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Stanford B. Hooker and Elaine R. Firestone, Editors

Volume 33, Proceedings of the First SeaWiFS Exploitation Initiative (SEI) Team Meeting

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Preface

In 1992 NASA selected the UK project SEASCOPE, co-ordinated by Dr. Jim Aiken, to be part of the SeaWiFS science programme. Recognising the potential impact which the deployment of SeaWiFS would have on British oceanography, the UK Natural Environment Research Council (NERC) provided £750,000 of funding for a Special Topic Research Programme called the SeaWiFS Exploitation Initiative (SEI) to run for three years from 1994 to 1997. The objective of the SEI was "to implement new research initiatives to enable the UK marine science community to exploit SeaWiFS data to the benefit of current and planned national (e.g., LOIS, PRIME, and BIOS) and international (e.g., JGOFS, WOCE, LOICZ, and GLOBEC) projects."

The steering committee created to manage the programme determined that the goal of SEI should be to encourage the creation in the UK of a collaborative community of marine scientists making full use of ocean colour from SeaWiFS in a way that would make an international impact. It decided that the funds should be targeted on projects which focused on the following tasks:

- Development of atmospheric correction strategies and algorithms suitable for application in coastal (Case-2) waters;
- Construction of algorithms for recovering a variety of biological parameters from remotely sensed ocean colour data, using both archived and new data;
- Innovative use of models which utilise SeaWiFS data in the study of oceanographic processes; and
- Measurement of *in situ* data as part of the SeaWiFS calibration and validation programme.

These targets recognised that the application of ocean colour in optically complex Case-2 waters is of special interest to the UK and this is the field in which we would expect to make a particular contribution to the international effort in exploiting SeaWiFS.

An open meeting was held in September 1993 to discuss UK utilisation of SeaWiFS, and was followed by a call for proposals. After international peer review, six proposals were selected for funding. Funds were allocated for the purchase of seagoing optical sensors available for use by the wider community. Projects commenced in 1994 and the principal and co-investigators of each project form the SEI science team of which this is the first meeting. Because the goal of SEI is to foster the growth of an ocean colour research community, this science team meeting welcomes other scientists who have an ocean colour interest and intend to make use of SeaWiFS data.

All the projects have now commenced and their progress is reported in the rest of this document. Because each project has a core of generic ocean colour science, none has been unduly hindered so far by the delays to the launch of SeaWiFS, although it is a cause for concern that plans for cruises and other fieldwork cannot yet be made with confidence. The meeting was pleased to welcome Dr. Stan Hooker from NASA Goddard Space Flight Center, particularly since his presence helped to emphasise the role of SEI as part of a wider international collaboration to use ocean colour measurements from SeaWiFS.

Southampton, England —Ian Robinson
June 1995 Chairman, SEI

Abstract

The first meeting of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Exploitation Initiative (SEI) Science Team was held 24 January 1995 in Southampton, England, and was hosted by the James Renell Center. The SEI steering committee decided four areas should be emphasized to ensure the UK marine science community has the opportunity to exploit SeaWiFS data to the benefit of existing and future projects: 1) development of atmospheric correction strategies and algorithms suitable for application in coastal (Case-2) waters; 2) construction of algorithms for recovering a variety of biological parameters from remotely sensed ocean color data, using both archived and new data; 3) innovative use of models that utilize SeaWiFS data in the study of oceanographic processes; and 4) measurement of *in situ* data as part of the SeaWiFS Calibration and Validation Program. The goal of SEI is to foster the growth of an ocean color community by supporting a set of core activities plus a selection of research topics, in particular, the application of ocean color in optically complex Case-2 waters. This document summarizes the many accomplishments of SEI Science Team members in preparation for the launch of the SeaWiFS instrument.

1. INTRODUCTION

Although the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) has not met its original launch schedule, the scientific communities poised to exploit the data have been able to continue their ocean color research due to an imaginative mixture of established and emerging scientific programs and technologies. A good example of this determination to advance in the presence of adversity can be found in the UK ocean optics community.

The first SeaWiFS Exploitation Initiative (SEI) meeting, although focused primarily on the goals of the SEI, was preceded by a series of meetings in the UK, many of which were convened under the auspices of the Remote Sensing Society (RSS). In addition to providing a progress report on the SEI, the meeting provided an opportunity to coordinate science relevant to SeaWiFS and ocean color, especially the coastal remote sensing campaigns associated with the Land-Ocean Interaction Study (LOIS).

Ocean color has been supported by the Natural Environment Research Council (NERC) within a number of special research topics and community programs in biological and physical oceanography. Part of the research presented that has direct relevance to the SeaWiFS mission has been carried out with funding over and above the SEI.

Airborne Remote Sensing (ARS) has been funded as a community research facility for a number of years by NERC. NERC initially provided a Daedalus Airborne Thematic Mapper (ATM) and now provides a Compact Airborne Spectrographic Imager (CASI), with enhanced blue sensitivity (see Appendix A). In the absence of SeaWiFS, ARS has provided an essential tool for the development of algorithms in the coastal zone. The utility of ARS is reflected in a number of the contributions. The Plymouth Atmospheric Correction Experiment (PACE), for example, is designed to give atmospheric closure by contemporaneously measuring the atmosphere and *in situ* light field while collecting optical imagery with existing airborne sensors. Atmospheric models will be adapted for use in sediment-laden waters which will allow the development of algorithms, e.g., chlorophyll and suspended sediment, from the corrected imagery.

In addition to relying on aircraft sensors, SEI scientists are making extensive use of in-water instruments. The Undulating Oceanographic Recorder (UOR) has been a reliable data collection vehicle and figures prominently in a number of SEI projects. Another example of a mature *in situ* capability is the Marine Radiometric Spectrometer (MARAS). Perhaps one of the more intriguing uses of an existing technology in a new deployment capability is the Plymouth Marine Bio-Optical Data Buoy (PlyMBODy). This buoy takes existing *in situ* radiometers and places them in an automonous package capable of collecting and transmitting the data to shore.

With the absence of SeaWiFS, the emphasis in SEI has properly been on airborne remote sensing and *in situ* sampling. Given the importance of Case-2 waters to the SEI, determining sediment concentration from the relationship between the inherent optical properties (IOPs) of particulate material and the ratios of remotely sensed reflectances has been an active area of research. Spaceborne systems, however, have not been forgotten. The Coastal Earth Observation Application for Sediment Transport (COAST) project is funded by the British National Space Center (BNSC) as part of an initiative to promote innovative uses for satellite data. Remotely sensed data will be obtained from both the spaceborne SeaWiFS instrument and the airborne CASI sensor; the latter will provide the fine detail and the former the large-scale temporal variations. These data, after atmospheric correction, will be used to generate local and wide area maps of suspended particulate material (SPM) concentration and water quality, and combined with vertical profile and transport models to generate maps of coastal sediment transport and potential coastal morpho-dynamic changes.

With so many individuals and projects involved with data collection, there is a concern about common access to the most relevant data. Within the SEI, it is not possible, nor is it appropriate, to develop a new data archive or database to centralize the bio-optical data being collected by SEI investigators. It is proposed to utilize the already established SeaWiFS Bio-Optical Archive and Storage System (SeaBASS) data archive (Hooker et al. 1994). A duplicate system, called the SeaWiFS Exploitation Initiative Bio-Optical Archive and Storage System (SEIBASS), will be set up at the Plymouth Marine Laboratory (PML). SEIBASS will be a *bio-optical* data validation and holding system for the SEI and will form the basis for providing enhanced processing capabilities. It is important to note that investigators are still expected to use the British Oceanic Data Center (BODC) as the primary UK database facility.

2. AGENDA

The SEI presentations were divided into morning Core Project Reports and afternoon Research Reports. The topics involved with these activities, along with the presentors for each, is given below.

0930	Chairman's Introduction	I. Robinson
0935	Update on SeaWiFS	S. Hooker
	Core Project Reports	
1010	Atmospheric Correction, I	P. Land
	Atmospheric Correction, II	A. Wilson
1050	*Break*	
1110	Dundee Satellite Receiving Station	S. Groom
1140	SeaWiFS Strawman Algorithm	G. Moore
1220	SEIBASS Database	J. Aiken
1230	Group Discussion	
1300	*Lunch*	
	Research Reports	
1400	Data to Models	M. Srokosz
1420	Norwegian Sea Studies	P. Smith
1440	Data Buoy	M. Pinkerton
1455	PACE	S. Hudson
1505	Reflectance and IOPs	A. Cunningham
1520	Group Discussion	
1530	*Break*	
1550	MARAS	S. Danaher
1610	Indian Ocean	A. Weeks
1620	Undulating Oceanographic Recorder (UOR) Arabesque	I. Bellan M. Pinkerton
1640	Antarctic Results	G. Moore
1650	COAST Project	H. Bottrell A. Matthews
1710	LOIS Airborne Remote Sensing	M. Robinson R. Murphy S. Hudson
1725	Chairman's Summary	I. Robinson
1800	*Adjourn*	

3. EXTENDED ABSTRACTS

SEI Science Team members gave short talks describing the work each has undertaken in support of the SEI program. The information presented in this section are extended abstracts provided by the investigators. In general, the abstracts convey much of the information the team member presented at the meeting, although in some cases, a more complete summary of the work involved is provided here than was actually given. Consequently, these summaries are sufficiently detailed as to allow a good appraisal of the scientific pursuits of each team member and the SEI program as a whole.

In many cases, the talks were prepared by several individuals, but presented by only one. The ensuing subsections are organized by the presentors, but to ensure proper acknowledgment of everyone associated with a particular presentation, the complete authorship is given below. The affiliations and communication particulars for individuals who contributed to the presentations, but were not able to attend the meeting, are given in Appendix B. The meeting attendees and their contact specifics are given in Appendix C.

3.1 Peter Land

3.2 Andrew Wilson

3.3 Steve Groom

3.4 Gerald Moore

3.5 James Aiken and Gerald Moore

3.6 Meric Srokosz, Peter Challenor, Mike Fasham, and Robin Harmon

3.7 Paul Smith and E. Gay Mitchelson-Jacob

3.8 Matthew Pinkerton

3.9 Samantha Hudson

3.10 Alex Cunningham and Ken Jones

3.11 Daniel Buckton and Seán Danaher

3.12 Alison Weeks

3.13 Ian Bellan and James Aiken

3.14 Gerald Moore

3.15 Howard Bottrell, Alison Matthews, Linda Nash, Simon Boxall, Tilsley Peck, Howard Southgate, and Ruth Wilson

3.16 Marie-Claire Robinson

3.17 Richard Murphy, Gerald Moore, Andrew Wilson, Karla Youngs, and Kevin Morris

The abstracts are presented *as submitted* with very minor modifications to correct typographic or obvious clerical errors and to present the material in the style adopted for the *SeaWiFS Technical Report Series.* Since most of the material was supplied by UK scientists, many of the needed changes were to reconcile differences between American and British language rules.

3.1 P. Land

Retrieval of Water-Leaving Radiances Over Case-2 Waters Using an Iterative Fitting Algorithm

An algorithm is described that uses an iterative global minimization routine [currently Powell's method from *Numerical Recipes* (Press et al. 1992) although another may trivially be substituted] to minimize the sum of squared deviations from the observed top of atmosphere radiances, $L_{\rm toa}$. The algorithm is modular, with a rigorous distinction between atmospheric and in-water effects, allowing atmospheric correction and water composition algorithms to be substituted with relative ease. Indeed, the in-water algorithm described is illustrative rather than being put forward as an optimum choice. The idea is that the knowledge gained from an in-water algorithm may be used to predict the water-leaving radiance L_W, enabling a better atmospheric correction to be performed, which in turn allows a better in-water estimation.

The first step is to initialize the atmospheric and in-water parameters. Atmospheric parameters are the relative proportions of three aerosol types, ideally representing the extreme values of single scattering albedo omega and phase function asymmetry likely to be found in the troposphere. In-water parameters used in the demonstration water model are the concentrations of three water constituents (phytoplankton and associated detritus, inorganic sediment, and Gelbstoff).

Next, the aerosol optical depth τ_a is calculated from $L_{\rm toa}$, ω, and phase function $\tilde{\beta}(\theta)$ in each band on the assumption that L_W is zero. This is done using the single scattering theory, corrected for multiple scattering effects using look-up tables. These apparent *optical depths* are a combination of attenuated water-leaving radiance effects and path radiance effects, and because the water albedo is small (typically less than 0.1), the effect of increasing τ_a for a given L_W is always to increase $L_{\rm toa}$, and, hence, the apparent optical depth. This means that the apparent optical depths represent an upper limit on τ_a. The value of τ_a is assumed to follow an Ångström wavelength dependence, and the largest Ångström-varying values no greater than the apparent values are found. These are then upper limits on τ_a within the Ångström approximation.

Now the iterative loop begins. First, L_W is calculated from $L_{\rm toa}$, τ_a, ω, and $\tilde{\beta}(\theta)$ and corrected for multiple scattering as above. Next, L_W is predicted from the water constituents by estimating the absorption coefficient a and backscatter coefficient b_b of each constituent (assumed proportional to concentration), summing them and using a relationship found by Gordon (1976) between the subsurface reflectance ratio R and $a/(a+b_b)$. L_W is then deduced from R and compared with that predicted from the atmosphere, and the differences minimized by changing the water constituent concentrations using a global minimization technique (Press et al. 1992).

Next, τ is calculated in each band from L_W, $L_{\rm toa}$, ω, and $\tilde{\beta}(\theta)$ and corrected for multiple scattering, and an Ångström dependence is found by least squares fitting. L_W is then calculated from $L_{\rm toa}$, the Ångström τ_a values, ω, and $\tilde{\beta}(\theta)$, and compared with the actual $L_{\rm toa}$. The difference is minimized by changing the proportions of the aerosol types [which changes ω and $\tilde{\beta}(\theta)$] and recalculating τ_a, the Ångström dependence, and $L_{\rm toa}$ as above using Powell's method. Finally, the remaining error in $L_{\rm toa}$ is compared with that found in the previous iteration, and if convergence has not occurred, another iteration begins.

3.2 A. Wilson

Atmospheric Correction of SeaWiFS Data; An Algorithm and Validation for Case-2 Waters

3.2.1 Introduction

A research study into the requirements for generating validation data, to test atmospheric correction algorithms, has been supported through a NERC SEI. A test-flight has been carried out to acquire simulated SeaWiFS ocean color data in a coastal region using an airborne imaging spectrometer, and ground-based instrumentation used to characterize the radiative properties of the atmosphere during the overflights. Some results of this preliminary airborne campaign are presented and developments in ground-based and airborne instrumentation are described.

A major obstacle to the successful utilization of SeaWiFS data in the coastal zone is the atmospheric correction of the optical data in the presence of high concentrations of suspended sediment (Case-2 waters). The development and validation of new atmospheric correction algorithms in this area has been supported by the UK NERC, through the SEI, which is also supporting key areas in the retrieval of biophysical parameters from water-leaving radiance as well as in data reception, processing, and distribution.

A joint research grant was awarded by the NERC to the Department of Space and Atmospheric Physics at Imperial College, London and the NERC Remote Sensing Applications Development Unit (RSADU) to address the atmospheric correction problem by two complementary research studies. The status of the algorithm development study, being carried out at Imperial College, has been covered elsewhere in this report (Section 3.1). This paper reports on the activities and status of the study by the RSADU, to provide a complete validation data set with which to test the various correction and retrieval algorithms.

The validation data is being generated by simulation of the spectral bands of the SeaWiFS instrument, using an airborne imaging spectrometer, and by fully characterizing the atmospheric radiative properties during data acquisition, using a variety of ground and airborne instrumentation. The algorithms for retrieving water-leaving radiance and the atmospheric contribution to the received signal, derived from the simulated sensor channels alone, will be compared with the directly measured atmospheric optical parameters using a full radiative transfer code to estimate the level of accuracy in retrieval.

3.2.2 Airborne Simulation of SeaWiFS Data

The eight SeaWiFS spectral channels are being simulated with a Canadian built CASI, which forms part of the NERC ARS Facility (Wilson 1994a). This airborne imaging spectrometer is a two-dimensional instrument utilizing charge coupled device (CCD) detectors and is capable of recording up to 18 programmable spatial channels, selected over the 400–915 nm wavelength range, in 512 pixel wide swaths. It is flown on the NERC Piper Chieftain aircraft along with an upgraded Daedalus 1268 ATM that can record data from 11 relatively wide spectral bands from the visible, near-infrared (NIR), shortwave infrared (SWIR), and thermal infrared. The aircraft can image from altitudes between approximately 800–3,000 m, providing a range of spatial resolutions of between 1.5–5.5 m. The aircraft is fitted with an Ashtech 3DF global positioning system (GPS) attitude and position referencing system which allows postprocessing geometric correction of both sensor data to standard map projections. Subpixel positional accuracy can be attained when used in conjunction with simultaneously recorded differential GPS ground station information.

3.2.2.1 Spectral Channels

The CASI spatial mode bands selected for this study, which simulate the channels of the SeaWiFS instrument and include additional channels for retrieval of atmospheric optical parameters along the flight lines, are shown in Appendix A (Table A1). The band set is generated by selecting which of the 288 possible CCD detector elements, which cover the wavelength range of the instrument, are to be summed into a given spatial band. Each detector element has a spectral sampling interval of 1.8 nm, but a spectral bandwidth of approximately 2.9 nm at 650 nm, which varies with wavelength. The actual center wavelengths of each detector element are characterized during laboratory calibrations and these determine which elements are used to make up the CASI band set.

Fourteen channels have been selected for this study, since there is a tradeoff in the maximum number of possible channels recordable at a given aircraft altitude. Channels 1-5, 7, 10, 12, and 14 are used to simulate the exact band centers and bandwidth characteristics of the SeaWiFS instrument. Because of the notch in SeaWiFS band 7, to avoid the strong oxygen absorption feature at 762 nm, this channel has been simulated using two separate CASI channels (10 and 12) that can be summed during data analysis. Channel 11 is included for completeness to measure the oxygen absorption feature itself. CASI channels 8 (682.5 nm) and 9 (710 nm), in association with channel 7 (670 nm) are included to observe any possible solar stimulated chlorophyll fluorescence expressed as increased signal in the narrow 682.5 nm channel. Channel 13 has been included in an attempt to retrieve atmospheric water column amounts by observing in the weak 825 nm water vapor absorption feature. Normal use of measurements at the stronger 942 nm feature are precluded by the upper wavelength limit of the CASI. Channel 6, at 620 nm, has been added to simulate one of the planned European Space Agency (ESA) Medium Resolution Imaging Spectrometer (MERIS) bands used to monitor suspended sediments. Table A1 also indicates the main purpose of the CASI channel selection in terms of the retrieved applications parameters of interest.

A flight of the CASI in support of this study took place on 25 July 1994 at a test site in the south of England, with the main objective of testing the selected band set and addressing any logistical problems that might arise during deployment of the ground instruments. The Thorney Island test site comprises a unused airfield, projecting into Chichester harbor, with the surrounding waters providing a variety of shallow and deeper water targets as it merges into the English Channel (Fig. 1a). Superimposed on the map are the flight line centers and swath widths for the low and high altitude flights recorded during this test. Future flights, following launch of the SeaWiFS instrument, will extend much further into the English Channel and provide sufficient spatial coverage during overpasses by the sensor with its nominal 1 km spatial resolution. The atmospheric conditions were ideal for this test, since there was a fairly high degree of uniform haze, useful to test the retrieval algorithms, and little, if any, visible clouds during most of the day.

3.2.2.2 CASI Data

Figure 1b is a CASI (channel 5) image from the high altitude flight line covering the map area of Fig. 1a. This image has not been geometrically corrected and shows considerable roll distortion of the *straight* runways. The scene was recorded at almost high tide, but still shows many features and variations within the water areas. Figure 2 provides a selection of calibrated CASI spectra (sensor received radiance), taken from along a central line of the CASI image moving from sediment-laden shallow water to clearer and deeper water. The spectra show consistent short wavelength channel radiances and a progressive

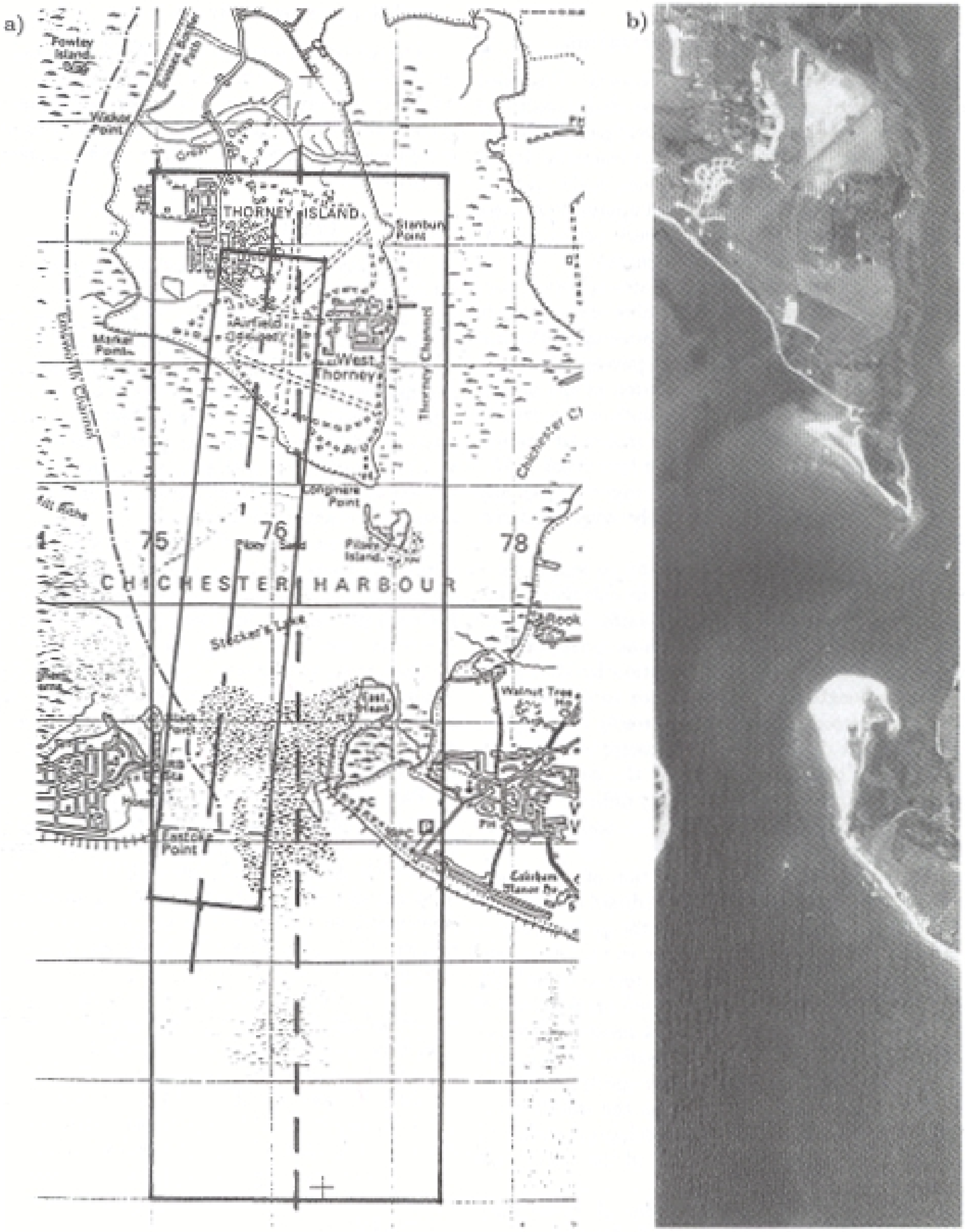

Fig. 1. a) Map of the test site at Thorney Island showing the low and high altitude flight line coverage (left) and **b)** channel 5 (555 nm) CASI image from the high level flight line (right).

decrease in the longer wavelength channel radiances with deeper water, due to the reduction in sediment reflectance in, or through, the water column.

3.2.3 Atmospheric Characterization

To complement the airborne data collection described above, the second half of the validation data consists of measured atmospheric optical and physical properties that provide a complete radiative transfer characterization of the atmosphere during the day and, more specifically, at the actual time of the flights. Most important of these optical properties are the total atmospheric optical depths at each of the SeaWiFS channel wavelengths.

The radiative transfer through the atmosphere, at optical wavelengths, is controlled by a number of components that attenuate the solar radiation by scattering and/or absorption and can be quantified by the (wavelength dependent) total optical depth $\tau(\lambda)$, a function of the atmospheric transmittance. Total optical depth is the sum of the component attenuations caused by molecular scattering $\tau_R(\lambda)$; scattering and/or absorption by aerosols $\tau_a(\lambda)$; and absorptions by ozone $\tau_o(\lambda)$, water vapor $\tau_{wv}(\lambda)$, and the uniformly mixed gases $\tau_g(\lambda)$, namely oxygen and carbon dioxide.

The amount of Rayleigh scattering by air molecules, a function of the air density profile, can be calculated from a knowledge of this profile shape and surface barometric pressure. Atmospheric gas species such as ozone, oxygen, and water vapor attenuate solar radiation by absorption at specific wavelengths and in proportion to their concentration. The scattering process by aerosols is controlled by the aerosol size distribution, and absorption by the refractive index of the material forming the particle. The radiative effect of aerosols is particularly difficult to model since their size distribution, concentration, and spatial distribution are so variable.

Since total optical depth is a function of the atmospheric transmittance, a measure of the direct solar irradiance at the ground and a knowledge of the extraterrestrial solar irradiance can be used to derive the total amount of attenuation over narrow wavelength regions—the basis of sun photometry. Using specific wavelengths to derive $\tau_o(\lambda)$, $\tau_{wv}(\lambda)$, and $\tau_g(\lambda)$, and using a measure of barometric pressure to derive $\tau_R(\lambda)$, the residual aerosol optical depth can be determined. Since the spectral variation of aerosol optical depth is a function of the size distribution and refractive index, making an assumption about the value of the latter provides a measure of the aerosol size distribution.

The more independent spectral values of aerosol optical depth that can be derived, the more detailed and accurate the numerical inversion to aerosol size distribution can be. Use of the Mie scattering theory can then enable the main aerosol radiative characteristics across the entire optical wavelength range to be determined, especially over the spectral bands of an Earth observing sensor, such as the SeaWiFS instrument.

3.2.4 Instrumentation

The RSADU is involved in the development and use of a range of ground-based instruments to retrieve some or all of the above mentioned atmospheric optical parameters. The current and planned instruments, to be used in support of this project, are described in more detail in the following sections.

3.2.4.1 ATLAS

The Auto-Tracking Land and Atmosphere Sensor (ATLAS) has been developed at RSADU, primarily to provide a single instrument that could acquire high spectral resolution directional surface reflectance of vegetation canopies and simultaneously measure atmospheric optical parameters. The instrument is based on the use of three separate Spectron Engineering SE-590 spectroradiometers which provide complementary spectral data in 252 (11 nm wide) channels from 400–1,100 nm using cosine, 1°, and 15° attachments and mounted on a computer controlled altazimuth platform (Fig. 3).

The instrument was first used in Niger, West Africa, during the Hydrological Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel), to retrieve the bidirectional reflectance distribution functions (BRDFs) of typical Sahelian cover-types (Wilson 1994b). The instrument was also designed to measure global irradiance over the 252 spectral channels and, using the 1° field-of-view (FOV) attachment, to derive spectral optical depths from direct beam solar irradiance and to sample the directional radiance from the diffuse sky hemisphere.

Part of the NERC SEI research grant was specifically allocated to the re-engineering of the ATLAS instrument, to overcome difficulties encountered in the Niger deployment with the optical alignment of the 1° FOV and the solar tracking device, and to enable the instrument to be operated directly from the heavy duty tripod, without requiring the 7 m long boom structure and leveling platform seen in Fig. 4.

This period of re-engineering, designed to reduce the overall weight of the instrument during deployment for atmospheric measurements only, precluded the use of ATLAS during the test flights on 25 July. Following the completion of this work and field tests, the instrument is now ready for deployment during the next airborne campaign. However, it is still a fairly cumbersome instrument to deploy, even in its reduced form, due to the control electronics and heavy duty batteries required for the altazimuth mount platform.

3.2.4.2 CIMEL CE-318 Sun Photometer

To support RSADU research into the atmospheric correction of airborne and satellite remotely sensed data with

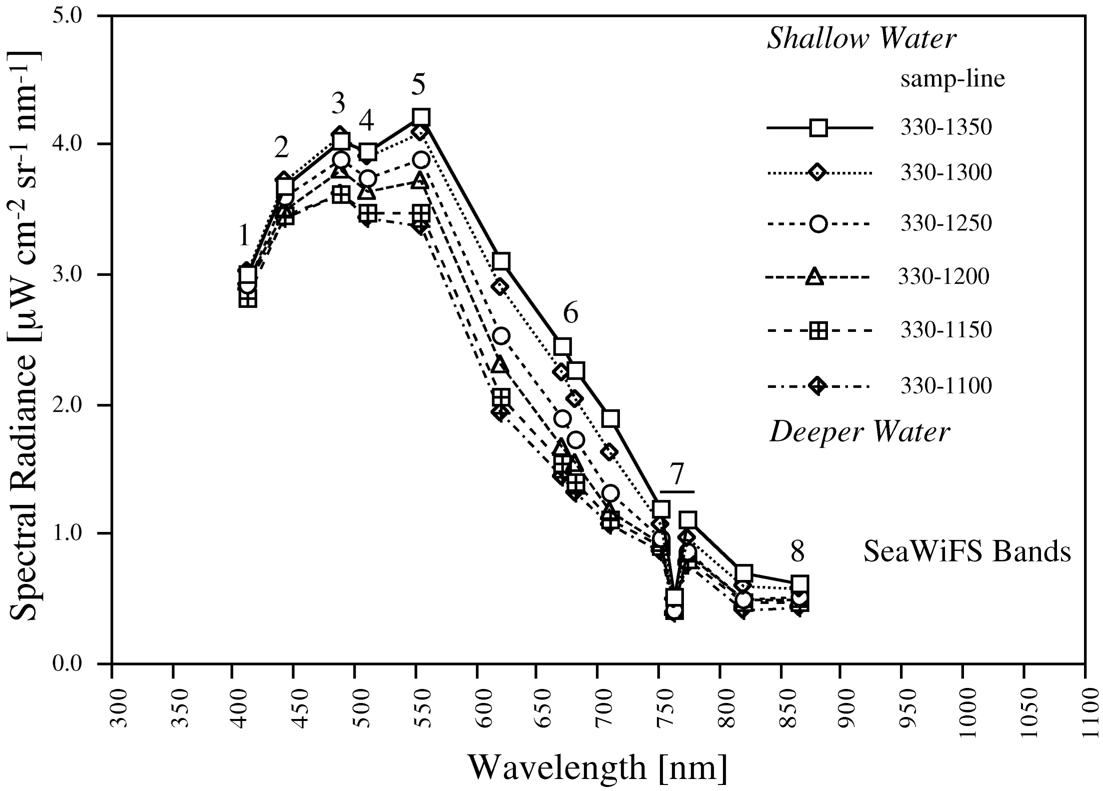

Fig. 2. Water-leaving radiance from the CASI 14 channel SeaWiFS simulation band set.

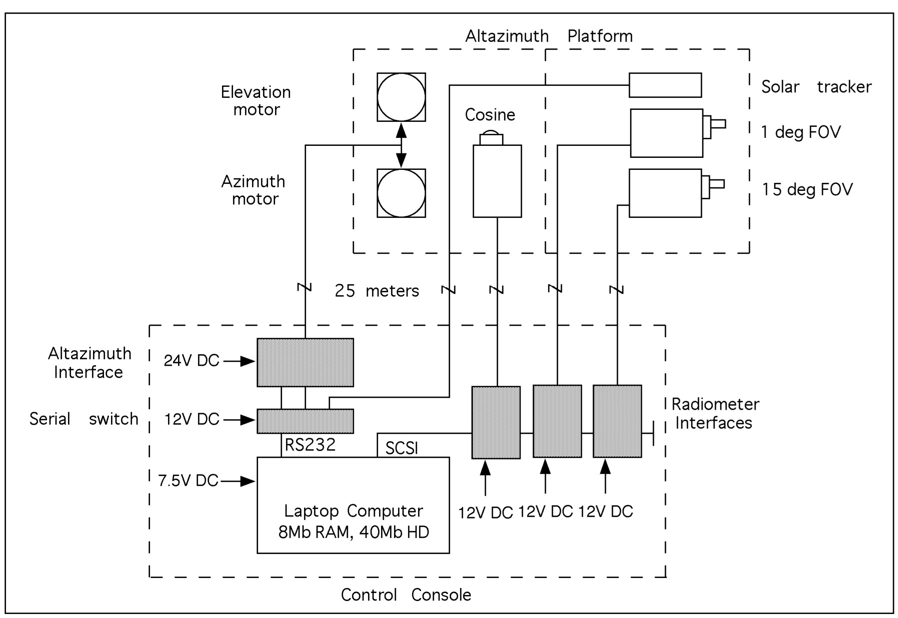

Fig. 3. Schematic diagram of ATLAS.

a more portable and easily deployable instrument, a commercially built sun photometer was acquired. The CIMEL Electronique CE-318 instrument is an automated *filter-wheel* sun photometer, designed to measure the direct solar irradiance using eight interference filters, located over the 300–1,040 nm spectral range of its silicon detector. Table 1 indicates the channel center wavelengths (CWL), bandwidths, and purpose. The two channels dedicated for ozone retrieval were not available at the time of purchase and are not fitted on the current instrument. In addition to the direct solar disk measurements for derivation of atmospheric optical depths, the instrument can be programmed to automatically take a series of measurements at fixed relative angles to the solar axis. These can be either horizontally, at the zenith angle of the sun (almucantar profile), or vertically through the sun at the solar azimuth angle (vertical profile). These angular scattering profiles, taken with the four *aerosol* channels, can be used to infer the aerosol size distribution using the inversion algorithm of Nakajima et al. (1983) and to derive the aerosol scattering phase function.

Table 1. The spectral bands of the CIMEL CE-318 sun photometer. Channel numbers 7 and 8 are not available on this instrument. The *Scientific Purpose* codes correspond to the following: A = aerosol optical depth, W = water vapor content, and O = ozone amount.

Channel Number	*CWL* [nm]	*Width* [nm]	*Scientific Purpose*
1	440	10	A
2	670	10	A
3	870	10	A
4	1,020	10	A
5	940	10	W
6	940	40	W
7	307	10	O
8	326	10	O

The CIMEL was deployed on 25 July 1994 at Thorney Island and retrieved a near-continuous set of direct solar beam irradiance with the six operating channels at one minute intervals throughout the day, punctuated hourly, by measurements of almucantar and vertical profiles. Figure 5 shows the variation in measured irradiance (instrument counts) during the day and indicates the times of the two overpasses of the NERC aircraft. The spectral variation of aerosol optical depth derived from these measurements can be used to monitor the variation in particle concentration with time.

Figure 6 shows the almucantar profile for 1100 Greenwich Mean Time (GMT) and the variation in solar aureole and sky radiance with relative scattering angle for the different wavelengths. The high degree of symmetry, from either side of the sun, is an indication of the clear sky conditions during the measurements, while the overall profile shapes are indicative of the highly forward scattering by atmospheric aerosols forming the solar aureole.

3.2.4.3 ICARUS

The main limitations of the currently owned CIMEL, for more advanced atmospheric research, is the lack of the two ultraviolet (UV) channels and, in general, the limited number and wavelength range of the aerosol channels. The maximum number of filter positions prevents the addition of a sufficient number of channels to retrieve a multimode aerosol size distribution. The sequential nature of the filter wheel system and time taken to record a single set of spectral measurements, together with the current solar tracking system, also precludes this type of instrument for deployment on moving platforms, such as on research vessels carrying out SeaWiFS validation at sea, or even for deployment on aircraft to sample the atmosphere at different altitudes.

The Instrumentation Characterizing Aerosol Radii Using Sun photometry (ICARUS) project is an active area of research at RSADU and is charged with developing an instrument to meet the needs for both the atmospheric correction of Earth observation data and climate change studies. Funding has just been approved for the development of a prototype instrument using up to 32 combined interference filter dectector units, covering the complete wavelength range from UV to SWIR (300–2,500 nm), and fed with light through a multistrand fiber-optic bundle. The use of a fiber-optic bundle enables a highly mobile and fast response, solar-tracking and pointing system to be employed to meet the requirement for use on moving platforms.

The available number of simultaneously recorded spectral channels will allow the use of multiple, independent, and complementary methods of retrieving atmospheric optical parameters, for example, using channels in both the UV Hartley band and the weak visible region Chappuis band to determine total column ozone amount. Similarly, a number of channels will be dedicated to retrieving total column water vapor content, by a variety of techniques, at either high or low concentrations. The primary aim, however, is to provide a sufficient number of independent spectral channels over a wide wavelength range for the inversion of aerosol size distribution from multispectral aerosol optical depths, following the methods of Twomey (1963) and King (1978).

The instrument will be built to accommodate a maximum of 32 spectral channels, but will initially employ 19 channels using UV-enhanced silicon detectors (Table 2). New detector materials will be used for the remaining channels to cover the 1.1–2.5 μm range once the prototype has been extensively field tested. All the spectral channels have been chosen to either avoid, or specifically include, the major atmospheric absorption features in the optical domain, as can be seen in Fig. 7. This diagram shows

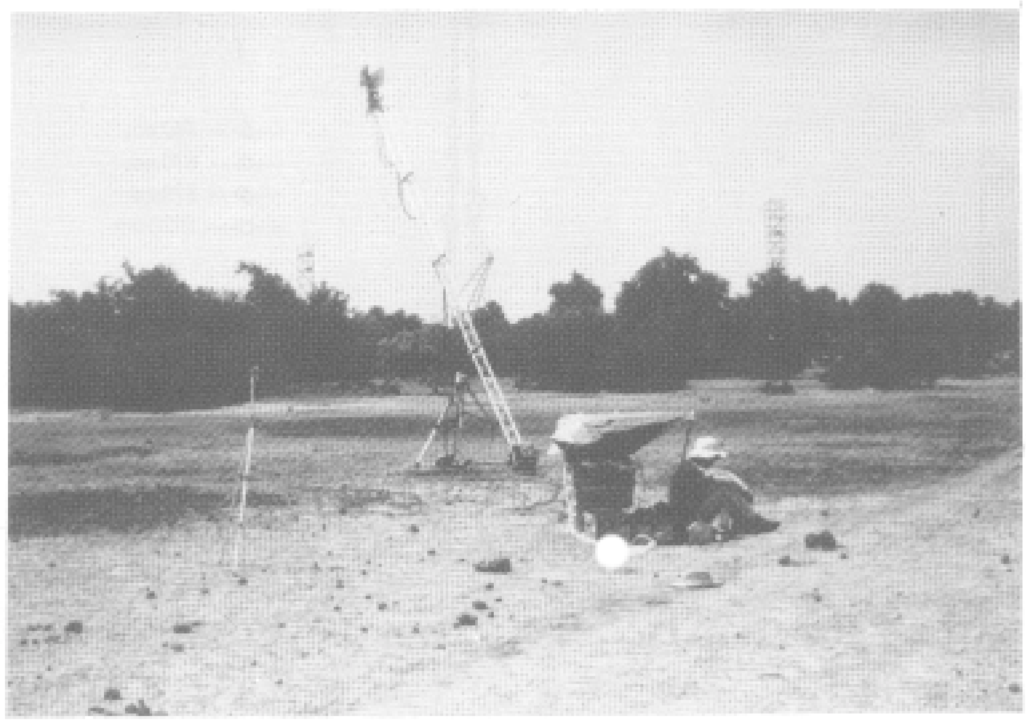

Fig. 4. Deployment of ATLAS on a 7 m boom and tripod during HAPEX-Sahel.

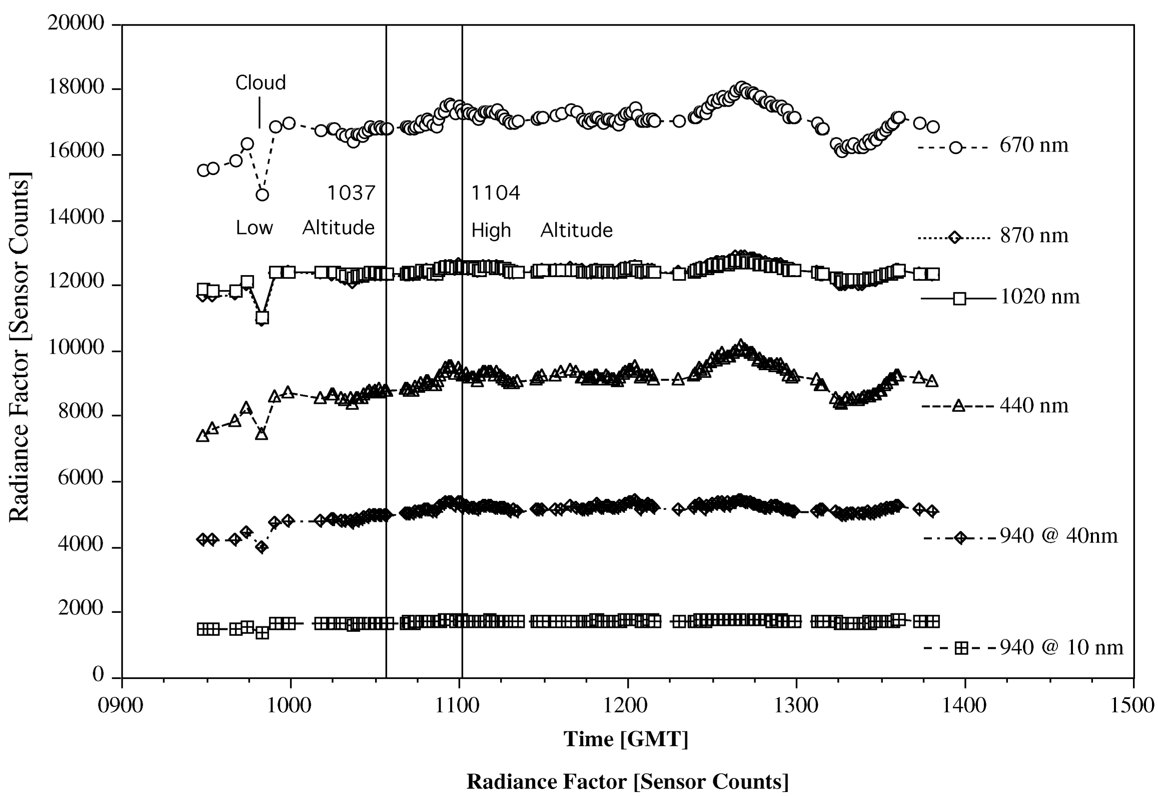

Fig. 5. Direct beam solar irradiance using CIMEL sun photometer on 25 July 1994.

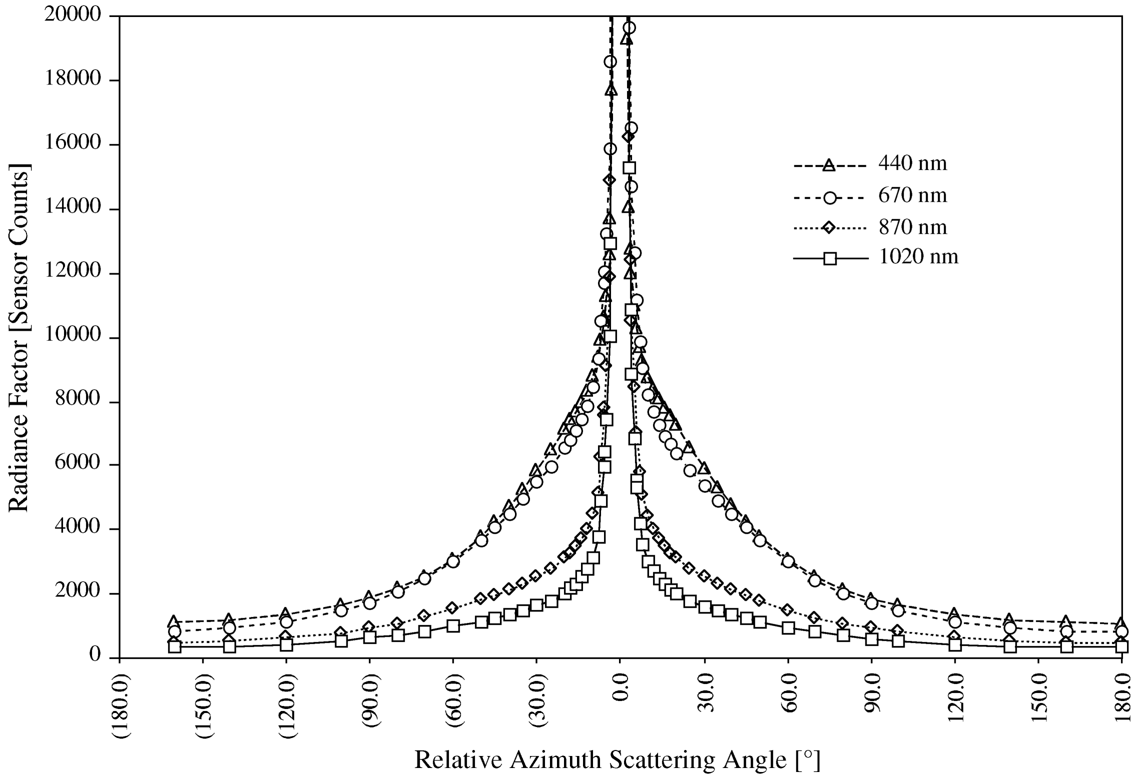

Fig. 6. Almucantar profile using the four *aerosol* channels of the CIMEL sun photometer.

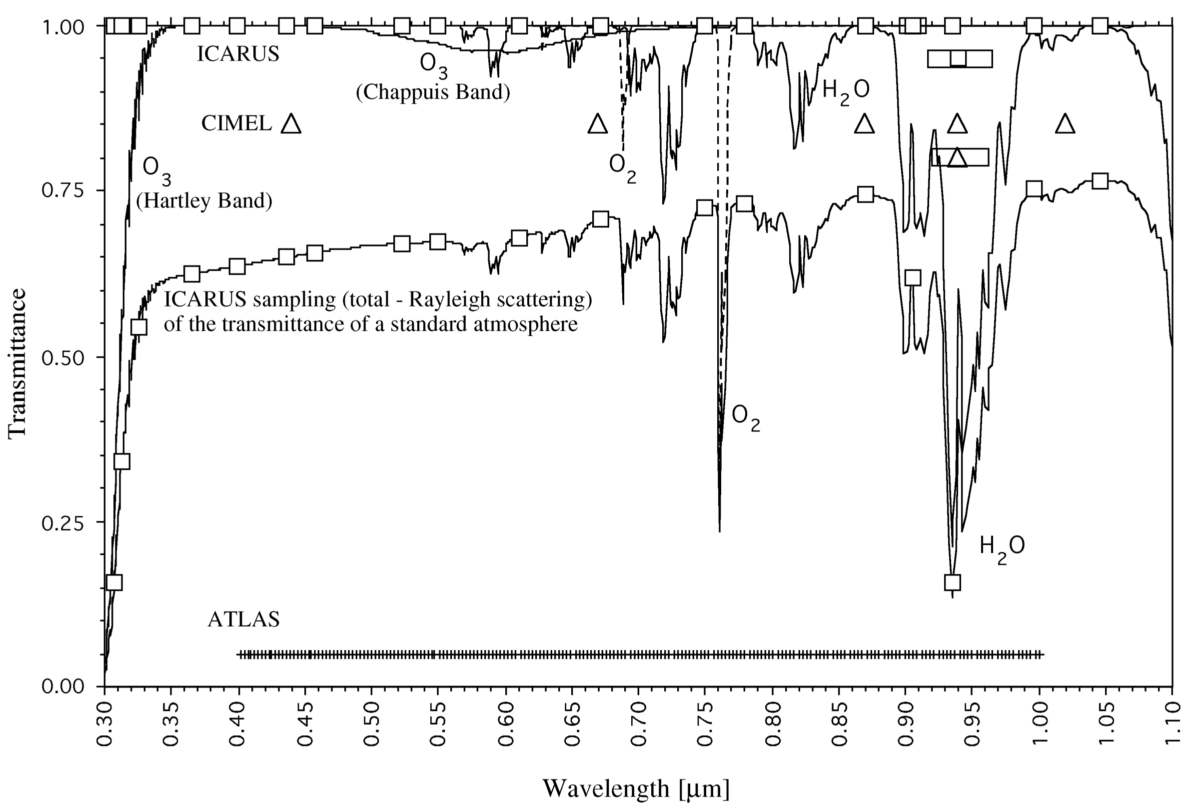

Fig. 7. Atmospheric transmittance for standard atmosphere, component absorptions, and spectral sampling of ATLAS, the CIMEL sun photometer, and ICARUS.

a typical atmospheric transmittance curve (total minus Rayleigh scattering attenuation) and the component atmospheric absorptions by ozone, oxygen, and water vapor over the 0.3–1.1 μm wavelength range. The diagram also shows the spectral sampling positions of the three ground-based instruments discussed in this paper.

Table 2. Spectral bands of the CIMEL CE-318 sun photometer as identified by the CWL of each. Bands 7 and 8 are not available on this instrument. The *Scientific Purpose* codes are as follows: A = aerosol optical depth, W = water vapor content, and O = ozone amount.

Band Number	*CWL* [nm]	*Width* [nm]	*Scientific Purpose*
1	307	10	O
2	313	10	O†
3	326	10	O
4	365	10	A
5	400	10	A
6	436	10	A and O
7	458	10	A and O
8	523	10	A and O
9	550	10	A and O
10	610	10	A and O‡
11	671	10	A and O
12	750	10	A and O
13	780	10	A
14	870	10	A and W
15	905	20	W
16	936	10	W
17	940	50	W
18	995	10	A and W
19	1,046	10	A and W

† UV Hartley Absorption Band
‡ Chappuis Absorption Band

3.2.4.4 Airborne Instrumentation

Besides the ground-based instruments described above, the CASI sensor on the NERC aircraft is fitted with an incident light sensor (ILS), which measures downwelling global irradiance at the same spectral channels as the sensor is imaging. This, hopefully, will provide some additional information on the variability of the solar irradiance along a flight line, once the data is filtered for variations due to aircraft attitude. A further airborne instrument is planned to be added to the NERC aircraft to physically sample the air, via an inlet tube, and derive a measure of the aerosol size distribution at approximately 12 size bins between 0.15–10 μm, The aircraft will then be able to sample the air it is flying through and, with multiheight flight lines, give an indication of the vertical distribution and variation of atmospheric aerosols for comparison with integrated column measurements from ground-based optical retrievals.

3.2.5 Conclusions

This paper has described the developing range of instrumentation and measurement techniques, which are being used to generate validation data to test atmospheric correction algorithms applicable to SeaWiFS data in coastal (Case-2) waters. A preliminary test-flight has been carried out to verify the simulation of SeaWiFS spectral channels, using an airborne imaging spectrometer, and to test the deployment of the available ground instrumentation. Developments in instrumentation are still proceeding and these, hopefully, will become available for future flights, using the NERC ARS facility, to collect validation data at Thorney Island and during other calibration campaigns following the launch of SeaWiFS. It is particularly important that good quality and comprehensive validation data is made available in a timely fashion, for the success of the algorithm development study being carried out by co-workers at Imperial College, London. The remote sensing community will then be in a position to immediately benefit from the various, atmospherically corrected, data products generated from this ocean color sensor as soon as it becomes operational.

Acknowledgments

A. Wilson thanks the air crew and the flight co-ordinator, John Cook, for obtaining the airborne imagery after many aborted attempts, due to poor weather, and to Dr. Ted Milton and David Emery, from the University of Southampton, who assisted in the logistics and data collection at Thorney Island.

3.3 S. Groom

UK SeaWiFS Data Acquisition and Processing Facilities

3.3.1 Overview

SeaWiFS reception and data processing for the UK academic community will be undertaken by the NERC Scientific Service through the receiving station at Dundee University, and the Remote Sensing Data Analysis Service (RSDAS) at PML. This article describes the tasks to be undertaken by the two groups, the associated processing of Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) imagery, the availability of SeaWiFS and AVHRR data in near-real time, and the visualization and analysis of SeaWiFS imagery in the ERDAS Imagine image analysis package, etc.

3.3.2 SeaWiFS Data Reception

It is planned to receive SeaWiFS High Resolution Picture Transmission (HRPT) data covering Europe and the Northeast Atlantic at the NERC Scientific Services Satellite Receiving Station at Dundee University, which has been approved by the National Aeronautics and Space Administration (NASA) as a research HRPT station. Dundee University has a long history of satellite data reception, starting in 1966 with automatic picture transmissions (APTs) from NIMBUS-2. In 1975, a Very High Resolution Radiometer (VHRR) station was constructed and a total of 2,500 passes were recorded from NOAA-5 until 1979, when the spacecraft was superseded. Since 1979, the station has received and archived five or six AVHRR passes each day. (Note that *VHRR* refers only to very early stations and data of this type.) Dundee also received and archived Coastal Zone Color Scanner (CZCS) data between August 1979 and June 1986.

To facilitate SeaWiFS reception, a complete reception system was manufactured in-house at Dundee, and installed in June 1993. By virtue of the compatibility with NOAA HRPT, this gives a total of three antennae providing enhanced redundancy for backup in the station. Computing resources were also upgraded with the purchase of two Sun/SPARC LX and two Sun/SPARC-10 workstations.

Low resolution overviews of raw AVHRR passes can be browsed shortly after reception on the World-Wide Web (`http//www.sat.dundee.ac.uk`). Registered users can order the full resolution data on 8 mm (Exabyte) tape, 9-track tape, possibly on Compact Disk-Read Only Memory (CD-ROM), and via file transfer over the Internet. It is expected that similar access will be available for SeaWiFS data, although all Internet access will require password security to restrict access to NASA authorized users. The station started transcribing the raw AVHRR archive onto CD-ROM in the spring of 1995. It is similarly planned to write the SeaWiFS level-1 data onto CD-ROM subsequent to decryption.

3.3.3 SeaWiFS Data Processing

The NASA SeaWiFS Data Analysis System (SeaDAS) software will be used for the analysis of the Dundee-received HRPT data; the HRPT product levels will be the same as the GAC processing. Level-0 data will be temporarily archived, and following decryption, will be converted to level-1a data; this will be the lowest level of product available to the UK community. Assuming that up to three passes are received each day, it will be feasible to store about 1 month of imagery on line at Dundee; this should enable authorized users to gain network access to the data for a reasonable period.

Processing to level-2 and level-3 data will be performed by RSDAS in Plymouth. At the start of the mission, the standard SeaDAS level-1a to level-2 programs will be used, accepting that for many coastal and shelf Case-2 waters the atmospheric correction algorithm will break down. As results from the SEI research into atmospheric correction over Case-2 waters become available, the entire data set will be reprocessed. It is expected that the new algorithms will be water specific, i.e., the Case-2 algorithm will give results over Case-1 waters equivalent to the Miami algorithm within SeaDAS. It will be important to ensure that reprocessed data are clearly differentiated from the standard SeaDAS products. This may involve adding to the Hierarchical Data Format (HDF) specification for Case-2, although for compatibility with other SeaWiFS users, this will be avoided if possible. Subsequent to processing, the data will be available to authorized users via the Internet. The long-term archive strategy is still undecided, but it will likely be through the Dundee station.

SeaWiFS does not detect thermal infrared, therefore, AVHRR imagery will be processed contemporaneously with SeaWiFS to provide SST information. This will be accomplished using existing software in Plymouth, which automatically processes AVHRR HRPT data received at Dundee and transferred over the Internet in near-real time to Plymouth. The format in which the AVHRR SST will be supplied to the user has not been determined as yet, although a product in HDF with navigation data in a similar form to SeaWiFS, which could then be manipulated by SeaDAS, is an attractive option. Because the NOAA satellites do not have GPS positioning, the navigation will be performed using a standard orbital model (SGP4) with satellite ephemeris data, with an empirical correction involving automatic control point fitting.

The remote sensing group in Plymouth currently operates a service to supply processed AVHRR images, in digital form, to ships at sea in near-real time (same day as reception). RSDAS will extend this service to SeaWiFS users who have been granted near-real time licenses by NASA.

3.3.4 SeaWiFS Data and ERDAS Imagine

SeaDAS is being developed to process SeaWiFS data, but it will not incorporate general image processing functionality, which is available in a wide variety of commercial or public domain packages. Such functionality may include multispectral classification, spectral, spatial, geographical information system (GIS), and textural enhancement, convolution and Fourier filtering, image presentation, as well as 24-bit (color composite) display capability.

In the UK academic community, the most commonly used software is the ERDAS Imagine package, which is available at low cost for non-profit research use through an agreement with ERDAS UK, Ltd. Imagine provides a wide variety of *standard* image processing functionality, and also allows new applications to be developed using an easy, graphical approach that links data sets to arrays, functions, constants, tables, etc. Since Imagine has its own internal image storage format, software is now being developed within RSDAS to facilitate easy conversion between the SeaDAS HDF and the ERDAS formats.

3.4 G. Moore

SeaWiFS Strawman Algorithm

The SeaWiFS mission will provide operational ocean color that will be superior to the previous CZCS proof-of-concept mission. An algorithm is needed that exploits the full functionality of SeaWiFS while remaining compatible in concept with algorithms used for CZCS. This document describes the theoretical rationale of radiance band-ratio methods for determining chlorophyll *a* and other important biogeochemical parameters, and their implementation for the SeaWiFS mission. Pigment interrelationships are examined to explain the success of the CZCS algorithms. In the context where chlorophyll *a* absorbs only weakly at 520 nm, the success of the CZCS 520:550 ratio needs to be discussed. This is explained by showing that in pigment data from a range of oceanic provinces chlorophyll *a* (absorbing at less than 490 nm), carotenoids (absorbing at greater than 460 nm), and total pigment are highly correlated. Correlations within pigment groups, particularly photoprotectant and photosynthetic carotenoids, are less robust. The sources of variability in optical data are examined using the NIMBUS Experiment Team (NET) bio-optical data set and bio-optical model.

In both the model and NET data, the majority of the variance in the optical data is attributed to variability in pigment (chlorophyll *a*), and total particulates, with less than 5% of the variability resulting from pigment assemblage. The relationships between band ratios and chlorophyll is examined analytically, and a new formulation based on a dual hyperbolic model is suggested which gives a better calibration curve than the conventional log-log linear regression fit. The new curve shows the 490:555 ratio is the best single-band ratio and is the recommended CZCS-type pigment algorithm. Using both the model and NET data, a number of multiband algorithms are developed; the best of which is an algorithm based on the 443:555 and 490:555 ratios. From model data, the form of potential algorithms for other products, such as total particulates and dissolved organic matter (DOM) are suggested.

3.5 J. Aiken and G. Moore

SEIBASS: A Proposal for an SEI Bio-optical Data Bank

The SEI represents a concerted effort by the UK ocean color community to provide algorithms, as well as calibration and validation data, for SeaWiFS. The data collected will conform to the *Ocean Optics Protocols for SeaWiFS Validation, Revision 1* (Mueller and Austin 1995). The sensors used will collect data in a wide range of oceanographic provinces, using instruments from a variety of different manufacturers. It will be essential to collect this data into a single coherent whole for the following reasons:

1) To make the data available to UK institutes developing interprovince algorithms;
2) To validate the calibration and quality of the data and ensure that SeaWiFS goals are met;
3) To integrate the data with the global calibration and validation data set provided by NASA; and
4) To produce a coherent data set on UK ocean color at the end of the SEI.

Within the SEI it is not possible, nor is it appropriate, to develop a new data archive or database. To achieve the above goals, it is proposed to set up a *mirror*, or duplicate, of the SeaBASS data archive (Hooker et al. 1994) called the SEIBASS. This system will form the basis for providing enhanced processing capabilities. It should be emphasized that this will be a *bio-optical* data validation and holding system for the SEI. It is important to note that investigators should still use BODC as the primary UK database facility.

The advantages of following the NASA SeaBASS model are:

- Compatibility with NASA holdings;
- Primary software maintained and validated by NASA;
- Provision of a *mirror* for a subset of NASA data (network access across the Atlantic is slow);
- Provision of a collection point to facilitate forwarding to NASA;
- Local validation and processing routines based on the first SeaWiFS Data Analysis Round-Robin (DARR) results (Siegel et al. 1995); and
- SeaBASS holds the calibration information for the radiance and irradiance scales used by manufacturers of common instruments and the SeaWiFS instrument.

Data will be held under the same conditions as the NASA SeaBASS system at the Goddard Space Flight Center (GSFC) and data access routes will be through NASA. It is hoped that the system will be in place by early 1996.

3.6 M. Srokosz, et al.

Using SeaWiFS (Ocean Color) Data in Biological Ocean Model Validation and Data Assimilation

3.6.1 Overview

This paper briefly describes the study that will be carried out, on the topic of biological ocean model validation and data assimilation, under funding from the SEI. A more detailed description of the study is given in the original proposal to the SEI (Srokosz et al. 1994). The background to the study is presented first (Section 3.6.2) and the objectives and methodology to be used are discussed next (Section 3.6.3). As the study is still in its initial stages, the paper concludes with some preliminary results (Section 3.6.4).

3.6.2 Background

One of the key questions in understanding climate change is the role of the oceans as a sink for carbon dioxide and, in particular, the role of ocean biology in that process (see the review of Siegenthaler and Sarmiento 1993). To come to grips with this problem, both observations and models of the biological processes involved are necessary, as is the ability to combine them in a manner that improves the ability both to understand and to predict what is happening in the oceans. Some aspects of biological modeling and ocean color observations that are relevant to this study are reviewed below.

The development of mathematical models of the production cycle in the upper ocean has exercised oceanographers from the early days of plankton modeling (Steele 1974). As in all ecosystem modeling, the key problem is how to reduce the apparent complexity of the marine ecosystem to a few functional groups of organisms that will encapsulate the dynamic features of the system. The main features of annual cycles of chlorophyll, primary production and nutrients have, perhaps rather surprisingly, been reproduced at various stations using models containing only a few (3–7) compartments (Fasham et al. 1990, Frost 1991, Fasham 1993, Fasham et al. 1993, and Steele and Henderson 1993). While such models may successfully predict annual cycles at particular stations, they may not perform well if used for a range of different locations. It is necessary to develop a geographically robust ecosystem model that, given the physical forcing at any locality, will predict the seasonal cycle of phytoplankton for comparison with satellite-derived ocean color observations. Such a model must incorporate the essential factors that influence phytoplankton dynamics: vertical mixing, light, nutrients, and zooplankton grazing.

A key test for such a model is whether it can simulate the very different seasonal cycles observed in the North Pacific and North Atlantic Oceans. In the subarctic North Atlantic, a pronounced spring bloom is invariably observed and summer nutrient levels reach limiting concentrations, whereas in the subarctic North Pacific there is very little annual variation in phytoplankton chlorophyll, and summer nutrient levels remain high (Parsons and Lalli 1988). High levels of nutrients throughout the year are also observed in the Antarctic Ocean. A number of hypotheses have been advanced to explain these differences (Cullen 1991 and Miller et al. 1991). These include differences in winter mixing (Evans and Parslow 1985), in the size structure of the herbivore population (Frost 1987), and in the input of atmospheric iron (Martin and Fitzwater 1988). Recent research (Fasham 1995) has shown that it is possible to construct a simple three-compartment phytoplankton, zooplankton, and nutrients (PZN) model that can reproduce the different annual cycles in the North Pacific and North Atlantic. The model is comparatively simple and it could be used as the basis of the assimilation experiments.

Although the CZCS instrument suffered from many problems, its flight on the NIMBUS-7 satellite from 1978–86 demonstrated the ability of an ocean color sensor to provide useful information on ocean biology (Abbott and Chelton 1991). SeaWiFS is a significant improvement over CZCS (Hooker and Esaias 1993) and, therefore, presents new opportunities for the study of ocean biology from space. First, its global coverage (unlike CZCS, which had no onboard data recording capacity) will allow the study of biological changes in different areas of the world's oceans on time scales of days to the lifetime of the mission (projected to be five years). Second, NASA plans to generate standard products, like pigment and chlorophyll *a* concentration (Hooker and Esaias 1993), which will be directly useful to biological studies. Finally, unlike *in situ* data sets, SeaWiFS will give synoptic information on the spatial patterns of biological activity in the ocean, as well as on the temporal variations. Thus, SeaWiFS will provide an ideal data set, both for the validation of, and for the assimilation of data into, biological ocean models.

3.6.3 Objectives and Methodology

The primary objective of the study is the development of techniques for combining observations, focusing especially on those from SeaWiFS, with biological and coupled biophysical models, both to validate the models and to improve them by the assimilation of data. Ultimately, the objective is to produce predictive coupled biophysical ocean models. To date, little work has been done, using remotely sensed data, in the area of validation of oceanic biological models and the assimilation of data into such models [the work of Ishizaka (1990a, 1990b, 1990c, and 1993), being a notable exception].

To fully exploit the potential of both the models and the ocean color data that will become available from SeaWiFS, it is necessary to develop appropriate methods for both validation and assimilation. Currently, many studies are being carried out on data assimilation for physical ocean models (Ghil and Malanotte-Rizzoli l991), and this study is complementary to those. It is worth noting that a major difference exists between physical and biological ocean models. Physical models are well established (being based on the fundamental equations of fluid dynamics) but need to handle the assimilation of large amounts of data efficiently. In contrast, biological models are not well established (the equations being ad hoc in nature) and few data are available for assimilation. These differences mean that methods developed for the physical assimilation problem may not be suitable for the biological one.

A consequence of the less established nature of biological models is the need to improve them, prior to assimilating data into them for predictive purposes. For this reason, the initial objective is to explore the use of data to improve models by fitting the models to the data. In particular, focus is placed on the use of data to estimate the parameters of the model; note that if parameter estimation is carried out sequentially, then the problem becomes one of data assimilation. To illustrate this issue, consider the relatively *simple* nitrogen-based biological model of Fasham et al. (1990). This seven-compartment [phytoplankton, zooplankton, nitrate, ammonium, dissolved organic nitrogen (DON), bacteria, detritus] model has 28 adjustable parameters, not all of which are well determined experimentally (some not being easily amenable to direct measurement). Improving the model parameters, by fitting the model to data, should improve the model, assuming that the model formulation does not neglect any key processes. How is this to be achieved?

The approach will employ both the *classical* twin experiment method used in data assimilation studies (Ghil and Malanotte-Rizzoli 1991), and the use of *in situ* data (once the SeaWiFS instrument is launched, ocean color data will also be used). The methods to be tested include:

a) The adjoint method, which is currently popular for physical problems, and has recently be applied to a simple predator-prey model using the twin experiment approach (Lawson et al. 1995);
b) Nonlinear optimization, using a cost function and constraints (some initial results using this approach are described below in Section 3.6.4);
c) Bayesian assimilation using the Metropolis-Hastings algorithm, which is a Markov Chain Monte Carlo (MCMC) method (again some initial results are given below); and
d) Simulated annealing, another MCMC method.

Given that any data set contains uncertainties (for example, noise or missing data), the latter two techniques might be expected, on theoretical grounds, to be more successful in determining the model parameter values. The first two techniques are more likely to be sensitive to the initial *guess* used for the parameter values. The advantage of testing the various methods using the twin experiment approach, over using real data, is that the *true* answer is known, therefore, the success (or otherwise) of the methods can be more easily assessed. The disadvantage is that the results obtained tend to give an overly optimistic view of what might be achieved in practice, hence the need to use real data as well.

Using this methodology, the authors hope to address such questions as: how many and what type of data are required to determine the model parameters to a given accuracy; what is the effect of noise on the results; and how efficient numerically are the techniques?

3.6.4 Preliminary Results

Some progress on the problem of parameter estimation has been made using two of the techniques described in the previous section, namely nonlinear optimization and the Metropolis-Hastings algorithm. More details on the nonlinear optimization approach can be found in Fasham and Evans (1995), while the details of the Metropolis-Hasting algorithm are available from Challenor (pers. comm.).

Fasham and Evans (1995) applied a nonlinear optimization technique to the seven-compartment model of Fasham et al. (1990) and data acquired during the 1989 Joint Global Ocean Flux Study (JGOFS) North Atlantic Bloom Experiment (NABE) at 20°W,47°N. The basic cost function minimized was formed from the squares of the differences between the square roots of the observed and predicted values of the variables. It was modified by the addition of penalty terms that were designed to restrict the estimated parameters to an expected range of values (Fasham and Evans 1995). The results were found to be sensitive to the initial guess used in the nonlinear optimization process and, while a similar fit to the overall data set was obtained (as measured by the final cost function value), considerable variation of the degree of fit to individual variables (such as zooplankton) occurred. Further work is necessary to explore and understand this behavior.

The Metropolis-Hastings algorithm is employed in solving the parameter estimation problem using Bayes theorem. The initial knowledge of the parameters is represented in terms of a probability density function—the prior distribution. This is combined with the likelihood of the data, through Bayes theorem, to obtain the probability density function of the parameters taking into account the data—the posterior distribution. From the posterior distribution, improved knowledge of the parameters (such as their means and variances), can be obtained. As some information is already known about the parameter values, perhaps an initial estimate with some measure of error, one can assume the prior distribution is Gaussian (with appropriate means and variances).

Calculating the likelihood of the data is more problematic with a large number of parameters (recall that the seven-compartment model has 28 parameters), as it would involve running the model for every point in the parameter space. For this reason, an MCMC method, the Metropolis-Hastings algorithm (Metropolis et al. 1953 and Clifford 1994), is used to efficiently obtain a solution by simulation. Challenor (pers. comm.) has applied the Metropolis-Hastings algorithm to the same predator-prey model as used by Lawson et al. (1995) in their study of the adjoint method, again using a twin experiment approach.

Initial results for a variety of situations (such as: initial ignorance, that is poor prior information; confident prior, that is good prior information; and incomplete data) seem promising, but the simplicity of the predator-prey model may be giving overly optimistic results. The results show that *initial ignorance*, assuming that the variances of the prior distribution are large, allows the recovery of the *true* parameter values, whereas *confident prior*, assuming that the variances of the prior distribution are small, is less successful if the initial parameter estimates are too far from their true values. In the latter case, the assumed prior distribution is in conflict with the data and this is reflected in the large variances associated with the posterior distribution (in the former case, the posterior distribution has small variances). Thus, the posterior distribution not only allows the determination of the parameters, but also gives information on how well determined they are (a variety of other information about the parameters, such as correlations, may be calculated from the posterior distribution). This demonstrates the advantages of using a Bayesian statistical framework for the parameter estimation problem (note that such a framework is equally applicable to the problem of data assimilation).

Clearly, much remains to be done, but the preliminary results reported here show that progress can be made. The authors hope to report further progress at the next SEI meeting.

3.7 P. Smith and E. Mitchelson-Jacob

Initial Results from Vestfjorden, Norway, Using the Satlantic Instrument

3.7.1 Introduction

Vestfjorden is a large fjord on the northwest coast of Norway between the Lofoten Islands and mainland Norway. The circulation of Vestfjorden is variable, depending on inflows of Norwegian Coastal Water, Atlantic Water, and river and glacial runoff (Fig. 8). With no prior optical measurements found for this region, these waters were presumed to be Case-2 waters due to the influence of coastal runoff and the strong Norwegian Coastal Current.

3.7.2 Results

Despite low solar radiance, Satlantic sensors were able to measure downwelling irradiance and upwelling radiance around Vestfjorden in October 1994. The following measurements were also made:

1) Phytoplankton *chlorophyll* (0.05–$0.2\,\mathrm{mg\,m^{-3}}$);
2) Phytoplankton speciation (diatoms offshore, dinoflagellates, and flagellates near shore);
3) Yellow substance absorption ($0.05\,\mathrm{m^{-1}}$); and
4) Suspended particulate matter (1–$3\,\mathrm{mg\,l^{-1}}$).

Color ratios were calculated to enable pigment algorithms, of the type used with CZCS data, to be derived (Gordon and Morel 1983). Chlorophyll measurements showed a small range in concentrations throughout the survey area. The dominant phytoplankton groups were found to be dinoflagellates and flagellates in the near-shore stations. Because of the low chlorophyll concentrations, however, there was no discernible difference in either the radiance or irradiance profiles made with the Satlantic sensors. Yellow substance values were also uniformly low and seston values remained fairly constant, but decreased slightly at the off-shore station; therefore, an independent algorithm could not be developed. In order to classify the water type, however, the data were added to existing plots representing Case-1 and Case-2 algorithms (Mitchelson et al. 1986) (Fig. 9). The Vestfjorden data points were well below the regression line for the Case-1 algorithms, but scattered around the mean of the Case-2 line.

According to Gordon and Morel (1983), a linear relationship exists between the scattering coefficient at 550 nm and seston concentration for near-surface waters. Examination of the scattering coefficient obtained from this relationship and the chlorophyll concentrations found in Vestfjorden, with respect to Case-1 and Case-2 definitions, confirmed that the Vestfjorden data values were indeed from Case-2 type waters.

3.7.3 Conclusions

Initial attempts at algorithm development, in the waters of Vestfjorden, Norway, were not possible due to uniformly low chlorophyll and SPM concentrations at this time of year. Despite the low SPM concentration, existing optical algorithms confirmed that waters around Vestfjorden are of type Case-2.

3.8 M. Pinkerton

Plymouth Marine Bio-Optical Data Buoy (PlyMBODy)

This is a summary of the PlyMBODy project which started on 18 April 1994 and is funded for three years under the SEI.

3.8.1 Project Rationale and Aims

Vicarious calibration of the optical sensors of CZCS was attempted by R. Evans of the CZCS Science Team using assumptions on the water-leaving radiance from clear water. The results implied high sensitivity degradation of all the CZCS optical bands over the eight years of its life. In order for SeaWiFS to address its science mission goals, it must be able to measure water-leaving radiance to within 5% absolute. Consequently, stringent verification and calibration procedures are necessary to monitor and correct for changes in the performance of the optical sensors. This will be addressed in two ways: onboard calibrations (solar and lunar viewing) and vicarious calibrations from ships, aircraft, and (moored and drifting) optical data buoys.

Direct sunlight falling onto a diffuser will be measured on board the satellite. The diffuser will degrade gradually over an estimated useful period of "several years" (McClain et al. 1992). This degradation will be tracked by comparison with scattered light from the moon, on the assumption that the moon surface is stable. Hence, changes in sensor sensitivity can be monitored and corrected for over time.

Vicarious calibration is achieved by comparing accurate measurements of water-leaving radiance, made by various means on Earth, with coincident data from the

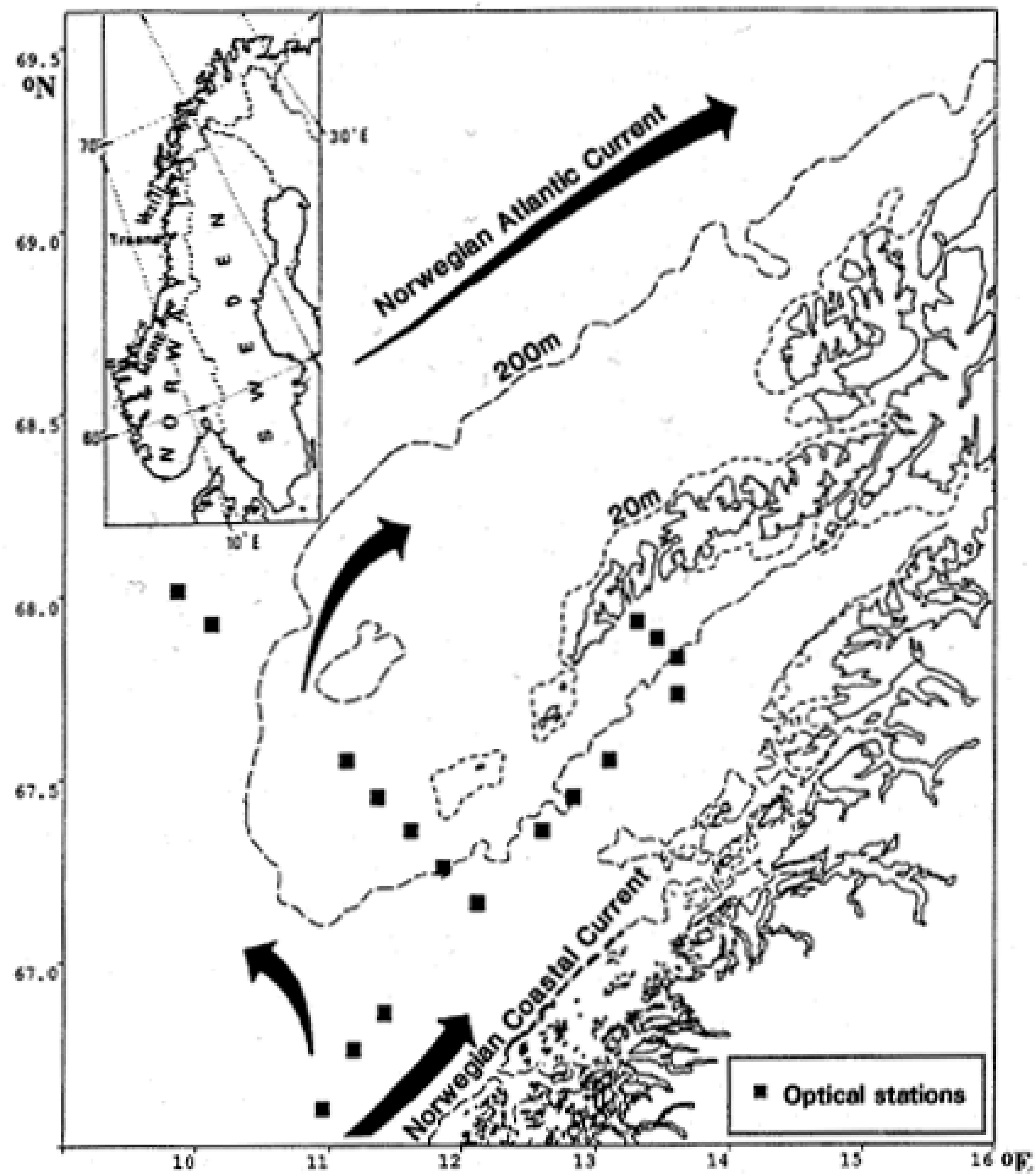

Fig. 8. A map of Vestfjord and the Lofoten Islands, showing the optical stations and principal currents in the region.

satellite. This approach treats the atmosphere and satellite sensor response as a single system for calibration and gives an overall check on sensor performance. By using the onboard calibrations, the magnitude of errors in the atmospheric correction procedure can be extracted. Reliable comparison between the ground measurement and the satellite requires the properties of the whole pixel [approximately $1.1 \times 1.1\,\mathrm{km}^2$ for local area coverage (LAC) and about $4 \times 4\,\mathrm{km}^2$ for global area coverage (GAC)] containing the ground sensor be known. Considering optical data buoys, this can be achieved in three ways:

1. Frequent optical surveys by boat around the site (using the UOR for example) to build up an understanding of the scales of variability of the optical properties of the water.
2. Choosing a site known to have low variation in optical properties, i.e., open Case-1 waters with low pigment concentrations. The location of the data buoy off Plymouth (4°14.4′W,50°15.0′N) is in an area of Case-1 water but subject to relatively high phytoplankton production in the spring and autumn.
3. Obtain a large number of corresponding points of *in situ* and satellite observation measurements to increase the confidence in the comparisons. In cloud-free conditions, the satellite overflies the buoy once daily and generates one observation pair. An op-

tical data buoy, therefore, allows the atmospheric correction procedure and sensor calibration to be checked at a rate of up to one comparison daily. This is far greater than can be achieved by aircraft or boat-based sensing of water-leaving radiance because of the high cost of airborne and ship platforms and the difficulties of ensuring concurrent measurements with the satellite overpass.

Since it remains at a fixed location, a moored optical data buoy will not allow validation of the satellite received water-leaving radiance over as wide a variety of optical provinces as a drifting optical buoy. Nonetheless, it has a number of advantages:

- A moored buoy can be expected to return a higher proportion of data (logged on it) to shore than a drifter, because its fixed position makes the solution of the telemetry problem simpler. Maintenance of the buoy is also possible which means enhanced reliability is to be expected. Should any systems on the buoy fail, it can be retrieved, and maintenance can be carried out on the boat or back at the laboratory.
- The calibration of a moored buoy can be an ongoing activity, with retrievals at prescribed intervals to check sensor degradation. This gives a moored buoy a longer useful lifetime than a drifting buoy. The biofouling of the optical windows can be assessed during these times and the windows cleaned if necessary.
- A moored buoy can carry more sensors than a drifter for two reasons. First, a higher data transmission rate to shore is possible if ARGOS (needed for a drifter) is not used. Second, the short lifetime and subsequent loss of a drifting buoy means expensive sensors will probably not produce enough data to justify their cost. This extra sensor capacity will allow optical sensors to be sited at different depths, facilitating the extrapolation of light data to the surface, a difficult task for drifting optical buoys, since they are likely to have optical sensors at only one depth (Mueller and Austin 1995). Also, bio-optical sensors (chlorophyll fluorescence and transmissometry) can be used on a moored buoy allowing for bio-optical science, as well as satellite sensor calibration and validation.
- Characterization of the surrounding water can be collected during regular boat deployments. This data aids in the interpretation of the buoy data for research purposes and increases the confidence that the buoy's optical measurements are representative of the pixel observed from space.
- Ocean color observations derived from satellite instruments are susceptible to systematic bias, since optical data is only obtained under one sampling condition—cloud free. If the observed property covaries with cloud cover, a bias will be introduced. Repeated measurements at a point under all weather conditions, over a relatively long period of time, can allow such a bias to be identified and quantified. Moored buoys are well suited for this application.

Taking all of these factors into consideration, the moored optical buoy off Plymouth will thus be designed with two main aims:

a) To carry out high quality bio-optical data collection for the calibration and validation of optical spaceborne sensors, including SeaWiFS, the Ocean Color Temperature Sensor (OCTS), the Moderate Resolution Imaging Spectroradiometer (MODIS), and MERIS; and

b) To investigate the bio-optical science of the western English Channel, looking particularly at the influence of chlorophyll concentrations on remotely sensed reflectance over time.

3.8.2 Program Overview

The PlyMBODy project involves four parts:

i) The bio-optical data buoy itself;

ii) Weekly boat surveys (using the PML boat *Squilla*) to characterize the area around the buoy by towing the UOR (with Guy Westbrook at the University of Plymouth);

iii) Weekly profiles adjacent to the buoy to check the buoy sensor calibrations and to collect water for analyzing biogeochemical parameters (with Guy Westbrook); and

iv) Siting of the instruments to measure atmospheric properties on the fixed platform of the Eddystone Lighthouse, which is close to the buoy (less than 5 km away).

The aim is to acquire uninterrupted measurements over a two year period.

3.8.3 The Buoy

The design of the buoy itself is an engineering problem once the specification and protocols for the sensors have been chosen on science grounds. The buoy will be designed to have spare sensor-carrying capacity to allow for future upgrading of sensors and the addition of novel automated sensors as they become available, for example, the fast repetition rate fluorometer (FRRF).

The present starting suite of sensors, designed to follow the SeaWiFS protocols (Mueller and Austin 1995), is as follows:

- In-water optical sensors at two depths for measuring downwelling irradiance and upwelling radiance (which will give K_d, as well as subsurface reflectance);

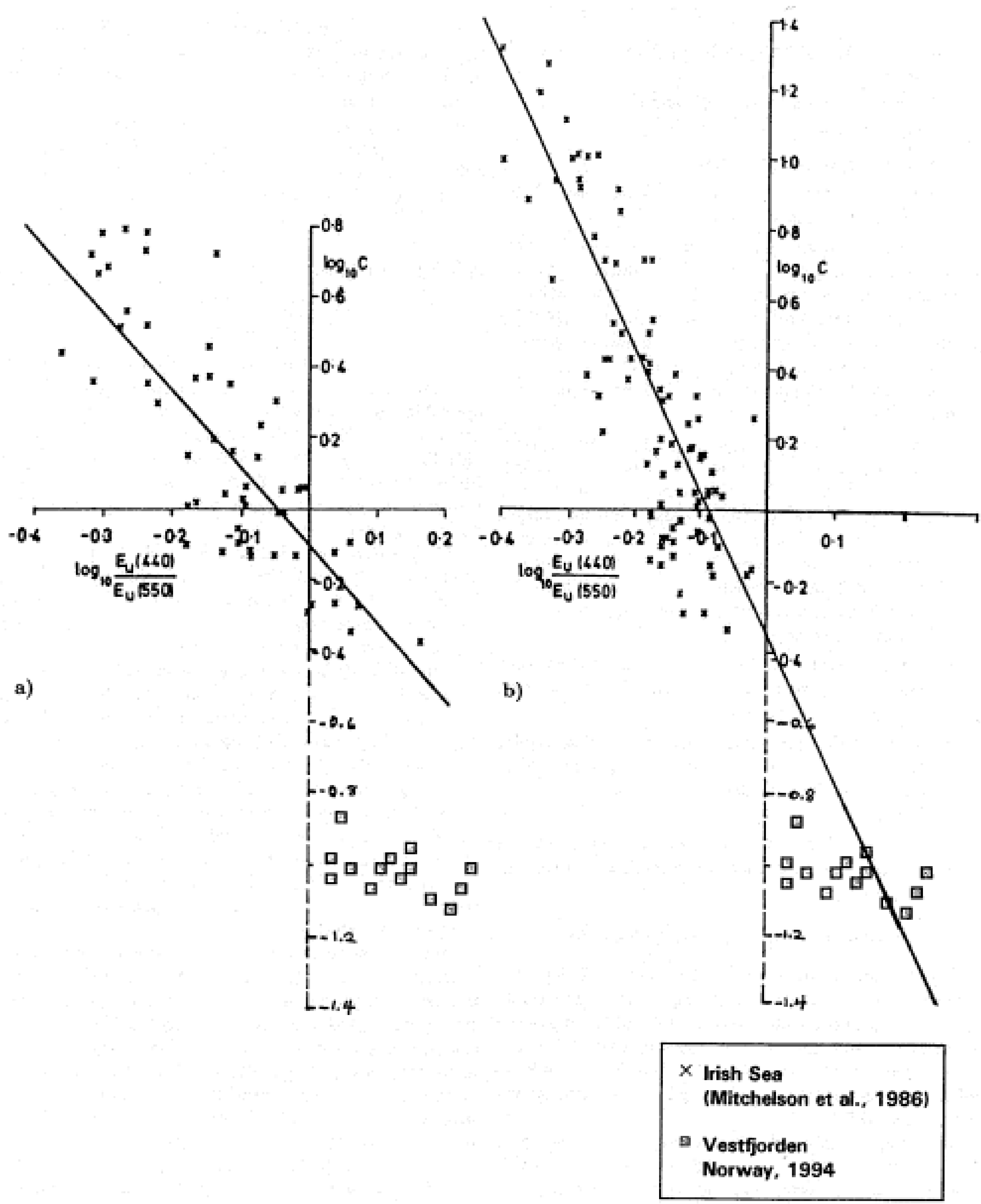

Fig. 9. Regression of $\log_{10}\left[E_u(440)/E_u(550)\right]$ against $\log_{10}\left[C\right]$ for all the data divided into Case-1 and Case-2 type waters: **a)** Case-1 data, and **b)** Case-2 data (Mitchelson et al. 1986).

- Deck cells for measuring downwelling solar irradiance;
- Buoy tilt and orientation (for quality control of optics data);
- Pressure, water temperature, and conductivity;
- Chlorophyll fluorescence;
- Red-beam transmissometry; and
- Dissolved colored organic matter (Gelbstoff) by blue-beam transmissometry.

The data sampling frequency will be on the order of a complete set of readings once every 30 minutes. A number of readings over a short period of time (0.5 second) will also be taken. This *burst mode* gives more confidence that the recorded value is representative of the conditions present than can be achieved from a single measurement.

To support this sampling, the other buoy components are given below.

- *Buoy Platform:* A fiberglass spar buoy will be used, approximately 4 m long by 0.7 m diameter. This will have features to reduce the chance of it being struck by a boat: flashing light, radar reflector, bright color, advance warning issued to Mariners before deployment, site chosen to avoid fishing grounds, etc. It will be recovered by the PML boat *Squilla* whenever maintenance is needed, e.g., because of excessive biofouling.
- *Power System:* The buoy will be powered by solar cells and reservoir batteries, similar to the system used by Trinity House buoys.
- *Sampling Control and Logging:* The timing of data input from the sensors needs to be controlled. This data must then be digitized, time-stamped, and logged.
- *Telemetry:* The data collected will be transmitted to PML on a daily basis via a modem and cellular telephone.

3.8.4 Project Progress and Schedule

The design, construction, and purchase of the buoy platform, most of the sensors, power system, and telemetry is in an advanced state. The control and logging of the data streams, and the timing of the telemetry link is the current focus of attention. Work is scheduled so the buoy will be operational by the current earliest planned launch date of SeaWiFS (July 1995).

The program of weekly UOR surveys and sampling at the buoy site is ready and waiting for the weather conditions to allow it to start. Gale force winds have stopped *Squilla* sailing for the last two weeks.

Work regarding atmospheric measurements from the Eddystone Lighthouse platform was started very recently and is still in its early stages.

3.8.5 Links to the Project

PlyMBODy will play a role in the PACE project due to start mid-June 1995 (Sam Hudson, University of Plymouth). Proposals for scientific collaboration involving siting new automated biogeochemical instrumentation on the data buoy will be welcomed and should be addressed to Matthew Pinkerton, PML. Proposals for taking part in one or several of the weekly *Squilla* visits to the data buoy site should be addressed to Matthew Pinkerton or James Aiken, PML.

3.9 S. Hudson

The Plymouth Atmospheric Correction Experiment

PACE is designed to give atmospheric closure by contemporaneously measuring the atmosphere and collecting optical imagery, this will initially involve two fieldwork experiments within the Plymouth area: 12–23 June and 31 July to 11 August 1995. There will be overflights by the Meteorological Research Flight (MRF) and the CASI, to measure atmospheric parameters and simulate SeaWiFS radiance, respectively.

Both aircraft will follow a loop of three flight lines around the Plymouth Sound area, including both Case-1 and Case-2 water conditions (Fig. 10). The overflights will occur at heights of 2,000, 5,000, and 10,000 ft to investigate the vertical atmospheric structure.

The MRF aircraft will continuously collect general atmospheric data, such as wind speed and humidity, plus more detailed aerosol measurements over each flight line. Atmospheric parameters, such as the total water content and ozone concentration, will be useful in determining water vapor absorption and looking at the contribution of tropospheric ozone to the total ozone optical depth. In calculating the aerosol single and multiple scattering phase functions, measurements of the number densities of aerosol particles (PCASP instrument), aerosol light scattering (nephlometer), and aerosol size spectrum (scattering laser spectrometer) will be useful.

Several research vessels and PlyMBODy will provide contemporaneous measurements of the in-water parameters and optical properties. Vessels will tow the UOR measuring chlorophyll fluorescence, suspended sediment concentration, and the upwelling and downwelling irradiance in six wavelengths (412, 443, 490, 510, 550, and 632 nm). At the end of each boat transect and when the aircraft sensor is directly overhead, a profiling reflectance radiometer will be lowered into the water to calculate the water-leaving radiance. In conjunction with the optics work, the boat will also take samples to classify the in-water parameters and calibrate the sensors.

The atmospheric and in-water information will be geolocated to the aircraft imagery to perform the atmospheric correction. Atmospheric models will be adapted

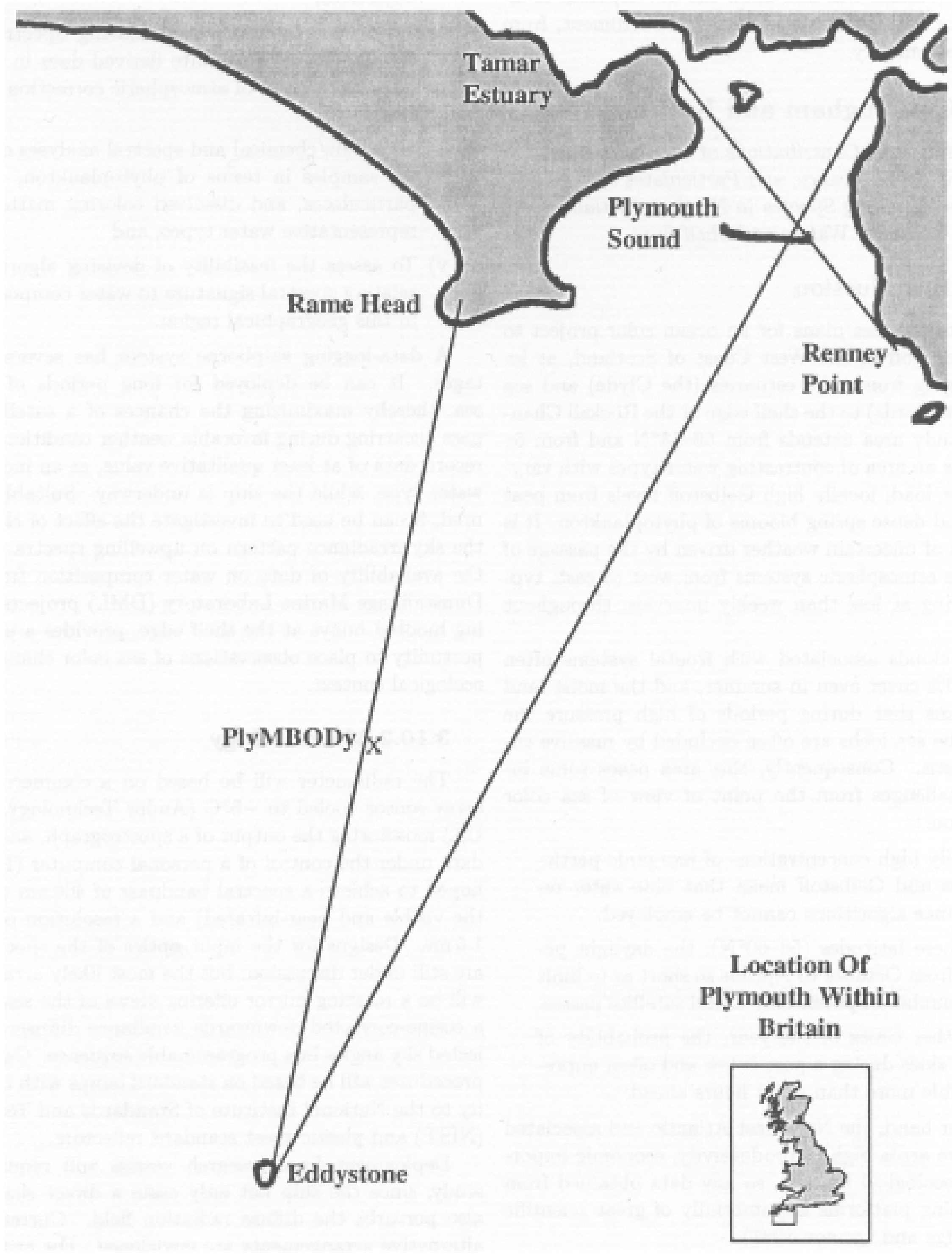

Fig. 10. Flight line positions for PACE.

for use in sediment-laden waters using the research that is currently being undertaken at Plymouth and in various atmospheric correction groups around the UK. The ground-truth measurements will also allow the development of algorithms, e.g., chlorophyll and suspended sediment, from the corrected imagery.

3.10 A. Cunningham and K. Jones

Quantifying the Contributions of Phytoplankton, Yellow Substance, and Particulates to Surface Upwelling Spectra in Northeast Atlantic Coastal Waters and Shelf Seas

3.10.1 Introduction

This note outlines plans for an ocean color project to be carried out off of the West Coast of Scotland, at locations ranging from tidal estuaries (the Clyde) and sea lochs (coastal fjords) to the shelf edge at the Rockall Channel. The study area extends from 56–58°N and from 6–9°W. This is an area of contrasting water types with varying sediment load, locally high Gelbstoff levels from peat drainage, and dense spring blooms of phytoplankton. It is also an area of uncertain weather driven by the passage of low-pressure atmospheric systems from west to east, typically occuring at less than weekly intervals, throughout the year.

Stratus clouds associated with frontal systems often produce 100% cover even in summer, and the moist land surface means that during periods of high pressure the skies over the sea lochs are often occluded by massive cumulus systems. Consequently, this area poses some interesting challenges from the point of view of sea color interpretation.

1. Locally high concentrations of inorganic particulates and Gelbstoff mean that blue-water reflectance algorithms cannot be employed.
2. At these latitudes (56–60°N), the daylight period from October to April is so short as to limit the number of potentially useful satellite passes.
3. At other times of the year, the probability of clear skies during a pass is low and often unpredictable more than a few hours ahead.

On the other hand, the Northeast Atlantic and associated shelf seas are areas high in productivity, economic importance, and ecological interest, so any data obtained from remote sensing platforms is potentially of great scientific value (Savidge and Lennon 1987).

The work proposed in this project, as part of the UK SEI, has five main aims:

i) To construct and calibrate a high-resolution data-logging spectroradiometer for shipborne deployment;
ii) To measure water-leaving spectra from Scottish coastal waters, mainly on an opportunistic basis on cruises already planned for other research objectives;
iii) To obtain accurate water-leaving spectra for comparison with satellite derived data in order to provide a test of atmospheric correction algorithms;
iv) To obtain chemical and spectral analyses of water samples in terms of phytoplankton, other particulates, and dissolved coloring matter for representative water types; and
v) To assess the feasibility of devising algorithms relating spectral signature to water composition in this geographical region.

A data-logging shipborne system has several advantages. It can be deployed for long periods of time at sea, thereby maximizing the chances of a satellite overpass occurring during favorable weather conditions. It can record data of at least qualitative value, as an indicator of water type, while the ship is underway. Suitably configured, it can be used to investigate the effect of changes in the sky irradiance pattern on upwelling spectra. Finally, the availability of data on water composition from other Dunstaffnage Marine Laboratory (DML) projects, including moored buoys at the shelf edge, provides a useful opportunity to place observations of sea color changes in an ecological context.

3.10.2 Methodology

The radiometer will be based on a commercial CCD array sensor cooled to −5°C (Andor Technology, Belfast, UK) monitoring the output of a spectrograph, and logging data under the control of a personal computer (PC). It is hoped to achieve a spectral bandpass of 400 nm (covering the visible and near-infrared) and a resolution of around 1.5 nm. Designs for the input optics of the spectrograph are still under discussion, but the most likely arrangement will be a rotating mirror offering views of the sea surface, a cosine-corrected downwards irradiance diffuser, and selected sky angles in a programmable sequence. Calibration procedures will be based on standard lamps with traceability to the National Institute of Standards and Technology (NIST) and plastic sheet standard reflectors.

Deployment from research vessels will require some study, since the ship not only casts a direct shadow but also perturbs the diffuse radiation field. Currently, two alternative arrangements are envisioned. For critical sea-truth data acquisition, the instrument will be mounted on an extending boom with the ship hove to. For rapid data collection with the ship underway, a more compact and rigid forward-looking arrangement is probably more feasible.

Water bottle samples will be analyzed by the usual oceanographic techniques for pigments, DOM, and suspended particulates. Attempts will be made to identify the most commonly occurring phytoplankton species in preserved samples by microscopy. Absorption spectra of phytoplankton collected on glass fiber filters, and of the colored filtrate that passes through 0.1 μm nucleopore filters, will be determined using a standard bench top spectrophotometer. Subject to resource availability, it is hoped to produce additional parameters for bio-optical modeling using a custom-built integrating sphere scattering and absorption meter.

Simple reflectance pair algorithms developed for Case-1 waters, mainly using CZCS data, are probably inapplicable in much of the study area. Blue absorption by Gelbstoff is likely to be strong in areas affected by land runoff (the West of Scotland has high rainfall and much of it is peat covered), and in the estuaries, there are episodic events of high turbidity. A range of algorithms based on SeaWiFS wavebands, however, have been published (Sathyendranath et al. 1994 and Tassan 1994), and it is hoped that sufficient data can be gathered in order to provide a thorough test of their performance.

A link with an NERC studentship should make it possible to carry out some bio-optical modeling, which immediately raises two challenges. The first is to achieve model closure given absorption, scattering, and beam attenuation measurements on natural samples (Stavn and Weidemann 1989). The second is to find the extent to which the inherent ambiguities in sea reflectance observations impose practical limits on the remote sensing of *in situ* concentrations of phytoplankton, yellow substance, and suspended sediment (Sathyendranath et al. 1989 and Zaneveld et al. 1993).

3.10.3 Timetable

In view of known uncertainties in the SeaWiFS launch date, this project has been deliberately slow in starting. It is intended that instrument construction and calibration will be carried out during 1995, with a view to making field measurements, starting with the spring bloom in the sea lochs in March 1996. Data collection will continue through at least 1997, and it is hoped that a postgraduate student will work on the project until 1998.

3.11 D. Buckton and S. Danaher

Ocean Color Measurements from the July 1994 North Sea Gauss Cruise using MARAS

3.11.1 Introduction

The MARAS instrument is a multisensor, fiberoptic-based radiometric spectrometer, capable of being submersed up to 200 m. The sensors include:

- Vector (cosine sensitive) upwelling, E_u, and downwelling, E_d, sensors at three relative depths (0, 0.6, and 1.2 m);
- Scalar (equally sensitive over 2π sr) upwelling, E_u, and downwelling, E_d, both at 0 m;
- Radiance upwelling sensor at a relative depth of 1.2 m;
- Coverage of the full optical spectrum, 400–800 nm, with less than 5 nm bandwidth;
- An active scatterometer; and
- Pressure and temperature sensors.

The MARAS instrument has been deployed on a number of cruises over the last few years including the Irish Sea, the Atlantic Ocean, the Baltic Sea, and the North Sea. Results from the North Sea (1994) cruise will be made available through the European Directory of Marine and Environmental Data (EDMED).

A number of fundamental optical parameters can be extracted from the MARAS instrument. The principal aim of the instrument is to reliably calculate the oceanic absorption coefficient, achieved using the equation

$$a = \frac{E(z)}{E_0(z)(z-z_0)} \log\left[\frac{E(z)}{E(z_0)}\right], \qquad (1)$$

where E_0 is the incident downwelling irradiance, and $E(z)$ is the net downward irradiance at depth z.

3.11.2 Estimation of Chlorophyll

The MARAS instrument has proved its capability in estimating the chlorophyll *a* concentration of the water body by the use of the absorption and attenuation coefficient derived from the vector and scalar sensors. This aids in understanding the optical processes. Remote sensors such as MERIS and SeaWiFS, however, will effectively be expected to provide constituent extraction from more limited parameters such as upwelling estimated radiance or subsurface reflectance. Examples of the upwelling radiation field from the Gauss cruise (1994) is shown in Fig. 11. On the last cruise, in the North Sea, the radiance sensor was calibrated using a standard lamp allowing the measurement in absolute units of the upwelling radiance. This, therefore, will improve the already existing knowledge of the signal expected to be observed with spaceborne sensors.

A simple method is presented here utilizing the algal fluorescence height at 683 nm as a function of the scattered radiation in the blue-green region. The chlorophyll concentration is estimated from this by using the following equation:

$$C_{\mathrm{est}} = \frac{L(683) - \dfrac{L(661)+L(705)}{2}}{\displaystyle\int_{400}^{550} L(\lambda)d\lambda}, \qquad (2)$$

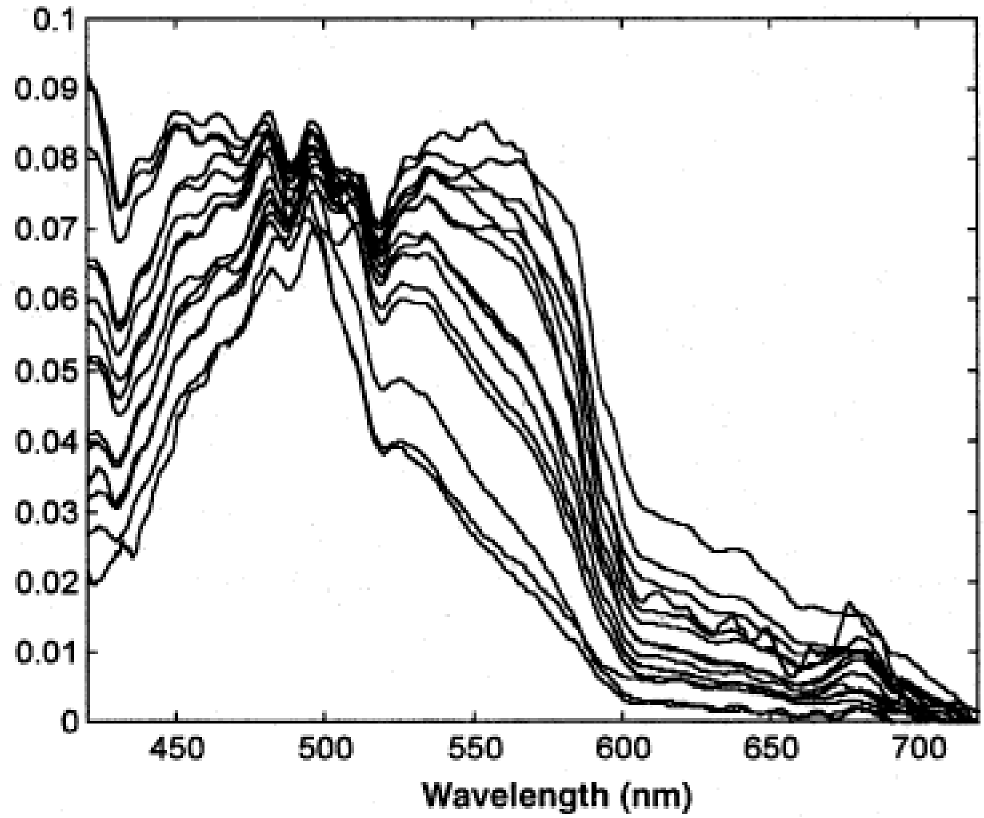

Fig. 11. Examples of the upwelling radiation field unitized from the Gauss cruise (1994).

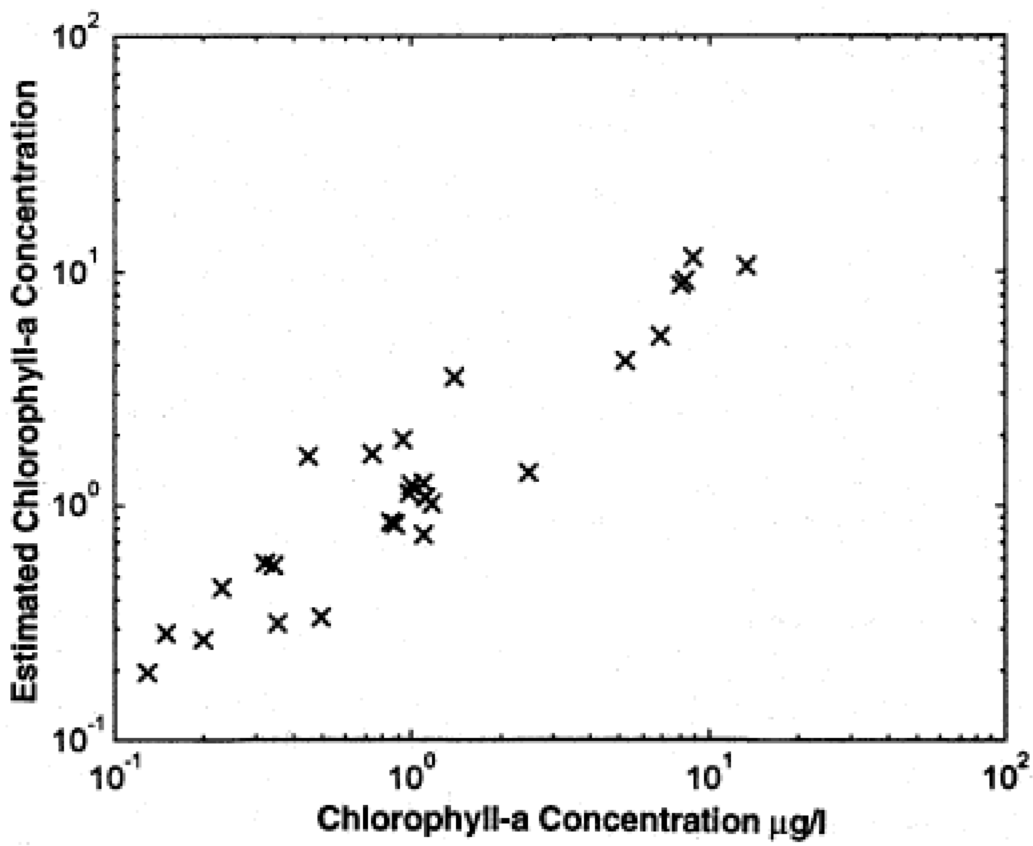

Fig. 12. Chlorophyll *a* concentration using the method given in (2).

where the wavelengths are all in units of nanometers and the radiances are ±5 nm.

A scatter plot produced using this method is shown in Fig. 12, giving an estimation root mean squared (rms) accuracy of −12.3 dB and a correlation of 0.955 with $N = 27$. This provides a simple algorithm for the estimation of the chlorophyll, which can be easily extended for remote sensing use. Present efforts are concentrating on the estimation of other oceanic constituents, such as sediment and yellow substance from the North Sea data set, which ideally, will lead to the development of a multiparameter model or algorithm allowing an assessment of the impact of constituent mixing.

3.12 A. Weeks

Optical Oceanography in the Arabian Sea, August 1994

Work carried out in the Arabian Sea in August 1994 during an Institute of Oceanographic Sciences, Deacon Laboratory (IOSDL) cruise with Peter Herring as the principal investigator (PI) was outlined. The objectives were to examine the spectral reflectance from the phytoplankton during the upwelling season in the early part of the southwest monsoon, and to determine the effect of the blooms on the diffuse attenuation coefficient at a number of spectral bands. The study area was 20–60 miles off the coast of Oman, a region covering the transition from shelf to deep (greater than 3,000 m) water, in a region of intense oxygen depletion commencing at about 150 m.

The subsurface reflectance ratios were obtained from Lightfish, a towed spectral upwelling and downwelling irradiance sensor system equipped with the SeaWiFS band set and designed by Southampton University's Department of Oceanography. Lightfish provided reflectance at the same frequency as the subsurface fluorescence (every 10 seconds) taken from the pumped supply. The fluorescence was calibrated by comparison with samples taken at regular intervals throughout the cruise.

Diffuse attenuation was calculated from downwelling irradiance measured using sensors made by Satlantic Inc. of Canada. The sensors (SeaWiFS bands) were mounted on a towed undulating system (SeaSoar) along with a fluorometer and a conductivity, temperature, and depth (CTD) sensor which, when compared with discrete samples, provided profiles of phytoplankton biomass.

There was evidence of upwelling near the coast during the first of the two SeaSoar surveys and chlorophyll concentration values were approximately 2.0 mg m^{-3}. During the second survey, a week later, the isopycnals were horizontal indicating that upwelling had ceased, but by now phytoplankton concentrations were greater than 4 mg m^{-3} near the shelf break.

The processing of the data and the calibration of the sensors is nearing completion and the work continues in collaboration with Daniel Ballestero, John Hemming, and Peter Herring.

3.13 I. Bellan and J. Aiken

Arabesque UOR: An Illustrated Discourse on Practical Optical Oceanography

Deploying the UOR and optical instrumentation packages present varied problems. Deployment facilities such as A-frames and cranes need to have the capacity to safely deploy instruments in a manner that is free from ship shadow. This consideration is important if the data collected is to conform to established protocols. There are other problems, rarely noted, which can influence data acquisition. These problems range from icebergs in Antarctica to large fish of varied species (sharks, etc.) in other provinces. The accumulation of large fish around profiling radiometers provides ample evidence of those *hard to explain*, suspect data and, in particular, *spikes* in otherwise *clean* profiles.

Photography is a valuable tool for recording *optical* conditions: clear blue water in tropical oligotrophic conditions, green water where productivity is high; sharp fronts between different water masses; and turquoise-blue coccolithophore blooms. All these problems were illustrated by slides of sensor deployments in a wide range of oceanic provinces.

3.14 G. Moore

Antarctic Bio-Optics from Sterna-92

Knowledge of carbon fluxes and biomass in the Southern Ocean (one fifth of the world's ocean surface) is crucial for the understanding of global carbon budgets. In the Southern Ocean, there is known to be variability in the biological CO_2 pump (Tréguer and Jacqueŝ 1992), but to date there is considerable under-sampling in this region. Satellite ocean color imagery, coupled to suitable models, can be used to determine basin-scale estimates of the biological pump, since it resolves the problems of spatial heterogeneity and under-sampling. Adequate validation of biomass algorithms is an essential prerequisite for the use of such imagery. Previous studies (Sullivan et al. 1993 and Mitchell 1992) suggest the NASA CZCS algorithm, developed from the NET studies on waters adjacent to the continental US (Clark 1981), results in an underestimate of biomass in the Southern Ocean. The NASA algorithm yields pigment concentrations at least 50% lower than those determined from a province-specific algorithm (Mitchell 1992).

Bio-optical studies during the Sterna 1992 Bellingshausen Sea cruise were undertaken to determine province specific algorithms and to confirm previous results; an overview of the biological oceanography is given in Turner (1995). Optical profiles of upwelling and downwelling irradiance sensors, using SeaWiFS compatible bands, were measured using SeaSoar. SeaSoar was deployed for two surveys: the first being to the north of the Antarctic

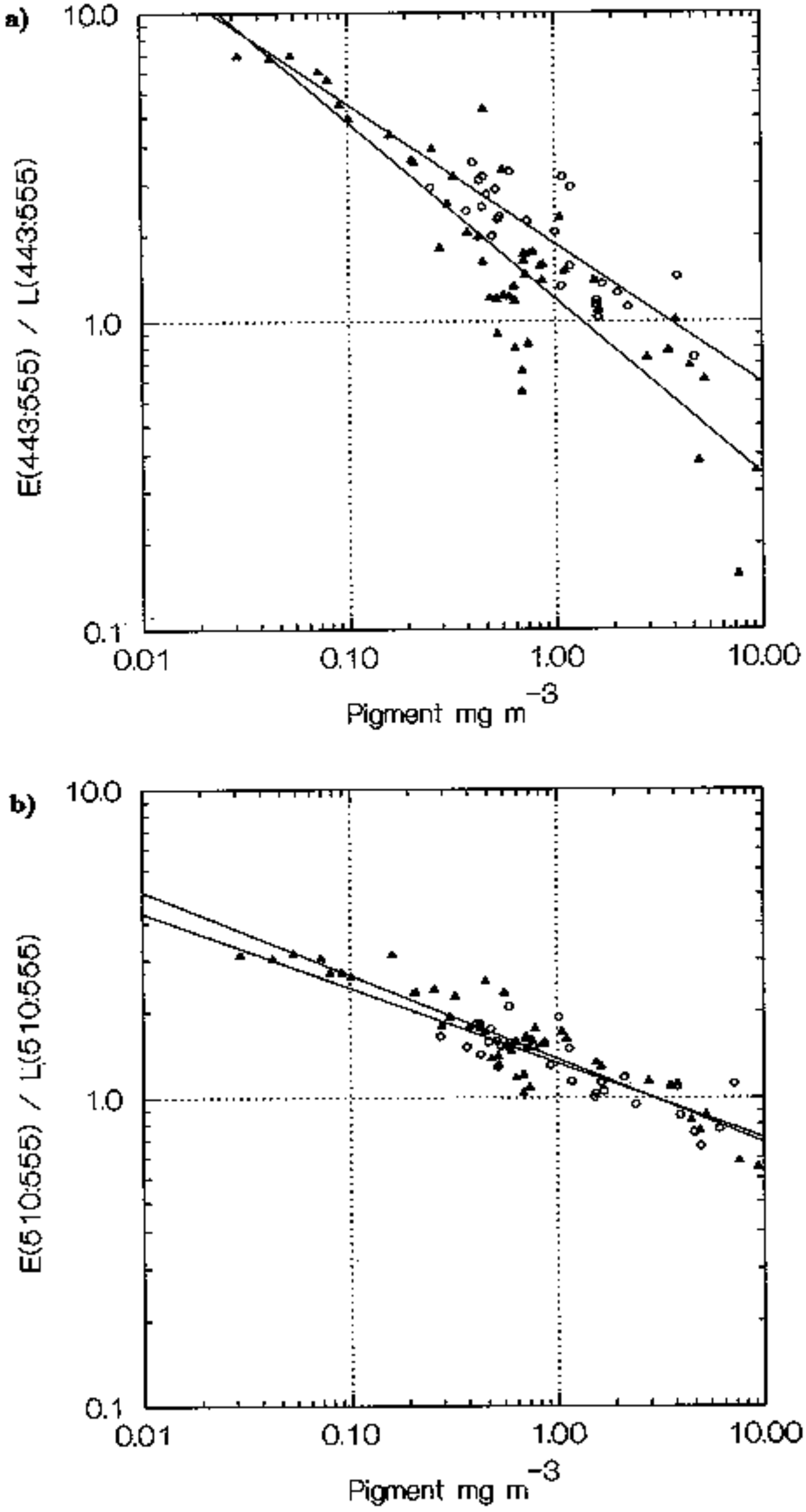

Fig. 13. Band ratios for **a)** NET and **b)** Sterna data.

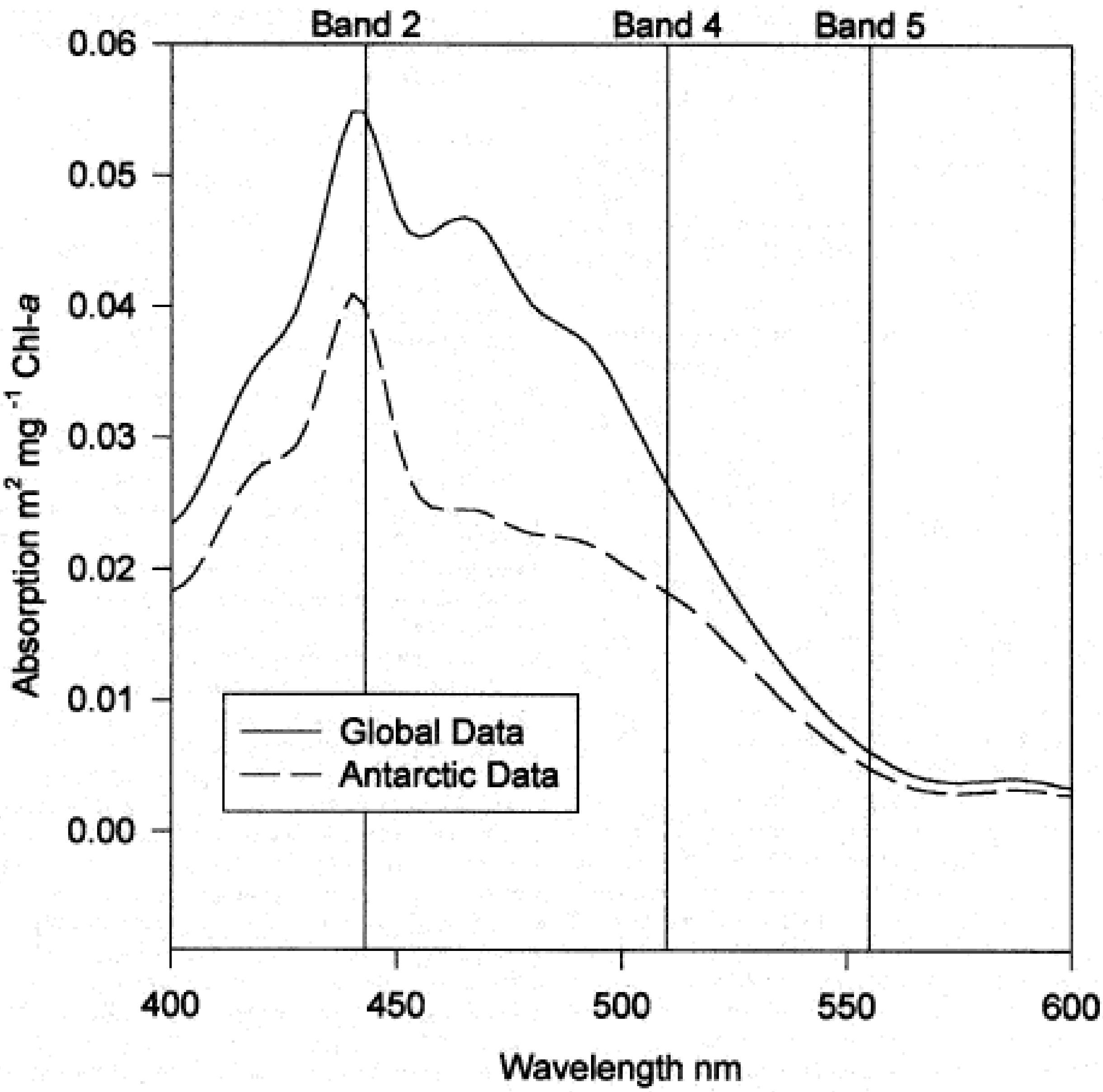

Fig. 14. Simulated Antarctic absorption of Sterna (Antarctic) data compared to a global average.

Peninsula, crossing the Polar Front, where chlorophyll values were less than 1.0 mg m^{-3}; and the second surveying a phytoplankton bloom in the Bellingshausen Sea (centered at 85.0°W,67.5°S) where chlorophyll values reached 7.0 mg m^{-3}. The irradiance values were corrected for sun angle and transmission through the water surface, thus converting the data to E_{WN} analogous to L_{WN} (Gordon et al. 1988). Ratios of the irradiance and radiance measurements should be identical apart from a small error caused by removing the spectral effect of Q.

The results for the CZCS compatible bands are shown in Figs. 13a and 13b, and are compared with the NET data. The two regressions shown are for the NET data and for the Sterna. The results from the SeaSoar surveys are similar to the Southern Ocean regressions shown in Table 3. It should be noted that both the NET data and the Sterna data regression line reach a similar value at low pigment, indicating that the *clear water* properties are similar, thus giving some confidence in the radiometric calibration of the sensors.

Table 3. Southern Ocean band ratio regressions. The R^2 regression line values are presented as percentages.

Ratio	*Study*	*A*	*B*	R^2
443:555	NET	0.118	−1.377	78.7
	Sterna	0.804	−1.479	66.9
441:555	Mitchell†	0.529	−1.700	83.0
510:555	NET	0.804	−3.075	83.5
	Sterna	0.768	−2.815	68.4
520:555	Mitchell†	0.483	−3.520	59.4

† Mitchell (1992)

Theoretical considerations of ratio algorithms (Aiken et al. 1995) indicate the slope of the 443:555 and 510:555 algorithms are largely determined by the absorption coefficients at 443 nm and 555 nm, respectively. The present study indicates that total absorption per unit chlorophyll at 443 nm (and to a lesser extent at 510 nm) in these waters is smaller than the values for the waters considered in the NET studies. Such a reduction in absorption could result from either a lower chlorophyll-to-particulate ratio or to a reduced chlorophyll specific absorption.

Sagan et al. (1995) considered the relationship between the beam attenuation coefficient (λ = 660 nm) and pigment, and found that the ratios of beam attenuation to pigment concentration were closer to those found in Case-2 waters. This would indicate the chlorophyll-to-particulate ratios were as high as, if not higher than, those found in other provinces.

Examination of the high performance liquid chromatography (HPLC) pigment data for the two cruises indicate that chlorophyll *b*, chlorophyll *c*, and photoprotectant carotenoids were present in lower relative quantities compared to the global mean (Aiken et al. 1995). The absorption data for the Sterna HPLC pigments were simulated using data (Bidigare et al. 1990) for pigment absorption. This simulated absorption shows that chlorophyll specific absorption is depressed, compared to the global average, with the depression being highest at the 443 nm waveband (Fig. 14).

No particulate absorption was measured in the Sterna cruises, but the pigment hypothesis represents one valid explanation for the difference in the Southern Ocean and Antarctic algorithms and is compatible with Mitchell and Holm-Hansen's (1991) K_d spectra. If these pigment changes can be determined from spaceborne data, the potential exists for an algorithm that is valid for both temperate and polar oceans.

3.15 H. Bottrell, et al.

The COAST Project

A brief overview of the aims, organization, and concept of the COAST project is provided below. Some details of the software development for atmospheric correction and retrieval of SPM concentration, together with preliminary results of SPM concentration retrieval, are also given.

3.15.1 Overview of the COAST Project

The COAST project is funded by the BNSC as part of an initiative to promote innovative uses for satellite data. The NERC placed a two year contract on behalf of BNSC with a UK consortium led by Smith System Engineering, Ltd. The consortium includes PML, the University of Southampton's Department of Oceanography, HR Wallingford, Ltd., and Laser-Scan, Ltd. COAST is a commercial enterprise with the aim of developing the techniques necessary for a coastal monitoring service. The COAST concept and the broad responsibilities of the consortium members are shown in Fig. 15.

Remotely sensed data will be obtained from both the SeaWiFS instrument and the CASI airborne sensor; CASI will provide the fine detail and SeaWiFS the large-scale temporal variations. These data, after atmospheric correction, will be used to generate local and wide area maps of surface SPM concentration and water quality, and, combined with vertical profile and transport models, to generate maps of coastal sediment transport and potential coastal morpho-dynamic changes. A GIS will be used to store, display, and manipulate these products. Potential customers are any of the numerous organizations interested in monitoring, understanding, and managing the coastal zone, or are actively involved in coastal engineering. In the UK, this would include the Ministry of Agriculture Fisheries and Food (MAFF), the National Rivers Authority (NRA), and local government authorities who have statutory responsibilities within the coastal zone; commercial concerns such as civil engineering companies, and dredging and extraction companies with interest in the coastal zone; and relevant research programs, such as the NERC-managed LOIS program.

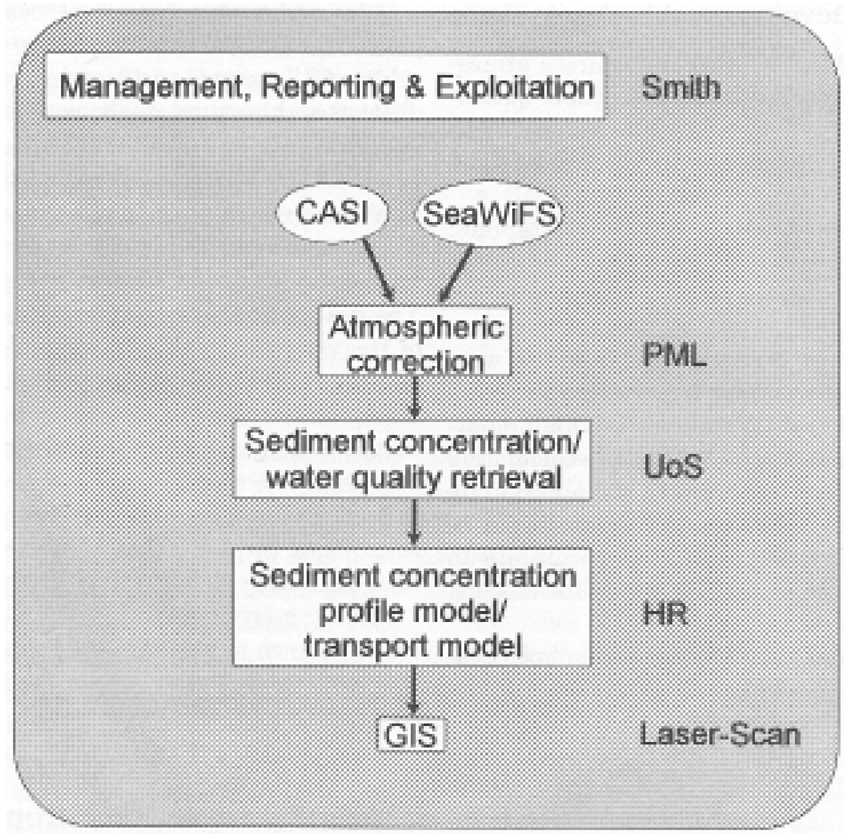

Fig. 15. The COAST concept and consortium responsibilities.

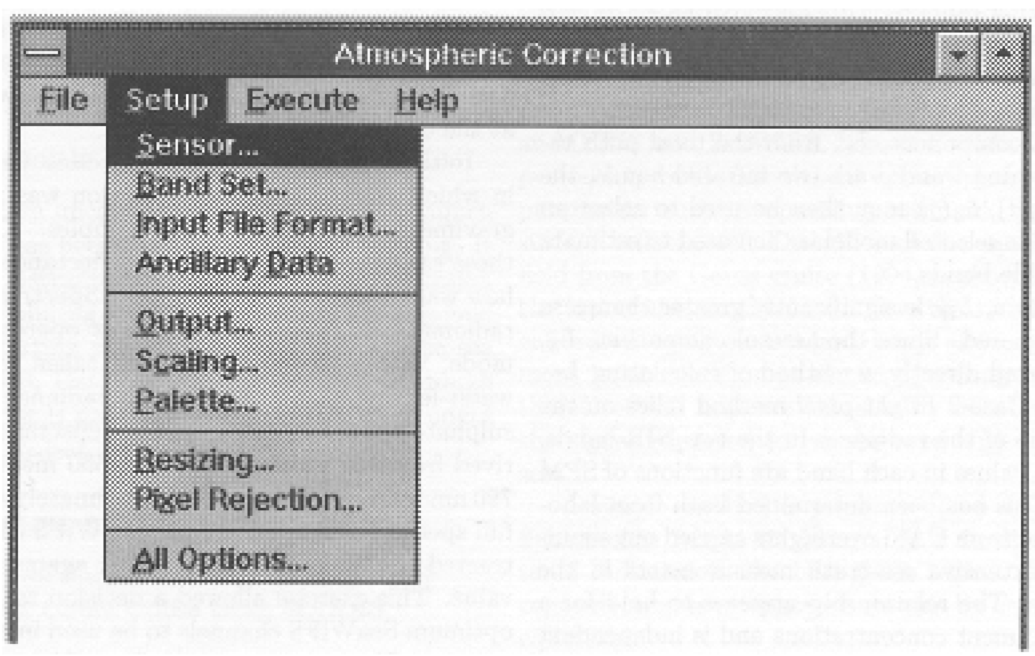

Fig. 16. The top-level window of the GUI and the main menu bar.

3.15.2 Software Development

The development and application of accurate atmospheric correction is of major importance if usable quantitative data are to be derived from remote sensing. The COAST project provides both a scientific and commercial need for atmospheric correction software.

The software was developed on a Silicon Graphics, Inc. (SGI) Indy UNIX workstation using the C programming language and has a Motif graphical user interface (GUI). The core atmospheric correction, geometric correction, SPM retrieval routines, and the GUI routines were developed in parallel. This greatly facilitated the prototyping, modification, and testing of these two quite different software elements. Once complete, the core calculation routines were relatively easy to hook into the appropriate parts of the GUI system. The separate development of the core and GUI routines also facilitated portability to Sun workstations and to high performance PCs running Microsoft Windows.

The software is designed to handle data from both SeaWiFS and CASI sensors, and to calculate the aerosol contribution to total path radiance for both Case-1 and Case-2 waters. The Case-1 calculations use the *Howard Gordon* model (Gordon 1978 and 1993, Gordon and Castaño 1987, and Gordon and Wang 1994) and the Case-2 calculations use the *Gerald Moore* model (Moore pers. comm., and Hudson et al. 1994). Both models use a channel ratio method, initially calculated in two NIR wavebands and then extrapolated to the visible wavebands.

The Case-1 *dark pixel* method relies on the fact that the sea acts as a blackbody in the NIR wavelengths, that is, the water-leaving radiance (L_W) approximates to zero and, thus, total path radiance is due almost entirely to Rayleigh and aerosol scattering. The aerosol component, L_a, in the NIR is easily obtained by subtracting the calculated Rayleigh component, L_r, from the total path radiance, L_t. Assuming i and j are two infrared bands, the ratio $\epsilon(i,j) = L_a(i)/L_a(j)$ may then be used to select an aerosol model. The selected model is then used to estimate $L_a(\lambda)$ in the visible bands.

In Case-2 waters, L_W is significantly greater than zero and cannot be ignored. Since the aerosol component, L_a, cannot be computed directly, a method of calculating L_W is required. The Case-2 *bright pixel* method relies on the fact that the ratio of the radiances in the two NIR bands, and the radiance values in each band are functions of SPM concentration. This has been determined both from laboratory studies and from CASI overflights carried out simultaneously with extensive sea-truth measurements in the Humber Estuary. The relationship appears to hold for a wide range of sediment concentrations and is independent of sediment type (Hudson et al. 1994). Both methods use a multiple scattering model and converge for the calculation of the parameter $\epsilon(i,j)$ for a number of aerosol models, the use of look-up tables to approximate to two of the aerosol models, and extrapolation to the visible wavebands.

The architectural goals of usability, portability, and performance have been alluded to by the decisions to develop a GUI using C and Motif on an SGI workstation. Additional architectural goals were that the software should be modifiable and flexible. The need for the software to be modifiable stems from the fact that atmospheric correction is an evolving area of remote sensing science and algorithm improvements are likely, and that a number of new sensors are under development, e.g., MERIS and MODIS. The goal of flexibility was particularly important because of the wide choice of primary and ancillary data sources, and the type and destination of output. It was considered important to give the user choices as to how the program should be run as distinct from the program dictating to the user what the next process will be. A GUI is essential for this approach. The following is a brief description of some features of the GUI that illustrates how these problems have been approached and, hopefully, solved.

The top-level window of the GUI and the main menu bar are shown in Fig. 16. The `File` drop-down menu offers the `Open`, `Save`, `Print`, `Close`, and `Exit` functions usually associated with the `File` menu. The `Setup` drop-down menu offers 10 options (Fig. 16).

3.15.2 Surface SPM from CASI Images

One of the key aims of the COAST project is to calibrate CASI and SeaWiFS data in terms of surface total SPM concentration. It is anticipated that either one or a small number of algorithms will be developed to account for the variability in sediment type around the UK coast. These algorithms are being derived empirically using regression techniques of remotely sensed radiance against *in situ* SPM concentration. The results presented here show just one example algorithm; the full set will be available at the end of the project.

Initially, a series of ship exercises were carried out, in which surface SPM concentration was measured using gravimetric analysis of water samples. Coincident with these samples being taken, the reflectance of the sea surface was measured using a PR650 Spectrascan™ spectroradiometer. This instrument was operated in biconical mode, with measurements being taken of the upwelling water-leaving radiance and the irradiance from a barium sulphate panel. Remote sensing reflectance was then derived from these results. The PR650 measures from 390–790 nm with a waveband of approximately 4 nm. From this full spectral data, the relevant SeaWiFS channels were extracted and these values regressed against the total SPM value. This exercise allowed a decision to be made on the optimum SeaWiFS channels to be used in algorithm development. The exercise was performed in a number of sites around the UK coast; over a total period of six months, 11 data sets showed that a simple ratio of SeaWiFS channels 5 and 3 gave the most accurate measure of total SPM concentration.

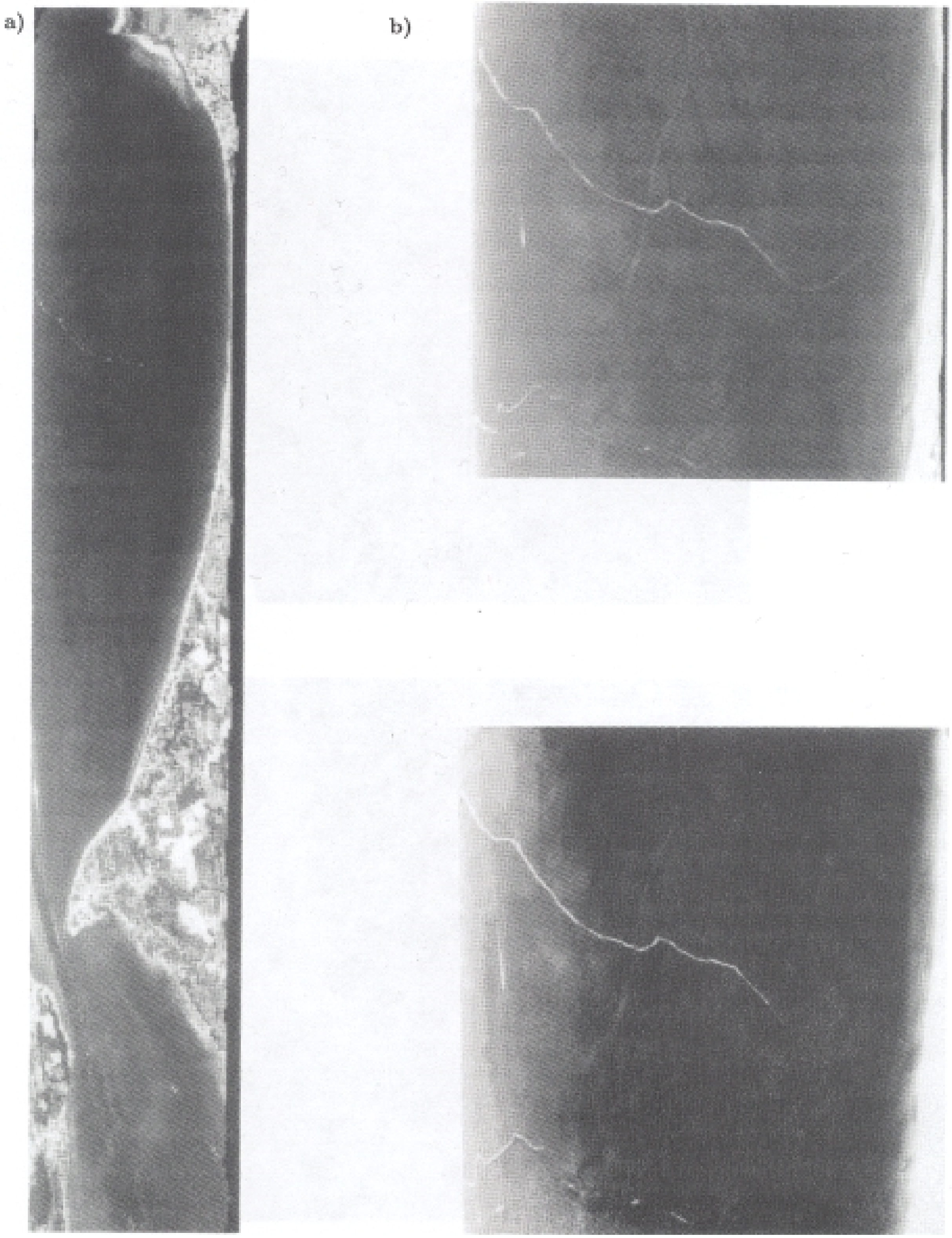

Fig. 17. CASI overpass images: **a)** the entire overpass (left) with The Solent to the east (bottom of the image), and Mudeford Bay to the west (top of the image); **b)** a full resolution subsection of the entire image before atmospheric correction (top right); and **c)** the atmospherically corrected subsection image (bottom right).

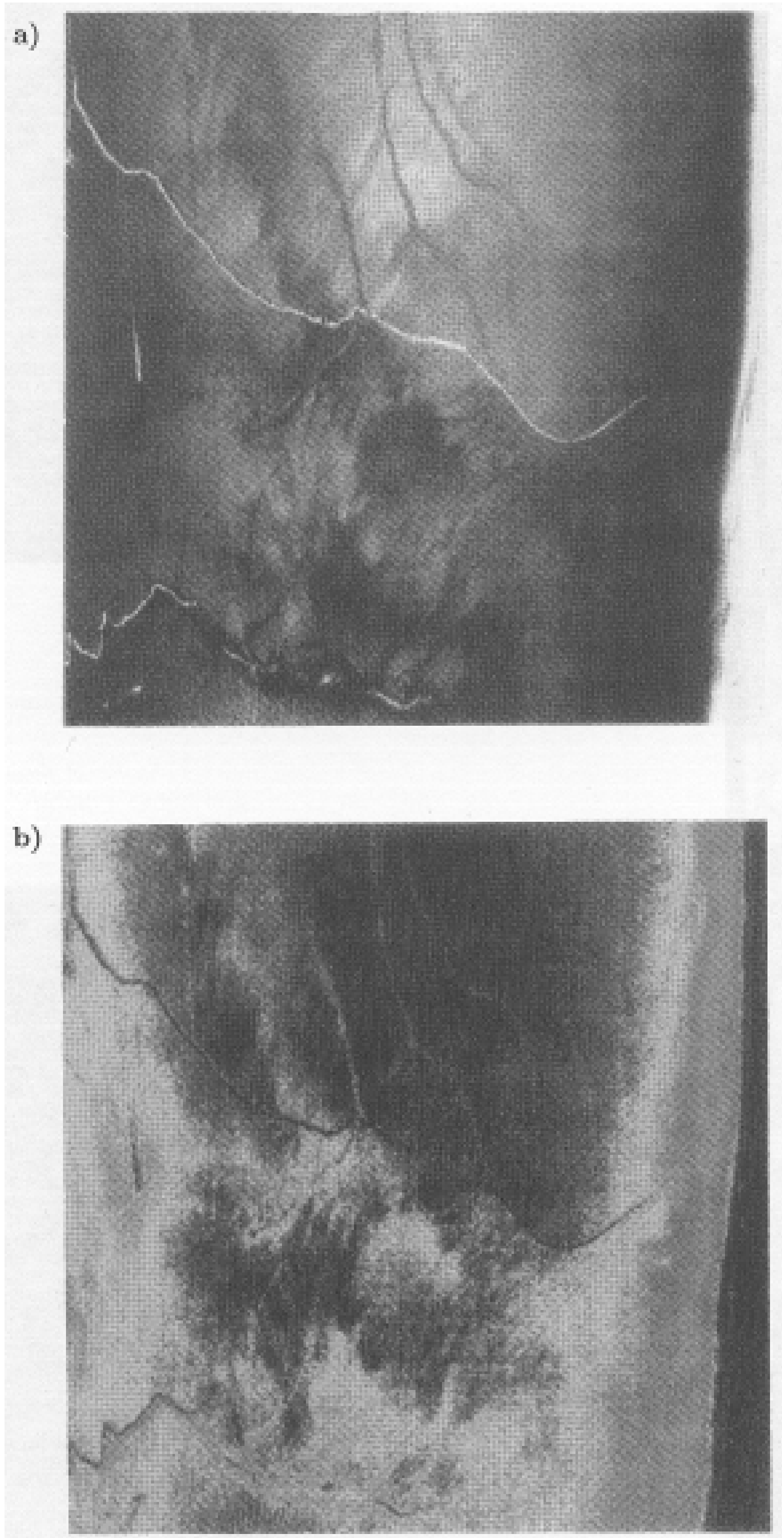

Fig. 18. Continued processing of the full resolution CASI overpass image shown in Figs. 17b and 17c: **a)** a grey scale representation of surface SPM concentration (top), and **b)** a grey scale representation of the final color image (bottom).

On the basis of these results, it was hoped to apply algorithms to both aircraft and satellite data. The delay in launch of the SeaWiFS satellite has led to all work, to this date, being carried out on aircraft data. The system used in the CASI, was designed by Itres Instruments (Calgary, Canada). This system is an imaging spectrometer, which may be operated in both spatial and spectral mode. For this project, the spatial mode was selected, with wavebands chosen to represent those of SeaWiFS. Two CASI instruments are available in the UK. The first is owned by NERC, and is provided for use by UK scientists in all fields. The second instrument is leased by the NRA to carry out a monitoring program of water quality in the UK coastal waters. Data from this instrument is again available for use by interested scientists. Within COAST, CASI data has been provided by both systems. The examples shown here are from the NRA system.

The example shown is from Christchurch Bay, on the southern UK coast. A combined ship and aircraft campaign was carried out on 15 June 1994. The boat traversed from the east of Christchurch Bay to the west via a series of zigzags and returned directly across the bay giving a total of 18 sampling sites within the bay. Analysis of the image data showed that a total of 14 of these fell within the area covered by the image. The ship campaign was carried out between 0800 and 1300 GMT, and the aircraft overpasses took place between 0900 and 1000 GMT. The data was contemporaneous, given the transit time and velocities of the ship and aircraft.

Figure 17a shows the entire overpass of the CASI with The Solent to the east (bottom) and Mudeford Bay to the west (top). This is a composite image of three channels of the uncorrected CASI data. The first analysis stage was to apply an atmospheric correction. This correction removed both the Rayleigh and Mie component of the atmosphere. In this image, a Case-1 single scattering correction has been applied, which accounts for the remnants of the atmosphere seen in the image towards the edges. Figure 17b shows a full resolution subsection of the entire image, before atmospheric correction, with the corresponding corrected image shown in Fig. 17c.

The SPM concentration was calculated from this atmospherically corrected image in an empirical manner. From the entire image, the image pixels that correspond to the sampling stations were extracted for the two channels corresponding to SeaWiFS channels 5 and 3. To allow for error in location of the sampling station within the image, an average of nine pixels was taken around the estimated site. The ratio of these radiance values was then regressed against the surface total SPM. A linear relationship was found with an R value of 0.8. This relationship was then applied to the entire image, resulting in a grey scale representation of surface SPM concentration, shown in Fig. 18a.

The final analysis stage was to color code the image for ease of interpretation. This was done because the ultimate user of the COAST software would require a sediment map, as opposed to a grey scale image. The technique used was density slicing, in which ranges of grey scale values are allocated to a different color. The result of this procedure is shown in Fig. 18b (in a grey scale representation). This is the same subsection of the image shown before, but has been calibrated in terms of total surface SPM. The technique used provides a good, clear representation of the SPM concentration at this time.

The results shown above are only preliminary. The waters in Christchurch Bay are Case-2 type as shown by the SPM concentrations found. A different algorithm for atmospheric correction will, therefore, be applied to images from this area. Development of this algorithm is ongoing within the COAST project. The results shown are valid as they have been derived by an empirical procedure. Application of the enhanced atmospheric correction will, however, allow this algorithm to be applied to a wider range of water types around the UK coast.

3.16 M. Robinson

LOIS ARS Research Report

Monthly campaigns in the Humber Estuary, one of the LOIS Rivers Basins-Atmosphere-Coast and Estuaries Study (Coastal) [RACS(C)] sites, were planned throughout the summer of 1994 with simultaneous overflights of the NERC CASI, operating in spatial mode with the band sets as shown in Table 1, and seaborne measurements. This database was expected to generate preliminary algorithms, and provide data for their validation, forming a basis for future overflights directed at investigating specific processes.

3.16.1 Field Campaign 1994

Optical sea truthing fieldwork was undertaken from the period April–August 1994. This was executed from the NRA's survey vessel the *Sea Vigil* as part of the core LOIS field program in the Humber Estuary. The vessel track followed a predetermined course encompassing a set of profiling stations chosen to identify those locations where an optical vertical profile should be taken using the Profiling Reflectance Radiometer (PRR-600). One set of stations follows a track extending out from the mouth of the Humber into the North Sea, another set was chosen as being along the transaxial flight lines.

Instrumentation employed consisted of the UOR (developed at PML) and the PRR-600. The former is self-contained and is towed astern of the vessel throughout the survey period. It is self-logging and records radiance and irradiance in six wavebands, temperature, chlorophyll (fluorescence), conductivity, SPM (transmission), and depth (pressure). The PRR-600 measures radiance at seven wavelengths and irradiance at six wavelengths and depth (pressure). It is lowered down over the side of the vessel and the data is logged onboard ship on a PC.

To enable the data collected to be accurately related to the imagery, it is merged with the navigational information as logged by the onboard QUBIT system. This also logs a variety of parameters such as temperature, conductivity, and dissolved oxygen.

Data was obtained from the cruise dates as listed in Table 2; however, CASI imagery was not obtained for all these dates due to the presence of clouds across the region on many of the cruises. Also, the imagery that was obtained from this year's campaign cannot be corrected radiometrically or for roll due to technical difficulties; hence, any comparison of these with sea truth would not be entirely accurate and justified. The imagery obtained, however, does provide a very useful synoptic view of the estuary and the dynamic processes at work. This alone may yield valuable information.

A completed system for routine processing and archiving of data has been established. The data acquired so far has not been processed fully [i.e., atmospherically corrected together with the production of sediment, chlorophyll, and dissolved organic carbon (DOC) maps] because of delays with the software. When this becomes available, the data will be retrospectively processed. Overflight data is available, from the months of April, June, and July for the Humber Estuary and Holderness Coast. A visual assessment of the data has been made according to:

1) The percentage of cloud cover in the image;
2) Evidence of roll in the image and whether or not it affects the image; and
3) The usefulness of the data.

Table 4. *Sea Vigil* cruises and CASI data obtained during the 1994 field campaign.

Sea Vigil		*Data Available*			CASI
No.	Date	QUBIT	PRR-600	UOR	Flight
7	25 Apr				×
	26 Apr	×			×
	27 Apr	×		×	
	28 Apr	×			
8	11 May	×	×	×	
9	18 May	×	×	×	
	19 May	×	×	×	
10	24 Jun				×
	28 Jun	×	×	×	×
	29 Jun	×			
	30 Jun	×	×	×	×
11	26 Jul	×	×	×	
	27 Jul	×			
	28 Jul	×			
	29 Jul				×
12	09 Aug	×		×	
	10 Aug	×			

3.16.2 Future Considerations for 1995

There have been several problems encountered in the acquisition of data during 1994. These included the delay of the introduction of the interim positioning system, and the postponement of the fully Integrated Data System (IDS). The IDS was due to be in place in November, but there have been technical delays both in the design and construction. It is planned that the IDS will be installed and running by 1 April 1995. Test-flights of IDS are planned sometime early this year. CASI has also had a few problems owing to poor performance, which resulted in the instrument being sent back to Itres in Canada. This coincided with the major data gathering campaign Challenger Cruise in October and November 1994; therefore, not as much data has been collected as expected. The data that is available is excellent for qualitative, but not for quantitative, research.

The weather was also a significant factor in the non-acquisition of data. There have been several months when the week scheduled for the overflights, in conjunction with acquisition of sea-truth data on the *Sea Vigil*, have yielded no data because of bad weather.

Steps are now being undertaken to devise a more comprehensive field campaign in 1995. More realistic windows for the collection of field data are being identified allowing greater flexibility both in the execution of the flight and the cruise programs. It has also been identified that it would be very advantageous to have the instrumentation permanently moored and recording at strategic locations in the Humber to ensure that, should particularly favorable conditions prevail for the CASI to fly, the imagery would be sea truthed.

Enough data is not available to test the correction algorithms being developed, and comparison with the *flux-curtain* data should provide adequate sea truth for some interpretation of imagery. The overflights in 1995, however, would appear to be a crucial data gathering opportunity.

The methodology involved in comparing the boat data with CASI imagery is being addressed in preparation for a more successful field campaign this year. This is being developed to run on the Interactive Data Language (IDL) package, which can itself be used for image processing work, and files can be easily exported for use in other processing packages. The possibility of using a GIS is also being explored.

3.17 R. Murphy, et al.

Remote Sensing of Coasts and Estuaries as Part of LOIS

3.17.1 Introduction

LOIS is a multidisciplinary study into coastal ecosystems and how they change in response to anthropogenic factors, within selected areas of the UK. The primary objective of LOIS is to develop models from a sound factual base in order to simulate the processes that govern material fluxes within the coastal zone. Within this context, a comprehensive airborne remote sensing campaign is currently underway to monitor suspended sediment load, chlorophyll

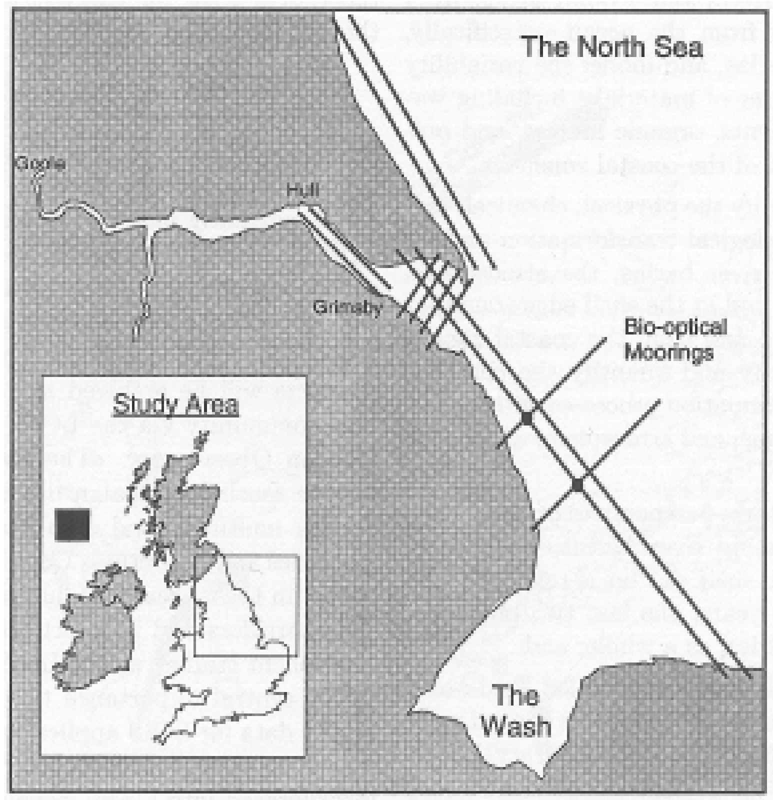

Fig. 19. The Humber Estuary, a specific LOIS study area.

concentration, and DOM in the Humber and Tweed Estuaries and their environs. The central goal of remote sensing within LOIS is to develop and drive dynamical models of the coastal zone. The aims of this paper are to provide an overview of the LOIS airborne remote sensing campaign and to describe its objectives. Specific reference will be made to the analytical strategies currently being developed to derive estimates of suspended sediment load from remotely sensed data acquired over the Humber Estuary.

3.17.2 Remote Sensing

The concept and utility of remote sensing for the mapping of suspended material, chlorophyll, and DOM in marine environments was proved in the 1980s with data gathered by the CZCS. With the forthcoming launch of SeaWiFS and OCTS, remote sensing will become a powerful tool for the study of marine environments throughout the 1990s and beyond. The coarse spatial resolution (800–900 m at nadir) of these sensors make them well suited to the study of marine environments, as they can cover large areas in a single overpass. The use of airborne platforms to spectrally characterize synoptically such large areas at the same temporal resolution of spaceborne platforms would be logistically impossible. However, to adequately characterize estuarine and near-shore environments, which are highly heterogeneous over small spatial scales, much finer spatial resolutions are required (currently only available from airborne sensors).

Using airborne remote sensing provides an ideal method of gathering contiguous data across the whole coastal zone, extending from the land through the littoral to the near-shore zone. Near-synoptic, inherently registered, multispectral data gathered from airborne platforms can be easily optimized in terms of areal coverage and spatial, spectral, and temporal resolution for a variety of applications. In highly dynamic and often inaccessible estuarine and near-shore environments, remotely sensed data will provide an important snapshot of contemporary biogeochemical fluxes. Near-synoptic data permits extrapolation into the wider spatial and temporal contexts from point observations made from ground-based floating platforms and remotely deployed moorings. No other approach to data acquisition could provide contiguous, near-synoptic data across the various components which characterize the coastal zone. Airborne remote sensing will, therefore, play a key role in fulfilling the overall objectives of LOIS.

3.17.3 An Overview of LOIS

Funded by NERC, LOIS has a six-year duration and will conclude in 1998. The study of coasts and estuaries as part of LOIS focuses on specific and representative areas of the UK coastal zone and continental shelf edge (Fig. 19). LOIS has four key objectives:

1) To characterize and measure the contemporary fluxes of energy and materials into the coastal zone from

the land by way of rivers and ground water, from the atmosphere and from the ocean—specifically, to measure, characterize, and model the variability of contemporary fluxes of materials, including water, sediments, nutrients, organic matter, and pollutants, into and out of the coastal zone;

2) To identify and quantify the physical, chemical, biogeochemical, and biological transformation and recycling processes in river basins, the atmosphere, and inner shelf seas, and at the shelf edge zone that govern such fluxes to and from the coastal zone—specifically, to identify and quantify the chemical and biological transformation processes within river basins, the coastal zone, and atmosphere which govern such fluxes;

3) To provide the long-term perspectives of energy and material fluxes affecting river basins, the coastal zone, and the wider shelf sea on a range of time scales—the last 200 years, the last two millennia, and the Holocene period as a whole; and

4) To initiate the development of coupled land-ocean models of environmental change in the coastal zone. These models will integrate contemporary behavior and past trends in coastal ecosystems. They will provide the basis for predicting the impact of environmental change over the next 50–100 years. Specifically, the models and contemporary observations of it will be used to determine how changes in land use, sea level, and other environmental conditions affect riverine and coastal ecosystems. The emphasis of these studies will be on the sustainability of living resources, on organic matter fluxes, and on geomorphological and geochemical processes in the coastal zone.

Within these contexts, the specific objectives of remote sensing are:

- To map, quantify, and classify key biophysical properties, [e.g., suspended sediments, plant pigments (chlorophylls and carotenoids), bulk DOM (principally the marine humic fraction), and other water constituents based on in-water and ground-truth measurements];
- To investigate changes in the distribution of the same properties over a range of time scales (e.g., hourly, weekly, seasonal, and annual) in relation to the processes that determine the dynamic properties of coastal and estuarine waters; and
- To assimilate the observed distributions into GIS-based databases and, using novel forecasting techniques, into hydrological and ecosystem models for purposes of model initialization and validation.

In addressing these objectives, airborne remote sensing will contribute significantly to the ultimate aims of the LOIS project as a whole, and will help to provide a sound theoretical basis for effective operational management of the coastal zone in the future.

3.17.4 The Airborne Campaign

The most comprehensive marine airborne remote sensing campaign undertaken thus far in the UK was devised, and is currently underway, to run for the duration of the LOIS project. Derivation of products (maps of suspended sediment load, chlorophyll concentration, and DOM from remotely sensed data will be accomplished at PML using both established and novel techniques. After validation, products will be archived and disseminated to the LOIS user community via the LOIS data center at the BODC, Bidston Observatory. The main thrust of the airborne remote sensing campaign during 1994–95 is aimed at acquiring multitemporal data over the Humber and Tweed Estuaries and Holderness Coast. Remotely sensed data acquired in these areas will link up with those collected over river corridors and in intertidal areas in support of other component studies within LOIS.

Of central importance to the acquisition of remotely sensed data for LOIS applications is the CASI instrument. Recent developments in sensor technology, such as those incorporated into CASI, have enhanced the usefulness of airborne remote sensing for estuarine and marine applications. Prior to the development of CASI and its predecesssor, the Programmable Multispectral Imager (PMI), there was little scope for effective operational airborne remote sensing in these areas. The radiometric sensitivity of CASI is such that subtle variations in water-leaving radiance arising as a result of spatial variations in suspended materials, plant pigments, and DOM can be detected and mapped.

Another advantage of CASI is that the user is able to determine the wavelength location and width of the 14 spectral bands, which are available when the sensor is operated in *spatial mode*. The CASI band set can, therefore, be optimized and configured for a particular application or to conform to the defined band sets of orbital sensors, which will be placed in Earth orbit in the near future, such as SeaWiFS or OCTS. The use of consistent band sets in this way permits the extrapolation of spatial variations in water quality parameters, as determined from CASI data, into the wider spatial context using data obtained from spaceborne platforms. Bands at specific locations in the spectrum can also be defined to detect and quantify atmospheric variables (such as aerosols) that represent key input parameters into atmospheric correction algorithms for Case-2 waters, which are currently being developed at PML (see Section 3.17.7.2). As atmospheric correction is seen as a prerequisite to product derivation for data gathered over water this ability offers a clear advantage over conventional sensors such as the ATM. CASI will, therefore, enable an integrated approach to the synoptic measurement of a wide range of variables from all components which characterize the land-ocean interface and atmosphere.

Although the ATM has been used for semi-quantitative determinations of chlorophyll concentration, its primary use in LOIS applications will be to map the surface skin temperature of water. Temperature maps will be integrated with maps of chlorophyll concentration and suspended sediment load derived from CASI data. Such integration, along with retrospective geo-referencing and geometric correction, will be possible, because the acquisition of all remotely sensed airborne data is being undertaken by the newly developed IDS.

3.17.5 The Integrated Data System

The function of the IDS is to integrate the data streams of CASI and ATM along with positional information obtained from the GPS. IDS has been developed under contract by NERC as part of its response to the UK ARS community's need for continuous access to state-of-the-art optical sensor imagery, provided as consistently high quality standard products. The NERC had previously provided an annual ARS service, through use of its own Piper Chieftain aircraft and hired-in sensors and aerial survey cameras, for limited period campaigns between 1982 and 1993. Despite the many successes of these campaigns, it was evident that the community needed year round access to these sensors and an increased consistency in both data quality and data formats, supplied by the various sensor operators used during this period. The IDS development follows on from the purchase, in 1993, of the Daedalus 1268 ATM, used under hire by NERC during the previous 10 years; purchase of an Itres CASI, specifically in support of the LOIS program; and installation of an Ashtech 3DF GPS-based attitude and position referencing system, to upgrade in-flight navigation and to enable the accurate geometric correction of both sensor data.

The IDS contract consists of the development of two complementary systems (Wilson 1994a). First, an onboard system has been developed to replace most of the data acquisition and recording for the Daedalus 1268 scanner, eliminating the need to support a high density data tape (HDDT) drive, and in providing operator display of collected flight line data. The system also records and time synchronizes the output from the four GPS antennae, mounted in a cruciform array on the aircraft roof, with scan line acquisition from the ATM and also the CASI sensor. The use of the GPS data in this manner is a unique implementation of this attitude and position referencing system in the field of airborne remote sensing. Second, a ground-based data processing system has been designed to ingest the time synchronized ATM, CASI, and GPS data and process through a series of levels, following the NASA standard family of data products:

Level-0: Raw *sensor format* data at original resolution.

Level-1a: Level-0 data reformatted to image files with ancillary files appended.

Level-1b: Level-1a data to which radiometric calibration algorithms have been applied, to produce radiance or irradiance, and to which location and navigational information has been appended.

Level-2: Geophysical or environmental parameters derived from level-1a or level-1b data (may include atmospheric correction).

level-3a: Level-1b or level-2 data mapped to a geographic coordinate system using onboard attitude and positional information only.

level-3b: Level-1b or level-2 data mapped to a geographic coordinate system using onboard attitude and positional information with additional ground-control points.

Level-4: Multitemporal or multisensor gridded data products.

This data processing system automatically applies the up-to-date, sensor specific, calibration coefficients to produce radiometrically calibrated data (level-1b). The in-flight navigation data is merged with differential GPS data, collected simultaneously at a ground station, to calculate the accurate attitude and absolute position of the aircraft on a scan-line-by-scan-line basis. These can be applied to the level-1b data to produce geometrically corrected data products (level-3a) or with additional ground control (level-3b). Software is being distributed to users of the NERC data to allow user control of the geometric correction process through the choice of map projection, output pixel size, and method of resampling. In addition, the ability to apply the correction after user-derived data products (level-2), including atmospheric correction, are generated. To further assist users in immediate usage of these remotely sensed data products, all data are generated in a standard data format (HDF) and issued on CD-ROMs for wide dissemination and easy access. Browse and data extraction tools are provided by NERC along with the data disks.

IDS will provide the consistently high quality data and ease of use that the ARS community have requested. This has also been an essential prerequisite before the successful utilization of airborne remotely sensed data in support of such a large-scale science program as LOIS.

3.17.6 Data Acquisition

3.17.6.1 Airborne Data

CASI and ATM data are acquired from the NERC Piper Chieftain aircraft. The design of CASI means that there is a tradeoff between spatial resolution and the number of spatial mode bands that can be defined. For the majority of coastal zone applications, a spatial resolution of 2 or 5 m is required, enabling a spatial band set to be formulated consisting of 6 and 14 bands and yielding a swath width of 2.3 km and 850 m, respectively. The CASI band set was defined to permit the mapping of key water quality and atmospheric parameters, and to reflect the wavelengths sampled by SeaWiFS (Table A-1 in Appendix A).

The majority of the airborne data acquired so far has been of the Humber Estuary and the rapidly eroding Holderness Coast. The Humber Estuary is the largest estuary in the British Isles, being approximately 15 km wide at its widest point and having a catchment area of about one-fifth of England. To acquire remotely sensed data over such a large area, the remote sensing campaign was organized into discrete blocks of axial and transaxial flight lines. These flight lines were designed specifically to provide full coverage of the upper, middle, and lower parts of the estuary and plume and to include remotely deployed moorings, collectively termed the Humber Flux Curtain (Section 3.17.6.2), at the mouth of the estuary. Data acquisition over the Holderness Coast was accomplished in a series of flight lines running parallel to the coast (Fig. 19). A block of flight lines oriented normal to the coastline were devised to collect data over remotely deployed bottom dwelling moorings. Remotely sensed data has also been acquired over many other flight tracts during cruises of the NERC research vessel *RRS Challenger*. The location and orientation of these flight lines depend upon the location of the ship at the time.

As the Tweed Estuary is considerably smaller than the Humber, CASI data was acquired at a spatial resolution of 2 m. This particular estuary is the focus for work to monitor the dynamics of the saline intrusion front. CASI flights were, therefore, acquired at half-hourly intervals during the course of the flood tide.

Sun glint effects are minimized in all data by flying into, or out of, the sun or flying at a specific time of day over those flight lines which have a fixed orientation or location.

3.17.6.2 Sea-Truth Data

In order to validate maps of water quality parameters, such as suspended sediment load and chlorophyll, *in situ* sea-truth data is required for comparison with parameter maps derived from CASI data. Validation is viewed as a two-stage process. The first stage will be to validate the atmospheric correction procedure. The second stage will be to validate derived product maps of suspended sediment, chlorophyll, and DOM. To accomplish both stages a variety of approaches to sea-truth data collection have been taken.

The primary source of sea-truth data is collected from ships using the UOR (Aiken and Bellan 1990) and PRR. The UOR is towed behind the ship and records temperature, salinity, fluorescence, and suspended sediment load, as well as upwelling and downwelling radiance measured in six channels. The PRR measures temperature, depth, plus upwelling and downwelling radiance over six wavelengths. It is deployed from the side of the ship whilst stationary and is lowered to a depth where photosynthetically active radiation is zero. The radiances obtained over the entire profile can then be used to extrapolate to the surface to provide water-leaving radiance. Other *in situ* measurements of suspended sediment load, chlorophyll, and DOM are continually obtained as part of the LOIS core program. For flight lines within the estuary, sea-truth data is collected from *Sea Vigil*, a small research vessel operated by the NRA. The seagoing *RRS Challenger* is used to collect sea-truth data from off-shore areas.

The use of remotely deployed moorings have simplified the acquisition of sea-truth data in support of the airborne remote sensing campaign. Remotely deployed moorings enable a variety of data to be collected on a regular basis without the considerable logistical problems and expense involved with the deployment of manned vessels. Several remotely deployed mooring packages are currently in operation as part of the LOIS project. Of importance to the airborne remote sensing campaign is the Humber Flux Curtain and two bio-optical buoys located off shore between the Humber Estuary and The Wash.

The Humber Flux Curtain comprises a suite of five moorings spaced at regular intervals across the mouth of the estuary. Each mooring measures suspended sediment load, salinity, temperature, and conductivity at several depths and telemeters the data hourly to Hull University where it is processed. In addition, a downwelling irradiance is currently being measured for validation of atmospheric correction procedures. The location of components of the Humber Flux Curtain within a transaxial flight line are shown in Fig. 20. The Humber Flux Curtain will provide a reliable source of data, which can be used to validate maps of suspended sediment and temperature derived from CASI and ATM data.

The bio-optical buoys are configured to monitor chlorophyll fluorescence and are positioned primarily to detect spring phytoplankton blooms, which are known to occur in this area. These buoys are overflown by CASI and ATM on a weekly basis.

3.17.7 Data Analysis

3.17.7.1 Atmospheric Correction

Effective atmospheric correction is a prerequisite to the retrieval of water-leaving radiance, which constitutes only 5–10% of the signal received by the sensor. In Case-1 waters (dominated by photosynthetic pigments), where the optical properties of water vary smoothly and the aerosol can be considered constant, atmospheric models have been reasonably successful (Gordon and Wang 1994). Such approaches work on the assumption that water-leaving radiance in the NIR is zero. Any radiance received by the

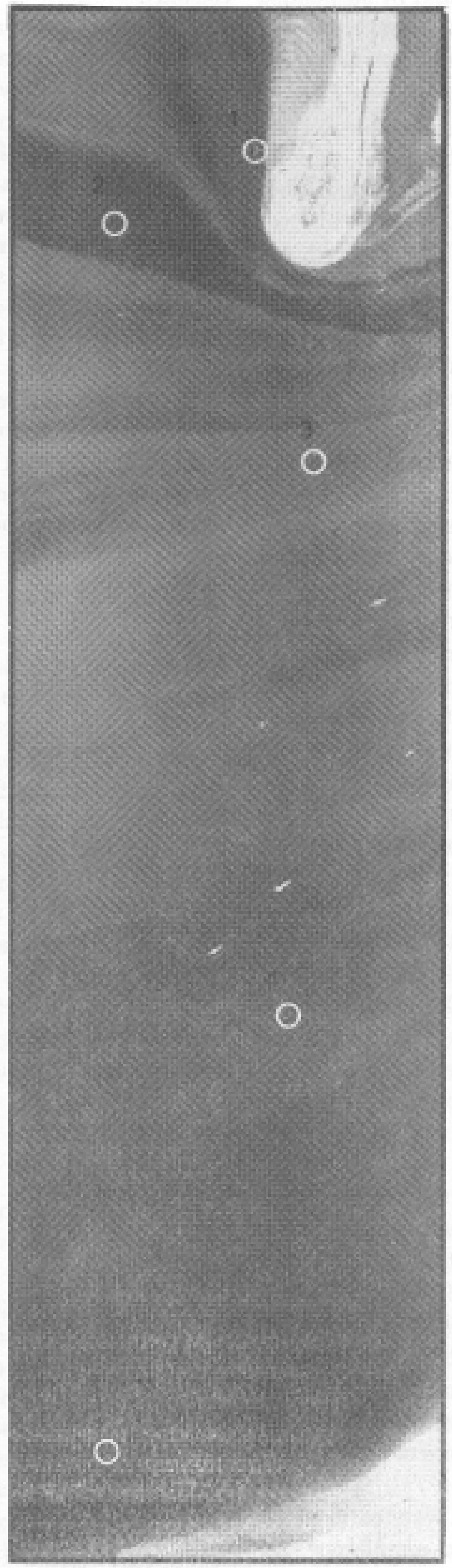

Fig. 20. The location of components of the Humber Flux Curtain (white circles).

sensor at this wavelength is, therefore, assumed to originate from atmospheric scattering and is removed. However, in Case-2 waters (which are dominated by suspended sediments), the assumption that there is no water-leaving radiance in the NIR cannot be made because suspended sediment scatters incident light back into the field of view of the sensor. This has important implications for remotely sensed data gathered in Case-2 waters, such as those present in the LOIS study area. New approaches to the correction of remotely sensed data acquired in estuarine and coastal environments is, therefore, required.

3.17.7.2 Hydrological Optics

In both LOIS and the Land-Ocean Interactions in the Coastal Zone (LOICZ), there is a clear requirement to develop atmospheric correction methods in Case-2 waters, and to develop methods to determine particulate concentration in terms of gravimetric units for use in mass flux studies. The term *Case-2 waters* describes those waters influenced by Gelbstoff and those influenced by particulates. The influence of Gelbstoff, although causing problems in the retrieval of biogeochemical parameters, has little effect on atmospheric correction. The term *bright pixel waters* is used to describe collectively those waters where NIR reflectance is significant, in contrast to the waters where conventional atmospheric correction works (Gordon and Wang 1994) where the dark pixel assumption holds true. In bright pixel waters, it is not possible to make the assumption of zero water-leaving radiance at any wavelength covered by ocean color sensors.

These dual aims of determining particulate concentration and atmospheric correction in bright pixel waters can be fulfilled by developing a coupled hydrological and atmosphere optical models in the NIR (700–900 nm). This coupled model can be used to *bootstrap* a Gordon and Wang (1994) atmospheric correction scheme to enable atmospheric correction throughout the visible and NIR range of SeaWiFS. To date, the principal work at PML has been to develop the hydrological NIR model.

Development of in-water models for the NIR requires parameters from field and laboratory measurements. Data for the pure water properties of absorption (Palmer and Williams 1974) and backscatter (Morel 1974) are available from the literature. Gordon and Ding (1992) indicate that instrument self shading is a serious problem for in-water radiance and irradiance measurements in the NIR, where the absorption of pure water is high. The approach in this study has been to use field and laboratory measurements of surface remotely sensed reflectance (L_W/E_d). The laboratory measurements (Bale et al. 1994) were carried out using a range of sediment types from a number of UK coastal sites representing diverse sediment mineralogies. The measurement of reflectance with a spectroradiometer under laboratory conditions, using a tank of feasible dimensions (2 m depth), is possible because of the high optical depths of pure water at NIR wavelengths (75 cm at 700 nm).

The tank experiments showed that the absolute reflectance of particulates compared to gravimetric concentrations varies widely between different sediment types and between size-fractionated sediments of the same type. In contrast, the ratio of remotely sensed reflectance between two NIR bands (SeaWiFS bands 7 and 8) showed a consistent relationship with gravimetric load, for a number of sediment types with modal particle diameters varying from 5–100 μm. The data are shown in Fig. 21, where band 12 corresponds to SeaWiFS band 8, and band 11 corresponds to SeaWiFS band 7. The sediment data that falls markedly below the main group is from artificial coarse sediment. The success in the ratio method in determining gravimetric sediment concentration results from the relationship between the IOPs of particulate material and band ratios. The remotely sensed reflectance at a particular wavelength can be expressed as:

$$R_{rs} = \frac{(1-\rho)(1-\tilde{\rho})R}{m^2(1-rR)Q}, \qquad (3)$$

where m is the refractive index of seawater, R is the irradiance reflectance, ρ is the Fresnel reflectance at normal incidence, $\tilde{\rho}$ is the Fresnel reflectance for sun and sky irradiance, r is the air-water reflectance for diffuse irradiance, and Q is the ratio of upwelling irradiance to radiance. Q varies with the angular distribution of the upwelling light field and is equal to π for an isotropic distribution, but may be up to 5 for bright pixel waters. The term $(1-rR)$ is normally assumed to be unity for Case-1 waters, but has to be explicitly modeled for bright pixel waters because of their high irradiance reflectance (up to 10%).

The irradiance reflectance in the NIR can be expressed as the following using Morel and Gentili's (1993) expression for irradiance reflectance:

$$R = f\left[\frac{0.5b_w + \tilde{b}_b b_s C_{\mathrm{sed}}}{a_w + a_s C_{\mathrm{sed}}}\right], \qquad (4)$$

where f is a factor that is determined by the incident light field, ω, and the relative scattering of water and particulates; b_w and a_w are the scattering and absorption coefficients for water, respectively; b_s and a_s are the sediment specific scattering and absorption coefficients, respectively; C_{sed} is the sediment concentration; and $\tilde{b}_b$ is the backscatter ratio. The dominant terms in the remotely sensed reflectance are the scattering, absorption, and backscatter ratio of the particulates. Models using the anomalous diffraction theory (van de Hulst 1957) indicate that the specific scattering coefficients for particulates varies from 0.238–0.006 $\mathrm{m^2\,g^{-1}}$ (λ=750 nm) as the particle diameter increases from 5.5–100 μm, whereas the absorption coefficient shows a smaller change 0.013–0.006 $\mathrm{m^2\,g^{-1}}$. Inversion of the IOPs from tank experiments shows a similar

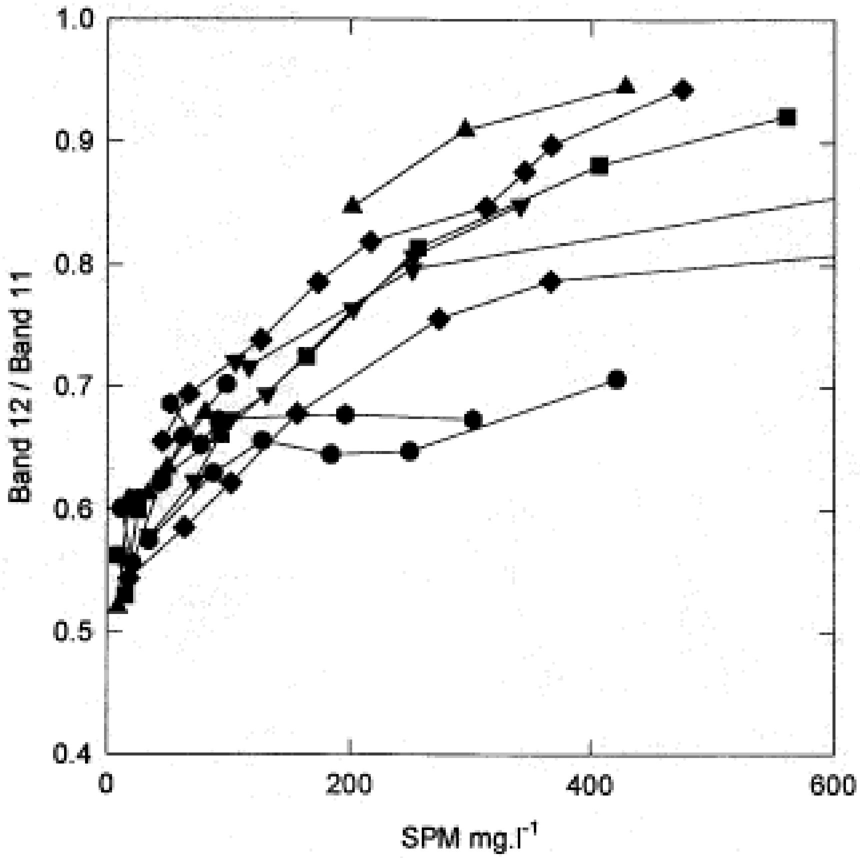

Fig. 21. The ratio of remotely sensed reflectance between two NIR bands.

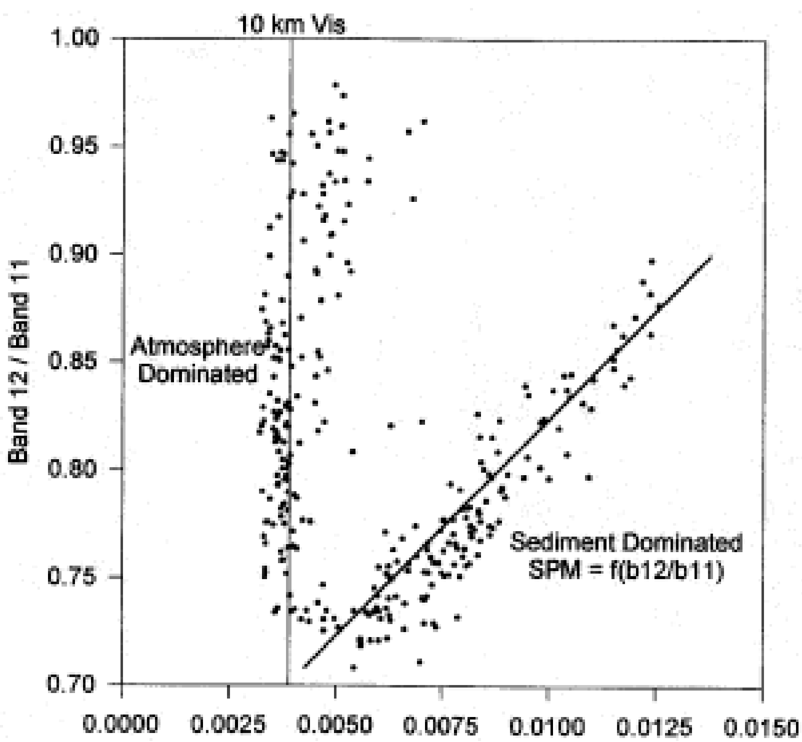

Fig. 22. The relationship between 860 nm reflectance and the band ratio from Fig. 21.

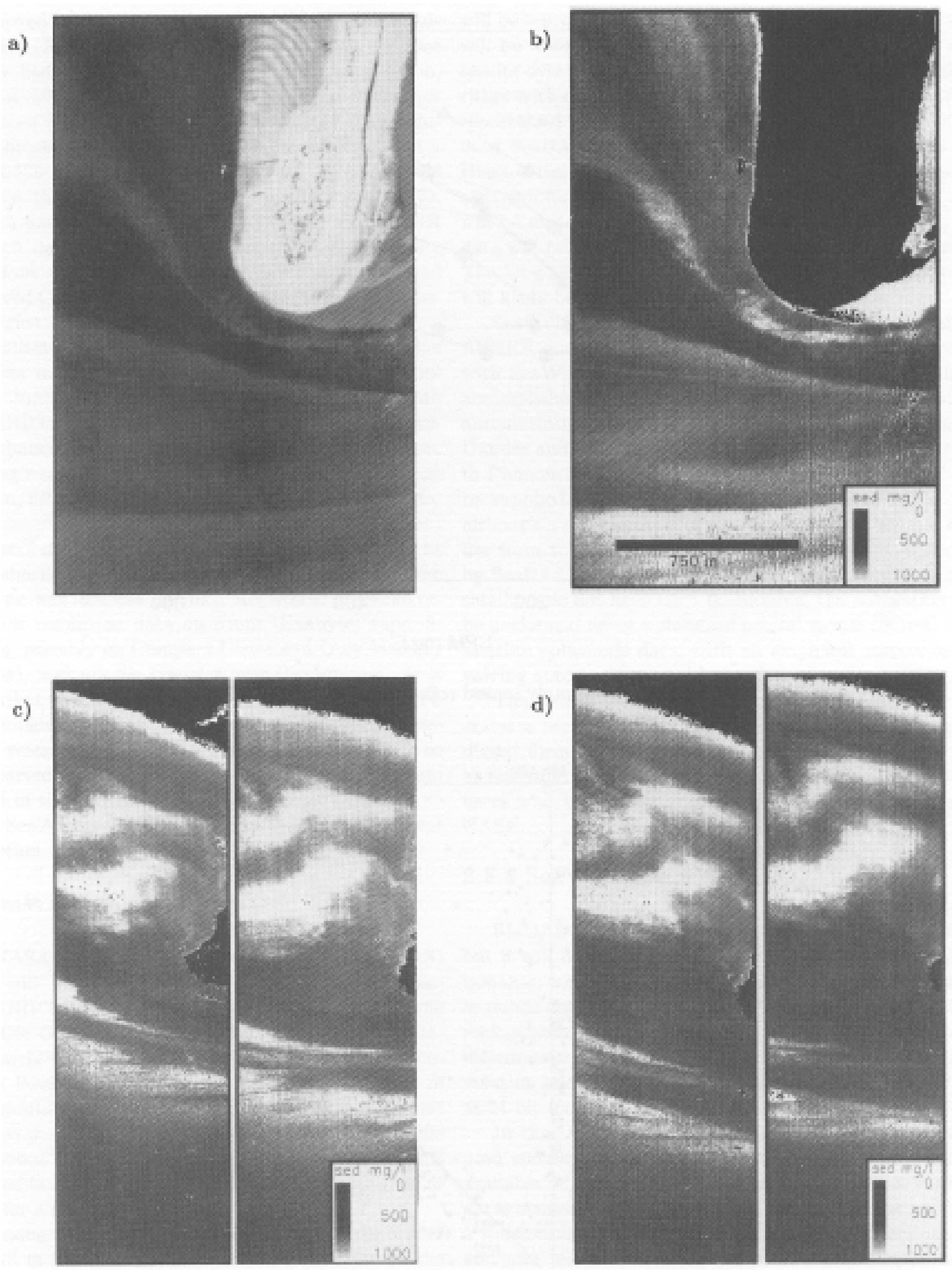

Fig. 23. A series of sediment maps derived from CASI data which was acquired over a transaxial flight line at the mouth of the Humber: **a)** a raw NIR image (top left); **b)** a sediment map derived from Fig. 23a (top right); **c)** sediment maps from 1402 and 1410 GMT imagery (bottom left); and **d)** sediment maps from 1417 and 1424 GMT imagery (bottom right).

range with the scattering coefficient varying from 0.295–0.032 $\mathrm{m}^2\,\mathrm{g}^{-1}$ (assuming $\tilde{b}_b = 0.02$), and the absorption coefficient varying from 0.022–0.011 $\mathrm{m}^2\,\mathrm{g}^{-1}$.

Ignoring any spectral variation in Q and f, and assuming b_w is insignificant, the band ratio can be modeled by the expression

$$\frac{R_{rs}(\lambda_1)}{R_{rs}(\lambda_2)} = \left[\frac{\tilde{b}_b(\lambda 1)}{\tilde{b}_b(\lambda_2)}\right]\left[\frac{b_s(\lambda 1)C_{\mathrm{sed}}}{b_s(\lambda_2)C_{\mathrm{sed}}}\right] g(a_w, a_s, b_s), \qquad (5)$$

where the function $g(a_w, a_s, b_s)$ is defined as

$$g = \frac{a_w(\lambda_2) + a_s(\lambda_2)C_{\mathrm{sed}} - rfb_s(\lambda_2)C_{\mathrm{sed}}}{a_w(\lambda_1) + a_s(\lambda_1)C_{\mathrm{sed}} - rfb_s(\lambda_1)C_{\mathrm{sed}}}. \qquad (6)$$

As can be seen, the ratio is dependant on the spectral ratio of backscatter ratio $\left[\tilde{b}_b(\lambda_1)/\tilde{b}_b(\lambda_2)\right]$, the sediment specific scattering coefficient $\left[b_s(\lambda_1)/b_s(\lambda_2)\right]$, and the absorption coefficients of water and sediment. Morel and Ahn (1990) demonstrate that the backscatter ratio is spectrally neutral. The scattering coefficient will have a λ^{-n} relationship where n depends on the particle size distribution and is typically 1.0 ± 0.5. The term $b_s(\lambda_1)/b_s(\lambda_2)$ can be replaced by $[\lambda_1/\lambda_2]^{-n}$ or 0.9^{-n} for SeaWiFS bands 7 and 8. Anomalous diffraction theory and tank experiments show that the absorption coefficient varies weakly with wavelength, e.g., at a modal diameter of 10 μm) the absorption coefficients are 0.011, $0.012 \pm 0.001\,\mathrm{m}^2\,\mathrm{g}^{-1}$ at band 7 and 0.011, $0.001 \pm 0.001\,\mathrm{m}^2\,\mathrm{g}^{-1}$ at band 8 for anomalous diffraction theory and tank experiments, respectively.

The ratio can be further simplified by assuming that a_s is wavelength independent (in the NIR) and, for any specific particulate, is a constant that has only a weak dependence on particle size. The term $-rfb(\lambda)C_{\mathrm{sed}}$ can be summed into a composite sediment term (k_s) since rf is typically around 0.1. This simplification gives the following expression that provides an adequate parameterization for the data from the tank experiments (Fig. 21):

$$\frac{R_{rs}(\lambda_1)}{R_{rs}(\lambda_2)} = \frac{a_w(\lambda_2) + k_s(\lambda_2)C_{\mathrm{sed}}}{a_w(\lambda_1) + k_s(\lambda_1)C_{\mathrm{sed}}}\left[\frac{\lambda_1}{\lambda_2}\right]^{-n}. \qquad (7)$$

Both expressions for the band ratio are less sensitive to the sediment scattering component, which has the highest sensitivity to particle size.

Since these are NIR ratios, they can be applied to non-atmospherically corrected aircraft data; τ_R is lower than satellite data. Figure 22 shows the relationship between 860 nm reflectance and the band ratio (SeaWiFS band 8 divided by band 7) for a transect across the image shown in Fig. 21. The absolute reflectance can be used as a local surrogate for sediment concentration. Figure 22 shows two regions, the first atmosphere dominated where the ratio is independent of 860 nm reflectance, and the second where there is a clear linear relationship between the 860 nm reflectance and the band ratio. This region of linearity is consistent from image to image and can be used to provide quasi-calibrated images for regions of high sediment load. Figures 23b–23d show examples of such imagery, which are discussed elsewhere in this article. Even without atmospheric correction, the use of the NIR ratio is able to enhance features that are not visible in the raw NIR images (Fig. 23a).

3.17.8 The Future

Remote sensing will continue to play a central role in the effort to understand estuarine and coastal zone processes. In the large areas that constitute the LOIS study area, it is the only realistic way in which contiguous, near-synoptic data can be acquired from the whole of the coastal zone. In this context, continued efforts will be made to develop automated and more reliable analytical strategies to extract estimates of suspended particulates and chlorophyll concentrations from CASI data. These strategies will form the basis for the ongoing development of algorithms for the processing of data acquired from spaceborne platforms.

Work is currently underway to automatically extract suspended sediment and chlorophyll concentrations from several hundred gigabytes of CASI data acquired over the past 12 months. This work is already contributing significantly to the understanding of sediment transport processes in estuarine environments. Figures 23b–23d show a series of sediment maps derived from CASI data which was acquired over a transaxial flight line at the mouth of the Humber every eight minutes. The sediment maps, clearly show discrete bands of high sediment concentrations, termed *snarks*, which are rapidly progressing up the estuary on a flood tide. Such images not only demonstrate the highly dynamic nature of estuarine environments, but will, when integrated into models of flow dynamics and sediment transport, provide detailed estimates of sediment fluxes at many different temporal scales. Additional work is being undertaken to relate snarks to tidal state, bathymetry, and flow dynamics within the estuary.

LOIS, by its very nature, will generate very large quantities of data that will require integration, analysis and interrogation. To accomplish this, LOIS is significantly enhancing its GIS capability. GIS will provide the ideal environment where the many data elements of LOIS, including those from studies of rivers, coastal environments, shelf edge and atmosphere, can be brought together and interfaced with dynamical models.

Remotely sensed data will not only be used as input to, and validation for, models of estuarine flow within the context of LOIS but will continue to contribute to the operational monitoring and assessment of environmental *events* such as oil spills, pollution episodes, and the monitoring of the development of toxic algal blooms. This will go a long way to realizing a coherent system for future operational management of all aspects of the coastal zone from onshore to deep water. Such a capability will be further advanced with the launch of SeaWiFS and OCTS in the near future. Data from these sensors will enable the extrapolation in space and time from CASI observations made in the near-shore zone and will present a unique opportunity for the study of the land-ocean interface from on shore to the shelf edge.

Acknowledgments

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Appendices

A. *The CASI Band Set*
B. *Meeting Contributors*
C. *Meeting Attendees*

Appendix A

The NERC CASI SeaWiFS Simulation Band Set

Table A-1. CASI band set definition [RACS(C)] and approximate SeaWiFS band relations. Wavelengths are given in nanometers.

Band		*Wavelength*		Sensing
CASI	SeaWiFS	Min.	Max.	Purpose
1	1	402.8	418.6	C, G
2	2	432.7	450.3	C, G
3	3	480.4	496.3	C, G, P
4	4	499.8	515.8	P
5	5	546.0	560.2	C, P
6		606.5	628.0	M
7	6	660.2	674.5	C, F, S
8		676.3	683.5	F, S
9		703.3	714.1	F, M
10	7a	744.7	753.7	A, S
11	7b	755.5	780.8	A, S
12		813.3	827.8	W
13	8	845.9	880.4	A, S
14		884.1	898.6	A, S

A = Atmospheric Aerosols
C = Chlorophyll
F = Chlorophyll Fluorescence
G = Gelbstoff
M = MERIS
P = Accessory Pigment
S = Sediment
W = Atmospheric Water Vapor

Appendix B

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Glossary

APT Automatic Picture Transmission
ARGOS Not an acronym, but the name given to the data collection and location system on the NOAA operational satellites.
ARS Airborne Remote Sensing
ATLAS Auto-Tracking Land and Atmosphere Sensor
ATM Airborne Thematic Mapper
AVHRR Advanced Very High Resolution Radiometer

BIOS Biophysical Interactions and Ocean Structure (NERC research program)
BNSC British National Space Center
BODC British Oceanic Data Center
BRDF Bidirectional Reflectance Distribution Function

Case-1 Water whose reflectance is determined solely by absorption.
Case-2 Water whose reflectance is significantly influenced by scattering.
CASI Compact Airborne Spectrographic Imager
CCD Charge Coupled Device
CD-ROM Compact Disk-Read Only Memory
CIMEL Not an acronym, but the name of of sun photometer manufacturer.
COAST Coastal Earth Observation Application for Sediment Transport
CTD Conductivity, Temperature, and Depth
CWL Center Wavelength
CZCS Coastal Zone Color Scanner

DARR Data Analysis Round-Robin
DML Dunstaffnage Marine Laboratory
DOC Dissolved Organic Carbon
DOM Dissolved Organic Matter
DON Dissolved Organic Nitrogen

EDMED European Directory of Marine and Environmental Data
ERDAS Not an acronym, but a trade name for an image analysis system.
ESA European Space Agency

FRRF Fast Repetition Rate Fluorometer
FOV Field of View

GAC Global Area Coverage, coarse resolution satellite data with a nominal ground resolution at nadir of approximately 4 km.
GIS Geographical Information System
GLOBEC Global Ocean Ecosystems (dynamics)
GMT Greenwich Mean Time
GPS Global Positioning System
GSFC Goddard Space Flight Center
GUI Graphical User Interface

HAPEX Hydrological Atmospheric Pilot Experiment
HDF Hierarchical Data Format
HDDT High Density Data Tape
HPLC High Performance Liquid Chromatography
HRPT High Resolution Picture Transmission

ICARUS Instrumentation Characterizing Aerosol Radii Using Sun photometry
IDL Interactive Data Language
IDS Integrated Data System
ILS Incident Light Sensor
IOP Inherent Optical Property
IOSDL Institute of Oceanographic Sciences, Deacon Laboratory

JGOFS Joint Global Ocean Flux Study

LAC Local Area Coverage, fine resolution satellite data with a nominal ground resolution at nadir of approximately 1 km.
LOICZ Land Ocean Interactions in the Coastal Zone
LOIS Land-Ocean Interaction Study

MAFF Ministry of Agriculture, Fisheries, and Food
MARAS Marine Radiometric Spectrometer
MCMC Markov Chain Monte Carlo
MERIS Medium Resolution Imaging Spectrometer
MODIS Moderate Resolution Imaging Spectroradiometer
MRF Meteorological Research Flight

NABE North Atlantic Bloom Experiment
NASA National Aeronautics and Space Administration
NERC (UK) Natural Environment Research Council
NET NIMBUS Experiment Team
NIMBUS Not an acronym, but a series of NASA experimental weather satellites containing a wide variety of atmosphere, ice, and ocean sensors.
NIR Near-Infrared
NIST National Institute of Standards and Technology
NOAA National Oceanic and Atmospheric Administration
NRA National Rivers Authority

OCTS Ocean Color Temperature Sensor (Japan)

PACE Plymouth Atmospheric Correction Experiment
PC (IBM) Personal Computer
PCASP UK Met Office LASER scatterometer for determination of aerosol size distribution
PI Principal Investigator
PlyMBODy Plymouth Marine Bio-Optical Data Buoy
PMI Programmable Multispectral Imager
PML Plymouth Marine Laboratory
PRIME Plankton Reactivity in the Marine Environment
PRR Profiling Reflectance Radiometer
PZN Phytoplankton, Zooplankton, and Nutrients

QUBIT Trade name of commercial data logging system.

RACS(C) Rivers Basins-Atmosphere-Coast and Estuaries Study (Coastal)
rms root mean squared
RSADU Remote Sensing Applications Development Unit
RSDAS Remote Sensing Data Analysis Service (PML)
RSS Remote Sensing Society

SeaBASS SeaWiFS Bio-Optical Archive and Storage System
SeaDAS SeaWiFS Data Analysis System
SeaWiFS Sea-viewing Wide Field-of-view Sensor
SEI SeaWiFS Exploitation Initiative
SEIBASS SeaWiFS Exploitation Initiative Bio-Optical Archive and Storage System
SGI Silicon Graphics, Incorporated
SPM Suspended Particulate Material
SST Sea Surface Temperature
Sterna Not an acronym, but a BOFS Antarctic research project.
SWIR Shortwave Infrared

UNIX Not an acronym, but a computer operating system.
UOR Undulating Oceanographic Recorder
UV Ultraviolet

VHRR Very High Resolution Radiometer

WOCE World Ocean Circulation Experiment

Symbols

$a(\lambda)$ The absorption coefficient.
$a_s(\lambda)$ The sediment specific absorption coefficient.
$a_w(\lambda)$ The absorption coefficient of pure sea water.

$b(\lambda)$ The scattering coefficient.
$b_b(\lambda)$ The backscatter coefficient.
$\tilde{b}_b(\lambda)$ The backscatter ratio (b_b/b).
$b_s(\lambda)$ The sediment specific scattering coefficient.
$b_w(\lambda)$ The scattering coefficient of pure seawater.

C Chlorophyll concentration.
$C_{\rm est}$ Estimated chlorophyll concentration.
$C_{\rm sed}$ Sediment concentration (SPM).

$E(z)$ Downwelling irradiance at depth z.
$E_d(\lambda)$ Downwelling irradiance.
$E_u(\lambda)$ Upwelling irradiance.
E_0 Incident downwelling irradiance.
$E_{WN}(\lambda)$ Normalized water-leaving irradiance.

f A factor relating IOPs to irradiance reflectance (see Morel and Gentili 1993).

i Variable infrared bands.

j Variable infrared bands.

K_d The attenuation coefficient for downwelling irradiance.
k_s A constant related to a_s and b_s.

$L(\lambda)$ Spectral radiance.
L_a Atmospheric path radiance due to aerosols.
L_r Atmospheric path radiance due to Rayleigh scattering.
L_t Total radiance observed by airborne or satellite sensor.
$L_{\rm toa}$ Radiance emerging at the top of the atmosphere.
$L_{WN}(\lambda)$ Normalized water-leaving radiance.
$L_W(\lambda)$ Water-leaving radiance.

m The index of refraction of seawater.

Q The ratio of upwelling irradiance to radiance, which varies with the angular distribution of the upwelling light field, and is π for an isotropic distribution.

r The air-water reflectance for diffuse irradiance.
R Linear correlation coefficient.
$R(\lambda)$ The irradiance reflectance at a specific wavelength.
R_{rs} The remotely sensed reflectance (L_W/E_d).

z Water depth.

$\tilde{\beta}(\theta)$ The normalized scattering phase function ($\beta(\theta)/b$).

$\epsilon(i,j)$ The ratio of L_a in two bands i and j.

λ Wavelength of light.

τ Optical thickness.
$\tau(\lambda)$ Total optical thickness.
$\tau_a(\lambda)$ Aerosol optical thickness.
$\tau_g(\lambda)$ Uniform mixed gas optical thickness.
$\tau_o(\lambda)$ Ozone optical thickness.
$\tau_R(\lambda)$ Rayleigh optical thickness.
$\tau_w v(\lambda)$ Water vapor optical thickness.

ω The single scattering albedo.

ρ The Fresnel reflectance at normal incidence.
$\tilde{\rho}$ The Fresnel reflectance for sun and sky irradiance.

Note: For quantities that vary spectrally, the spectral variation is assumed in much of the text, e.g., b and $b(\lambda)$, etc.

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13. ABSTRACT *(Maximum 200 words)*

The first meeting of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Exploitation Initiative (SEI) Science Team was held 24 January 1995 in Southampton, England, and was hosted by the James Renell Center. The SEI steering committee decided four areas should be emphasized to ensure the UK marine science community has the opportunity to exploit SeaWiFS data to the benefit of existing and future projects: 1) development of atmospheric correction strategies and algorithms suitable for application in coastal (Case-2) waters; 2) construction of algorithms for recovering a variety of biological parameters from remotely sensed ocean color data, using both archived and new data; 3) innovative use of models that utilize SeaWiFS data in the study of oceanographic processes; and 4) measurement of *in situ* data as part of the SeaWiFS Calibration and Validation Program. The goal of SEI is to foster the growth of an ocean color community by supporting a set of core activities plus a selection of research topics, in particular, the application of ocean color in optically complex Case-2 waters. This document summarizes the many accomplishments of SEI Science Team members in preparation for the launch of the SeaWiFS instrument.

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