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Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 4, Volume VI: Special Topics in Ocean Optics Protocols and Appendices

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April 2003
Preface

This document stipulates protocols for measuring bio-optical and radiometric data for the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Project activities and algorithm development. The document is organized into 6 separate volumes as:

Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 4

Volume I: Introduction, Background and Conventions
Volume II: Instrument Specifications, Characterization and Calibration
Volume III: Radiometric Measurements and Data Analysis Methods
Volume IV: Inherent Optical Properties: Instruments, Characterization, Field Measurements and Data Analysis Protocols
Volume V: Biogeochemical and Bio-Optical Measurements and Data Analysis Methods
Volume VI: Special Topics in Ocean Optics Protocols and Appendices

The earlier version of *Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 3* (Mueller and Fargion 2002, Volumes 1 and 2) is entirely superseded by the seven Volumes of Revision 4 listed above.

The new multi-volume format for publishing the ocean optics protocols is intended to allow timely future revisions to be made reflecting important evolution of instruments and methods in some areas, without reissuing the entire document. Over the years, as existing protocols were revised, or expanded for clarification, and new protocol topics were added, the ocean optics protocol document has grown from 45pp (Mueller and Austin 1992) to 308pp in Revision 3 (Mueller and Fargion 2002). This rate of growth continues in Revision 4. The writing and editorial tasks needed to publish each revised version of the protocol manual as a single document has become progressively more difficult as its size increases. Chapters that change but little, must nevertheless be rewritten for each revision to reflect relatively minor changes in, *e.g.*, cross-referencing and to maintain self-contained consistency in the protocol manual. More critically, as it grows bigger, the book becomes more difficult to use by its intended audience. A massive new protocol manual is difficult for a reader to peruse thoroughly enough to stay current with and apply important new material and revisions it may contain. Many people simply find it too time consuming to keep up with changing protocols presented in this format - which may explain why some relatively recent technical reports and journal articles cite Mueller and Austin (1995), rather than the then current, more correct protocol document. It is hoped that the new format will improve community access to current protocols by stabilizing those volumes and chapters that do not change significantly over periods of several years, and introducing most new major revisions as new chapters to be added to an existing volume without revision of its previous contents.

The relationships between the Revision 4 chapters of each protocol volume and those of Revision 3 (Mueller and Fargion 2002), and the topics new chapters, are briefly summarized below:

**Volume I:** This volume covers perspectives on ocean color research and validation (Chapter 1), fundamental definitions, terminology, relationships and conventions used throughout the protocol document (Chapter 2), requirements for specific *in situ* observations (Chapter 3), and general protocols for field measurements, metadata, logbooks, sampling strategies, and data archival (Chapter 4). Chapters 1, 2 and 3 of Volume I correspond directly to Chapters 1, 2 and 3 of Revision 3 with no substantive changes. Two new variables, Particulate Organic Carbon (POC) and Particle Size Distribution (PSD) have been added to Tables 3.1 and 3.2 and the related discussion in Section 3.4; protocols covering these measurements will be added in a subsequent revision to Volume V (see below). Chapter 4 of Volume I combines material from Chapter 9 of Revision 3 with a brief summary of SeaBASS policy and archival requirements (detailed SeaBASS information in Chapter 18 and Appendix B of Revision 3 has been separated from the optics protocols).

**Volume II:** The chapters of this volume review instrument performance characteristics required for *in situ* observations to support validation (Chapter 1), detailed instrument specifications and underlying rationale (Chapter 2) and protocols for instrument calibration and characterization standards and methods (Chapters 3 through 5). Chapters 1 through 5 of Volume II correspond directly to Revision 3 chapters 4 through 8, respectively, with only minor modifications.
Volume III: The chapters of this volume briefly review methods used in the field to make the in situ radiometric measurements for ocean color validation, together with methods of analyzing the data (Chapter 1), detailed measurement and data analysis protocols for in-water radiometric profiles (Chapter 2), above water measurements of remote sensing reflectance (Chapter III-3), determinations of exact normalized water-leaving radiance (Chapter 4), and atmospheric radiometric measurements to determine aerosol optical thickness and sky radiance distributions (Chapter 5). Chapter 1 is adapted from relevant portions of Chapter 9 in Revision 3. Chapter 2 of Volume III corresponds to Chapter 10 of Revision 3, and Chapters 3 through 5 to Revision 3 Chapters 12 through 14, respectively. Aside from reorganization, there are no changes in the protocols presented in this volume.

Volume IV: This volume includes a chapter reviewing the scope of inherent optical properties (IOP) measurements (Chapter 1), followed by 4 chapters giving detailed calibration, measurement and analysis protocols for the beam attenuation coefficient (Chapter 2), the volume absorption coefficient measured in situ (Chapter 3), laboratory measurements of the volume absorption coefficients from discrete filtered seawater samples (Chapter 4), and in situ measurements of the volume scattering function, including determinations of the backscattering coefficient (Chapter 5). Chapter 4 of Volume IV is a slightly revised version of Chapter 15 in Revision 3, while the remaining chapters of this volume are entirely new contributions to the ocean optics protocols. These new chapters may be significantly revised in the future, given the rapidly developing state-of-the-art in IOP measurement instruments and methods.

Volume V: The overview chapter (Chapter 1) briefly reviews biogeochemical and bio-optical measurements, and points to literature covering methods for measuring these variables; some of the material in this overview is drawn from Chapter 9 of Revision 3. Detailed protocols for HPLC measurement of phytoplankton pigment concentrations are given in Chapter 2, which differs from Chapter 16 of Revision 3 only by its specification of a new solvent program. Chapter 3 gives protocols for Fluorometric measurement of chlorophyll a concentration, and is not significantly changed from Chapter 17 of Revision 3. New chapters covering protocols for measuring, Phycoerythrin concentrations, Particle Size Distribution (PSD) and Particulate Organic Carbon (POC) concentrations are likely future additions to this volume.

Volume VI: This volume gathers chapters covering more specialized topics in the ocean optics protocols. Chapter 1 introduces these special topics in the context of the overall protocols. Chapter 2 is a reformatted, but otherwise unchanged, version of Chapter 11 in Revision 3 describing specialized protocols used for radiometric measurements associated with the Marine Optical Buoy (MOBY) ocean color vicarious calibration observatory. The remaining chapters are new in Revision 4 and cover protocols for radiometric and bio-optical measurements from moored and drifting buoys (Chapter 3), ocean color measurements from aircraft (Chapter 4), and methods and results using LASER sources for stray-light characterization and correction of the MOBY spectrographs (Chapter 5). In the next few years, it is likely that most new additions to the protocols will appear as chapters added to this volume.

Volume VI also collects appendices of useful information. Appendix A is an updated version of Appendix A in Revision 3 summarizing characteristics of past, present and future satellite ocean color missions. Appendix B is the List of Acronyms used in the report and is an updated version of Appendix C in Revision 3. Similarly, Appendix C, the list of Frequently Used Symbols, is an updated version of Appendix D from Rev. 3. The SeaBASS file format information given in Appendix B of Revision 3 has been removed from the protocols and is promulgated separately by the SIMBIOS Project.

In the Revision 4 multi-volume format of the ocean optics protocols, Volumes I, II and III are unlikely to require significant changes for several years. The chapters of Volume IV may require near term revisions to reflect the rapidly evolving state-of-the-art in measurements of inherent optical properties, particularly concerning instruments and methods for measuring the Volume Scattering Function of seawater. It is anticipated that new chapters will be also be added to Volumes V and VI in Revision 5 (2003).

This technical report is not meant as a substitute for scientific literature. Instead, it will provide a ready and responsive vehicle for the multitude of technical reports issued by an operational Project. The contributions are published as submitted, after only minor editing to correct obvious grammatical or clerical errors.
# Table of Contents

## CHAPTER 1
**INTRODUCTION TO SPECIAL TOPICS IN OCEAN OPTICS FOR OCEAN COLOR SENSOR VALIDATION**

## CHAPTER 2
**MOBY, A RADIOMETRIC BUOY FOR PERFORMANCE MONITORING AND VICARIOUS CALIBRATION OF SATELLITE OCEAN COLOR SENSORS: MEASUREMENT AND DATA ANALYSIS PROTOCOLS**

- 2.1 INTRODUCTION ................................................................. 3
- 2.2 MOBY PRIMARY VICARIOUS CALIBRATION SITE....................... 5
  - MOBY and the Marine Optical System (MOS) ..................................... 5
  - Ancillary Measurements on MOBY ....................................................... 8
  - Mooring Buoy Measurements .............................................................. 10
  - Data Communications ....................................................................... 10
- 2.3 MOBY OPERATIONS AND MEASUREMENT METHODS .......... 10
  - Deployment Schedule and Methods ................................................. 10
  - MOCE and Other Validation Shipboard Operations .......................... 11
  - MOBY System Operations Scheduling .............................................. 13
  - Radiometric Measurements ................................................................ 13
  - Methods for Mitigating Bio-Fouling ................................................. 15
  - Ancillary Measurements .................................................................... 15
  - Sun Photometer and Sky Radiance Measurements (on Lanai and Oahu) 16
- 2.4 CALIBRATION AND QUALITY CONTROL ............................... 16
  - Radiometric Calibration and Characterization of MOS ................. 16
  - Field Tests of Radiometric Stability Using Diver Deployed Sources 17
  - Wavelength Stability Tests Using Fraunhofer Lines ..................... 17
  - Stray Light Characterization .............................................................. 18
  - CIMEL Sun Photometer and Sky Radiance Sensor Calibrations ........ 20
- 2.5 DATA ANALYSIS METHODS ............................................... 20
  - Temporal Averaging ......................................................................... 21
  - System Spectral Response Functions ............................................... 21
  - Measurement Depths ....................................................................... 21
  - Determining LW(l) by Upward Extrapolation ................................. 22
  - Normalized Water-Leaving Radiance .............................................. 22
  - Spectral Band Averaging .................................................................. 23
- 2.6 DATA ARCHIVAL AND RECORDKEEPING ............................. 24
- 2.7 FUTURE DIRECTIONS ......................................................... 24
  - Temperature Characterizations ......................................................... 24
  - Stray Light Characterizations ............................................................ 25

## CHAPTER 3
**RADIOMETRIC AND BIO-OPTICAL MEASUREMENTS FROM MOORED AND DRIFTING BUOYS: MEASUREMENT AND DATA ANALYSIS PROTOCOLS**

- 3.1 INTRODUCTION ......................................................................... 35
  - Bio-optical measurements from moored and drifter platforms .......... 36
- 3.2 BIO-OPTICAL MOORING NETWORKS AND DRIFTING BUOY EXPERIMENTS: STRATEGIC PRINCIPLES ................................. 38
  - Coastal and Continental Shelf Oceanographic Features and Processes 39
  - Equatorial Oceanographic and Air-Sea Interaction Processes ............ 41
  - Oceanographic Processes in Oligotrophic Water Masses .................. 43
  - The Southern Ocean ......................................................................... 45
  - California Current System Drifter Studies ........................................ 46
- 3.3 MOORING AND DRIFTER ARRAY CONFIGURATIONS ................ 46
<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moored Surface Buoys</td>
<td>46</td>
</tr>
<tr>
<td>Subsurface Moorings</td>
<td>51</td>
</tr>
<tr>
<td>Profiling Moorings</td>
<td>51</td>
</tr>
<tr>
<td>Drifting Buoy Configurations</td>
<td>51</td>
</tr>
<tr>
<td>3.4 MEASUREMENT METHODS AND INSTRUMENTATION</td>
<td>52</td>
</tr>
<tr>
<td>Instrument Control and Data Acquisition</td>
<td>54</td>
</tr>
<tr>
<td>Radiometric Measurement Methods</td>
<td>57</td>
</tr>
<tr>
<td>Radiometers</td>
<td>60</td>
</tr>
<tr>
<td>Inherent Optical Properties Measurement Methods</td>
<td>61</td>
</tr>
<tr>
<td>Methods for Other Measurements</td>
<td>63</td>
</tr>
<tr>
<td>Validation Using Shipboard Measurements</td>
<td>63</td>
</tr>
<tr>
<td>3.5 DATA BUOY OPERATIONS AND MEASUREMENT METHODS</td>
<td>64</td>
</tr>
<tr>
<td>Deployment/recovery schedules and methods</td>
<td>64</td>
</tr>
<tr>
<td>Instrument Controllers, Data Recording, and Telemetry Scheduling</td>
<td>64</td>
</tr>
<tr>
<td>3.6 DATA ANALYSIS AND QUALITY CONTROL METHODS</td>
<td>66</td>
</tr>
<tr>
<td>Above-Water Spectral Irradiance</td>
<td>66</td>
</tr>
<tr>
<td>In-Water Radiometric Data</td>
<td>68</td>
</tr>
<tr>
<td>IOP Data</td>
<td>73</td>
</tr>
<tr>
<td>Chlorophyll a Fluorescence Data</td>
<td>74</td>
</tr>
<tr>
<td>3.7 RECORDKEEPING AND DATA ARCHIVAL</td>
<td>75</td>
</tr>
<tr>
<td>Logs and supporting documentation</td>
<td>75</td>
</tr>
<tr>
<td>Data Archival</td>
<td>75</td>
</tr>
<tr>
<td>CHAPTER 4</td>
<td>79</td>
</tr>
<tr>
<td>OCEAN COLOR RADIOMETRY FROM AIRCRAFT: I. LOW ALTITUDE MEASUREMENTS FROM LIGHT AIRCRAFT</td>
<td>79</td>
</tr>
<tr>
<td>4.1 INTRODUCTION</td>
<td>79</td>
</tr>
<tr>
<td>4.2 MEASUREMENT METHODS</td>
<td>79</td>
</tr>
<tr>
<td>4.3 RADIOMETRIC CORRECTION METHODS FOR AIRBORNE OCEAN COLOR RADIANCE MEASUREMENTS</td>
<td>80</td>
</tr>
<tr>
<td>Atmospheric Attenuation</td>
<td>80</td>
</tr>
<tr>
<td>Atmospheric Path Radiance</td>
<td>81</td>
</tr>
<tr>
<td>Surface Glint</td>
<td>82</td>
</tr>
<tr>
<td>Water-Leaving Radiance from Low-Altitude Radiance Measurements</td>
<td>83</td>
</tr>
<tr>
<td>4.4 CHLOROPHYLL A DETERMINATION</td>
<td>83</td>
</tr>
<tr>
<td>Water-Leaving Radiance Ratio Algorithms</td>
<td>83</td>
</tr>
<tr>
<td>Spectral Curvature Algorithm</td>
<td>83</td>
</tr>
<tr>
<td>4.5 DISCUSSION</td>
<td>84</td>
</tr>
<tr>
<td>CHAPTER 5</td>
<td>87</td>
</tr>
<tr>
<td>STRAY-LIGHT CORRECTION OF THE MARINE OPTICAL BUOY</td>
<td>87</td>
</tr>
<tr>
<td>5.1 INTRODUCTION</td>
<td>87</td>
</tr>
<tr>
<td>5.2 STRAY-LIGHT CORRECTION ALGORITHM</td>
<td>91</td>
</tr>
<tr>
<td>5.3 DERIVATION OF MOBY SLC MODEL PARAMETERS</td>
<td>93</td>
</tr>
<tr>
<td>Experimental</td>
<td>93</td>
</tr>
<tr>
<td>MOS205/MOBY219 BSG in-band area</td>
<td>97</td>
</tr>
<tr>
<td>MOS205/MOBY219 BSG out-of-band slit-scatter function component</td>
<td>98</td>
</tr>
<tr>
<td>MOS205/MOBY219 BSG Reflection peaks</td>
<td>99</td>
</tr>
<tr>
<td>M205/MOBY219 BSG Off-CCD Scattering</td>
<td>104</td>
</tr>
<tr>
<td>MOS205/MOBY219 Red Spectrograph (RSG)</td>
<td>104</td>
</tr>
<tr>
<td>MOS205/M219 RSG in-band area</td>
<td>104</td>
</tr>
<tr>
<td>MOS205/M219 LuMid RSG OOB Slit-scatter Function</td>
<td>104</td>
</tr>
<tr>
<td>MOS205/M219 LuMid RSG Reflection peaks</td>
<td>104</td>
</tr>
<tr>
<td>5.4 STRAY-LIGHT CORRECTION OF MOBY</td>
<td>109</td>
</tr>
<tr>
<td>5.5 ALGORITHM VALIDATION</td>
<td>113</td>
</tr>
<tr>
<td>5.6 UNCERTAINTIES</td>
<td>115</td>
</tr>
</tbody>
</table>
Chapter 3

Radiometric and Bio-optical Measurements from Moored and Drifting Buoys: Measurement and Data Analysis Protocols

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3.1 INTRODUCTION

No single type of observational platform provides radiometric and other bio-optical measurements at all scales of spatial and temporal variability that are important for research in oceanic primary productivity and regional, or global, carbon cycles, for example (Figure 3.1). Traditional shipboard observations enable detailed regional studies, but provide limited spatial and temporal coverage. Observations from instruments on moored and drifting buoys afford excellent temporal and vertical resolutions, but are limited to Eulerian and Lagrangian spatial contexts, respectively. Ocean color satellites offer excellent spatial and daily-to-weekly coverage, but are limited to clear-sky conditions and cannot account for variations with depth in the water column. In recent years, it has become increasingly clear that the combined data from moorings, drifters, ships and satellites provide a powerful tool for identifying and describing oceanographic processes (Dickey, 1991, 2003). The purpose of this chapter is to provide protocols describing methods for making and applying time-series measurements from moored and drifting buoys in this context.

The deployment and operation of moored and drifting observation platforms has proven to be a successful and reliable means of acquiring oceanographic and meteorological data (Dickey 1991, 2003; Smith et al. 1991; Chavez et al. 1997). Bio-optical, radiometric and physical time-series measurements, made at high temporal resolution throughout periods of several months duration from moored platforms, provide data describing important episodic and periodic oceanographic processes that are difficult to observe using other methods. Moorings have formed the foundation of several long term ocean monitoring projects, including the Tropical Ocean Global Atmosphere (TOGA) observing system (McPhaden et al. 1998), the Hawaii Ocean Time-series (HOT; Karl and Lukas, 1996), and the Bermuda Testbed Mooring (BTM; Dickey et al. 1998a, 2001) at the Bermuda Atlantic Time Series (BATS; Siegel et al. 2001) site, as well as several ONR and NSF JGOFS funded process studies of one or more years duration, including Biowatt (Dickey et al. 1987), the Marine Light in the Mixed Layer (Dickey et al. 1991), JGOFS/ONR Arabian Sea Experiment (Dickey et al., 1998b), JGOFS Equatorial Pacific Study (Foley et al., 1998), and the ONR Coastal Mixing and Optics Experiment (Dickey and Williams, 2001). Moorred bio-optical arrays were used in the Antarctic Environment Southern Ocean Process Study as part of the U.S. Joint Global Ocean Flux Study (JGOFS) to study mesoscale processes in the Antarctic Polar Front (Abbott et al., 2000). Instrumented drifting buoys of many different types have also been used in a variety of field campaigns including the TOGA-TAO project (McPhaden et al., 1998), the IronEx cruises (Kudela and Chavez, 1996) and the World Ocean Circulation...
Regional ocean observing systems, such as the Gulf of Maine Ocean Observing System (GoMOOS; www.gomoos.org) are now in operation, or are being planned in the near future with the long-term goal of forming a network of integrated, sustained operational observing systems for the U.S. coastal waters (see Ocean.US web site). Government agencies now recognize the importance of moorings and drifters and plan to implement an integrated ocean observing system incorporating both technologies (www.ocean.us.net).

Moorings carry significant payloads, allowing many different variables to be measured from each platform. As a result of the large number of instruments and the necessary hardware needed to support a mooring (float, line, glass balls, anchor, acoustic release, etc.), these platforms are relatively expensive to build, deploy, operate and maintain. Drifters, on the other hand, are usually smaller, carry fewer instruments, need much less hardware, and each copy is far less expensive than a typical moored array. In addition, since drifters are designed to track water masses they can quantify the time-dependent evolution of physical and bio-optical properties within particular water mass features. However, large numbers of drifters are needed, and as they are generally not recoverable, they must be considered expendable. Moored instruments, on the other hand, are recovered and reused. Moreover the methods of interpreting mooring data are much better developed. Nevertheless, equivalent ship-based observations are even more expensive than mooring, or drifter, observations. A relatively large number of drifting data buoys can be used to augment high-resolution time-series measured with moored arrays at a few fixed locations, seeking an optimal balance between spatial and temporal coverage (Dickey, 2003).

**Bio-optical measurements from moored and drifter platforms**

The deployment of radiometers, and other bio-optical sensors, on moorings and drifters facilitates bio-optical measurements that transcend the spatial and temporal boundaries of classical shipboard methods (e.g. shipboard radiometric profiles) to enhance our understanding of oceanographic processes, particularly biological-physical coupling. Moored arrays observe bio-optical variables and ocean current velocities from an Eulerian perspective, yielding vector transport of bio-optical properties at a fixed point. It was recognized in the initial version of the
Ocean Optics Protocols (Mueller and Austin, 1992) that optical measurements from moorings would provide new insight into optical, oceanographic and biophysical measurements in the field and be important platforms for the validation of SeaWiFS. In particular, optical moorings were recommended as important platforms for the collection of long-term, in situ data that could be used, together with satellite ocean color data, for:

- Radiometric validation of SeaWiFS normalized water-leaving radiance. This concept has been implemented in the Moored Optical Buoy observatory off Lanai, Hawaii (Vol. VI, Chapter 2), data from which have been used as the primary reference for vicarious calibration of SeaWiFS and other satellite ocean color sensors (Gordon and Wang, 1994; Clark et al. 1997; McClain et al. 2000a, 200b).

- Developing and validating algorithms for pigment biomass and phytoplankton primary productivity (Dickey et al. 1998a, 2001; Chavez et al. 1999).

- Providing long-term, virtually continuous, time series of in situ observations characterizing biogeochemical processes in the upper ocean.

Chavez et al. (1999) and (Dickey et al. 1998a, 2001) expanded these ideas as they relate to combining satellite ocean color time series data with measurements from moored and drifting buoys to obtain regional and global descriptions of biological variability. These applications require the use of in situ radiometers, and other bio-optical sensors, for long periods of time to evaluate and correct for inherent satellite under-sampling and degradation of satellite color sensors.

Multi-year deployments of optical moorings and frequent drifter deployments are now realistic as a result of recent technological advances such as in hardware, power sources, and anti-fouling devices (Dickey et al. 1998a, 2001; Chavez et al. 1997, 2000; Manov et al. 2003). In order to assure that radiometric and bio-optical data acquired from various optical moorings meet uniform standards of quality and accuracy, clear and rigorous sampling and data processing methods must be used consistently throughout the community.

The purpose of this chapter is to describe protocols covering:

1. Strategic principles for the location and deployment duration of moored instrument arrays, and for numbers, locations and frequency of deploying instrumented drifting buoys, to augment satellite ocean color imagery and shipboard sampling (or vice versa) in studies of mesoscale and regional scale oceanographic phenomena.

2. State of the art design and fabrication of bio-optical moored and drifting data buoys

3. Methods for maintaining and operating moored instrument arrays, including:
   a. Mooring deployment
   b. Periodic maintenance during deployments and replacement of moorings and instruments.

4. System operation methods, including:
   a. Instrumentation
   b. Bio-fouling avoidance and mitigation
   c. On-board autonomous instrument operations, data acquisition, data storage, sampling schedules, time base methods (e.g. GPS on on-board clock), and time synchronization of data records from multiple instruments.
   d. On-board data processing and near-real-time data communications
   e. Platform geo-location, for tracking drifting buoys, and as a safety measure should a mooring come adrift.

5. Methods of data processing, quality control and analysis.

6. Data archival and retrieval.

The chapter concludes with insights into future directions for the design and applications of moored and drifting bio-optical buoys, together with satellite ocean color imagery, in studies of oceanographic biogeochemical phenomena.
3.2 BIO-OPTICAL MOORING NETWORKS AND DRIFTING BUOY EXPERIMENTS: STRATEGIC PRINCIPLES

The configuration of a mooring, or drifter, is dependent upon the objective and strategy of the respective projects. Ideally, the combination of the two types of instrumented buoys, shipboard oceanographic surveys, and satellite remote sensing measurements will result in a four-dimensional observation system that encompasses time and space scales, ranging from seconds to decades and meters to global proportions, respectively (e.g., Dickey, 1991, 2003; Dickey et al., 2003). Careful planning is critical if the desired results, products and benefits are to be realized. The configuration of an ocean observatory must consider the following factors:

- **Scientific Objectives**: such as satellite sensor validation, studies of biogeochemical cycling and temporal variability in bio-optical properties of the upper ocean, and biological responses to physical forcing.
- **Space Scales of Processes**: water mass formation, transformation, or advection
- **Time Scales of Processes**: diurnal, seasonal, episodic, or decadal
- **Location**: coastal, equatorial, or central gyre oceanographic regimes
- **Array Type**: drifter, single instrumented mooring, or a geographic array of moorings.
- **Coordination with Other Sampling Methods**: such as shipboard measurements and satellite remote sensing
- **Regional Issues and Users Needs**: Regional ocean observatories may not be strictly science driven. GoMOOS is an excellent example of an observatory maintained to serve the broader public good through
an infrastructure that collects data pertinent to the public, academic, private, and governmental institutions. In the design of future ocean observatories, therefore, a balance must be maintained between scientific objectives and the information needs associated with coastal issues of operational importance to regional institutions, governments, and commercial enterprises.

The purpose and locations (illustrated in Figure 3.2) of some successful moored and drifting projects are described below (organized by types of oceanographic regimes).

**Coastal and Continental Shelf Oceanographic Features and Processes**

**MOOS:** The Monterey Bay Aquarium Research Institute (MBARI) has employed advanced mooring platforms in coastal waters for over a decade as part of an ongoing comprehensive Monterey Bay Ocean Observing System (MOOS; Figure 3.3). The main reasons for deploying moorings in coastal settings are to observe the time-series relationship between physical and biological dynamics in upwelling settings, study harmful algal blooms, advance our understanding of the three dimensional carbon cycling process, determine the impact of iron limitation on coastal primary productivity, and serve as a test and development site for new sensors and mooring technology. MOOS utilizes two moorings, located at 36.755°N, 122.025°W (M1) and 36.692°N, 122.390°W (M2), that work together as an array. The MOOS program also includes bi-monthly shipboard oceanographic surveys and routine monitoring of the study region using remote sensing observations. Recently, MBARI has modified the MOOS mooring concept to include satellite based bi-directional communications, event detection and response, as well as...
integration and operation with Autonomous Unmanned Vehicles AUV's and automated vertical profilers fitted with optical instruments.

Since 1993, a series of research initiatives, including the US GLOBEC North East Pacific and Coastal Advances in Shelf Transport programs, have supported the deployment of a series of subsurface moored radiometers and optical drifters off the Oregon Coast and Northern California (Abbott and Letelier, 1998). The drifters deployed were WOCE Ocean Color Monitor (OCM) Lagrangian drifters, manufactured by METOCEAN Data Systems Ltd. and Satlantic, Inc. These instruments measure the location, sea surface temperature, upwelling radiance at 7 wavebands in the visible (412, 443, 490, 510, 555, and 670 nm (20 nm bandpass); and 683 nm (10 nm bandpass)) and downwelling irradiance at 490 nm (20 nm bandpass). Measurements are made every 90 seconds, averaged over a one hour period, and transmitted to shore-based laboratories via ARGOS. The subsurface moored radiometers are deployed below the first optical depth, between 5 and 10 m depth, and measure downwelling irradiance at the same 7 visible wavebands used in the drifters. All these optical sensors are calibrated by Satlantic, Inc., before deployment.

AVPPO: The Woods Hole Oceanographic Institution has developed a profiling mooring for coastal waters, the Autonomous Vertically Profiling Plankton Observatory (AVPPO). The AVPPO consists of buoyant sampling vehicle and a trawl-resistant bottom-mounted enclosure, which holds a winch, the vehicle (when not sampling), batteries, and controller. Three sampling systems are present on the vehicle: a video plankton recorder, a CTD with accessory sensors, and a suite of bio-optical sensors including Satlantic OCI-200 and OCR-200 spectral radiometers and a WetLabs ac-9 dual path absorption and attenuation meter. At preprogrammed times the vehicle is released, floats to the surface, and is then winched back into the enclosure with power and data connection maintained through the winch cable. Communication to shore is possible through a bottom cable and nearby surface telemetry buoy, equipped with a mobile modem, giving the capability for near-real time data transmission and interactive sampling control.

GoMOOS: The Gulf of Maine Ocean Observing System was initiated in late 2000, with the first deployment of the entire mooring array completed in July 2001. GoMOOS was initiated as an operational observatory, serving as a benchmark for other user-driven ocean observing systems. The primary objective of GoMOOS is to provide the
infrastructure for collecting sustained, long-term observations of the Gulf of Maine region. The backbone of the GoMOOS is the mooring program. Ten mooring are located throughout the Gulf of Maine (Fig. 3.4; see www.gomoos.org for exact locations); one in the deep basin, 4 along the shelf waters, and 6 located in nearshore environments. The standard suite of measurements on each mooring includes meteorologic and hydrologic conditions (Fig. AHB2). Four of the GoMOOS moorings also have instrumentation to measure the bio-optical conditions. The GoMOOS program also includes a series of CODAR stations to map the surface currents over the entire Gulf of Maine, circulation and wave modeling programs, as well as utilizing NASA and NOAA remote sensing time series (ocean color, sea surface temperature, winds).

**CMO and PRIMER:** The interdisciplinary oceanographic programs known as Coastal Mixing and Optics (CMO), Shelfbreak PRIMER (not an acronym), and Synthetic Aperture Sonar (SAS) PRIMER conducted a number of coordinated field experiments in the vicinity of the New England continental shelf over the period from September 1995 to August 1997 (Dickey and Williams, 2001; see www.opl.ucsb.edu). CMO focused on physical, bio-optical, and sedimentary processes on the continental shelf, while the Shelfbreak PRIMER investigated physical processes over the shelf and slope and their influence on sound transmission onto the shelf. The experiment utilized several different observing platforms enabling measurements over space scales from centimeters in the vertical to tens of kilometers in the horizontal and time scales from minutes to the annual cycle. The results of the experiment have led to improved understanding of inter-relationships and couplings among physical, bio-optical, sedimentary, and acoustical properties and processes. Two hurricanes passed near the study site enabling novel research concerning the physical and bio-optical effects of intense atmospheric forcing. Internal solitary waves and their relation to bio-optical events was another highlighted study area.

**HyCODE:** The Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) was an Office of Naval Research (ONR) sponsored five-year interdisciplinary program (see www.opl.ucsb.edu). HyCODE field experiments were located off the coast of New Jersey at the Long-term Ecological Observatory site in 15 m water depth (LEO-15), on the west Florida Shelf as part of the ONR Ecology of Harmful Algal Blooms (EcoHAB) program, and in the Bahamas near Lee Stocking Island as part of the ONR Coastal Benthic Optical Processes (CoBOP) program. The main objective of the HyCODE program was to develop an understanding of the diverse processes that control inherent optical properties (IOP) and apparent optical properties (AOP) in the coastal ocean by use of hyperspectral imagery. Platforms included moorings, ships, gliders, AUVs, and aircraft, most of which were equipped with hyperspectral instrumentation. Basic research was centered on the investigation of the impact of relatively small-scale physical, biological, and chemical processes on near-surface spectral IOP and AOP. Some of the processes under investigation for the HyCODE project include advection of optically important material, phytoplankton growth and loss, bubble injection, sediment resuspension, fronts, and internal waves. Applied research focuses on the development and validation of hyperspectral ocean color algorithms. Moorings were used to provide high temporal resolution bio-optical (i.e., IOP and AOP) and physical data sets. These experiments were designed to sample the maximum possible number of matched in situ IOP and AOP observations for calibrating, groundtruthing, and relating subsurface optical properties (algorithm development) to satellite data, and to develop, test, and validate optical models and high-resolution interdisciplinary models of the coastal ocean.

**MEPS:** The Marine Environmental Prediction System (MEPS) is a network of moored buoys in Lunenburg Bay, Canada (see www.phys.ocean.dal.ca/programs/cmep/cmep.html). MEPS is part of the CMEP (Centre for Marine Environmental Prediction), a initiative led by Dalhousie University and funded through the Canadian Foundation for Innovation. MEPS consists of three heavily instrumented buoys, a real-time, high speed broadband communications network, and a modeling and analysis system for transforming sensor data into information that can be visualized by a broad range of system users. The buoy network provides data from AOP, acoustic, physical and meteorological sensors to monitor the biological variability and transport of sediments within Lunenburg Bay. The system is designed to provide both high temporal, spatial and vertical resolution of processes within Lunenburg Bay. This combination of a wide range of sensors and flexible data acquisition system with a large power system and high bandwidth wireless telemetry make this system ideal for validating remote sensing data in the coastal zone.

**Equatorial Oceanographic and Air-Sea Interaction Processes**

**TOGA TAO/TRITON:** The Tropical Ocean-Global Atmosphere (TOGA) observing system consists of ~70 moored platforms along the equatorial Pacific to observe oscillations associated with the El Nino and Southern Oscillation (ENSO). These ENSO specific moorings cover the entire equatorial Pacific from 95°W across the date line to 165°E, from 8°N to 8°S. Recently the project name was changed to the Tropical Atmosphere Ocean/Triangle
Trans-Ocean Buoy Network (TAO/TRITON) array to recognize the introduction of TRITON mooring array (http://www.jamstec.go.jp/jamstec/TRITON/) of buoys in the western Pacific by the Japan Marine Science and Technology Center (JAMSTEC); these moorings replaced 12 ATLAS buoys along 137°E, 147°E, and 156°E in 1999.

EqPac: The first moored bio-optical measurements in the equatorial Pacific (0°, 140°W) were conducted by the UCSB (formerly USC) during JGOFS in 1991-1993 (Foley et al., 1998). More recently, two selected ATLAS buoys in the equatorial Pacific were modified by MBARI to accommodate robust instrument packages for open-ocean bio-optical and biogeochemical measurements as part of SIMBIOS ocean color validation (Figure 3.5). The designs of the two moorings, commonly referred to by MBARI as EP1 (0°, 155°W) and EP2 (2°S, 170°W), are TAO ATLAS buoys modified to host optical and chemical instruments with the objectives:

1. To obtain near real-time moored bio-optical measurements, including $L_{WN}$, at two locations in the equatorial Pacific for calibration-validation of satellite ocean color sensors.

2. To obtain optical profiles at up to 30 stations per year in the equatorial Pacific, including derivation of $L_{WN}$, for calibration-validation of satellite ocean color sensors.

3. To use hyperspectral optical data from Monterey Bay and the equatorial Pacific, in conjunction with in situ biogeochemical sampling and satellite data, to contribute to bio-optical algorithm development.

4. To determine the spatio-temporal variability in phytoplankton biomass, primary production, carbon dioxide and nutrient distributions, as a result of physical perturbations.

PIRATA: The project PIRATA (Pilot Research Moored Array in the Tropical Atlantic) maintains a string of moorings in the Equatorial Atlantic Ocean that is equivalent to the Pacific TAO array (Servain et al. 1998). PIRATA is a multinational pilot experiment in operational oceanography, with the participation of Brazil, France and the USA. The PIRATA network consists of 12 ATLAS moorings, extending along the equator and two meridional lines. This geographic configuration is designed to monitor persistently strong wind forcing over the
western Equatorial Atlantic basin, together with seasonal-to-interannual variability in SST in the central and eastern basins. The meridional arrays cover the regions of high SST variability associated with the SST dipole mode. A set of spectroradiometers and fluorometers have been deployed at the Lambada mooring (8N, 38W) in the PIRATA array to add a biogeochemical component to the program and to study the effect of the Amazon River/North Equatorial Counter Current, tropical instability vortices, the effect of dust on phytoplankton productivity and carbon cycling in this region. This bio-optical mooring addresses the following three specific objectives:

1. Provide high temporal resolution (6 times daily) in-situ spectroradiometric measurements to fill missing satellite measurements due to dust, clouds, and gaps due to satellite orbit patterns, sun glint avoidance and tilt maneuvers.
2. Use the in-situ measurements to evaluate atmospheric correction algorithms by comparing the in-situ and satellite derived normalized water leaving radiance estimates.
3. Use the combination of the chlorophyll concentrations derived from the in-situ spectroradiometric measurements and fluorometric measurements to study both temporally short events, such as tropical instability waves and the effect of aeolian dust deposition on marine productivity (including the time lag between dust deposition and increased chlorophyll biomass), as well as long-term trends in primary production and biogeochemical cycles in this region.

**JGOFS EQPAC Drifter Studies:** The first deployment of a drifting buoy with high precision optics (McLean and Lewis, 1991) was carried out in 1994, in association with the JGOFS Equatorial Pacific Process Study. The drifters were air-launched from a NASA P-3 low altitude aircraft, which was carrying out remote sensing support of the seagoing mission. The buoy was a modified Compact Meteorological and Oceanographic Drifter (CMOD) manufactured by MetOcean Data Systems. A seven channel (450, 492, 532, 562, 656, 683, 700 nm) downlooking radiance sensor (Satlantic) was deployed on the buoy approximately 0.5 meters below the sea-surface and a single uplooking irradiance sensor (490 nm) was deployed on the extendable mast above the surface. Raw data was communicated via the ARGOS system. Radiances were propagated to and through the sea-surface using empirical algorithms for spectral attenuation, and normalized by the spectral downwelling irradiance inferred from the measured value at 490 nm and a model for spectral sun and sky irradiance. Two buoys were successfully deployed during this experiment and operated for several months. The resulting normalized water-leaving radiances were used to estimate chlorophyll concentrations. Based on these data, several novel syntheses resulted, ranging from a means to integrate shipboard estimates of primary production and grazing over the larger scale (Landry et al., 1997), and an improved understanding of the role of tropical instability waves in the production dynamics of this region (Foley et al., 1997). These first drifting buoys were the predecessors for subsequent optical deployments on several platforms, notably the surface WOCÉ/OCM drifters used extensively by Oregon State University (Abbott and Letelier, 1998).

**Oceanographic Processes in Oligotrophic Water Masses**

**BATS/BTM:** The Bermuda Testbed Mooring (BTM) was first deployed in 1994 and continues in operation today (Dickey et al., 1998b, 2001a). High frequency, long-term data measured by the BTM instruments are used for studies and models of upper ocean biogeochemistry and physics, to develop and test new multi-disciplinary sensors and systems, and to provide validation data for satellite ocean color imagers including SeaWiFS. The complementary Bermuda Atlantic Time-series Study (BATS) was established in 1988 as part of the U.S. JGOFS program, to characterize, quantify, and understand processes in the Sargasso Sea that control ocean biogeochemistry, especially carbon, on seasonal to decadal time scales. BATS ship sampling is done monthly and every two weeks during the springtime. Ship-based bio-optical profiles (sampling in concert with BATS) and remotely-sensed ocean color data have been obtained at the BATS site (Fig. 3.2) since 1992 by the Bermuda Bio-Optics Program (BBOP; Siegel et al. 2001). BTM measurements were an important addition as processes with time scales of less than a few weeks (e.g., eddies, wind-events, and transient blooms) cannot be resolved with monthly or bi-weekly shipboard observations. The BTM program has tested and utilized a broad range of autonomous sampling sensors and systems. These include new measurements of pCO2, dissolved oxygen, nitrate, trace elements (e.g., iron and lead), several spectral inherent and apparent bio-optical properties, 13C for primary production, and currents (Dickey et al., 1998a, 2001). Several bio-optical systems designed to measure IOP and AOP have been tested using the BTM (Figure 3.6). The bio-optical instruments (placed on the surface buoy and at 2 to 4 different depths) are used to determine relevant remote sensing parameters such as remote sensing reflectance (e.g., Dickey et al., 2001; Zheng et al., 2002, 2003). The depths are optimally selected to enable extrapolation of subsurface radiance to the
surface. An advantage of mooring validation is the high number of match-up data for satellite calibrations (data are collected regardless of cloud cover as well).

**Fig. 3.6.** Schematic illustration of the Bermuda Testbed Mooring (BTM), showing an example of the taut-wire mooring, surface buoy, and instrument locations.

**HOT:** The Hawaii Ocean Time-series (HOT) program was initiated in 1988 in parallel with the BATS program. The HOT measurements are conducted at the oligotrophic Station ALOHA (22°-45'N, 158°-00'W) site north of Oahu. HOT’s main objective is to obtain a long time-series of physical and biogeochemical observations in the North Pacific subtropical gyre to:

- document and understand seasonal and interannual variability of water masses, develop climatologies of physical and chemical variables,
- document and understand seasonal and interannual variability in primary production, new production and particle export from the surface ocean,
- quantify time-varying concentrations of carbon dioxide, and
- study the ecology of a subtropical gyre.

HOT’s core measurements were selected to provide a data set to improve existing C-N-P biogeochemical models. Selected data trends related to the intensification of N and P cycles, changes in microbial community structure and the role of high frequency physical events have been documented. An interdisciplinary instrumented mooring was deployed at the HOT site in 1996, and continued in operation until about 2000 (Letelier et al., 2000). The mooring experiment, dubbed HALE ALOHA (Hawaii Air-sea Listening Experiment; Hale is also a Hawaiian word translated “at the house of”) initially included meteorological, physical, optical and chemical sensors. Additional instruments,
including two water samplers designed for trace metal and nutrient analyses (Ed Boyle, MIT; Pers. Comm.), current meters, conductivity-temperature (CT) sensors, and a cellular phone for daily data transmission and instrument interrogation, were added during the HALE ALOHA-II experiment. Since that time, the mooring has been recovered and redeployed a total of five more times, and the mooring instrument configuration has remained more, or less, the same. The data collected by this deep-sea mooring facility are critical to the detection and understanding of the mesoscale processes hypothesized to be the dominant causes of biogeochemical variability in this subtropical gyre habitat. The recently funded NOPP MOSEAN program (www.opl.ucsb.edu) will deploy a new HALE ALOHA mooring, quite similar to the BTM, near the HOT site as well as a shallow water mooring in Santa Barbara Channel off California. Data collected by the deep-sea mooring are essential for detection and understanding of the mesoscale processes that contribute significantly to biogeochemical variability in this subtropical gyre habitat.

The Southern Ocean

The Antarctic Polar Front is a complex set of meandering jets, which appear to support enhanced primary productivity. The U.S. Joint Global Ocean Flux Study (JGOFS) conducted a series of survey and process studies in part to study the processes regulating primary productivity in this high nutrient, low chlorophyll (HNLC) region. Abbott et al. (2001) deployed a set of surface velocity drifters, some of which were equipped with bio-optical sensors, to study the temporal and spatial scales of biological and physical processes in the Antarctic Polar Frontal Zone (APFZ). There were two primary sets of deployments: November 1997 before the spring bloom and January 1998 after the spring bloom. The November deployment revealed a strong spring bloom, although it decreased over time, persisted at somewhat higher values throughout the drifter deployment than the bloom observed at a fixed moored optical array. In late spring when incoming solar radiation began to increase, the vertical motions associated with the meanders strongly affected the accumulation of phytoplankton biomass, primarily through their impact on light availability. Weaker meandering was observed in the January deployment, and chlorophyll values remained relatively constant. As the bloom began to decay, it appears that nutrient availability became more important in regulating phytoplankton photosynthesis. Some of the drifters in the November deployment were deployed in coherent clusters, thus allowing us to calculate vertical velocities associated with the meanders. Estimates of fluorescence/chlorophyll suggest that areas of upwelling and downwelling alternately decrease and increase photosynthetic stress, perhaps as a result of changes in the availability of iron or light during the formation of the bloom.
deployed during Southern Ocean JGOFS (Abbot et al. 2000).

As part of the Southern Ocean JGOFS program, 12 subsurface optical moorings were deployed in a grid formation to study the mesoscale variability around 60.5°S, 170.0°W, between October 1997 and March 1998. Each mooring was a bottom-tethered mooring extending from the sea floor to 50 m below the sea surface (Fig. 3.7). Attached to each of these moorings was an irradiance sensor head that measured downwelling irradiance at seven wavebands in the visible from a depth of 50 m (Abbot et al. 2000). In addition, an array of physical and optical drifters was deployed within the Antarctic Polar Front zone to study the dynamics of the water masses meandering along this front (Abbott et al. 2001). Previously, optical drifter deployments had been successful in sampling eddies off the Antarctic peninsula (Letelier et al. 1997).

California Current System Drifter Studies

Abbott and Letelier (1998) used data from bio-optical drifters deployed in the California Current to estimate the decorrelation time scales (a measure of persistence) for chlorophyll (as estimated from radiance ratios) and for sun-stimulated fluorescence/chlorophyll (as a proxy for photosynthetic rate). These scales were significantly different in the nearshore zone (<200 km from shore) while they were nearly identical in the offshore zone (>400 km from shore). This implies that the ability to harvest light (as indicated by chlorophyll content) was not in balance with the ability to use light (as indicated by fluorescence/chlorophyll) in the nearshore zone. The similarity of the decorrelation time scales in the offshore zone suggest that the phytoplankton was more nearly in equilibrium. Abbott and Letelier (1998) also noted that physical time scales (as indicated by sea surface temperature) were nearly the same as the biological time scales in the nearshore zone but were significantly longer in the offshore zone. The short time scales (2 days) in the nearshore zone is consistent with variable upwelling and with previous observations of strong correlations between temperature and phytoplankton chlorophyll. In the offshore zone, physical processes affecting SST and chlorophyll are different, and there was little correlation between the two. Thus bio-optical drifters can be used to study the relative roles of physical and physiological processes in governing the spatial patterns of phytoplankton. Similar drifter deployments have been made as part of the Global Ecosystem Dynamics (GLOBEC) Northeast Pacific Program off the Oregon coast in 2000 and 2002.

3.3 MOORING AND DRIFTER ARRAY CONFIGURATIONS

Optical moorings designed for long-term deployments at open ocean sites must be capable of maintaining the integrity of optical and other measurements while the instruments are unattended for prolonged periods of time. Details of traditional mooring engineering concepts, theories and hardware configurations can be found in Bertaux (1991). Successful early examples of multiple-task optical moorings were the Multivariable Moored System (MVMS; Dickey et al. 1991, 1993) and the Bio-optical Moored System (BOMS; Smith et al. 1991). Optical drifters can be designed for short or long term deployments, as recoverable, or disposable, in coordination with various oceanographic sampling methods.

Moored Surface Buoys

Moored buoys generally have similar design configurations consisting of a tower, flotation buoy, bridle, mooring line, acoustic release, and anchor (Table 3.1). The TOGA array, for example, uses both the Profile Telemetry of Upper Ocean Currents design (PROTEUS; McPhaden et al., 1991) and the Autonomous Temperature Line Acquisition System (ATLAS) buoys designed by NOAA/PMEL (Milburn and McClain 1986). The PROTEUS and ATLAS frames are essentially similar in design (Figures 3.3 and 3.5). The ATLAS buoy employs a 2.3 m diameter toroid, fabricated with fiberglass over a foam core, a simple aluminum tower (~4.9 m) and a stainless steel bridle capable of holding a stainless-steel instrument cage. Each mooring platform is equipped with a low-cost ATLAS wind and thermistor chain array (Hayes et al. 1991). Two of the ATLAS buoys in the equatorial Pacific (M1 and M2, see above) were modified to host optical and chemical instruments. Currently deployed MOOS moorings are also of a PROTEUS design, modified to accommodate an instrument controller, solar panels, an elevator assembly for mounting near-surface sensors, and instrument cages for additional sensors at 0, 10 and 20 m depth. The elevators allow service of sensors, which are subject to substantial bio-fouling, at monthly intervals. The
stainless steel cages at 10 and 20 m protect the instruments. The new MOOS moorings are welded from aluminum utilizing a Surlyn discus buoy.
Table 3.1: Characteristics of moored bio-optical buoys, selected as examples from instrumented mooring networks covering the oceanographic regimes illustrated in Figure 3.1.

<table>
<thead>
<tr>
<th>PROJECT:</th>
<th>MOOS M1 &amp; M2</th>
<th>TAO/TRITON EP1</th>
<th>TAO/TRITON EP2</th>
<th>PIRATA Lambaba</th>
<th>HOT: HALE ALOHA</th>
<th>MEPS</th>
<th>BATS BTM</th>
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<tr>
<td>INSTITUTION:</td>
<td>MBARI</td>
<td>MBARI</td>
<td>MBARI</td>
<td>Multinational</td>
<td>UH</td>
<td>Dalhousie University</td>
<td>UCSB</td>
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<tr>
<td>LOCATION:</td>
<td>36.76°N, 122.02°W</td>
<td>0°N, 155°W</td>
<td>2°S, 170°W</td>
<td>8°N, 38°W</td>
<td>22.75°N, 158°W</td>
<td>Lunenburg Bay, Canada</td>
<td>31.7°N, 64.2°W</td>
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<tr>
<td>DEPTH (m)</td>
<td>2000 to ~4000 m</td>
<td>&gt;2000</td>
<td>&gt;2000</td>
<td>4750</td>
<td>20 m</td>
<td>4600</td>
<td></td>
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<tr>
<td>BUOY TYPE:</td>
<td>PROTEUS</td>
<td>ATLAS</td>
<td>ATLAS</td>
<td>ATLAS</td>
<td>Guardian</td>
<td>Surlyn discus</td>
<td>WHOI/UHCSB</td>
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<tr>
<td>Diameter (m)</td>
<td>2.5</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>3</td>
<td>1.2m</td>
<td>3</td>
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<tr>
<td>Height (m)</td>
<td>5.5</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>~5?</td>
<td>4</td>
<td>5</td>
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<tr>
<td>MOORING TYPE:</td>
<td>Semi-Slack</td>
<td>Taut Wire</td>
<td>Taut Wire</td>
<td>Taut Wire</td>
<td>Semi-Taut Wire</td>
<td>Semi-Taut Bi-moor</td>
<td>Semi-Taut Wire</td>
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<tr>
<td>DEPLOYMENT DURATION*</td>
<td>1 Month</td>
<td>1 Year</td>
<td>1 Year</td>
<td>???</td>
<td>1 Month</td>
<td>6-12 months</td>
<td>6 Months</td>
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<td>CONTROLLER/ DATA-LOGGER</td>
<td>OASIS (MBARI)</td>
<td>OASIS &amp; ATLAS</td>
<td>OASIS &amp; ATLAS</td>
<td>STORE-X</td>
<td>Multiple Data Loggers</td>
<td>DACNet</td>
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<td>Yes</td>
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<td>NEAR REAL-TIME TELECOMM</td>
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<td>High speed broadband wireless</td>
<td>Inductive Link, Acoustic &amp; ARGOS Telemetry</td>
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<td>3.6 &amp; 3.8</td>
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</table>

* Nominal operating service life between refurbishment/replacement visits.
A newly designed buoy was developed jointly by UCSB and WHOI to accommodate a variety of interdisciplinary sensors and systems (Figure 3.8). Some of the technical features of the new buoy include: reduced size for safer ship operations, removable instrumentation well, upgraded tower, improved and removable bridal, and overall total weight reduction. The buoy is equipped for satellite data telemetry, using ARGOS at present, and an Iridium system will be added in May 2003. The expected lifetime of the new buoy is about 10 years. The new buoy was deployed at the BTM site in September 2002, and another of this design is currently under construction to replace the present HALE-ALOHA (see above).

Fig. 3.8: Photograph of the newly designed and recently deployed interdisciplinary BTM surface buoy (www.opl.ucsb.edu).

The MEPS buoys are 1.2m Surlyn discus buoys. These house the DACNet computer system, wireless telemetry system, batteries and solar panels. The AOP sensors are deployed on a secondary surface-tracking package with a 33cm float to minimize shading. This small float is suspended within a triangular guard frame 9m on a side. The AOP package consists of a hyperspectral Es, a hyperspectral Lu sensor (at 40cm), and a chain of four, four channel irradiance sensors placed at 2, 4, 8, and 12m below the small surface float. The system also includes two ADVs (acoustic doppler velocimeters) and an ADCP (acoustic doppler current profiler) on a bottom-mounted frame. Power and real-time telemetry are connected via special Kevlar electromechanical cables to the main discus buoy. To avoid tangling of cables and the various packages, both the surface tracking AOPs and the main discus buoy are bi-moored to train wheels at the bottom. A schematic of the system configuration is shown in Figure 3.9. A photo of one of the buoy systems deployed is shown in Figure 3.10.

Another buoy package in common use is the HyperTSRB, a tethered buoy often deployed for vicarious calibration of remote sensing platforms. This system was originally developed for the ONR CoBOP and HyCODE programs to measure hyperspectral reflectance near the ocean surface. A typical configuration uses an in-air hyperspectral irradiance sensor to measure incident irradiance and a hyperspectral radiance sensor to measure upwelled radiance 50 cm below the surface. The buoy hull uses a 33 cm diameter flotation collar to keep the radiometers at the surface. Eight of these systems were used as calibration/validation references for the hyperspectral NRL PHILLS airborne imager during both HyCODE and CoBOP experiments. More recent configurations also utilize a multichannel chain of four irradiance radiometers below the surface (typically at 2, 4, 8 and 16m) for computing the diffuse attenuation coefficient. This type of configuration is used as part of MEPS. Other autonomous coastal monitoring systems have used these sensors as well, using the STOR-X and a cellular phone for data telemetry.
Figure 3.9: MEPS bi-moored system configuration showing the three main packages, the surface discus buoy, the surface tracking hyperspectral TSRB and four channel K Chain, and the bottom mounted acoustics. This configuration minimizes the effects of platform shading from the main buoy, and allows subsurface radiometers to be placed close to the surface without interference. This provides optimal performance in turbid coastal waters.

Figure 3.10: Photograph of one of the MEPS buoy systems in Lunenburg, Canada (a UNESCO World Heritage Site). This buoy is located in 20m of water near the harbour mouth. The main package containing batteries, solar panels, DACNet computer, meteorological station and wireless telemetry system is on the right. The surface tracking optical package, located about 50m away from the main buoy is in the left foreground.
Figure 3.11: Conceptual drawing of the “Ocean Color” GoMOOS moorings that have bio-optical instrumentation for use in ocean color remote sensing validation/calibration. The right panel shows the above water irradiance sensor mounted on the buoy, the ocean color bio-optical instrumentation package mounted at 3m, and the small optics package mounted on the mooring at 18 m (from top to bottom).

Buoys are usually moored using either a taut, or slack, wire design, although the recent introduction of wires with more spring offers advantages of both designs. Wire types include:

- **Taut-Wire Surface Moorings**: For the ATLAS systems used in the TAO, TRITON and PIRATA mooring networks, the upper 500 m of the mooring utilizes a jacketed 1.27 cm non-rotating (nilspin). This segment is followed by an eight-strand plaited nylon line (1.9 cm) extending to just above the ocean bottom, where an acoustic release couples it to a ~2000 kg railroad wheel anchor. Taut-line moorings, with a nominal scope of 0.985 (ratio of mooring line length to water depth) are used in water depths greater than 1800 m to ensure that the upper section of the mooring is nearly vertical. More detailed information on the ATLAS taut-wire mooring design is available on-line at (http://www.pmel.noaa.gov/tao).

- **Slack-Wire Moorings**: The TAO slack-line moorings have a scope of 1.35, due to either shallow bathymetry, or severe current regimes. GoMOOS moorings are slack-wire moorings, with a scope of ~1.32, using 80 m of wire and 100 m of chain, anchored by 3 railroad wheels (Fig. 3.11). In these cases, the upper portion of the mooring is kept close to vertical (but less so than with taut-line moorings) by using a reverse catenary design. The reverse catenary design allows the capabilities of being stretched under tension while utilizing traditional catenary concepts through a semi-slack method. Although taut-line moorings maintain subsurface sensor locations at or near desired depths, surface instruments may be subjected to stronger forces from waves and currents. The slack-line moorings provide greater flexibility in the upper water column, which may help reduce these forces.

- **Semi-slack/taut Wire Mooring**: MOOS moorings are on ‘semi-slack’ S shaped tethers with a 1.20% scope. The BTM and HALE ALOHA 3 m diameter buoy platforms have been previously configured as semi-slack moorings. However, the new configurations will be an inverse catenary design to reduce stress on all mooring components.

**Subsurface Moorings**

Subsurface moorings tested off Hawaii and used in the Southern Ocean during JGOFS (Fig. 3.7) are designed to minimize the vertical motion of radiometers derived from wave action and to remove the shading effect of a surface buoy and wiring. The mooring hardware includes two glass spheres and one large steel sphere. The 17" glass sphere beneath the sensor head was used to limit the range of tilt of the sensors. Note, however, that the mooring design allows vertical and horizontal movement of the sensors with variations in currents.

**Profiling Moorings**

Profiling optical moorings generally consist of a buoyant instrumented vehicle and a bottom-mounted enclosure housing a winch, controller and batteries if used autonomously. Profiles are achieved by paying out a tether which can also allow communications between the controller and instruments on the vehicle. Communications with a shore-based server, for example with a cell phone modem, allows data transmission and periodic updating of mission parameters such as profiling frequencies and minimum profile depth. Surface detachment of the profiling vehicle from the tether can facilitate instrument maintenance without recovery of the whole system.

**Drifting Buoy Configurations**

Drifting buoys have been deployed with AOP sensors in various configurations, most notably the ship-launched or air-launched CMOD type (McLean and Lewis, 1991), and the more common WOCE/OCM type, both manufactured by MetOcean Data Systems Limited. Both systems have surface tracking in-water multichannel radiance radiometers, and a single channel above water irradiance sensor (490 nm) and telemeter data back to the user via the ARGOS system. Due to bandwidth restrictions, the systems report an hourly average of radiometric measurements sampled every 90 seconds. Typically (latitude dependent) 12 data collections are reported to the user per day.
The CMOD type utilized a gas cartridge inflatable float around an 11cm diameter hull containing batteries, computer system and an ARGOS transmitter. At the base of the hull a seven channel radiance sensor (OCR-100) provided a nadir view of the light field at a depth of 50cm. At the top of the ARGOS antenna mast, a single channel (490 nm) irradiance sensor provided a reference for ambient solar radiation. A conical cloth drogue and base weight provided platform stability.

The WOCE type drifter uses a standard 35cm fiberglass hull with batteries, computer and ARGOS transmitter (Fig. 3.12). In the WOCE type buoys, a 1m diameter holey sock drogue located about 10m below the buoy is used to significantly improve water current tracking capabilities. A seven channel radiance sensor (OCR-100) is placed on the bottom of the hull, offset and angled ten degrees off nadir to avoid interference from the drogue. A single channel (490 nm) irradiance sensor is located on top of the hull. Since the irradiance sensor is very close to the water surface, it may become submerged, thus a submergence sensor is used to avoid collecting surface irradiance when the sensor is below the surface. In experiments off the Oregon Coast, the typical lifetime for these drifters was 3 - 7 months, although some failed immediately upon, or shortly after, deployment, and one lasted for 10 months. During the Southern Ocean Iron Enrichment Experiment (SOFeX) in 2002, several WOCE drifters were deployed by OSU, in coordination with deployments of a more heavily instrumented recoverable drifter by MBARI (Fig. 3.12 and Table 3.2).

Fig. 3.12: Configurations of drifters that were used during SOFeX 2002. The panel on the left schematically shows the configuration of the “short term” MBARI drifter, while the panel on the right shows the configuration of the “one-use” OSU/WOCE drifter.

3.4 MEASUREMENT METHODS AND INSTRUMENTATION
Many of the variables described as required and highly desired in Volume I, Chapter 3 (Table 3.1) can be measured using arrays of instruments mounted on buoys\(^3\), either moored or free-drifting. The protocols covering instrument performance characteristics, and related characterization and calibration methods, for radiometers (Volume II, Chapters 2 and 3), IOP instruments (Volume IV, Chapters 2, 3 and 5), \textit{in situ} chlorophyll a fluorometers (Volume V, Chapter 3), and instruments for ancillary measurements such as Conductivity-Temperature-Depth (CTD), wind speed and direction, and barometric pressure (Volume II, Chapter 1) are fully applicable to the use of such instruments on buoys. These topics will not be repeated here. On the other hand, while methods for making these measurements from buoys have much in common with the corresponding shipboard measurement methods for radiometry (Volume III, Chapter 2), IOP (Volume IV), and ancillary measurements (Volume I, Chapter 4), the protocols for measurement methods on buoys must take account of special factors:

1. All measurements must take place autonomously, without real-time hands-on operator intervention.
2. Automated measurements must be reduced to digital (or less-often analog) form, and either transmitted via a telecommunications link to a base laboratory, and/or stored on board for retrieval when the buoy is visited for maintenance, or recovery, at time intervals typically ranging from weeks to months. Especially in the case of free-drifting buoys, which are often treated as expendable and are not routinely recovered, the data must be retrieved over typically low-bandwidth telecommunications links (such as ARGOS); therefore, data retrieved in this way must usually be processed on-board and only limited data, \textit{e.g.} temporal averages and standard deviations, are transmitted.
3. Although special buoy designs permit continuous profile measurements of some variables over depth in the water column, more typical buoy configurations are instrumented to make time series measurements only at the surface and a few discrete depths.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{PROJECT:} & SOFeX & JGOFS EQPAC & SOFeX \\
\hline
\textbf{INSTITUTION:} & MBARI & Dalhousie University & OSU \\
\hline
\textbf{LOCATION:} & Southern Ocean & Equatorial Pacific & Southern Ocean \\
\hline
\textbf{DEPTH (m):} & $>2000$ & $>2000$ & $>2000$ \\
\hline
\textbf{BUOY TYPE:} & Toroid Float & CMOD (A size sonobuoy) & WOCE (sphere) \\
\textbf{Diameter (m):} & 1 & .33 & 0.35 \\
\textbf{Height (m)*:} & 1 & .6 & < 0.3 \\
\textbf{DROGUE:} & Holey Sock & cloth cone and base weight & WOCE type** \\
\textbf{POWER} & Batteries & Batteries & Batteries \\
\textbf{DEPLOYMENT DURATION***} & 2 Weeks (recovered) & 3-6 Months(expendable) & 6 Months (expendable) \\
\textbf{CONTROLLER/DATA-LOGGER} & OASIS (MBARI) & MetOcean & ?? \\
\textbf{ON-BOARD DATA STORAGE} & Yes & No & No \\
\textbf{TELECOMM} & RF Packet Radio & ARGOS & ARGOS \\
\textbf{PLATFORM} & GPS & ARGOS & GPS & ARGOS? \\
\hline
\end{tabular}
\caption{Characteristics of drifting bio-optical buoys, selected as examples from the experimental projects discussed in the text.}
\end{table}

\(^3\) An instrumented buoy that is tethered to a ship, tower, or shore facility, and is actively attended by an operator during use, is simply a particular instrument deployment mechanism used in shipboard (or equivalent platform) measurements. The protocols for this type of buoy and instrument configuration are those applicable to any other shipboard measurement method, and they do not fall within the context of this chapter.
4. Radiometric field measurement methods designed to minimize platform shading and reflection artifacts are needed for autonomous measurements on buoys. The more successful methods used for shading avoidance in operator attended measurements from ships, *i.e.* free-fall profiling (Volume III, Chapter 2), are not readily applied to radiometric measurements on moorings and drifters. The unusual MOBY platform (Volume VI, Chapter 2) is an example of a buoy and instrument configuration designed specifically to address this problem, but it would be neither affordable, nor practical, to replicate such a configuration in the vast majority of projects where bio-optical buoys are appropriately deployed (Section 3.2 above).

5. Unattended instruments on buoys are either immersed in water, or exposed to the atmosphere, continuously for periods of weeks to months without opportunity to clean optical windows, or other exposed sensor surfaces. In this situation, the performance of buoy instrumentation is subject to progressive degradation due to marine organism growth on sensors in water (biofouling), or salt, dust and/or bird dung deposition in air.

The remainder of this section describes methods for acquiring reliable measurements under the constraining conditions described above (see also the related methods in Vol. VI, Chapter 2, as applied to the more specialized MOBY observatory). The discussion emphasizes the mounting and integration of radiometric, optical, fluorescence, meteorological, CTD, and other sensors under the control of an on-board microcomputer, pre-processing and storage of the data measured by those sensors, and near-real-time transmission of selected data values to ships, or laboratories ashore. Essential characteristics of instrument arrays are summarized in Tables 3.3 and 3.4, respectively, for moored and drifting buoy examples. Specific commercial and custom instruments listed by model, or name, in Tables 3.3 and 3.4 are briefly described below.

**Instrument Control and Data Acquisition**

A critical aspect of any mooring or drifter platform is its instrument controller and its ability to perform in harsh environments. The system controller must be configured to communicate with instruments, operate electromechanical devices (*e.g.* shutter mechanisms), store measured data and metadata (*e.g.* GPS time, latitude and longitude), preprocess measurements and transmit the resulting parameters to a ship or laboratory. Generically, a system controller consists of a microcomputer interfaced to an array of instruments, the buoy’s power source (batteries and/or solar cells), and sometimes a telecommunications link. Many of the instruments used on buoys have some sort of internal microcomputer, operate semi-autonomously to acquire data scans, store the data internally, perhaps average scans over a specified time interval, and transmit digital data to the controller; the instrument controller interfaces to these digital-format instruments using either multiple single channel interfaces (*e.g.* serial RS232), or a network protocol interface (*e.g.* serial RS485 or parallel IEEE-488). Other instruments may produce an analog output, in which event the controller’s microcomputer must also be interfaced to one or more analog-to-digital (A-to-D) converters; for most such applications, it is necessary to calibrate the A-to-D converter by recording its digital responses to known voltage inputs. In other controller-instrument configurations, analog devices may be connected to A-to-D ports of a digital instrument, *e.g.* a CTD, and communicated to the controller as part of its data frame.

Recent development of smaller Ethernet devices has allowed the creation of Local Area Network on moorings, which can provide easy communications between both individual system controllers and serial output from instruments. For example a controller may be physically separated from instruments connected to an Ethernet RS-

---

4 Certain commercial equipment, instruments, or materials are identified in this document to foster understanding. Such identification does not imply recommendation or endorsement by the National Aeronautics and Space Administration, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.
232 hub. In another variant developed by UCSB for the BTM, self-contained, battery operated data acquisition systems at three depths combine acoustic telemetry with ARGOS satellite data telemetry for near real-time data transmission.

The systems used on the GoMOOS bio-optical moorings are a blend of the examples described above. Each GoMOOS mooring is controlled by a Campbell Scientific CR10X control system. The Campbell system controls the power and sampling for all of the meteorological sensors, the current (Aanderra and RDI ADCP) and hydrographic (SeaBird SBE37 and SBE16 temperature and conductivity) sensors, as well as the wave sensor. The Campbell system also controls the mooring to shore transmissions of the data, which are mainly done using hourly cellular phone communications. Most moorings also utilize GOES transmissions as a backup method to transmit data to shore in case of cellular phone problems. Because of limitations of the Campbell data logger in terms of storage space and data resolution, it was necessary to utilize a separate data logger to collect, store and pre-process the bio-optical data. The data logger was developed with WETLabs for implementation on the GoMOOS moorings. The data logger has a microprocessor and firmware to control the power and sampling to 4 externally connected sensors. The data logger has 4 serial (RS232) input ports, one RS232 output port and a power port that can be connected to a battery power supply. The GoMOOS implementation of the data logger firmware controls the sampling period and power to each of the 4 serial input ports. The GoMOOS optics data logger can either be set up to run in autonomous mode, or can be controlled externally via RS232 communications. The optics data logger records all of the raw data onto an on board flash disk for later retrieval and processing. The data logger is programmed to average each of the input data streams from each instrument, and outputs the averages and diagnostics to the output RS232 serial port.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sensor</th>
<th>MOOS</th>
<th>TAO (EP1 &amp; EP2)</th>
<th>PIRATA (Lambaba)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{a}(\lambda)$</td>
<td>PRR-620</td>
<td>~ +4</td>
<td>+3</td>
<td>+3</td>
</tr>
<tr>
<td></td>
<td>HR3</td>
<td>~ +4</td>
<td>+2.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MiniSpec-I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCR504 ICSA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{d}(z, \lambda)$</td>
<td>PRR-600</td>
<td>-10, -20</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR3</td>
<td>-10, -20</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCI100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCI1200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCR504 ICSW</td>
<td></td>
<td></td>
<td>-2, -4, -8, -12</td>
</tr>
<tr>
<td>$L_{d}(z, \lambda)$</td>
<td>PRR-600</td>
<td>-10, -20</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR3</td>
<td>-10, -20</td>
<td>-10</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>OCR100</td>
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<td>-1.5</td>
<td>-3.6, -9.6</td>
</tr>
<tr>
<td></td>
<td>OCR200</td>
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</tr>
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<td></td>
<td>MiniSpec-R</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCR507 R10W</td>
<td></td>
<td></td>
<td>-0.5</td>
</tr>
<tr>
<td>$E_{d}(z, \lambda)$</td>
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<td>-10, -20</td>
<td>-20</td>
<td></td>
</tr>
<tr>
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<td>HR3</td>
<td>-10, -20</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Chl a Fluorescence</td>
<td>WETStar</td>
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<td>-1.5</td>
<td>-9, 40</td>
</tr>
<tr>
<td></td>
<td>DFLS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HS2</td>
<td>-1.5</td>
<td>-1.5</td>
<td></td>
</tr>
<tr>
<td>$b_{t}(z,\lambda)$</td>
<td>HS-2, 4 or 6</td>
<td>-1.5</td>
<td>-1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VSF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c(z,\lambda)$</td>
<td>ac9</td>
<td>-1.5</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>-1.5,-10,-20,-40, -60,-80,-100,-150, -200,-250,-300</td>
<td>-1.5*</td>
<td>-2,-4,-6,-12</td>
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<td>---</td>
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</tr>
<tr>
<td>Surface Wave Spectrum</td>
<td>Accelerometer</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>ADCP</td>
<td>-5 to -75 m in 4 m bins</td>
<td>*</td>
<td>-20 (Sontek)</td>
</tr>
<tr>
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<td>Anemometer</td>
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<td>+5</td>
<td>+4</td>
</tr>
<tr>
<td>Air Temperature (°C)</td>
<td>Thermistor</td>
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<td>*</td>
<td>4</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Hygrometer?</td>
<td>+3</td>
<td>*</td>
<td>4</td>
</tr>
<tr>
<td>ΔpCO₂</td>
<td>Custom (MBARI)</td>
<td>+1.5</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

* See Hayes et al. 1991 for a description of the TAO ATLAS core measurements and instrumentation.

### Table 3.3 (Part 2 of 2): Radiometric, bio-optical and ancillary measurements and instruments on selected moored bio-optical buoys; see Table 3.1 and Figures 3.1 and 3.2 for information on the location, buoy type and mooring configuration of each.

<table>
<thead>
<tr>
<th>Moored Buoy Array:</th>
<th>GoMOOS</th>
<th>HOT (HALE-ALOHA)</th>
<th>BATS (BTM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable</strong></td>
<td><strong>Sensor</strong></td>
<td><strong>z (m)</strong></td>
<td><strong>z (m)</strong></td>
</tr>
<tr>
<td>(E_d(\lambda))</td>
<td>PRR-620</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>HR3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCR507</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>ICSA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCI200</td>
<td>+3</td>
<td></td>
</tr>
<tr>
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<td>PRR-600</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>HR3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCI100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCI200</td>
<td>-25</td>
<td>-15, -35</td>
</tr>
<tr>
<td></td>
<td>OCR504 ICSW</td>
<td>-3, -18</td>
<td></td>
</tr>
<tr>
<td>(L_d(z, \lambda))</td>
<td>PRR-600</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OCR100</td>
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</tr>
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<td>OCR200</td>
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<td>OCR507 R10W</td>
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<td>PRR-600</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR3</td>
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<td>Chl (a) Fluorescence</td>
<td>WETStar</td>
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<tr>
<td></td>
<td>DFLS</td>
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<td></td>
<td>HS2</td>
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<td></td>
</tr>
<tr>
<td>(b_i(z, \lambda))</td>
<td>HS-2, 4 or 6</td>
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<td></td>
<td>VSF</td>
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<td></td>
<td>ac9</td>
<td></td>
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</tr>
<tr>
<td>(c(z, \lambda))</td>
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<td>-3.4</td>
<td></td>
</tr>
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<td>Water Temp. (°C) &amp; Conductivity</td>
<td>SBE/CT</td>
<td>-1, -2 (T only), -10,-50</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>-50,-120,-180</td>
<td>-34, -45, -55, -71, -100, -150, -200, -250, -500, -750</td>
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<tr>
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<td></td>
<td>-410,-475,-540</td>
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</tr>
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<td></td>
<td></td>
<td>-560,-650,-785</td>
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<td>Surface Wave Spectrum</td>
<td>Accelerometer</td>
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<td>Current Velocity</td>
<td>ADCP</td>
<td>-10 m to -80 m in 4 m bins</td>
<td></td>
</tr>
</tbody>
</table>
The STOR-X (used on PIRATA) is a commercial data acquisition system designed for data storage and telemetry of up to five serial (RS-232) inputs. The system operates a preprogrammed user schedule, switches sensor power, acquires data from the various sensors, and stores the time tagged data onto a solid-state flash disk. The system can also be programmed to process and transmit data on ARGOS (as in PIRATA), cellular phone systems and broadband telemetry systems such as Freewave.

The data acquisition system used on MEPS is DACNet, which is a complete mooring management system capable of multinode operation. DACNet typically consists of three main components, a PC104 computer system on each buoy node, a wireless telemetry system, and a shore based central server. The MEPS configuration of DACNet has three buoy nodes located within 6km of a shore station. Each buoy node has 12 high-speed (up to 115kbps) serial (RS-232) inputs, some of which were connected to serial instrument networks. In the initial deployment MEPS had 18 individual sensors connected to each node collecting approximately 3MB of data in 20 minutes of data collection each hour. This data was stored on a 1GB microdrive in each buoy and transmitted via a wireless telemetry system at up to 11Mbps back to the central server. Each buoy has four 85W solar panels charging a 250Ah battery pack which is sufficient to serve a peak load of 40W for 20 minutes each hour, 24 hours a day. Guest ports on each buoy allow for the easy addition of new sensors and the ability to allow visiting scientists to connect sensors into the system, while device drivers are remotely loaded via the central server over the internet. User access to the system for configuration control and maintenance is via web browser using secure HTTP. Data

### Table 3.4: Radiometric, bio-optical and ancillary measurements and instruments on selected examples of drifting bio-optical buoys used in oceanographic experiments.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sensor</th>
<th>JGOFS EQPAC (Dalhousie)</th>
<th>SOFeX (MBARI)</th>
<th>SOFeX (OSU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_s(\lambda)$</td>
<td><strong>ED-100</strong></td>
<td>+1</td>
<td>+0.5</td>
<td>+0.25</td>
</tr>
<tr>
<td></td>
<td>(490 NM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_u(z, \lambda)$</td>
<td>OCR100</td>
<td>-0.5</td>
<td>-2.5</td>
<td>-0.2</td>
</tr>
<tr>
<td>Chl a Fluorescence</td>
<td>HS2</td>
<td>-2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b_h(z, \lambda)$</td>
<td>HS2</td>
<td>-2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Temp. ($^\circ$C) &amp; Conductivity</td>
<td><strong>SBE/CT</strong></td>
<td>-.05</td>
<td>-2.5</td>
<td>-0.2 (SST only)</td>
</tr>
<tr>
<td>Dissolved O$_2$</td>
<td>SBE</td>
<td>-2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td>ISUS (MBARI)</td>
<td>-2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Licor GasHound (LI-800)</td>
<td>+0.5 and – 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric pressure</td>
<td></td>
<td>+1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Temp ($^\circ$C)</td>
<td></td>
<td>+1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* See Hayes et al. 1991 for a description of the TAO ATLAS core measurements and instrumentation.
access is via FTP and SMTP interfaces. Data is provided in raw native format with time tags appended to each frame for later data processing by CMEP. The system has the capability to allow direct user connection to any sensor on the platform over the internet, via using TCP/IP facility within DACNet, which is useful for remote sensor configuration, sensor testing, and special measurement sequences.

DACNet will also be used in the MERIS cal/val buoy, BOUSSOLE, to be deployed at the DYFAMED site the Ligurian Sea. This system is operated by CNRS/INSU in Villefranche Sur Mer, France. On the BOUSSOLE buoy, data is stored on disk and downloaded via high-speed wireless telemetry during periodic cruises to the area. System parameters and a limited amount of processed AOP data are sent back to CNRS via an ARGOS transmitter.

Radiometric Measurement Methods

Above-water incident spectral irradiance \( E_i(\lambda) \), and in-water downwelling and upwelling spectral irradiance \( E_d(z,\lambda) \) and \( E_u(z,\lambda) \), and upwelling spectral radiance \( L_u(z,\lambda,\theta',\phi') \), are often measured using arrays of radiometers mounted on moored or drifting buoys. The notation here follows the definitions of Volume I, Chapter 2, where \( z \) is depth in m, \( \lambda \) is wavelength in nm, and \( (\theta',\phi') \) are the nadir and azimuth angles of the in-water directional radiance measurement. The directional nature of the in-water radiance field becomes critical when measured \( L_u(z,\lambda,\theta',\phi') \) field data are used to determine normalized water-leaving radiance \( L_{wn}(\lambda) \) and exact normalized water-leaving radiance \( L_{wn}^{es}(\lambda) \) (Section 3.6 below and Volume III, Chapter 4).

Radiometric measurements are typically acquired for relatively brief sampling periods at preprogrammed intervals during each day. The number and duration of radiometric measurement samples scheduled in a buoys instrument controller program is based on factors including diurnal variability in incident radiation, productivity and other light-sensitive biological processes, scheduled ocean color satellite overpasses, and the buoy’s electrical power management plan for the particular deployment. Examples of radiometric sampling schedules for particular buoy experiments are described below in Section 3.5, in addition to the following general guidelines:

- In a single radiometric measurement sequence, measurements should be recorded for 10 to 15 minutes to allow averaging over variations in incident irradiance (due to clouds) and in-water radiometric variations resulting from surface waves.
- In addition to daylight measurement sequences, it is recommended to acquire a dark measurement sequence near local midnight.

In most of the instrument configurations listed as examples in Tables 3.3 and 3.4, radiometric collectors (either individual radiometers, or collector optics connected via a fiber-optic lead to a remotely located radiometer) are mounted at one or more fixed depths in the water column. The \( E_i(\lambda) \) sensor is typically mounted on the buoy superstructure, while \( E_d(z,\lambda) \) and \( E_u(z,\lambda) \) sensors are typically mounted on the mooring cable at one or more depths, and are often combined with a nadir-viewing \( L_u(z,\lambda) \) sensor at each depth.

The depths at which radiometers are mounted in a fixed array depend on the particular buoy and the diffuse attenuation coefficient typical of the water masses the buoy is expected to observe. For many small drifting buoys, instruments are mounted directly on the buoy to measure only \( E_i(\lambda) \) and \( L_u(z,\lambda) \), with the hull mounted radiance sensor at a depth \( z \approx 1 \text{ m} \). When additional wire-mounted radiometers are included in the array, they should be deployed at depths spaced to approximately determine the diffuse attenuation coefficient

\[
K(\lambda_{ref}) = \frac{\int_{z_{90}}^{z_0} K_d(z,\lambda_{ref}) \, dz}{z_{90}}
\]

averaged over the first attenuation length \( z_{90} \) for a selected reference wavelength \( \lambda_{ref} \).

When \( \lambda_{ref} = 490 \text{ nm} \), \( K(\lambda_{ref}) \) is the diffuse attenuation coefficient determined from satellite ocean color data (Austin and Petzold 1981), and \( z_{90} = K(490)^{-1} \text{ m} \) is the depth from which 90% of the radiance contributing to \( L_{wn}(490) \) originates by backscattering. Note that \( z_{90} \) is a function of wavelength, and that 490 nm is often used as a reference wavelength because it is the wavelength of maximum transparency in oligotrophic and mesotrophic water.
masses. The median $K_{med}(490)$ and maximum $K_{max}(490)$ expected to be sampled during a particular buoy deployment can be estimated from satellite ocean color images, combined with radiometric profiles from previous research cruises and optical buoy deployments in that water mass regime. Given that information, a reasonable guideline for $K_{med}(490) \leq 0.1 \text{ m}^{-1}$ situations would be to place a single wire-mounted set of $E_d(z,\lambda)$ and $L_u(z,\lambda)$ at a depth midway between the minimum and median values of $z_{90}$, i.e. at $\bar{z}_{90} = \left[ \frac{K_{med}(490) + K_{max}(490)}{2} \right]^{-1}$ m, and if available, a second such radiometer package could be mounted at $\frac{z_{90}}{2}$ m.

The approach used on the GoMOOS moorings, for example, is to place the $E_d(z,\lambda)$ sensors at the surface and at the yearly averaged 90% light level depth (for the 490 nm wavelength), typically 3 m and 18 m for the nearshore coastal moorings, and 5 m and 30 m for the more oligotrophic, deep basin moorings. The GoMOOS moored arrays have only have one $L_u(z,\lambda)$ sensor placed at 3m, a depth as near as to the surface as the mooring configuration will allow, and to minimize the effects of shadowing.

Platform shading effects on wire-mounted $E_d(z,\lambda)$ and $L_u(z,\lambda)$ spectral irradiance sensors are similar to the ship shadow effects discussed in Volume III, Chapter 2 (Section 2.2), but are considerably reduced by the much smaller size of a buoy, compared to a ship.

Upwelling radiance sensors may be mounted either on the underside of a buoy hull, to measure $L_u(z,\lambda,\theta',\phi)$ at a depth $z \approx 1$ m, and/or on a mooring cable at fixed depths (often paired with a downwelling irradiance sensor) to measure $L_u(z,\lambda)$ in a nadir-viewing geometry.

- **Platform shading effects for wire-mounted radiance sensors** are directly analogous to ship shadow (and reflection) effects, again mitigated by the relatively small size of a buoy Volume III, Chapter 2 (Section 2.2). For the larger buoys ($r \geq 0.5$ m), at least, the uncertainties associated with platform shading for a wire-mounted measurement configuration are better understood, and more widely accepted within the ocean color community, than are those associated with hull-mounted configurations.

- For a **hull-mounted radiance sensor, the shadows and reflections** due to a buoy hull are more directly analogous to the instrument self-shading case for a sensor radius equal to half the buoy hull diameter. When a nadir-viewing radiometer is mounted in the center of a buoy hull, the instrument self-shading correction protocol (Volume III, Chapter 2. Section 2.4) based on Gordon and Ding (1992) is directly applicable. The correction will be large in even clear, Case I water masses, however, and shading will significantly increase the uncertainty of water-leaving radiances derived from such measurements. In an attempt to reduce shading, some investigators have mounted radiance sensors near the edge of the buoy hull, and in some cases have pointed the radiometer radially away from the buoy center at a nadir angle $\theta' > 0$. In either of these cases, a modified self-shading correction algorithm must be devised, and validated to correct for platform shading and to determine the uncertainty of the resulting water-leaving radiance.

- **For profiling moorings**, shading of downwelling radiometers is often not an issue. This may not the case for upwelling sensors where engineering considerations may dictate a profiling package having a fairly large diameter.

Perhaps the most significant factor distinguishing subsurface radiometric measurements using buoy arrays from similar shipboard measurements is biofouling due to growth of marine organism on optical collectors and windows during prolonged, unattended deployments.

Historically, anti-fouling chemical compounds were applied to optical surfaces in an attempt to prevent microbial growth and settlement of larvae of sessile invertebrates. The results of this chemical approach were typically unsatisfactory. In some recorded cases, biofouling was actually enhanced when chemical anti-fouling compounds provided a rougher surface for organism attachments (McLean et al. 1997). In general, the toxicity and limited retention time of antifouling compounds was proved to be undesirable.
A copper shutter mechanism was developed to protect optical sensors from exposure except intermittently, when the shutter is opened to expose the windows/collectors for brief periods while measurements are made (Chavez et al., 2000; Manov et al., 2003). The buoy’s instrument controller, as part of the programmed measurement schedule, activates the shutter mechanism. In the TOGA/TRITON, MOOS, and some other examples described in Tables 3.3 and 3.4, such a copper shutter device is used to protect the subsurface radiometers from fouling. UCSB OPL and WETLabs, Inc. have designed non-contact servo controlled copper-shuttered devices for radiometers and other bio-optical sensors (Manov et al., 2003). This new battery-powered shuttered system uses a commercial high torque servo with dual ball bearings and metal gears (Figure 3.13). A copper plate is attached to the servo arm through a waterproof dynamic o-ring seal. The copper shutter is kept closed over the sensor’s optical elements until a measurement is required. Several minutes of data are collected, and then the copper plate is swung back over the sensor to keep the optical elements protected from biofouling between measurement intervals. The OPL/WETLabs, Inc. battery-operated shutter system is self-contained and flexible, and is designed to be easily interfaced and integrated into a complete data logging system.

The radiometric windows/collectors on MOBY, although continuously exposed to the water, are surrounded by a copper bezel. The optical surfaces are cleaned monthly by divers, who also document the in-water radiometric responsivities of the system using a portable, underwater lamp source (Vol. VI, Chapter 2).

Profiling moorings can allow cleaning of radiometers by deploying the profiler to the surface where the windows/collectors can be cleaned in-water. Ship-board and shore-based maintenance may also be possible if the profiling vehicle can be detached from the tether.
Radiometers

The buoy instrumentation arrays listed as examples in Tables 3.3 and 3.4 incorporate a variety of commercially available radiometers, listed by the manufacturers model nomenclature. The wavelength characteristics of these sensors comply with those specified in Volume II, Chapter 2 (Table 2.1), and all comply with the other performance characteristics specified Volume II, Chapter 2. Several of the irradiance sensors may be configured to measure irradiance either in air, i.e. $E_s(\lambda)$, or in water, i.e. $E_d(z, \lambda)$ or $E_u(z, \lambda)$. The reader is referred to Vol. II, Chapter 3, Sects. 3.5 and 3.7 for more information on irradiance immersion factors and cosine response functions in water and air.

The filter radiometers appearing in Tables 3.3 and 3.4 are the:

- **OCR-100**: A 7-channel analog spectral radiance sensor manufactured by Satlantic, Inc.
- **OCR-200**: A 7-channel analog spectral radiance sensor manufactured by Satlantic, Inc.
- **OCL-200**: A 7-channel spectral irradiance radiometer, counterpart to the OCR-200, also manufactured by Satlantic, Inc. The cosine collectors on this instrument – a separate one is used at each wavelength - may be ordered to measure spectral irradiance either in air [i.e. $E_s(\lambda)$], or in water [i.e. $E_d(z, \lambda)$ or $E_u(z, \lambda)$].
- **OCR-504/507**: A 4 or 7 channel digital spectral irradiance or radiance sensor manufactured by Satlantic Inc. The cosine collectors on this instrument – a separate one is used at each wavelength - may be ordered to measure spectral irradiance either in air [i.e. $E_s(\lambda)$], or in water [i.e. $E_d(z, \lambda)$ or $E_u(z, \lambda)$].
- **OCR-504/507**: A 4 or 7 channel digital spectral irradiance or radiance sensor manufactured by Satlantic Inc. The cosine collectors on this instrument – a separate one is used at each wavelength - may be ordered to measure spectral irradiance either in air [i.e. $E_s(\lambda)$], or in water [i.e. $E_d(z, \lambda)$ or $E_u(z, \lambda)$].
- **ED-100**: A single-channel (usually 490 nm) radiometer manufactured by Satlantic, Inc. and configured to measure $E_s(490)$ in air.
- **PRR-600**: A filter radiometer manufactured by Biospherical Instruments, Inc., configured to measure $E_d(z, \lambda)$ and $L_u(z, \lambda)$ in water at 7 wavelengths.
- **PRR-620**: A filter radiometer manufactured by Biospherical Instruments, Inc., configured to measure $E_s(\lambda)$ in air at 7 wavelengths.
- **MER-2020A**: A filter radiometer manufactured by Biospherical Instruments, Inc., configured to measure $E_d(z, \lambda)$ and $L_u(z, \lambda)$ in water at 8 wavelengths.

Also used with moored and drifting buoys are two commercially available hyperspectral radiometers, both of which are based on miniature fiber-optic monochromators:

- **HR-3**: The HydroRad-3 manufactured by HobiLabs, Inc. In the examples given in this chapter, the HR-3 is configured with collector optics to measure $E_d(\lambda)$, $E_u(z, \lambda)$ and $L_u(z, \lambda)$ from 400 to 700 nm, with approximately 2 nm resolution in each variable.
- **MiniSpec**: A series of Satlantic hyperspectral radiometers configured to measure irradiance (MiniSpec I) $E_s(\lambda)$ or $E_d(z, \lambda)$, and radiance (MiniSpec R) $L_u(z, \lambda)$, from 350 nm to 800 nm with a spectral resolution of approximately 10 nm, sampled at 3.3 nm intervals.

Inherent Optical Properties Measurement Methods

Some buoy instrument arrays incorporate sensors to measure inherent optical properties (IOP): the volume beam attenuation coefficient $c(z, \lambda)$, the volume absorption coefficient $a(z, \lambda)$, and the backscattering coefficient $b_b(z, \lambda)$, as defined in Volume I, Chapter 2 (Section 2.4). Given these IOP measurements, the volume scattering coefficient may be calculated as $b(z, \lambda) = c(z, \lambda) - a(z, \lambda)$.

IOP sensors often used on buoys (Tables 3.3 and 3.4) include the:

- **AC9**: An instrument manufactured by WETLabs, Inc. that may be used to measure the absorption coefficient, using a reflecting tube to capture forward-scattered photons, and beam attenuation at 9 wavelengths. Water must be pumped through the enclosed optical paths of this instrument. The instrument
is calibrated against optically pure water, and the derived absorption and beam attenuation coefficients are 
\[ a(z, \lambda) - a_u(z, \lambda) \] and 
\[ c(z, \lambda) - c_u(z, \lambda), \] respectively (Volume IV, Chapters 2 and 3).

- **HYDROSCAT-N (HS-N):** A “backscattering meter” manufactured by HOBLABS, that measures a weighted integral of the volume scattering function (VSF) \( \beta(\Psi, c) \) at a central scattering angle of \( \Psi = 140^\circ \), at N wavelengths. The backscattering coefficient \( b_b(z, \lambda) \), is then determined using a model relating it to \( \beta(\Psi, 140^\circ, c) \) (Volume IV, Chapter 5). Alternatively, one of the N channels may be configured to measure chlorophyll a fluorescence, rather than backscattering. On the MOOS buoy, for example, a hull-mounted HS-2 is used to determine \( b_b(z, 532) \) and chlorophyll a fluorescence at a depth of approximately 1.5 m.

- **VSF:** A device similar to the HS-N, but which measures \( \beta(\Psi, c) \) at 3 centroid angles, \( \Psi = 100^\circ, 120^\circ, 150^\circ \), at a single wavelength, and determines \( b_b(z, \lambda) \) using a model of the VSF that is different from that used with the HS-N (Volume IV, Chapter 5).

Protocols describing methods for measuring these variables, including laboratory and field calibrations of instruments and quality control measures, are described in Volume IV, Chapters 2, 3 and 5 for \( c(z, \lambda) \), \( a(z, \lambda) \) and \( b_b(z, \lambda) \) respectively. As with radiometry, the measurement protocols for IOP instruments on buoys differ from shipboard protocols in that they are usually placed at fixed depths, they are subject to biofouling during lengthy deployments, and the instrument cleaning and field calibrations recommended for shipboard use can only be carried out before and after the deployment. Profiling moorings may mitigate bio-fouling problems by “storing” the instrument package in the dark at a depth below the euphotic zone.

Manov et al. (2003) review methods for reducing biofouling of IOP, as well as AOP, sensors. In particular, they (OPL UCSB) have developed An anti-foulant copper tubing flow-through system was developed by USCB OPL for the ac-9 and HiSTAR (100-wavelength ac-meter) (Figure 3.14), for closed path flow-through fluorometers (WET Labs, Inc. WETStar) and transmissometers (WET Labs, Inc. C-Stars). The copper tubing systems were tested on a mooring, at depths of 5, 11, and 20 m, during the Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) in productive inland waters off New Jersey, U.S.A (Chang et al., 2002). One-half inch copper tubing was utilized to connect the intakes of the ac-9 to a pump. Between one-hour measurement cycles, copper from the tubing was allowed to leach into the water contained in the tubes of the instrumentation system. Prior to taking the absorption and attenuation measurements, the pump was run on for 10 seconds to clear the system of the leached copper and to pump non-contaminated water into the intake port for sampling. The pump was then left on during the 70 s measurement period. Stainless steel screen filters were used to remove large particles, e.g., seaweed, macroorganisms, and large detritus, from the sensor elements. Separate pumped water systems were utilized for the plumbing the WETStars and C-Stars. One-quarter inch copper tubing was utilized to fit the two instruments together and to a pump. Isolation of the copper by Tygon tubing (black tubing is used to reduce ambient light levels) was made in order to avoid dissimilar metal corrosion effects with the sensors pressure cases, mounting brackets, and the stainless steel instrumentation cage. Manov et al. (2003) concluded that copper-tubing based systems provide biofouling protection superior to that achieved with chemically-based methods.

It is recommended to deploy one set of IOP sensors in the near-surface layer at a depth centered between those at which radiometers are placed to determine \( K(\lambda) \) and \( L_{\psi N}(\lambda) \) (see above). If additional IOP sensors are deployed in an array, the usual practice is to distribute them to optically characterize the water column throughout the euphotic zone.

These guidelines are appropriate, though perhaps difficult to adhere to in practice. The GoMOOS moorings, for example, deploy one set of IOP sensors at 3.5 m depth. This IOP package includes:

- Three WETLabs VSF (440, 530, and 650 nm) volume scattering meters are integrated with a VSF3S controller that controls the sampling period for each of the 3 sensors, and collates the data from all 3 sensors into a single output stream to the buoy’s DH4 data logger, where sample period averages are formed. Each VSF sensor has a small copper shutter that covers the optical sensing area when not in operation, and rotates out of the way during the measurement period. The copper shutter sits about 1-2 mm above the optical face. Copper foil tape is also wrapped around the outside of the sensor to deter growth.
One WETLabs ac9 absorption and beam attenuation meter is used to measure $a(\lambda)$ and $c(\lambda)$. Short lengths of copper pipe added to the the intake and outflow ends of the flow-through tubing (Fig. 3.14). The copper pipe sections provide a toxic barrier on each end of the flow tube system to prevent biological organisms from entering the flow tube area when the pump is off between sampling periods. This system yields approximately 2-3 months protection before effects of biofouling begin to become apparent in the data record. Bromide, or bleach, leaching methods are not used, because these reactive materials may etch of the quartz window surfaces during a several month deployment.

Methods for Other Measurements

The MBARI-ISUS (Johnson and Coletti, 2002) is a new system for the optical determination of nitrate concentrations \textit{in situ} without the use of reagents. The system has been successfully deployed on a number of buoys (MOOS-M1, TAO, and SOFeX). ISUS uses UV spectroscopic techniques to provide a measure of nitrate in a 1 cm path length cell in approximately one second. ISUS provides a real time nitrate concentration (in analog and digital formats) and optionally, a full UV absorption spectrum from 200-400nm. Real time nitrate concentrations are accurate to 2mM with a precision of 0.05mM. For moored systems, a novel antifouling chamber has been developed by MBARI using a perforated copper tube and Nitex filter cloth over the probe.

Validation Using Shipboard Measurements

During any recovery, deployment, or servicing of optical moorings or drifters, it is strongly recommended that shipboard bio-optical and radiometric profiles of the water column be measured for comparison with the concurrent buoy measurements. The appropriate measurements are those listed in Vol. I, Chapter 3, Table 3.1, where the protocols covering each measurement are provided in the volumes and chapters indicated in Table 3.2, of Volume I, Chapter 3. Examples of data sets used for this purpose are described in Dickey \textit{et al.} (2001). In the present context, the shipboard radiometric profile measurements made just after a drifting or moored buoy’s radiometers are placed in the water, and just before they are recovered, provide invaluable information on the extent of biofouling during a deployment and the quality of water-leaving radiances and diffuse attenuation derived from the buoy measurements. A similar suite of samples are collected off the Oregon Coast when optical drifters are deployed. In addition, a calibrated Tethered Spectral Radiometer Buoy (Satlantic Inc.) is used to collect optical data in the vicinity of the drifters for comparative purposes.

It is also useful to acquire \textit{in situ} fluorometric chlorophyll $a$ before or after radiometric profiles and optical mooring or drifter deployments. Samples to determine the chlorophyll-specific absorption coefficient ($a^*$) are also
important near optical mooring locations. Recently, strong emphasis has been placed on determining other pigments by means of HPLC analysis to confirm the fluorometric chlorophyll \(a\) and phaeopigment measurements (Volume V, Chapter 3) and to quantify the influence that other pigments may have on remote sensing data quality.

During MOOS and BTM mooring recovery/maintenance/deployments for example, CTD rosette casts are made to measure physical and biological water column attributes and primary productivity studies, and radiometric profiles are measured. During equatorial Pacific mooring visits a SeaWiFS Profiling Multi-channel Radiometer (SPMR) profiles are measured and various water samples are collected for measurements of pigments concentration (Vol. V, Chapters 2 and 3) and absorption on filters (Vol. IV, Chapter 4).

### 3.5 DATA BUOY OPERATIONS AND MEASUREMENT METHODS

Upon determining the objective, location, configuration and instrumentation of the mooring or drifter platform, the specific measurement and operation methods, logistics, and shipboard support must be determined.

**Deployment/recovery schedules and methods**

Deployment and recovery schedules for moorings and drifters will vary dependent upon the selected location, available power supply, and at which expected rates of bio-fouling may significantly degrade sensor performance. For example, MOOS moorings in Monterey Bay take advantage of maintenance visits every 3-4 weeks (sometimes by divers) to maintain the instrument integrity, check for bio-fouling, and replace power supply. The moorings undergo yearly recovery and deployments (turn-arounds) but have bi-annual instrument and OASIS controller swap-outs dependent upon status. Each buoy, tower, and bridle (annotated with serial numbers) is checked for any faults caused from corrosion and documented accordingly. The moorings are built in a staging area at MBARI and undergo rigorous testing before being deployed from the R/V Pt. Sur.

In the GoMOOS project, each mooring is on a 6-month duty cycle, during which time servicing or maintenance is performed on an as needed basis only. This is mainly due to programmatic cost limitations. Each mooring, buoy and associated instruments are completely replaced approximately every 6 months, depending on weather and ship scheduling. Thus, the operational goal of GoMOOS is deployments of 6 months without (or minimal) servicing. In terms of the optical sensors, the 6 month duty cycle is too long for most of the instrumentation due to the effects of biofouling. In our analysis, the above water downwelling irradiance sensor, the chlorophyll fluorometers, and the VSF sensors performance over 6 months is acceptable, and most of the effects of biofouling can be removed or minimized using post-processing procedures and pre- and post-calibrations. However, the ac9 and the in water radiometric sensors do suffer from biofouling that is very difficult to account for using post-recovery processing procedures. We feel that once an effective copper shutter system is developed, the in water irradiances and radiance sensors will be able to collect data over the 6 month duty cycle with only minimal effects of biofouling. The ac9, however, is in need of further anti-biofouling prevention above the copper pipe tubing system we use. The main problem we are having is with the organic film that builds up over the first 2 months of deployment on the optical surfaces. Originally we had proposed to GoMOOS to have divers service the optical systems every 2-3 months, by retrieving the optical packages off of the mooring, and then cleaning and calibrating the sensors before returning them to the mooring system. In fact all of our in water optical packages can easily be removed from the mooring chain without having to retrieve the entire mooring (using a set of strongbacks and clamping systems) or interrupt the hourly mooring sampling schedule (using under water protective cable connectors). However, again, due to GoMOOS programmatic cost limitations, this proposed servicing of the optical sensors was cut from the program.

In remote locations such as in the equatorial Pacific, TAO mooring visits may only occur every 3-6 months with annual turnarounds. Therefore, those moorings are designed to stay completely operational for one year without visits. As a result of the schedule and deck space aboard the R/V Kaʻiminoana, the buoys are built, tested, and deployed sometimes within a 24 hour time period. Prior to leaving port, all mooring hardware is checked for integrity and serial numbers are carefully documented before deployment. Immediately following deployment, ARGOS data transmission is verified and deployment locations are documented.
At the HOT/HALE ALOHA and BATS/BTM sites, monthly\(^5\) visits are made to the mooring location during regularly scheduled HOT cruises. After a thorough evaluation of biofouling and other considerations, it was determined an optimal duty cycle for the mooring (4-6 months).

Drifters are generally deployed from ships, although some drifting bio-optical buoys are designed to be deployed from aircraft.

**Instrument Controllers, Data Recording, and Telemetry Scheduling**

A critical aspect of any mooring or drifter platform is its instrument controller and its ability to perform in harsh environments (Section 3.4 above). The system must be configured to communicate with instruments, store and transmit data. The availability of power is dependent on platform design and frequency of visit or deployment duration, which in turn structures the controller to operate at higher or lower sampling frequencies.

The equatorial Pacific, (EqPac) instrument controller and instruments are powered by two battery packs as described in a previous section. The power consumption to sampling rate of all instruments is calculated so that the instruments can be functional for a year. Typically, the OASIS controller commands optical instruments to measure irradiance and radiance at 15 min intervals from 6 am to 6 pm. At each 15 min sampling interval the anti-fouling shutters (Chavez \textit{et al.}, 2000) on the subsurface radiometer open for approximately 30 seconds and the radiometer samples for 20 seconds. Data obtained between 10:00 and 14:00 local are averaged to provide representative daily readings, and are then processed to obtain bio-optical parameters. In addition to the measurements during daylight hours, dark readings (00:00 local) are also recorded to provide a zero offset and information on the status of the radiometers. All of the data are stored on a hard drive within the OASIS controller and daily noon readings of selected instruments are transmitted via one-way ARGOS. The total data for ~6 months is ~3 Mb of memory.

GoMOOS: The programmatic goals of GoMOOS are to provide hourly, near-real time data of all oceanic and meteorologic conditions from 10 mooring locations, with each mooring having a 6 month duty cycle before replacement of the entire mooring. Each mooring has two 12V Glassmat (gel cell) batteries, and 4 solar panels, which provide power to the main buoy controller (Campbell Scientific CR10X), the cellular phone, and all instruments with the exception of the deep optics package at 18 m, which is powered by a twenty-four 9V lithium battery pack. Hourly sampling is done in “burst” mode, sampling between 20 seconds to 10 minutes depending on the instrument. The hourly sampling intervals for each instrument were selected based on trade-offs between power usage, disk storage space, and temporal resolution. Each hourly sample period is initiated 10 minutes before the top of each hour and ends at 10 minutes after the top of the hour. During this period, each instrument is powered, collects data, and reports the average data to the main data logger (Campbell system). Note that each instrument may have a slightly different sampling interval. Almost all of the raw resolution data is stored by the main data logger system, or stored by the individual sensors for later retrieval. All of the optics systems data loggers store the raw resolution data on a resident flash disk (64 or 192 MB). Transmission of the averaged hourly data samples from all instruments (including diagnostic information such as position, battery voltage, etc) is initiated between 12 and 25 minutes after the top of each hour, with each buoy calling in at a different time frame. The main mode of data transmission to shore is via cellular phone to a shore based modem.

At HOT/HALE-ALOHA and BATS/BTM sites, optical parameters are sampled at 20 min intervals and recorded to a data logger (Letelier \textit{et al.}, 2000), and are telemetered to shore via satellite.

As another example, all instruments on the MBARI SOFeX drifter were connected to the logger/controller unit, which was a customized version of the OASIS system (Chavez \textit{et al.}, 1997). The OASIS internal power supply (28 D-cell alkaline batteries) provided power to the controller unit itself and to all of the instruments except the ISUS and GasHound (Table 3.4), which were powered by internal batteries. Sampling frequencies of the instruments were selected to provide the best trade-off between temporal resolution and length of deployment, since battery life (as opposed to fouling) was the most important variable governing deployment duration. In addition to measuring biological, physical and chemical properties of the surface waters, the other major purpose of the drifters was to provide a Lagrangian framework for ship navigation around the Fe fertilized patch. Consequently, GPS data were acquired, and radio connections attempted every 5 min – these two processes were the largest drain on the batteries. Data from all other instruments were collected at hourly intervals. At the temperatures of the Southern Ocean, battery life was significantly shortened, and with the sampling frequencies just described, each drifter could be

\(^5\) The interval between visits to the HALE-ALOHA mooring is likely to increase to 3 months in the near future.
deployed for at most 2 weeks before the package was recovered and new batteries installed. All data were stored in memory (RAM) and transmitted via packet radio to the supporting ship when it was in range (~5 Km to 10 Km depending on sea state). In contrast to equatorial mooring applications, no hard drive was included in this configuration of the OASIS.

The unique nature and increased vulnerability of profiling moorings can necessitate specialized logic on the part of the controller. Two way communications with a shore-based server allows the updating of mission and scheduling files. Amongst other parameters mission files can determine profile speed, the systems activated, and the minimum profile depth. Increasing the minimum profile depth is an effective method to prevent instrument damage during bad weather. Inclement conditions may also be detected, for example, from the vertical motion of profiling vehicle and/or the wave height from bottom mounted pressure sensor, and subsequently acted on by the controller. A default, or safe, mission program to be used by the controller in the absence of shore communication may be advantageous. In common with other type of moorings a low-power standby mode can be entered between activity periods. An example of a simple control sequence upon waking is:

1. establish communications with the shore station to check for updated mission or scheduling files,
2. perform the profile, and stream some data in real-time,
3. preprocess the profile data for telemetry, and
4. transmit this data to the shore station.

3.6 DATA ANALYSIS AND QUALITY CONTROL METHODS

As described above, the data recorded by an array of sensors mounted on a buoy are retrieved either remotely via a telecommunications link, or by directly downloading it when the buoy is visited for service or retrieval. As with methods of measurement and instrument deployment (Sect. 3.4 above), many aspect of data processing, analysis and quality control are already covered by protocols specified for similar shipboard measurements. Radiometric characterization and calibration requirements and conversion of sensor counts to irradiance and radiance units must follow the protocols described in Volume II (Chapters 2 and 3) and Volume III (Chapter 2), with adjustments to account for:

1. in-water spectral irradiance and radiance measurements at only 1 to 3 depths in the water column,
2. prolonged sensor operation for weeks to months without hands-on stability checks and cleaning, and
3. bio-fouling of submerged optical surfaces, and contamination of above-water sensors by deposition of dust, salt and/or bird droppings.

Similarly, IOP sensors are calibrated, and the data processed, analyzed and checked for quality, following the protocols described in Volume IV, with adjustments for the special circumstances applicable to sensors deployed on buoys.

The following subsections describe recommended methods for handling Above-Water Spectral Irradiance Data, In-Water Radiometric Data, Absorption and Beam Attenuation Data, Backscattering Data, and Chlorophyll a Fluorescence Data, respectively. The contents of each subsection describe procedures for Data Processing, Data Analysis and Quality Control, in that order. In general terms:

- “Data Processing” covers conversion of sensor response counts to engineering and scientific measurement units, including adjustments for pre- and post-deployment sensor calibration results.
- “Data Analysis” covers methods for determining derived quantities such as, for example, water-leaving radiance, diffuse attenuation coefficients, volume scattering coefficients and backscattering.
- “Quality Control” describes methods for analyzing the time series of each measurement, together with derived quantities, for internal consistency, symptoms of instrument failure, symptoms of biofouling, consistency with other on-board measurement channels and/or sensors, and consistency with external information (e.g. SeaWiFS water-leaving radiance spectra comparisons with measured upwelled radiance spectra).
Above-Water Spectral Irradiance

A radiometer mounted above the water surface (Tables 3.3 and 3.4) is frequently used to measure incident spectral irradiance $E_s(\lambda, t)$ at one or more wavelengths $\lambda$, at times $t$ programmed into a particular buoy’s Instrument Controller (Sects. 3.4 and 3.5).

**Data Processing** steps, which may be implemented either in a buoy’s Instrument Controller, or retrospectively applied to data downloaded when a buoy is visited for maintenance, or retrieved, include:

1. Dark counts, obtained by averaging data scans obtained at local midnight, are first subtracted from each channel.
2. The radiometer’s spectral irradiance responsivity calibration factors are applied to convert dark-corrected counts in each channel into spectral irradiance units $[\mu\text{W cm}^{-2}\text{nm}^{-1}]$. The calibration factors are obtained from pre-deployment responsivity calibrations, in air, using characterization methods consistent with protocols described in Vol. II, Chapter 3 (Section 3.2). The detailed algorithms by which these coefficients are applied are provided by the instrument manufacturer; these may, or may not, include adjustments for detector temperature (if measured internally in the instrument). In some cases, it may be appropriate to adjust the responsivity calibration coefficients to account for differences observed in pre- and post-deployment calibrations; such adjustments must be approached with extreme caution, however, as changes in detector sensitivity are not necessarily linear over time.
3. It may be necessary, or desirable, to average $E_s(\lambda, t)$ observations over a period of minutes-to-hours, and to transmit (or store) only the temporal average $\bar{E}_s(\lambda, t)$.

**Data Analysis:**

1. The time series of spectral irradiance incident above the sea surface $E_d(0^+, \lambda, t) \equiv E_s(\lambda, t)$ is obtained directly from the calibrated data.
2. To obtain downwelled spectral irradiance just beneath the water surface $E_d(0^-, \lambda, t)$ it is necessary to account for not only the downward transmission of $E_d(0^+, \lambda, t)$ across the interface, but also the downward reflectance at the interface of upwelled spectral irradiance $E_u(0^-, \lambda, t)$. The reader is referred to Vol. I, Chapter 2 (Sect. 2.7) and Vol. III, Chapter 4 (Sects. 4.2, 4.4 and 4.6). From Vol. III, Chapter 4, in particular, equation (4.11) gives the relationship $E_d(0^-, \lambda) \equiv E_d(0^+, \lambda) \frac{1 - \rho}{1 - \tau R(0^+, \lambda)}$, and the related discussion gives $\rho \equiv 0.043 \pm 0.02$, $\tau \equiv 0.48$, and $0 < R(0^+, \lambda) \leq 0.1$. Combining this information for clear sky conditions and Case I waters, a useful approximation may be obtained as

$$E_d(0^-, \lambda, t) \equiv 0.98 E_s(\lambda, t). \quad (3.1)$$

**Quality Control:**

1. Inspect the time-series of raw data in each channel of the radiometer for bad data points (e.g. obvious dropouts), instrument failure, power failure, and symptoms of salt or other depositions on the irradiance collector.
2. Calculate time series of normalized irradiance spectra $\hat{E}_s(\lambda, t) = \frac{E_s(\lambda, t)}{E_s(\lambda_{\text{REF}}, t)}$ and test whether the shape of the spectrum, as defined by the relative magnitudes of normalized irradiance at all wavelengths, fall within limits defined by clear sky, partly cloudy and overcast models of incident daylight. This is sometimes termed a “rank-order” test between ratios for different wavelengths within a given spectral measurement at time $t$. 

67
3. Compare the magnitudes of measured \( E_s(\lambda, t) \) to clear-sky model estimates \( \hat{E}_s(\lambda, t) \) (e.g. Frouin et al. 1989, Gregg and Carder 1990) calculated for the solar zenith angle at each time \( t \). Reject as suspect any measurements exceeding the threshold

\[ E_s(\lambda, t) > 1.25\hat{E}_s(\lambda, t). \]  

(3.2)

The factor 1.25 allows measured spectral irradiances to moderately exceed calculated clear sky irradiances due to reflections from scattered clouds. Although larger \( E_s(\lambda, t) \) values (up to factor of 3) may occur under some cloud conditions (e.g. scattered cumulus), these large values are intermittent and will not persist over the averaging periods usually applied to buoy measurements.

4. Combining the previous two steps, the shape of each \( \hat{E}_s(\lambda, t) \) spectrum should be consistent with its magnitudes relative to the clear-sky model. In other words, if the magnitudes of \( E_s(\lambda, t) \) indicate clear-sky conditions, then the spectral shape should fall off significantly with increasing wavelength. And conversely, if relatively low \( E_s(\lambda, t) \) magnitudes suggest overcast conditions, the shape of the spectrum should be relatively flat and not decrease strongly with wavelength.

5. Examine the \( E_s(\lambda, t) \) time series for consistency with the seasonal cycle of incident solar irradiance throughout the period of the deployment.

6. If \( E_s(\lambda, t) \) is measured at 6 or more wavelengths consistent with the specifications of Volume II, Chapter 2 (Table 2.1), it should be possible to compute an estimate of Photosynthetically Available Radiation (PAR) at each time \( t \). As a further quality control measure, these PAR estimates may be compared to independently measured PAR (if a PAR sensor is mounted on the buoy) and/or to regional PAR estimates modeled using cloud imagery measured using radiometers on geostationary satellites (e.g. Frouin et al. 1989).

**In-Water Radiometric Data**

Radiometers are mounted underwater on moored and drifting buoys, in a variety of configurations, to measure time series of upwelled spectral radiance \( L_u(z, \lambda, t) \), downwelled spectral irradiance \( E_d(z, \lambda, t) \), and less often, upwelled spectral irradiance \( E_u(z, \lambda, t) \) (Sect. 3.4; Tables 3.3 and 3.4).

**Data Processing:** The initial steps in processing data from underwater radiometers are the same as for the above-water spectral irradiance:

1. Dark counts, from local midnight scans, are subtracted from each the data for radiometric channel.
2. Responsivity calibration factors determined in air are applied to convert radiance sensor counts to spectral radiance \( \mu W \text{ cm}^{-2}\text{nm}^{-1}\text{sr}^{-1} \) and irradiance sensor counts to spectral irradiance \( \mu W \text{ cm}^{-2}\text{nm}^{-1} \) units. The above comments regarding \( E_s(\lambda, t) \) calibrations apply here also.
3. Calibrated radiances in each radiance sensor channel are multiplied by radiance immersion factors to determine \( L_u(z, \lambda, t) \), and calibrated downwelled and upwelled irradiances are multiplied by irradiance immersion factors to determine \( E_d(z, \lambda, t) \) and \( E_u(z, \lambda, t) \), respectively. The immersion factors for radiance are calculated based on the refractive index of the radiometer’s window material, and immersion factors for spectral irradiance sensors must be determined experimentally, following the protocols described in Volume II, Chapter 3 (Sect. 3.5). The instrument manufacturer ordinarily provides these factors, but frequently, only “representative values” for a “collector class” are listed. As pointed out in in Volume II, Chapter 3 (Sect. 3.5), immersion factors may vary up to 8% between irradiance sensors of the same design and material specifications. To comply with these protocols, therefore, an investigator must ensure that the immersion factors for each in-water irradiance instrument have been experimentally characterized.
4. As with \( E_d(\lambda,t) \), it is often necessary, or desirable, to average individual \( L_u(z,\lambda,t) \) and \( E_d(z,\lambda,t) \) measurements over periods of minutes, or hours. If so, clearly the averaging interval for the in-water and above water data must be the same. Averaging should be applied with caution, if at all, in situations where bio-optical conditions (e.g. chlorophyll a concentration) at the measurement site may be expected to vary significantly during the averaging period. When chlorophyll a variability during the averaging period is large, Chl determined using, e.g., \( \frac{L_u(0.443,T)}{L_u(0.555,T)} \) in a remote sensing algorithm is always an underestimate of the mean chlorophyll a concentration. This is a well-known, direct consequence of the nonlinear relationship between remote sensing reflectance and absorption in seawater.

**Data Analysis:** methods are described to determine diffuse attenuation coefficients, water-leaving radiance, normalized water-leaving radiance, and remote sensing parameters including chlorophyll concentration Chl. The methods applicable to data from a particular buoy are determined by the available combination of measurements. Small, expendable drifters often carry only a single radiance sensor (e.g. 7 wavelength Satlantic OCR-100) mounted beneath the buoy’s hull (or flotation collar) at a depth \( z_o - 1 \) m (for example the OSU SOFeX drifter illustrated in Figure 3.12). The MOOS (Fig. 3.3) and ARGOS (Fig. 3.5) moored arrays, on the other hand, combine an \( L_u(z,\lambda,t) \) sensor (OCR-100) mounted immediately beneath the buoy hull with paired \( L_u(z,\lambda,t) \) and \( E_d(z,\lambda,t) \) sensors at 10 m and 20 m depths. The GoMOOS optical moorings have paired Lu and Ed sensors at 3m, and an Ed sensor at 18m. Somewhat different data analysis schemes are possible with data from each of these and other radiometer configurations on a buoy. Zheng et al. (2002, 2003) describe procedures for the BTM data sets. In general, the uncertainty of derived quantities will be both lower and better understood for configurations with radiometers at several depths. Many of these uncertainties are not as important with profiling moorings, where virtually continuous profiles may be obtained and analysed using the methods of Vol. III, Chapter 2.

1. **Diffuse Attenuation Coefficients** \( K_4(z,\lambda) \) for \( E_d(z,\lambda) \) and \( K_1(z,\lambda) \) for \( L_u(z,\lambda) \) may be determined directly either from radiometric measurements at two depths \( (z_i, z_j) \), \( j > i \), or modeled, from ratios \( \frac{L_w(\lambda_m)}{L_u(\lambda_u)} \) using remote sensing algorithms, as average values \( K(\lambda) \) (denoted also as, e.g., \( K490 \) or \( K520 \), for wavelengths of 490 nm or 520 nm).

a. \( K490(t) \) and \( K(\lambda,t) \) from water-leaving radiance ratios: Assuming that \( \frac{L_u(z_o,\lambda_1,t)}{L_u(z_o,\lambda_2,t)} \equiv \frac{L_w(\lambda_1,t)}{L_w(\lambda_2,t)} \), ratios of upwelled radiance from a radiometer mounted under the buoy at a depth \( z_o - 1 \) m may be directly substituted into satellite remote sensing algorithms to determine Chl concentration [mg m\(^{-3}\)] (e.g. O’Reilly et al. 2000, Strutton et al. 2001) and \( K490 \) [m\(^{-1}\)] (e.g. Austin and Petzold 1981). The remote sensing parameter \( K490(t) \) is the diffuse attenuation coefficient at 490 nm averaged over the first attenuation depth, i.e. the depth where \( E_d(z,490,t) \) is 37% of \( E_d(0,490,t) \). Given \( K(490) \), the empirical algorithm and coefficient tables of Austin and Petzold (1986) may be used to determine \( K(\lambda) \) at other wavelengths. Morel (1988) provides an alternative algorithm for determining \( K(\lambda) \) from remote sensing Chl.

b. \( K_d(z_o,\lambda_1) \) from \( E_d(\lambda,t) \) and \( E_d(z_1,\lambda,t) \): Given irradiances measured by radiometers located above the surface and at depth \( z_1 \) [m], \( E_d(0^+,\lambda,t) \) is determined from \( E_d(\lambda,t) \) using...
equation (3.1), and the diffuse attenuation coefficient averaged from the surface to \( z_1 \) is calculated as

\[ K_d(z_1, \lambda, t) = \frac{1}{z_1} \ln \left( \frac{E_d(z_1, \lambda, t)}{E_d(0^+, \lambda, t)} \right), \tag{3.3} \]

where \( z_0 = \frac{z_1}{2} \).

c. \( K_d(z_j, \lambda, t) \) from \( E_d(z_j, \lambda, t) \) and \( E_d(z_j, \lambda, t) \): Given two underwater downwelled irradiance sensors at depths \( z_j > z_i \), the diffuse attenuation coefficient averaged over that depth interval is given by

\[ K_d(z_j, \lambda, t) = \frac{1}{z_j - z_i} \ln \left( \frac{E_d(z_j, \lambda, t)}{E_d(z_i, \lambda, t)} \right), \tag{3.4} \]

where \( z_0 = \frac{z_i + z_j}{2} \).

d. \( K_u(z_j, \lambda, t) \) from \( L_u(z_j, \lambda, t) \) and \( L_u(z_j, \lambda, t) \): Given two underwater upwelled radiance sensors at depths \( z_j > z_i \), the diffuse attenuation coefficient averaged over that depth interval is given by

\[ K_u(z_j, \lambda, t) = \frac{1}{z_j - z_i} \ln \left( \frac{L_u(z_j, \lambda, t)}{L_u(z_i, \lambda, t)} \right), \tag{3.5} \]

where \( z_0 = \frac{z_i + z_j}{2} \).

In principle, the uncertainties of the diffuse attenuation coefficients determined using (3.4) and (3.5) should be better than that from (3.3), and the uncertainty associated with any of those 3 methods should be better than the estimates of \( K(z, \lambda) \) modeled using ratios of upwelled radiance measured just below the sea surface. If the measurement combination from a particular buoy is sufficient, it is recommended that diffuse attenuation coefficients be calculated for comparison and quality control purposes.

2. **Water-Leaving Radiance** \( L_w(\lambda, t) \) is determined by extrapolating upwelled radiance measured at depth \( z \) to the surface as

\[ L_w(0^-, \lambda, t) = L_w(z, \lambda, t) e^{\int_{z}^{0} K_u(z, \lambda) dz}, \tag{3.6} \]

where \( K_u(z, \lambda) = \frac{1}{z} \int_{0}^{z} K_u(z, \lambda) dz \). Upwelled radiance is then propagated upward through the interface as

\[ L_w(\lambda, 0, \phi) = \frac{1 - p(\theta', 0; W)}{n^2} L_w(0^-, \lambda, \theta', \phi) \]

for general viewing angles \( \theta' > 0 \) [see Vol. I, Chapter 2, (Sect. 2.5) and Vol. III, Chapter 4]. If only nadir-viewing geometry is considered, then the surface reflectance term becomes independent of wind speed \( W \), and the upward transmittance term is constant at \( \frac{1 - p(0, 0; W)}{n^2} = 0.543 \) (Austin 1974), and water-leaving radiance is calculated as

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\( ^{6} \) Note that \( p(0', 0; W) \) is reflectance for a wind-roughened sea surface, and not the Fresnel reflectance.
Given only discrete radiometric measurements, \( \bar{K}_L(z, \lambda) \) must be estimated as some combination of the methods 1a) through 1d), described above, for determining the diffuse attenuation coefficient. Some possible approaches are:

a. If upwelled radiance is measured using two wire-mounted radiometers at depths \( z_2 > z_1 \), for example, \( K_L(\pi_{z_2}, \lambda, t) \) may be calculated with (3.5) for the interval between the two depths. [Combining radiance measurements in this way between hull-mounted and wire-mounted radiometers, \( i.e. \) to determine \( K_L(\pi_{z_0}, \lambda, t) \), may be less straightforward if the buoy diameter is large and/or the measurement at \( z_0 \) is not nadir-viewing] In clear oligotrophic water masses, it may be reasonable to assume optical homogeneity from the surface to depth \( z_2 \), or that \( \bar{K}_L(z, \lambda, t) \equiv K_L(\pi_{z_2}, \lambda, t) \). Other approximations must be considered if there is reason to believe that optical properties vary strongly in the layer above depth \( z_2 \).

b. If upwelled radiance is measured at only one depth, whether using a hull-mounted or wire-mounted radiometer, and downwelled irradiance is measured at one or more depths, it can usually be assumed that \( K_L(z, \lambda) \approx K_L(z, \lambda) \) within approximately 5 \% (Kirk 1994). Then, \( \bar{K}_L(z, \lambda) \) may be determined using some combination of (3.3) and (3.4).

c. If upwelled radiance is measured only at depth \( z_o \), just beneath the buoy hull, then there is no choice but to assume that \( \bar{K}_L(z, \lambda) \approx \bar{K}(\lambda) \) and apply remote sensing algorithms such as those cited above under 1a).

3. **Normalized Water-Leaving Radiance** \( L_{WN}(\lambda, t) \) is calculated from \( L_w(\lambda, t) \) following the definition of (Gordon and Clark 1981)\(^7\) as

\[
L_{WN}(\lambda, t) = L_w(\lambda, t) \frac{\bar{F}_o(\lambda)}{E_s(\lambda, t)},
\]

where \( \bar{F}_o(\lambda) \) is mean extraterrestrial solar irradiance (Neckle and Labs 1984) [see also Vol. I, Chapter 2, equation (2.55) in and Vol. III, Chapter 4 (Sect. 4.1)]. If reliable measurements of \( E_s(\lambda, t) \) are available, they are substituted directly in (3.8). Otherwise, incident surface irradiance may be approximated either as the modeled clear-sky irradiance \( \bar{E}_s(\lambda, t) \) (\( e.g. \) Frouin et al. 1989, Gregg and Carder 1990) calculated for the solar zenith angle \( \theta_o \) at time \( t \), or more simply as

\[
\bar{E}_s(\lambda, t) = \bar{F}_o(\lambda) t_{\text{sun}}(\lambda, \theta_o) \cos \theta_o \left( \frac{d_o}{d} \right)^2,
\]

where at time \( t \), \( t_{\text{sun}}(\lambda, \theta_o) \) is the diffuse transmission of the atmosphere, and \( d_o \) and \( d \) are the mean and actual earth-sun differences, respectively. Finally, \( L_{WN}(\lambda, t) \) must be converted to Exact Normalized Water-Leaving Radiance by the methods described in Vol. III, Chapter 4.

4. **Ocean Color Remote Sensing Parameters**, Chl – chlorophyll a concentration in mg m\(^{-3}\) – and \( K_{490} \) – the diffuse attenuation coefficient in m\(^{-1}\) averaged over the first e-folding attenuation depth - are

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\(^7\) Gordon et al. (1988) introduced a variant definition of Normalized Water-Leaving Radiance that included an adjustment for the downward Fresnel transmittance of incident direct solar flux into the ocean. Although this approximation has the correct sign, its magnitude is not correct for a real ocean surface (even under calm conditions). Therefore, the Gordon et al. (1988) definition is not used, because it is inconsistent with the definition of Exact Normalized Water-Leaving Radiance (Vol. III, Chapter 4), which correctly accounts for downward irradiance transmittance through the sea surface.
calculated from ratios of either water-leaving radiance at different wavelengths, or more directly from ratios of near-surface measurements of upwelled spectral radiance (e.g. Sutton et al. 2001). Algorithms for calculating these parameters are cited in item 1a) above, as part of the discussion of methods to determine diffuse attenuation coefficient.

**Quality Control:**

1. Inspect the time-series of raw data in each radiometric channel for bad data points (e.g. obvious dropouts), instrument failure, power failure, and symptoms of biofouling.

2. Calculate time series of normalized spectra 
\[
\hat{E}_d(z, \lambda, t) = \frac{E_d(z, \lambda, t)}{E_d(z, \lambda_{REF}, t)}, \quad \hat{L}_u(z, \lambda, t) = \frac{L_u(z, \lambda, t)}{L_u(z, \lambda_{REF}, t)}
\]
and 
\[
\hat{L}_w(\lambda, t) = \frac{L_w(\lambda, t)}{L_w(\lambda_{REF}, t)}.
\]
Test whether

   a. The shapes of these spectra should be consistent with those of normalized spectra from previous deployments in the site, and from earlier in the current deployment.

   b. The shapes of \( \hat{L}_u(\lambda, t) \) spectra should be consistent with similar spectra of wavelength ratios in time-series of water-leaving radiances determined from SeaWiFS, MODIS, and other ocean color satellites.

   c. Following Abbott and Letelier (1998), set \( \lambda_{er} = 555 \text{ nm} \) and use \( \hat{L}_u(z, 683, t) \) and \( \hat{E}_d(z, 683, t) \) to test for biofouling. In theory, if chlorophyll bearing organisms aggregate on or near the radiometer’s window (or collector), the transmittance of the window (or collector) at 555 nm would be severely decreased while chlorophyll fluorescence on or near the surface would continue to provide a significant signal. Abbott and Letelier (1998) suggest that biofouling is indicated when either ratio exceeds 0.1, a value appropriate for clear oligotrophic water masses. In very productive coastal water masses, a threshold of 0.5 may be more appropriate. A regional threshold may be established by comparing the \( \hat{L}_u(z, 683, t) \) and \( \hat{E}_d(z, 683, t) \) (555 nm reference) ratio history during each deployment to the extent of biofouling observed when the sensor is recovered.

3. Compare absolute values of water-leaving radiances derived from the buoy measurements with those determined from SeaWiFS and other satellite ocean color sensors. These comparisons are best done in a time-series mode to detect outliers, and divergences indicating the onset and growth of biofouling organisms on the optical surface. Caution must be used in this method if the in situ data are collected in regions that are characterized by Case 2 water types with high concentrations of colored dissolved and particulate organic matter, relative to phytoplankton pigment concentration. Moreover, the atmospheric correction procedure used by SeaWiFS, and other ocean color sensors, may underestimate the normalized water leaving radiance estimates in Case 2 waters.

4. Examine diffuse attenuation coefficients calculated from the data

   a. Check whether \( K_d(z, \lambda) \geq a_w(\lambda) \), where \( a_w(\lambda) \) is the spectral volume absorption coefficient of pure water [Vol. I, Chapter 2 (Sect. 2.5) and references cited therein]. If 
\[
0 < \left[ a_w(\lambda) - K(\lambda) \right] \leq 0.005 \text{ m}^{-1},
\]
flag the data as suspect, but if 
\[
\left[ a_w(\lambda) - K(\lambda) \right] > 0.005 \text{ m}^{-1},
\]
the diffuse attenuation coefficients are clearly bad data. If such conditions persist, it is likely that one of the radiometric channels used to determine the diffuse attenuation coefficient has either failed, or has experienced significant biofouling. In MBARI’s experience in the equatorial Pacific, less than 5% of the calculated data fail this test, and this percentage should be less in mesotrophic or eutrophic waters. Measurements not meeting this criterion usually occur during extremely cloudy or overcast days, and are possibly result from unresolved incident irradiance variability during the 4-hour period over which the data are averaged.
b. When the data permit, compare diffuse attenuation coefficients calculated by the different methods outlined above to determine internal offsets and uncertainties in the data set. These comparisons can also be used, in time series mode, to detect the onset and extent of biofouling in different radiometers. Fig. 3.15, shows time series of \( K_d (z_0,490,t) \) for a 5 month MOOS buoy deployment in Monterey Bay. The three time series were computed using equation (3.3) with surface values determined from \( E_d (\lambda, t) \) in (3.1) and \( E_d (z,\lambda,t) \) for \( z_1 = 10 \) m (top curve), \( z_2 = 20 \) m (bottom curve), and \( z_3 = 30 \) m (middle curve). After approximately 2 months, the 3 curves diverge in a manner that cannot be explained by optical stratification of the water column, offering strong evidence of progressive biofouling of the radiometers at 10 m and 30 m.

c. When \( K_d (\tau_0,\lambda,t) \) is determined from in-water measurements alone, i.e. independently from \( E_0 (\lambda) \), measures of internal consistency between in-water and the above-water radiometer may be calculated as the unbiased percent differences

\[
\Delta_{ul}(\lambda,t) = 100 \left( \frac{E_d (z_k,\lambda,t) e^{-K_d (\tau_0,\lambda,t) z_k}}{E_d (0,\lambda,t)} - E_d (0,\lambda,t) \right) \%
\]  

(3.10)

where \( k = i \) or \( j \), and \( E_d (0,\lambda,t) \) is calculated using \( E_0 (\lambda) \) in equation (3.1). If running means and standard deviations of \( \Delta_{ui}(\lambda,t) \) and \( \Delta_{uj}(\lambda,t) \) are calculated over a suitable averaging period - perhaps 2 weeks - the comparative time series may be used to provide additional diagnostic indications of instrument degradation and biofouling.

5. Chl and K490 derived from ratios of water-leaving radiance should agree with the parameters determined from satellite ocean color data within approximately 35 % and 20 %, respectively. Fig. 3.16 illustrates an example time series of Chl derived from the MBARI radiometers on the EP1 TAO mooring compared with Chl derived from SeaWiFS data and with chlorophyll a concentration from shipboard samples.

![Fig. 3.15: An example of biofouling symptoms, as evidenced by the divergences in K490 over different depth intervals, beginning midway through a 135 day time series of radiometric measurements on a mooring in Monterey Bay, CA.](image-url)
Protocols for data analysis and quality control of beam attenuation and absorption coefficients are described in Vol. IV, Chapters 2 and 3, respectively. Protocols for determining the backscattering coefficient \( b_b(\lambda) \) from measurements of the volume scattering function at one or more scattering angles are described in Vol. IV, Chapter 5.

Fig. 3.16: Time series of chlorophyll concentrations derived from MBARI optical instruments, calculated from two depths (surface and 20 m depth) on the TAO mooring at EP1 (0°, 155°W). For comparison, SeaWiFS derived Chl and in situ shipboard chlorophyll a concentration measurements for the mooring location are also plotted.

Chlorophyll a Fluorescence Data

The GoMOOS moorings use the WETLabs Inc digital ECO shuttered fluorometer (DFLS) series for all chlorophyll fluorescence measurements (Table 3.3). This instrument is low power, stable, and has a copper shutter to prevent biofouling. The sensor is wrapped in copper foil tape as an additional prevention measure. The epoxy facing of the DFLS prevents calibrating the instrument against a chlorophyll standard dissolved in acetone. Therefore, the GoMOOS project calibrates the DFLS sensors against a dilution series of a monoculture of phytoplankton (\( T. \) pseudonana) in vitro, the chlorophyll a concentration of which is measured using the protocols of Vol. V, Chapter 2. The fluorometer responses are fit to a linear regression equation as a model for converting the data to chlorophyll concentration. Each DFLS is additionally characterized for stability (using a pure water standard) and for temperature dependence using a controlled water bath. All sensors are calibrated against a dilution series of phytoplankton and for the pure water offset before and after each deployment.

Data Processing

1. Temperature correction of the linear regression offset is applied based on the in situ water temperature and the results of the temperature characterization.
2. Average digital counts reported to shore are converted to chlorophyll concentration units (mg l-1) based on the linear regression equation from the calibration.
3. Upon recovery of the mooring, the entire raw data record is analyzed again. For each hourly sampling period, the raw digital counts are are filtered using a 1.5 standard deviation filter and then steps 1 and 2 are repeated.

Data Analysis
1. Upon recovery of the mooring, the DFLS is recalibrated against pure water and 0.2 micron filtered seawater to check for instrument drift and for biofouling of the optical face. If significant instrument drift or biofouling is detected, a linear correction is applied to the temporal data to account for these effects based on the pre- and post-calibrations against the phytoplankton dilutions.

2. The fluorometric chlorophyll concentration values are compared to Morel’s chlorophyll estimates using $K_d(z,\lambda)$ values calculated from the downwelling irradiance data (see above). Comparisons are only made between the average night time fluorometric chlorophyll data and the day time $K_d(z,\lambda)$ values in order to minimize the influence of fluorescence quenching of the fluorometric data. Note that in many of the GoMOOS mooring locations, the surface fluorometric chlorophyll data time series show a strong diurnal response, with high chlorophyll values at night and the lowest values at local noon due to fluorescence quenching.

Quality Control

1. The data are inspected to ensure that all values fall between minimum and maximum limits derived from the DFLS calibrations. Any data point that is outside of these limits is flagged as questionable data.

2. The entire raw data set of chlorophyll fluorometric data is analyzed after recovery of the mooring and corrections are applied based on the pre- and post-calibrations of the DFLS sensor.

3.7 RECORDKEEPING AND DATA ARCHIVAL

Logs and supporting documentation

The configuration of a mooring or drifter design and instrumentation can change continuously due to various upgrades between deployments. Therefore, concise documentation of deployment, maintenance, recovery and any changes to instruments should be clearly recorded in both hard and soft copy format. Serial numbers should be issued to each part of a mooring or drifter to determine the life span of the hardware from eventual corrosion. Instrument serial numbers and calibration files must also be carefully documented and stored. Examples of deployment reports for respective projects covered in this chapter can be found at

- MOOS: http://www.mbari.org/bog/MOOS/mooringlog.html
- TAO/TRITON (optical platforms only): http://bog.shore.mbari.org/~bog/eqpac_log.txt
- BTM: http://www.opl.ucsb.edu
- OSU Drifters and moorings: http://picasso.coas.oregonstate.edu/ORSOO
- GoMOOS: http://gyre.umeoce.maine.edu/GoMoos/gominfo.php

Data Archival

Data archiving and methods also vary with projects. For example, MBARI maintains an extensive mooring data archive in NetCDF format. All of the data from high frequency raw to averaged quality controlled data is stored in internal databases. Data access to the public is limited to the quality controlled data. The various projects described in this chapter offer websites with limited access to there respective data as follows

- MOOS: http://www.mbari.org/oasis/
- TAO/TRITON: http://www.pmel.noaa.gov/tao/jsdisplay/
- PIRATA: http://www.pmel.noaa.gov/tao/data_deliv/deliv-pir.html
- EQPAC: http://bog.shore.mbari.org/~bog/oasis.html
- BTM: http://www.opl.ucsb.edu
REFERENCES


Chapter 4

Ocean Color Radiometry from Aircraft: I. Low Altitude Measurements from Light Aircraft

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4.1 INTRODUCTION

Low altitude, passive remote sensing of ocean color from aircraft spans nearly three decades and has used a variety of sensors. The Multichannel Ocean Color Sensor (MOCS) was first used in field experiments in 1980-82. MOCS measured spectral radiances in twenty contiguous 15-nm wide bands from 400 to 700 nm. Early applications of a spectral curvature ocean color algorithm for chlorophyll \( a \) concentration, \( Chl \) [mg m\(^{-3}\)], used data from MOCS along the East coast of the US over a six-year period (Grew, 1981; Campbell & Esaias, 1983). The spectral curvature algorithm (Sect. 4.4 below) was applied in real-time without calibration to estimate \( Chl \). MOCS was operated with the Airborne Oceanographic Lidar (AOL) that combined active and passive radiometry and produced independent estimates of \( Chl \). Study sites for the comparisons included shelf waters of the western Atlantic Ocean, Chesapeake Bay, Nantucket Shoals, and warm-core Gulf Stream rings. MOCS- and AOL-derived chl-a and in-situ measurements of chl-a from ships showed good agreement.

The successful retrieval of \( Chl \) using MOCS data and the spectral curvature algorithm led to the development of a small and relatively simple ocean color instrument, the Ocean Data Acquisition System (ODAS) in the mid-1980s, supported by NASA and NOAA. Following on the findings of Grew (1981) and Campbell and Esaias (1983) using equally spaced bands around MOCS band 7, ODAS was designed with three bands in the blue-green region of the visible spectrum at 460, 490, and 520 nm. The instrument was specifically designed for missions on light aircraft, an attribute rare, or absent, in previous ocean color instruments. The goal was to enable repeat coverage with high spatial resolution on affordable, relatively slow flying platforms, thus to move from demonstration to operational mode in acquiring remotely sensed data on \( Chl \) in estuarine and coastal waters. The ODAS nadir-viewing radiance sensor was designed to collect data along a line-of-flight at a sampling rate of 10 Hz. It was equipped with Loran-C for onboard navigation and was usually flown together with an infrared temperature sensor (PRT-5 or Heimann instruments) to sample sea surface temperature (SST) concurrently with ocean color measurements. The early uses of ODAS were in waters of the middle Atlantic bight, and it subsequently received heavy use from 1989-96 in Chesapeake Bay as part of the Chesapeake Bay Remote Sensing Program (CBRSP – http://www.cbrsp.org). Nearly 150 flights were conducted with ODAS to study seasonal and inter-annual variability of phytoplankton biomass and primary productivity in the Bay.

4.2 MEASUREMENT METHODS

Key operational attributes of ODAS flights were low altitude (150 m), low speed (100 knots = 50 m s\(^{-1}\)), and schedules timed to avoid high sun angles (flights conducted at 08:30 – 10:30 h and 14:30 – 16:30 h local time), high