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An integrated submersible fluorometer/nephelometer/transmissometer: design and testing at sea

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This paper describes a new submersible instrument which makes simultaneous measurements of chlorophyll fluorescence, beam attenuation and wide-angle scattering using a single xenon flashlamp as the light source. Cross-calibration against single-parameter commercial instruments shows satisfactory linear correlations, comparable resolution and enhanced dynamic range. The instrument package includes microprocessor control of data acquisition and a rechargeable battery pack. It is capable of acquiring high-resolution vertical profiles when deployed from a ship, or bio-optical time series from moorings. Results are presented here from initial deployments in inshore waters and in a deck tank at sea.
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KEYWORDS: marine monitoring, submersible instrumentation, ocean optics

Introduction

Optical measurements have significant advantages for environmental monitoring. They can be made directly on the surrounding water without the need for sample abstraction or consumption of reagents, they have relatively low power requirements, and the instrumentation can be mechanically robust with no moving parts[1]. Moreover, submersed optical instruments can provide ground-truthing for satellite images and also complementary data in the form of depth profiles and time series[2,3]. Indeed, unravelling the relationship between satellite images, *in situ* optical properties and concentrations of suspended materials is a major goal of contemporary optical oceanography[4]. It is therefore unfortunate that many of the quantities actually required in environmental monitoring (such as phytoplankton population density, mass of suspended detrital material, and resuspended sediment loadings) are only ambiguously related to any single bulk optical property[5]. For example, optical attenuation measured by transmissometry could be due to absorption by dissolved colouring matter, scattering by suspended inorganic particulates, absorption and scattering by phytoplankton cells, or any combination of these factors. Much of this ambiguity can be removed by measuring other optical parameters simultaneously. Thus, nephelometry reveals the presence or absence of particulate material, and the addition of fluorometry indicates whether the particles contain chlorophyll. This multiparameter approach has proved immensely fruitful in the analysis of single phytoplankton cells by flow cytometry[6], and one of the main reasons for constructing the present instrument was to investigate its applicability to bulk optical measurements of the marine environment.

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Instrument design and construction

The apparatus consists of three optical sensors (fluorometer, nephelometer and transmissometer) with supporting sub-systems including microprocessor controller, data storage, power supplies and a submersible housing. The optics and electronics are housed in one waterproof chamber and the batteries in a second. The two chambers can be coupled for integrated deployment (Fig. 1), but it is also possible to use the optics/electronics module on its own. Power can then be drawn from a larger capacity battery (on a buoy for example) or from a purpose-built low-voltage supply (in the laboratory or on the deck of a ship). Key aspects of the design are considered in more detail below.

Flashlamp, high-voltage supply and triggering electronics

The light source is an EG&G FX20 short-arc pulsed xenon flashlamp with a Flashpac trigger unit and encapsulated EG&G Pulsepac 600 V power supply. A 1 μF discharge capacitor is used, producing a light pulse of 5 μs duration. The entire lamp and high-voltage assembly is housed in a grounded aluminium container

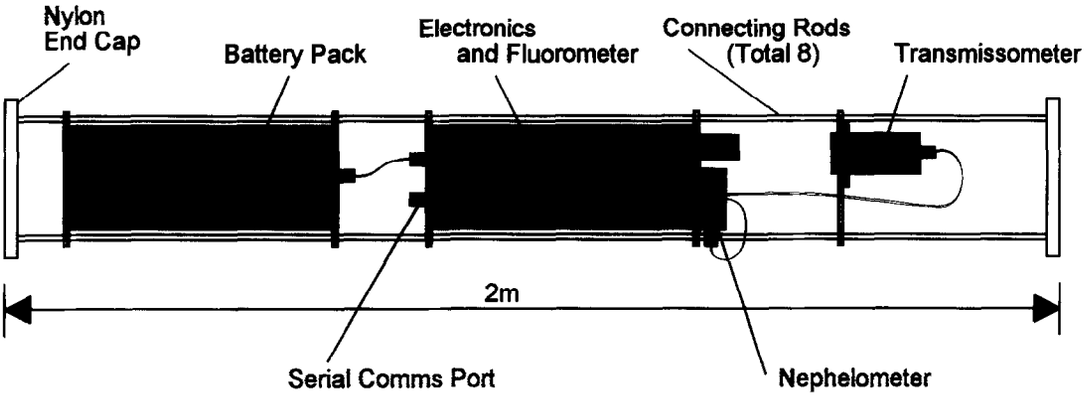

Fig. 1 The complete instrument package, showing the main modules assembled with a cage of stainless steel connecting rods

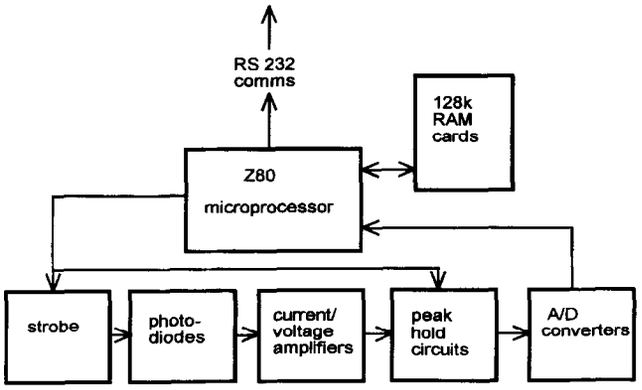

Fig. 2 Schematic diagram of the electronics for instrument control and data logging

with an opto-isolated input receiving logic-level trigger pulses from the microprocessor system.

Detectors and data logging

There are four detection channels, three for the optical measurements and one for monitoring the flashlamp output. 5 mm^2 silicon photodiode detectors have proved to be sensitive enough for detecting all the signals, including fluorescence: photomultipliers were not required. Optical signals are converted to voltage pulses which are passed to resettable peak detectors, and simultaneous analogue/digital conversion of the peak heights is carried out using four converters operating in parallel.

The microprocessor system used for data logging and control was specifically designed and constructed for this project (Fig. 2). It consists of a C-MOS Z80 microprocessor running at 1 MHz, a 16k EPROM for the operating program, 16k of non-volatile RAM for temporary data storage and additional 128k battery-backed RAM cards for expandable data logging capacity. There is a real-time clock and a separate system, based on a ST62E20 microcontroller, for managing shutdowns between logging events. The microprocessor controls the flashlamp as well as the data digitizing and logging process, and transfers data files to a PC through an RS232 output port at 2400 baud. The strobe is fired in pulse trains of predetermined spacing (usually five pulses at one second intervals followed by an adjustable pause period). At the end of each program cycle, the system checks for a connection on the RS232 port: if the presence of a communicating computer is confirmed by a software handshake, data can be downloaded for further analysis.

Instrument optics

The overall optical layout is illustrated in Fig. 3. Light from the flashlamp is collimated, filtered to remove wavelengths above 490 nm, passed through a dichroic beam-splitter and focused to an approximately 1.5 mm

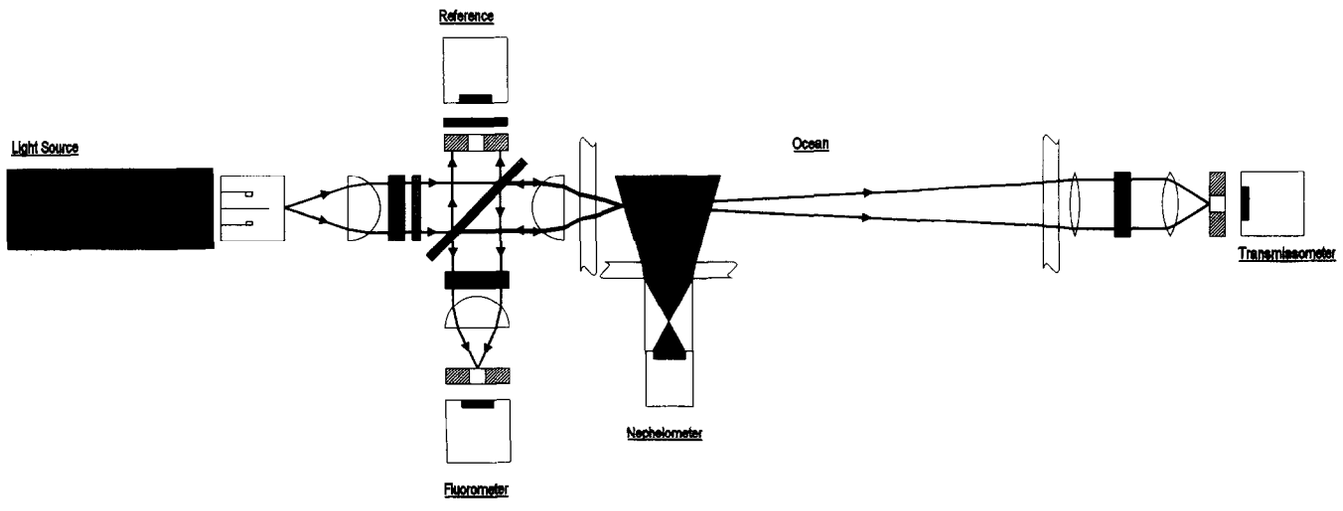

Fig. 3 Overall layout of the optical paths. Note that the fluorometer works in an epifluorescence configuration

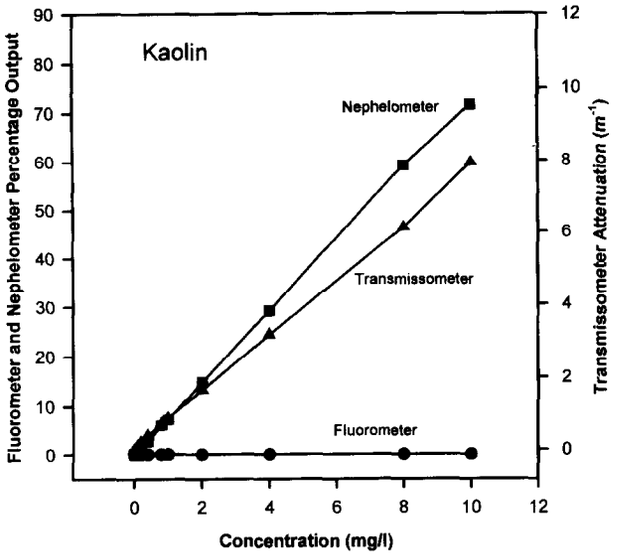

Fig. 4 Calibration using a suspension of kaolin (a pure scatter). There is negligible breakthrough of the scattered light into the fluorescence channel even at very high suspended solids concentrations

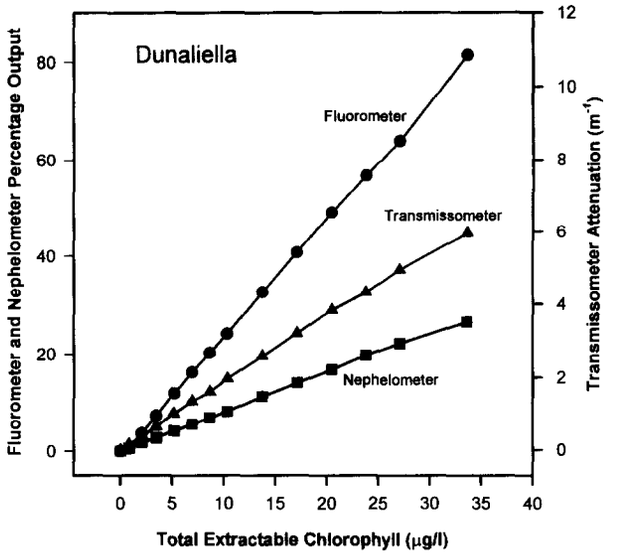

Fig. 5 Calibration using a culture of the green flagellate *Dunalliela tertiolecta*, which has cells around 10 µm in diameter which fluoresce owing to their chlorophyll content, while at the same time being efficient scatterers and absorbers of the illuminating beam. The sensitivity and range of the instrument is adjusted for coastal waters: amplifier gains can be increased for oceanic conditions

diameter spot just outside an acrylic window. Returning red light from chlorophyll fluorescence is diverted by the beam-splitter and passes through a 645 nm long pass interference filter before being detected by a photodiode.

The nephelometer measures light scattered at roughly 90° to the propagating beam. The collection angle is determined by a simple collimator tube, and an arched shield with a blackened inner wall prevents the ingress of daylight into the system.

The transmissometer, which has a path length of 250 mm, images the illumination source on a 0.2 mm pinhole in front of a photodiode. Light which is absorbed by the transmission medium or deflected from rectilinear propagation by scattering fails to reach the transmission sensor, which is shielded from ambient illumination by a 450 ± 20 nm bandpass interference filter and by the instrument geometry.

Submersible housing and power supplies

Instrument housings are constructed of 210 mm od × 15 mm wall aluminium tube with 25 mm thick end plates, hard anodized and dyed dark grey. The main chambers are sealed with single groove-in-piston Viton O-rings, and the optical windows with single compression O-rings. Electrical connections are via Seacon moulded rubber multipin connectors and cables. The instrument requires two power inputs, 13.5–35 V for the strobe and 6.75–30 V for the rest of the electronics. These are regulated internally to 12 V, 5 V and ± 12 V. The submersible battery pack, which contains 60 Ni-Cad 'D' cells, provides power for at least 50 h continuous running, or over 1 month's deployment with hourly sampling. The assembled instrument has been immersion tested to a depth of 150 m.

Calibrations

Calibration runs were carried out in a tank containing 75 l of filtered seawater, with vigorous stirring to keep particulate material in suspension. Figures 4 and 5 show results obtained using mineral particles (kaolin) and cultured microalgal cells (*Dunaliella primolecta*), chosen to illustrate the response of the instrument to non-fluorescent and fluorescent scatterers. They also illustrate the high sensitivity and wide dynamic range of each of the three optical components of the instrument. The lack of breakthrough of scattered light into the fluorescence channel in Fig. 4 is particularly notable.

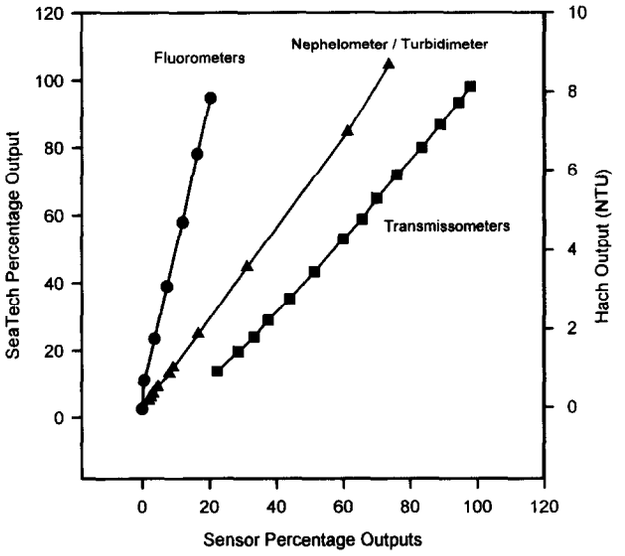

Fig. 6 Cross calibration with three commercial single parameter instruments: Seatech oceanographic transmissometer and fluorometer, and Hach laboratory turbidimeter

Figure 6 shows cross-calibration with commercially available instruments: a SeaTech oceanographic fluorometer and transmissometer and a Hach RX bench-top turbidimeter. In each case a strong linear relationship between corresponding instruments was observed.

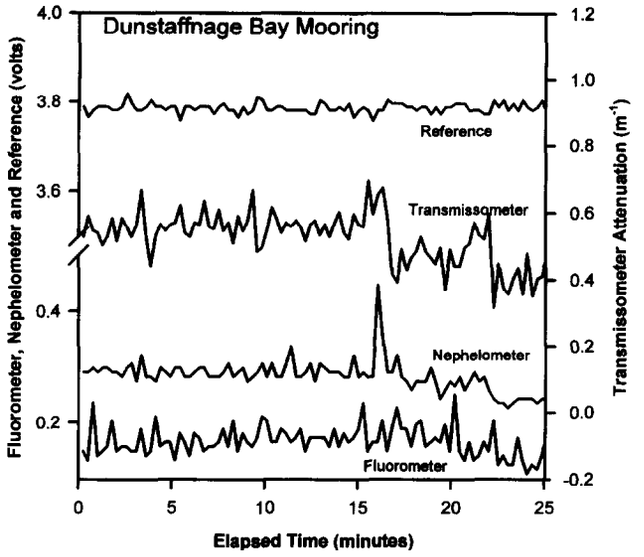

Fig. 7 A short section of a time series obtained in Dunstaffnage Bay

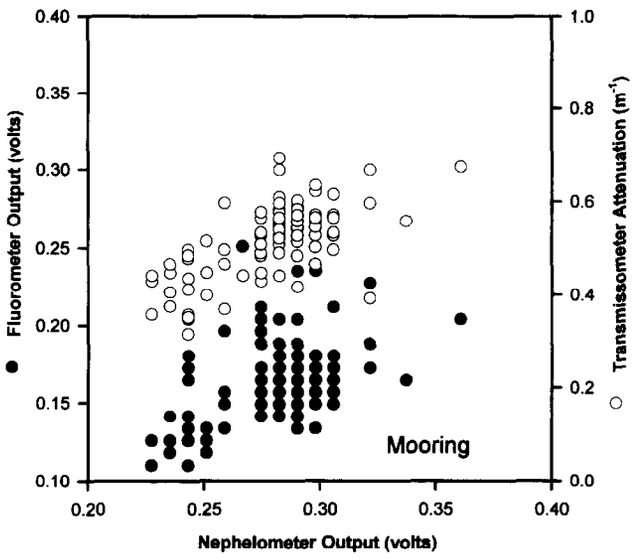

Fig. 9 Data from the mooring in Dunstaffnage Bay plotted to show the variation in fluorescence and beam attenuation as a function of wide angle scattering. Increased scattering is accompanied by increases in fluorescence and attenuation

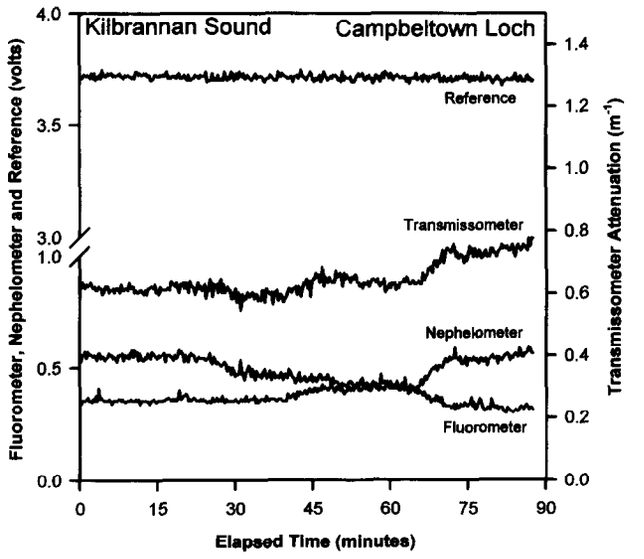

Fig. 8 Record obtained by operating the instrument in a deck tank through which seawater was pumped continuously as the ship steamed from open water into Campbeltown Loch

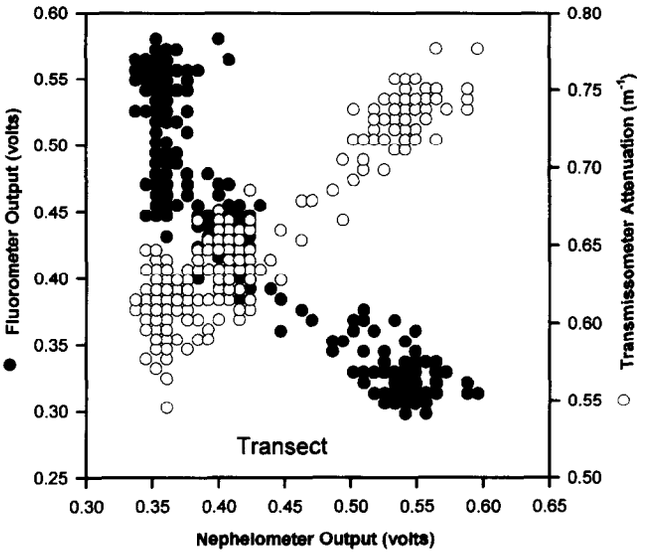

Fig. 10 Data from the transect entering Campbeltown Loch plotted to show the variation in fluorescence and beam attenuation as a function of wide angle scattering. Increased scattering is accompanied by decreasing fluorescence, but by increasing attenuation

Deployment at sea

The instrument was field tested during late summer and autumn 1995 off the West coast of Scotland. Figure 7 shows a short section of a time series obtained close to the shore in Dunstaffnage Bay, a muddy tidal inlet: the instrument was suspended from a jetty while the tide flowed past. The high frequency variations are not noise, but rather reveal microstructure in the water. At around 20 minutes, the record shows a decrease in both scattering and fluorescence (indicating a reduction in phytoplankton concentration) with a simultaneous decrease in beam attenuation in the clearer water. Figure 8 illustrates results obtained from a deck tank through which water was being pumped continuously as a ship steamed from open water into Campbeltown Loch. The rise in attenuation and corresponding increase in scattering indicate the presence of more turbid water, while the drop in the fluorometer reading suggests that this increase in turbidity is due to suspended particles rather than phytoplankton cells. Data from the two deployments are replotted in Figs 9 and 10 to show differences in the covariation between optical variables at the two sites. The data show considerable spread, but general trends can be discerned. At the mooring, an increase in wide angle scattering is accompanied by rises in both fluorescence and beam attenuation: the suggested interpretation is that increases in turbidity can be attributed to the patchy occurrence of phytoplankton cells in the water flowing past the instrument. In the transect, samples with higher wide angle scattering show an

accompanying increase in beam attenuation, but lower fluorescence. This is probably due to inshore water containing more suspended sediment and a reduced phytoplankton population.

Discussion

Combining three optical measurements using one light source inevitably involves some compromises. In this instance the fluorometer determined the overall optical layout and the transmissometer and nephelometer were designed to accommodate the optical paths produced. The resulting configurations are unorthodox, but the cross-calibrations indicate that the response of these sensors correlates well with their commercial equivalents. Initial trials indicate that the overall design is sufficiently robust for deployment at sea, and that each of the combined instruments has a sensitivity and dynamic range suitable for operation in coastal and estuarine waters. We are currently working on reducing the size of the instrument package and adding additional sensors for depth and temperature. However, the main scientific challenge now is to derive algorithms for interpreting the acquired time series in terms of bio-optical events.

Acknowledgements

John Redgate and Keith Andrew in the Biophysics Group at Strathclyde University helped with the technical development of this instrument package. John Leftley at Dunstaffnage Marine Laboratory gave advice and assistance with calibration procedures. Dave Bowers (UCNW, Bangor) provided an opportunity for initial trials at sea. This work was funded by NERC (UK) as part of the SIDAL special topic.

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