A one-year pilot study for the inclusion of active optical sensors into PALACE floats.

ABSTRACT

We propose to carry out a one-year program to instrument two PALACE floats with small, newly-developed solid-state, active optical sensors that measure chlorophyll *a* fluorescence of phytoplankton and scattering of particles in the back direction. The study is timely because the electronics of the PALACE floats are currently being upgraded and outfitted with new boards that will support integration of ancillary sensors as part of the ARGO program. The ARGO program, if funded at the level of effort proposed by the physical oceanographic community, will be responsible for the deployment of thousands of PALACE floats in the ocean. The incorporation of this new generation of optical sensors on a even a subset of the ARGO floats would provide unprecedented information on vertical and horizontal distributions of chlorophyll *a* fluorescence and scattering by suspended particulate matter. These optical measurements will provide estimates of phytoplankton biomass and particulate organic carbon concentration, through documented empirical relationships. In addition, optically-instrumented PALACE floats would provide a spatial network of sensors for validation of ocean color satellite data products. In order to persuade the physical oceanography community to incorporate optical sensors that have a high payoff for understanding the ocean carbon cycle into the ARGO program we need a proof-of-concept study wherein the optical sensors are used successfully and without compromising the quality of the physical measurements. This proposal is intended to provide such a study. We believe that this study can pave the road for instrumenting PALACE floats, and those of the ARGO program in particular, with a variety of existing and future sensors measuring different biogeochemical parameters.

PROJECT DESCRIPTION

OBJECTIVES AND SIGNIFICANCE

The goal of this proposal is to test the use of a new generation of low drag, low power, active optical sensors on PALACE floats, similar to those used in the ARGO program (Fig. 1). Measurements of chlorophyll *a* fluorescence and scattering of particles in the backward direction will provide estimates of phytoplankton biomass and particulate concentration (which in the open ocean is mostly from biogenic sources). The major objective of this proposal is to demonstrate to the physical oceanographic community that measurements of critical interest to understanding the global carbon cycle can be made without compromising the quality of the physical measurements or the ARGO mission requirements. Without the physical oceanographic community's consent and endorsement, there is little hope of obtaining biogeochemical measurements within the AGRO program. We believe that the ARGO program, in which thousands of floats will be deployed in the world's oceans, provides a unique opportunity to improve our understanding of the global carbon, particularly at subsurface depths inaccessible to observations by satellite.

This proposal directly addresses research topic 4. of the NRA:

New approaches for Carbon Cycle Information.

A major limitation of satellite-based data is that the vertical structure of parameters cannot be determined directly. Truly global information critical to understanding the oceanic carbon cycle could be obtained if the global horizontal distributions obtained from satellites combined with a global set of vertical profiles, such as could be measured with profiling drifters. We see the combination of surface-observing ocean satellites with a global fleet of profiling drifters equipped with biogeochemical sensors as an extremely powerful tool with which to address carbon cycle related research topics.

We propose to combine existing technologies (PALACE floats with CTDs; inexpensive, reliable, solid state biogeochemical sensors) in an innovative manner to provide a proof of concept for inclusion of biogeochemical sensors on PALACE floats. We expect this proposed work, to lead to a much larger community-based proposal for the inclusion of biogeochemical sensors on the PALACE fleet. The plans for the ARGO . If we act now, there is still a chance to instrument a significant proportion of the floats with biogeochemical sensors. We must demonstrate to the physical oceanographic community that this can be done without compromising the physical oceanographic data.

The inclusion of biogeochemical sensors on the global PALACE float plan addresses two other Carbon Cycle Science components in the NRA: 1) global and regional sources and sinks for carbon, and 2) global and regional productivity.

Global and regional sources and sinks for carbon.

The U.S. Carbon Cycle Interagency Working Group's science implementation plan identified the urgent need for better information on the global distribution of carbon sources and sinks and how these are changing. The combination of satellite observations and PALACE floats will aid in quantifying the standing stocks of POC that are needed to compute carbon sources and sinks. For example, missing carbon sinks now thought to exist in the Southern Ocean could be studied by addressing POC stocks in the interior of the ocean. Significant chlorophyll concentration have been found in many instances below the euphotic depth in both oceanic (e.g. Stramska et al., 1995) and near-coastal environments (e.g. Murphy. and Cowles, 1997) due to mixed layer deepening and subduction. Instrumentation that could measure chlorophyll concentration below the euphotic depth would help to assess importance of the contribution of such subduction events to the carbon flux.

Year-round observations from floats in regions that are not accessible to ships will provide a systematic observation program to delineate and track POC distribution in time and space. In addition, floats can provide measurements under cloudy conditions when satellite imagery is unavailable, thus expanding the global coverage. Such coverage would be particularly useful in remote regions routinely covered by clouds. Empirical data linking the POC distributions at depth with the primary production at the surface will help to test the feasibility of using remotely sensed data to predict the vertical distribution of POC below the surface layers.

Global and regional productivity

Global productivity algorithms require, in addition to vertical distribution of phytoplankton standing stocks (as approximated by chlorophyll concentration), information of the depth of the mixed layer (as determined by CTD profiles), and photosynthetically active radiation (PAR) levels at the bottom of the mixed layer (e.g. Behrenfeld and Falkowski, 1997). At present, these parameters are poorly constrained by satellite observations. The PALACE floats as proposed herein will provide both the depth of the mixed layer and the vertical distribution of phytoplankton standing stock (based on both scattering and fluorescence). The third parameter, PAR at the bottom of the mixed layer, can also be measured with appropriately equipped floats. In an analogous demonstrational test with profiling floats in the Sea of Japan, spectral downwelling irradiance profiles at three wavelengths were measured every few days over a period of several months (Mitchell et al., 2000). We believe that the community goal of determining primary productivity on regional and global scales could be accelerated by having access to both satellite surface measurements and vertical profiles of optical properties collected by a network of PALACE floats. The ability to measure both phytoplankton biomass and POC (through the empirical relationships with light scatter, *sensu* Bishop and others) would also allow a more direct coupling between primary productivity and the flux of carbon to the deep sea.

Added links to NASA's mission

The measurements proposed here will allow us to obtain global distributions of particulate matter and phytoplankton in four dimensions. These data will provide input for assimilation into global carbon models (cf. Sarmiento and others).

Global distribution of chlorophyll fluorescence and backscattering coefficients should also provide excellent validation data for remote sensing platforms (e.g. SeaWIFS, MODIS), enhancing their accuracy and contributions to understanding the global carbon cycle. The remotely sensed reflectance is strongly dependent on the backscattering to absorption ratio (e.g. Gordon et al., 1988). Knowledge of the backscattering coefficient allows a more accurate determination of the absorption coefficient than could be carried out by inversion of satellite data only. More accurate absorption determinations can play a role in productivity models. In combination with chlorophyll fluorescence from the floats, some physiological information related to quantum efficiency could be obtained.

Besides enabling calculations of production and fluxes on global scales, this effort will establish on global scales the relationship in the upper ocean between gradients in physical properties and gradients in optical properties. As such, this effort can also provide important input for projects such as NASA's proposed Mixed Layer Lidar, which depends for determination of the mixed layer depth on a change in particulate, and hence optical properties, at the top of the thermocline.

Community involvement

We stress that our proposal is a feasibility study: to demonstrate the ability of PALACE floats to collect optical data of interest to biological, optical, chemical, and carbon modeling communities; to provide test data sets that will be posted on the web to document the value of vertical profiles of chlorophyll fluorescence and light scatter; and to convince the physical oceanographic community that these measurements can be made in tandem without compromising the quality of the physical measurements or the ARGO mission.

BACKGROUND

The ARGO Program.

The ARGO program consists of a broad-scale global array of profiling floats (Fig. 2), planned as a major component of the ocean observing system. The main objectives of ARGO are:
1.To provide a quantitative description of the evolving state of the upper ocean and the patterns of ocean climate variability, including heat and freshwater storage and transport.
2. To enhance the values of the Jason altimeter through the measurements of subsurface vertical structure of temperature and salinity, and reference velocity.
3. To initialize ocean and coupled forecast models, data assimilation, and dynamical

model testing.
4. To determine seasonal to decadal climate variability and predictability.

The design of the ARGO network will provide approximately 100,000 vertical profiles per year from about 3000 floats distributed over the global ocean at 3-degree spacing (Fig. 3). Floats will cycle to 2000m depth every 10 days (Fig. 4) with a 4-5 year lifetime for individual floats. All ARGO data will be made publicly available in near real-time and in a scientifically quality-controlled form with a few months delay.

ARGO and biogeochemical measurements

In a recent 'Sensor Technology for Remote, Interactive Aquatic Experiments Workshop and Special Session' conducted following the ASLO Copenhagen meeting, concluded with a report (http://www.soc.soton.ac.uk/OED/gxg/Sensors_Workshop.pdf) stating that:

> *There was consensus among the workshop participants that development and validation of chemical and biological sensors were urgently needed. Lack of inexpensive and reliable sensors generally limit chemical and biological observations. For example, 3,000 profiling floats will be deployed as part of the ARGO Program (www.ARGO.ucsd.edu) to monitor global changes in ocean temperature and salinity as part of a climate observing system. The inability of biogeochemists to utilize these floats was perceived as a tremendous missed opportunity to link physical, chemical, and biological processes to climate variability*.

The design of the ARGO floats allows for deployment with auxiliary sensors. If we can convince the ARGO science team in particular and the physical oceanography community in general that the auxiliary sensors will not compromise their mission, the ARGO opportunity may *not* be missed. In addition, there exist tested, robust, and inexpensive sensors which measure important biogeochemical parameters that can be deployed on the ARGO floats. Examples of such sensors are described below.

A meeting to discuss a strategy for placing bio-optical sensors on ARGO drifters is being organized by Dr. J. Marra of NASA for the next ASLO meeting in Feb 2001. It is our intent to be involved in this community initiative and to contribute the fruits of this proposed study to a future community-wide initiative.

The partnership

Dr. Perry, Dr. Zaneveld and Dr. Boss have been collaborating successfully (with Dr. C. Ericksen of UW) as part of a NOPP project to incorporate bio-optical sensors into autonomous gliders. Fluorescence measurements have been successfully made during glider missions and a novel dual scattering-fluorescence sensor is currently being incorporated to the glider with initial tests due in Feb-March 2001. We expect the addition of Dr. Riser, a world renown autonomous float expert, to strengthen and enrich this partnership.

TECHNICAL APPROACH

Satellites can provide horizontal distributions of bio-optical parameters. Vertical structure must be obtained by other means. Significant scientific information can therefore be obtained from instrumenting PALACE floats with bio-optical instrumentation and combining the data output with remote sensing observations.
Ultimately it is hoped that bio-optical sensors can be added to a large number of PALACE floats. Before that can be done, is necessary to carry out pilot projects to demonstrate the feasibility. Obvious concerns are power supply, data transmission and bio-fouling, which we propose to address here. The use of diffuse irradiance profilers has already been demonstrated in the Sea of Japan (Mitchell et al., 2000). Chlorophyll fluorescence and light scattering measurements have not yet been integrated into floats. These parameters are closely related to chlorophyll concentration and total suspended mass of particulates, respectively. They can be measured with very low power consumption, all-solid state devices. We propose here to instrument and field test two PALACE floats. Future, much larger, programs will decide on the configuration, quantity, deployment, etc. of a larger fleet of floats. The intent of this proposal is to gain time so that a larger proposal that will be submitted by a broader cross section of the bio-optical community, that inevitably will take a fairly long time to develop, can be based on realistic engineering, scientific, and cost parameters. Realistic parameters based on actual tests will allow us to make a more reasoned appeal for the inclusion of bio-optical measurements in a global float plan. We also wish to demonstrate that biogeochemical sensors can be added to the PALACE floats without degradation of the physical oceanographic measurements, in order to remove potential resistance to the inclusion of the sensors.

PALACE Floats

Currently, Dr. S. Riser (a co-PI) has funding from Pilot-ARGO until Oct. 2001 to deploy approximately 50 floats in the North East Pacific and Atlantic Oceans. He will instrument and deploy an additional two floats equipped with optical sensors, purchased under this proposal (the floats are *not* part of the ARGO program, though they are of similar design). A number of developments underway make a pilot study in 2001 feasible:
1. Power: likely to change to Lithium batteries, thus extending the life of the floats and removing much of the power constraints for ancillary instrumentation. This modification is likely to occur by summer 2001.
2. Controllers: the internal controllers of the floats are being replaced by units that allow easy integration of ancillary sensors such as the chlorophyll fluorescence and light scattering sensors proposed here.

Sensors

The sensor proposed for this effort is a combined chlorophyll fluorescence and light scattering instrument. This instrument has a diameter of 5 cm and is about 3 cm thick (Fig. 4). It can be mounted with a copper shutter to prevent biofouling. This sensor will be similar to the one that is being developed under NOPP funding for Dr. M. J. Perry and

Dr. C. Eriksen in collaboration with WET Labs (Eriksen et al., 2000, talk to be presented at Decembet 2000 AGU meeting; Perry et al., 2001, talk to be presented at the February 2001 ASLO meeting). Figure 4 shows the design of the device. It uses a blue LED to excite chlorophyll fluorescence. An infrared LED is used as a source for light scatter. Both fluorescence and light scatter are detected by the same red-infrared sensitive detector (which includes electronics to reject ambient light). It has been shown (Bishop et al., 1999) that the beam attenuation coefficient is well correlated with POC concentration. Light scattering and beam attenuation measurements in the open ocean were compared by Gardner et al. (1985), who showed an r = 0.93. The scattering sensor employed in that study is a different design than the one employed here. It can be shown that when the particulate properties do not change (concentration only changes), beam attenuation and light scattering are perfectly correlated (Zaneveld, 1973).

The sensors will have a flat surface and will not affect the hydrodynamics of the float. Power consumption will be tens of milliwatts. Because the floats spend very little time at the surface, biofouling should not be a major problem. Floats that have been deployed for several years have shown little fouling of the conductivity cell, and no biological growth on the float besides what looked like a thin bacterial film (D. Swift, personal communication). The sensors will be all solid state and will be potted in epoxy. Solid state optical sensors have shown exceptional stability over time. The optical sensor's stability will be monitored as part of this project with respect to the properties in the deep water. It is possible to equip the sensor with a copper shutter to prevent biofouling. Though we do not anticipate using one, future missions may require it. The sensors are equipped with internal boards that average the data over a pre-set sampling period, apply correction and calibration, and output the data as a serial stream and in scientific units.

Future sensors

We are in the process of designing new low-power solid-state flat face sensors that will measure other optical properties to assist in estimation of other biogeochemical parameters. These sensors will have similar characteristic to those in Fig. 4 and would integrate in the same manner with the PALACE float. We anticipate a working version of these sensors to be available within a year. We also anticipate a large reduction in the sensors cost with the increase in the quantity produced. For example, the LSS, a solid-state scattering sensor manufactured by WET-Labs, costs approximately $900.

Data telemetry

Currently the PALACE floats telemeter data to ARGOS requiring a long stay at the surface (as much as 10hrs) and significant data compression (currently down to about 350 bytes of CTD data). In order not to significantly affect the physical oceanography mission, the bio-optical data should be less than 30% of the physical data volume. This requires new approaches to data compression, with on board processing. We propose to study this problem by using a functional fit to the data on board and sending to ARGOS the coefficient of these fits together with measures of the maximum error and the

standard error of this fit. Using historical data of distribution we will evaluate the best types of fit to use (e.g Chebychev polynomials).
Future mission could and should be equipped with higher bandwidth data communication options (e.g. GlobalStar of Qualcomm and Orbcomm). However, at the time this proposal was written, none of these options seems viable, given the financial problems of the companies involved. In addition, by virtue of the two-way communication, adaptive sampling may be possible in the future.

WORK PLAN AND MANAGEMENT APPROACH

This research will be carried as a joint collaboration between the Environmental Optics Group at Oregon State University, WET Labs, the University of Washington and the University of Maine. The overall effort will be coordinated at Oregon State University by the Principal Investigator (E. Boss).

The optical sensors are being developed by WET Labs under a NOPP contract to Dr. M. J. Perry (U. of Maine) and will be delivered in February of 2001. They will be thoroughly tested and will be deployed on an autonomous glider by April 2001.

The floats will be build and deployed Dr. S. Riser (U. of Washington).

The mission will be divided into five main parts:

1. Optical sensor integration into floats (lead U. of Washington in collaboration with WET Labs).
2. Development of data transmission protocol for high and low data transmission floats (lead OSU in collaboration with U. of Washington).
3. Testing of sensors and data transmission (lead U. of Washington in colaboration with WET Labs and OSU).
4. Float deployment (lead U. of Washington).
5. Data analysis (lead OSU in collaboration with WET Labs, U. of Maine and U. of Washington).

Dr. Perry, Dr. Zaneveld and Dr. Boss have been collaborating successfully as part of a NOPP project to incorporate of bio-optical sensors into autonomous gliders. We anticipate the addition of Dr. Riser to strengthen and enrich our collaboration.

SCHEDULE

The integration of the sensors to the floats and the development of the transmission protocols will take place in the summer of 2001. Testing and deployment will take place in the fall of 2001. Analysis will start as soon as the first profile is transmitted from the floats.

Data Management

All the data from the floats will be placed on the web in near real time. All the optical data will be quality checked at OSU (E. Boss) and will be merged to the physical data processed by the U. of Washington (D. Swift). Data will be submitted to SeaBASS in the required format

REPORTS

The results of this research activity will be reported in the form of a data report (to be made available online), a final report from each institution, and as reprints of articles prepared for submission to refereed journals.

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FIGURES

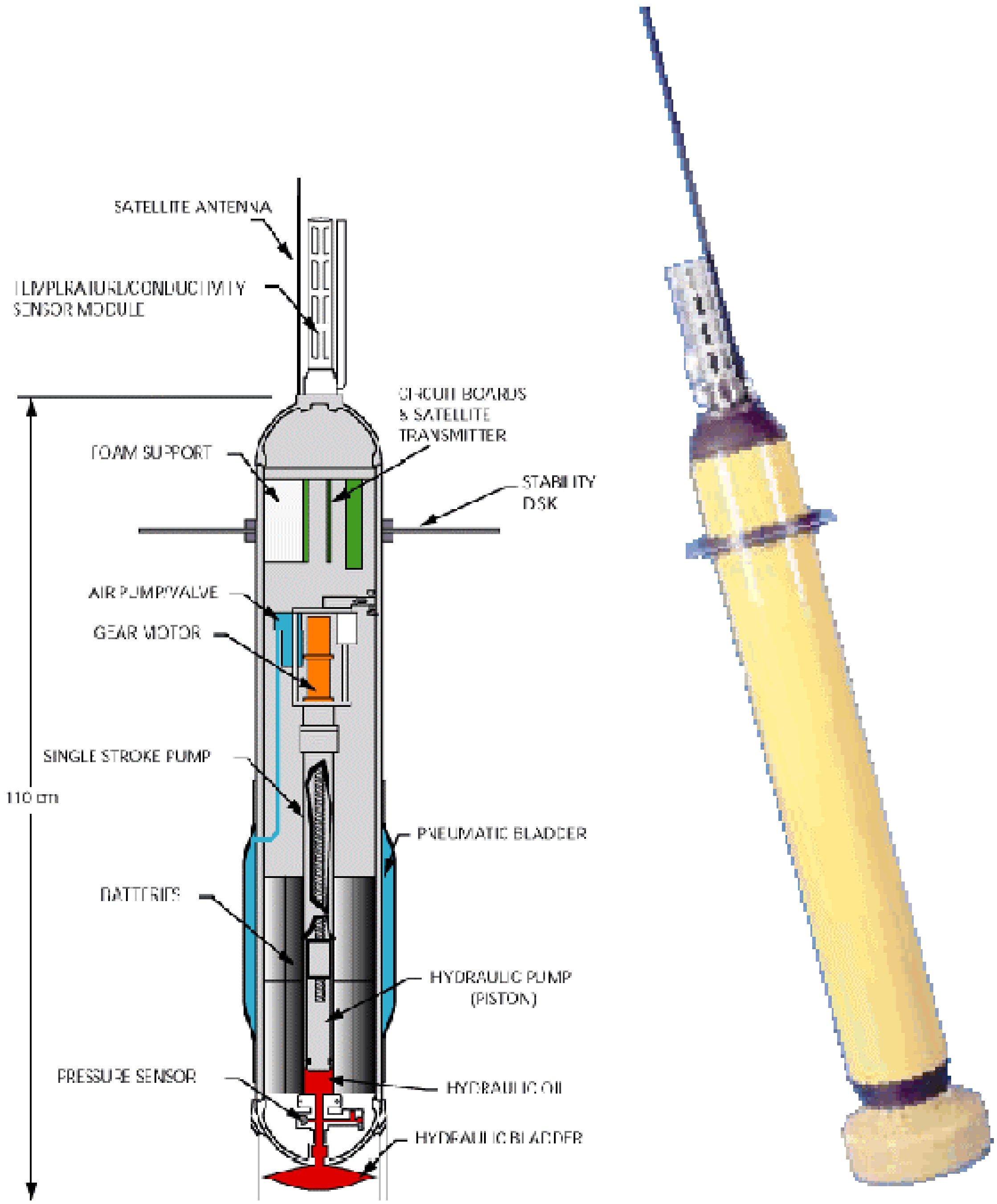

Figure 1: Schematic of a PALACE float to be used in ARGO (left) and an assembled float (right). From Wilson (2000).

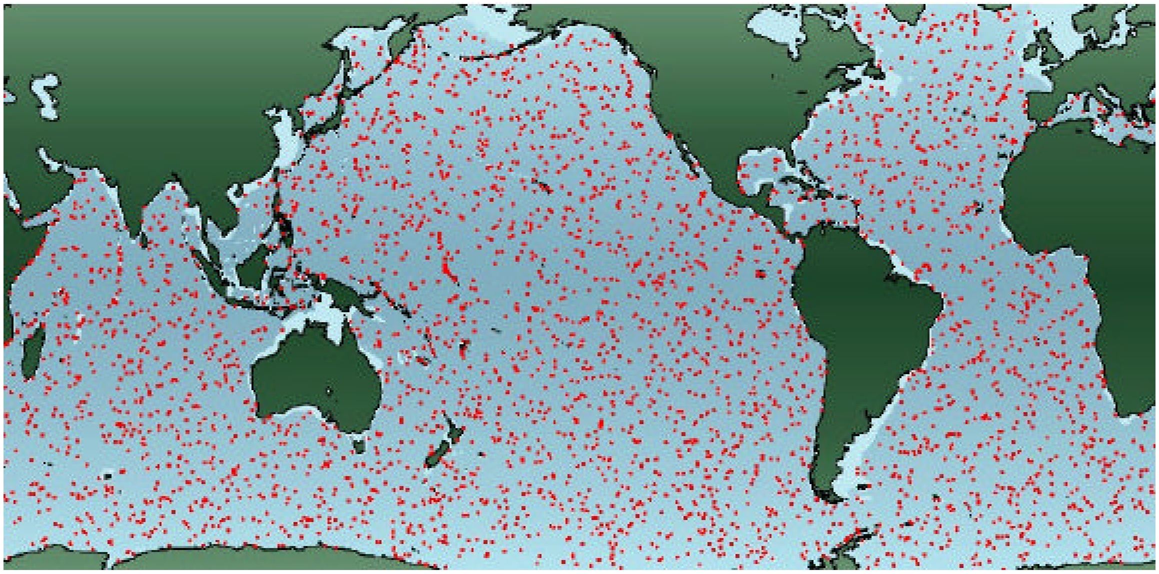

Figure 2: Hypothetical random distribution of 3000 floats on the world ocean (the ARGO array), expected to be in place by 2005. From Wilson (2000).

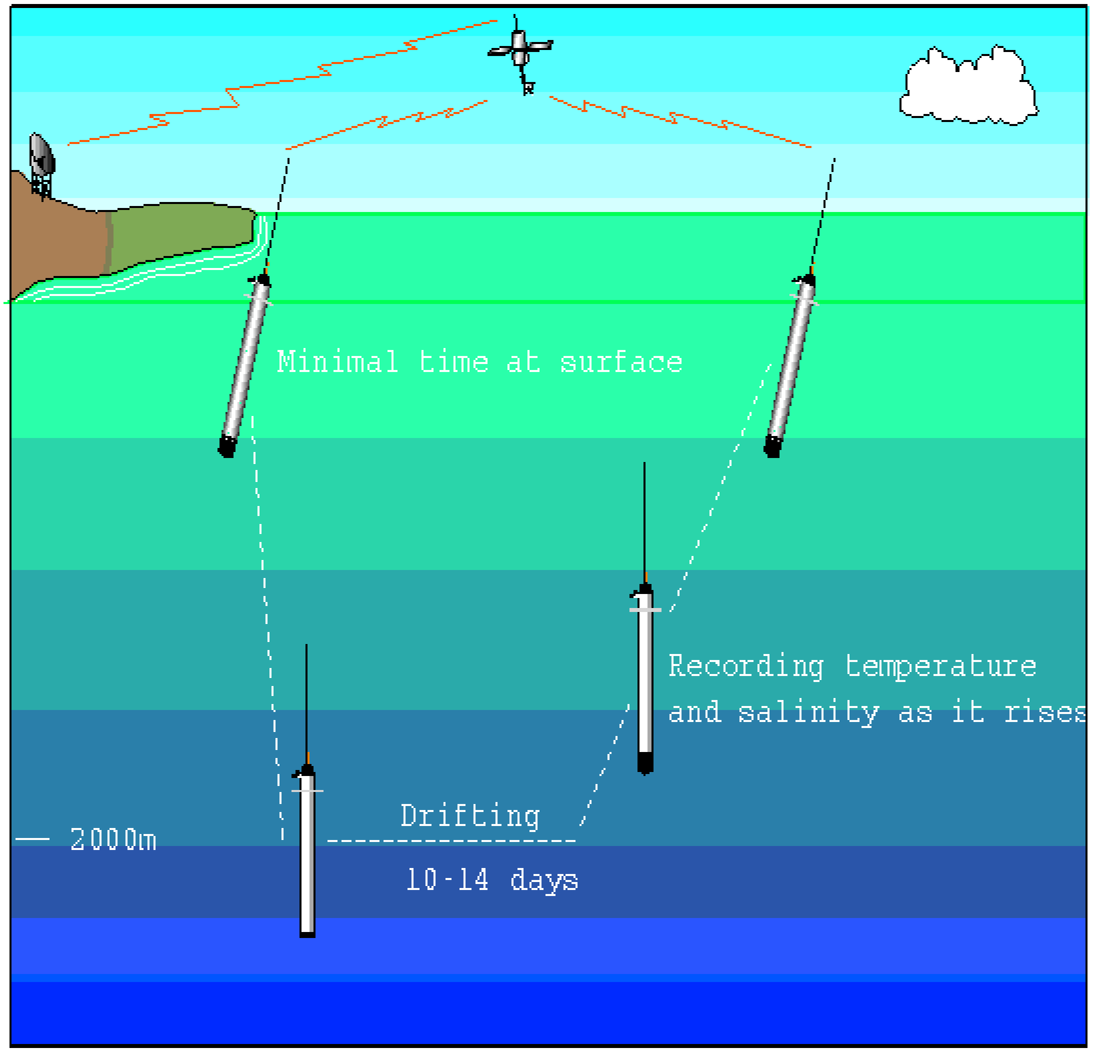

Figure 3: A typical mission of an ARGO float. From Wilson (2000).

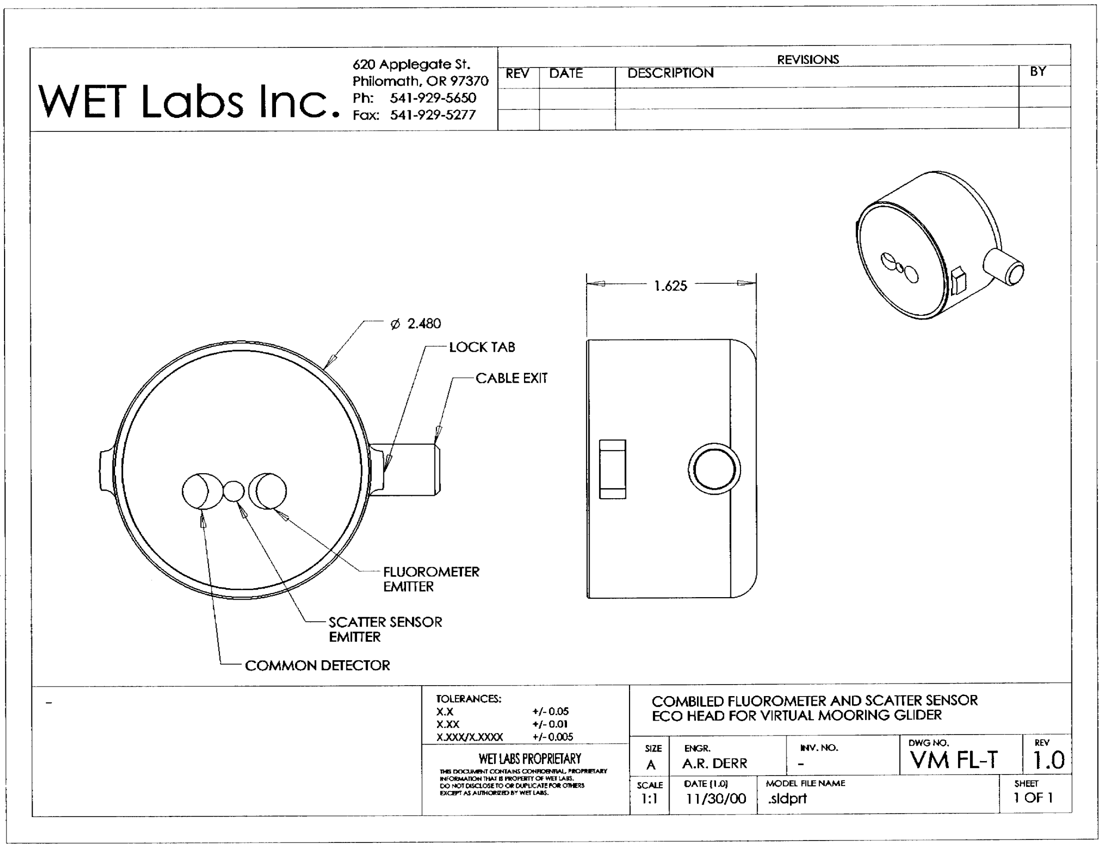

Figure 4: Schematic of fluorescence and backscattering sensor.