1 of 1

DOE/ER/61443-**1**

DEVELOPMENT OF A MULTI-SENSOR IN SITU FIBER OPTIC FLUOROMETER

Progress Report
for Period June 1, 1992 - October 31, 1993

S. E. Lohrenz and Vernon L. Asper

University of Southern Mississippi
Stennis Space Center, MS 39529

Michael J. Morris and Roy A. Walters

Ocean Optics, Inc.
Dunedin, FL 34698

November 1993

Prepared for

THE U. S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-FG02-92ER61443

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately-owned rights.

MASTER

als
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DEVELOPMENT OF A MULTI-SENSOR IN SITU FIBER OPTIC FLUOROMETER

TABLE OF CONTENTS

ABSTRACT	3
SCOPE OF INVESTIGATION	3
SIGNIFICANCE OF PROPOSED RESEARCH	5
PROGRESS TO DATE	6
<i>Development and testing of a PC-interfaced prototype instrument</i>	6
<u>Xenon strobe excitation source:</u>	7
<u>Detection module:</u>	7
<u>Operating software:</u>	7
<i>Performance of the PC-interfaced prototype (FP-1)</i>	7
<u>Detection:</u>	7
<u>Selection of fiber optic cable:</u>	8
<u>Sensor Optimization:</u>	8
<u>Field Test:</u>	8
<i>Multi-sensor autonomous prototype instrument (FP-2)</i>	9
<u>Description of the instrument:</u>	9
<u>Spatial Resolution:</u>	9
<u>Field Test:</u>	9
<i>Additional Activities in Year 2 and Schedule of Work</i>	10
<u>Review and design revision:</u>	10
<u>Calibration:</u>	10
ACTIVITIES OF PRINCIPAL INVESTIGATORS	11
REFERENCES	12

ABSTRACT

Our objective is to develop and evaluate a multi-sensor in situ fiber optic fluorometer. The instrument is designed to sample and store in vivo strobe-stimulated fluorescence data at multiple depths and high frequencies (1 Hz). This information may be used for estimating the distribution and abundance of particulate pigment biomass, for supporting models of water column primary production and as a complement to remotely sensed ocean color estimates of pigment biomass. The instrument is unique in that it uses fiber optic technology to increase vertical resolution. While it is theoretically possible to accomplish this task using a large number of commercially available fluorometers, our proposed design would provide a less expensive approach. Two prototype instruments have been built and are being tested. The first, a single sensor instrument interfaced with a 486 personal computer, has been used to optimize hardware and sensor design and to evaluate fiber performance and instrument detection limits. The second instrument, containing 8 sensors and capable of autonomous operation with time-series data acquisition and storage, was recently deployed in a cruise in the Gulf of Mexico. Preliminary results indicate that the instrument meets all the project goals and that low cost, high frequency, high spatial resolution fluorescence data are obtainable with the current design. Additional work will focus on further optimization of hardware design and software algorithms, and construction of an additional instrument specifically designed for deployment in the benthic boundary layer.

SCOPE OF INVESTIGATION

Goals of the Department of Energy's (DOE) Ocean Margins Program (OMP) include quantification of primary production and flux of phytoplankton biomass on the continental shelf and determination of controlling mechanisms. To accomplish these objectives, high resolution time series observations of the distribution and abundance of particulate pigment biomass will be required. Discrete shipboard sampling is inadequate to fully resolve variations in particulate pigment biomass related to changing environmental conditions. Many important physical variables have time scales ranging from minutes to hours. Hence, the coarse temporal resolution provided by discrete sampling techniques may lead to aliasing (e.g. Dickey et al., 1991). Furthermore, shipboard studies have limited duration and may miss episodic (e.g. weather related) as well as seasonal scale events.

The estimation of chlorophyll concentration from in vivo light-stimulated fluorescence has long been recognized as useful for oceanographic applications (e.g. Lorenzen, 1966). The method allows for greatly increased resolution over that possible by discrete measurements of extracted chlorophyll (e.g. Holm-Hansen et al., 1965) or through direct observations of phytoplankton cell concentrations.

Furthermore, measurements can be accomplished *in situ*, thus eliminating the need for acquiring and manipulating a water sample. *In situ* fluorometers have long been used to obtain high resolution vertical profiles (e.g. Platt, 1972; Derenbach et al., 1979) and in towed instrument packages for high resolution spatial assessments of chlorophyll concentrations (e.g. Platt, 1972; Aiken, 1977; Herman and Denman, 1977, 1979; Denman and Herman, 1978; Fasham et al., 1985; Strass, 1990). More recently, they have been deployed on moorings (Whitledge and Wirick, 1983, 1986; Dickey et al., 1986; Falkowski et al., 1988; Walsh et al., 1988; Fukuchi et al., 1988; Walsh et al., 1989) and free-drifting instrumentation (Hitchcock et al., 1989). Thus far, vertical resolution in moored applications of *in situ* fluorometers has been achieved through deployment of multiple individual instruments. Our system would expand the effectiveness of individual strobe and detector packages by the use of multiple optical fibers to allow increased vertical resolution.

The fluorescence yield (R , the ratio of the fluorescence signal to the chlorophyll concentration within the fluorometer detection volume) is variable. Variations in fluorescence yield have been attributed to the following (cf. Falkowski and Kiefer, 1985; Strass, 1990):

- Species composition (Flemer, 1969; Loftus and Seliger, 1975; Slovacek and Hannan, 1977; Yentsch and Yentsch, 1979; Soohoo et al., 1986)
- Light history and photoadaptive state (Steeman-Nielsen and Jorgensen, 1968; Kiefer, 1973a,b; Loftus and Seliger, 1975; Falkowski and Owens, 1980; Perry et al., 1981; Setser et al., 1982; Falkowski, 1984; Falkowski et al., 1986; Neale and Richardson, 1987)
- Nutrient supply (Kiefer, 1973a; Slovacek and Hannan, 1977)
- Physiological state and endogenous rhythms (Loftus and Seliger, 1975; Prezelin and Sweeney, 1977; Cullen and Renger, 1979; Prezelin and Ley, 1980; Harris, 1980)

Besides these factors related to phytoplankton physiology, fluorescence yield may be sensitive to variations of the irradiance within the detection volume, which is subject to changes in particle concentrations and size distributions (Morel and Bricaud, 1981; Baker and Lavelle, 1984; Collins et al., 1985). In addition, fluorescence yield will be affected by the presence of fluorescent substances other than chlorophyll *a*, such as phaeopigments (e.g. Herbrand, 1978; 1988).

In view of the many sources of variation, it is not surprising that fluorescent yield in natural populations has been observed to vary by one order of magnitude (Kiefer, 1973a; Loftus and Seliger, 1975). It is beyond the scope of this proposal to exhaustively characterize all sources of variability. However, such variability must be considered during field applications of the instrument. Previous investigations have shown that reasonable precision in estimates of chlorophyll concentrations can be

derived from knowledge of fluorescence yield relationships. Best results were achieved when calibrations were made for a specific area of study (spatial scales of 10-100 km) and adjusted for effects of light-dependent fluorescence quenching (cf. Weber, 1986; Strass, 1990). Examples to support this view include a regression of *in situ* fluorescence versus extracted chlorophyll derived for combined data from various water masses in the western Mediterranean Sea over a three week period ($r^2 = 0.80$, $N = 456$, D. Wiesenburg, unpublished). Lohrenz et al. (1993), using a multiple linear regression of fluorescence and depth versus extracted chlorophyll, obtained an r^2 of between 0.72 ($N = 76$) and 0.90 ($N = 117$) for data collected from Gulf Stream and Slope water masses over a five week period. Whitledge and Wirick (1986) reported that chlorophyll concentrations estimated by fluorescence agreed within a factor of 2 with extracted chlorophyll measurements for prototype deployments of a moored instrument off Long Island. Correlations between fluorescence and chlorophyll for data collected recently in the northern Gulf of Mexico indicate an r^2 ranging from 0.65 to 0.76 (Figure 1). Since natural variations in chlorophyll concentration encompass several orders of magnitude, this level of precision can provide useful information. Clearly, the interpretation of the fluorescence measurement as an indicator of distributions of particulate pigment biomass necessitates an extensive calibration procedure. As part of our proposed research, we will continue to evaluate sensitivity, precision and signal response of our prototype instruments in conditions where variations in chlorophyll *a* concentration are controlled. Subsequent field tests will take into account the temporal and spatial dependence of the auto-correlation function of fluorescence yield (cf. Strass, 1990).

SIGNIFICANCE OF PROPOSED RESEARCH

The utility of moored fluorometers has been demonstrated in studies of flux of particulate pigment biomass (Falkowski et al., 1988; Walsh et al., 1988; Walsh et al., 1989) and of bio-optical models of primary production (e.g. Ryther and Yentsch, 1957; Platt, 1986; Bidigare et al., 1987; Kiefer et al., 1987; Smith et al., 1987; Platt and Sathyendranath, 1988; Keller, 1989; Platt et al., 1989; Sakshaug et al., 1989; Sathyendranath and Platt, 1989; Dickey et al., 1991; Balch et al., 1992). This monitoring capability will allow the identification of periodic high productivity events (e.g. Glover et al., 1988; Lohrenz et al., 1988a; Marra et al., 1990). It has been suggested that inadequate sampling of these episodic events in the open ocean may lead to underestimation of regional primary production (Platt et al., 1989; Dickey et al., 1991). Since primary production in the continental margins is both higher and more variable than in the open ocean (Platt and Subba Rao, 1975; Malone, 1980; Walsh, 1989; Lohrenz et al., 1990), there is a need for high resolution temporal and spatial information about particulate pigment biomass. Another important application of moored vertically resolving fluorometers is that of ground truth applications for

Figure 1. Relationship between extracted chlorophyll and in situ fluorescence as measured with a SeaTech fluorometer during two R/V *Pelican* cruises in the Gulf of Mexico.

satellites, providing both near surface and subsurface information in support of algorithms for estimate of pigment biomass from ocean color. The moored data would also provide data between satellite missions and in periods when satellite measurements are not possible (night and cloudy periods). Finally, the design is sufficiently flexible to be adapted for high resolution spatial and temporal characterization of fluorescent material associated with the benthic boundary (e.g. SEEP I and SEEP II). Recent observations of the benthic boundary layer in the western Barents Sea indicated a substantial vertical gradient in chlorophyll concentration (Thomsen et al., 1993). Precise descriptions of such a gradient in relation to the current velocity structure would enable determinations of transport of pigments in the benthic boundary layer.

PROGRESS TO DATE

The goal of this 2 year project has been to develop a multi-sensor fiber optic fluorometer with the following capabilities:

- 1) autonomous collection of data at a moored location for long term (weeks to months) deployments.
- 2) large number of sensors for increased vertical resolution.
- 3) high data sampling frequencies (1 Hz).
- 4) low cost components to permit deployment at multiple locations.

In Year 1, the specific objective was to develop a PC-interfaced single sensor unit that could be used to optimize hardware and sensor design and to evaluate fiber performance and instrument detection limits. A multi-sensor autonomous version was built in Year 2. Preliminary results indicate that the instrument meets all the project goals and that low cost, high frequency, high spatial resolution fluorescence data are obtainable with the current design. Further work is required to optimize hardware design and software algorithms. Construction of an additional instrument specifically designed for deployment in the benthic boundary layer is proposed as part of a renewal proposal.

Development and testing of a PC-interfaced prototype instrument

The PC-interfaced prototype fiber optic fluorometer (FP-1) consists of 3 components: 1) an EG&G xenon strobe excitation source, 2) a Hamamatsu photomultiplier - phototransistor detection module interfaced to a PC computer, and 3) a fiber optic sensor. The components are all capable of battery operation. The strobe is capable of operation over extended time periods. Deployment duration is limited currently by computer power consumption.

Xenon strobe excitation source: The strobe uses a standard "U" shaped xenon tube with integral inverter for high voltage generation. The pulse bandwidth is approximately 20 msec. The strobe firing circuit uses optical isolation to eliminate possible discharge events through the trigger line that is connected to the detection module. Power is supplied by a rechargeable 12 V gel cell with a storage capacity of 3.4 amp h. This will provide power for flashes at the rate of 1 KHz for approximately 34 h. Provision is made for recharge via a standard plug in power module.

The light output of the strobe passes through a set of dichroic filters to a standard SMA connector that couples to the excitation line of the fiber optic sensor. The dichroics block light > 500 nm from entering the excitation line. A second SMA connector is mounted away from the filters in a partially shielded region to provide light to a fiber that illuminates the strobe monitor.

Detection module: The detection module consists of a Hamamatsu HC125-01MOD70 photomultiplier tube (PMT) assembly for measuring fluorescence and a Motorola MFOD100 phototransistor (PT) to monitor the strobe intensity. The detectors are connected to a Computer Boards Inc. PC plug-in board (ADC) capable of data acquisition rates up to 330 KHz. The output of the PMT (0-10 V) is connected directly to channel 0 of the ADC board. The output of the PT is connected to channel 1 of the ADC through a transimpedance amplifier. Power is supplied by +5 V from the ADC. The read fiber from the fiber sensor is coupled to the PMT with an SMA bulkhead connector. A narrow bandpass dielectric filter centered at 680 nm is sandwiched between the PMT and the fiber end.

Operating software: Operating software has been written in modular Borland Turbo C so that modifications can be easily implemented and so that the code can be transported to the data logger in the seagoing system or to other platforms. The PC based software is designed as a development tool to investigate data manipulation strategies and to optimize system performance. The code initializes the ADC board, outputs strobe trigger pulses and provides a series of menus from which to choose the various functions including oscilloscope, data collection, and specification of program parameters.

Performance of the PC-interfaced prototype (FP-1)

Detection: The detection limits of the FP-1 instrument were initially determined using two 1 m lengths of encapsulated 1 mm diameter acrylic fiber joined at the sensor and terminated with SMA connectors at the detector and excitation ends. At the sensor end, flat sections of black encapsulant are removed from each fiber and the two are bound together in parallel such that one fiber illuminates the target and the other views approximately the same region to within about 1 mm of the fiber surface. The

large numerical aperture of the fiber results in a significant overlap between illumination and read volumes. Tests were conducted to assess instrument sensitivity, dynamic range, linearity, and timing sequence (i.e., the optimal sampling time in response to variable fluorescence response, e.g., Papageorgio, 1975; Falkowski and Kiefer, 1985). A standard curve showing fluorescence signal in relation to concentration of a pure chlorophyll *a* standard (Sigma) in methanol is illustrated in Figure 2. Estimated detection limit was 0.1 mg m^{-3} . The signal response appeared to be linear with an upper limit of dynamic range of at least 60 mg m^{-3} , a value greater than that encountered in most coastal waters. A time-series of the fluorescence signal in relation to the strobe excitation indicated a close coupling between excitation energy and fluorescence signal (Figure 3).

To determine the performance of the instrument with live cells, fluorescence was measured in a dilution series of a culture of *Nannochloris atomus* Butcher (a euryhaline chlorophyte isolated from Great South Bay, clone GSB Nanno from the Bigelow Laboratory Culture Collection). Chlorophyll *a* concentration was determined fluorometrically (Holm-Hansen et al., 1965) by 90% acetone extraction of filtered (GF/F) samples. As in the case of the pure chlorophyll standard, signal response appeared linear (Figure 4). Estimated detection limit was 0.15 mg m^{-3} .

Selection of fiber optic cable: The performance of a variety of fibers was evaluated in using the configuration described above as a reference for comparison. While we had initially hoped to use extended lengths of low cost acrylic fibers for deployments at sea, this was not feasible due to the attenuation characteristics of these fiber types. Instead we selected a high performance $600 \mu\text{m}$ core silica fiber with silicon cladding and a Kevlar reinforced polyvinyl chloride (PVC) sheath. This fiber represented an optimal tradeoff between attenuation characteristics and numerical aperture. Field trials using this fiber have demonstrated its durability and ease of handling.

Sensor Optimization: Optimization of sensor design was accomplished by evaluating instrument performance with various sensor probe design configurations using the original parallel fiber arrangement described above as a basis for comparison. Angle between excitation and detection fiber ends was found to be a critical parameter in optimizing instrument signal response. An angle of 30° was found to provide the greatest improvement in signal response. We are currently exploring further improvements in sensor design that may reduce interference from ambient light and improve the signal to noise ratio of the instrument.

Field Test: Cruises aboard the R/V *Pelican* in April and October 1993 provided information on the performance of the FP-1 instrument as a profiling instrument. Profiles of fluorescence obtained with the FP-1 compared well with those obtained with a SeaTech fluorometer (Figure 5). In addition, we used the FP-1 to monitor

Figure 2. Relationship between standard chlorophyll *a* (Sigma) concentrations in methanol and fluorescence peak height (7 pixel average) measured using the FP-1 instrument. Excitation and detection fibers consisted of 1 m long, 1 mm diameter acrylic fibers oriented in parallel. Lower limit of detection was estimated to be 0.1 mg m⁻³.

Figure 3. Timing of fluorescence signal in relation to flash intensity for a) a solution of chlorophyll *a* in methanol and b) for a seawater sample containing a natural population of phytoplankton. DIW-distilled water blank

Figure 4. Relationship between extracted chlorophyll concentration determined in a culture of *Nannochloris atomus* Butcher and fluorescence peak height measured as in Figure 2. Lower limit of detection was estimated to be 0.15 mg m⁻³.

Figure 5. Profiles of fluorescence determined on two R/V *Pelican* cruises in the Gulf of Mexico using the FP-1 instrument (●). Data obtained at the same location with a SeaTech fluorometer (—) are shown for comparison. A. March 1993 profile obtained using 50 m long 1 mm diameter silica core fibers oriented at the sensor end in parallel. B. October 1993 profile obtained using 70 m long 0.6 mm diameter silica core fiber with fibers oriented at a 30° angle at the sensor end.

fluorescence in the surface water outflow of an underway pumping system available on the ship. This same water was also monitored for fluorescence with a Turner Designs fluorometer and data were logged by the Multiple Interface Data Acquisition System (MIDAS) provided by the ship. A plot of FP-1 fluorescence versus the MIDAS output demonstrated excellent correspondence in the signals over the range of fluorescence measured (Figure 6). These results provide ample evidence for the feasibility of the multi-sensor fluorometer design. Moreover, we feel that better instrument performance can be achieved using some additional inexpensive design modifications.

Multi-sensor autonomous prototype instrument (FP-2)

Description of the instrument: The FP-2 is an autonomous instrument capable of measuring and storing fluorescence data at eight different depths (Figure 7). The present system is contained within a 13 cm diameter, 2.6 m long PVC casing with 16 fiber optic feedthroughs at one end. Autonomous operation and data logging are achieved using a Tattletail 7 (TT7) with a 40 Mbyte hard drive and interface board on which additional logic has been constructed. The TT7 is interfaced with the Ocean Optics PC1000-ADC board (500 kHz/12 bit). Programming and data transfer is accomplished via an RS-232 with a PC using an Aztec C compiler designed to generate TT7 compatible code. Excitation light is provided by 8 strobe units (EG&G LS-182A manufactured specifically for fiber optic interface and 12 V operation). The light is filtered using a Schott BG-28 blue transmission filters. Strobe intensity is monitored with separate fibers going to a phototransistor. Detection of fluorescence is achieved with a Hamamatsu HC125-01MOD photomultiplier tube equipped with a 676 nm narrow bandpass filter (Edmund A43, 140, 1 in diam.). Battery power is provided using 4 Panasonic LCR 12V3.4P rechargeable Gel cells (12 V at 3.4 Ah).

Spatial Resolution: The fiber optic sensor, as currently designed, has a detection volume of about 1 mm³. Multiple sensors can be easily packed to provide a vertical resolution as fine as 2-3 mm for fine scale resolution of pigment gradients as, for example, in near bottom or sea surface boundary layers. Alternatively, sensors can be spread out along a mooring cable within the limits imposed by fiber attenuation. Currently, the instrument has been configured to sample at 4, 8, 12, 16, 20, 25, 35 and 45 m.

Field Test: An initial field test of the FP-2 instrument was recently conducted aboard the R/V *Pelican* in October 1993. Test deployments during the cruise provided an opportunity to test hardware and software, which performed well. Calibration of the instrument was not available at the time this report was prepared. However, uncalibrated time series data are shown in Figure 8 for illustration. Experiences on the

Comparison of MIDAS and USM/OOI Signals

Mar/Apr 1993

Figure 6. Comparison of fluorescence measurements of surface water sampled with an underway pumping system during a cruise on the R/V *Pelican*. The ship's MIDAS fluorescence data (Turner Designs fluorometer) are compared with data collected with the FP-1 system using 50 m long 1 mm diameter silica core fibers oriented at a 30° angle at the sensor end.

USM/OOI Fiber Optic Fluorometer

Figure 7. Schematic of the autonomous multi-sensor fluorometer (FP-2). Excitation irradiance travels from the strobes via 600 μm fibers to the sensor and the fluorescence signal is returned to the photomultiplier tube (PMT). A phototransistor (PT) monitors strobe intensity. See text for further description.

18 Oct 93 Station 14

Figure 8. Uncalibrated time-series of fluorescence measured at selected depths with the FP-2 instrument. Data were collected during a recent R/V *Pelican* cruise in the Gulf of Mexico.

cruise were constructive in identifying areas of focus for further optimization of hardware design and software algorithms.

Additional Activities in Year 2 and Schedule of Work

Review and design revision: The sensor and instrument design will be reviewed in light of results of the performance evaluation of the FP-1 and FP-2 instruments and modified as warranted. Further tests (field and laboratory) will be conducted with both instruments. Another cruise will be scheduled sometime in the spring. Design improvements currently under study include a new sensor design to reduce ambient light effects (Figure 9), and the possibility of increasing the efficiency of energy transfer from the strobe to the fiber via a focusing lens. Plans are also in progress to use an improved pressure case design with watertight optical connectors that will result in increased pressure tolerance. Software revision will be an ongoing process.

Bio-fouling will be considered as a potential factor influencing the fluorometer signal response. This will be especially critical during long deployments. Previous strategies for dealing with fouling problems included both mechanical (Whitledge and Wirick, 1986) and chemical (Whitledge and Wirick, 1983; Dickey et al., 1991) methods. In addition to use of an anti-fouling clear organo-metallic polymer (tributyl tin), design is in progress for construction of a hydraulic system for periodic scrubbing of the optical sensors (Figure 9) as well as "self calibration" of the instrument. This is described in greater detail in an accompanying renewal proposal.

In addition to plans for modification of the instrument, we propose to deploy the modified instrument in conjunction with the bottom tripod system of Williams, Pietrafesa, and Churchill in the interest of studying fluorescence gradients in the benthic boundary layer. Many of the revisions described here will be directly applicable to the bottom-moored instrument.

Calibration: Calibration of the autonomous instrument represents a major challenge to the research effort. A considerable proportion of our efforts during the remainder of Year 2 (and proposed for Year 3) will focus on instrument calibration and factors which may modify this. Our strategy is to initially evaluate instrument calibration and drift in a controlled laboratory setting. Factors to be considered include effects of ambient light and temperature. In addition, the possible influence of changes in particle concentrations and size distributions will be examined empirically and through the use of Monte Carlo simulations (see accompanying proposal for more discussion). Subsequently, the instrument will be deployed in field situations and cross-calibrated on the basis of contemporaneous measurements of fluorescence from other fluorometers (FP-1, SeaTech) and of extracted chlorophyll and phaeopigments from water samples. In addition, the development of a "self calibrating" capability is discussed in an accompanying renewal proposal.

SENSOR BLOCK

SENSOR HOLDER

Figure 9. Proposed design for fiber optic sensor. Modifications include baffles to reduce ambient light effects and a hydraulic antifouling mechanism.

Based on the schedule projected for the second year of this project (see below), we are making good progress.

SCHEDULE OF WORK

Year 2

ACTIVITIES OF PRINCIPAL INVESTIGATORS

S. E. Lohrenz (USM)

Dr. Lohrenz is co-principal investigator on the project and primary point of contact for the contract. He has been responsible for administrative operations. He has been directly involved in consultations and decisions regarding design options of the prototype. He also served as the project representative at program planning meetings held at Brookhaven Laboratories. Dr. Lohrenz has had extensive experience in working with marine algal cultures, photosynthetic pigment analyses, and in the measurement of in vivo fluorescence in natural populations. He will oversee evaluation of instrument performance and calibration procedures in collaboration with Dr. V. L. Asper. Dr. Lohrenz has and will continue to devote 20% of his time to this project.

V. L. Asper (USM)

Dr. Asper is the other co-principal investigator. He has been directly involved in consultations and decisions regarding design options and participated in field trials of both the FP-1 and FP-2 instruments. Dr. Asper has had extensive experience in constructing and deploying oceanographic instrumentation in various mooring configurations. He will oversee evaluation of instrument performance and calibration procedures in collaboration with Dr. Lohrenz. Dr. Asper has and will continue to spend about 10% of his time on this project.

Mr. M. J. Morris (contractor, OOI)

Mr. Morris is president of Ocean Optics, Inc., the agency contracted to construct the lab prototype and field instruments. He has had extensive experience in the design of fiber optic based sensors and has been directly involved in consultations and decisions regarding design options of the prototype. He will provide the evaluation and approval of design revisions. Dr. Morris has and will continue to devote 20% of his time on this project.

Dr. R. A. Walters (contractor, OOI)

Dr. R. Walters has been primarily responsible for construction of the instrument and implementation of design and construction options selected by the principal investigators. He is an optical engineer with extensive research and design experience with fiber optical instruments. Dr. Walters has and will continue to devote 20% of his time on this project.

REFERENCES

Aiken, J., R. H. Bruce and J. A. Lindley. 1977. Ecological investigations with the undulating oceanographic recorder: the hydrography and plankton of the waters adjacent to the Orkeny and Shetland Islands. *Mar. Biol.* 39, 77-91.

Baker, E. T. and J. W. Lavelle. 1984. The effect of particle size on the light attenuation coefficient of natural suspensions. *J. Geophys. Res.*, 89, 8197-8204.

Balch, W. M., R. Evans, J. Brown, G. Feldman, C. McClain and W. Esaias. 1992. The remote sensing of ocean primary productivity: use of a new data compilation to test satellite algorithms. *J. Geophys. Res.*, 97, 2279-2293.

Bidigare, R. R., R. C. Smith, K. S. Baker, and J. Marra. 1987. Oceanic primary production estimates from measurements of spectral irradiance and pigment concentrations. *Glob. Biogeo. Cycles*, 1, 171-186.

Campbell, J. W. and J. E. O'Reilly. 1988. Role of satellites in estimating primary productivity on the northwest Atlantic continental shelf. *Cont. Shelf Res.*, 8, 179-204.

Chamberlain, W. S., C. R. Booth, D. A. Kiefer, J. H. Morrow, and R. C. Murphy. 1990. Evidence for a simple relationship between natural fluorescence, photosynthesis, and chlorophyll in the sea. *Deep Sea Res.* 37, 951-973.

- Collins, D. J., D. A. Kiefer, J. B. Soohoo, and I. S. McDermid. 1985. The role of reabsorption in the spectral distribution of phytoplankton fluorescence emission. *Deep-Sea Res.* 32, 983-1003.
- Cullen, J. J. and E. H. Renger. 1979. Continuous measurment of DCMU-induced fluorescence response of natural phytoplankton populations. *Mar. Biol.*, 53, 13-20.
- Denman, K. L. and A. W. Herman. 1978. Space-time structure of a continental shelf ecosystem measured by a towed porpoising vehicle. *J. Mar. Res.* 36, 693-714.
- Dickey, T. D., J. Marra, T. Granata, C. Langdon, M. Hamilton, J. Wiggert, D. Siegel, and A. Bratkovich. 1991. Concurrent high resolution bio-optical and physical time series observations in the Sargasso Sea during the spring of 1987. *J. Geophys. Res.* 96, 8643-8663.
- Falkowski, P. G. 1984. Physiological responses of phytoplankton to natural light regimes. *J. Plank. Res.* 6, 295-308.
- Falkowski, P. G. and T. G. Owens. 1980. Light-shade adaptation: two strategies in marine phytoplankton. *Plant Phys.* 66, 592-595.
- Falkowski, P. G., Z. Dubinsky, and K. Wyman. 1985. Growth- irradiance relationships in phytoplankton. *Limnol. Oceanogr.*, 30, 311-321.
- Falkowski, P. G., K. Wyman, A. C. Ley and D. C. Mauzerall. 1986. Relationship of steady-state photosynthesis to fluorescence in eucaryotic algae. *Biochim. Biophys. Acta* 849, 183-192.
- Falkowski, P. G., C. N. Flagg, G. T. Rowe, S. L. Smith, T. E. Whitledge, and C. D. Wirick. 1988. The fate of a spring phytoplankton bloom: export or oxidation? *Cont. Shelf Res.* 8, 457-484.
- Fasham, J. J. R., T. Platt, B. Irwin and K. Jones. 1985. Factors affecting the spatial pattern of the deep chlorophyll maximum in the region of the Azores Front. *Prog. Oceanogr.* 14, 129-165.
- Flemer, D. A. 1969. Continuous measurment of in vivo chlorophyll of a dinoflagellate bloom in Chesapeake Bay. *Chesapeake Sci.*, 10, 99-103.
- Fukuchi, M., H. Hattori, H. Sasaki, and T. Hoshiai. 1988. A phytoplankton bloom and associated processes observed with a long-term moored system in Antarctic waters.

Mar. Ecol. Prog. Ser. 45, 279-288.

Glover, H. E., B. B. Prezelin, L. Campbell, M. Wyman, and C. Garside. 1988. A nitrate-dependent *Synechococcus* bloom in surface Sargasso Sea water. *Nature*, 331, 161-163.

Gowing, M. M. and M. W. Silver. 1983. Origins and microenvironments of bacteria mediating fecal pellet decomposition in the sea. *Mar. Biol.* 73, 7-16.

Harris, G. P. (1980) The relationship between chlorophyll a fluorescence, diffuse attenuation changes and photosynthesis in natural phytoplankton populations. *J. Plank. Res.* 2, 109-127.

Hayward, T. L. and E. L. Venrick. 1982. Relation between surface chlorophyll, integrated chlorophyll, and integrated primary production. *Mar. Biol.*, 69, 247-252.

Herbland, A. 1978. The soluble fluorescence in the open sea: distribution and ecological significance in the equatorial Atlantic Ocean. *J. Exp. Mar. Biol. Ecol.* 32, 275-284.

Herbland, A. 1988. The deep phaeophytin maximum in the ocean-reality or illusion? In: *Toward a theory on biological-physical interactions in the World ocean*, B. Rothschild, ed. Kluwer Academic Publications, Dordrecht, pp. 51-70.

Herman, A. W. and K. L. Denman. 1977. Rapid underway profiling of chlorophyll with an *in situ* fluorometer mounted on a 'Batfish' vehicle. *Deep Sea Res.* 24, 385-397.

Herman, A. W. and K. L. Denman. 1979. Intrusions and vertical mixing of the shelf/slope water front south of Nova Scotia. *J. Fish. Res. Bd. Can.* 36, 1445-1453.

Hitchcock, G. L., E. J. Lessard, D. Dorson, J. Fontaine and T. Rossby. 1989. The IFF: the isopycnal float fluorometer. *J. Atmosph. Ocean. Tech.*, 6, 19-25.

Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes and J. D. H. Strickland. 1965. Fluorometric determination of chlorophyll. *J. Cons. Int. Explor. Mer*, 30, 3-15.

Keller, A. 1989. Modeling effects of temperature, light, and nutrients on primary productivity, an empirical and a mechanistic approach compared. *Limnol. Oceanogr.*, 34, 82-96.

Kiefer, D. A. 1973a. Fluorescence properties of natural phytoplankton populations.

Mar. Biol., 22, 263-269.

Kiefer, D. A. 1973b. Chlorophyll a fluorescence in marine centric diatoms: responses of chloroplasts to light nutrient stress. Mar. Biol., 23, 39-46.

Kolber, Z., J. Zehr, and P. Falkowski. 1988. Effects of growth irradiance and nitrogen limitation on photosynthetic energy conversion in photosystem II. Plant. Phys., 88, 923-929.

Loftus, M. E. and H. H. Seliger. 1975. Some limitations of the in vivo fluorescence technique. Chesapeake Science, 16, 79-92.

Lohrenz, S. E., R. A. Arnone, D. A. Wiesenburg and I. P. DePalma. 1988a. Satellite detection of transient enhanced primary production in the western Mediterranean Sea. Nature, 335, 245-247.

Lohrenz, S. E., D. A. Wiesenburg, I. P. DePalma, K. S. Johnson, and D. E. Gustafson, Jr. 1988b. Interrelationships among primary production, chlorophyll, and environmental conditions in frontal regions of the western Mediterranean Sea. Deep-Sea Res., 35, 793-810.

Lohrenz, S. E., D. A. Phinney, J. J. Cullen, D. Olson, and C. S. Yentsch (1993) Pigment and primary production distributions in a Gulf Stream meander. J. Geophys. Res., in press.

Lorenzen, C. J. 1966. A method for the continuous measurement of in vivo chlorophyll concentration. Deep-Sea Res., 13, 223- 227.

Marra, J., R. R. Bidigare, and T. D. Dickey. 1990. Nutrients and mixing, chlorophyll and phytoplankton growth. Deep-Sea Res., 37, 127-143.

Malone, T. C. (1980) Algal size. In: The Physiological Ecology of Marine Phytoplankton, I. Morris, ed. Blackwell Press, London, pp. 433-463.

Mantoura, R. C. F. and C. A. Llewellyn. 1983. The rapid determination of algal chlorophyll and carotenoid pigments and high-performance liquid chromatography. Anal. Chim. Acta, 151, 297--314.

Morel, A. and A. Bricaud. 1981. Theoretical results concerning light absorption in a discrete medium, and application to specific absorption of phytoplankton. Deep-Sea Res., 28A, 1375-1393.

- Neale, P. J. and P. J. Richerson. 1987. Photoinhibition and the diurnal variation of phytoplankton photosynthesis-I. Development of a photosynthesis-irradiance model from studies of *in situ* responses. *J. Plank. Res.* 9, 167-193.
- Papageorgio, G. 1975. Chlorophyll fluorescence: an intrinsic probe of photosynthesis. In: *Bioenergetics of Photosynthesis*, R. Govindjee, ed., Academic Press, New York, pp. 319-371.
- Perry, M. J., M. C. Talbot, and R. S. Alberte. 1981. Photoadaptation in marine phytoplankton: response of the photosynthetic unit. *Mar. Biol.* 62, 91-101.
- Platt, T. 1972. Local phytoplankton abundance and turbulence. *Deep-Sea Res.*, 19, 183-188.
- Platt, T. 1986. Primary production of the ocean water column as a function of surface light intensity, Algorithms for remote sensing. *Deep-Sea Res.*, 33, 149-163.
- Platt, T., C. L. Gallegos, and W. G. Harrison. 1980. Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton. *J. Mar. Res.*, 38, 687-701.
- Platt, T. and S. Sathyendranath. 1988. Oceanic primary production: estimation by remote sensing at local and regional scales. *Science*, 241, 1613-1620.
- Platt, T. and others. 1989a. Biological production of the oceans, the case for a consensus. *Mar. Ecol. Prog. Ser.*, 52, 77-88.
- Ryther, J. H. and C. S. Yentsch. 1957. The estimation of phytoplankton production in the ocean from chlorophyll and light data. *Limnol. Oceanogr.*, 2, 281-286.
- Sakshaug, E., K. Andresen, and D. A. Kiefer. 1989. A steady state description of growth and light absorption in the marine planktonic diatom *Skeletonema costatum*. *Limnol. Oceanogr.*, 34, 198-205.
- Sathyendranath, S. and T. Platt. 1989. Computation of aquatic primary production, extended formalism to include effects of angular and spectral distribution of light. *Limnol. Oceanogr.*, 34, 188-198.
- Setser, P. J., N. L. Guinasso, Jr., and D. R. Schink. 1982. Daily patterns of fluorescence *in vivo* in the central equatorial Pacific. *J. Mar. Res.* 40, 453-471.
- Slovacek, R. E., and P. J. Hannan. 1977. *In vivo* fluorescence determination of

phytoplankton chlorophyll a. Limnol. Oceanogr. 22, 919-925.

Smith, R. C., R. R. Bidigare, B. B. Prezelin, K. S. Baker, and J. M. Brooks, 1987. Optical characterization of primary productivity across a coastal front. Mar. Biol., 96, 575-591.

Sournia, A. 1978. Phytoplankton manual. UNESCO, Paris.

Soohoo, J. B., D. A. Kiefer, and D. J. Collins. 1986. In vivo fluorescence excitation and absorption spectra of marine phytoplankton. I. Taxonomic characteristics and responses to photoadaptation. J. Plank. Res. 8, 197-214.

Steeman-Nielsen, E. and E. G. Jorgensen. 1968. The adaptation of plankton algae: I. General part. Physiol. Plant. 21, 401-413.

Strass, V. 1990. On the calibration of large-scale fluorometric chlorophyll measurements from towed undulating vehicles. Deep-Sea Res. 37, 525-540.

Thomsen, L., G. Graf, V. Martens and E. Steen (1993) An instrument for sampling water from the benthic boundary layer. Cont. Shelf Res., in press.

Walsh, J. J., C. D. Wirick, L. J. Pietrafesa, T. E. Whitledge, F. E. Hoge, and R. N. Swift. 1988. High-frequency sampling of the 1984 spring bloom with the Mid-Atlantic bight: synoptic shipboard, aircraft, and *in situ* perspectives of the SEEP-I experiment. Cont. Shelf Res. 8, 529-563.

Walsh, J. J. and others. 1989. Carbon and nitrogen cycling with the Bering/Chukchi Seas: source regions for organic matter effecting AOU demands of the Arctic Ocean. Prog. Oceanogr. 22, 277-359.

Weber, L. H., S. Z. El-Sayed and I. Hampton. 1986. The variance spectra of phytoplankton, krill and water temperature in the Antarctic Ocean south of Africa. Deep Sea Res. 33, 1327-1343.

Whitledge, T. E. and C. D. Wirick. 1983. Observations of chlorophyll concentrations off Long Island from a moored *in situ* fluorometer. Deep-Sea Res., 30, 297-309.

Whitledge, T. E. and C. D. Wirick. 1986. Development of a moored *in situ* fluorometer for phytoplankton studies. In: Tidal Mixing and Plankton Dynamics, J. Bowman, M. Yentsch and W. T. Peterson, eds., Springer-Verlag, Berlin, pp. 449-462.

Yentsch, C. S. and C. M. Yentsch. 1979. Fluorescence spectral signatures: the characterization of phytoplankton population by the use of excitation and emission spectra. *J. Mar. Res.* 37, 471-483.

**DATE
FILMED**

1 / 28 / 94

END