DEVELOPMENT, ASSESSMENT, AND COMMERCIALIZATION OF A BIOGEOCHEMICAL PROFILING FLOAT FOR CALIBRATION AND VALIDATION OF OCEAN COLOR AND OCEAN CARBON STUDIES

Final Report

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1. Overview

This document reports the progress on this project between 1 October, 2009 and 25 November, 2012. The work is a collaborative project between seven partners. University of Maine has coordinated the work, provided guidance and standards for the mission's science goals, deployed and tested the instruments, and analyzed the observational data. WET Labs and Satlantic have modified and produced instruments, housings, and control software, all of which are now commercially available. Teledyne Webb Research has integrated their float software and hardware with the new instruments and flexible mission parameters needed for this project. CLS America has developed protocols for handling both the new data and the two-way communication it requires. NASA-Goddard and CLS America have developed tools that integrate real-time float data with NASA's satellite products around the location and time of the float's surfacing. Laboratoire d'Oceanographie, Villefranche-sur-mer (unfunded collaborator) has provided a ship of opportunity and support for deployment and evaluation of the float and is sharing expertise on calibration and validation activities and on the use of profiling floats with optical sensors.

Project goals were to:

1. Work package 1: develop, integrate, and test optical sensor packages on profiling float (Satlantic, WET Labs, Teledyne Webb, UMaine)
2. Work package 2: develop advanced communications capability for retrieving data and modifying mission parameters (CLS America, Teledyne Webb)
3. Work package 3: develop software for display and dissemination of data (UMaine, CLS America)
4. Work Package 4: develop a novel web tool that will provide NASAs products to provide context at the vicinity of each float profile (NASA GSFC, UMaine)
5. Work Package 5: deploy and evaluate floats (UMaine and all partners)
6. Work Package 6: assess utility of floats for a.) the evaluation of biogeochemical processes on a routine basis and b.) vicarious calibration and product validation of ocean color satellites (UMaine and all partners)

We have made a total of eleven float deployments. The first was a daylong test deployment in Bedford Basin, near Halifax, Nova Scotia. Two floats have been deployed at BOUSSOLE for a total of six deployments, the most recent on 24 November, 2012. Two of those deployments lasted about two months each before the floats were recovered. Two others lasted only a few days and the floats were recovered due to problems with float communication and electronics that have since been addressed and corrected in the manufacturing process. The remaining four floats were deployed in pairs in Hawaii, near MOBY, in December, 2011, and north of Bermuda in May, 2012. All four of these floats continue to operate, although biofouling has degraded data quality from some of the sensors. In addition to the floats funded under this grant, five similar floats that were acquired using ONR funding have been deployed some multiple times in biogeochemical studies in the North Atlantic. Those floats use much of the hardware and software developed in this project.

We have presented technical and scientific results at two international meetings and are collaborating with groups from NASA and NOAA regarding the use of the data collected for calibration of VIIRS. We are in the process of writing a technical paper describing the floats and their utility for evaluating satellite ocean color data. That analysis will be finished after data are collected in the most recent BOUSSOLE deployment.

2. Vehicle, Payload, and Mechanical Integration (Work Package 1)

a. Design and Construction

The vehicle is an Apex Float manufactured by Teledyne Webb Research in Falmouth, Massachusetts. The float contains science instruments in two sets (figure 1). The Seabird SBE41-CP CTD and Aanderaa 4330 Optode are mechanically integrated with the float end cap and communicate directly with the float processor (Apex APF9i). The optical instruments are integrated in what we call the profiler hub. Satlantic and WET Labs collaborated on design and construction of the profiler hub, with WET Labs responsible for most hardware development and Satlantic responsible for most software development. This contains components from WET Labs (inherent optical property sensors and pressure housing) and Satlantic (radiometers and integration and processing hardware). The profiler hub has 5 main components (figure 2); the WET Labs C-Rover VII subassembly (650nm wavelength beam transmissometer), a WET Labs ECO FLBB subassembly (combined chlorophyll fluorometer and 700 nm wavelength backscattering sensor), a WET Labs ECO BB2FL subassembly (combined 412 and 440 nm wavelength backscattering and CDOM fluorescence sensor), a downward-looking Satlantic OCR-504 R10W radiance sensor, and the profiler hub electronics subassembly (Satlantic and WET Labs). The upward-looking Satlantic OCR-504 ICSW irradiance sensor is mechanically separate from the rest of the sensors because of its field of view requirement, but is electrically and logically integrated like the others. The profiler hub communicates to the float via an external cable.

Several modifications were made to traditional Apex floats. A new mount was developed to attach the downwelling irradience sensor to the CTD guard and to ensure alignment with the float body and optics package (where the tilt sensor is located). Handles were added for ease of deployment and recovery (unnecessary in single-deployment floats). Plastic cradles were developed to seat the hub against the outside of the float, allowing easy attachment and removal. A counterweight was added to the outside of the hull to balance the hub and keep tilt angles small during ascent. At depths below those affected by surface gravity waves the floats have achieved steady tilt angles less than 1.5 degrees throughout deployment, despite the asymmetry introduced by attaching the optics package to one side of the float (figure 3). This small tilt angle is crucial to measurements from several of the optical sensors. For half the floats, the exhaust from the CTD pump has been modified so that it points onto the lower window of the beam transmissometer. This was done as an attempt to minimize sediment accumulation on the lens (see Bishop et al. (2004)).

All components are rated for pressures of 2000 decibars. The hub is tested at each assembly step, and the combined system is tested to this pressure by Teledyne Webb prior to shipment. In most operations, floats do not descend deeper than 1000 m, but on one occasion a float was successfully tested to a depth of 1900 m.

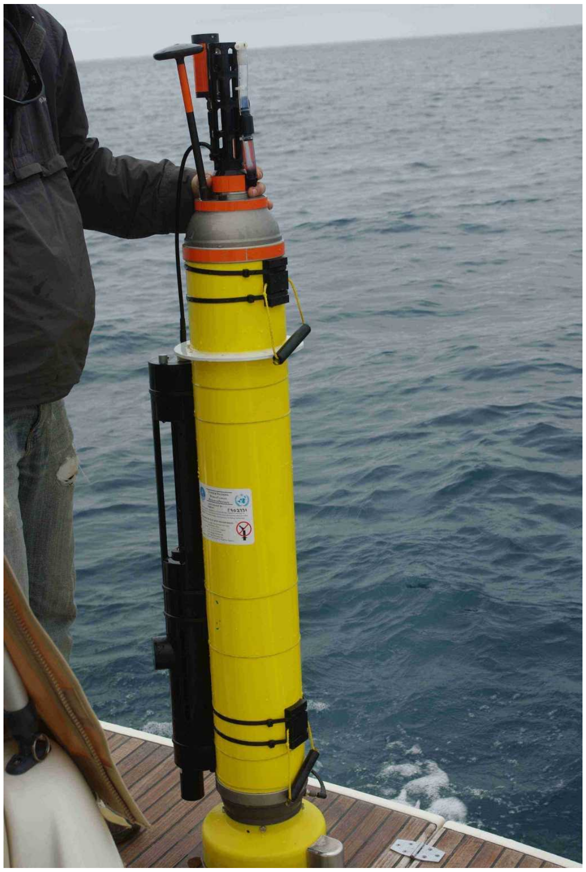

FIG. 1. Biogeochemical float with optics suite attached to side and irradiance sensor on top.

To meet the commercialization goals of this project, the profiler hub has a modular design, allowing construction of similar optical packages with different types and combinations of instruments. In addition to the sensor suite funded by this NOPP project, WET Labs, Satlantic, and Webb have already developed four variants for other projects led by Boss and Claustre and funded by the Office of Naval Research (ONR, US) and Centre National de la Recherche Scientifique (CNRS, France). Each of these variants is available commercially (http://satlantic.com/boss).

b. Problems and Adaptations

Four major unexpected mechanical issues were encountered. Leakage of profiler hub pressure case, pressure-induced failure of the cable connecting the hub to the float, intermittent pressure-induced inoperability of a single downwelling radiometer, and deformation of the diffusers on the radiometers.

Pressure case leakage was eliminated with improved assembly procedures and required no design changes.

Failure of the cable connecting the hub to the float occurred in the right-angle connector as voids in the potting collapsed under pressure. Teledyne Webb developed and implemented testing procedures to examine every cable for quality prior to deployment and we have had no additional

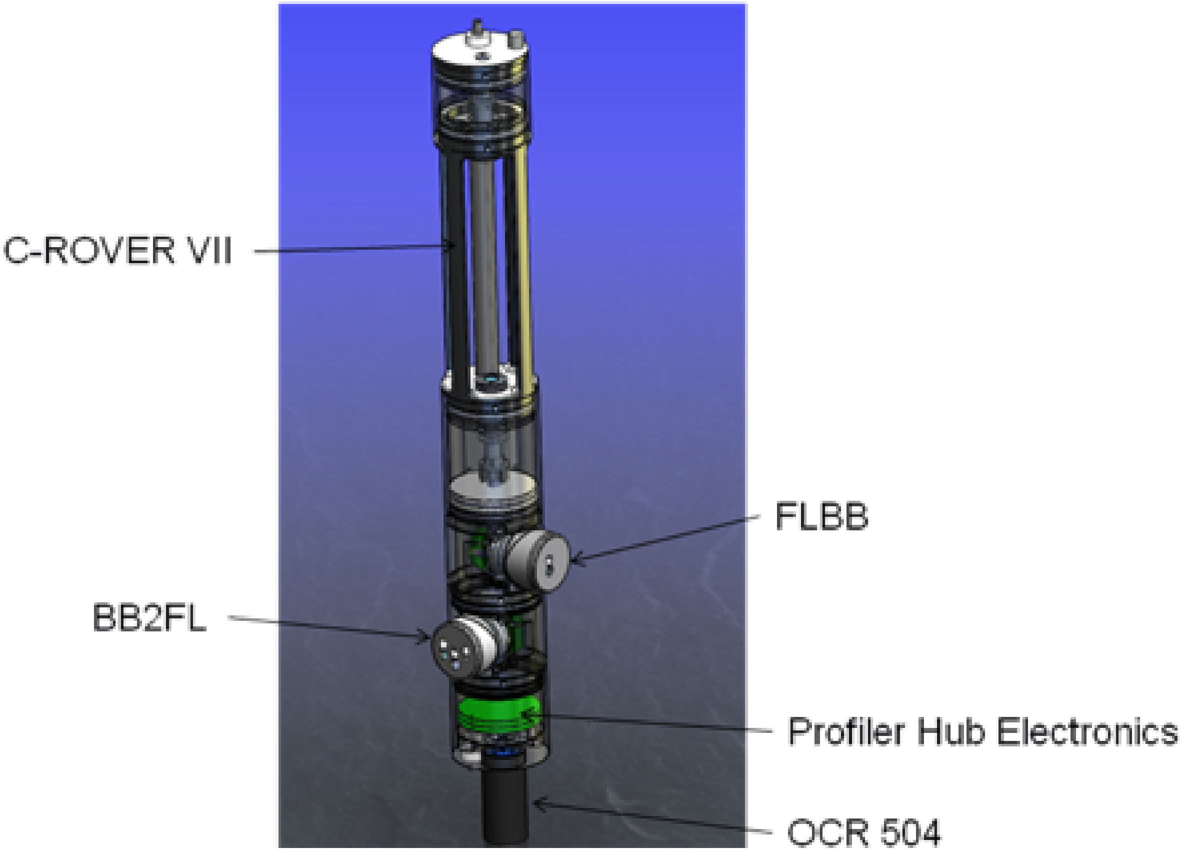

FIG. 2. The optics suite.

cable failures.

The intermittent problem with one radiometer manifested itself as lack of communcation at pressures above 1500 dbar. Satlantic determined the cause to be minor deformation of the radiometer pressure housing leading to internal deformation that affected electrical connections between circuit boards in the radiometer. Improvements to the board assembly and mounting process were implemented to isolate the electronics assembly from pressure effects.

Deformation in the diffusers was observed only during re-calibration of the instruments following the two-month BOUSSOLE deployment in 2011. The spatial response of each of the four channels on both radiometers was found to have changed slightly during the deployment. Although the instrument response still fell within the performance specification, the change was unexpected. Testing for this effect was conducted during the original design phase. However, the deployment provided real-world conditions of longer duration pressure exposure and temperature and pressure cycles. A series of experiments was conducted to measure permanent change in the spatial response of the instruments following pressure exposure. The outer diffuser of the detector, designed to provide a response to irradiance proportional to the cosine of the angle of incidence, was found to be depressed by a small amount into the diffuser holder, resulting in reduced sensor response at great angles of incidence. As a result of this finding, a change in the diffuser mounting design was implemented and validated through extended pressure test and precise measurement of

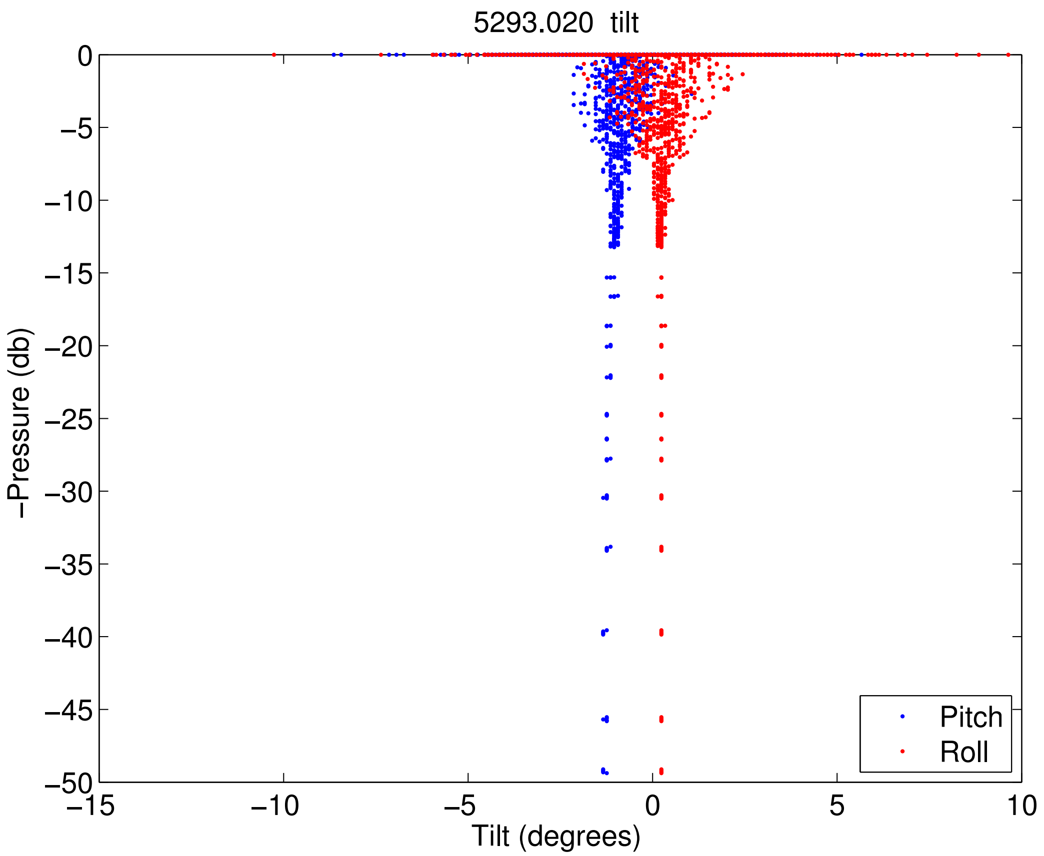

FIG. 3. Tilt during ascent for a single profile near BOUSSOLE in summer, 2011. Tilt measurements are made with each radiometer measurement. For the float shown here (float 2) there are steady offsets of 1.3° in pitch and 0.3° in roll. The offsets are smaller for float 1.

spatial response.

3. Float and Hub Software Development and Integration (Work Package 1)

Satlantic and Teledyne Webb Research collaborated closely to integrate the Profiler Hub, which controls the external sensor suite and logs all sensor data, with the Apex APF9i float controller. During deployment, primary operations are controlled by Apex. This includes parking, ascent, and sampling, all of which are specified remotely by the user. Based on either pressure or time, the float processor sends commands to the Profiler Hub for customizable sampling of the optical instruments.

a. Profiler Hub

The optical instruments are capable of sampling in bursts of several samples, of which the median is transmitted, or in continuous mode, sampling at approximately 1 Hz. Energy use in the hub was minimized by active control of instrument power during burst sampling. Data storage volume was minimized by minimal metadata storage which was aided by the post-processing infrastructure. Sensor firmware was adapted for this project to be capable of emitting data in either raw ADC counts or in calibrated physical units. The original plan was for sensors to perform their own conversion from raw to calibrated data. In early testing, it was instead considered advantageous to transmit raw data and perform the conversion at the shore end. This change had minimal impact on the Profiler Hub firmware.

b. Apex Float

Several additions and modifications were developed for the software that controls float behavior. For onshore testing, the command line user interface was enhanced to account for the new sensors and additional mission complexity. In addition, a direct communications link to the hub was developed. This allows straightforward determination of instrument dark currents prior to deployment.

During the park phase of the profiles, the float samples every hour. Standard Apex sampling has been modified to include optical properties but not salinity and temperature. This choice was made so that the exhaust hose of the CTD that had been rerouted to the transmissometer windows did not clean the lenses prior to ascent.

Because high-quality measurements near the surface are essential for comparison to satellite observations, two important modifications were made. First, a slow ascent option was developed so that float can ascend either at the standard nominal rate of $\sim$8 cm/s or at a slower rate of about $\sim$4 cm/s. Second, an option was added to allow the pressure to be measured rapidly, approximately every 2-3 seconds, near the surface. The ascent rates are somewhat variable given density changes near the surface, so this pressure measurement allows minimization of the pressure uncertainty in the radiometric measurements.

c. Remaining Problems

Software was continually modified throughout the project based on results of onshore testing and from data collected during deployments. The resulting float behavior is robust and predictable and serves the needs of this project. Two moderate software problems remain.

Recent deployments have shown errors in the pressures recorded only during the park phase of the deployment. This has made precise determination of park depths difficult, although course resolution estimates (within 50 m) are possible. This problem was extremely difficult to replicate during onshore testing, so diagnosis has been difficult. The cause of this problem is thought to be the timing of repeated sample requests to the pressure sensor. A workaround has been developed to record multiple pressure measurements.

To match profile timing with satellite overpasses, surfacing at the same solar time each day is essential. Apex software was developed to compute solar time using the position of the previous profile. Bugs remain in that software, which prevents us from using the solar time to determine ascent time of the floats. Instead, we must vary the ascent timing as the floats drift zonally. This adds to the management effort, but not substantially.

4. Control, Telemetry, and Data Handling (Work Package 2)

a. Control

Float behavior and sampling are specified by a mission configuration file downloaded by the float from CLS each time the float surfaces. Currently, any changes in a mission require a mission configuration file to be built by hand using tools developed by Teledyne Webb. That file must then be manually posted to the server by someone at CLS America. The CLS office in Tolouse is developing a web-based interface to allow end users to write and post mission configurations without involving manual file manipulation at CLS. This must be done carefully because errors in a mission configuration could cause loss of a float. Several iterations of interface design and product testing have taken place involving CLS, Teledyne Webb, and UMaine. It is expected that when the most recent recommendations from UMaine have been implemented the interface control tool will be ready for implementation (early in 2013).

b. Telemetry

All data are stored in binary form on the Profiler Hub. At the end of each profile the data are transferred from the Hub to the Apex controller, from which they are telemetered via Iridium x-modem to shore at CLS America. For transfer efficiency in intermittent Iridium coverage, the data are transmitted in a series of small files (21 kilobytes). After the data are transferred from the hub to the float, but before telemetry, the data are encoded as base-64 ASCII to avoid problems with misinterpreted characters. Previous Apex floats have not transmitted data as binary, so this problem had not been encountered. Two telemetry options are available. One transmits all the data. The second does not transmit the subsamples of burst observations, and transmits only some of the raw Optode data. This reduces time, energy, and expense of telemetry. The data are stored on the hub in perpetuity so that if floats are recovered, all the data can be extracted.

The Iridium network transfers the data to CLS America where files are concatenated and decoded back to the binary form in which they were stored on the hub. CLS has developed new communications protocols to improve the quality and speed of transfer of the large data volumes (200-30 kilobytes) from these floats. After decoding and concatenated, the data are pushed to UMaine's server for archiving and analysis. Preliminary analysis and display is also performed at CLS America.

The binary files use Satlantic's compression and packaging formats and are unpacked and converted to a human readable format with their SatCon software. Satlantic developed a command line version of SatCon to enable automated processing. For preliminary display and dissemination, CLS America has integrated SatConCL into its processing, allowing conversion of raw data into scientific units. UMaine uses the raw data and converts to scientific units in postprocessing.

5. Data Display and Dissemination Tools (Work Packages 3 and 4)

After telemetry, float data are processed by three different organizations, UMaine, CLS America, and NASA Goddard Earth Sciences Data and Information Services Center (GES DISC). CLS America archives data and produces plots of observations during each profile (figure 4). These plots allow rapid examination of data and help guide upcoming missions and are available at http://biofloat.clsamerica.com. This system is commercially available to other CLS customers. UMaine also makes preliminary plots of float observations, but the UMaine system is not as robust as the CLS system. UMaine's primary objective is to process data for the scientific analysis. That analysis is ongoing.

The plots produced at UMaine and CLS America are integrated into a system developed at NASA GES DISC. Using a web interface to access a map server and web coverage service, this system displays profile location, gives access to the profile plots, and makes available maps and data for satellite ocean color products (figure 5). This system is capable of adaptation for other floats or anchored buoys, providing a simple way to view, access, and display relevant ocean radiometric parameters together with data from buoys. It is can be accessed at http://ws.csiss.gmu.edu/NASA_GESDISC/buoy.htm.

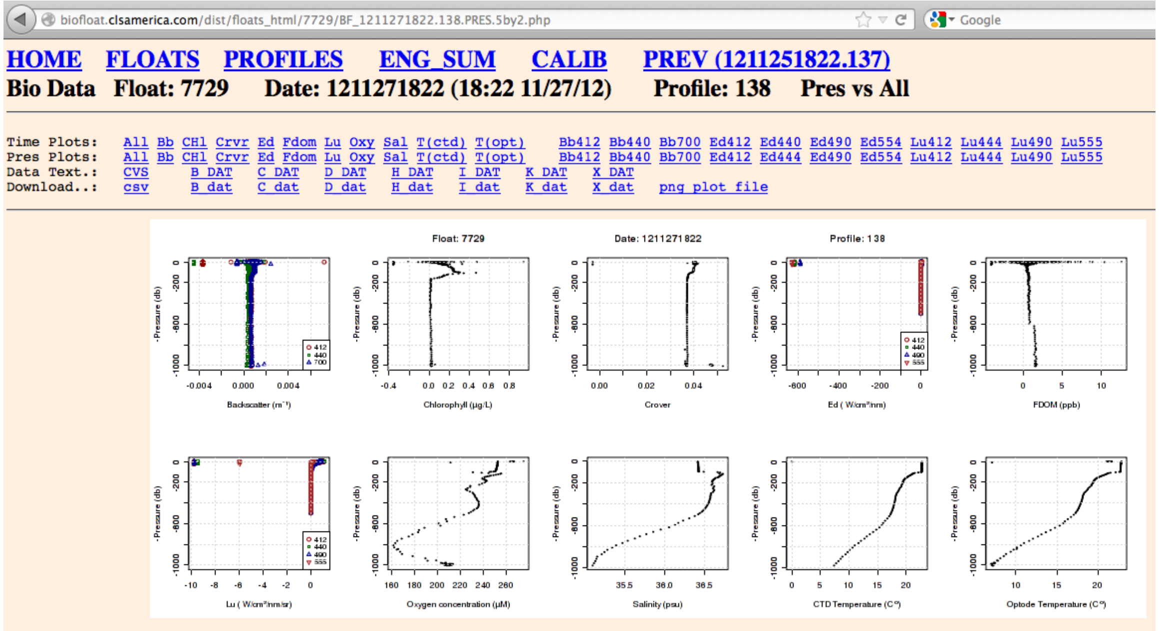
biofloat.clsamerica.com/dist/floats_html/7729/BF_1211271822.138.PRES.5by2.php

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FIG. 4. Screen capture of CLS America's data display web page for a recent profile in the North Atlantic.

6. Operations (Work Package 5)

Prior to shipment, Teledyne Webb measures dark currents of the fluorometers and backscatter sensors using a protocol developed in concert with WET Labs. They also calibrate the compass to account for magnetic effects of the electronics inside the float. After Teledyne Webb has shipped the floats, if facilities and personal allow it, the transmissometer is tested in deionized water to check for changes in lens alignment during shipping.

Our deployments have several measurement phases. The floats park for two days and take a few hours to reach the surface from park. During the park phase a single measurement of all optical instruments and the Optode are made every hour. During profiling, quantities are measured

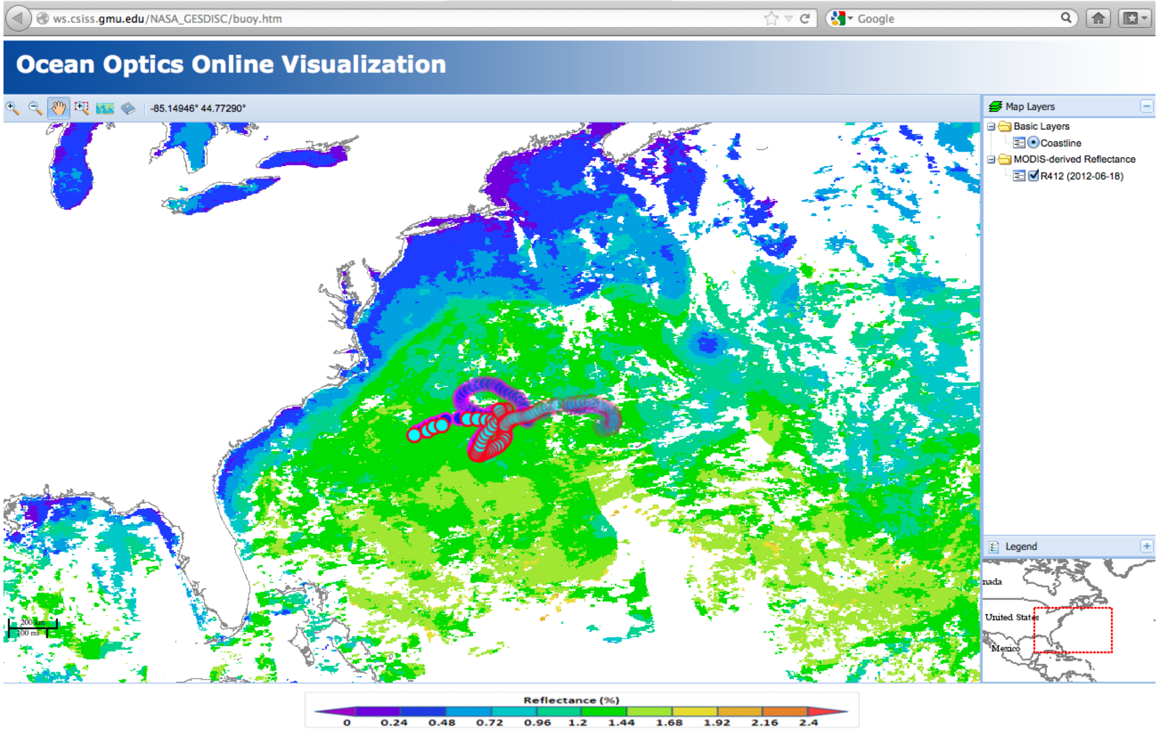

FIG. 5. Screen capture of NASA GES DISC web page showing locations of profiles for the North Atlantic floats and an eight day composite map of remote sensing reflectance at 412 nm in June, 2012.

in burst samples, beginning with 20 m resolution. The resolution gets increasingly fine as the float ascends, with 1-2 m resolution in the upper 100 m. At 25 m depth the float begins to sample the radiometers and optical properties continuously at 1 Hz. After reaching the surface the float samples for five minutes to determine mean downwelling irradiance and upwelling radiance.

We have made several deployments of the floats, the most recent being 24 November, 2012. Deployments have been made at MOBY in Hawaii, in the North Atlantic, and at BOUSSOLE in the Mediterranean. The floats deployed in December, 2011, remain operational after nearly one year and almost 200 profiles. Some biofouling has been observed on some floats, particularly on the downwelling radiometers and the transmissometer lenses. It is not yet known whether the upwelling radiometers have been contaminated by fouling. It is anticipated that because they look downward they will take longer to foul.

The deployments have become as routine as might be expected for this kind of work. After shipment from Webb, human interaction is required only to check dark currents and the transmissometer. Mission planning with UMaine and CLS America has gone smoothly for the recent deployments.

7. Scientific Results (Work Package 6)

Full analysis of the float data is waiting for observations from the most recent BOUSSOLE deployment. Preliminary results have been presented at the 2012 Ocean Sciences meeting and the 2012 Ocean Optics meeting. Technological developments were also presented at the 2012 Ocean Sciences Meeting. A technical paper describing the floats and their utility for calibration and validation will be submitted to the Journal of Atmospheric and Oceanic Technology in 2013.

Float tilts have been stable and small beneath the wave-affected surface layer. Ascent rates vary within about 2 cm/s of the target rates, as dictated by the float control software (figure 6). Sensors have been operational and observations show qualitative agreement between radiometric quantities (diffuse attenuation coefficients) and inherent optical properties (figure 7).

Near surface radiometric observations are used to extrapolate the upwelling radiance measured at a depth of 1.2 m to the surface by fitting an exponential decay profile to the observations (figure 8). The upwelling radiance and downwelling irradiance can be compared directly to satellite estimates, or can be used to compute remote sensing reflectance. Comparisons between float estimates and satellite estimates of remote sensing reflectance have been made for data collected before September, 2012. They have shown substantial scatter (figure 9). Comparisons of float observations to buoy observations at BOUSSOLE and MOBY have shown better agreement.

Computation of radiometric quantities for calibration and validation of satellite observations has begun but proceeds slowly. We have been collaborating with Jeremy Werdell and Chris Proctor in the NASA GSFC Ocean Biology Processing Group and with Menghua Wang and Seunghyun Son in the NOAA STAR Satellite Oceanography and Climatology Division for comparison of float observations to observations by MODIS Aqua and VIIRS. Similar to rates with with shipboard observations, only about 10% of the float profiles occur when conditions are favorable for high quality matchups with satellite observations. These floats have, to date, made nearly 700 profiles. Analysis of the data in figure 9 suggested that several times this number of profiles would be necessary for gain estimates of satellite observations to be accurate within 1%.

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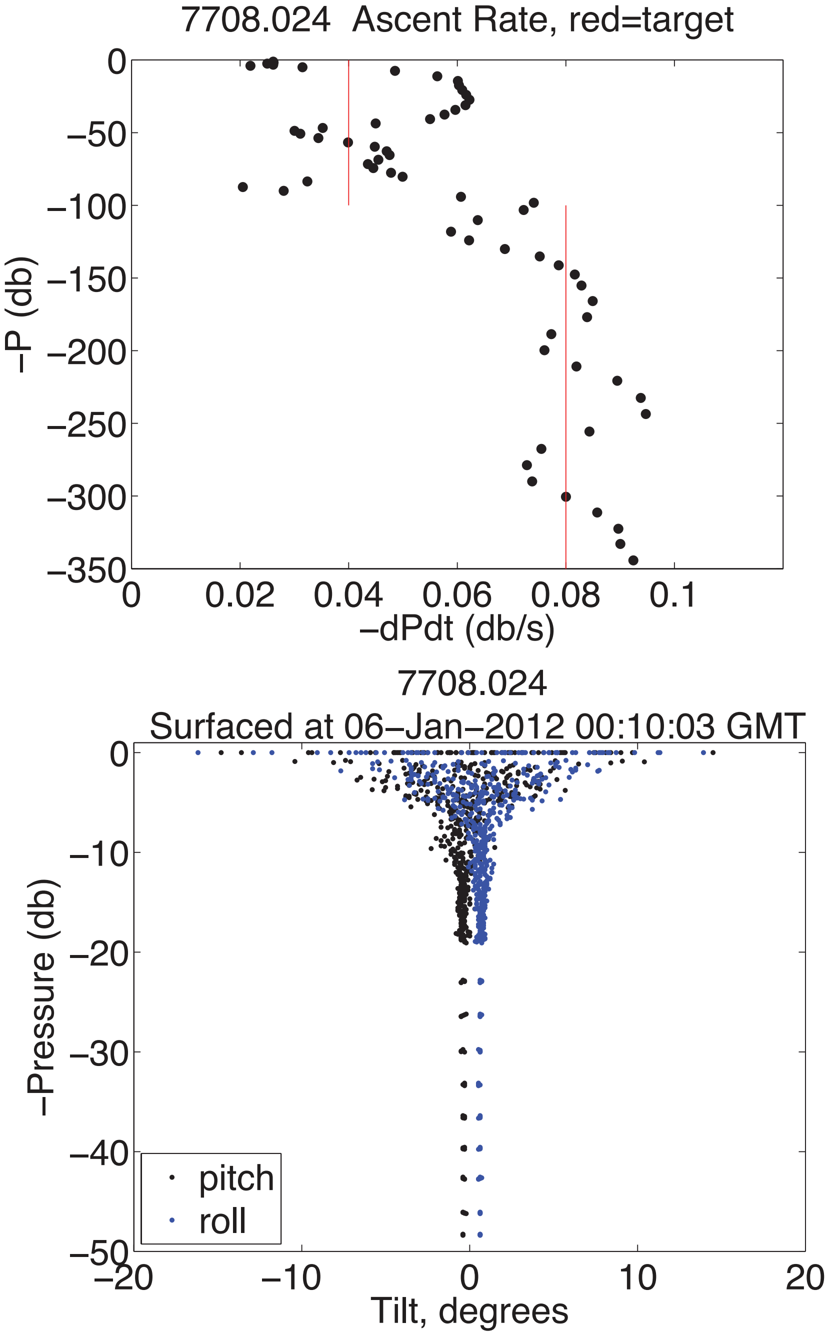

FIG. 6. Ascent rate and tilt of a float near the ocean surface for a profile near Hawaii in January, 2012. Upper panel: Ascent rate. The target rates were 8 cm/s at depth and 4 cm/s above 100 m. Bottom panel: Tilt of the float during burst sampling (below 20 m) and during continuous sampling (above 20 m). Waves are not felt significantly at depths below about 15 m.

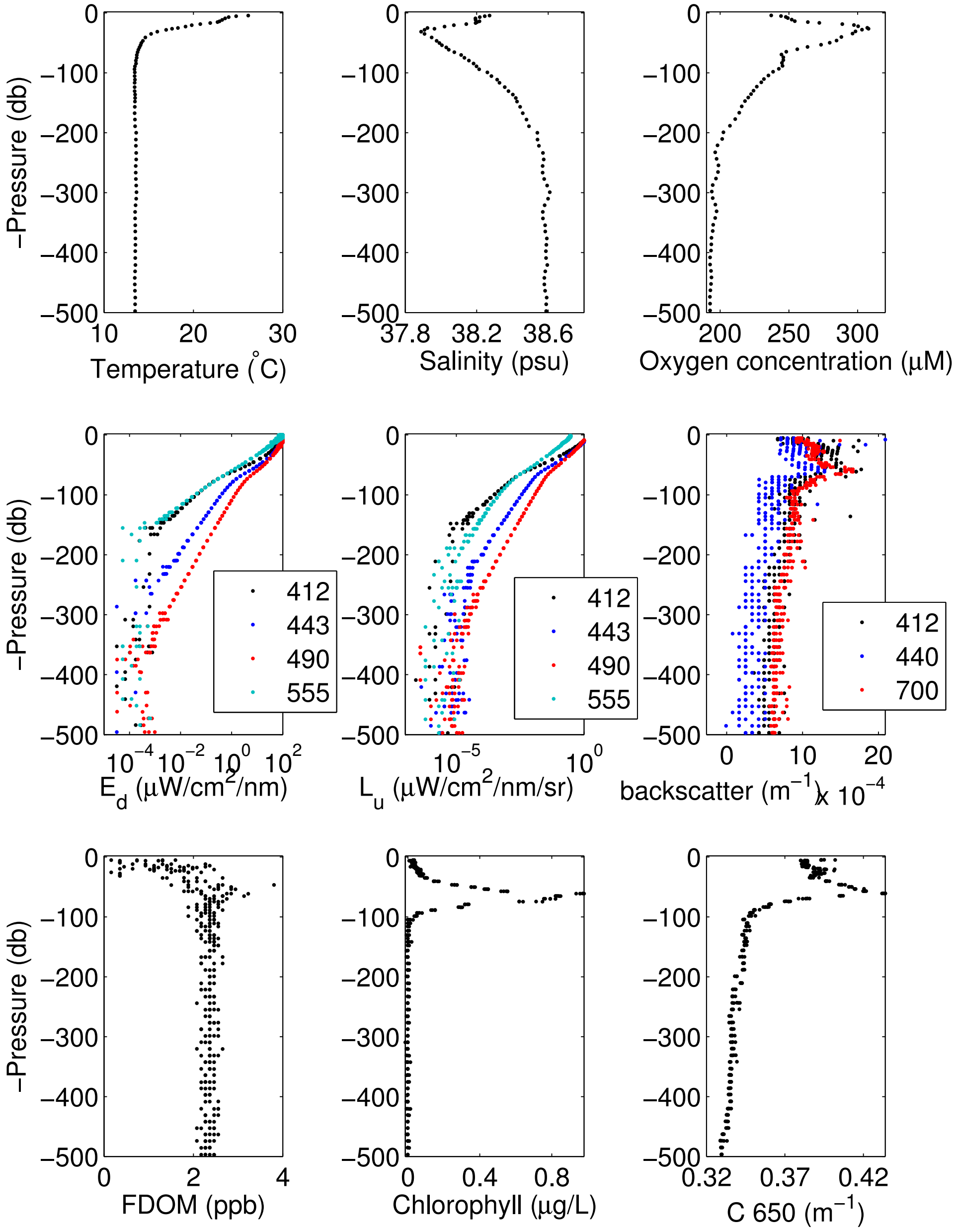

FIG. 7. Observations from a profile near BOUSSOLE in summer, 2011. Legend entries are wavelengths in nanometers

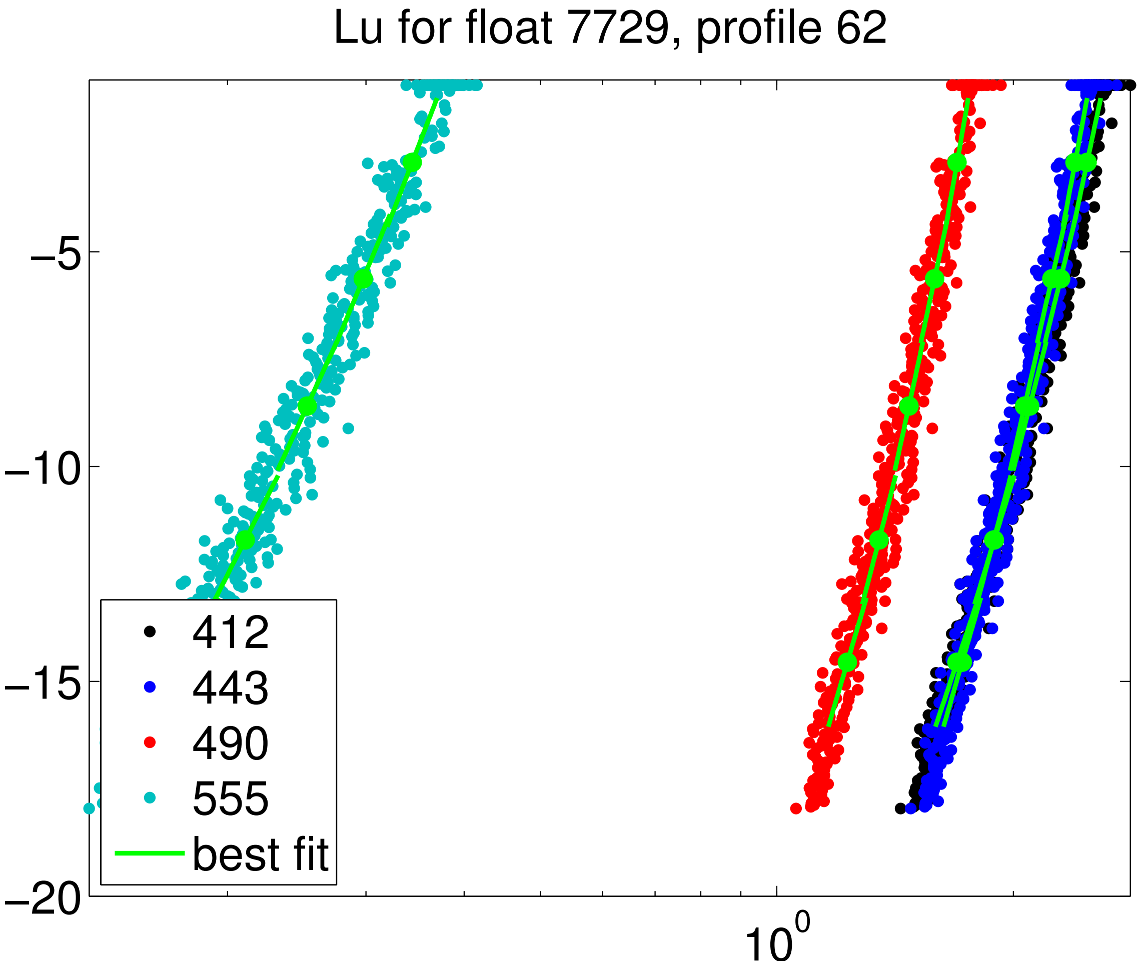

FIG. 8. Measurements of upwelling radiance, L_u, four all four wavelengths (412, 443, 490, and 555 nm) for a profile in the north Atlantic on 25 July, 2012. Superimposed on the profiles are the estimates of L_u in each bin center and the profile that is formed from that value and the best fit attenuation coefficient. The large number of values at 1.229 m demonstrated the measurements made while the float was at the sea surface.

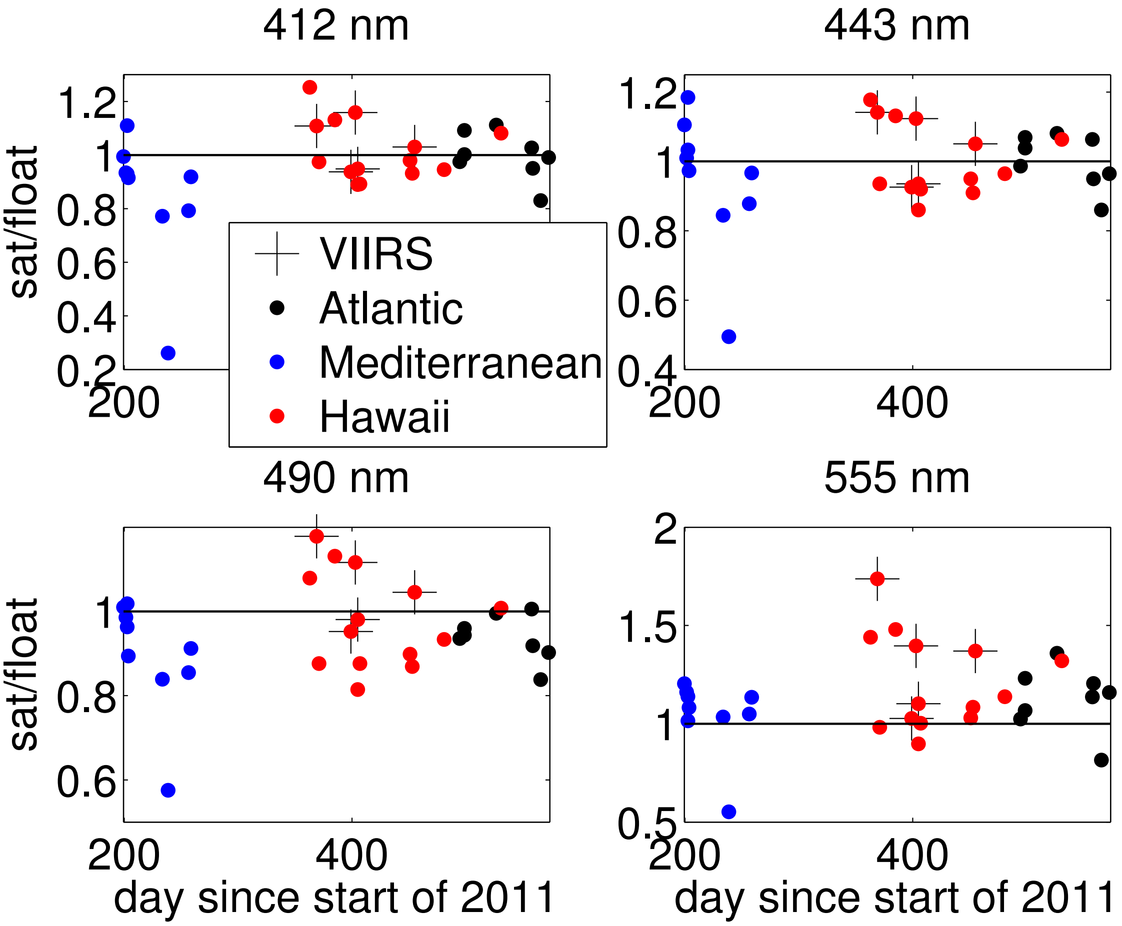

FIG. 9. Ratios of R_{rs} measured by MODIS-Aqua or VIIRS to R_{rs} measured by the floats. Each wavelength is shown in a different panel and the colors show the locations of the float deployments. Note the different axis scales in each panel. Variability is larger than that seen by Franz et al. (2007) and Bailey et al. (2008) in comparisons of *in situ* and satellite observations.