

Mapping coastal waters with high resolution imagery: atmospheric correction of multi-height airborne imagery

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Abstract

Remote sensing is a tool that can provide an increasing number of environmental properties over a range of spatial and temporal ranges. In coastal and estuarine studies, variability (physical, biological and optical) can occur over high spatial and temporal scales, and at present airborne sensors are the most appropriate platforms for such observations. The compact airborne spectrographic imager was flown over the Plymouth Sound area as part of the 1995 Plymouth atmospheric correction experiment. An atmospheric correction scheme has been developed and preliminary results are presented.

Keywords: Remote sensing, atmospheric correction, ocean colour, CASI, coastal

1. Introduction

Coastal ecosystems are influenced by turbid water distributions composed of terrigenous particles that affect the light penetration and hence productivity (through the phytoplankton concentrations and therefore photosynthesis). Therefore, suspended particulate matter (SPM) distributions and properties are valuable indices that can be used to describe physical marine systems with investigations of sediment movement dynamics needed for effective estuarine/coastal zone management practice, e.g. regulation of activities such as dredging.

The Plymouth Sound area has been the focus of much attention (e.g. Morris *et al* (1982), Pilgrim and Millward (1989), Fitzpatrick (1990)) with numerous optical and biogeochemical studies extending from the Plym and Tamar estuaries to beyond the Eddystone Lighthouse (around 5 km offshore). Previous fieldwork carried out in the Tamar Estuary, during the 1980s and early 1990s (e.g. Uncles and Stephens (1996)) indicated that there were strong seasonal variations in the shape and volume of inter-tidal areas. However, these observations were largely visual and so further research

was needed to produce quantitative rather than qualitative assessments.

The mapping of an estuary as opposed to coastal or oceanic features requires sensors with high spatial and temporal resolutions, as the water movements (particularly in UK estuaries) can be very rapid. Cracknell (1999) argued that earth observation has been far less successful in the shallow coastal zone compared to the deep ocean and atmosphere, in part because of limited scanner resolution and image frequency that have prevented observation of the relevant scales in shelf seas and estuaries.

Airborne remote sensing (ARS) can provide quantitative large-scale maps of SPM concentration and distribution throughout an estuary. Airborne rather than satellite remote sensing can be used because the current ocean colour sensors, e.g. the sea-viewing wide field-of-view sensor (SeaWiFS), have a limited spatial resolution (around 1 km) and the current land sensors have a limited radiometric resolution and wavebands. However, there are distinct disadvantages to airborne as opposed to satellite based sensors. The platform has greater instability, so there is a need for an accurate positioning system (Wilson 1997). The platform is within

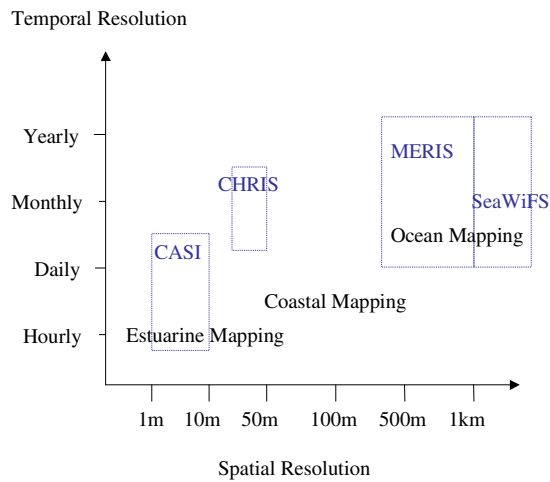


Figure 1. An inter-comparison of the ocean colour remote sensing sensors that can be used for studying phenomena of different spatial and temporal scales.

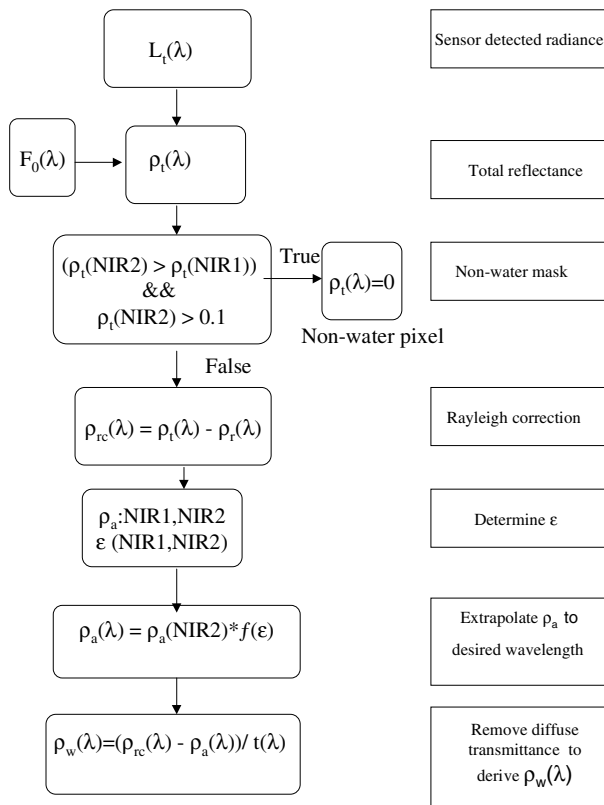


Figure 2. CASI AC scheme.

the atmosphere, so the atmospheric correction (AC) is more complex as the downwelling solar irradiance at the aircraft's altitude has been modified by the atmosphere.

Figure 1 shows an inter-comparison of the ocean colour satellite remote sensing sensors that can be used for studying phenomena of different spatial and temporal scales. The compact high resolution imaging spectrometer (CHRIS), launched on board the Project for On-Board Autonomy (PROBA) small satellite in October 2001, has a spatial resolution of up to 25 m

Table 1. CASI specifications.

| Channel | Centre wavelength (nm) | Channel | Centre wavelength (nm) |
|-------------------|------------------------|----------------------|------------------------|
| 1 | 412.134 | 8 | 682.064 |
| 2 | 443.51 | 9 | 710.747 |
| 3 | 490.025 | 10 | 750.281 |
| 4 | 509.678 | 11 | 769.207 |
| 5 | 554.312 | 12 | 822.549 |
| 6 | 620.368 | 13 | 864.402 |
| 7 | 668.638 | 14 | 893.627 |
| Quantization bits | | 10 bits | |
| Altitude | | 5000 and 10 000 feet | |
| FOV | | 42° | |
| Swathe | | 512 pixels | |

(<http://www.chris-proba.org.uk/>). The medium resolution imaging spectrometer (MERIS) will be launched on board the ENVISAT platform in 2002 and will have a spatial resolution of 300 m in European coastal waters (<http://envisat.esa.int/>).

The remote sensing of SPM is complicated by its variable character: particle size has a large influence on backscattering; and the colour is influenced by the biological and chemical composition (Bunt *et al* 1999, Jago and Bull 2000). This has often been addressed by the use of site- (and often time-) specific algorithms. However, time-series ocean colour data of coastal and shelf sea regions is important as these areas are often very productive economically (in terms of fisheries, aquaculture and leisure activities) and vulnerable ecologically (to anthropogenic nutrient inputs, accidental contamination from industrial activities and blooms of toxic phytoplankton).

2. PACE atmospheric correction methodology

The coastal waters surrounding Plymouth (in this case classified as the Tamar Estuary, Plymouth Sound and coastal waters out to the Eddystone Lighthouse) were the focus of the PACE multi-aircraft ARS campaign in 1995 (Lavender *et al* 1996). PACE included the collection of *in situ* data, environment agency (EA) compact airborne spectrographic imager (CASI) imagery, Natural Environment Research Council (NERC) CASI imagery and Meteorological Research Flight data. After an initial analysis, the data was archived while awaiting the NERC CASI data. This was supplied in 2000 and the data are now being analysed.

CASI is a programmable imaging spectrometer that is capable of high spectral and spatial resolution (Anger *et al* 1990). It can operate over a 430–870 nm wavelength range, with a spectral resolution of 2.8–2.9 nm, and can have a spatial resolution of 2–10 m, depending on aircraft altitude. In PACE, the NERC CASI system was flown at altitudes of 10 000 and 5000 feet with a band set of 14 wavebands (see table 1) that were designed to match up to SeaWiFS (Lavender *et al* 1996).

AC, the removal of the absorbing or scattering effects of the atmosphere that mask the water signal, is essential for the accurate retrieval of the ocean signal. Correction techniques for case I waters (e.g. Gordon (1997)) are well established and generally rely on the assumption of zero or near-zero (Siegel *et al* 2000) water-leaving radiance in the near-infrared (NIR). However, in turbid coastal waters the zero

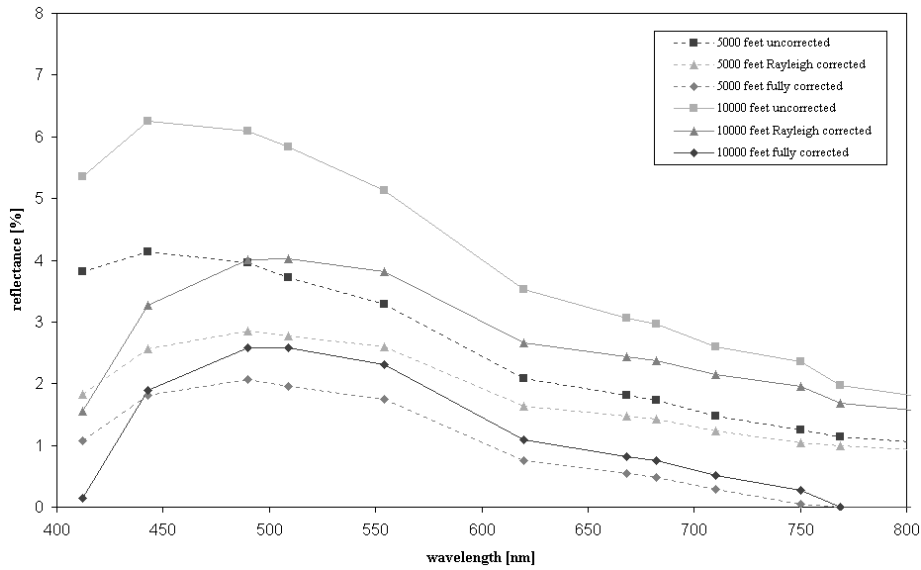


Figure 3. Initial results from CASIDAS showing an extracted spectral pixel from the Rame Head end of the Rame Head to Eddystone flightlines at 10 000 and 5000 feet.

NIR water radiance assumption is invalidated by the additional particulate scattering due to SPM and has been described as ‘bright pixel’ (Moore *et al* 1999, Siegel *et al* 2000). A number of case II approaches have been proposed: however, subjective approaches (Ruddick *et al* 2000) are not realistic for automated processing and may be limited by the assumption that aerosol properties are constant over a few 100 km.

By flying CASI at several altitudes over a short period of time, AC models can be validated by comparing the derived water-leaving reflectance at the same location, but with different plane altitudes. The methodology can also be applied to satellite data if there are suitable cloud-free conditions, but no ocean colour sensors were operational in 1995. Overflights occurred at altitudes of 2000, 5000 and 10 000 feet to investigate the vertical atmospheric structure, with this paper concentrating on the 5000 and 10 000 feet flightlines flown over predominantly low SPM waters between Rame Head and the Eddystone.

The CASI AC (see figure 2) is based on the methodology developed by Lavender (1996) from Guzzi *et al* (1987) and the software that has been used operationally for SeaWiFS (Lavender and Groom 1999) and has been developed for MERIS (Moore *et al* 1999). The case I AC takes the total sensor detected reflectance, $\rho_t(\lambda)$, at the aircraft altitude and splits it into the total atmospheric path reflectance, $\rho_{atm}(\lambda)$, and the desired water-leaving reflectance, $\rho_w(\lambda)$, where $t(\lambda)$ is the diffuse transmittance:

$$\rho_t(\lambda) = \rho_{atm}(\lambda) + t(\lambda)\rho_w(\lambda). \quad (1)$$

The atmospheric path reflectance is then split into the aerosol, $\rho_a(\lambda)$, and Rayleigh path reflectance, $\rho_r(\lambda)$, according to equation (2):

$$\rho_{atm}(\lambda) = \rho_a(\lambda) + \rho_r(\lambda). \quad (2)$$

A non-water mask is then used to discard the land and cloud pixels (see figure 2). The mask is based on the threshold values at two NIR wavelengths, NIR1 and NIR2, which equate to

864 and 769 nm in the PACE CASI imagery. Any further computations are then only applied to the water pixels.

The Rayleigh scattering reflectance was computed using the well established theory (Cornette and Shanks 1992). At present the Rayleigh correction does not attempt to use actual meteorological values, but climatological values: atmospheric pressure of 1013.25 mbar; water vapour concentration of 2 g cm^{-2} ; ozone concentration of 0.33 atm cm. However, the correction does account for the across-swath variation in the view angle. The Rayleigh-corrected reflectance is calculated by subtracting the Rayleigh reflectance from the total sensor detected radiance (equation (3)):

$$\rho_{rc}(\lambda) = \rho_t(\lambda) - \rho_r(\lambda). \quad (3)$$

For the case I assumption, the NIR channels water-leaving radiance is then assumed to be near zero (Gordon *et al* 1981) and the effect of sun glitter is currently neglected. Equation (1) can then be rewritten to give equation (3) when the Rayleigh reflectance is subtracted:

$$\rho_{rc}(\lambda > 700 \text{ nm}) = \rho_a(\lambda). \quad (4)$$

The aerosol path reflectance can then be calculated for NIR wavelengths ($>700 \text{ nm}$) according to Gordon and Wang (1994), who proposed an exponential relationship for the spectral behaviour of aerosol optical depth. The visible water-leaving reflectance ($\lambda < 700 \text{ nm}$) was then estimated according to equations (5) and (6):

$$\rho_w(\lambda) = \left[\rho_{rc}(\lambda) - \rho_a(\text{NIR2}) \right] \times \exp\left(\frac{(\lambda - \lambda(\text{NIR2}))}{(\lambda(\text{NIR1}) - \lambda(\text{NIR2}))} \log(\varepsilon)\right) t(\lambda)^{-1} \quad (5)$$

$$\varepsilon = \frac{\rho_a(\text{NIR1})}{\rho_a(\text{NIR2})}. \quad (6)$$

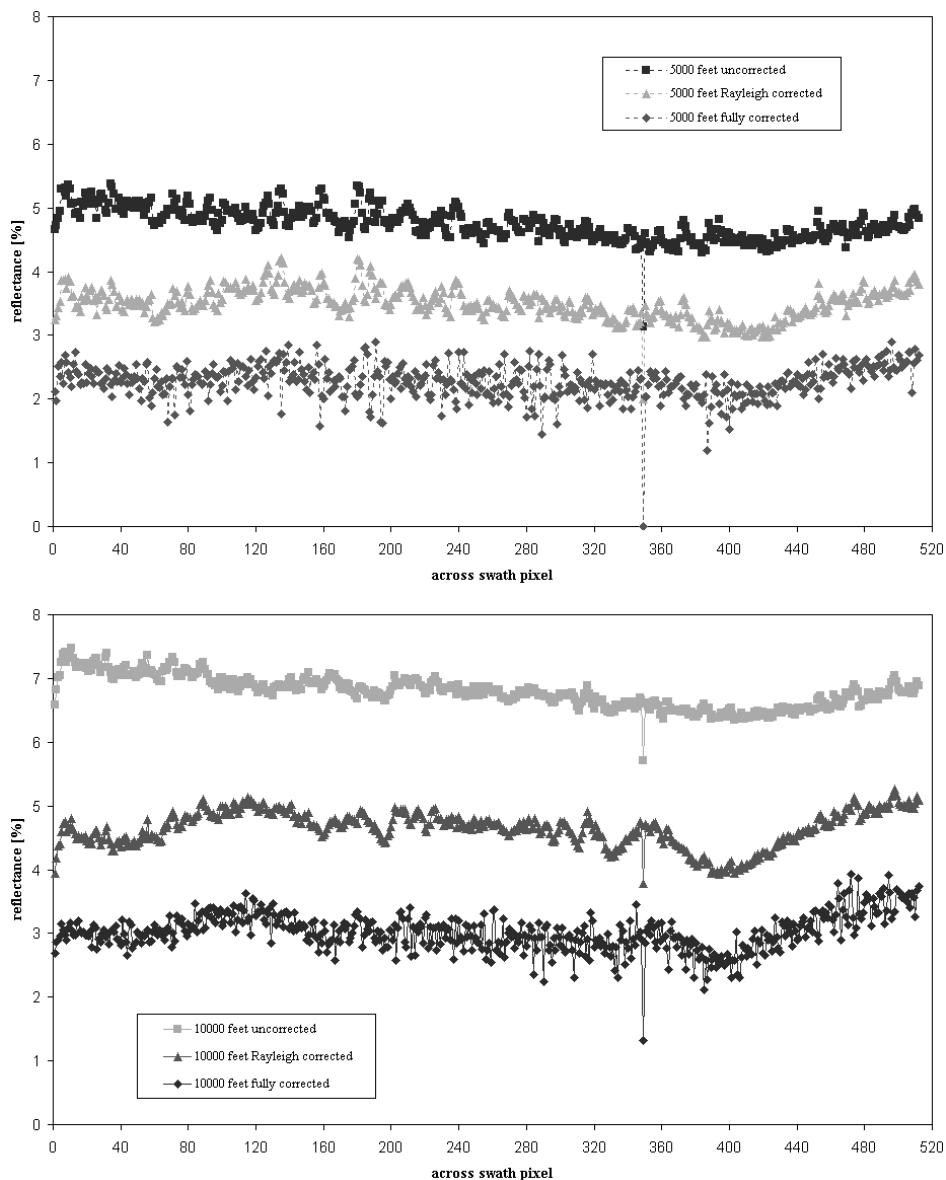


Figure 4. Initial results from CASIDAS showing the 490 nm pixels extracted across the swathe from the Rame Head end of the Rame Head to Eddystone flightlines at (top graph) 5000 and (bottom graph) 10000 feet.

3. Preliminary results from PACE

Figures 3 and 4 show some preliminary quantitative results from the CASI data analysis software (CASIDAS). The spectra (figure 3) and across-swath line data (figure 4) were extracted from the Rame Head end of the Rame Head to Eddystone flightlines at 10000 and 5000 feet (see figures 5 and 6). The uncorrected spectra (figure 3) and line of across-swath pixels for the 490 nm wavelength (figure 4(a)) show the higher uncorrected reflectance values for the higher (10000 feet) flightline. Figure 4 also shows the increasing atmospheric reflectance at the edge of the swathe caused by field-of-view geometry (a slightly longer path length through the atmosphere). The atmospherically corrected spectra (figure 3) and line of across swath pixels for the 490 nm wavelength (figure 4) show that a large proportion of the uncorrected imagery was atmospheric reflectance and that the data from

two flightlines is similar after the AC. At this stage (preliminary analysis) the corresponding distance from Rame Head for the two flightlines was estimated, and so the two sets of extracted data do not represent exactly the same region.

Figure 5 shows the uncorrected (490 nm waveband), non-water mask and atmospherically corrected (490 nm waveband) CASI imagery from the Rame head end of the 5000 and feet Rame Head to Eddystone flightline. Figure 6 shows the same, but for the 10000 feet flightline.

The 5000 feet flightline (figure 5) shows a significant proportion of glitter from long water waves in the uncorrected imagery, and a vessel with a long wake. The non-water mask detected the vessel and land, and the glitter failed the AC. It is also apparent from the corrected image that the charge-coupled detector (CCD) array is demonstrating some across-swath differences in the pixel-to-pixel calibration, with vertical stripes appearing in the processed image. Across swath

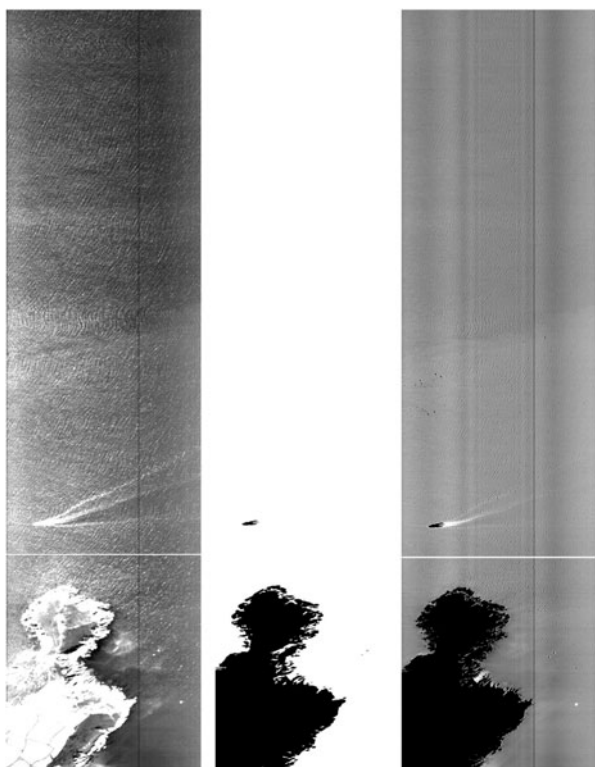


Figure 5. From left to right the images are of the uncorrected (490 nm waveband), non-water mask (black indicates the pixels that were masked) and atmospherically corrected (490 nm waveband) CASI imagery from the Rame Head end of the 5000 feet Rame Head to Eddystone flightline. The imagery was flown at 11:34 on 9 August 1995 at a pixel resolution of approximately 3 m and heading of 13°. The white dot to the right of Rame Head (bottom of the image) and white line just above Rame Head indicate where the pixel (spectral values in figure 3) and swathe line (figure 4) were extracted from.

pixel 349 (also seen in figure 4) had very low initial spectral values throughout the image and failed the AC.

The 10 000 feet flightline (figure 6) has again been successfully masked, so that the land was not processed, and also shows the same pixel–pixel striping and problem with pixel 349. However, the glitter was not so evident at the higher altitude.

4. Outlook

In the future, inputs to the AC model will also include the downwelling light at the aircraft altitude (from the instantaneous light sensor on the NERC aircraft) and atmospheric parameters (such as the surface pressure and relative humidity) which are available from either the automatic weather station at the University of Plymouth or global SeaWiFS ancillary data.

Further multi-height flightlines were undertaken by NERC in August 2001 and will occur in 2002 as part of the CHRIS-PROBA validation project, which will allow the comparison of multi-height CASI and satellite ocean colour imagery. These data sets also cover the Tamar estuary, which is predominantly case II sediment dominated, and so the additional ‘bright pixel’



Figure 6. From left to right the images are of the uncorrected (490 nm waveband), non-water mask (black indicates the pixels that were masked) and atmospherically corrected (490 nm waveband) CASI imagery from the Rame Head end of the 10 000 feet Rame Head to Eddystone flightline. The imagery was flown at 11:55 on 9 August 1995 at a pixel resolution of approximately 6 m and heading of 19°. The white dot to the right of Rame Head (bottom of the image) and white line just above Rame Head indicate where the pixel (spectral values in figure 3) and swathe line (figure 4) were extracted from.

component of the AC will be required as the assumption of zero water-leaving radiance in the NIR will become invalid.

An SPM algorithm is being developed with SeaWiFS validation data (Lavender *et al* 1998) and from previous algorithms applied to CASI imagery (e.g. Morris and Youngs (1997) and Robinson *et al* (1998)). The algorithm will be designed so that it is portable to other locations, but the validity will need to be assessed. A geometric correction (Wilson 1997) will be applied after the SPM algorithm so that the results can be combined with other datasets using a geographical information system (GIS).

5. Summary

Preliminary results from CASIDAS are encouraging with the spectral and across-swathe plots (figures 3 and 4) showing the expected decrease in reflectance as the atmospheric Rayleigh and aerosol contributions are removed. However, this needs further validation with additional CASI datasets and *in situ* measurements of reflectance.

The atmospherically corrected imagery highlight features, such as fronts and turbidity variations, which are not easily evident in the uncorrected imagery (figures 5 and 6). The non-water mask has also worked well in removing land pixels, but has still to be tested in its ability to remove cloud pixels. The next stage is to apply biogeochemical algorithms so that quantitative parameters such as SPM can be derived.

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References

- Anger C D, Babey S K and Adamson R J 1990 A new approach to imaging spectroscopy *Imaging Spectroscopy of the Terrestrial Environment Proc. SPIE* **1298** ed G Vane 72–86
- Bunt J, Larcombe P and Jago C F 1999 Quantifying the response of optical backscatter devices and transmissometers to variations in suspended particulate matter (SPM) *Cont. Shelf Res.* **19** 1199–220
- Cornette W M and Shanks J G 1992 Physically reasonable analytic expression for the single-scattering phase function *Appl. Opt.* **31** 3152–60
- Cracknell A P 1999 Remote sensing techniques in estuaries and coastal zones—an update *Int. J. Remote Sens.* **20** 485–96
- Fitzpatrick F 1990 The use of airborne thematic mapper data in the correlation of surface waters and sedimentary environments; Plymouth sound *Proc. NERC Symp. on Remote Sensing* (Swindon: Natural Environment Research Council) pp 235–47
- Gordon H R 1997 Atmospheric correction of ocean color imagery in the earth observing system era *J. Geophys. Res.* **102** 17081–106
- Gordon H R and Clark D K 1981 Clear water radiances for atmospheric correction of coastal zone color scanner imagery *Appl. Opt.* **20** 4175–80
- Gordon H R and Wang M 1994 Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm *Appl. Opt.* **33** 443–52
- Guzzi R, Rizzi R and Zibordi G 1987 Atmospheric correction of data measured by a flying platform over the sea: elements of a model and its experimental validation *Appl. Opt.* **26** 3043–51
- Jago C F and Bull C F 2000 Quantification of errors in transmissometer-derived concentration of suspended particulate matter in the coastal zone: implications for flux determinations *Mar. Geol.* **169** 273–86
- Lavender S, Froidefond J, Herbland A, Laborde P and Lafon V 1998 SeaWiFS data interpretation in relationship with in situ measurements in a coastal area *Oceans 98 (Nice, France)* (Piscataway, NJ: IEEE)
- Lavender S, Westbrook A, Moore G and Bottrell H 1996 Plymouth atmospheric correction experiment (PACE) *Proc. 22nd Annual Conf. of the Remote Sensing Society (Durham, UK)* ed D N M Donoghue and Y Zong (Nottingham, UK: Remote Sensing Society) pp 309–16
- Lavender S J 1996 Remote sensing of suspended sediment *PhD Thesis* Institute of Marine Studies, University of Plymouth and in collaboration with Plymouth Marine Laboratory
- Lavender S J and Groom S B 1999 The SeaWiFS automatic data processing system (SeaAPS) *Int. J. Remote Sens.* **20** 1051–6
- Moore G F, Aiken J and Lavender S J 1999 The atmospheric correction of water colour and the quantitative retrieval of suspended particulate matter in case II waters: application to MERIS *Int. J. Remote Sens.* **20** 1713–33
- Morris A W, Bale A J and Howland R J M 1982 Chemical variability in the Tamar estuary, Southwest England *Estuarine Coastal Shelf Sci.* **14** 649–61
- Morris K P and Youngs K 1997 The use of airborne remotely sensed data in the determination of water quality within the coastal zone *Proc. 3rd Int. Airborne Remote Sensing Conf. (Copenhagen)* ed N Wallman (Ann Arbor, MI: Environmental Research Institute of Michigan) pp 118–25
- Pilgrim D A and Millward G E 1989 Variation in the diffuse optical depth of the bed of a tidal estuary *Developments in Estuarine and Coastal Study Techniques* ed J McManus and M Elloit (Fredensborg, Denmark: Olsen and Olsen)
- Robinson M C, Morris K P and Dyer K R 1998 Deriving fluxes of suspended particulate matter in the Humber estuary, UK, using airborne remote sensing *Mar. Pollut. Bull.* **37** 155–63
- Ruddick K G, Ovidio F and Rijkeboer M 2000 Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters *Appl. Opt.* **39** 897–912
- Siegel D A, Wang M H, Maritorena S and Robinson W 2000 Atmospheric correction of satellite ocean color imagery: the black pixel assumption *Appl. Opt.* **39** 3582–91
- Uncles R J and Stephens J A 1996 Seasonal variations of fine sediment in the Tamar Estuary *Archiv Hydrobiol.* **47** 411–4
- Wilson A K 1997 An integrated data system for airborne remote sensing *Int. J. Remote Sens.* **18** 1889–901