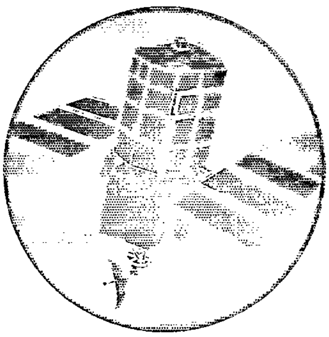
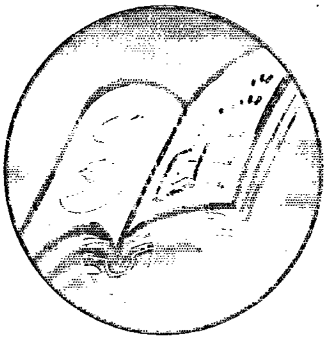
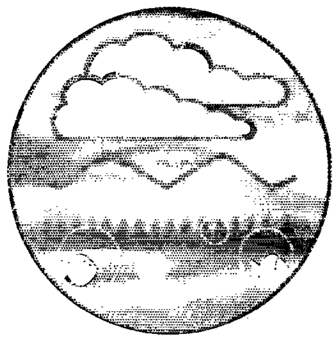
Further Development of Airborne Remote Sensing Techniques







Research and Development

Project Record
E1/509/10

ENVIRONMENT AGENCY

Further Development of Airborne Remote Sensing Techniques

R&D Project Record E1/509/10

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Research Contractor:
Plymouth Marine Laboratory

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This report is for use by the National Centre for Environmental Data & Surveillance for the evaluation of the spatial extent and concentration of algal blooms through chlorophyll *a* estimation. The algorithms may be applied to the data from the Agency's Compact Aerial Multi-Spectral Imager. This work supports the Agency's work in relationship to the EC Directive on Urban Waste Water Treatment.

Research contractor
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Nick Holden, Environment Agency

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LIST OF ACRONYMS

ATBD	Algorithm Theoretical Basis Document
BNSC	British National Space Centre
CASI	Compact Airborne Spectrographic Imager
COAST	Coastal earth Observation Application for Sediment Transport
the Agency	Environment Agency
ESA	European Space Agency
LOIS	Land-Ocean Interaction Study
MERIS	Medium Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NIR	Near infrared
NRA	National Rivers Authority
PACE	Plymouth Atmospheric Correction Experiment
PML	Plymouth Marine Laboratory
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SPM	Suspended particulate matter

1. INTRODUCTION

This is the fourth report to the Environment Agency (the Agency), formerly the National Rivers Authority) under the contract with the Natural Environment Research Council's Plymouth Marine Laboratory (NERC, PML) entitled: "FURTHER DEVELOPMENT OF AIRBORNE REMOTE SENSING TECHNIQUES".

The tasks for PML under this contract, were the development of novel methods for the improved interpretation of airborne remote sensing by Compact Airborne Spectrographic Imager (CASI) a relatively new instrument having high radiometric sensitivity, optimised for low-level water leaving radiances, high spectral resolution (1.8 nm) and broad spectral range (400 - 900 nm). Essentially, these special features of CASI required the development of new techniques and new algorithms to interpret the imagery with maximum precision and exploit the sensor capabilities to the full. Most significantly, with high radiometric sensitivity, in the near infrared NIR (700 - 900 nm), atmospheric correction of the measured radiances over water would be possible, provided new procedures could be developed.

The three previous reports were concerned with:

Preliminary Report (Aiken, Hudson, Moore & Bottrell, March 1995): The requirements to evaluate and validate airborne remotely sensed data of the coastal zone, principally the atmospheric correction procedures and their validation.

Second Report (Moore & Aiken, Sept., 1995): The theory of the proposed atmospheric correction scheme and its implementation. A revised and extended version of the Second Report (Bottrell, November 1996) includes a new Section 2 and the "Algorithm Theoretical Basis Documents" (ATBD's) for all the algorithms used in the atmospheric correction processing chain developed by PML for CASI imagery. The ATBD format is the standard method used by NASA and ESA for describing any processing algorithm and include the basic equations and parameter specifications.

Third Report (Aiken, Moore, Bottrell & Lavender, March, 1996; Revised Third Report: Bottrell, November 1996): Full implementation of the methods, processed test imagery and validation, limited to data obtained during the initial validation campaign over the Humber Estuary, August & September 1993. The Third report represents the major achievements of the research project; *viz.* the atmospheric correction of CASI imagery over Case 2, high sediment laden waters, the demonstration of acceptable accuracy of retrieval of water leaving radiances (a validation of the atmospheric correction procedures) and accurate retrieved values of the water constituents, SPM and Chlorophyll concentrations, as compared to concurrent measurements. A new Section 5.1 provides further validation of the procedures across the survey area for the imagery of 1 September 1996. As only limited data exist of concurrent CASI imagery and in water measurements of multi-spectral radiances, SPM and chlorophyll, these comparisons represent the extent to which validation of the NRA imagery was possible at this time.

The Fourth Report presents new imagery from Plymouth Sound and Southampton Water which demonstrate the need for atmospheric correction as a pre-cursor to deriving quantitative estimates of retrieved products, and the robustness and accuracy of the new Case 1 / Case 2 discrimination flag reported in the Revised Second and Third Reports. The imagery also illustrates some problems that have become apparent only after atmospheric correction. The report also presents a set of recommendations for the operational analysis and interpretation of CASI imagery. A single copy of a compendium of all the images supplied by the Agency (formerly the NRA) to PML throughout the period of the contract is deposited at the Environment Agency's National Centre for Environmental Data and Surveillance, Twerton. Concurrently with the submission of this report, PML is providing the complete atmospheric correction and product retrieval software suite for processing CASI imagery, (subject to an academic non-commercial licence agreement), free of charge to the Agency. The algorithms were developed and the software written at PML as part of the Coastal earth Observation Application for Sediment Transport project (COAST) funded by the British National Space Centre (BNSC), and through funding from the Environment Agency as part of the NERC Land Ocean Interaction Study (LOIS) programme.

2. THE PROBLEM OF THE ATMOSPHERE

Sensors such as CASI are essentially measuring water colour, and in theory any factor which affects water colour can, given appropriate algorithms, be derived from the image data. The major obstacle to obtaining quantitative data from remotely sensed imagery is the profound effect the varying amounts of atmosphere between the water surface and the sensor have on the intensity and spectral composition of the radiation received by the sensor. These effects are due to atmospheric scattering and absorption. Atmospheric scattering both adds radiation into and removes radiation from the path sampled by the remote sensor through two mechanisms, Rayleigh (molecular) scattering and aerosol (Mie) scattering. Rayleigh scattering is the result of radiation interacting with atmospheric molecules and is inversely proportional to the fourth power of wavelength. Thus scattering by this mechanism is strongest in the shorter blue wavelengths. Atmospheric aerosols, primarily water vapour and dust particles, are the major cause of Mie scattering which is inversely proportional to wavelength and thus tends to influence longer wavelengths compared to Rayleigh scattering. Atmospheric absorption in the visible wavelengths by water vapour and ozone results in a loss of radiation from the path sampled by the remote sensor. Atmospheric effects account for 80% to 95% of the signal detected by satellite sensors, and 65% to 85% of the signal detected by airborne sensors. The importance of atmospheric correction in obtaining quantitative estimates of that portion of the remotely sensed signal due to interaction with sea-water and its dissolved and particulate constituents, the water-leaving radiance, cannot be over-estimated.

Since the molecular composition of the atmosphere can be considered stable the calculation of the Rayleigh component, although complex, is relatively easy and accurate compared to calculation of the aerosol component. The aerosol contribution is difficult to calculate because atmospheric aerosols are highly variable, both spatially and temporally, and cannot be predicted *a priori*. The atmospheric correction problem is further complicated by the need for different correction methods for clear Case 1 waters, typified by open ocean and stratified shelf seas in which the primary factor affecting water colour is phytoplankton, and Case 2 waters, typified by coastal waters with significant concentrations of suspended particulate matter (SPM) where water colour is determined by optically active material, often of terrestrial origin, other than chlorophyll and its derivatives.

3. ATMOSPHERIC CORRECTION: THEORY AND IMPLEMENTATION

The theory for the atmospheric correction of clear Case 1 waters is well established and based on the assumption that water-leaving radiance in the near infrared (NIR) is zero due to high water absorption at these wavelengths. Thus, in the NIR, all the signals measured remotely can be assumed to originate from the atmosphere between the sensor and the target, and the aerosol component in the NIR can be obtained by subtracting the calculated Rayleigh component from the total path radiance. Extrapolation of results from the NIR to the visible wavelengths is made in order to derive water-leaving radiance in these bands. This method was developed by Howard Gordon and his colleagues at the University of Miami and because it utilises the fact that water acts as a black body in the NIR, is known as the "dark pixel" method (Gordon *et al.*, 1988; Gordon, 1993; Gordon and Wang, 1994). In coastal Case 2 waters with significant concentrations of suspended particulate material (SPM), which are a focus of interest for the NERC LOIS project and the Agency, there is significant water-leaving radiance at NIR wavelengths and the dark pixel method of atmospheric correction fails. By coupled hydro-optical and atmospheric modelling, field and laboratory measurements, researchers at PML (Bale *et al.*, 1994; Hudson *et al.*, 1994; Moore *et al.*, in press) have developed an entirely new method for atmospheric correction in Case 2 waters - the "bright pixel" method. The coupled hydrological and atmospheric optical model developed at PML is bootstrapped to a Gordon type atmospheric correction scheme to enable a seamless atmospheric correction procedure throughout the visible and NIR bands of CASI and SeaWiFS for both Case 1 and Case 2 (dark pixel and bright pixel water). Each pixel is processed initially to mask off land and cloud followed by calculation of the Rayleigh scattering component. A flag is then set based on the water reflectance at 710 ± 5 nm (corrected for Rayleigh scattering) which discriminates between Case 1 and Case 2 waters at SPM values as low as 1 mg litre^{-1} over a whole range of atmospheric aerosols. This discrimination determines which of the correction schemes - dark or bright pixel - will be used to calculate the aerosol component of the atmospheric correction procedure.

4. THE NEED FOR ATMOSPHERIC CORRECTION

An aim of remote sensing is to derive quantitative estimates of various in-water constituents (*e.g.* SPM and chlorophyll) for input into mass flux studies, environmental impact and assessment models, and to provide strategic overviews of the environment both spatially and temporally. The primary purpose of atmospheric correction is to quantify the water-leaving radiance in order to subsequently derive the concentration of SPM and chlorophyll from the remotely sensed imagery. It has been a central tenet of the remote sensing group at Plymouth Marine Laboratory that **the precision atmospheric correction of remotely sensed visible band radiances is the essential pre-requisite for the quantitative utilisation of these data.** This strongly held view is a result of the highly variable and unpredictable nature of the atmospheric aerosols, and the large effect the atmosphere has on remotely sensed imagery.

Currently, the concentration and size distribution of atmospheric aerosols can only be determined by detailed sampling and analysis of the atmosphere with specialised equipment. This is not feasible during routine remote sensing operations. Moreover, the aerosols are not predictable. This is particularly acute in coastal areas where both maritime aerosol and urban aerosol types are likely to be present in variable quantities and of variable distribution dependent on such factors as wind direction. As weather conditions can vary within a day, from day to day, and over longer time scales, it would be impossible, without atmospheric correction, to assess the influence of the atmosphere for any set of images even if all other factors such as sun and sensor angles, altitude and atmospheric pressure were identical for all the images. In other words, since the atmospheric aerosols cannot be deduced *a priori* the spatially and temporally variable effects of the atmosphere can only be quantified through atmospheric correction.. It follows from this, that there seems little possibility of deriving generalised product retrieval algorithms based on relationships between uncorrected radiance data and concurrent quantitative measurements of in-water constituents. Since atmospheric scattering and absorption are wavelength dependent (*e.g.* Rayleigh scattering - λ^{-4}; aerosol scattering - λ^{-1}) the degree of atmospheric correction will vary with wavelength. This has significant implications for product retrieval algorithms, many of which require radiance data from two or more wavelengths. The theoretical rationale of radiance band-ratio methods for determining chlorophyll *a* and other important biogeochemical parameters, and the need for these calculations to be based on precision atmospherically corrected data are detailed in Aiken *et al.* (1995).

A further practical justification for the atmospheric correction of remotely sensed imagery is provided by those images in which features become apparent only after atmospheric correction, and which can be interpreted in relation to the hydrography. Two sets of CASI images, from Plymouth Sound (Fig. 1a-c, and Fig. 2) and Southampton Water (Fig. 3a-d), will be used to illustrate this point.

The image from Plymouth Sound was collected by the NERC CASI as part of the Plymouth Atmospheric Correction Experiment (PACE) on the 16 August 1995 at 1010 GMT, 1 hour after high water. The diagrams are oriented such that south-east is at the top of the image with the River Tamar entering Plymouth Sound at the bottom of the image through the Hamoaze, the narrow waterway which separates the Millbay area of Plymouth on the left of the image from Mount Edgecumbe on the right. Drake's Island is situated just offshore of Millbay. Plymouth

Breakwater is prominent in mid-image, with Bovisand, Heybrook Bay and the Mewstone towards the top of the image. A prominent feature which is out of view but whose influence is clearly seen in the atmospherically corrected image is the River Plym which enters Plymouth Sound from the left centre of the image. Fig 1a shows the uncorrected radiance scaled to the maximum radiance value of the image, which occurs over land. Fig. 1b shows the uncorrected radiance re-scaled such that most of the land is over-scale and appears black and thus the image is essentially scaled to the uncorrected radiance over water. Both Figs. 1a and 1b show the same pattern of radiance, that is weak limb brightening particularly towards the left hand edge of the image, and with an indication of a feature at the top end of the Breakwater. Fig. 1c shows the water-leaving radiance for the same image, *i.e.* after atmospheric correction. The land has been masked black during this process. The pattern of radiance is quite different from the uncorrected image and shows features which are interpretable in terms of the bathymetry and prevailing tidal conditions. One hour after high water, high radiance water can be seen entering Plymouth Sound from the direction of the River Plym, spreading across much of the Sound and out past the end of the Breakwater. High radiance water also enters from the River Tamar but diminishes as it reaches the 35 fathom deep water of Barn Pool. In this image the Tamar water is kept separated from the major part of Plymouth Sound by the shallow reef which forms the southern edge of Barn Pool and runs from the southern edge of Drake's Island to Mount Edgecumbe. The same features are confirmed in the atmospherically corrected image shown in Fig. 2, which was taken along the same flight line at a lower altitude 48 minutes after the image in Fig. 1.

Fig. 3a-d shows the uncorrected, corrected, and the derived SPM values for a CASI image collected by the Environment Agency over Southampton Water. The image was collected on the 3 August 1995 at 1146 GMT, 4 hours after low water. The diagrams are oriented such that south is at the top of the image with the River Test entering Southampton Water at the bottom of the image, the River Itchen a third of the way up the image and the River Hamble entering just over half way up the image. This is most easily seen in Fig. 3b where the land has been masked off and appears black. After atmospheric correction Figs. 3b and 3c show in-water features that are not evident in the uncorrected image (Fig. 3a). At 600 nm (Fig. 3b) water-leaving radiance in the Rivers Test, Itchen and Hamble and much of Southampton water is low. Higher areas of water-leaving radiance occur along much of the shoreline and an area off Lee-on-Solent at the confluence of the two arms of the Solent (top of image).

In the majority of these images the band centred on 600 nm has been used for display because it usually has the highest radiance values and shows features well.

5. CASE 1 / CASE 2 DISCRIMINATION

In order to produce a seamless atmospheric correction scheme for both Case 1 and Case 2 waters it was necessary to implement a flagging procedure which determined how each pixel would be processed for aerosol scattering. Originally the Case 2 flag was set by comparison of the calculated epsilon value (ϵ) against the calculated maximum epsilon value (ϵ_{max}). This method was less robust than expected and in very turbid atmosphere the separation between Case 1 and Case 2 corresponded to SPM concentrations as high as 20 mg litre^{-1}. An arbitrary SPM value of 1-2 mg litre^{-1} is accepted by many marine scientists as the typical threshold for the separation of Case 1 and Case 2 waters. A flag based purely on the value of water reflectance, after Rayleigh correction, at 710 ± 5 nm provided a robust Case 2 flag ("bright pixel" flag) over the whole range of atmospheric aerosol types modelled. This test provided a sharper and more consistent separation of water types and showed that Case 2 water could be discriminated at SPM concentrations as low as 1 mg litre^{-1}.

In the Southampton image (Fig. 2c) the Case 1 and Case 2 areas are well defined at 865 nm (NIR). The black central portion of Southampton Water indicates the zero water-leaving radiance of Case 1 water (as predicted by theory), and the purple areas indicate the measurable water-leaving radiance of the Case 2 areas. The SPM concentration derived from the corrected imagery (Fig. 2d) follows very closely the pattern seen in the corrected image (Fig. 2c) with the lowest values (1 mg litre^{-1} or less) in the Rivers Test, Itchen and Hamble and much of Southampton Water. Higher (Case 2) levels of SPM occur along much of the shoreline and are probably due to tidal re-suspension of sediment from shallow mud banks such as the Weston Shelf near the mouth of the River Itchen and Hamble Spit at the mouth of the River Hamble. A more extensive area of high SPM concentration (up to 13 mg litre^{-1}) occurs off Lee-on-Solent at the confluence of the two arms of the Solent and Southampton Water and is also likely to be due to tidal re-suspension over the Bramble Bank. A comparison of water-leaving radiance in the NIR (Fig. 3c) with the SPM concentration (Fig. 3d) shows how the two lowest categories on the SPM scale (0-0.85, 0.86-1.70 mg litre^{-1}) follow closely the area of zero water-leaving radiance (Case 1) indicating that the "bright pixel" flag is performing satisfactorily.

6. RECOMMENDATIONS

Always atmospherically correct remotely sensed imagery prior to interpretation or retrieval of products from the data. Given the large effect the atmosphere has, and the spatial and temporal variability of atmospheric aerosols; it is impossible to know *a priori* to what extent the atmosphere is masking features in the uncorrected image which become apparent or can be quantified only after atmospheric correction.

Instrument calibration must be done to a high standard, and rigorously tested. The measurement of remote sensed radiances (water colour) by CASI are absolute measurements by a precision instrument which requires absolute calibration. The measured data comprises atmospheric signals and water-leaving radiance, so atmospheric correction is essential to retrieve the signal of interest. In the course of this work we have detected a number of CASI data sets which failed to return meaningful results from the atmospheric correction process. This indicates that more than likely, there was some error in the original data, either spectrally or radiometrically (*i.e.* absolute calibration). Since these errors are only "trapped" by the atmospheric correction process, it is essential that the quality of the data is assessed rapidly if the time and effort on their acquisition and processing is to be justified.

Operator training and operational standards should be improved. Operators should be aware that radiance over water is the measurement that must be optimised. There are a number of images with excellent imagery over land but low radiance values over water, which after atmospheric correction result in negative, zero or very low water-leaving radiance which results in a black or very dark image showing no in-water detail. This renders the corrected imagery useless. CASI must be set-up for optimisation over water not land. Whenever possible flightlines should not include land or at least minimise the amount of land in an image. Although land often provides visual confirmation of geo-location of an image, data from a GPS does this more accurately and usually in a machine readable format. A further operator problem is the incorrect recording of information on flight logs. These must be checked more rigorously as they could be the only record of navigation, date and time, altitude and f-stop information if instrument components failed.

10,000 feet is a good operational altitude at which to deploy CASI. However, pilots should be prepared to fly under high cloud and haze as conditions dictate, and operators should be familiar with how to, and recognise when to, adjust integration time accordingly.

Some problems may be overcome by changing from the 80° lens angle to a lower one. The operational advantage of using a wide lens angle to monitor the coastal zone out to the 3 mile limit is accepted. However, it is a fact that the 80° lens angle increases both limb brightening and susceptibility to sun glint. Changing to a lower lens angle (*e.g.* 42°) for gathering of critical data is recommended, and should be considered in relation to the operational advantages/disadvantages for routine survey work.

7. CONCLUSIONS

This fourth report represents the conclusion of a research study performed by PML for the Agency on the "Development of Airborne Remote Sensing Techniques". It has demonstrated that atmospheric correction, using the novel algorithms and the software developed at PML, is a valid methodology for both Case 1 and Case 2 waters. Many CASI images from diverse coastal environments (Humber, Plymouth, Aberdovey) have been analysed which, after atmospheric correction, show good discrimination of Case 1 and Case 2 waters, show in-water features which are not apparent in uncorrected imagery and which are interpretable in relation to the hydrography of the area, show that the correction process gives very similar water-leaving radiance values for simultaneous different height flights, and provides derived SPM and chlorophyll concentrations which are in close agreement with contemporaneously measured *in situ* values of SPM and chlorophyll. These achievements now make possible the quantitative study of coastal waters by remote sensing, an hitherto intractable problem.

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9. APPENDIX A : IMAGES

Fig. 1. PACE 3 (c22801) Plymouth Sound

Altitude 3000m Top of image: South-east 600nm (Band 5)

(a) Uncorrected radiance (b) Re-scaled uncorrected radiance

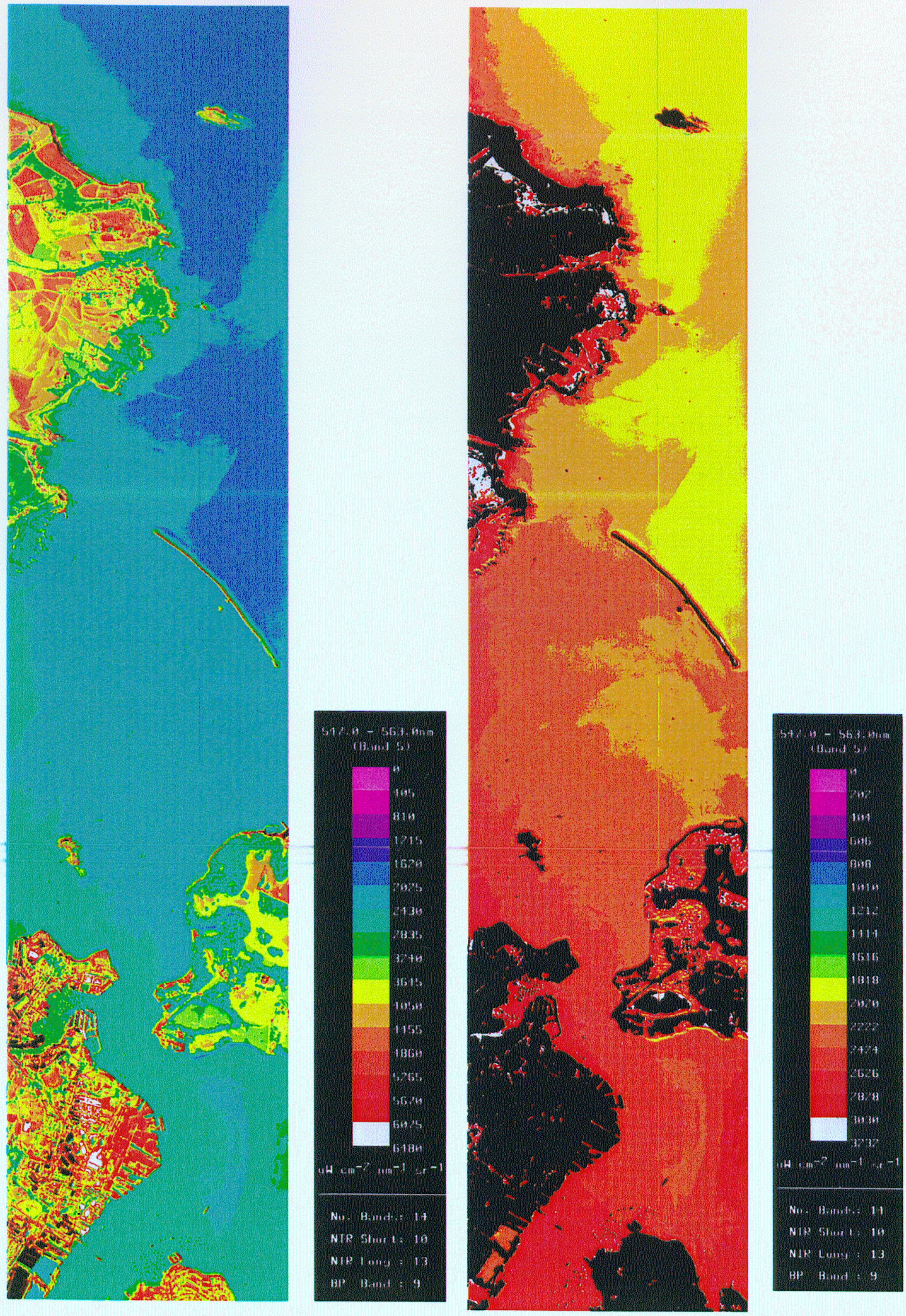


Fig. 1. (continued)

(c) Water-leaving radiance

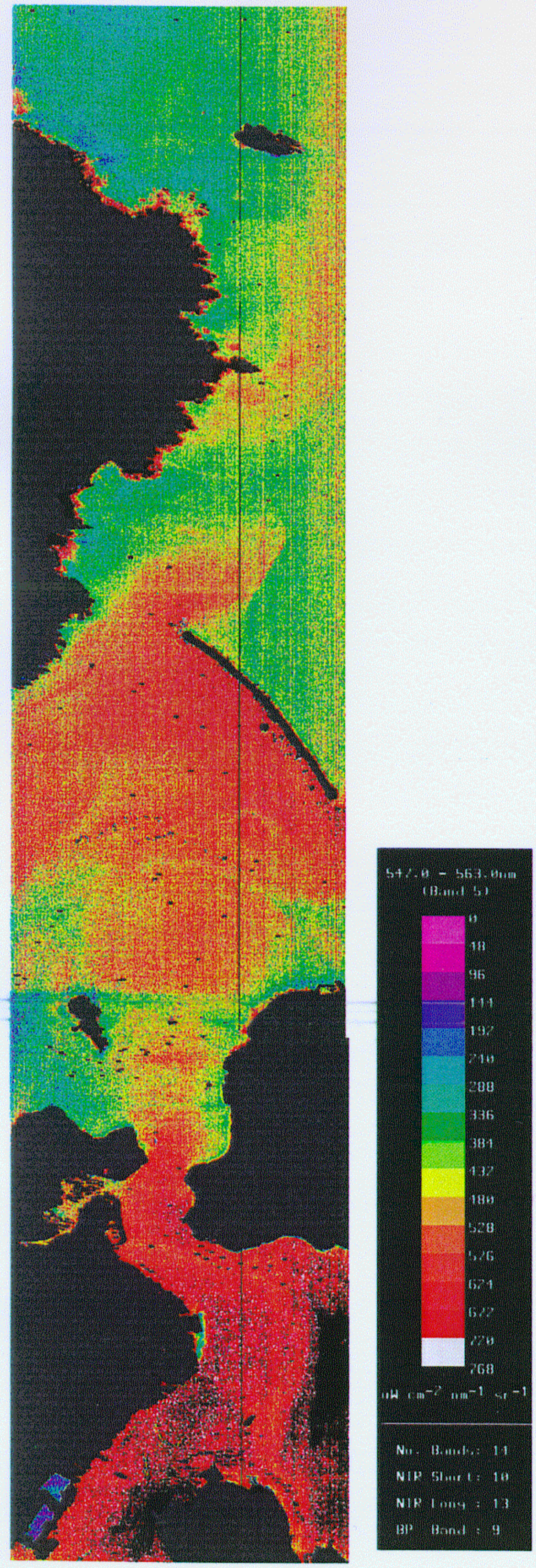


Fig. 2.

c22805 (PACE 3)

Plymouth Sound.

1500 m

Top of image:
South-east.

Water leaving radiance

600 nm (Band 5)

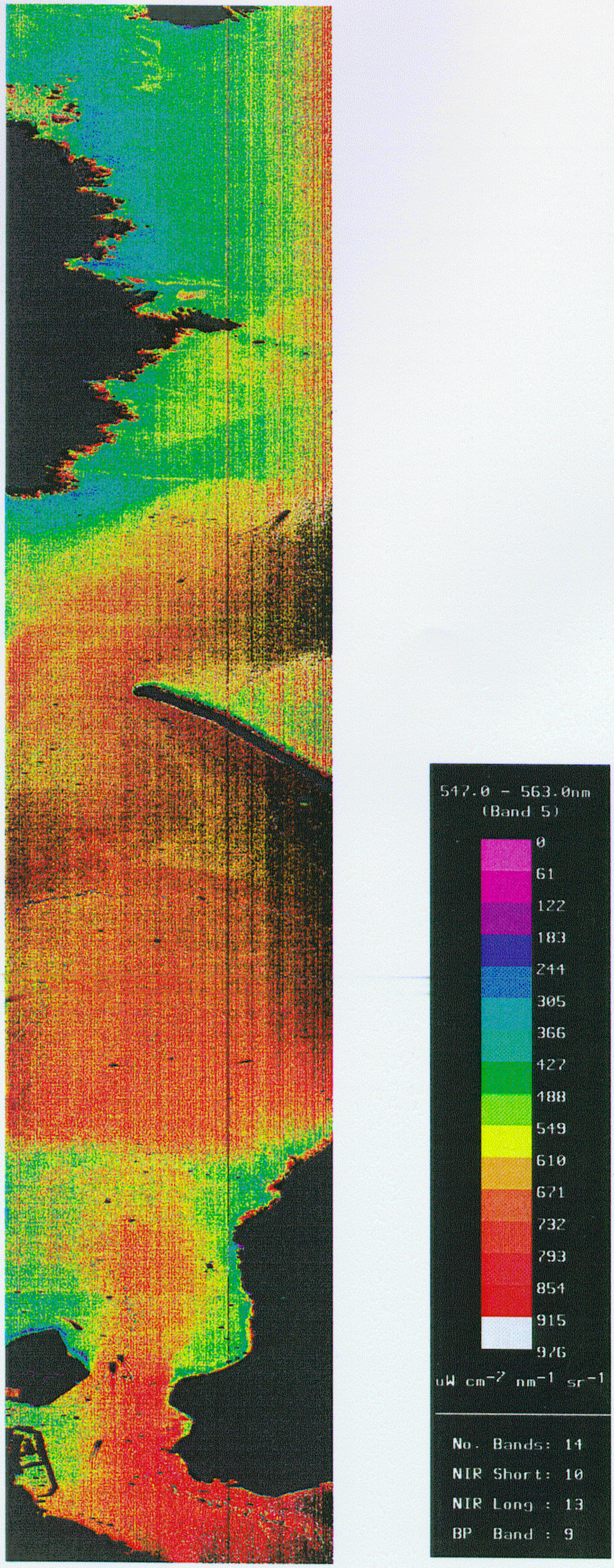


Fig. 3a

imag1304

Southampton Water.

Top of image: South.

Total uncorrected radiance.

600 nm (Band 5)

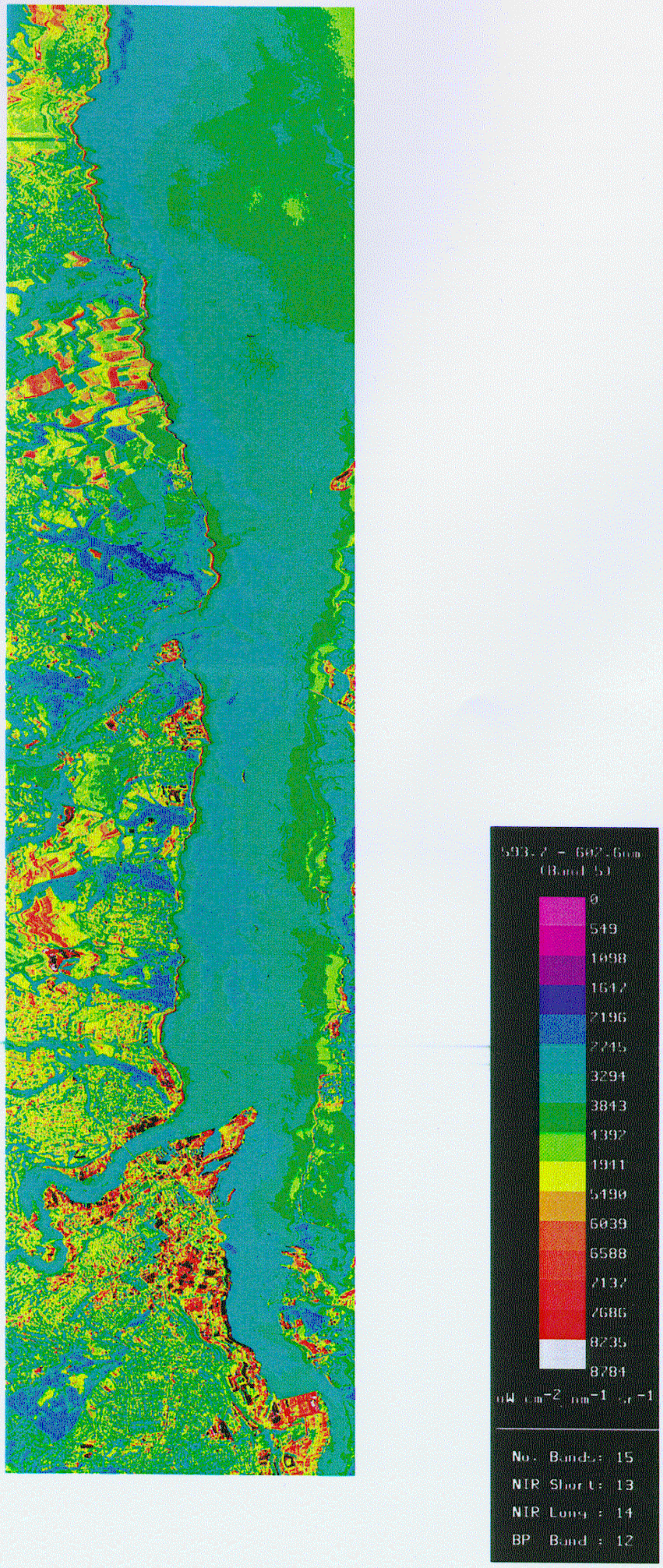


Fig. 3b

imag1304

Southampton Water.

Top of image: South.

Water leaving radiance

600 nm (Band 5)

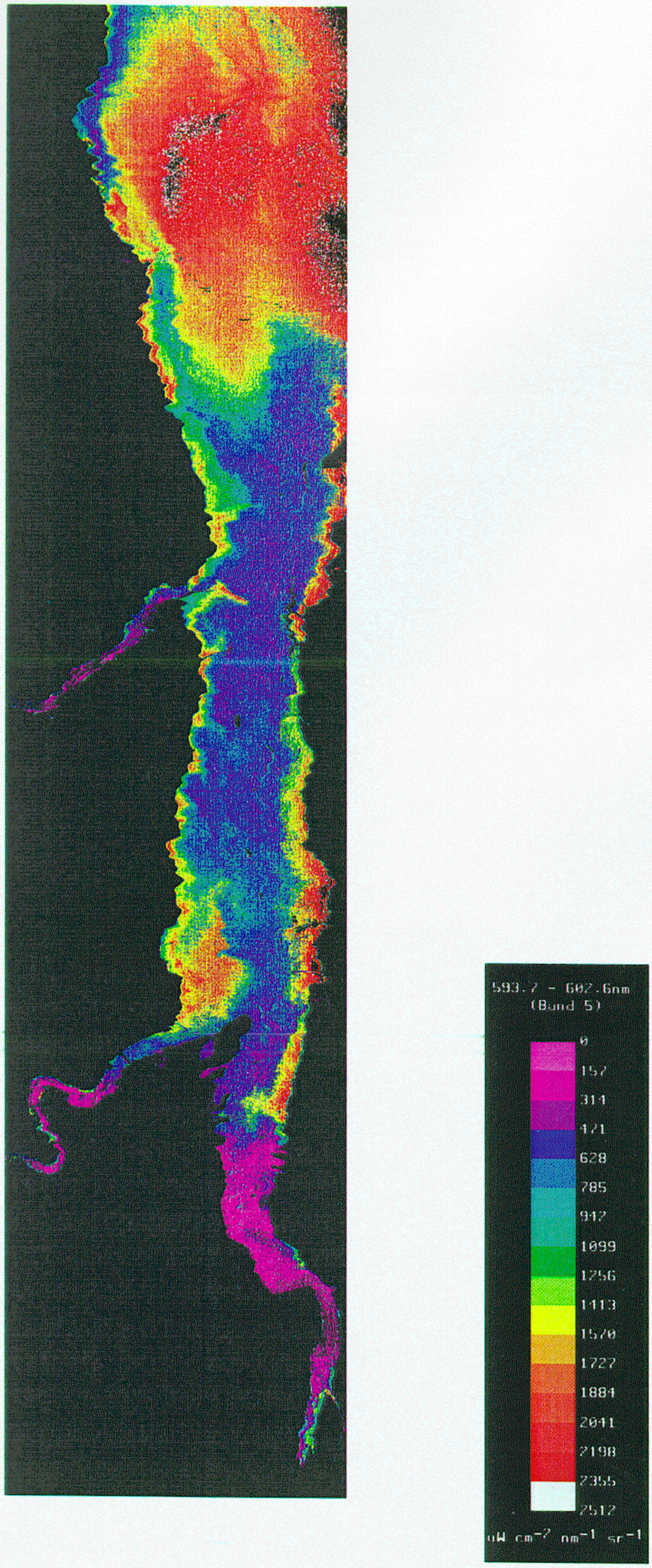


Fig. 3c

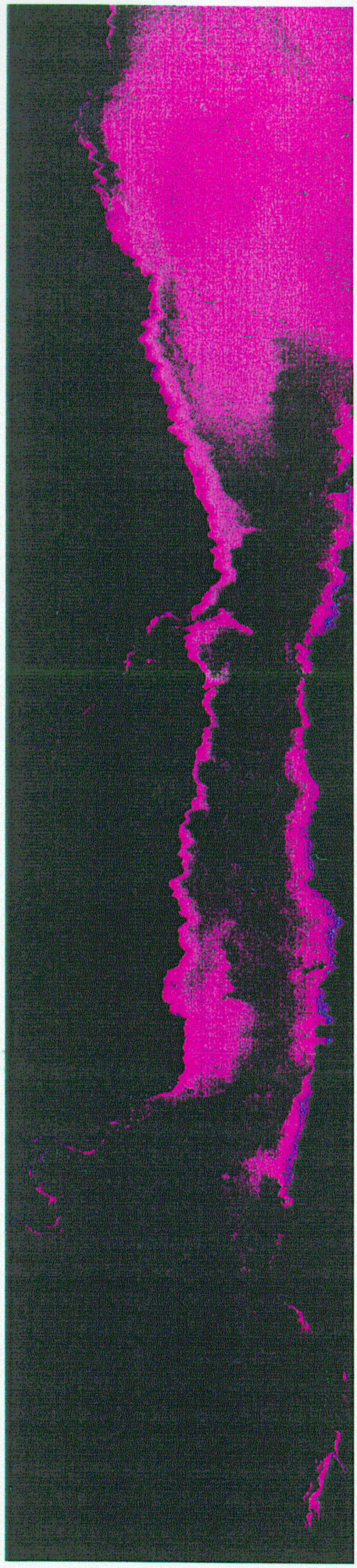
imag1304

Southampton Water.

Top of image: South.

Water leaving radiance

865 nm   (Band 14)



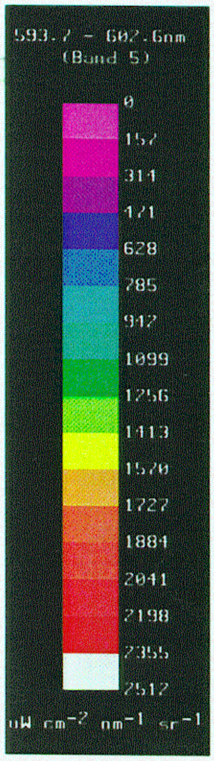


Fig. 3d

imag1304

Southampton Water.

Top of image: South.

SPM concentration.