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# Collaborative Research: Incorporation of Sensors into Autonomous Gliders for 4-D Measurement of Bio-Optical and Chemical Parameters

Mary Jane Perry
*Principal Investigator; University of Maine, Orono*, perrymj@maine.edu

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**Principal Investigator:** Perry, Mary J. **Award ID:** 9911037

**Organization:** University of Maine

**Title:**

Collaborative Research: Incorporation of Sensors into Autonomous Gliders for 4-D Measurement of Bio-Optical and Chemical Parameters

## Project Participants

### Senior Personnel

**Name:** Perry, Mary

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

**Name:** Moore, Casey

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Lead Project Engineer on optical sensor development; Subcontractor at WET Lab

**Name:** Zaneveld, Ron

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Subcontractor at WET Labs; theoretical design of optical sensors

**Name:** Boss, Emmanuel

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Subcontractor at Oregon State University; field interpretation of optical dat

**Name:** Newton, Jan

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Subcontractor at Washington State Department of Ecology; field testing of oxygen senso

**Name:** Karp-Boss, Lee

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

She was involved in calibration and evaluation of backscattering sensors.

### Post-doc

### Graduate Student

**Name:** Sackmann, Brandon

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Analysis of glider data from Washington Coast

**Name:** Thompson, Brian

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

He provided chlorophyll data and tested sensors in the local marine waters.

**Name:** Carter, Caleb

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

He provided engineering assistance with sensors.

**Name:** Rehm, Eric

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

He participated in field experiments in which we analyzed solar quenching of fluorescence.

**Undergraduate Student**

**Technician, Programmer**

**Name:** Boss, Julia

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Subcontractor at Washington State Department of Ecology; field measurement

**Name:** Strubhar, Wes

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

technical support for sensor development of optical sensors

**Name:** Kallin, David

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Sensor evaluation and calibraton

**Name:** Kallin, Emily

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

She grew phytoplankton cultures and ran laboratory/field calibrations of chlorophyll sensors.

**Other Participant**

**Research Experience for Undergraduates**

## Organizational Partners

**Oregon State University**

no longer a partner

**WET Labs, Inc.**

Development of optical sensors

**Washington Department of Ecology**

**University of Washington**

## Other Collaborators or Contacts

Collaboration with Dr. Craig Lee, University of Washington, in this project. He is involved with other glider deployments.

## Activities and Findings

**Research and Education Activities: (See PDF version submitted by PI at the end of the report)**

Please see attached pfd file

**Findings: (See PDF version submitted by PI at the end of the report)**

Please see attached pfd file

**Training and Development:**

During the last year, four graduate students and one high school student worked on various aspects of the project and learned instrument calibration skills, optical techniques, data analysis, MATLAB, oral presentation skills and manuscript preparation. Data from Seaglider was used in classroom situations at the University of Maine and was made available to a group of six high school teachers who worked for several weeks in summer 2004 and 2005.

**Outreach Activities:**

The PI has given a number of talks to the general public (environmental monitoring groups) on autonomous monitoring of the environment and the role of ocean color in sensing the changes in phytoplankton concentration in the ocean. The PI has participated in meetings with the marine resources community in Maine. K-12 groups routinely visit the Darling Marine Center. My laboratory group provides hands-on learning to these students by involving them in chlorophyll and optical measurements, and relating these to glider measurements. The PI lectured in the local high school.

## Journal Publications


Boss E. and W. Scott Pegau, 2001., "The relationship of light scattering at an angle in the backward direction to the backscattering coefficient.", Applied Optics, p. , 5503, vol. 40, (2001). Published

Rudnick, D.L., R. E. Davis, C. C. Eriksen, D. Fratantoni, and M.J. Perry, "Underwater Gliders for Ocean Research.", Mar. Tech. Soc. J, p. , vol. , ( ). Submitted

Daly, K. L., R. H. Byrne, A. G. Dickson, S. M. Gallager, M. J. Perry, and M. K. Tivey, "Chemical and biological sensors for time-series research: Current status and new directions", Mar. Tech. Soc. J., p. 121, vol. 38, (2004). Published

Perry, M.J., and D.L. Rudnick, "Observing the Ocean with Autonomous and Lagrangian Platforms and Sensors (A:PS): the role of ALPS in Sustained Ocean Observing Systems", Oceanography, p. 31, vol. 16, (2003). Published

Daly, K.L, R.H. Byrne, A.G. Dickson, S.M. Gallager, M.J. Perry, and M.K. Tivey, "Chemical and Biological Sensors for Time-Series Research; Current Status and New Directions.", J. Mar. Tech. Soc., p. 73, vol. 38, (2004). Published

Sackmann, B. S., and M. J. Perry, "Ocean color observations of a surface water transport event: Implications for Pseudo-nitzschia on the Washington coast. Harmful Algae.", Harmful Algae, p. , vol. , (2006). Accepted

Perry, M.J., C.C. Eriksen, B.S. Sackmann, adn C. M. Lee, "Autonomous glider observations of an extensive thin sheet in Washington coastal waters in June 2004 AND other manuscripts", Applied Optics, p. , vol. , ( ). in preparation

## Books or Other One-time Publications

Rudnick, D.L., and M.J. Perry, "ALPS: Autonomous and Lagrangian Platforms and Sensors, Workshop Report", (2003). Workshop Report, Published
Bibliography: Workshop Report, 64 pp.,
www.geo-prose.com/ALPS

## Web/Internet Site

**URL(s):**

**Description:**

## Other Specific Products

**Product Type:**

**Instruments or equipment developed**

**Product Description:**

Under the auspices of the partnership sponsored by this project, WET Labs developed a minaturized optical sensor for incorporation in ocean observing systems. It is small, robust, has low power consumption, and allows flexiblity in manufacture of various combinations of fluorescence and optical backscattering.

**Sharing Information:**

This instrument is commerically available through WET Labs and is being used on other oceanographic platforms. The development of this sensor is a major accomplishment of the grant and will continue to contribute to ocean observing activities for many years.

**Product Type:**

**Data or databases**

**Product Description:**

A large database of optical biogeochemical proxies was collected and organized by this project, and in collaboration with University of Washington partners.

**Sharing Information:**

The process data are being posted to the laboratory web site, and have been given freely to other oceanographers and K-12 teachers.

## Contributions

**Contributions within Discipline:**

The development of these miniaturized sensors have allowed biogeochemical variables to be measured on autonomous underwater vehicles on the same time and space scale as the physical variables. The inclusion of small, low-power optical sensors on underwater gliders presents a new capability that is providing unprecedented views of the distribution of phytoplankton and particles as a function of space and time. In addition, the sensors developed under this project are being used for a number of other applications for sustained ocean observing, including incorporation on profiling ocean floats and drifters, powered AUVs, moorings and shipboard monitoring of phytoplankton biomass. Because this new sensor is small and energy-conserving, it is having a significant positive impact on ocean observing systems and on pollution monitoring.

**Contributions to Other Disciplines:**

Direct measurement of subsurface distributions of marine phytoplankton, the primary photosynthetic organisms in the ocean, will contribute to an improved understanding of global carbon cycling. The ability to observe the evolution of blooms, such as noxious algal, in both freshwater and marine systems will contribute toward protecting environmental health. The massive amounts of spatial/temporal data are intriguing to geospatial statisticians, potentially leading to new analysis methods.

**Contributions to Human Resource Development:**

The concept of an underwater glider, operating autonomously, captures the imagination. The glider and the data collected on glider missions are intriguing way to engage students in ocean exploration. A Maine high school student, because of her internship in my laboratory, is now firmly launched in a science major at Carleton College; she plans to return to my lab this summer. A graduate student from Computer Sciences and Engineering who worked on the project this summer is now being jointly advised by me and a CSE facility to work on glider data visualization; he otherwise would not have explored ocean sciences applications. Three other graduate students have been exposed to and excited by the science enabled by gliders. Through a presentation of glider results and ensuing dialogues with a high school science teacher in Maine, a new collaboration has been launched that will improve the teacherÆs first-hand understanding of how science and technology interact. He will bring fresh ideas to his classroom and I will benefit from techniques he learned through his years of teaching.

**Contributions to Resources for Research and Education:**

As part of the collaboration between the University of Washington and the University of Maine, construction of Seagliders was supported by this project. They are being used as a base infrastructure for a continuation project now in progress.

**Contributions Beyond Science and Engineering:**

The NOPP project has already had a positive impact on a small business with the commercialization of the bb2f optical sensor. Other optical sensors resulting from this project are also being commercialized as new products. The small, robust, power-stingy sensors developed to meet the stringent requirements of Seaglider are proving valuable in other ocean observing activities, including on other gliders, profiling floats, and moorings.

The incorporation of interdisciplinary gliders in coastal monitoring will make a significant contribution to tracking pollution and providing early warning for harmful algal blooms. A better understanding of the ecosystem, measured on the space and time scales that are important to organisms, should also contribute to improving marine resources management strategies.

**Categories for which nothing is reported:**

The specific goal of this project was to develop autonomous underwater gliders with the capability of measuring ocean biology, chemistry and physics in four-dimensions and for extended periods of time. The long-term goal is development of distributed networks of gliders that operate as autonomous sensing systems in both the coastal and global ocean. The University of Maine components of this collaborative project with the University of Washington (Eriksen) were: 1) to develop a new generation of optical sensors that were sufficiently small to be incorporated in underwater gliders and that had minimal power requirements; 2) to characterize the optical sensors and interpret their data in a diversity of field environments; and 3) to demonstrate the unique scientific utility of a sustained glider program off the coast of Washington State, USA, and its application in future ocean observatories.

One of the major accomplishments of this partnership was the development by WET Labs – specifically for this project – of a versatile and robust miniaturized optical sensor for incorporation into Seaglider. The prototype sensor measured chlorophyll fluorescence (a proxy for phytoplankton biomass) and optical backscatter at two wavelengths (a proxy for particle concentration). This prototype sensor had two LED light sources, one blue and one infrared, and two detectors. With support from this project, miniaturized sensor development continued with several major improvements in performance and reductions in power consumption. The latest version is a versatile "triplet" sensor with three pairs of LED sources and detectors, allowing the user maximum flexibility to choose from a combination of fluorescence (chlorophyll or CDOM) and optical backscattering wavelengths. The power consumption has been further reduced with the newest board set. The WET Labs sensor, commercially available as the ECO puck, is highly regarded by the oceanographic community and has been incorporated into gliders at Woods Hole Oceanographic, Rutgers, the Navy and elsewhere, as well as into powered AUVs and moorings.

During previous years we made advancements in the interpretation of chlorophyll fluorescence and optical backscattering signals. We characterized the behavior of the fluorescence sensor in diverse environments, particularly focusing on the solar quenching of fluorescence. When living phytoplankton cells are exposed to bright light, particularly during mid-day, chlorophyll fluorescence is chemically quenched within the cell. The consequence is a decrease in the fluorescence-to-chlorophyll ratio and a serious bias in the computed, apparent chlorophyll concentration. By analyzing the temporal pattern of the fluorescence-to-backscattering ratio in the mixed layer, we were able to develop an algorithm to account for fluorescence quenching and thereby minimize the error in chlorophyll concentrations computed from near-surface samples with fluorescence quenching. Using this algorithm we were able to obtain an excellent match-ups between glider chlorophyll (derived from fluorescence) and satellite ocean color estimates of chlorophyll (Figure 1). We also previous demonstrated, using scattering theory and field data, that the backscattering coefficient can be estimated from scattering at a single angle in the back direction. In the last year of this project we conducted experiments to link solar quenching of fluorescence with variable fluorescence, a tool to probe photosynthetic quantum yield. These results will allow us to better use the Seaglider fluorescence signal to model primary productivity.

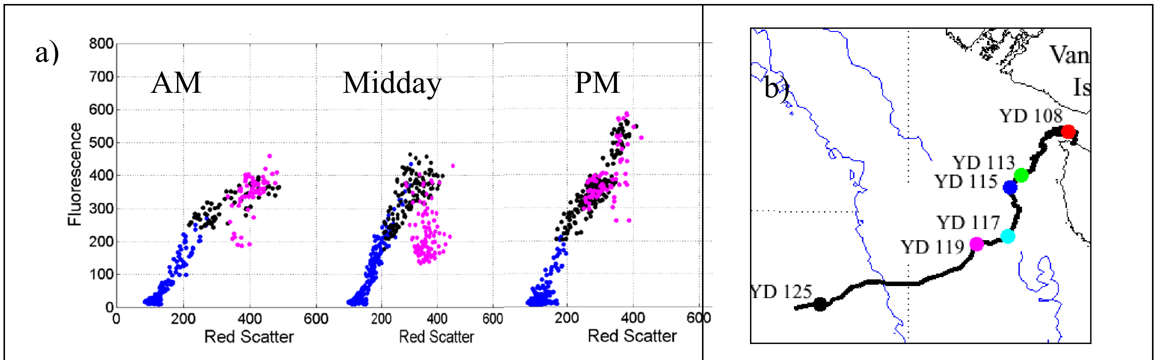
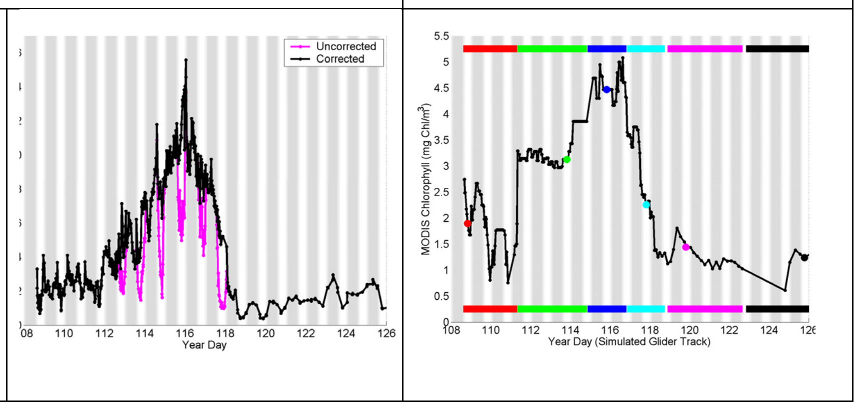



Figure 1.
a) Phytoplankton in upper 5m (pink) exhibit midday quenching;
b) Location of MODIS images that are coincident with glider profiles;
c) Uncorrected near-surface fluorescence (black);
d) MODIS chlorophyll.




The longest continuous glider missions – in excess of five months of continuous operation – have been carried out under the auspices of this grant. Seaglider has been deployed off the Washington coast almost continuously since August 2003. Using these data we have begun to build a climatology for the Washington coast and link it to satellite imagery. The data collected has allowed us to observe the seasonal cycles of phytoplankton in coastal and offshore waters, including the evolution and demise of the deep chlorophyll maximum layer (Figure 2). Ephemeral features such as thin layers of phytoplankton have been observed, including an extensive thin sheet that extended for almost 100 km and persisted for over two weeks (Figure 3). An unusual movement of a cyclonic eddy into slope waters occurred in autumn 2004. By combining SeaWiFS surface imagery and Seaglider optics, we were able to generate a comprehensive four-dimensional view of the distribution of phytoplankton in these waters (Figure 4). Fluorescence data from daytime dives, particularly during weakly stratified times of the year, exhibited secondary structure in the vertical patterns; in addition to fluorescence quenching at the surface, we also observed layers of subsurface reduction in fluorescence but not in optical backscattering. We now interpret these as manifestations of Langmuir turbulence; the depressions in fluorescence are due to cells that have recently been at the surface, and hence exhibit photoquenching (Figure 5). Data analysis is continuing with a goal of providing a better insight into phytoplankton processes.

Four graduate students (three from the University of Maine and one guest student from the University of Washington) and one high school student gained research experience working on this project. Data from Seaglider was used in classroom situations at the University of Maine and was made available to a group of six high school teachers who worked for several weeks in summer 2004 and 2005.

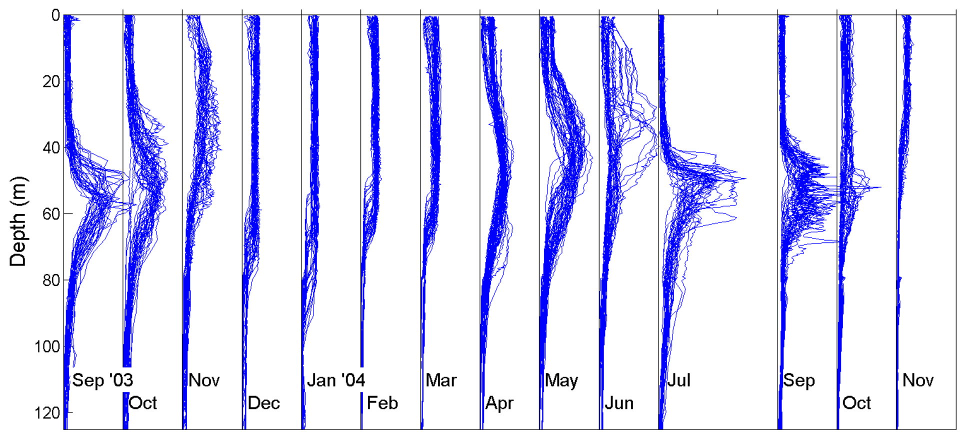



Figure 2. Profiles of chlorophyll fluorescence at the end of the "V" (transect in Fig. 3b) from September 2003 to November 2004.

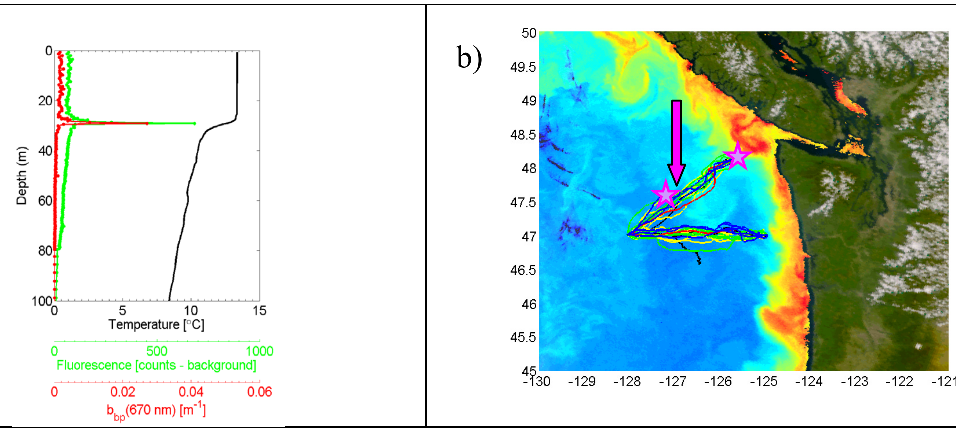
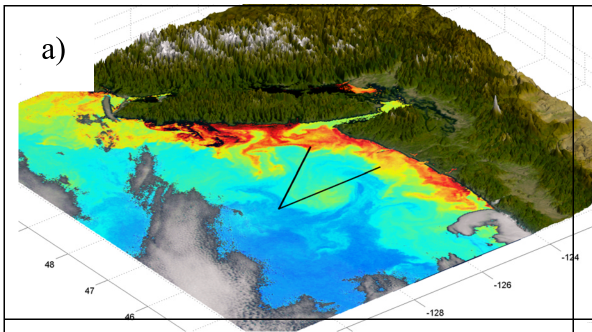



Figure 3. a) Seaglider profile from 14 June 2004 off the Washington coast showing a thin layer of chlorophyll fluorescence (green) and backscatter (red) located at the thermocline (black).
b) Multiple Seaglider repeat transects, overlain on SeaWiFS image; arrow indicates location of profile in "a"; stars indicate horizontal extend of thin sheet observed in June 2004 deployment.

a)



b)

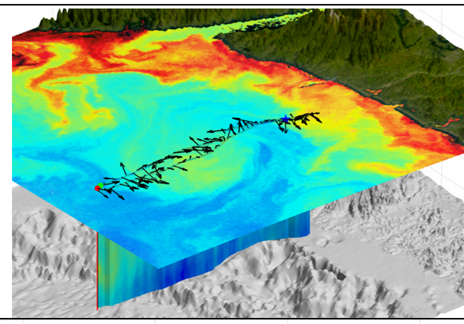


Figure 4. a) SeaWiFS image from 4 October 2004 with Seaglider V-transect. b) Surface velocity vectors for two legs of Seaglider transect in late September–early October. c) Subsurface phytoplankton distribution from in-bound Seaglider transect.

c)

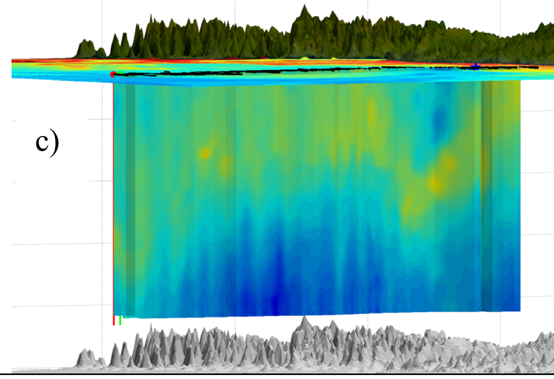
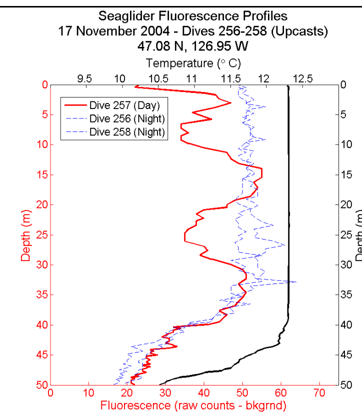
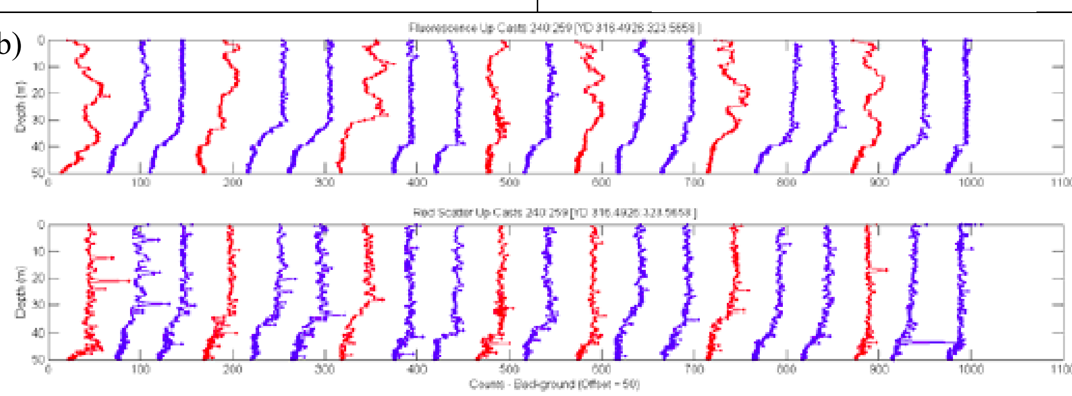


Figure 5. a) Seaglider vertical profiles of chlorophyll fluorescence; red is daytime profile and blue are nighttime. The daytime fluorescence exhibits surface quenching, but also subsurface quenching, due to displacement of cells by Langmuir turbulence.
b) Seaglider vertical profiles of chlorophyll fluorescence (upper) and optical backscatter (lower); red are daytime profiles and blue are nighttime. Only daytime fluorescence profiles (red, upper) exhibit vertical structure.

a)




b)



Our major findings are:

1) Gliders work! They are capable of observing selected oceanographic and biogeochemical variables completely autonomously and for sustained periods of time. This mode of ocean observing provides a unique window to observe climate change and episodic events.

2) Miniaturized optical sensors work! They provide proxies for biogeochemical varies – phytoplankton biomass, particle concentration, and away from sources of terrigenous sediment, particulate organic carbon. The sensors developed under this project have become "the" optical sensor of choice for gliders, AUVs, moorings, and profiling instruments.

3) Biases in phytoplankton biomass estimates due to the solar quenching of fluorescence can be corrected by using fluorescence–to–backscattering ratios.

4) Changes in solar fluorescence of chlorophyll mirror changes in photosynthetic electron flow (as determined from fluorescence induction kinetic measurements) and suggest that assessments of fluorescence quenching can be used to improve near-surface models of primary productivity.