vegetation and clear
(measured twice)	deep water can be used.
NE $\Delta\rho \leq 0{,}05\%$ for all bands	NE $\Delta\rho \leq 0{,}5\%$ for all bands
Spatial resolution: 0,5x0,5 m (minimal)	Spatial resolution: between 10 and 20 m
Total field of view (nadir looking): 25.7°. Instantaneous field of view: 0.26 mrad.	

Configuration of the sensor system

During the different trade-off studies it was concluded that the optimum choice would be a cluster of 4 cameras. Each camera should measure in three spectral channels. The measurements in 3 different spectral bands could be realised by means of field separation and the insertion of spectral filters mounted in front of each of the 3 CCD's. By aligning three cameras in nadir direction, for land observation a high accuracy of the interband registration could be obtained by using for instance the central CCD's. For sea observation the combination of the 3 cameras provided the required 9 bands for which the triplets of forward, nadir and aft looking channels are already geometrically registered. The system software should be applied off-line for averaging by increasing the pixel size and for interband registration of all channels. The module containing the three cameras could also be tilted along the same axis.
A cut-away view of the design of the CAESAR camera module is shown in figure 1. The field separation for the forward and aft looking channels is minimized by means of reflection prisms. The pushbroom scan principle and the consecutive scanning in the object space by means of three CCD's per camera for sea observation is illustrated in figure 2.

Realisation and flight testing

Figure 3 shows the the CAESAR sensor system. Three identical CCD camera modules are mounted on a common base plate and are protected by means of a box. This downlooking box is mounted in a support structure. Beside the three modules, a forward-looking module is mounted within the support structure.
The internal temperature of both modules can be maintained at a nominal level by means of a flow of dry cooled air. This is required in case of operations in tropical regions.
The electronics, the inertial navigation platform and the high density recorder are mounted in removable racks inside the aircraft. The first in-flight tests have been executed in 1984 for initial performance testing of the integrated system. Figures 4 and 5 represents examples of raw images in sea mode. No geometric and radiometric corrections have been applied, except the real time roll correction.

Radiometric calibration and preprocessing

The CAESAR system has been calibrated relatively and absolutely. For a calibration of the sensor part, a dedicated facility has been built. For each detector element and each spectral band the response function is measured, including the measurement of the darkcurrent. By means of a calibrated detector the radiance at the entrance pupil of the CAESAR modules is determined, providing input data for the absolute calibration.
Equally important is the radiometric calibration, for all channels, of the analog to digital conversion. By the NLR for this purpose an electrical calibration facility has been built.
During the data preprocessing systematic corrections are applied for the removal of radiometric and geometric errors. Time, aircraft position, velocity and attitude data are measured by an inertial navigation platform during flight recorded together with CAESAR sensor data.
Geometric correction software developed earlier for preprocessing of airborne side-looking radar data, has been modified in order to comply with the different scanning geometries of the down- and forward-looking channels of CAESAR. Geometric distortions are to a large extent removed using platform data. After the preprocessing images from different spectral channels and different dates of overflight can be registered. Precision registration can be performed as a next step by means of ground control points. In such a way CAESAR data can be used as overlays for existing map projections.

3.2. Radiometers

Underwater measurements

The investigations on the spectral properties (i.e. the absorption and scattering signatures) of natural waters, resultimg into establishment of the relationships between the upwelling optical signals and the composition of the watercolumn, so called "colour algorithms", are preferably to be performed near surface underwater. Doing this, no influence of the surface reflection (glitter) and of the atmosphere is accounted, though experimental constrains are introduced by wave motion. Optimal depth of the measurements must be chosen, depending on the seastate, possible stratification of the watercolumn and on the solar conditions. Both, upwelling and downwelling spectral irradiance must be measured in real time, giving then the quasi-inherent reflectance. The spectral behaviour of the reflectance depends on the composition of the seawater (sea truth). Inversly, the absorption and scattering signatures and hence the concentrations of the suspended and dissolved materials can be derived from the reflectance. Short duration of a spectral scan is crucial, with respect to the horizontal and vertical instability of the watermass and to the variability of the incident solar radiation.

The developed Advanced Spectral Irradiancemeter (ASIR) can scan simultaneously 22 spectral channels between 400 nm and 720 nm within several seconds. Spectral bandwidth of each channel is within 10 nm. Radiation is collected by two cosine diffusers at each side (up and down) on the instrument mounted in gimbals. The upwelling and downwelling irradiance are simultaneously detected and recorded on board by means of an HP data acquisition and storage system controlled by microcomputer. Variations of the incident solar radiation are recorded by a separate instrument mounted at the top of the measuring platform (vessel). Irradiance depth profiles, characteristic for the structure of the water-column, can be recorded at a single chosen channel as well.

Spectral measurements above water

When large spatial diversity of aquatic conditions and/or influence of the glitter and of the lower part of the atmosphere are investigated, measurements are to be performed above water. In order to allow the comparison between the underwater reflectance with the upwelling radiation recorded above the seasurface, rapid detection of downwelling irradiance and of downwelling radiance in the sun-detector plane is needed along with the measurements of the upwelling radiation. From a set of the collected radiance data, corrected for the glitter and atmospheric effects and related to the sea truth, algorithms and their variability can be studied. The instrument can be mounted on a stable platform (turret) above water, or preferably employed from a survey aircraft flying at low altitudes. Spatial resolution (angle of view) must be chosen accordingly to the expected horizontal inhomogeneity of the surface layer and to the wave amplitude and frequency. Fine spectral resolution of the measurements allows then final tuning of the algorithms.

Coastal Remote Sensing Airborne Radiometer (CORSAIR) was constructed employing a zoom objective lens for the radiance measurements, cosine collector for the downwelling irradiance measurements, liquid light guides, automatic optical switch and correction filters assembly, detector, polychromator, optical multichannel analyser, console and a microcomputer system providing rapid data acquisition and storage. Field of view and tilt of the objective can be adjusted. 125 channels between 400 and 720 nm can be scanned within 32 ms.

4. CONCLUSIONS

Interests of the Dutch users community in development and application of the optical remote sensing techniques are obvious. Programmes are being performed by various institutions and supported by the National Remote Sensing Program Board. Instrumentation both in situ and airborne is available for validation and calibration experiments in relation to the satellite measurements.
International cooperation and participation in large projects for preparation of the future ocean colour satellite missions is to be emphasized.

REFERENCES

1. Spitzer D & Dirks RWJ 1985, Contamination of the reflectance of natural waters by solar-induced fluorescence of dissolved organic matter, Appl Opt, 24, 444-445.

2. Buitenveld H et al 1986, Shape and variability of the absorption spectrum of aquatic humus, Proc 7th Int Symp ISPRS, 703-706.

3. Spitzer D & Dirks RWJ 1986, Chlorophyll fluoresence effects in the red part of the reflectance spectra of natural waters, Cont Shelf Res 6,385-395.

4. Spitzer D & Dirks RWJ 1987, Bottom influence on the reflectance of the sea, Int J Remote Sensing, in press.

5. Dirks RWJ & Spitzer D 1986, On the radiative transfer in the sea including fluorescence and stratification effects, Limnol Oceanogr, in press.

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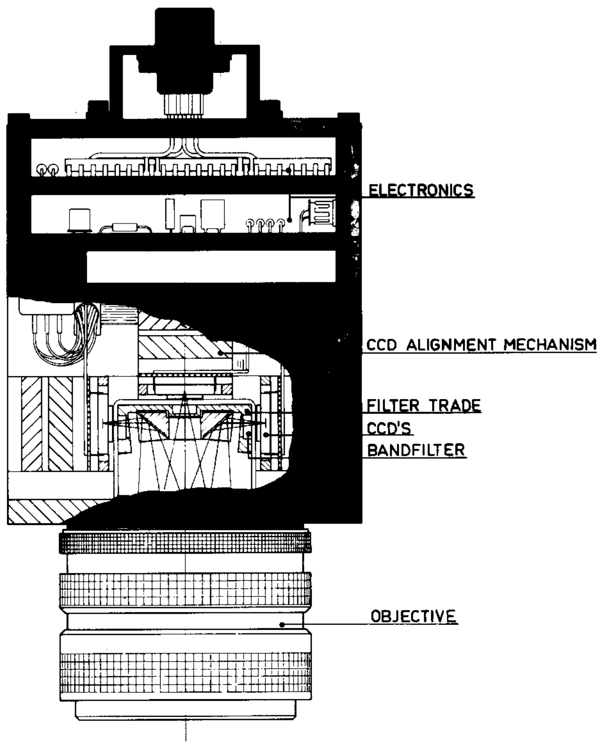

Fig. 1 CAESAR CCD camera module.
The main components are the standard object-lens, the spectral separation, the band-filters, the CCD detectors and the detector electronics

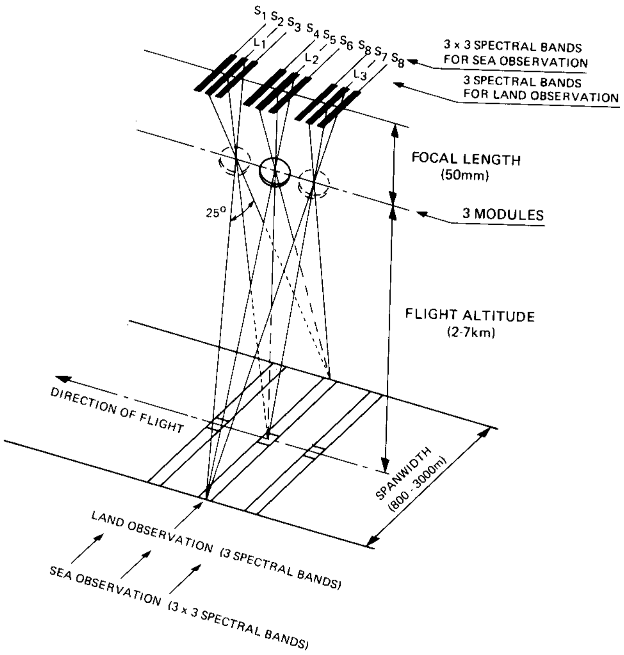

Fig. 2 Pushbroom scanning for land observation with 3 co-registered (central) channels of the modules; for sea observation all 9 channels (3 x 3 co-registered) are used

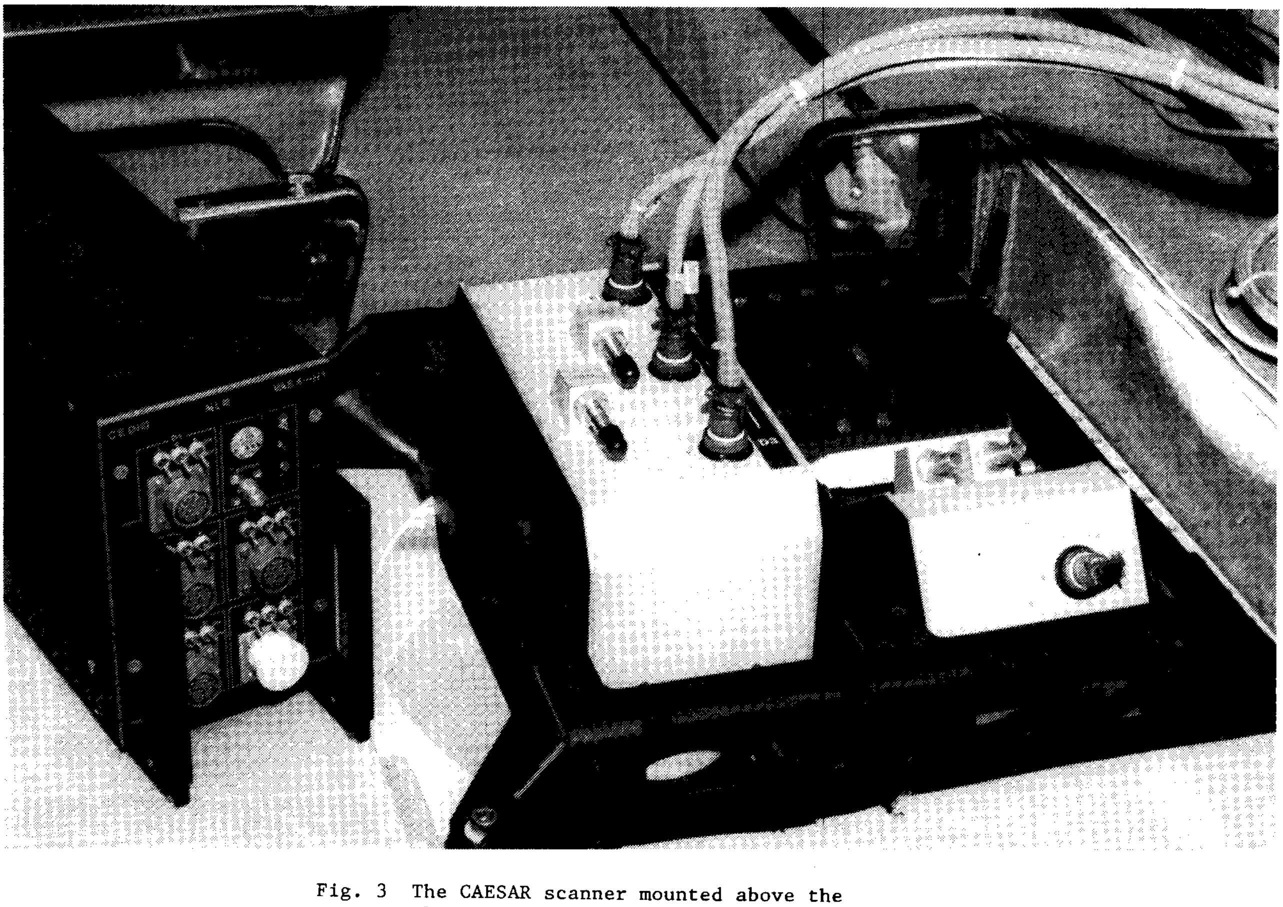

Fig. 3 The CAESAR scanner mounted above the observation window in the aircraft with the digitizer on display

Fig. 4 CAESAR 3 x 3 channels.
Raw data via look up tables.
Oosterscheldedam May 1986

Fig. 5 CAESAR 3 x 3 channels.
Raw data via look up tables.
Scheveningen May 1986

DEVELOPMENTS IN OCEAN COLOUR RESEARCH IN THE UNITED KINGDOM

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ABSTRACT

Activities within the U.K. in the field of Ocean Colour remote sensing are reviewed. Some present work is described, and the objectives for continuing research during the next decade are presented. Requirements for ocean colour sensors are outlined. Finally some of the U.K.'s co-ordinated programmes for marine science, having an ocean colour component, are mentioned, and some details are given of the Ocean Fluxes Study.

1. INTRODUCTION

Ocean colour research is a relatively small but thriving component of the oceanographic remote sensing activity within the U.K. An informal Ocean Colour Working Group of UK scientists exists to promote this work and to foster collaboration in the development of data processing techniques for atmospheric correction and ocean parameter interpretation. In November 1985, under the auspices of the Natural Environment Research Council (NERC), an Ocean Colour workshop was held at Southampton University to define the objectives of U.K. ocean colour research in the next decade, and the associated requirements for sensor developments. All research groups with an interest in ocean colour were represented and the outcome was a report (Ref. 1) prepared for the NERC. Much of the material in this paper is based on that report, particularly the review of recent activities in section 2, the statement of objectives and sensor requirements in section 3, and (in section 4) the definition of a preparatory programme which is desirable if full advantage is to be taken of the opportunities for satellite ocean colour remote sensing promised in the next decade.

The above report was produced in the context of wide-ranging discussions within the remote sensing community to define the U.K. requirements for the Polar Platform element of ESA's Columbus Programme. To enable all aspects of ocean remote sensing to be considered, a "Columbus Ocean Workshop" was held at Southampton in July 1986, initiated by the British National Space Centre. This provided input to a report (Ref. 2) from the Columbus Ocean Science Panel, which includes a discussion of the role of ocean colour within a coordinated programme of Oceanography from Space.

Two re-organisations of scientific management structure in the U.K. deserve note since they promise to provide for the more effective promotion of coordinated ocean remote sensing exercises. The formation of the British National Space Centre (BNSC) has provided a single focus for U.K. Space developments, so that the community of scientists concerned with ocean applications of remote sensing now has a clearly defined route for influencing the planning of future earth observation missions. At the same time, a restructuring of the NERC, which included the establishment of a directorate of marine science with responsibility for all oceanographic science at a variety of Institutes, has made possible the more effective planning of multidisciplinary marine science research programmes. Within these programmes the role of remote sensing can be clearly defined, and in some cases aspects of the programme can be directed towards improving the calibration of remote sensing techniques. Those aspects of NERC's marine science programmes in which Ocean Colour is important are described in section 5 of this paper.

2. RECENT PROGRESS IN OCEAN COLOUR RESEARCH

Interest in ocean colour remote sensing has grown steadily within the U.K. over the last decade, particularly since CZCS data have been available from the University of Dundee Satellite Receiving Station (Ref 3.). An archive of most NW European CZCS overpasses is held (including some data not held in the NASA archives) and the rapid and easy availability of this information has encouraged the development of a user community amongst physical and biological oceanographers. Every oceanographic establishment within the UK now contains a group or an individual with an interest in the subject.

Most of the research work has been driven by the needs of oceanographic science applications rather than its pace being forced by sensor technology developments. Pioneering work has been performed by Pingree's group at Plymouth in demonstrating how colour imagery can be exploited in dynamical studies of shallow sea processes

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

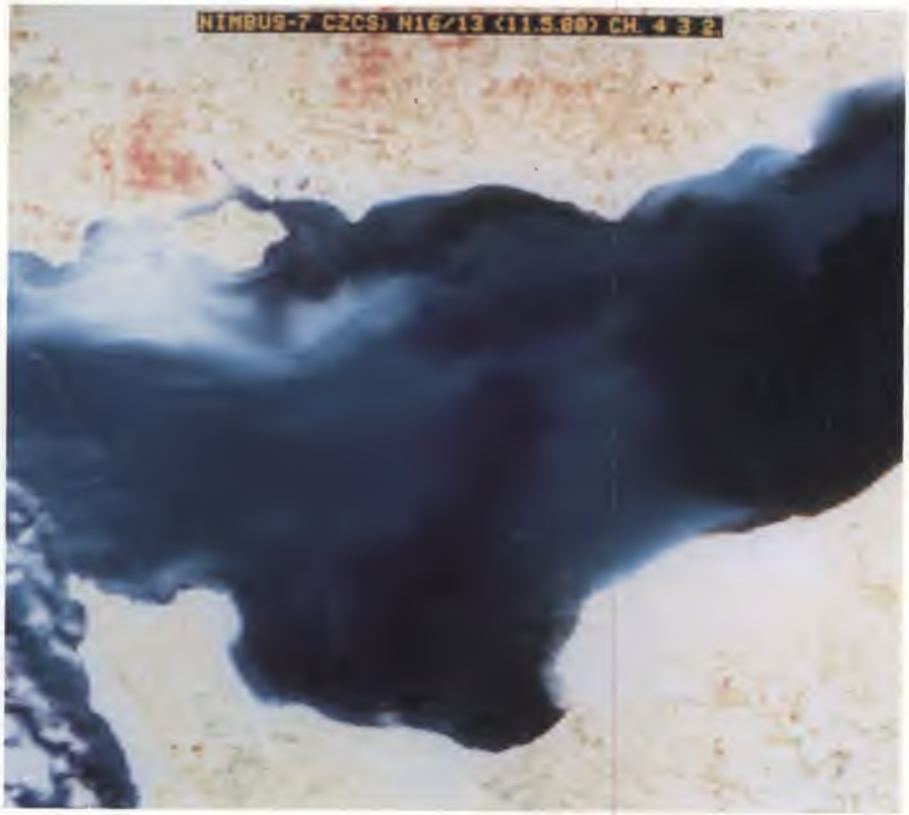
NIMBUS-7 CZCS; N16/13 (11.5.80) CH. 4 3 2

Figure 1 A geometrically corrected CZCS image (Channels 4, 3, 2) of the Eastern English Channel on May 11th, 1980, one of a series of similar images for this month, which have been studied for information they contain about water circulation and dynamical processes. The short banded structure to the south of the Isle of Wight gives an indication of the scale and orientation of both the tidal and residual circulation. The dark patch near the coast of Southern England indicates a different water mass to that of the lighter patch further offshore.

Figure 2 A principal components analysis of the four visible channels (1-4) of the same image as figure 1 classifies various water masses in the English Channel having similar spectral signatures. Such an image can provide some indication as to the origins and circulations of water masses. For example, in the North Central part of the Channel the offshore water (labelled white) has its origins to the west and is distinguished by a high chalk or clay seston picked up to the west of the Isle of Wight. This is in agreement with theories about the dynamics of the region. However, the inshore water, labelled blue, appears to originate in the east, contrary to expectations based on previous work in the area. Subsequent in situ observations have supported the evidence of the image which has prompted further investigation of seasonal variability of residual circulation.

(Refs 4,5), whilst systematic surveys of colour data are revealing seasonal patterns of water circulation and mixing in the English Channel (Ref 6 and Figs 1 & 2). In this case the satellite information has prompted a return to conventional observing techniques to confirm hypotheses suggested by the colour data. Regional studies of plankton distribution have also been significantly assisted by CZCS imagery, confirming the location of enhanced productivity at shelf sea fronts or above the continental edge (Ref 7). A particular emphasis of the UK marine biological applications (Ref 8,9) has been the detection of coccolithophore blooms which generate a high optical reflectance across the whole of the spectrum, and do not conform to the typical spectral signatures assumed for standard chlorophyll retrieval algorithms. Interest has now extended beyond the shelf seas to the N. Atlantic where biological and dynamical processes are being studied in association with NASA.s Ocean Basin Carbon Fluxes Programme (Fig 3).

In support of these ocean applications of CZCS there have been developments in data processing techniques (Ref 9,10) for sensor calibration and atmospheric correction, and the production of calibration algorithms for chlorophyll pigment concentration in the U.K.'s case two waters (Ref 11). The search for effective atmospheric correction and water quality calibration of CZCS data has promoted renewed interest in *in situ* optical measurements. Instruments to measure subsurface irradiance and reflectance have been built at UCNW, Bangor (Ref 11), MBA, Plymouth (Ref 12) and IOS, Wormley.

In addition to research utilizing the CZCS, further achievements have been made in the application of Landsat (MSS and TM) data to studies of suspended sediments in estuaries (Refs 13,14), plankton blooms (Fig. 4) and pollution in coastal waters. For the last few years airborne remote sensing campaigns using a Daedalus multispectral scanner have been sponsored by NERC and some of the experiments have overflown estuarine regions, applying the observations of water colour to the detection of suspended sediment (Refs 15,16) or sea outfall discharges (Ref 17).

3. OBJECTIVES AND SENSOR REQUIREMENTS FOR THE NEXT DECADE

The UK ocean colour science community has defined (Ref 1) a set of objectives to aim for during the next decade, in relation to both scientific applications and the potential for commercial exploitation. Tentative though these are, they enable the requirements for sensor developments to be stated.

3.1 Scientific goals

The scientific objectives are primarily those which have evolved out of the work described above, but specific problems have been identified as requiring solution. In addition new fields of study have emerged, and it is clear that there is a firm demand within UK oceanographic science for a continued provision of ocean colour data from space. The fields of study will be considered separately:-

3.1.1. Primary productivity. A limited goal is to estimate chlorophyll concentrations from improved ocean colour algorithms which will need to be site- (and possibly time-) specific to cope with the variety of plankton species and the other water constituents (yellow substance and inorganic sediments) found in UK Case 2 waters. At the least it will be possible to detect the patchiness of plankton populations and their time variability over time scales of weeks or longer. However the more ambitious goal is to measure productivity , and research is needed to determine whether this can be done directly from ocean colour measurements.

3.1.2 Biogeochemical flux studies can also benefit from ocean colour measurements of chlorophyll or productivity. Only satellite measurements can provide the synoptic spatial view, and the global coverage, which flux studies require, and this will make access to ocean colour data from space essential for many more oceanographers than presently take an interest in them. This will be discussed further in the context of UK multidisciplinary research programmes (section 5).

3.1.3 Inorganic Seston is clearly revealed in colour images of the Shelf Seas around Britain but the quantitative estimation of suspended sediment concentration from colour data will need further research. Initially the collection of *in situ* water quality and optical data is required simultaneously with remote sensing of ocean colour. This must then lead to the modelling and improved understanding of optical processes to determine what spectral sampling is required to distinguish the sediment from chlorophyll, yellow substance or any other content of the water.

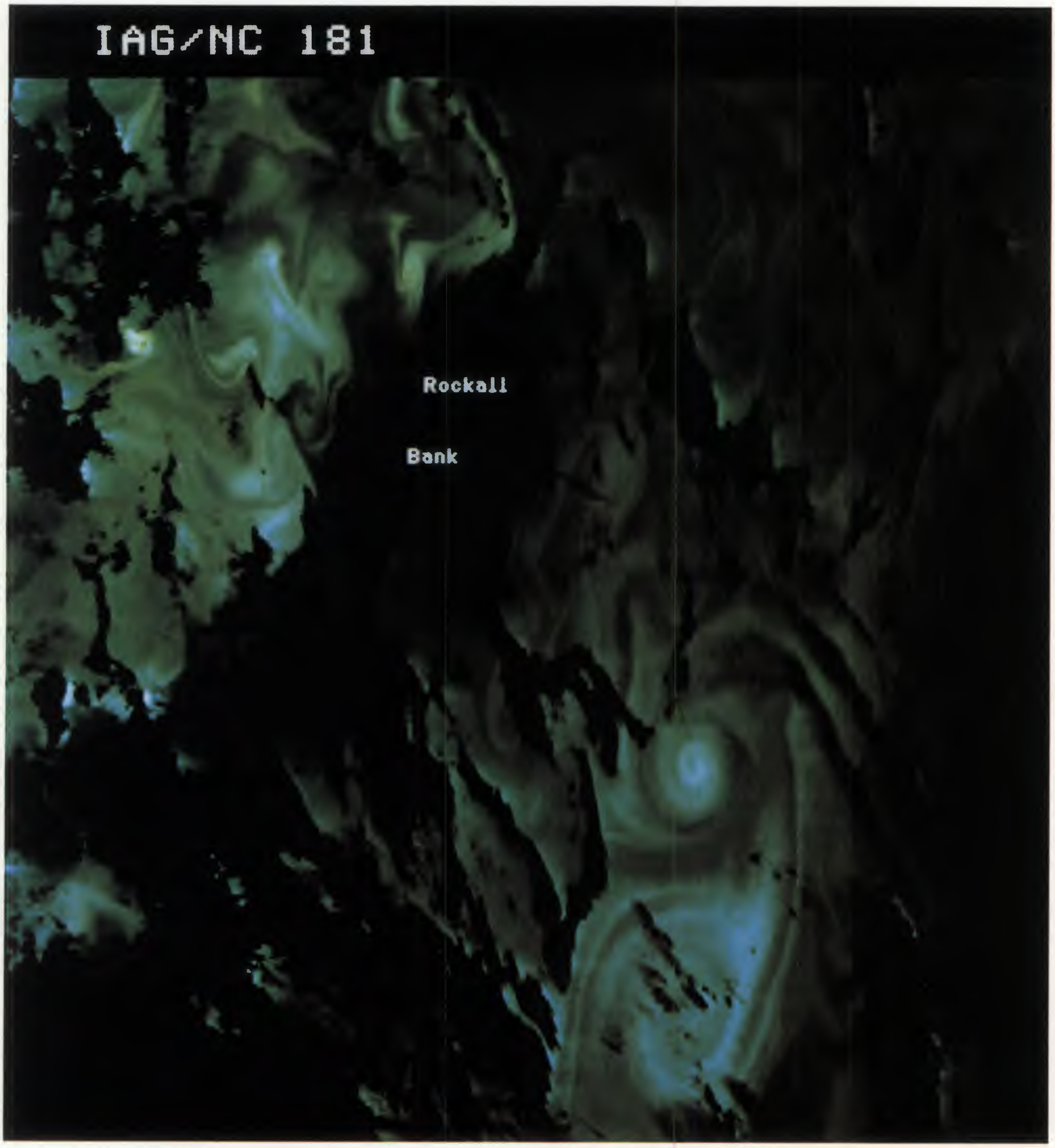

Figure 3 1 August 1980 512 x 512 scene to the west of the UK showing coccolithophores over much of the N.E.Atlantic except over the Rockall Bank. The image is a colour composite of Rayleigh and aerosol corrected channel 3, 2 and 1 reflectances. The colour differences may be interpreted as variations in the relative abundances of free coccoliths and living cells which respectively cause backscatter and absorption and can act as tracers for dynamical processes. An eddy pair is amongst the many features which can be detected in this image between the clouds (which are black).

3.1.4 Ocean dynamics, particularly the study of mesoscale features, ocean eddies and frontal systems which often have a distinct colour signature, will benefit from future ocean colour missions. UK dynamical oceanographers have a particular interest in the N.W. Atlantic, the Rockall Trough, the Iceland-Faroes Front and the Norwegian Sea. Since these are often cloud covered it is important that accurate techniques are made available for locating small cloud-free areas which may have no distinctive landmarks for control points, so that images can be accurately registered to build up mosaics and overlays on other types of imagery (e.g. thermal). Further study is also intended of the extent to which optical properties of the water derived from colour imagery can be used in modelling the penetration of solar heating in the upper ocean.

3.1.5 Shallow sea dynamics can also be studied using colour as a tracer for water masses and their movement. In the tidally dominated British waters the sampling interval achieved by a satellite will not resolve tidal advection but the tidal mean distribution of tracers which have a colour signature can be studied from colour imagery. The goal of such work will be the deduction of horizontal dispersion and mixing coefficients in vertically well mixed seas, by matching satellite data to appropriate models.

3.1.6 Coastal Processes. Most of the previous fields of study anticipate the continued provision of CZCS-scale images whereas coastal processes, such as beach erosion, sediment transport, discharge plumes from outfalls and rivers, plankton blooms in estuaries etc., require much higher spatial resolution. In the UK there is a significant community of coastal scientists, geographers and engineers who will pursue this work independently of mainstream ocean science programmes.

3.1.7 Polar applications. Despite the difficulties of using ocean colour measurements in the poorly illuminated polar regions, polar oceanographers in the UK have identified several study areas where they intend to exploit satellite data if possible. These include the detection of polynias and biological activity within them, the definition of meltwater plumes and their dispersion and mixing characteristics, and the observation of meltwater fronts in the marginal ice zone.

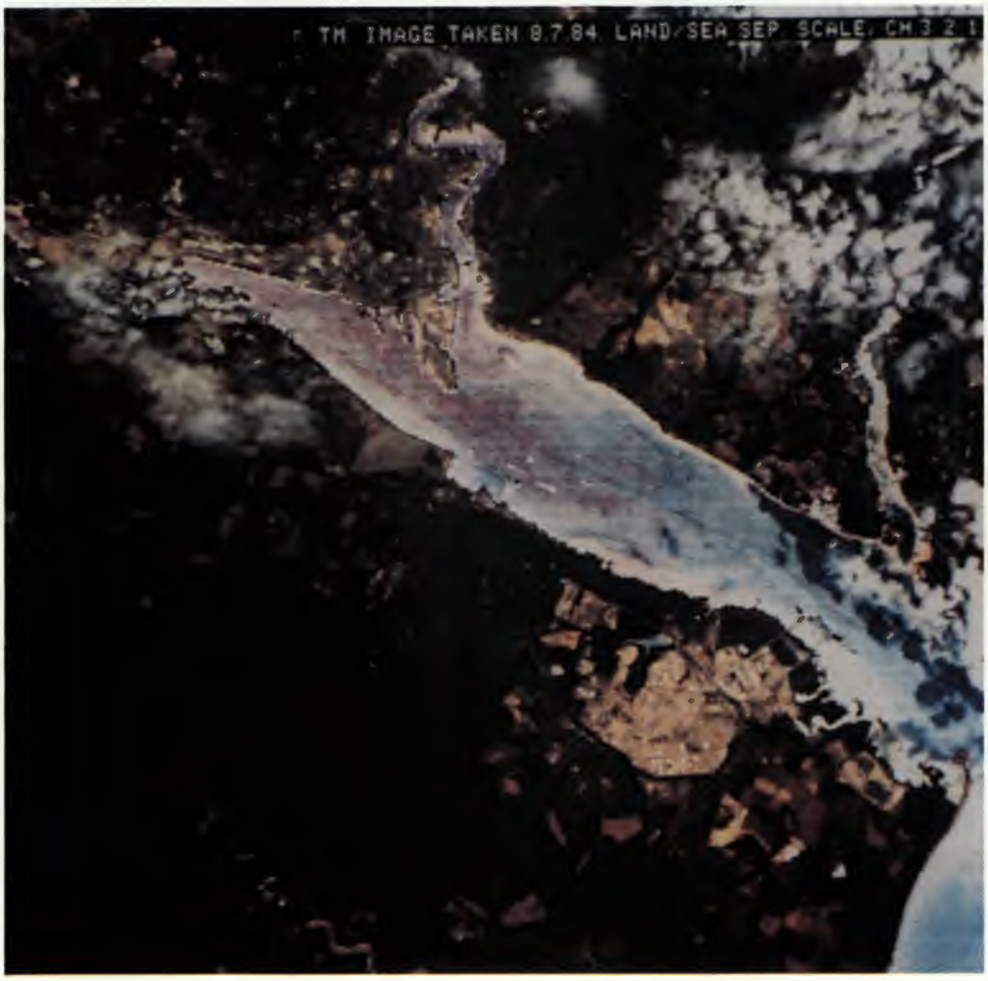

Figure 4 A Landsat TM image (False-colour composite Channels 3, 2, 1) of Southampton Water on 8th July 1984. The red regions are believed to show the distribution of Mesodinium rubrum, a species that has been under study in Southampton water for some years. Mesodinium have a very distinctive red colouration with strong blue-green absorption and high red reflectance. As a result blooms appear to be readily detectable from the TM sensor. The satellite data give synoptic coverage not afforded by observations made at ground level and enable more objective measurements to be made of the extent of blooms.

Figure 5 1 May 1986 600 x 1000 scene of the North Sea comprising a colour composite of Rayleigh and aerosol corrected channel 3, 2 and 1 reflectances. The aerosol correction was performed using the Viollier algorithm for non zero $R_w^{670} = 0.15\ R_w^{550}$, which is not valid for sediment rich water. The colour of the sediment laden water to the South is therefore suspect. To the North the dark patches are probably due to phytoplankton absorption and the sinuous dark feature is probably related to the Flamborough Head front.

3.2. Commercial exploitation

Whilst the primary benefit envisaged in the next decade from continued ocean colour measurements from space is perceived to be scientific, there is a concern in the UK to ensure that the increased scientific knowledge is applied in the commercial sector. A series of recent reports has addressed this question (Ref 18). Anticipated applications of ocean colour include the operational provision of colour charts to fisheries, or survey information for coastal engineering consultants. It is noted that whilst colour data cannot be provided operationally for European seas because of cloud cover, and may not offer coastal engineers much local information they do not already possess, the worldwide situation is different. The daily world coverage of ocean colour sensors offers the potential for improving the global competitiveness of European offshore environmental consultants, forecasters and engineers.

3.3 Sensor requirements

Given the above objectives for UK developments of ocean colour science, the requirements for future satellite sensor provision can be defined. In the following the first two categories represent the minimum specification to enable the present work based on CZCS and Landsat TM to maintain its momentum, whilst the last two point towards more ambitious sensor requirements.

3.3.1 Large swath sensors. To succeed the CZCS, the minimal requirement is for a sensor offering daily global coverage, with spatial resolution 500-1000m, six to eight 10-20nm bandwidth channels in the visible/near IR including bands centred at 443nm, 520nm, 550nm, 680nm and 780nm, and improved radiometric sensitivity and on-board calibration compared to the CZCS. The addition of a narrow band within the 700-800nm range is essential to improve atmospheric correction with a true "zero water leaving radiance" channel. In addition sun glint avoidance using a tilt facility is desirable and there will be advantages if a thermal IR sensor can scan the same scenes simultaneously.

3.3.2 High resolution sensors. For coastal and estuarine studies a continuation of the Landsat TM type sensor is required. It is inevitable that the prime purpose for which such a high resolution sensor is designed will be land applications. Nevertheless it is desirable that future sensors have improved spectral sensitivity, with at least some narrow channels to detect absorption bands and to define the blue/green ratio. For effective use over water the radiometric sensitivity should either be switchable from its coarser overland value, or have sufficient dynamic range to cope with the subtle variations of water leaving radiance without saturating over brightly illuminated land.

3.3.3 Sensors with high spectral resolution. If UK ocean colour science is to progress to detecting and distinguishing a variety of in-water constituents, sensors with high spectral sensitivity are required. These will be spectroradiometer type sensors, probably employing punch-broom array technology to sample a large number of very narrow bands, capable of detecting fluorescence.

For many applications it is also desirable that the temporal sampling be improved beyond existing capabilities. For the wide swath sensors, sampling which is more frequent than daily can only be obtained by having more than one satellite in operation at a time. For the high resolution sensor, daily (or better) time sampling might be achieved for limited time spans by off-track pointing.

3.3.4 Other sensor possibilities for which UK scientists have expressed an interest include the development of active optical instruments (lidars) and a sun-glitter sensor. It is difficult to envisage the former in the near future, and airborne experiments to evaluate lidar applications in bathymetric measurement, oil spill monitoring etc. will indicate whether the technique is worth considering for space applications. The sun glitter sensor would be a small-field colour scanner directed at the sun glint point which operated automatically in the absence of cloud. Its application is related to surface roughness rather than ocean colour and its suggestion has been inspired by the US Space Shuttle photography which revealed a wealth of oceanographic features in the glitter patterns.

4. OUTLINE FOR A PREPARATORY PROGRAMME

Given the inevitable delay before further colour scanners fly to replace the CZCS, the UK Ocean Colour Working Group also addressed the question of what programme of preparatory work should be commenced in order that maximum benefit could be derived from future sensors when eventually they are launched. In summary the elements of such a programme are:-

a) The processing, application and interpretation of CZCS archived data must continue. The wealth of archived material contains much valuable information and, as more scientists learn to use it, the oceanographic objectives of future ocean colour missions will become more focussed.

b) The implementation of standard atmospheric correction software packages for common use by workers accessing the Dundee CZCS archives.

c) Improvement of the UK capability for making *in situ* optical measurements. This will require improved underwater instrument design and the provision of adequate optical calibration facilities.

d) Improve algorithms for chlorophyll appropriate for different plankton species, and explore the possibility of direct productivity measurements. This will require *in situ* biological, chemical and optical measurements from research vessels, if possible combined sometimes with airborne scanner measurements.

e) Incorporation of colour measurements as standard in co-ordinated marine science programmes. This will enhance our ability in future to relate satellite colour observations to other oceanographic parameters.

f) Development of commercial applications. One way of achieving this is to organise demonstration programmes which foster the emergence of a commercial user community.

g) Improved training and education of young scientists will be necessary in order to meet the need for trained personnel when the next colour scanner is launched. This will include the training of young oceanographers in the processing and interpretation of colour data and in the use of *in situ* optical instruments. It will also mean educating remote sensing scientists and space technologists in the requirements of the oceanographic community.

5. INTERDISCIPLINARY OCEANOGRAPHIC PROGRAMMES

The Marine Sciences directorate of NERC is planning several interdisciplinary oceanographic programmes, including the following which have a significant ocean colour component.

5.1 North Sea Programme

Objectives: To develop a water quality model of the North Sea.

Timescale: 1987-92, with a 15-month ship programme in 1988-89.

Ocean colour work:

a) Analysis of CZCS archive to provide suspended sediment and chlorophyll distributions for particular areas (Fig. 5), and to use time-sequences of images to investigate the distributions of water properties with respect to mixing across fronts.

b) Airborne MSS (Daedalus) observations in support of ship programme.

c) If possible routine measurement of spectral reflectance along cruise tracks during monitoring survey legs of cruise programme.

5.2 Continental Shelf Break

Objectives: To investigate physical mixing processes at the shelf-ocean boundary and their effect on primary production and the exchange of water properties.

Timescale: Continuing interdisciplinary studies, no formal programme as yet.

Ocean colour work: Analysis of the CZCS archive to investigate chlorophyll and coccolith distributions during the summer months along the shelf break to the west of the British Isles. Apart from their biological/geochemical importance, coccoliths are also good indicators of physical dispersion/mixing processes.

5.3 UK Biogeochemical Ocean Fluxes Programme (BOFS)

Objectives: To understand the cycling of elements in the atmosphere - ocean - marine sediment system. To predict the chemical and biological consequences of natural and man-induced changes in the atmosphere - ocean system.

Timescale: 1987-92. Preparatory and pilot study phases leading to main field programme in the NE Atlantic Ocean in 1990-92 (to tie in with the next generation of satellite colour scanners).

Ocean colour work: In the pilot and preparatory phases:-

a) Development of biomass and production algorithms for oceanic waters, based on ship optical measurements.

b) Development of passive optical sensors for current meter moorings and drifting buoys to measure upwelling and downwelling irradiance.

c) Analysis of CZCS archive with particular reference to the different productivity/ sedimentation environments of the NE Atlantic, and to the proposed major study sites for 1990-92.

Description of the Programme: BOFS will be coordinated with comparable programmes in other countries as part of the Global Ocean Fluxes Study (GOFS). With emphasis on high latitude regions and on carbon cycling it will be complementary to WOCE (World Ocean Circulation Experiment). Considerable attention will be given to innovative technology and to the training of young scientists.

6. CONCLUSIONS

There is an active scientific community in the UK making use of available satellite ocean colour data, anxious to see a continuation of its provision following the termination of the CZCS, and interested in exploring the new measurement possibilities and associated applications which improved sensors promise. The availability of airborne MSS flights, and the commitment of the oceanographic community to programmes requiring some ocean colour measurements, confirms that ocean colour research will be maintained over the next decade, and there should be opportunities for fruitful collaboration with our partners in ESA.

7. REFERENCES

1. Robinson I S & Boxall S R 1986, *U.K. Ocean colour research in relation to the proposed Polar Platform*, Report for NERC contract No F60/G6/13.

2. IOS 1986, *Columbus Ocean Panel Final Report - 1986*, Institute of Oceanographic Sciences, Wormley, Surrey.

3. Bayliss P E 1983, University of Dundee satellite data reception and archiving facility, *Remote Sensing Applications in Marine Science and Technology, ed. A P Cracknell*, Dordrecht, D. Reidel Publ. Co., 29-34.

4. Pingree R D 1984, Some applications of remote sensing to studies in the Bay of Biscay, Celtic Sea and English Channel, *Remote Sensing of Shelf Seas Hydrodynamics, ed. J C J Nihoul*, Amsterdam, Elsevier.

5. Pingree R D, Mardell G.T & Maddock L 1985, Tidal mixing in the Channel Isles region derived from results of remote sensing and measurements at sea, *Estuarine coastal and Shelf Science*, 20, 1-18.

6. Boxall S R & Robinson I S 1987, Shallow sea dynamics from CZCS imagery, *Proc. Topical Meeting A3, 26th COSPAR Assembly, Toulouse 9-10th July, 1986.*

7. Holligan P M *et al* 1983, Satellite studies on the distributions of chlorophyll and dinoflagellate blooms in the western English Channel, *Continental Shelf Research*, 2, 81-96.

8. Holligan P M *et al* 1983, Satellite and ship studies of coccolithophore production along a continental shelf edge, *Nature*, 304, 339-342.

9. Groom S B & Holligan P M 1987, Remote Sensing of coccolithophore blooms. *Proc. XXVI COSPAR Meeting, Toulouse, 1986.*

10. Singh S M, Cracknell A P & Spitzer D 1985, Evaluation of sensitivity decay of CZCS detectors by comparison with *in situ* near-surface radiance measurements, *Int. J. Remote Sensing*, 6(5), 749-758.

11. Mitchelson E G, Jacob N J & Simpson J H 1986, Ocean colour algorithms from the Case 2 waters of the Irish Sea in comparison to algorithms from Case 1 waters, *Cont. Shelf Res.*, 5(3) 403-417.

12. Aiken J & Bellan I 1986, Synoptic Optical Oceanography with the Undulating Oceanographic Recorder. *Ocean Optics VIII, ed M.A Blizard, Proc. S.P.I.E.*, 637, 221-229.

13. MacFarlane N & Robinson I S 1984, Atmospheric correction of Landsat MSS data for a multidate suspended sediment algorithm, *Int. J.Remote Sensing*, 5, 561-576.

14. Robinson I S & Srisaengthong D 1981, The use of Landsat MSS to observe sediment distribution and movement in the Solent coastal area, *Application of remote sensing data on the continental shelf*, ESA SP-167, 221-232.

15. Collins M B & Pattiaratchi C B 1984 Indentification of suspended sediment in coastal waters using airborne thematic mapper data. *Int. J.Remote Sensing*, 5, 635.

16. Anderson J M, McManus J & Evans H 1986, The detection of sediment laden water masses and their associated thermal fronts in the Tay Estuary using the airborne MSS system, *Proc. NERC 1985 Airborne Campaign Workshop, 26 Nov 1986*, C, 1-13.

17. Davies P A *et al* 1985, The application of remote sensing techniques to the monitoring of a sea outfall system. *Int. J. Remote Sensing*, 6(6), 967-973.

18. Oxford Computer Services Ltd., Reports, 1985. Satellite ocean colour scanners, their performance, application and potential for commercial exploitation.

a. Robinson I S Volume 1 - Ocean colour remote sensing.

b. Aranuvachapun S and Robertson Y C Volume 2, Part 1 - Case studies: ocean colour imaging.

c. Robertson Y C , Robinson I S , Aranuvachapun S and Thomas J O Volume 2, Part 2 - Potential for commercial applications.

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Recent Research Activities supported by ESA

THE USE OF CHLOROPHYLL FLUORESCENCE MEASUREMENTS FROM SPACE FOR SEPARATING CONSTITUENTS OF SEA WATER

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ABSTRACT

Chlorophyll-a, a pigment common to all marine algae, shows a sun stimulated fluorescence line peaking at 685 nm wavelength. This spectral feature is detectable from air-planes at all chlorophyll-a concentrations at least down to a chlorophyll-a content of 1 g m^{-3} also in turbid coastal waters. For space applications absorption by atmospheric gases for wavelengths above 688 nm forces a fluorescence channel to the shortwave part of the fluorescence line. The influence of non-chlorophyllous suspensions and of Gelbstoff on fluorescence is rather small. Also the fluorescence efficiency dependence on insolation is small at sun elevations above 20 - 30°, the typical remote sensing conditions. The report concludes with a list of recommendations for a future space application.

1. INTRODUCTION

The chlorophyll molecule in plants plays the central role in photosynthesis of land plants and marine algae. It absorbs sunlight in broad spectral bands covering - differently for different chlorophyll types and accessory pigments - the visible spectrum. The absorbed sunlight is either used directly for photosynthesis or for heating, however, a small part is given back to the environment via fluorescence, peaking at 685 nm wavelength for chlorophyll-a. Since this type of chlorophyll is common to all marine algae it should be possible - if the fluorescence signal can be detected - to find a specific spectral feature for phytoplankton. This would allow the measurement of phytoplankton mass, the base of the marine food chain, at the presence of other admixtures to sea water.

1.1 Historical Review of Chlorophyll Fluorescence

Although chlorophyll fluorescence has long been used via flash-light induced fluorescence to estimate phytoplankton concentration in-situ, only during the last ten years remote measurements became available showing the sun-stimulated chlorophyll-fluorescence at 685 nm both from measured upward radiances just below the sea surface (Ref. 1) and from an airplane (Ref. 2 and 3). While Neville and Gower, taking their data 1975 over Saanich Inlet off the coast of Canada, applied polarizers and viewed the surface under the Brewster angle, Doerffer, 1976, looking without polarizers 20° off the nadir direction, did not suppress surface reflection. As an example for the basic feature for this report, namely the chlorophyll fluorescence peak, we include in Figure 1 measured reflectance spectra of the sea for not at all exaggerated chlorophyll concentrations over three different coastal waters.

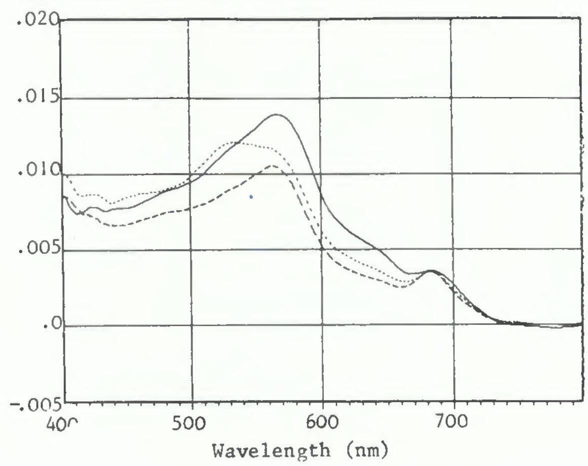


Figure 1: Reflectance spectra from FLUREX'82 (Baltic Sea, April 20, 150 m height), Saanich Inlet (---) and Satellite Channel (...); (Gower, this study).

In many later experiments the correlation between fluorescence line height - taken as the upward radiance over a linear or parabolic baseline through nearby socalled windows - has been established, however, a uniform algorithm did not result. It was the main goal of the FLUREX (Fluorescence Experiment) group, which as a whole has contributed to this report, to look specifically into

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

- the daily cycle of fluorescence
- atmospheric masking
- the change of fluorescence line height due to admixtures
- fluorescence line height algorithm comparison.

These tasks were tackled in the April 1982 FLUREX experiment in both the North Sea and the Baltic. The material compiled in this report strongly draws from the FLUREX'82 data bank and to a minor extent from the FLUREX'85 data and other experiments in the North Sea. At the same time we also tried to compile the knowledge on the basic photosynthetic mechanisms related to fluorescence and its dependence on environmental influences. The present summary is a highly condensed version of a summary report and sixteen appendices containing detailed information (see section for contributors).

1.2 Principles of Sunlight Stimulated Fluorescence Measurements

The remote detection of substances in sea water is restricted to the visible part of the electromagnetic spectrum since pure sea water absorbs too strong at all other wavelengths. Thus all information on constituents like phytoplankton, zooplankton, bacteria, Gelbstoff and nonliving suspensions is contained just in water colour. If there were specific spectral features colour and its intensity would directly tell us what constituent is present at what amount. However, extinction or attenuation - the sum of scattering and absorption - is varying rather smoothly with wavelength and the impact of an absorption band is additionally depending on the size of the suspension. These facts have hindered a separation of substance classes in nearly all cases up to now. It is clear then that the discovery of a specific feature, the chlorophyll fluorescence, promised a new approach in remote sensing of ocean water substances. When, however, more fluorescence line height (FLH) measurements became available, differing relations between phytoplankton chlorophyll and FLH were established. The differences are due to different:

- phytoplankton species
- sun elevation
- season
- physiological state
- observation geometry
- correction of atmospheric masking.

The FLUREX group tried to explain as many as possible of these impacts on chlorophyll fluorescence by measuring or sampling

in situ

- concentrations of water constituents (partly vertical profiles)
- global radiation at the surface
- temperature and salinity of the deck layer
- phytoplankton species
- radiance field in sea water
- atmospheric turbidity
- nutrient supply

remote from a ship
- upwelling spectral radiances of sea water
- downwelling spectral sky radiance and irradiance
- surface skin temperature

remote from an air-plane
- upwelling spectral radiances at the surface from measurements in different altitudes
- surface skin temperature.

1.3 The Problem of Remote Sensing of Chlorophyll in Coastal Areas

While phytoplankton concentration is strongly correlated with suspended matter concentration in open ocean waters, named case I waters, there is often no correlation between both substance classes themselves and also Gelbstoff in coastal waters as the North and Baltic Sea, named case II waters. Since the turbidity of coastal waters is frequently dominated by resuspended sediments, and distinct spectral features (besides fluorescence at 685 nm) are not visible in most reflectance spectra phytoplankton chlorophyll can not be isolated without measurements around 685 nm. Moreover, the presence of Gelbstoff, nearly a pure absorber, strongly reduces upwelling radiances in the blue as does phytoplankton.

1.4 Why do we Need Another Method than Green-Blue?

The arguments in section 1.3 easily forecast the failure of blue/green ratios as a measure of chlorophyll and thus phytoplankton in all waters with Gelbstoff or resuspended sediments, i.e. turbid coastal waters. But also in case I waters the tested ratios (Ref. 4) are a function of area and season because of at least the dependence on size distribution and species. However, before we claim that we should shift to the fluorescence peak measurement the problems named in section 1.2 have to be resolved, bringing us back to the main topic of this report.

1.5 Which Problems have to be Solved Concerning Fluorescence?

Problems to be discussed here are only those related to the use of chlorophyll fluorescence as a measure for remote detection of chlorophyll. At a first glance there are many advantages of measuring chlorophyll fluorescence remotely for the derivation of chlorophyll, or phytoplankton biomass, or even productivity:

- signal specific for chlorophyll-a
- all algae contain chlorophyll-a
- Rayleigh backscattering by the atmosphere (proportional to λ^{-4}) strongly reduced at 685 nm
- Gelbstoff no longer strongly absorbing
- aerosol extinction smaller than at blue and green wavelengths
- variations in spectral solar emission smaller, thus wavelength shifts of window channels used for baseline of minor importance.

These advantages survive also after a closer look, but there also exist some basic drawbacks:

- the fluorescence efficiency is a function of daytime, species, physiological state of the algae and other parameters

- absorption by pure sea water is so strong at 685 nm, that the upwelling radiance just below sea surface stems from only a few meters

- well mixed and strongly varying atmospheric gases interfere both with the fluorescence peak itself and baseline channels.

It is the main purpose of this report to show how strong the impact of these drawbacks is; in other words, are they a real disadvantage? Could they in combination with other water colour information be turned into a source of additional information? If no answer can be given we will specifically mention it in order to show the direction of future research.

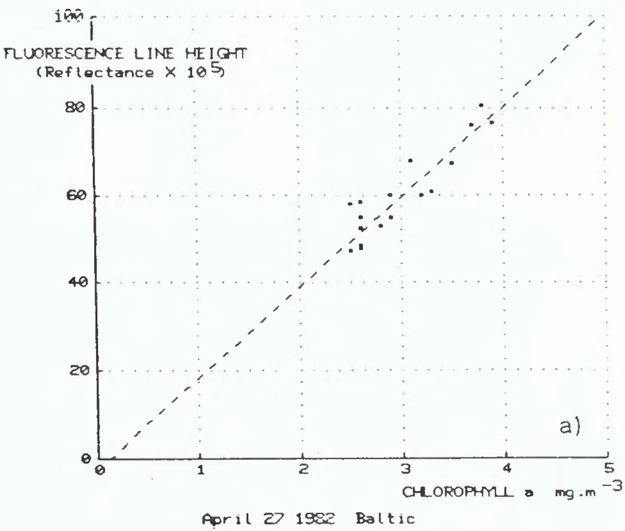
2. MAIN RESULTS

The following list shortly describes our main study achievements partly illustrated by a basic figure drawn from the corresponding appendix.

1) Sun stimulated chlorophyll-a fluorescence at 685 nm is a generally detectable though small spectral feature in upward radiation spectra over the sea containing chlorophyll-a concentrations down to at least 1 mg m^{-3}.

2) Under typical coastal conditions very simple extraction algorithms give a linear dependence of chlorophyll fluorescence on chlorophyll concentration with a relatively low standard deviation (Fig. 2). This fact confirms that airborne fluorescence measurements allow us to resolve small differences in surface chlorophyll concentrations as good as with conventional techniques using water samples or in situ fluorometers.

   For all airborne experiments, carried out up to now in different areas of the Northwest Pacific Coast, the Atlantic Ocean, the North and Baltic Seas and the Mediterranean Sea at different seasons, this linear regression holds within a factor of two including physiological variations for different species.



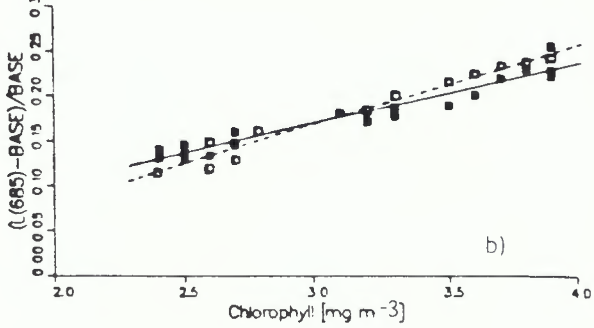


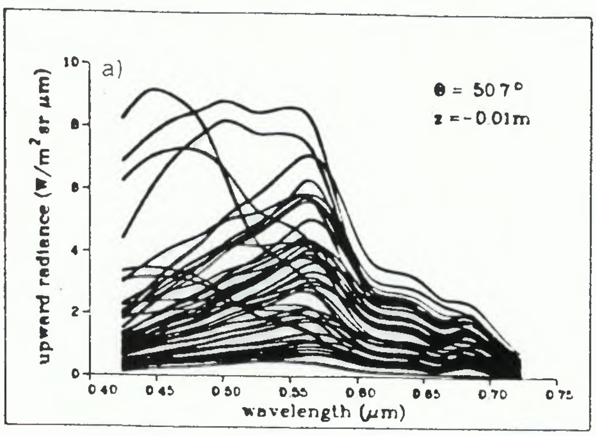
Figure 2: Fluorescence line height versus chlorophyll concentration for April 27, 1982, Kiel Bight, Baltic.
a) Ship-borne upward radiance spectra taken by Gower
b) Ship-borne radiances from a 18-channel radiometer taken by Doerffer (7) and model result by Fischer (5).

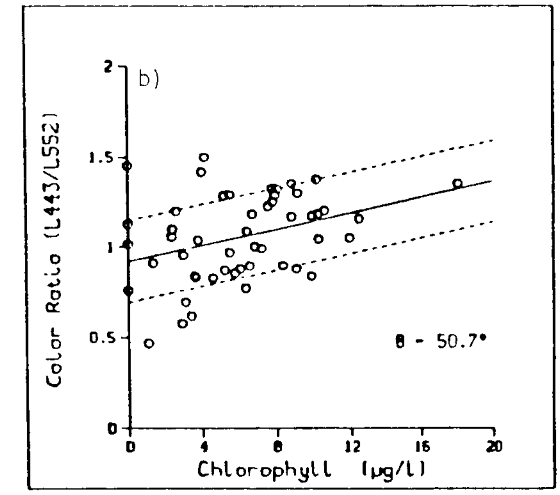
3) The primary productivity of marine algae is inversely related to in situ chlorophyll-a fluorescence. We propose to investigate the relation between fluorescence, green-blue ratio, chlorophyll concentration and primary productivity in order to retrieve more information from spectral radiances about phytoplankton activity.

4) Suspended matter and Gelbstoff may induce problems in the following ways:

   The 'blue-green ratio' algorithm is no measure of chlorophyll in those coastal waters, containing Gelbstoff and/or other suspended matter in considerable amounts (Fig. 3).

   The chlorophyll fluorescence signal is reduced by increasing amounts of Gelbstoff, suspended matter and aerosol scattering.
   Phaeopigment containing suspended matter in estuaries and coastal waters cause a fluorescence signal without living phytoplankton present.





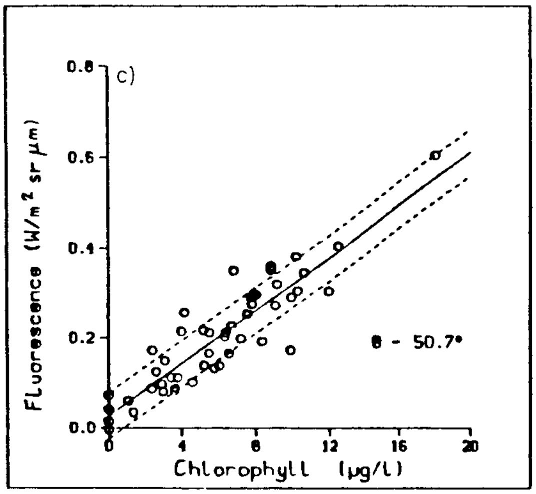


Figure 3: a) Calculated radiances just below the ocean surface for coastal water (for some case studies in agreement with measured spectra) with substance variations typical for the North Sea;
b) Colour ratio versus chlorophyll content;
c) Fluorescence line height versus chlorophyll content; (Fischer, this study).

5) The longwave wing of the fluorescence peak is perturbed by rather strong absorption of atmospheric oxygen and weak water vapour absorption (Fig. 4). In case of high chlorophyll concentrations as found in lakes or bays, the shortwave wing can be reduced by the absorption of chlorophyll centred at 670 nm, so that the fluorescence peak seems to be shifted to the red with a maximum at 700 nm.

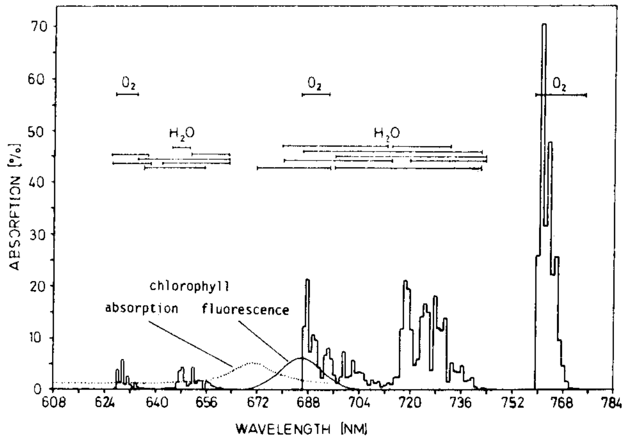


Figure 4: Calculated gaseous absorption (1 nm resolution) of incoming solar radiation (in percent) for an atmosphere containing 20.9 percent O_2 and an exaggerated water vapour column content of 10 g cm^{-2}. 18 H_2O and 3 O_2 absorption band intervals as well as chlorophyll an absorption and fluorescence are also indicated (Schlüssel, this study).

6) The diurnal variation of the sun stimulated chlorophyll fluorescence efficiency is less than 10 % for sun elevations above 30 degrees.

7) The fluorescence efficiency is varying within the annual cycle due to the occurrence of different phytoplankton populations and nutrient limitations.

8) Specific spectral signatures exist for exceptional plankton blooms such as red tides, which show a relative minimum in upward radiance at 520 nm (Fig. 5).

9) Especially for high altitude aircraft observations simple baselines for the extraction of the fluorescence radiance are not adequate for all circumstances, i.e. information on atmospheric turbidity is needed.

10) The optimum range of viewing angles for remote detection of fluorescence is similar to those for the other part of the visible spectrum.

11) The depth from which 90 % of the fluorescence signal derives is limited by the absorption of pure water to about 2 m. Phytoplankton maxima, which occur in off-shore waters below this depth are undetectable by fluorescence.

12) Distribution patterns of phytoplankton occur on all scales in time and space. For repetition rates of satellite images of 1 day a spatial resolution of 1 km is sufficient for time series analysis. The detection of red tides may need a spatial resolution of 300 m.

13) Vertical distribution and the variability in chlorophyll fluorescence efficiency require ground truth measurements for an accuracy better than to a factor of two.

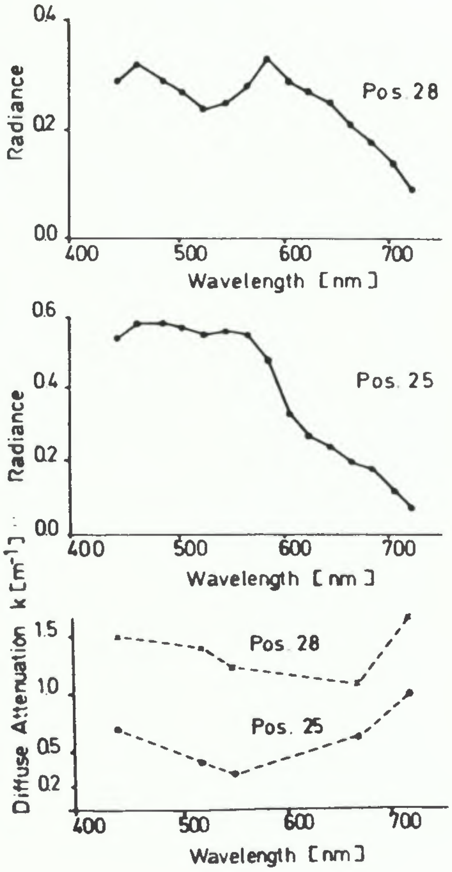


Figure 5: Measured Upward spectral radiances in μW cm^{-2} sr^{-1} nm^{-1} (upper two panels) and diffuse attennuation coefficient k during a red tide, 31st August and 1st September 1979, Marine Remote Sensing Experiment in the Norht Sea (Doerffer, this study).

3. REQUIREMENTS FOR A SATELLITE-BORNE FLUORESCENCE SCANNER

3.1 Center and Bandwidth of Spectral Channels

The spectral channels should cover the range 440-850 nm in order to retrieve information about Gelbstoff, suspended matter, chlorophyll-a, other pigments such as of exceptional plankton blooms and aerosols. Only a combination of all these parameters allows a correct interpretation of the coastal zone water colour.

The best choice would be a programmable imaging spectrometer covering the range 440-850 nm with 5 nm resolution, which allows the user or operator to select specific channels and bandwidths, in order to match the demands of different areas and seasons.

With respect to the fluorescence channels the following requirements have to be satisfied:

In order to avoid disturbance by changing atmospheric absorption the center wavelength of the fluorescence channel should be fixed to the shortwave part of the fluorescence peak:

$\Delta\lambda = |682 \text{ nm} - 687 \text{ nm}| = 5$ nm. Wavelength above 688 nm must be excluded. Part of chlorophyll absorption centered at 670 nm thus will slightly reduce the fluorescence line height. Extremely high chlorophyll concentration with a shift of the maximum to longer wavelength will not be detectable from space, unless the baseline channel at 711 nm shows a signal increase and a further baseline channel is available.

The two baseline channels should be as near as possible to the fluorescence peak in order to reduce spectral dependence of scattering by particles both in water and air. To include fresh water systems with high concentrations the baseline channels should also be programmable with respect to their center wavelength.

Due to water vapor absorption in the near infrared a very narrow ($\Delta\lambda = 5$ nm) channel at 711 nm center wavelength is the optimum for the long side of the spectrum. The shortwave side is rather free of atmospheric gas absorption. The chlorophyll absorption at 670 nm and the strong Fraunhofer line at 656 nm as well as weak absorption of water vapour forces us to put the shortwave baseline channel at $\lambda < 645$ nm. A good position from the point of view of absorption of gases is 640 nm, however, this causes some disturbance if the nonlinearity of the baseline changes due to atmospheric turbidity variations.

3.2 Requirements for Radiometric Resolution

Although the path radiance is low in the red part of the spectrum, the weak fluorescence radiance in the order of 0.03 W m^{-2} sr^{-1} μm^{-1} for 1 mg m^{-3} chlorophyll and a sun elevation of 40° has to be extracted from 8-14 W m^{-2} sr^{-1} μm^{-1} at the top of the atmosphere; this requires a signal-to-noise ratio of about 1000.

Of particular importance is the relative calibration between the fluorescence and the baseline channels, which should be in the order of 1 %. Shifts of the center wavelength of these 3 channels have to be avoided. In the case of imaging spectrometers a possibility of inflight monitoring of wavelength shifts exists through solar or atmospheric absorption lines.

3.3 Pixel Size, Swath Width and Repetition Rate

The specifications of the CZCS have been proven appropriate for most applications. However, a spatial resolution in the order of 300 m would open new applications, for instance the detection of red tides and small scale structures in coastal area.

3.4 Tilting Capability

Avoidance of sun glitter is a prerequisite; a tilting capability of > 20° is necessary. Equatorial areas with high sun elevations may require a tilt of 30°.

3.5 Optimum for Local Hour of Overpass

A morning pass at a local hour of about 10-11 h is preferred for the following reasons:

- cloud coverage is generally lower in the morning in coastal areas
- high sun elevations can cause sun glitter disturbance of the signal in equatorial lati-

tudes
- fluorescence efficiency is more stable in the morning

If applications of the satellite are concentrated to mid and high latitudes only, a high noon overpass would give maximum energy with only little disturbance by specular reflection.

3.6 In Situ Truth Requirements

In situ truth is necessary because of the following facts:

- annual variability of the fluorescence efficiency
- vertical stratification of phytoplankton
- influence of phaeopigments
- variable relation between chlorophyll concentration and productivity or phytoplankton biomass

In addition to water samples and vertical profiles continuous horizontal profiles would improve the comparibility between satellite and ship data. Low flying aircrafts using radiometers and laser fluorometers are an excellent link between ship and satellite data. They also allow analysis of small scale distributions and rapid variations.

3.7 Recommendations for Data Evaluation Procedures

It has been pointed out, that simple colour ratio algorithms are not appropriate to detect a single water constituent and measure its concentration in coastal waters containing large amounts of various substances. Although the fluorescence technique extracts the specific spectral signature of chlorophyll, high amounts of suspended matter and Gelbstoff interfere with this signal. One way to solve this problem is to apply inverse radiative transfer modelling for data evaluation using the spectral signatures of all relevant water constituents. Areas with low concentrations of Gelbstoff and suspended matter allow the usage of the fluorescence line heigth without that procedure.

The influence of aerosols should be derived from at least two channels in the near infrared.

To minimize the ground truth effort future systems should include data banks of water constituents and their corresponding absorption, scattering and fluorescence properties as well as radiance spectra, which are typical for different areas and seasons. The evaluation procedure could be programmed in form of an expert system, to introduce as much information as possible besides the satellite data into the evaluation process.

3.8 Recommendations of Further Effort to Support an Eventual Satellite Mission

No insurmountable problems have been recognized in this study, but areas needing more clarification are the following:

Baseline construction under various atmospheric conditions: To verify model calculations high altitude data are needed. This would include the aerosol detection procedure using near infrared channels.

Contribution of phaeopigments and pigments of exceptional plankton blooms to the entire visible spectrum including fluorescence: more datasets combining optical and concentration parameters are needed.

The question how to derive information about primary productivity from ocean colour measurements is still open and requires strong effort.

Finally, we recommend a case study about the usage of expert systems in ocean colour data processing.

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REFERENCES

1. Morel, A. and L. Prieur, 1977: Analysis of variations in ocean colour; Limnol. Oceanogr. 22, 709-722

2. Neville, R.A. and J.F.R. Gower, 1977: Passive remote sensing of phytoplankton via chlorophyll-a fluorescence; J. Geophys. Res. 82, 3487-3493

3. Doerffer, R., 1981: Factor analysis in ocean colour interpretation; in Oceanography from Space, J.F.R. Gower (Ed), Plenum, New York, 339-345

4. Gordon H.R. and A.Y. Morel, 1983: Remote Assessment of Ocean Colour for Interpretation of Satellite Visible Imagery; A Review; Springer, New York

THE INFLUENCE OF YELLOW SUBSTANCES ON REMOTE SENSING OF SEA-WATER CONSTITUENTS FROM SPACE

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ABSTRACT

Gelbstoff, the uncharacterized fraction of dissolved organic carbon in natural waters, changes water colour due to absorption in the blue. Thus, remotely sensed water colour also contains Gelbstoff information. This report summarizes a study on both the Gelbstoff influence on upward radiance spectra at the surface as well as at satellite altitude and on the use of Gelbstoff as a tracer for salinity. Main results are:

- At present only inverse modelling using absolutely calibrated multichannel radiance values is able to separate Gelstoff from phytoplankton and suspended matter.

- Gelbstoff is stable enough to be used as a tracer for salinity in coastal waters as long as the riverine concentration is known.

The report ends with recommendations for a satellite Gelbstoff sensor.

1. INTRODUCTION

The Baltic Sea and some coastal areas of the North Sea contain high amounts of Gelbstoff (Ref. 1), also called yellow substance. Generally this water constituent is defined as the dissolved fraction, which passes a 0.45 µm filter <u>and</u> absorbs light in the UV and blue spectral range.

A further characteristic is the smooth nearly exponential decrease in absorption from the UV to the red part of the spectrum. Typical absorption coefficients at 380 nm wave length range from 0.5 - 3.0 m^{-1} in coastal and estuarine waters.

Gelbstoff is transported into the sea mainly by rivers; because of its chemical stability it approximately behaves as a conservative parameter like salinity and thus can be used to trace the freshwater input from rivers into the sea. Only a few observations on the production of Gelbstoff in the sea exist.

Gelbstoff reduces the water leaving radiance strongly in the blue part of the spectrum. This fact can cause severe problems in the retrieval of chlorophyll concentrations with the "green/blue" algorithm, the latter using the broad band chlorophyll absorption maximum around 440 nm wavelength. In areas, containing large amounts of Gelbstoff it is impossible to apply simple colour ratio algorithms for mapping the phytoplankton distribution.

The task of the study group (see section 10) was to analyze the impact of Gelbstoff on radiance spectra of the sea. Furthermore methods will be discussed, which are appropriate to incorporate Gelbstoff in an evaluation procedure of ocean colour spectra measured at satellite altitude. This compilation is a highly condensed version of a summary report and nine accompanying papers presented to ESA in September 1986, discussed at the Villefranche Workshop on ocean colour and approved December 1, 1986 by ESA.

2. CHEMICAL PROPERTIES OF GELBSTOFF

The chemical nature of Gelbstoff cannot be characterized by one single structure formula. Gelbstoff is much more a mixture of stable, in most cases polymerized organic molecules, which are formed from degradation products of plants and animals under the activity of microbes.

Because of the difficulty to identify the chemical nature of a Gelbstoff sample, a methodological approach is used to characterize and classify the organic material in a water sample, by indicating parameters like: molecular weight, dissolved organic carbon concentration, oxygen and nitrogen content, acidity, resemblence to lignin.

Only 30 % of the Dissolved Organic Carbon (DOC) can be chemically charaterized, 70 % form a mixture of various molecules, which can only be described in a statistical way or by sum parameters (Fig. 1). In the deep sea more than 90 percent of DOC is Gelbstoff with an average age of 3 - 4 000 years.

After microbial degradation and decomposition of dead organisms new complex molecules are formed by biochemical and chemical condensation. The polymers have molecular weights in the order of 100 - 100000. They form colloids, which may agglomerate to flocks exceeding the 0.45 µm definition boundary.

Gelbstoff is formed in the soil, the ground water and the fresh or sea water itself. The soil mainly produces humic acids of high molecular weight and a hydrophobic aromatic chemical structure (Ref. 2).

Proceedings of an ESA Workshop held at Villefranche-sur-mer, France, 4–5 November 1987. (ESA SP-1083, June 1987).

The ground water contains mainly aliphatic and hydrophilic fulvo acids of low molecular weight. The autochtone material in the sea consists of polyunsaturated fatty acids, sugars, amino acids and amino sugars.

The coastal water and the open sea receive mainly the fulvic acid fraction with low molecular weight, while a major part of the fraction of high molecular weights coprecipitates with mineralic and organic suspended matter in the brackish water zone of an estuary.

3. OPTICAL PROPERTIES OF GELBSTOFF: ABSORPTION AND FLUORESCENCE

The absorption of Gelbstoff measured with high resolution instruments reveals the existence of various absorption bands covering the UV, the entire visible and the near infrared spectrum. Within the red the bands are weak but distinct (Fig. 2). With respect to remote sensing the fine structure of absorption at the red wavelengths can be neglected since water absorption itself is significantly higher than that of typical Gelbstoff concentrations. The overlapping bands in the near UV and blue form a spectrum , which nearly decreases exponentially to longer wavelengths. The apparent slope has a regional and temporal variability.

Variability is also observed in the artificially stimulated Gelbstoff fluorescence covering all visible wavelengths above the excitation line (Fig. 3). Since no significant covariance of both fluorescence and absorption spectra is found, we conclude that absorbing and fluorescent compounds are not identical.

Although we propose to use optical parameters as a measure of Gelbstoff, i.e. absorption or attenuation coefficients, or fluorescence intensities further fundamental investigations are necessary, before Gelbstoff mass concentrations, in units of mg/l, can be derived reliably from optical measurements.

4. THE OCCURENCE OF GELBSTOFF AND ITS RELATION TO SALINITY

The chemical composition and concentration of fresh water Gelbstoff depends on factors as type of soils the river passes, vegetation, length of the river etc.; particularly rainfall can dilute Gelbstoff concentrations rather strong. As a consequence the Gelbstoff concentration of the fresh water component in an estuary varies leading to different regression slopes in the relation between salinity and Gelbstoff in the mixing zone (Fig. 4).

Within the salinity range 1 - 30 permille of estuarine and coastal waters of the German Bight, the negative correlation between salinity and Gelbstoff is very high. Thus, the Gelbstoff distribution reflects the distribution or river water in the German Bight.

Another area of high Gelbstoff variability is the Skagerrak, where Gelbstoff rich Baltic waters are mixed with North Sea waters.

Only little is known about the production of Gelbstoff in the Sea. In areas of exceptional plankton blooms extrem high Gelbstoff absorption (2.5 m^{-1} at 380 nm) was observed in upper layers where the plankton was concentrated. In this case Gelbstoff is not correlated with salinity but with the plankton cell concentration, while in the deeper layers, with normal plankton concentrations, the expected negative correlation with salinity is still present.

5. LONG TERM STABILITY OF OPTICAL PROPERTIES OF GELBSTOFF

One prerequisite to use Gelbstoff as a natural tracer is the stability of Gelbstoff with respect to its optical properties: attenuation and fluorescence. These properties may change due to microbiological metabolism and - at the sea surface - due to photochemical reactions. The requirement for the time range, in which Gelbstoff has to remain stable in the sea, is determinded by the time, in which Gelbstoff is diluted by mixing with sea water to a concentration, just detectable in radiance spectra.

A first indication of stability within a few weeks can be derived from the high negative correlation of salinity with Gelbstoff.

For an in-depth analysis laboratory experiments were carried out particularly for this study.

Water samples from the Elbe river (fresh water zone) and the German Bight were kept for more than 3 months in closed tanks under illuminated as well as dark conditions. Subsamples were taken with intervals of 3 - 4 days to measure fluorescence and attenuation.

The attenuation of Elbe Gelbstoff at 450 nm shows at the end of the 100 day period a reduction of about 50 % for the lighted sample, and a 25 % reduction for the dark sample. The decrease occurs within the first 20 days.

The fluorescence of the same samples was much more variable: the lighted sample was reduced by 50 % during the first 5 days and then remained nearly constant, while the dark sample fluorescence increased by 50 %.

The German Bight sample (Fig. 5) showed similar tendencies with the difference that the attenuation of the dark sample slowly increased.

Conclusions:

The decay of Gelbstoff is mainly due to photochemical reactions.

Both, the temporal decay of Gelbstoff as well as its dilution by mixing with sea water, causes the negative correlation between salinity and Gelbstoff. Because dilution and decay are both time dependent, it is necessary to investigate the time scales of both effects for a particular season and area, before applying this tracer method.

However, the experience from field studies in the German Bight has proven, that Gellbstoff can be used to trace the river water masses in the sea. Preference for investigations should be given to the winter period, where Gelbstoff originating from plankton blooms can be excluded and where photochemical reactions are of minor importance.

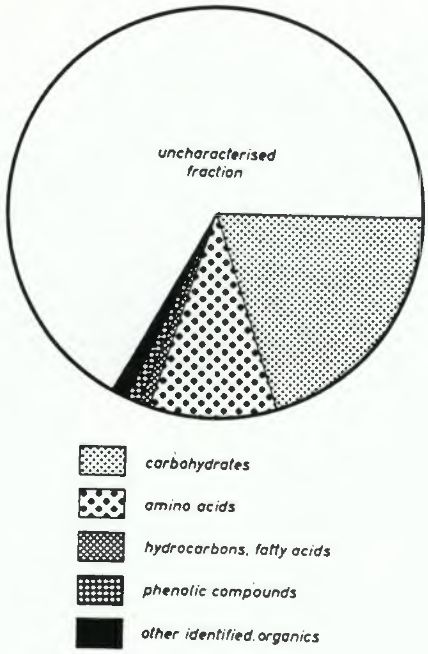

Figure 1: Chemical charaterization of DOC (Ref. 3).

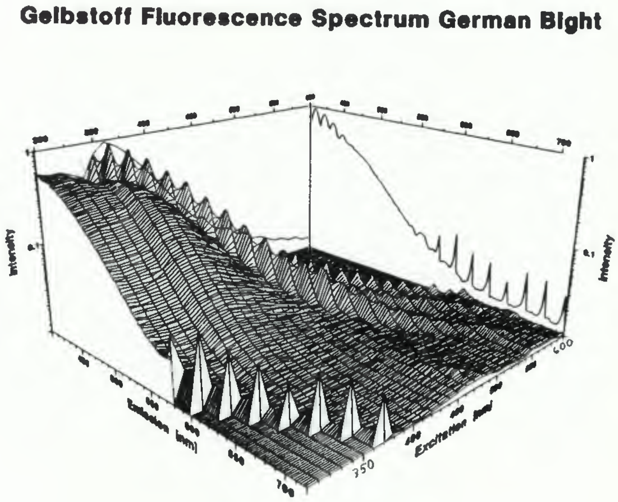

Figure 3: 3D-Plot of the fluorescence emission (2 nm steps) with varying excitation wavelength (10 nm steps) of a filtered water sample taken in the German Bight. The first weak peak beyond the excitation wavelength corresponds to bending Raman scattering, the second stronger peak to stretching Raman scatter of the water. Gelbstoff fluorescence is dominant at blue emission wavelengths. The small pyramids observed at low excitation and high emission wavelengths are due to second order diffraction of the excitation line from the grating. (Doerffer, this study).

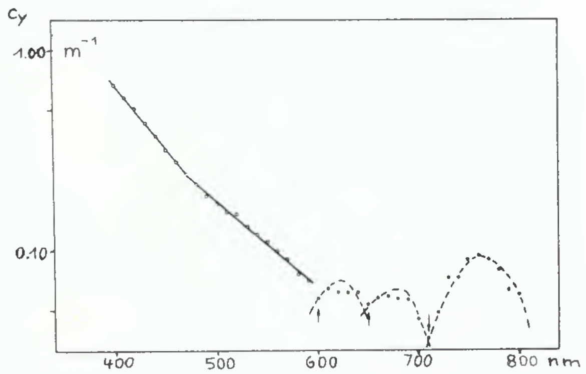

Figure 2: Spectral attenuation coefficient c_y of a water sample taken from Eckernförde bay, Baltic Sea. Water depth 2.5 m. July 12, 1978. Adopted from Diehl and Haardt (1980).

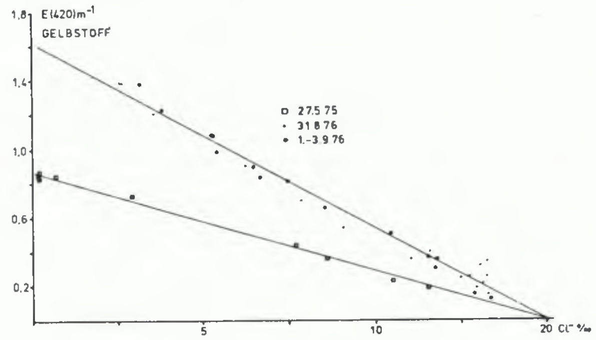

Figure 4: Salinity dependent absorption coefficient at 420 nm, Gelbstoff in the Elbe - estuary from 3 cruises (Ref. 5).

6. THE INFLUENCE OF GELBSTOFF ON RADIANCE SPECTRA OF THE SEA

Here the influence of Gelbstoff on multispectral radiances is mainly studied with radiative transfer calculations because calculated and measured radiances agree for different sun elevations and in-situ measured substance concentrations, however, calculated radiances allow a more systematic variation.

The main results for typical substance variations are:

1. The absorption of Gelbstoff changes the spectral behaviour of the water leaving radiances drastically in estuaries and still significantly in those coastal waters, where the Gelbstoff amount has been reduced strongly by mixing processes. Variations at high levels have less influence on radiance spectra than the same variations at low levels.

2. Multispectral upward radiances over fresh water - as the Elbe estuary - are characterized by a strong depression in the blue caused by high amounts of Gelbstoff: for typical suspended matter and phytoplankton densities of 10 mg/l and 15 mg/m^3, respectively, the radiances in the blue are reduced from 11 to 3.5 $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$ for a Gelbstoff absorption coefficient of 2 m^{-1} at a wavelength of 380 nm. In the green the radiances values are still reduced by a factor of two.

3. Even at rather low densities of suspended matter (1.5 mg/l) and phytoplankton (1.5 mg/m^3), the radiances are significantly reduced in the blue by a Gelbstoff absorption as low as 0.2 m^{-1}.

4. Only a minor influence of Gelbstoff variations on the zenith and azimuth angle dependence of the upwelling radiance field was found.

As a next step, we extracted with factor analysis of multispectral radiances the characteristic signatures of phytoplankton, suspended matter and Gelbstoff. This analysis determines the information content of multispectral radiances and helps in understanding how the inherent optical properties of a substance are reflected in multispectral radiances, here for the case of independent substance variations.

5 data sets, each constituting a family of 50 calculated multispectral radiances (at 17 wavelengths) accounting for substance variations observed in coastal areas of the North Sea, led to the following statements:

1. Gelbstoff seems to be the most difficult water constituent for remote sensing.

2. As a consequence of the similarities of factor loading spectra we conclude: A reliable method for Gelbstoff detection should also simultaneously consider chlorophyll, because of similarities of both water constituents with respect to their enhanced absorption in the blue part of the spectrum.

3. A separation of the phytoplankton and Gelbstoff may be possible only after measuring chlorophyll-a via its fluorescence at 685 nm, which is a characteristic feature of all plankton types.

4. Algorithms for total suspended matter in coastal waters should easily be derivable.

7. REMOTE SENSING OF PHYTOPLANKTON IN THE PRESENCE OF GELBSTOFF

Gelbstoff and chlorophyll-a absorb blue light and thus alter the spectral characteristic of the water leaving radiances. Therefore, the detection of phytoplankton from radiance measurements in the blue is strongly hampered by Gelbstoff, if chlorophyll is not measured via its chlorophyll fluorescence. This chapter is dedicated to the applicability of chlorophyll algorithms for Gelbstoff containing waters.

The chlorophyll algorithms based on colour ratios mainly differ in regression coefficients derived from different in-situ verification compaigns. In order to study the utility of the blue-green ratio to derive chlorophyll densities in coastal waters, we performed radiative transfer calculations based on mesured concentrations of water substances. We found:

- Although for clear water areas of the North Sea a fair agreement between derived (by colour ratio) and in situ measured chlorophyll densities exists, the decrease of the estimated chlorophyll density surmounts 50 % if Gelbstoff is neglected.

- For the Adratic Sea no acceptable relation between the density derived from the blue-green ratio and the in situ chlorophyll densities was found.

A statistical approach, based on radiative transfer calculations for measured variations of suspended matter, phytoplankton and Gelbstoff concentrations in the North Sea and Baltic, shows:

- The blue/green ratio is significantly uncorrelated to phytoplankton concentrations.

- The blue-green ratio points to Gelbstoff and/or suspended matter rather than to phytoplankton.

However, from chlorophyll fluorescence measurements and radiative transfer calculations we found a solution, because the chlorophyll fluorescence is a characteristic feature of phytoplankton, detectable also in Gelbstoff rich and turbid coastal waters. For typical Gelbstoff absorption coefficients smaller than 1 m^{-1} the reduction of fluorescence line height (defined as the radiance above a baseline) is smaller than 25 percent.

8. THE DETERMINATION OF GELBSTOFF CONCENTRATION FROM RADIANCE SPECTRA

There is no generally accepted remote sensing technique for the detection of Gelbstoff from passive radiance measurements. However, Gelbstoff may be derived besides suspended matter and phytoplankton from multispectral radiances, as found by eigenvalue and factor analysis:

The characteristic absorption feature of Gelbstoff is represented in the factor loadings, although no distinct wavelength can be identified to estimate Gelbstoff from radiance measurements, because of the similarities of the spectral dependence of extinction or the overlapping of absorption bands for the water constituents.

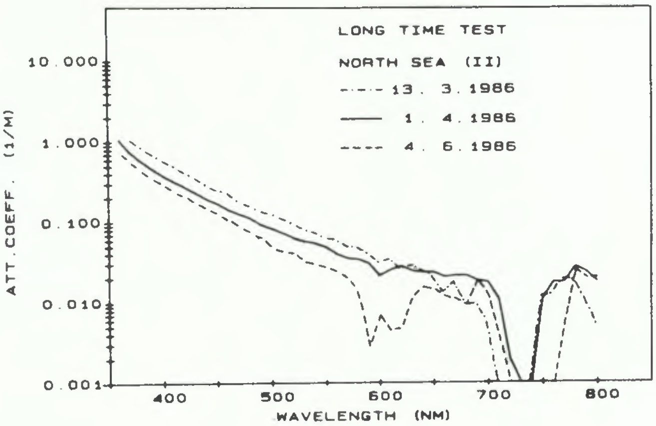

Figure 5: Spectra of the Gelbstoff attenuation coefficient for a North Sea sample on 13.3.86 (start of the long term stability test, dashed-dotted line), 1.4.86 (full line), and 4.6.86 (dashed line); (Reuter, this study).

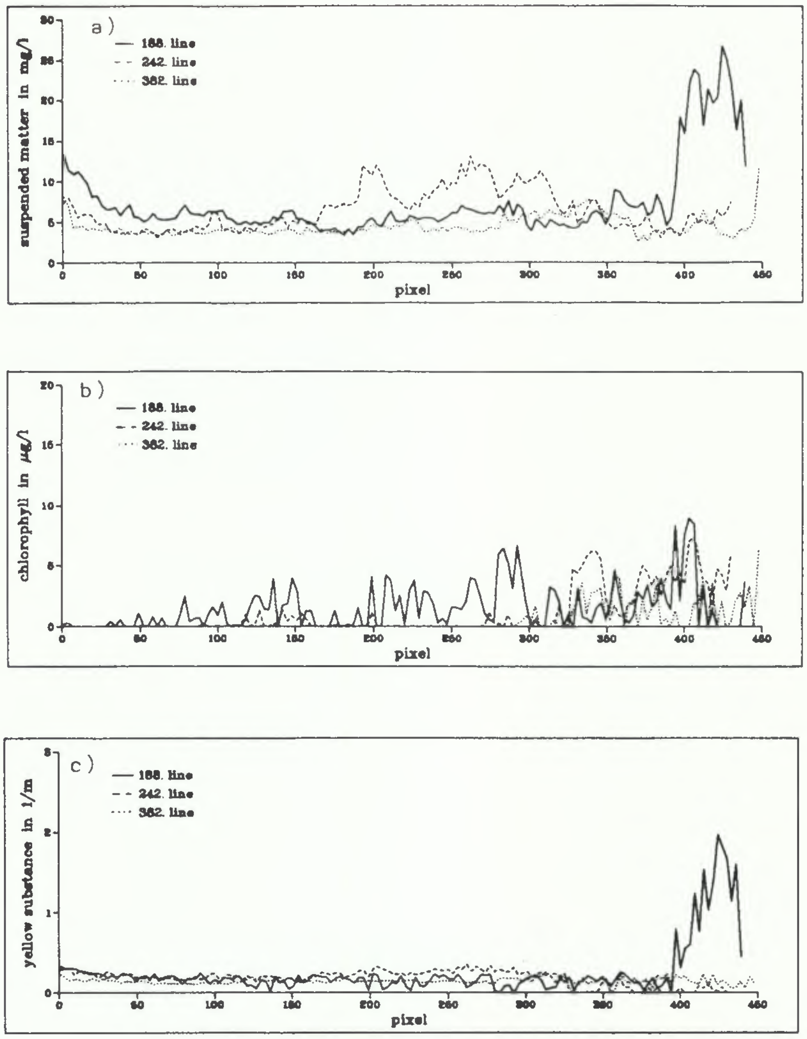

Figure 7: Retrieved water constituents from measurements of CZCS for the lines indicated in Fig. b; pixels are counted from left to right:
a) suspended matter densities in mg/l,
b) phytoplankton in µg/l,
c) yellow substance absorption coefficient in m^{-1}; (Fischer, this study)

We then developed an inverse modelling technique, which uses the entire information content of multispectral radiances for a simultaneous detection of suspended matter, phytoplankton and Gelbstoff. This procedure is based on a complete radiative transfer model and an optimization procedure. The first application of this technique to CZCS measurements (Fig. 6a,b) over the North Sea shows:

1. Suspended matter, phytoplankton and Gelbstoff are retrievable from CZCS measurements (Fig. 7), if the combined errors of the correction of the intervening atmosphere and the calibration are below 5 %,

2. a separation of chlorophyll and Gelbstoff poses problems at higher errors due to the common absorption of these two water constituents in the blue.

3. For the detection of 3 substances even from CZCS measurements the use of absolute radiances is necessary, thus a careful calibration of a satellite radiometer becomes most important.

The inverse modelling technique still has problems: The spectrum of the inherent optical properties has to be known for each constituent. Any variation of these spectra causes errors in the retrieved parameters. An introduction of the chlorophyll fluorescence into this procedure improves not only the detection of chlorophyll but also the capability to retrieve Gelbstoff.

9. RECOMMENDATIONS FOR A SATELLITE GELBSTOFF SENSOR

9.1 Center and bandwidth of Spectral Channels

Since the solar irradiance increases strongly between 390 and 405 nm, a radiometer channel is only useful for center wavelengths ≥ 410 nm, but should also avoid wavelengths around 430 nm (± 3 nm), because of a strong Fraunhofer line. The competing effects of chlorophyll absorption, with a broad maximum around 440 nm, and Gelbstoff absorption allow no specific channel wavelength in the blue to detect Gelbstoff. In order to reduce the effects of molecular scattering in the atmosphere, and thus to enhance the relative Gelbstoff signal we recommend at least two channels between 440 and 480 nm.

Since the optical properties of the water constituents are broad band features, a bandwidth of 10 nm of the spectral channels is sufficient in the blue and green.

A separation of chlorophyll and Gelbstoff from multispectral radiance measurements can be strongly improved, if the chlorophyll concentration is estimated via its fluorescence around 685 nm.

The spectral aerosol extinction should be known at least within 5 % of its actual value, in order to retrieve the water substances from multispectral radiance. Additional radiance measurements in the near infrared, which are free of back-scattering effects of the water constituents, are required.

The best choice would be a programmable imaging spectrometer covering the range 440 - 850 nm with 5nm resolution, which allows the user or operator to select specific channels and bandwidths, in order to match the demands of different areas and seasons.

9.2 Requirements for Radiometric Resolution

Gelbstoff absorption variations of 1 to 3 m^{-1} at 380 nm are frequently observed in the German Bight and the Elbe river. In order to retrieve absorption changes of 0.1 m^{-1} from radiances in the blue a signal-to-noise ratio of at least 550 is required.

The fluorescence radiance at 685 nm is in the order of 0.03 $Wm^{-2}sr^{-1}\mu m^{-1}$ for a chlorophyll increase of 1 mg/m^3, which implies already a signal-to-noise ratio of ≥ 500 if only a change of 1 mg/m^3 has to be detected.

We recommend for the radiometric resolution a signal-to-noise ratio of 1000 for all channels in the visible.

9.3 Pixel Size, Swatch Width and Repetition Rate

An important application of Gelbstoff monitoring is the study of the transport and dispersion of rivers into the sea. Although the Gelbstoff distribution is more uniform compared to those of suspended matter and phytoplankton, the small scale topography of estuaries and coastal zones requires a resolution in the order of 300 m.

A swath width of only 100 km is necessary to observe the transport and mixing processes of the river Elbe, but estuaries as large as the Amazon require a swath width of at least 500 km.

A repetition rate of several hours is needed to study the mixing processes driven by tidal currents as well as an observation period of at least two weeks for plankton monitoring. Additionally, a fast repetition rate is contrary to the requirements of a global coverage.

The specification of the Coastal Zone Color Scanner with respect to pixel size, swath width and repetition rate has been proven to be useful for most applications. However, for the detection of events as red tides and small scale structures in coastal areas a spatial resolution in the order of 300 m would open a new application field.

9.4 Tilting Capability

Since the sun glitter has to be avoided, a tilting capability of ≥ 20° is necessary. Equatorial areas with high sun elevations may require a tilting angle of 30°.

9.5 Optimum for Local Hour of Overpass

A morning pass at a local hour of 10 to 11 h is peferred for following reasons:

- cloud coverage is generally lower in the morning over coastal areas,

- high sun elevations can cause sun glitter.

If the preference is given to mid and high latitude ocean monitoring, an overpass at noon should be chosen. This would surely open new applications in polar research.

9.6 In Situ Truth Requirements

The riverine Gelbstoff coomponents are stable at least over several weeks. Therefore no in situ measurements converning Gelbstoff are required normally.

Figure 6: CZCS measurements from Orbit 4384 (6 Sept. 1979); southeastern part of the North Sea:
a) true colour composite of satellite radiances
b) true colour composite of the water leaving radiances
the 3 scan-lines represent lines where the inverse modelling technique (see fig. 7) has been applied; (Fischer, this study)

For the use of Gelbstoff as a measure of salinity in estuarine and coastal waters, the relation between salinity and the fresh water Gelbstoff has to be determined.

During the summer extraordinary plankton blooms (red tides) produce components, which behave optically similar as Gelbstoff, but with a stronger decrease of the absorption with increasing wavelength. Then, in situ truth requirements for Gelbstoff are absorption measurements at the wavelengths chosen for Gelbstoff detection.

9.7 Recommendations for Data Evaluation Procedures

It has been pointed out, that no distinct channel for a Gelbstoff detection exists and that simple colour ratio algorithms are not appropriate to detect a single water constituent in coastal waters containing significant amounts of various substances; even the fluorescence technique, which extracts the specific spectral signature of chlorophyll, is affected by high amounts of suspended matter and Gelbstoff.

At present only the application of inverse radiative transfer modelling, using the spectral signatures of all relevant water constituents, allows to derive Gelbstoff properties from space.

The influence of aerosols should be derived from at least two channels in the near infrared.

To minimize the ground truth effort future systems should include data banks of water constituents and their corresponding absorption, scattering and fluorescence properties as well as radiance spectra, which are typical for different areas and seasons. The evaluation procedure could be programmed in form of an expert system, to introduce as much information as possible beside the satellite data into the evaluation process.

9.8 Recommendations of Further Effort to support an Eventual Satellite Mission

No unsurmountable problems have been recognized in this study, but some areas need clarification.

The chemical and optical properties of Gelbstoff have to be measured simultaneously, in order to get a better understanding of the relations between absorbing and fluorescent dissolved matter. Particularly, the influence of sun stimulated Gelbstoff fluorescence on radiance spectra is not known accurate enough.

The remote determination of the optical properties of aerosols, especially over coastal waters, have to be improved: This includes the aerosol detection procedure using near infrared channels.

Pigments and Gelbstoff of exceptional plankton blooms contribute to the entire visible spectrum by absorption and fluorescence: more data sets combining optical and concentration parameters are needed.

Finally, we recommend a case study for an expert system in ocean colour data processing.

10. STUDY GROUP

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REFERENCES

1. Kalle, K. 1966, The problem of the Gelbstoff in the sea. Mar. Biol. Ann. Rev., 4: 91 - 104.

2. Hatcher, P.G., 1983, Symposium on Early Diagenesis and Formation of Humic Substances. - Amer. Chem. Soc., Seattle, Washington, March 20 - 25.

3. Ittekkot, V., 1981, Verteilung von gelöstem organischem Kohlenstoff, gelösten Zuckern und Aminosäuren im Fladengrund, nördliche Nordsee (FLEX 1976). - Mitt. Geol. Paläontol. Inst. Univ. Hamburg, 51, 115 - 187.

4. Diehl, P. and Haardt, H. 1980, Measurement of the spectral attenuation to support biological research in a plankton tube experiment. Oceanol. Acta, 3(1): 89 - 96.

5. Doerffer, R., 1979, Untersuchungen über die Verteilung oberflächennaher Substanzen im Elbe Estuar mit Hilfe von Fernmeßverfahren. Arch. Hydrobiol. - Suppl. 43, 2/3.