VOLUME 1 - TECHNICAL

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TITLE: **Development, Assessment and Commercialization of a Biogeochemical Profiling Float for Calibration and Validation of Ocean Color and Ocean Carbon Studies**

RESEARCH OPPORTUNITY: National Oceanographic Partnership Program (NOPP) and Interagency Committee on Ocean Science and Resource Management Integration (ICOSRMI): ONR-BAA-09-012

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UNIVERSITY OFFICE TO BE CONTACTED REGARDING GRANT NEGOTIATION: Office of Research and Sponsored Programs
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DATE: 10 April 2009

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1. Project Summary/Abstract

One of the major limitations of optical remote sensing using satellites is that while this data in general provides excellent temporal and horizontal coverage, very limited information on the vertical structure of biogeochemical parameters is obtained. Yet this data is needed to study global biogeochemical processes. In order to eventually provide this global coverage of variability in all three spatial dimensions we propose to add passive and active optical instrumentation to profiling floats and to show that these instruments can be used routinely and can maintain useful calibration over periods of several years. The combination of optical remote sensing and profiling floats will be a powerful tool for the full understanding of ocean processes.

We propose to integrate existing high precision bio-optical sensors (both active and passive) onto profiling floats, deploy the floats in interesting dynamic ocean regimes, and demonstrate the efficacy of this stable, autonomous and sustainable technology for a.) the calibration and product validation of orbiting ocean color radiometers and b.) investigation of the dynamics of carbon in the upper ocean on time and space scales appropriate for the evaluation of the role of the ocean in the global carbon cycle.

Currently, profiling float technology is used by only a handful of labs and investigators. Fewer still incorporate biogeochemical sensors onto the floats. Our overall goal is that the greater oceanographic community will be able to use and be interested in using these technologies as a result of hardware, software and scientific innovations that will be developed as part of this proposal.

In the process, the following will be achieved:

a. Novel integration of active and passive optical sensor packages to APEX profiling floats.
b. Rigorous evaluation of the capabilities and limitations of profiling floats to provide data for calibration and validation of satellite retrieved ocean color and derived parameters, including a thorough analysis of the uncertainties of float based measurements.
c. Demonstration of capabilities to deploy and retrieve floats for relatively short duration experiments.
d. Development of adaptive profiling regimes to capitalize on events, e.g. the spring bloom.
e. Development of software for display and dissemination of data.
f. Development of a novel web tool that will provide NASA's products in the vicinity of the profiling float (in space and time) to provide a context for the float's profile as well as needed inputs for the scientific analysis of the float's data.
g. Scientific discoveries regarding the dynamics of phytoplankton in the upper ocean.

The result is a science-driven, full end-to-end mission operations capability for the community.

2. Statement of Work

2.1 Introduction

The rapid development of robotic vehicles and sensors during the last decade has led to nothing short of a revolution in oceanography: for the first time, we are able to observe physical, biological and chemical properties as they vary in three-dimensional space and time on the physical and ecological scales that matter. They represent a major complementary step to surface ocean satellite observations because they can extend our measurement capability into the third, vertical, spatial dimension. In addition, they are not compromised by clouds, can potentially sample at higher spatial and temporal resolution than satellites, and greatly extend the suite of observable parameters. They can also be used to provide vicarious calibration and product validation inputs for use with satellite sensors observing the spectral distribution of radiance upwelled from the ocean interior.

Optical sensors onboard autonomous platforms have provided exceptional insight: Surface drifting buoys have been successfully used to measure the optical characteristics of the upper ocean, which for the open ocean, are largely dependent on the concentration and activity of phytoplankton. The first of such floats was deployed in the Equatorial Pacific, and measured the upwelling spectral radiance just below the sea surface which was used for the estimation of the dynamics of near-surface chlorophyll concentrations (Foley et al. 1997, Landry et al. 1997). Subsequent deployments using expendable WOCE standard Surface Velocity buoys equipped with optical sensors have been successfully made in many oceans (see Letelier et al. 1997, Abbott et al. 1990, Abbott and Letelier 1998, Abbott et al. 2000, Letelier et al. 2000, Shallenberg et al., 2008), and a set of community consensus protocols have been developed for further applications (Kuwahara et al. 2004).

More recently, profiling floats, which use buoyancy changes to move vertically, have provided real-time hydrological data throughout the water column collected during their rise and descent at 10-day intervals from ~1000 or 2000 m depths to the surface (e.g. Wilson 2000, ARGOS Science Team, 2001). While the international ARGO program has marked an impressive milestone with the 3000th float deployed in October of 2007 (e.g. http://www-argo.ucsd.edu/FrArgo_3000.html) and the application of this technology to Physical Oceanography is mature, unfortunately very few of these floats are equipped with sensors other than conductivity, temperature and depth (CTD). Yet the potential applications to studies related to biogeochemistry of the oceans are very large.

For example, Mitchell et al. (2000) have instrumented a Sounding Oceanographic Lagrangian Observer (SOLO; Davis et al., 2001) profiling float to measure the diffuse attenuation coefficient at three wavelengths in the Sea of Japan/East Sea. The floats were able to capture mesoscale features in the distribution of phytoplankton through their influence on the attenuation coefficient of visible light in the upper ocean. Other optical instruments for determining particulate organic carbon (POC) have been used on C-Argo floats (specially programmed to cycle 3 times per day in the upper ~200m) by Bishop et al. (2002) in a study of carbon enhancement by dust storms in the North Pacific and in another case, in a study of the consequences of deliberate introduction of iron into the Southern Ocean (Bishop et al. 2004). These sensors rely largely on the scattering of light by particles in the sea using an active light source, unlike the sensors used for the estimation of the diffuse attenuation coefficient which depend on the irradiance from the Sun. The sensors using an active source of light can profile throughout the water column in both day and night. Active light sources are also used for fluorometers, which measure the light emitted by phytoplankton (or with different wavelength sets, Chromophoric Dissolved Organic Matter, CDOM) after absorption at a different (shorter) wavelength. New fluorescence-based optical sensors for the measurement of oxygen concentration have recently provided unique insight into the seasonal "breathing" of the upper ocean (Körtzinger et al., 2005; Riser and Johnson, 2008).

In a previous NASA funded project we (University of Maine, WET Labs) together with Dr. Riser's group at the University of Washington integrated bio-optical sensors into two profiling floats and successfully demonstrated their utility for obtaining high quality optical measurements over a long period deployment and thus their promise for providing validation of ocean color products (Boss et al., 2008a,b). Float 0005 completed 221 1000m deep profiles from 1000m depth exhibiting no noticeable drift. The other profiling float just ended its mission in the North Pacific (2/5/2009) completing 253 1000m deep profiles (all data at: http://misclab.umeoce.maine.edu/research/ , with 0005's data uploaded to SeaBASS).

Scienfically speaking, we have found a single float to provide a wealth of new insights into the workings of the ocean. Following its crossing of the North Atlantic Current (9/2006) the float got entrained into an anticyclonic particle-laden eddy and stayed within it for three months. The eddy was barely detectable in ocean color radiometery yet had an integrated particle load rivaling that associated with the spring bloom. In addition, the eddy was the only instance where the surface particle signal was correlated with that at 1000m depth. These observations suggest that current oceanographic sampling may be missing important processes that are fluxing particles to depth (see Boss et al., 2008a for a broader acount regarding this event). Additionally, the float's data are now challenging our (mis)conceptions regarding phytoplankton dynamics in the upper ocean of the North Atlantic. We are finding that the net growth rate of phytoplankton (based on time differentiation of the data) is positive as early as in December and January, before winter mixing has subsided (contrary to the Sverdrup hypothesis) and continues at about the same rate until May (Boss and Behrenfeld, in prep., Figure 1). Differences between results based on surface and depth-integrated properties illustrate the limitations of using ocean-color radiometry *only* for such analysis (e.g. Siegel et al., 2002). Boss has two more floats with WETLabs' FLNTU optics and irridium communication funded through a collaboration with Dr. Westberry for OSU and funded by NASA. The floats will be deployed later this year and be used to constrain phytoplankton dynamics in the North Pacific.

In another joint project with our French colleagues, we (Satlantic, WET Labs, MARTEC, CNRS) have also had success with deployment of prototype passive optical sensors to measure the downwelling irradiance profile from the French profiling PROVOR floats, along with direct measurement of beam transmission, fluorescence, and backscattering. This variant, termed PRO-BIO, has been extraordinarily successful, and currently 17 floats have been deployed – 11 in the Mediterranean, 2 in the North Atlantic, 2 in the North Pacific and 2 in the South Pacific Gyre – with 9 currently active (some were deployed and recovered after testing (http://www.obs-vlfr.fr/OAO/). From the measured vertical gradients in spectral irradiance, the spectral diffuse attenuation coefficient can be computed, and from this, the chlorophyll profile can be determined based on established bio-optical algorithms (Morel and Maritorena, 2001, Fig. 2). In some of the deployments, a cycling strategy has been developed, with floats rising near dawn, then descending to 200 meters and rising again at noon, descending again, and then rising near dusk. The diel variation in optical properties can in principle be used to estimate growth rates in the upper ocean (see Cullen et al., 1992, Claustre et al. 1999, 2008), and compared with other approaches to the estimation of primary productivity and growth rates in the upper ocean based on optical means (e.g. Friedrichs et al. 2007, Behrenfeld et al. 2005, Westberry et al., 2008).

While the float and sensor technology seems mature, we (and other groups) have encountered several problems with both O_2 and the optical sensors on the floats. The North Pacific float backscattering channel did not work properly and the O_2 sensors on both floats failed early in the deployment. In addition, several other groups had problem with the WETLabs' FLNTU optical puck, and as a result, WET Labs and Dana Swift of the University of Washington went through a 3 months long process to isolate the problem. The problem has been found and WETLabs has redesigned the puck which is currently being tested at UW. All the partners in this proposal are committed to insure that all the sensors used will work well be fully tested to insure they will work well with profiling floats and will be tested with profiling float.

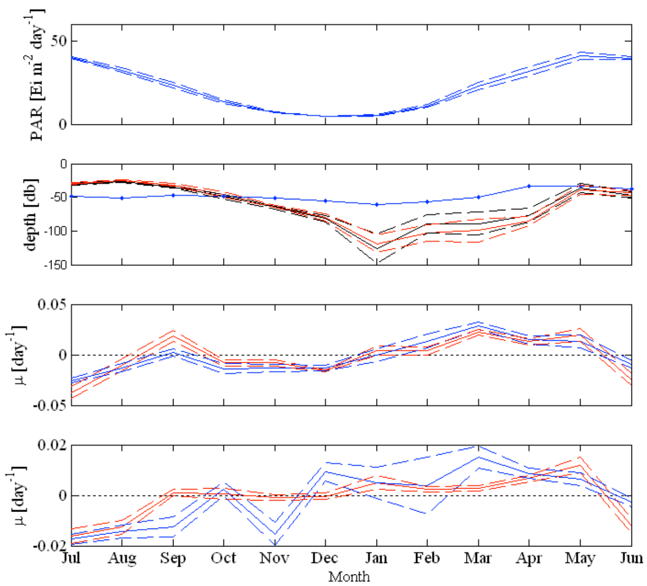

Figure 1. Analysis of data collected with Apex float 0005 in the Sub Arctic North Atlantic. Monthly averages of surface PAR (top panel), Mixed layer depths (0.125 kg m^{-3} increase from surface-red, gradient criteria-black) and Euphotic depth (blue, 2nd panel), phytoplankton carbon net growth rates based on surface values (blue: backscattering, red: chlorophyll-based, third panel), and depth-integrated phytoplankton carbon net growth rates (blue: backscatteirng, red: chlorophyll-based, bottom panel). Dashed lines represent one standard error of the mean.PAR and euphotic depths are NASA SeaWIFS products at the vicinity of the float surfacing.

In 2008, the International Ocean Color Coordinating Group established a working group, chaired by Hervé Claustre (http://www.ioccg.org/groups/argo.html). and with E. Boss as a member, to examine all the aspects associated with deployment of optical sensors onboard profiling floats The report of the working group will be published later this year. Our effort will benefit directly from the fruits of the working group as they include consensus recommendations regarding all aspects of integration, communication, deployment and data dissemination associated with biogeochemical floats.

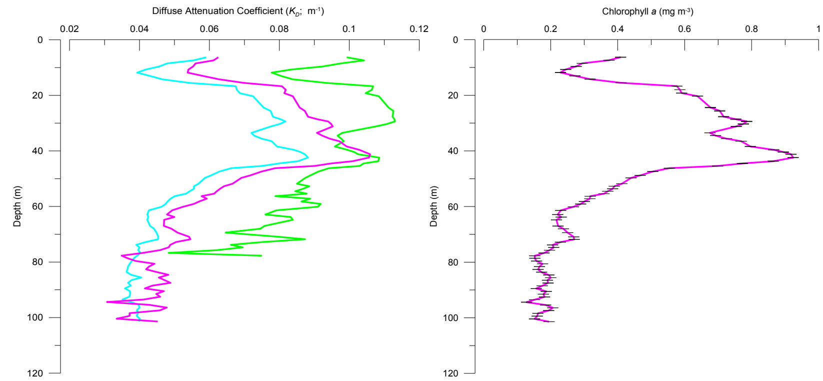

Figure 2. Vertical distribution of the spectral diffuse attenuation coefficients derived from the vertical gradients in measured spectral downwelling irradiance using prototype sensors deployed on robotic profilers (blue = 412 nm, magenta = 443 nm, green =555 nm, left panel). b. The vertical profile of chlorophyll derived from the diffuse attenuation coefficients (right panel). Horizontal lines about each data point represent the dispersion associated with the computation using all three wavelengths and established bio-optical algorithms, which were developed statistically from a large database (Morel and Maritorena, 2001)

Here, we propose to build on this experience to develop the next generation of operational biogeochemical floats, to deploy them, and, along with the rich data set from other bio-optical floats, to evaluate the efficacy of this stable, autonomous and sustainable technology for a.) the calibration and product validation of orbiting ocean color radiometers and b.) the investigation of the dynamics of carbon in the upper ocean on time and space scales appropriate for the evaluation of the role of the ocean in the global carbon cycle.

2.2. Background and Bases

Ocean color measurements from space, whether they are from polar orbiting or geostationary platforms, require similar calibration and product validation efforts. An extensive pre-launch sensor characterization is critical for all ocean color missions but because of changes and uncertainties in the sensor and its optical alignment after launch, *in situ* match-up measurements are required to validate and/or diagnose systematic artifacts in the sensor, in atmospheric aerosol models and ocean Bidirectional Reflectance Distribution Function (BRDF) models. Furthermore, *in situ* match-up measurements are required to validate, on an ongoing basis, and on an extensive geographic domain, the products derived from direct measurements of spectral radiance at the level of the satellite, and which use a particular algorithm for the derivation (see below).

The importance of vicarious calibration of ocean color radiometry, and product validation and their fundamental considerations have been summarized in Mueller (2005), Hooker et al. (2007), and Bailey et al. (2008). The fundamental objective of vicarious calibration is to isolate the effects of a satellite sensor's systematic gain and offset on the difference in a matched pair of exact normalized water-leaving radiances derived from satellite and *in situ* measurements. This is accomplished by combining complete characterization of both sensors with constraints on the measurement conditions to minimize all other components of the combined uncertainty of the two measurements. Product validation can make use of the same data products, but generally requires a broader set of observations over a wider range of natural variability (Hooker et al. 2007, Werdell et al. 2007).

Previous *in situ* calibration and validation studies have focused on measurements of upwelled spectral radiance, because this is what ocean color sensors measure, and because common standards of spectral radiance (e.g. NIST) exist to relate the in-water and on-orbit observations (see review by Bailey and Werdell, 2006). Yet there are a number of reasons to measure as well the inherent optical properties (IOP). First, these are the properties that modify the radiance distribution in the ocean, and are needed to carry out radiative transfer calculations to propagate radiances within the ocean. Second, recent algorithms make use of satellite-based radiances in an inverse sense to derive IOP's such as the scattering coefficient (IOCCG, 2006). Third, IOP's such as backscattering, and chlorophyll fluorescence provide additional constraints on various derived products such as POC and Chlorophyll a (see Table 1). Most importantly, the IOP's and their spatial and temporal dynamics are of interest themselves as inputs into a hierarchy of three-dimensional models of biogeochemical dynamics (e.g. Fujii et al., 2007). Lastly, recent inversion methodologies applied to derive IOP's from vertical profiles of irradiance and radiance have been remarkably successful, and the simultaneous measurement of IOP's in turn provides an effective "internal standard" on the ocean color radiometry vicarious calibration. The combination of IOP's and radiometric quantities such as radiance and irradiance is therefore a powerful tool.

Radiance, $L(z,\lambda,\theta,\varphi)$, is the fundamental radiometric quantity (units W m^{-2} sr^{-1} nm^{-1}) and is defined as the power in a specified direction (θ,φ) per unit solid angle and per unit area. All other radiometric quantities can be derived from this fundamental one (e.g. downwelling irradiance, $E_d(\lambda)$). Spectral integration of the irradiances returns the so-called Photosynthetically Available Radiation (PAR), a key derived variable for the computation of local and depth and time-integrated photosynthesis (e.g. Ryther and Yentsch, 1957; Behrenfeld and Falkowski, 1997). Diffuse attenuation coefficients describe the rate of change in radiances or the various irradiances taken in a particular direction and are required in extrapolating near surface measurements to just below the surface and in the propagation of energy in the vertical. Note that diffuse attenuation coefficients are somewhat sensitive to the radiance distribution; they are also functions of the IOPs (specifically absorption and scattering) and vary spectrally. The diffuse attenuation coefficients are an important product derived from satellite-measured radiances, as they can be used to estimate chlorophyll concentrations and for the estimation of energy transfer (and irradiance divergence) as well as heating rates of the upper ocean. Recently several models have estimated the vertical structure of IOPs and biogeochemical properties from ocean color remote sensing measurements (Uitz et al., 2006, Westberry et al., 2008) for the computation of vertically integrated primary production and phytoplankton standing stocks. Validation data, such as measured by profiling floats, will assist in improving such efforts.

IOPs have been linked directly to biogeochemical properties in the ocean. Table 1 summarizes the priority measurements for the float deployments, and the products that we propose to derive from them.

Measured variable	Estimated biogeochemical or optical quantity	Reference
Upwelling radiance profile	Normalized Water-Leaving Radiance	Mueller et al. 2003
Spectral diffuse attenuation coefficient (irradiance & radiance profiles)	K_D (λ), K_{Lu} (λ) , Chlorophyll, CDOM, Spectral absorption and backscattering	Morel and Maritorena, 2001. Huot et al., 2007, Gordon and Boynton 1998.

	coefficients	
Downwelling irradiance and CT profiles	Euphotic Zone Depth, Isolumes depth and Mixed Layer Depth.	Morel and Maritorena, 2001, Monterey and Levitus, 1997, Letelier et al., 2004.
Backscattering coefficient	Particulate organic matter, Phytoplankton carbon, Total Suspended Solids	Stramski et al., 1999, 2008, Behrenfeld et al., 2005, Downing et al., 1981; Conner and Visser, 1992
Chlorophyll fluorescence	Chlorophyll	Lorenzen, 1966
CDOM fluorescence	Colored dissolved organic material	Kalle, 1963
Beam attenuation	Particulate organic matter	e.g. Gardner et al. 1993, 2003, Bishop, 1999.
Chlorophyll (fluorescence or K_D) + PAR+ ML depth + temperature all averaged over a large geographical area	Primary Productivity	e.g. Behrenfeld and Falkowski, 1997, Ryther and Yentsch, 1957.
Backscattering coefficient + chlorophyll + ML depth + temperature all averaged over a large geographical area	Phytoplankton growth rate	Behrenfeld et al., 2005
Spectral backscattering coefficient + spectral diffuse attenuation coefficient	Spectral remote sensing reflectance as approximated by a polynom in $b_b/(a+ b_b)$	Gordon et al., 1975

Table 1. Measured variables and derived quantities.

2.3 Proposed technical effort

Here we propose to build upon our earlier successes and develop the next generation of biogeochemical profiling floats that will form the basis for commercial product. These will combine active and passive optical sensors which will provide relevant data to upper-ocean productivity and carbon dynamics studies as well as validation of ocean color products. In this proposal we will also evaluate the possibility of using data collected by the profiling floats for vicarious calibration of satellite radiometry (see letter of support by Werdell and Bailey). Redundancy is planned so that fouling of sensors will not affect success of operation as well as to constrain uncertainties. Matchup with remote sensing will additionally provide a check on measurement (e.g. Boss et al., 2008b). The measurement suite is based on and is consistent with upcoming IOCCG working group recommendations on 'bio-optical sensors on Argo floats'.

The products which will be developed (and commercialized by our commercial partners where applicable) include:

- A profiling Float designed for studies focused on organic carbon dynamics in the upper ocean and validation of remotely sensed ocean color products. Data collected by these floats will be evaluated for their potential to provide vicarious calibration irradiance data. A web interface developed by CLSAmerica will facilitate 2-way communication with the float and data visualization.

- A web utility based on the NASA's Giovanni data dissemination and analysis platform (http://reason.gsfc.nasa.gov/Giovanni/) that will provide a variety of oceanographic parameters (e.g. Sea Surface Height, temperature, ocean color products) in the vicinity of the float to provide horizontal and oceanographic context to the float data.
- Assist in the development for a mechanism for near-real-time data posting on an international web site (in collaboration with the Coriolis office, see http://www.coriolis.eu.org/cdc/default.htm), similar to current ARGO data, so that data could be used by biogeochemical modelers.

The measured radiance and the irradiances will form the input data set for the subsequent computation of the normalized water-leaving radiances, the diffuse attenuation coefficients, and, with the proposed IOP measurements, the derived products (spectral backscattering and absorption, phytoplankton and CDM absorption). We recognize that propagation of the measured irradiances to and through the sea-surface may provide a challenge (see Zaneveld et al., 2001, Bailey and Werdell, 2006), and that current processing protocols rely on estimates of surface irradiance based on theoretical clear-sky values at the time of satellite overpass. We are particularly motivated to carry out this development effort in order to significantly expand the number of quality vicarious cal/val data points available, particularly over the open oligotrophic ocean which currently only represents a very small fraction (~5%) of the entire NASA SeaBASS data holdings (Bailey and Werdell, 2006).

All data from the float will be combined with satellite ocean color measurements to evaluate matchup criteria and to carry out direct intercomparisons and product validation using the philosophy and approach taken currently the NASA Ocean Processing Group (Bailey and Werdell 2006, Bailey et al., 2008). With the extensive database from these sensors, we will optimize this approach and evaluate use for direct vicarious calibration of the satellite on orbit.

We propose to integrate proven sensors which have a strong heritage of intense evaluation by the oceanographic community together with a proven platform (APEX, Webb Research) to achieve this objective. The calibration, characterization, and long term stability of the sensors are such that the data could provide a useful globally distributed complement for vicarious calibration of satellite spectral radiance measurements. The data would be of direct use for validation of ocean color remote sensing products (Table 1). The recent availability of higher bandwidth and two-way communication will enable more data throughput providing for better in-water resolution and minimizing the time spent at the surface attempting to communicate with satellites as well as allowing users to retrieve the floats at the end of an experiment for future deployments. We will implement novel adaptive sampling methods which will permit derivation of biological rate processes from short-term (days to weeks) variations in biomass (e.g. estimating growth rates from diel changes in optical properties, e.g. Claustre et al., 2008 and references therein). Finally, by developing state of the art automated web-based tools which will fuse satellite observations with buoy data retrievals, users will be able to make adaptive decisions about future float dives (enabled via two-way communication) and be provided with satellite-derived remotely sensed data (Chl, SST, Vector winds and perhaps SSH and euphotic zone depth, Z_{eu}) around the float (providing temporal and spatial context). These data will be provided to data bases where they are easily accessed for assimilation into models as well as for end-to-end vicarious calibration of onboard radiances and the validation of remotely sensed ocean color products. The following will be achieved (see below for compliance with RFP call):

a. **Work Package 1 (Year 1): Novel integration of active and passive optical sensor packages into APEX profiling floats (Primary Responsibility for Sensor Package Integration: Satlantic/Wet Labs; Primary Responsibility for Float Integration: Webb. Primary Responsibility for Test and Evaluation: U. Maine**

Instruments will be procured, and mechanically and electrically integrated to achieve weight and buoyancy requirements and to best access the data and power interface to the float electronics. The package will have a depth rating of 2000m. The package includes a 4 channel downwelling irradiance sensor, a 4-channel upwelling radiance sensor (both Satlantic Inc), a WET Labs FLNTU with chlorophyll fluorescence and a single wavelength backscattering channel, a WET Labs triplet with two backscattering channels and CDOM fluorescence, and a single wavelength WET Labs beam transmissometer (C-Rover). A CTD and Aanderaa oxygen sensor will be included. Spectral channels will be matched as nearly as possible to current ocean color sensors (e.g. SeaWiFS or MODIS), and the optical sensors will be integrated as a single physical package which will be mounted on the exterior of the float. Trade-off studies are planned for Year 1 to optimize the scientific data collection subject to the constraints of available energy, communication bandwidth and cost.

This work package includes the development of routine procedures for sensor characterization and calibration in the integrated configuration following established community consensus protocols (see Mueller et al. 2003). An extensive testing and evaluation program is also planned. All the sensors in their integrated package will be independently pressure tested prior to integration into the float to 25% deeper depth than the float intended mission, including testing pressure sensitivity of the electronics while the sensors are operating. The testing will include simulations of dive and surfacing at similar rates as that of the float in the ocean. The sensor-float combination will then be tested with the float's hardware simulating at least ten preprogrammed dives including modification of dive program through Iridium communication. Subsequently, the entire package will be pressure tested together simulating the pressures they will experience in-situ and ballasted for the mission.

We plan to evaluate effects of self shading by the float on radiometer data through radiative transfer modeling for our specific geometry (e.g. Leathers et al., 2001, Pizkozub, 2004) in consultation with H. Claustre whose group has conducted such calculations specifically for profiling floats. These effects will be propagated to the error analysis on radiometry data . These deployments will also be used to test communication protocols. Zaneveld et al. (2001) have shown that while the preferred method for extrapolating radiance to the surface is multiple profiles, a method based on integrating the profile and so obtaining the radiance attenuation coefficient can be applied to single profiles and will be tested.

We will consult with our colleagues at the University of Washington (Dana Swift in particular) on aspects of the testing. We have a long relationship with Dr. Riser's lab and Dana Swift assured us of their availability.

b. **Work Package 2: Development of advanced high bandwidth communication capabilities (Iridium) for routine operations. Primary Responsibility: Webb for "Wet Side", CLS America for "Dry Side".**

This work package is designed to provide high bandwidth, two way communication capabilities on an "end-to-end" basis to ensure tight coupling between the sensor communication system, and the shore based command and control, and data retrieval systems. The Iridium capabilities have been proven within the APEX float, but our goal is to provide a seamless commercial interface for a broader section of the oceanographic community. The high bandwidth is required because the additional sensors generate data volumes in excess of that which can be communicated via ARGOS. The two-way communications are needed to support the adaptive sampling requirements, and for changes to mid-course mission operations. This capability enables the potential to retrieve packages for relatively short duration experiments (see Work Package 3). In addition, high bandwidth will result in significant reduction of surfacing time (e.g. from 10hrs for current ARGO floats to ~5 minutes), resulting in significant reduction in potential biofouling and in energy costs currently spent on one-way broadcasting to ARGOS.

The advanced communication options provide an opportunity to carry out specialized missions on an adaptive basis. For example, while the nominal ARGO mission profile is to profile once every 10 days from a depth of 2000 meters, it would be of great scientific interest to periodically resolve diel changes in particulate scattering, absorption and fluorescence, which could provide direct input data into a number of models of diel carbon dynamics and photosynthesis (see Cullen et al., 1992, Claustre et al. 1999, 2008, Behrenfeld et al. 2005, 2006). In addition, new approaches to reduce uncertainties in the estimation of normalized water-leaving radiances (and attenuation coefficients; Zaneveld et al. 2001) can be evaluated through repeated profiling of the upper optical depth. Repeated profiles are the recommended method to extrapolate radiance to the surface, but obviously are power consuming. We will evaluate the advantage of this approach compared to integrating single profiles to get the radiance attenuation coefficient (Zaneveld et al., 2001).

c. **Work Package 3: Development of software for processing, display and dissemination of data. Primary Responsibility: U. Maine to coordinate/communicate requirements, CLS for implementation.**

A primary goal of this proposal is to expand the application of profiling float technology from a relatively small number of investigators to the greater oceanographic community. A major step towards accomplishing this is to implement an "operational" end-to-end data processing capability available to all who use the float technology. The objective of this work package is to develop the elements needed to acquire, decode, process, archive, merge, distribute and display the data being collected by the floats. CLS has recently developed a comprehensive Iridium Processing Center (IPC). This work package will build on this IPC at CLS to adapt where possible the current modules to float applications and to develop new ones where needed. This will include, among other things, decoding modules, customized data management and processing modules combined with an appropriately sized data base with tailored query language for archival and distribution of the float data to a web-based data integration, display and user access capability. CLS America will perform the software development work needed enable proper decoding of the float transmissions and to manage the data flow within the CLS IPC.

d. **Work Package 4: Development of a novel web tool that will provide NASA's products at the vicinity of the profiling float (in space and time) to provide a context to the float's profile. Primary Responsibility: U. Maine to coordinate/communicate requirements, NASA GSFC for implementation.**

Overall the intent is that as a result of technologies developed here the instrumentation and data transmission will be transparent to future users. Such a user will deploy the instrument and will be able to obtain the data from the profiles on the CLS website, together with NASA remote sensing data that puts the profile in context. The NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) will create a user interface for the input of geographical location data from the deployed floats to generate user-selected visualizations of available remote-sensing data. The visualizations will be generated by the GES DISC "Giovanni" data system utilizing 4 km spatial resolution and 8-day temporal resolution Level 3 mapped data products. GES DISC staff will a.) Create software which receives the geographical location information and generates the user-specified visualizations; b.)Create a user interface for the input specification of desired visualizations and user-selected criteria for each visualization (time ranges, color palette ranges, Y-axis value ranges, etc.); c.) Create a delivery system for the specified visualizations (email, temporary FTP directory, or alternatives) and d.) Maintain the data sets in the Giovanni system to provide up-to-date data, depending on the generation and availability from the data providers.

***e.* Work Package 5. Deploy and evaluate floats. Primary Responsibility: U. Maine in coordination with all partners.**

There are several deployments planned under this Work Package, which we allocate to the following experiments:

Intercomparison Experiment: The first two of profilers are planned to be deployed in the Mediterranean Sea in the vicinity of the BOUSSOLE mooring in Year 2. BOUSSOLE, a deep-water (2000 m) taut mooring using sensors similar to those proposed here, has been demonstrably successful in the provision of high quality vicarious calibration (and validation) data sets for ocean color (Antoine et al. 2006) with agreement with MOBY to within 0.6% for 443-670 nm and to within 3.4% for 412 nm (Hooker et al. 2007). Our objective for this experiment is to evaluate the float technology and approach to Cal/Val through direct intercomparison with this proven system. We also plan to use this opportunity to recover the floats if their drift does not place them a great distance from potential pickup sites by ships of opportunity.

Extensive Vicarious Calibration Array Experiment: For this experiment, we plan to deploy a total of 6 floats (including the 2 used for the Intercomparison Experiment) to first evaluate the incremental reduction in uncertainty associated with a distributed network of sensors. The strength of our approach then lies in the cumulative effect of profiles in multiple locations over long time periods. We plan launches in the North Atlantic for a higher latitude intercomparison site, which is as well a location where there is a large dynamic range and interesting biological oceanographic questions. We will deploy the floats in two clusters of three floats each (One in Yr. 2 and one in Yr. 3) using ships of opportunity.

For example, these deployments will be used to evaluate the effectiveness of this observational approach to the evaluation of hypotheses related to the biological dynamics in the open ocean. Floats will be used for both the evaluation of the conditions under which phytoplankton net growth is positive (e.g. Fig. 3), the evaluation of the depth horizon down to which phytoplankton growth is still positive in stratified environments (e.g. Letelier et al., 2004), and the evaluation of assumption imbedded in current algorithms to computed depth integrated standing-stocks of phytoplankton and primary production from remotely sensed ocean color (e.g. Uitz et al., 2006, Westberry et al., 2008). Note that no funds are requested for ships. Ships associated with the BOUSSOLE project will be used for the intercomparison and calibration evaluation work (Yr 1). Ships of opportunity will be used to deploy clusters in Yr2 and Yr3.

f. Work Package 6. Provide critical assessment of the utility of float technology for a.) the evaluation of biogeochemical processes on a routine basis by the international oceanographic community and b.) the ability of optical sensors onboard profiling floats in the provision of quality data for the vicarious calibration and product validation of ocean color satellites. Primary Responsibility: U. Maine coordination with all partners.

Float technology presents significant cost savings in $/data compared to traditional ship based measurements (though without the added direct biogeochemical measurements) or moorings. In addition they provide for permanent (though drifting) presence in the oceans, an impossibility with current ship-based approaches, and at a much larger potential coverage than is possible with open ocean moorings. By analyzing the radiometric data collected with the floats and comparing it to remote sensors we will be able to evaluate the accuracy to which the float measurements can provide vicarious calibration of water-leaving radiances, and validation of a wide range of products derived from satellite ocean color radiometry. Comparing it to other available techniques (e.g. mooring, ship based measurements) we will be able to assess whether this technology is robust enough to provide quality calibration and validation data. To date, we have compared chlorophyll and backscattering coefficients collected by a float and derived from MODIS (Boss et al., 2008b). Here we will be able to achieve a larger statistical matchup comparison, at more regions of the ocean and with more products (e.g. CDOM, chl, K_D, PAR, Z_{eu}, MLD, and spectral backscattering) and assess the possibility and usefulness of using floats to fill gaps in satellite data in periods of clouds (for example, Boss et al., 2008b, found that during cloudy periods the ocean exhibited relatively little variability).

In addition to the specific floats planned for deployment under this project, we will have the benefit from analysis of data from other bio-optical floats which have been successfully launched by University of Maine and by Herve Claustre in the North Atlantic, North Pacific, Med. and South Pacific gyre.

2.4 Goals of the Partnership

The goals of the partnership are as follows:

a. Develop the next generation of commercially available profiling bio-optical floats with two-way communication and adaptive sampling capabilities.
b. Design a novel web-based tool providing float users relevant remotely sensed data around the location of the float to assist in the interpretation of the float data (e.g. provide context) as well as for decision making for adaptive sampling.
c. Rigorously evaluate the use of this technology for calibration and product validation of ocean color remote sensing and biogeochemical process studies.

2.5 The Partnership

This proposal consist of a collaboration between global leaders in float technology (Webb Research), sensor technology (Satlantic, WET Labs), wireless communication and data dissemination (CLS America), remote sensing (NASA), and interpretation of remote and in-situ bio-optical data (Boss, Lewis, Zaneveld, Claustre, Antoine).

2.6 Relevant Accomplishments of the Partners

Emmanuel Boss, has worked for ten years on a variety of problems in optical oceanography pertaining to this proposal; they include developing and testing algorithms to use IOPs as proxies of biogeochemical properties (e.g. concentration, size and composition of particles and dissolved substances), use of novel platforms to deploy optical instrumentation (e.g. on divers and floats) and issues pertaining to primary production (e.g. his collaboration with Dr. M. Behrenfeld of OSU, for more seehttp://misclab.umeoce.maine.edu/).

WET Labs has extensive experience in developing prototypes and commercializing IOP instrumentation. The company's extensive research and manufacturing facilities including a machine shop, 2 small research vessels, environmental testing capabilities, and an extensive analytical and field instrumentation inventory. Field instrumentation and equipment include all WET Labs commercial products, irradiance and radiance sensors, and a towed vehicle with integrated water sampling system. (http://www.wetlabs.com).

Satlantic has a rich 19 year history of providing the most accurate, precise and stable optical sensors to the oceanographic community, and has been an active participant in all NASA sensor intercomparison and characterization efforts. The company occupies approximately 15000 square feet of laboratory, office and assembly space; all calibration and most characterization activities are carried out within a Class 10000 clean room environment. A Class 1000 clean room is used for assembly of optical components (www.satlantic.com). A deep water test and evaluation site (Bedford Basin) is adjacent to the facility.

Teledyne Webb Research Corporation (WRC), founded in 1982, is located in Falmouth Massachusetts. WRC employs 30, and occupies a custom-built 15,000 square foot facility. Specialists in neutral and variable buoyancy sensor platforms, WRC conceived and has developed several widely used oceanographic sensor platforms, including PALACE/APEX profiling floats, and the SLOCUM glider. WRC has delivered over 4700 profiling floats, including approximately two thirds of the 3000 ARGO floats presently operating worldwide. Long range, autonomous low frequency acoustic sources, used in acoustic tomography, are another specialty. (http://www.webbresearch.com/)

CLS America, Inc. (formerly Service Argos, Inc.) with its parent company CLS, has 25 years of ongoing experience in serving the oceanographic and marine meteorology community with both global satellite data communications via the Argos system and now with Iridium, and extensive operational data processing and dissemination capabilities. CLS has significant ongoing operational activities as well, in oceanographic modeling, satellite altimetry data processing, analysis and product generation. Bill Woodward has been President of Service Argos/CLS America since 2000. Prior to that he spent nearly 30 years at NOAA with various engineering and program responsibilities including Advanced Technology Development and operational ocean observation program management and implementation. www.clsamerica.com

The NASA GSFC/GES DISC has more than 12 years of experience archiving, distributing, and managing remotely-sensed Earth Science data. Currently, the GES DISC holds 1.6 Petabytes of atmosphere, ocean, hydrology, and biosphere data, from 12 missions and dozens of instruments, serving more than 100,000 users. The GES DISC has a proven record of developing and deploying robust, reusable, and cost-effective systems such as S4P, the Web Hierarchical Ordering Mechanism, Near-line Archive Data Mining system, the TRMM data mining system, and most notably, the GES DISC Online Visualization and Analysis Infrastructure (Giovanni), which provides Web-based data access and analysis for several remotely-sensed data sets. The

GES DISC will provide computing facilities, Giovanni data implementation and interface development, and data archive capability for generated data and analyses.

Hervé Claustre and David Antoine of the Laboratoire d'Oceanographie, Villefranche-sur-mer (unfunded PIs on this proposal) bring to this proposal their extensive experience with autonomous biogeochemical platforms and the willingness to coordinate intercomparison activities between both platform systems, and the permanent, deep-water cal/val mooring BOUSSOLE (see letter in CV section).

2.7 Rapid Transition to the Scientific Community

Our team has ample experience transitioning sensors, sensor platforms and web utilities to the greater scientific community. The FLNTU float is an example where we recently transitioned float-and-sensor technology (including an auxiliary board developed under the previous grant by SeaBird Inc., sensors developed by WET Labs, and software developed at UW) to commercialization. Satlantic and WETLABS have extensive background in transitioning scientific innovations into commercial products (e.g. ISUS nitrate sensor from MBARI, FIRe fluorometer from Rutgers University, Phosphate sensor from URI etc.). The proposed sensors all have proven heritage of use within the oceanographic community; this proposal is unique in that these sensors will be integrated together into a measurement package than can provided sustained "boresighted" observations over long time scales in remote ocean areas.

3 Project Schedule and Milestones

Task	Lead partner	Begin	End
Work Package 1: Develop Integrate, Test Optical Sensor Packages on Profiling Float.	Satlantic/WET Labs/Webb/U Maine	ARO	ARO + 12 months
Work Package 2 Development of advanced comm. capability	Webb/CLS	ARO + 6 months	ARO +12 months
Work Package 3: Develop Software for Data System	U. Maine/CLS	ARO	ARO + 12 months
Work Package 4 Develop web tool for satellite/buoy fusion	U. Maine/NASA	ARO	ARO _+ 12 months
Work Package 5. Cal/Val Test Deployment (BOUSSOLE))	U. Maine/LOV	ARO + 24 months	
Work Package 5 Cal/Val Extensive Deployment	U. Maine	ARO +36 months	
Work Package 6 Evaluation and Uncertainty Assessment.	U. Maine	ARO +36 months	

4. Deliverables

- Commercialization of a new type of float sensor packages after thorough testing.
- Development of data portals for profiling floats to facilitate their use by the greater oceanographic community.
- Development of a web-based remotely sensed data portals associated with the float location.
- Publications in both technical and basic science journals.

5. Management Approach

UMaine and Boss will be in overall management of the project. He will have responsibility for allocation of development tasks to the partners, and for establishing accountable sub-contracts governing their respective work packages. He will be responsible for periodic reviews of technical progress (via scheduled monthly teleconferences) as well as sub-contract performance and compliance monitoring. Annual meetings will be scheduled in conjunction with major oceanographic conferences (e.g. AGU Ocean Sciences). Within each of the so-allocated work packages, each partner will manage their own responsibility, participate in monthly reviews, and provide written progress statements to and as requested by the Principal Investigator. Financial management will be the responsibility of the University of Maine following standard operating procedures governing Federal Government grants.

6. Compliance with NOPP Call for Proposals

The proposed program is directly relevant to several of the goals of NOPP as a whole and this specific RFP. Within the framework of this call we are directly addressing: Topic 2. **Sub-Topic 1. Integration of existing or emerging *in situ* optical or bio-optical sensors on nontraditional or novel sampling platforms and Sub-topic 2A. Development of the next generation of optical and bio-optical fied sensors to further exploit current "ocean color" satellite data, and/or new observations from ocean color satellite retrievals (e.g., open-ocean and optically complex coastal waters).** Specific compliance details are addressed here**:**

We propose deploying a novel advanced integrated system constructed of existing sensors on APEX profiling floats. The sensors have known and quantifiable uncertainties and established calibration procedures and observed stability in field operations. Repeated profiles, comparison between sensors and between similar sensors on different floats and values at deep waters will provide for check on possible sensor degradation. We plan to evaluate effects of self shading of radiometers through models and experiment (see Work Package 1). Our team has a history of assembling and deploying similar floats on profiling floats (e.g. the Claustre-Satlantic collaboration, Boss et al., 2008ab). Lessons we will learn will be generalizable to a variety of other autonomous deployment platforms. All the vendors of this technology are partners in the proposal insuring continued improvements in the technology and rapid feedback.

We plan to investigate a number of different sampling protocols as part of this effort, and will benefit from work currently underway by Hervé Claustre and co-workers. Included are multiple profiles over a range of scales and investigation of appropriate vertical resolution (highest will be ~ 10 cm in the vertical). We will deploy sensors measuring precision radiometric quantities as well as inherent optical properties and biogeochemical properties that directly influence ocean color (spectral backscattering, chlorophyll, CDOM). Radiometer calibration is based on NIST standards of spectral irradiance, and backscattering calibration is based on beads with NIST traceable properties. CDOM fluorometers are calibrated with Quinine sulfate (and related to absorption through field deployments) while chlorophyll fluorometers are calibrated with spinach, phytoplankton cultures, as well as taking in-situ samples when deploying the floats (NB: NPQ will be addressed). A further useful constraint will be through the use of inverse models which relate IOPs to measured radiometric quantities and their vertical gradients, where recent work has shown remarkable ability to estimate IOP's from irradiance and radiance measurements (IOCCG 2006, unpublished work by Howard Gordon, pers. commun. 2009).

We believe the results of this effort will provide a much wider geographical coverage of match-up with satellites at a fraction of the costs of using research vessels or fixed moorings.

7. Ship Use

We are not requesting ship time. We will use ships of opportunity associated with BOUSSOLE and other projects to perform the work planned in this proposal.

8. Assertion of Data Rights

All data collected by the floats will be made available to the public as soon as possible (and no later than two months) on the UMaine web site, and will be submitted to international data bases (we will register the floats with the ARGO program). We will work with the Coriolis office for the dissemination bio-optical data in quasi-real time within the profiling float data base (see letter).
Software developed by NASA will remain the property of NASA.
Firmware and hardware designs developed by Webb Research, Satlantic and Wet Labs will remain their property.

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