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

Progress Report, Year 2

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1. Overview

This document reports the progress on this project between 1 August, 2010 and 26 August, 2011. At completion of this project we will have integrated existing high precision bio-optical sensors (both active and passive) onto profiling floats, deployed and tested the floats in interesting dynamic ocean regimes, and demonstrated 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.

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, and deployed and tested the instruments. WET Labs and Satlantic have modified and produced instruments, housings, and control software. 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 are developing 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.

Year 2 goals were:

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)

Throughout the fall and winter of 2010-2011 software development for communications, control, and data handling continued. One day-long deployment was performed in Bedford Basin, Nove Scotia, and three deployments in the Mediterranean Sea were made. One float was deployed in March, 2011, near BOUSSOLE, offshore of Villefranche sur mer. That float made one successful profile and was recovered following failure of a cable connecting the optics package to the float. Two floats were deployed at BOUSSOLE in July, 2011, and each has made $\sim$20 profiles over more than 40 days. Including the previous deployments these two floats have made more than 40 profiles of optical properties in the ocean.

2. Vehicle

The vehicle is an APEX Float manufactured by Teledyne Webb Research in Falmouth, Massachusetts. The float has been adapted to support the suite of optical instrumentation for measuring the biogeochemical parameters required by the project, and refinements of mounting strategies are ongoing. A new mount has been developed for the downwelling irradience sensor to ensure alignment with the float body and optics package (where the tilt sensor is located). Handles were designed and added for ease of deployment and recovery (unnecessary in single-deployment floats). Mechanical integration of the external sensor packages has been achieved while meeting the requirement of a stable sensor platform throughout deployment. 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 2). This small tilt angle is crucial to measurements from several of the optical sensors. The float software has been modified so that the float can ascend either "quickly" ($\sim$8 cm/s) or "slowly" ($\sim$4 cm/s), which allows improved estimates of radiometric quantities near the sea surface. For one float, 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)).

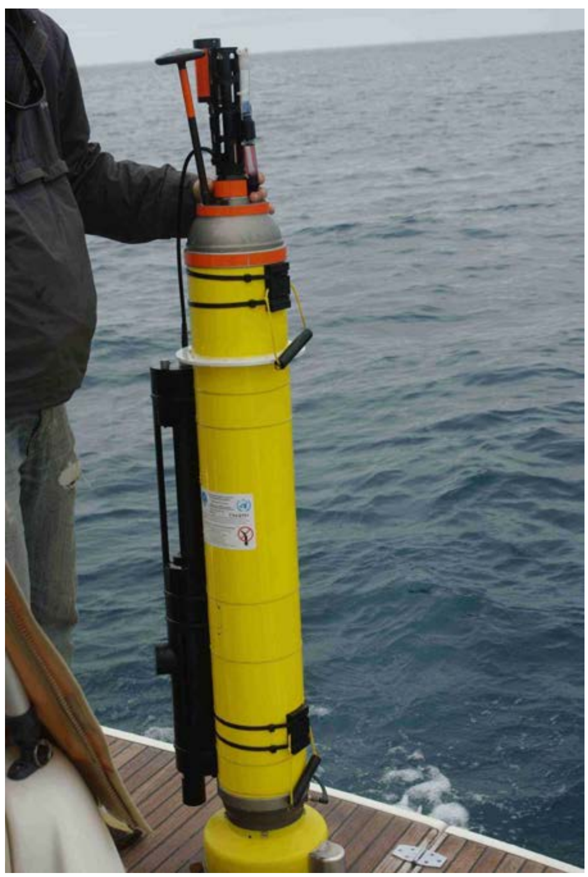

FIG. 1. Biogeochemical float with optics suite attached to side and irradiance sensor on top.

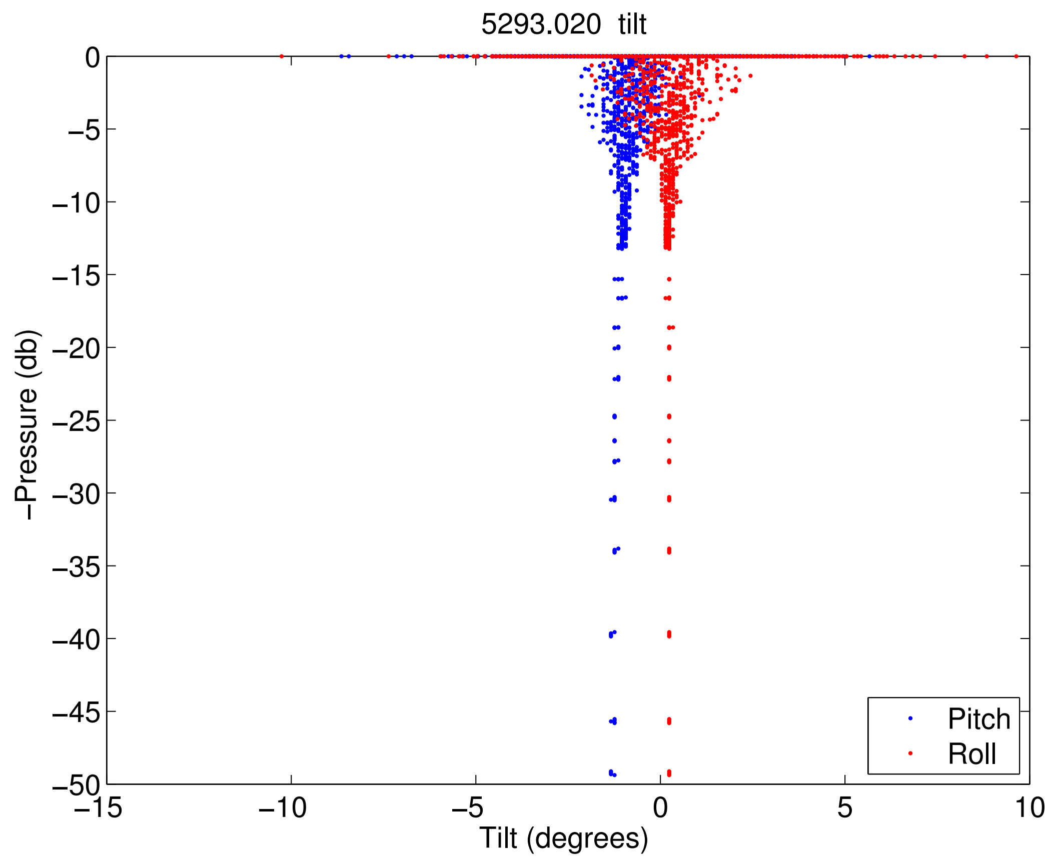

FIG. 2. Tilt during ascent. Tilt measurements are made with each radiometer measurement. For the float shown here (float 2) there are steady offsets of 1.3° in pitch and 0.3° in roll. The offsets are smaller for float 1.

3. Payload

The floats contain science instruments in two sets. The Seabird SBE41-CP CTD and Aanderaa 4330 Optode communicate directly with the float processor (APF9i). The optical instruments are integrated in the Profiler Hub, which contains components from WET Labs (inherent optical property sensors and pressure housing) and Satlantic (radiometers and integration and processing hardware). The first two Profiler Hubs, were completed and delivered to Teledyne Webb under the sobriquet Bio-Optical Sensor Suite (BOSS) in October and December 2010.

The bio-optical sensor suite has 5 main components (figure 3); 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 backscatter data have some uncertainty in their calibration. With input from UMaine, WET Labs has developed a new calibration procedure for backscatter sensors that will be used for post-calibration of the current deployment and for future deployments.

All components are rated for pressures of 2000 decibars. The floats were tested to this pressure in a pressure tank by Teledyne Webb. All systems were operational, except that one downwelling irradiance sensor did not work at pressures greater than 1500 db, likely due to minor deformation of the pressure housing interrupting a connection. This problem did not seem to affect operations at lower pressures. In the field float 1 has been deployed to a depth of 1900 m and float 2 to 1100 m.

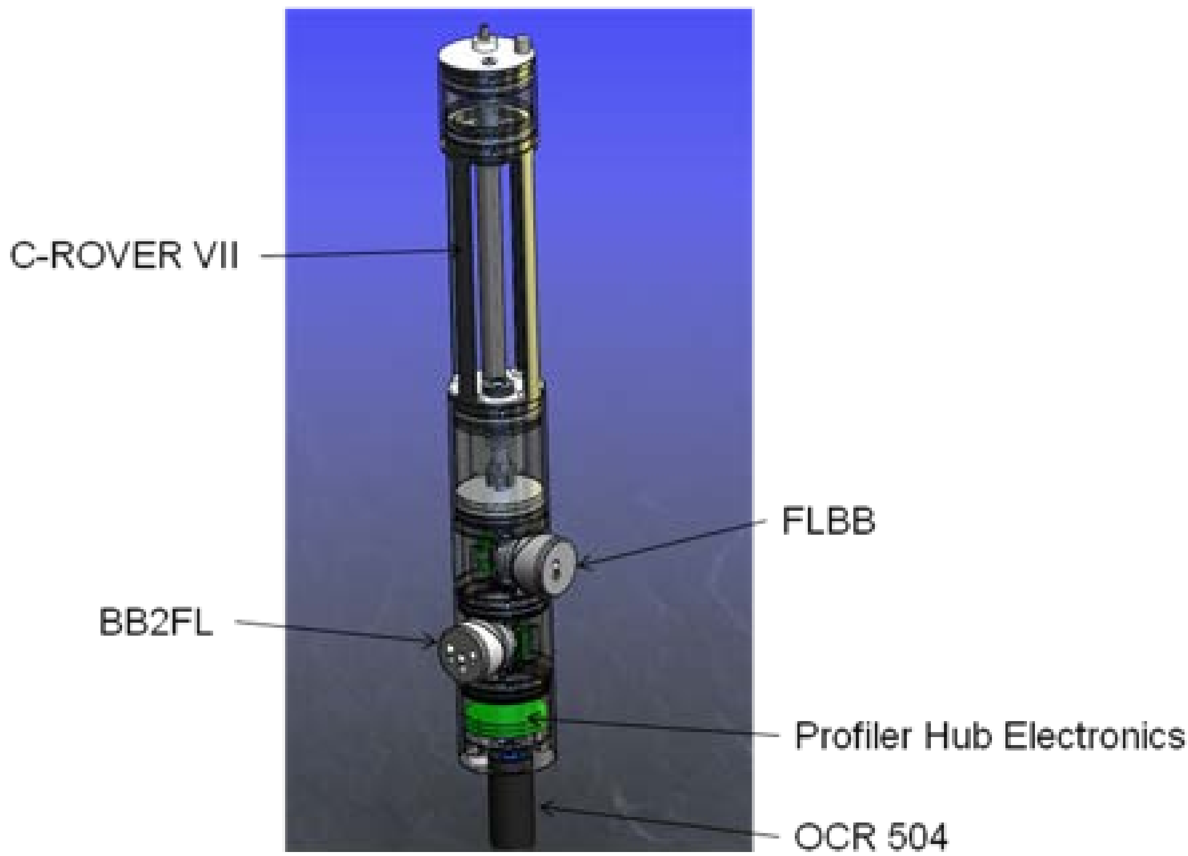

FIG. 3. The optics suite.

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. This year, Teledyne-Webb and Satlantic have gotten several requests for quotes for systems that are based on the product develop through this NOPP project.

4. Software Development

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. Satlantic supplied a Profiler Hub simulator to TWR in advance of the delivery of the first system to facilitate development and testing. During deployment, all operations are controlled by the APF9i. The float uses user input to determine parking and profiling depths and the time of float ascent. Based on pressure or time, the float processor sends commands to the Profiler Hub for user-determined samples.

a. Apex Float

Firmware updates to Teledyne Webb's Apex float have included a solar time option, allowing the float's surfacing time to be set by the sun angle (using the geographic position of the previous profile). For programming & querying Biogeochemical floats, the command-line interface has also been enhanced to account for the complexity of missions using the larger array of sensors found in the float Hub. These enhancements have been documented in the latest User Manual specific to NOPP Biogeochemical profiler floats.

b. Profiler Hub

Throughout integration development and pre-deployment testing of the Biogeochemical Profiler, Satlantic refined Profiler Hub firmware to add features, adjust data formats, adapt to float controller interface changes, and fix bugs.

Sensors 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 but added significantly to the task of managing metadata, in the form of telemetry definition files, for the floats. In the raw data transmission case, each float has a unique set of telemetry definitions since each sensor has unique calibration coefficients. In the physical units data transmission case, all floats with the same sensor suite share telemetry definitions.

5. Telemetry, Data Handling and Dissemination, and Control

a. Telemetry

All data are stored on the Profiler Hub. At the end of each profile the data are transferred from the Hub to the APF9i, from which they are telemetered via Iridium x-modem to shore at CLS America. Teledyne Webb was forced to encode the data as base-64 ASCII to avoid problems with misinterpreted characters. Previous floats have not transmitted data as binary, so this problem had not been encountered.

The shore-side network infrastructure for acquiring the real-time data from the floats and delivering it to the project scientists has been in place at CLS America since early 2011. Successful demonstrations of the system capabilities were completed early in 2011 using testing and simulated data sets. The at-sea deployments in March and July, 2011 provided the first comprehensive opportunities with floats to evaluate the ability of the telemetry data link and the access network to accommodate the very large data files (200-300 Kbytes) from the floats. Changes to communications protocols in the access network have improved the efficiency and quality of data transfer from the floats to CLS.

b. Data Handling and Dissemination

Float data are telemetered as base-64 encoded binary files. The binary files use Satlantic's compression and packaging formats and are unpacked and converted to a human readable format with their SatCon software. Adjustments to data formats required corresponding adjustments to the telemetry definition files that inform SatCon how to decode the binary files. Satcon is capable of outputting either raw data or fitted data.

Satcon is a graphical user interface program. A unix command line version, SatConCL, was developed by Satlantic for in-line processing of the float science data to formats suitable for later processing or for import to database applications. A pre-release version of SatConCL was provided by Satlantic to the University of Maine for use during current deployments and has greatly improved efficiency for handling the large volumes of incoming data. A commercial version will be provided in September to the University of Maine for use by CLS America to decode and reformat the telemetered data files. This software will be integrated into the CLS processing chain in September 2011 and will decode the data from each profile and deliver properly formatted data to the web-based data access and display tools inspired by and being developed in partnership with the U. of Washington.

NASA GSFC has begun integrating float profile locations and data with their Giovanni environment, allowing float data to be viewed in context with MODIS 8-day data products. They are creating a Mapserver interface for these data files. The Mapserver interface will show each buoy position, and by clicking on the position the user will be able to access all of the 8-day ocean color data products for that position and the float data from that profile. When the NASA-wide data center user registration system is in place, GSFC will allow users to access an individual profile for their data products of choice, creating something like a "one-click" Giovanni with lat/lon and date input. GSFC is also working on an email system that will respond to users who email buoy locations, and they may create a user "library" of images corresponding to buoy profile locations that can be examined and downloaded without having to go through Giovanni each time.

c. 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 requires someone at Teledyne Webb to make a new mission configuration. That file must then be manually posted to the server by someone at CLS America. Teledyne Webb has given support to CLS America to implement an automated approach to changing a mission configuration through a web-based user interface. This must be done carefully because errors in a mission configuration could cause loss of a float, so CLS is proceeding conservatively. They plan for CLS in Toulouse to begin testing the mission configuration modification module by end of September 2011 with a web-based prototype capability available by late October 2011.

6. Deployment and Operations

One float was tested in Bedford Basin, Nova Scotia, in February, 2011 at a water depth of about 60 m. The float profiled as it was supposed to do; this was a useful demonstration of float behavior and communications for the operators at UMaine and for the programmers at Satlantic.

The same float was deployed at BOUSSOLE in March, 2011 (figure 4). Some difficulties were encountered in having the float sink, likely because of air trapped in the float body or the seams of Profiler Hub body. The float made two profiles, but only returned data from part of one profile. Because it was not working properly the deployment was aborted and the float was recovered by scientists at Laboratoire d'Oceanographie, Villefranche-sur-mer and shipped to Teledyne Webb for analysis. It was determined that a connector (IE55, supplied by Teledyne Impulse) in the cable between the float and the Profiler Hub had failed because of a manufacturing defect. The connector had a void in the potting that was crushed at pressure causing either a broken connection or crossed wires. These connectors are standard in most floats with optical sensors, so other users were alerted At least one faulty cable was detected in another lab. To prevent such a problem in the future, Teledyne Webb will expose every cable to pressure and will measure impedances and connectivity between wires before installation on a float. The currently used cables were cycled once to a pressure of 10000 psi and cycled 1000 times over a weekend to 3000 psi with no changes in connectivity or impedance.

FIG. 4. Biogeochemical float near BOUSSOLE.

Two floats were deployed at BOUSSOLE in July, 2011 (figure 5). For the first 12 days they profiled daily and have since profiled every five days (as of 25 August). We are in the early stages of analyzing scientific data, and analysis of float behavior has been ongoing, including timing of ascent, ascent rate, tilt, and adherence to high resolution sample requests. Two major issues have become apparent in float behavior: long surface intervals, and difficulty reaching the surface.

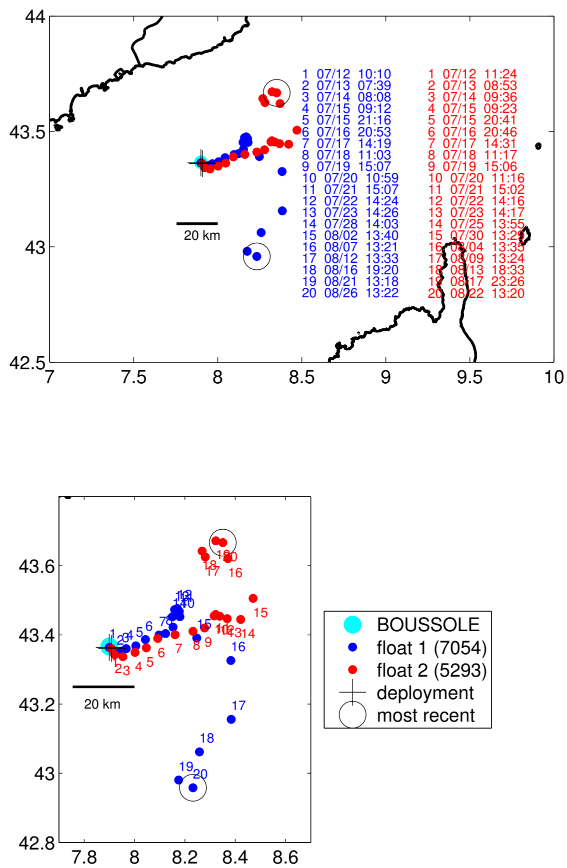

FIG. 5. Profile locations for July deployment.

a. *Surface Interval*

For certain applications, having short intervals between profiles is desirable, for example when trying to match up with more than one satellite overpass in a single day. However, the surface interval between profiles lasts much longer than had initially been hoped. The surface interval has several components, The first group includes short operations such as inflating the oil bladder and air bladder, self tests, obtaining a GPS fix and measuring optical properties at the surface. The second group of surface activities are the most time-consuming components: data transfer from the Profiler Hub to the APF9i and telemetry of data via Iridium. The data volumes are much larger for these floats than for previous Apex floats, and the majority of the data are high resolution radiometer data required for accurate estimates of diffuse attenuation coefficients. We have reduced the amount of high resolution data to the upper 15 m of water and have cut surface intervals from several hours to 1-2 hours per profile.

b. Surface Attainment and Surface Sample

The floats end their profile by measuring 3 minutes after they pass 4 db pressure. This method was chosen because previous Apex floats have had errors in their pressure sensors as large at 2 db. At the nominal ascent rate of 4 cm/s, this provides ample time for the float to reach the surface. However, we did not anticipate the slow response of the float to the strongly stratified pycnocline in the Mediterranean Sea (more than 2.5 kg/km^3 in the upper 50 m). The float attempts to maintain its ascent rate by inflating the oil bladder, but the limited size and limited frequency (for other operational reasons) of buoyancy changes makes the float unable to maintain its ascent rate to the sea surface, and ascent rates often fell to 1/4 of their targets (figure 6).

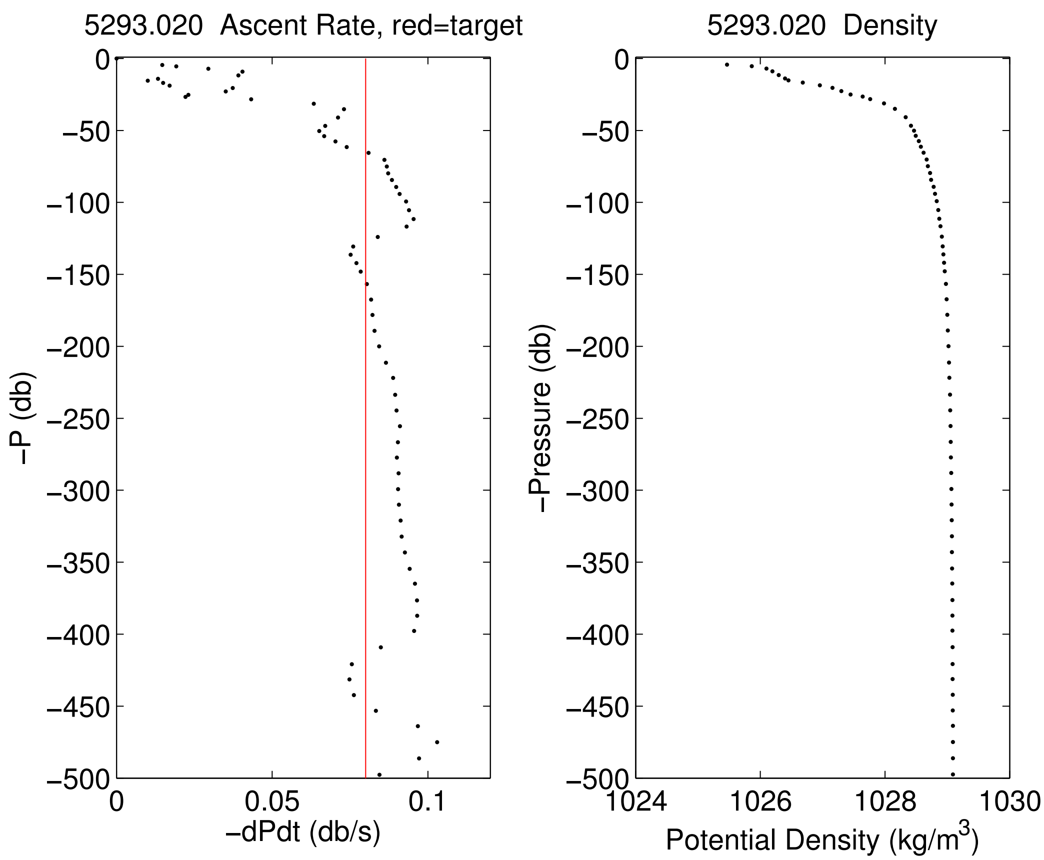

FIG. 6. Ascent rate and density.

The failure of the float to reach the surface in 3 minutes after passing 4 db caused the floats to end the profiles in such a way that the optical measurements at the sea surface were corrupted, so those critical parts of the profiles were lost. Recently we have increased the ascent rates and the sizes of the buoyancy nudges and have had some success in the float reaching the sea surface in the allotted time. In future deployments we will consider an alternative method of identifying the surface.

c. Scientific Results

Float profiles show relatively constant values of most quantities at depths below 200 m (figure 7). Most quantities change at shallower depths. Density changes the most in the upper 30 m, and inherent optical properties change significantly at all depths shallower than 100 m. The radiometer data are affected by waves near the sea surface (figure 8), but the slow ascent has allowed us to estimate diffuse attenuation coefficients that will be used to determine water leaving radiances for comparison to satellite measurements.

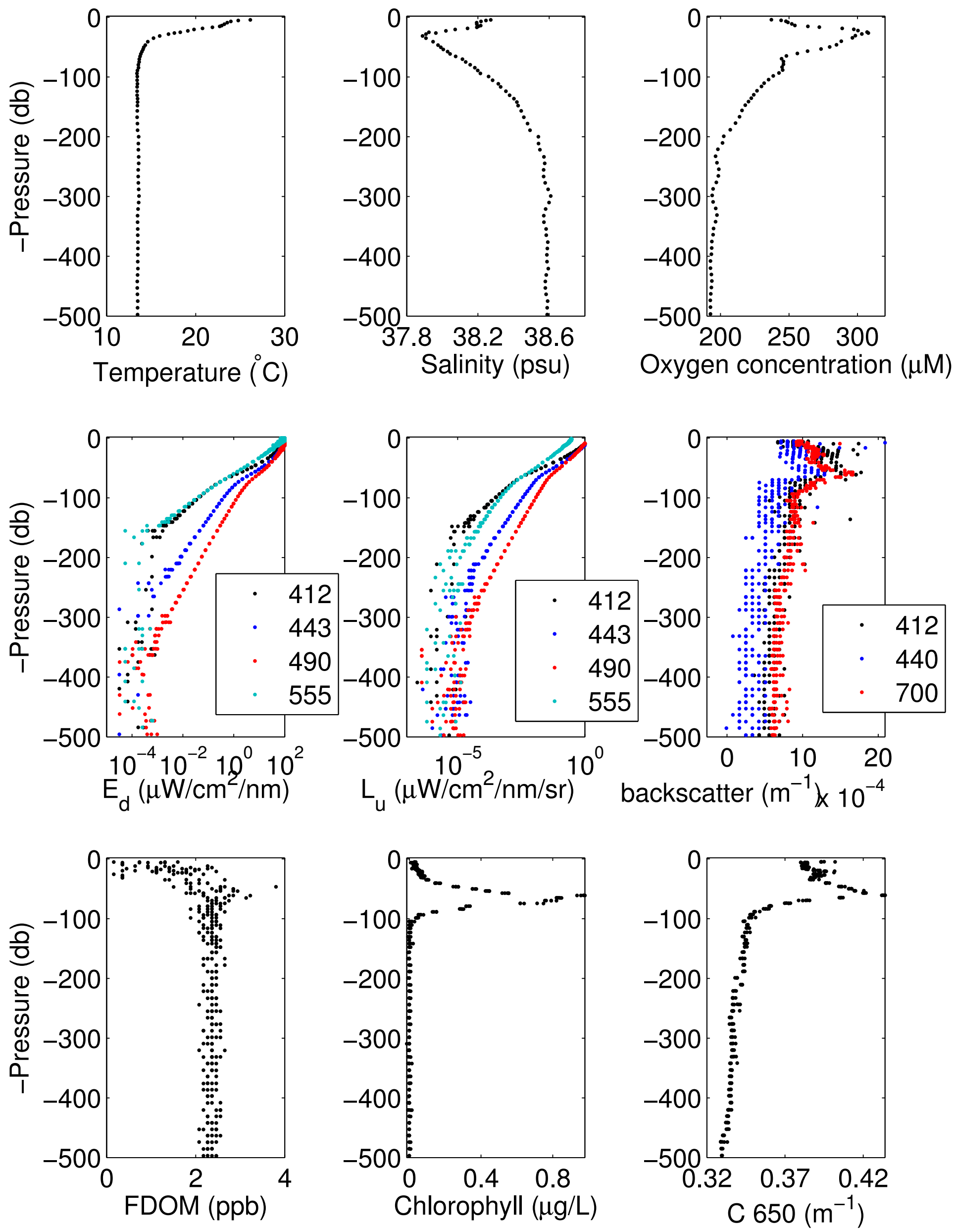

FIG. 7. Profile data. Legend entries are wavelengths in nanometers

The profiles show maxima in backscatter, fluorescent dissolved organic matter (FDOM), chlorophyll concentration, and beam attenuation at about 60 m depth (figure 7). These features are found in both day and night profiles and in profiles from both floats (which are now separated by about 60 km). Estimates of diffuse attenuation coefficients from the radiometers are also increased at these depths (figure 9). The precision of FDOM data is poor because of instrument limitations, but is also measurably enhanced near 60 m. It is most likely a byproduct of primary and/or secondary production.

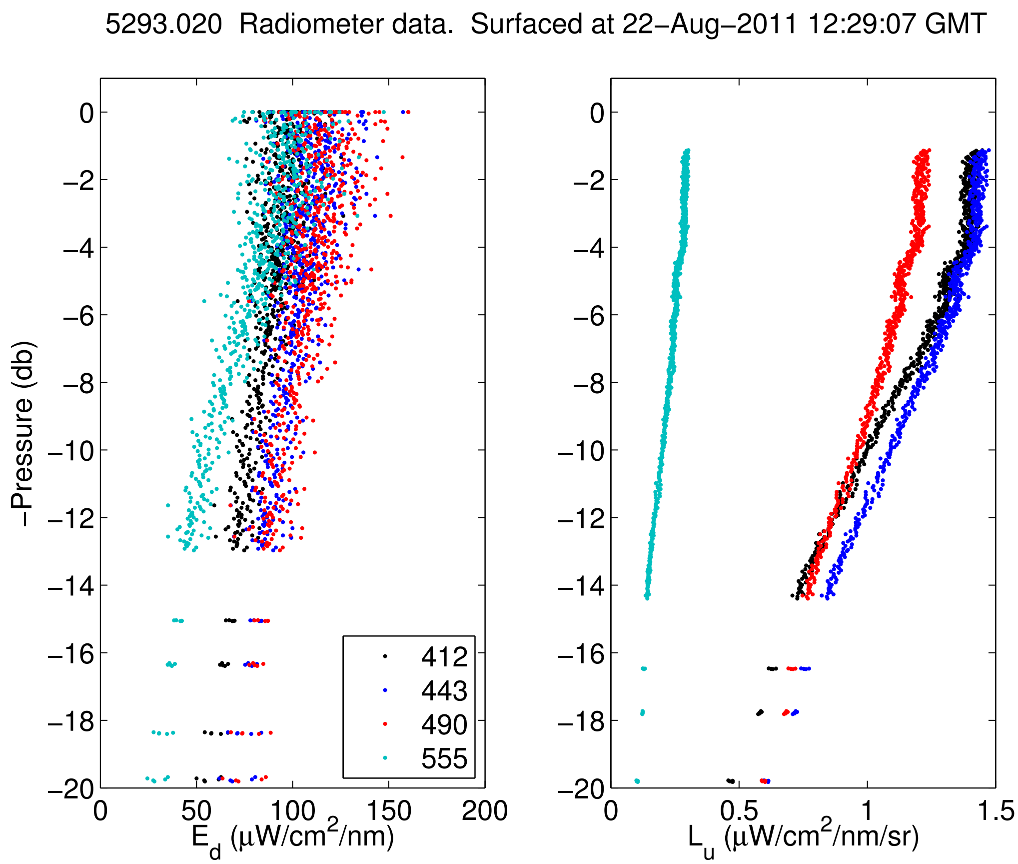

FIG. 8. near-surface radiometer data.

7. Summary

a. Major achievements to date

1. Physical integration of Apex float and Profiler Hub optical package that profiles stably.
2. Electronic integration of Apex float and Profiler Hub optical package allowing user-specified sampling.
3. Modular Profiler Hub design allowing flexible commercialization.
4. Identifying hardware and software issues that benefit the community of optical float users.

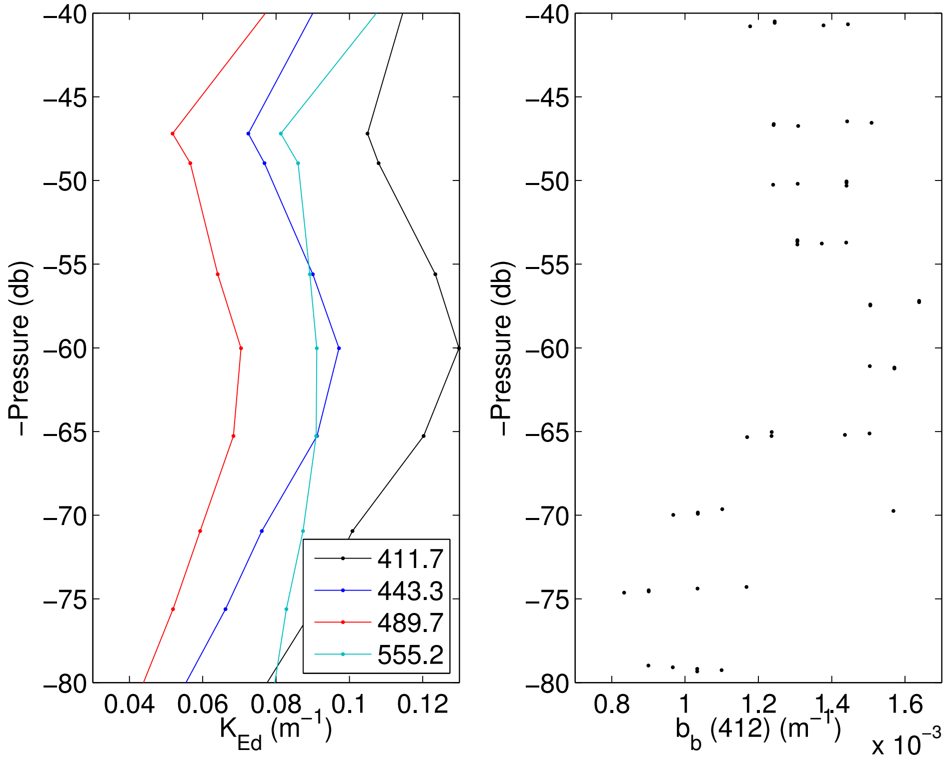

FIG. 9. Diffuse attenuation coefficient and backscatter near backscatter maximum.

5. Deployments showing robust technology capable of reaching 1900 m depth or more.

6. Collection of high quality inherent optical property and radiometric data.

b. Plans for year 3

1. Deployment of additional floats at MOBY calibration/validation site.

2. Detailed analysis of data quality to assess potential use for calibration/validation efforts.

3. Analysis of data to optimize sampling.

4. Write a manuscript for publication (targeting JTECH) that describes the technology, uses, and limitations.

REFERENCES

Bishop, J. K. B., T. J. Wood, R. E. Davis, and J. T. Sherman, 2004: Robotic observations of enhanced carbon biomass and export at 55S. *Science*, **304**, 417–420.