Measurement of in-situ optical properties

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Some (personal) background

“There is nothing, absolutely nothing half so much worth doing as simply messing around in boats, or with boats. In 'em, or out of 'em, it doesn't matter.” Rat, Wind in the Willows.

Hawaii w/ JAMSTEC
Simply messing around in boats...

Lac LaBiche, w/ Dave Schindler

Off Miami, w/ U.S.N.

Villefranche-sur-mer w/ fishermen

Equatorial Pacific w/ JAMSTEC

Easter Island w/ LOV

Med w/David Antoine

La Have River, w/ my dog.

If the coconuts don’t grow, don’t go.
The fundamental radiometric quantity is the spectral radiance distribution \( L(z,x,y,t,\theta,\phi,\lambda) \), the radiant flux per unit wavelength or frequency interval per unit solid angle per unit of projected area; the usual unit is watt per nanometer per steradian per square meter.

“Spectral radiance is the fundamental quantity of interest in hydrologic optics….all other radiometric quantities can be derived from (this)” Mobley, 1994
\[ L(x, y, z, \theta, \phi, \lambda, t) \]

\[(I, Q, U, V)\]
Background

• In principle, all of the apparent and inherent optical properties as well can be derived from a measurement of the radiance field and its gradient in the upper ocean.
Background

Another good reason for focusing on radiance: Modelling the dynamic radiance distribution is what makes *Avatar* possible (Weta Digital).
The 'Avatar' Sequels Will Use Groundbreaking Underwater Technology

20th Century Fox

When "Avatar" came out in 2009, James Cameron helped reinvent the way both 3D and motion capture are used in film.

Now, he'll be taking that technology one step further in the next two "Avatar" sequels. Producer Jon Landau revealed at the 2013 NAB Technology Summit on Cinema that James Cameron will use motion capture performance in water in the upcoming sequels.

"We could simulate water [in computer graphics], but we can't simulate the actor's experience, so we are going to capture performance in a tank," said Landau.
And if you need another good reason...
Background

Solution – measure the radiance distribution simultaneously in $x, y, z, t$, all angles, all wavelengths, and all polarization components.

A caveat: Life consists of trade-offs.
Background (2)

- The radiance field in the ocean is set first at the surface by that of sun & sky, and by the nature of the air-sea interface.

- In the ocean interior, the radiance field is further modified by the inherent optical properties (the absorption coefficient, the volume scattering function), various "inelastic scattering" processes (e.g. Raman, fluorescence), and internal sources (e.g. bioluminescence).
Losses due to absorption & scattering ($c=a+b$).

Gains due to photons scattering in (involves radiance distribution, and VSF). Also, may be other sources, e.g. Raman, Flu.

\[
\cos \theta \frac{dL(z, \theta, \phi)}{dz} = -cL(z, \theta, \phi) + \int \beta(\theta', \phi' \rightarrow \theta, \phi)L(z, \theta', \phi')d\Omega' + \text{Other Sources}
\]
Some good reasons for measuring variability in the full radiance field,

- Many of the measurements currently made, such as planar and scalar irradiance, angle-dependent Q factor etc., could be made by various integration operations on the measured radiance field rather than with mechanical diffusers.
- The potential interferences of various deployment platforms (e.g. shading, reflectances by ships, buoys and towers) could be measured directly rather than inferred based on inaccurate assumptions about the underwater radiance distribution.
- A direct confirmation of the asymptotic radiance distribution can be made.
- Finally, high quality quantitative (and radiometrically calibrated) measurements of the radiance distribution, and their time and depth (path) derivatives, can in principle (but not yet in practice) be used to estimate all the inherent optical properties (both absorption and volume scattering coefficient) and as well the nature of the air-sea interface.
Despite the fundamental importance of the radiance distribution, it is perhaps surprising that, while this received a great deal of interest in the 50’s and early 60’s, there have been few direct observations in more recent years.
Measurement of Radiance

The Gershun Tube

\[ L(\vec{x}, t, \hat{\xi}, \lambda) = \frac{\partial^4 Q}{\partial t \partial A \partial \Omega \partial \lambda}. \]

Mobley, 1994
Figure 2

Underwater Photometer

* Measuring Head and Positioning Equipment
Data from Tyler

(a) $\Delta \phi = 180 \leftrightarrow \Delta \phi = 0$

(b) $\Delta \phi = +/- 90$

![Graphs showing data](image)
Porcupine

Miroslaw Darecki
Radiance Camera: a hard problem!

First approach was by Ray Smith and John Tyler – a photographic camera with a fisheye lens.

Subsequent solid-state (CCD) versions developed by Voss.

Two recent manifestations using CMOS arrays are the RADCAM (Satlantic) and the camera built by LOV.
RAD-CAM takes advantage of recent advances in CMOS imaging technology to provide operational instrumentation for investigation of the underwater radiance field.

Downwelling field in particular is very challenging, as it can result in a requirement for a scene dynamic range $\sim 10^6$-$10^7$. 
Off Hawaii
Joys of being a graduate student
R/V FLIP

U.S. Navy
Free-falling
Above and below surface downward radiance field
Optical manhole
Surface and Dive
Three primary deployments for the measurement of variability in the underwater radiance distribution:

- Eutrophic, Bedford Basin
- Mesotrophic, Santa Barbara Channel
- Oligotrophic, Hawaii

See Wei et al., 2014 to explain this!

Wave-induced light field fluctuations in measured irradiance depth profiles: A wavelet analysis.
Upwelling spectral radiance distributions, 4 environments (Antoine et al. 2012)
Oligotrophic Environment

Hawaii - Clear Sky

Radiance [\mu W/cm^2/nm/sr]

- >3000
- 1000
- 100
- 10
- 1
- <0.1
- <0.01
- <0.001

10m
20m
30m
40m
48m

10m
20m
30m
40m
48m
Oligotrophic Environment

Irradiances found by integrating radiance fields

\[ E_d = \int L(\theta, \phi) \cos \theta \, d\Omega \]

\[ E_{od} = \int L(\theta, \phi) \, d\Omega \]

\[ E_u = \int L(\theta, \phi) \cos \theta \, d\Omega \]

\[ E_{ou} = \int L(\theta, \phi) \, d\Omega \]
Oligotrophic Environment

\[ \bar{\mu}_d = \frac{E_d}{E_{od}} = \frac{\int L(\theta, \phi) \cos \theta d\Omega}{\int_{E_d} L(\theta, \phi) d\Omega} \]

\[ \frac{1}{E_n(z)} \frac{d(E_n(z))}{dz} = -K_n(z) \]

\[ \nabla \cdot \mathbf{E} = -aE_o + \text{Sources} \]

All quantities calculated from radiance fields
Eutrophic Environment
Bedford Basin, Nova Scotia

Radiance [µW/cm²/nm/sr]

3m
50
100

5m
5

9m
0.5

12m
0.05

15m
<0.005

3m
20

6m
10

9m
1

12m
0.1

15m
0.01

<0.001
Eutrophic Environment

Irradiances found by integrating radiance fields
Eutrophic Environment

All quantities calculated from radiance fields
Time dependency

Profile, Downwelling

Profile, Upwelling
Even with all of this… can we invert for $\beta(\theta)$?

$$\cos \theta \frac{dL(z, \theta, \varphi)}{dz} = -cL(z, \theta, \varphi) + \int_{\Omega} \beta(\theta', \varphi' \rightarrow \theta, \varphi)L(z, \theta', \varphi')d\Omega' + \text{Other Sources}$$

Zaneveld and Pak, 1972?

Other (analytical, numerical) approaches?
Or can we do something really useful???

Avatar II!
Measurement of in-situ optical properties (contd)

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So why do anything other than measure the full radiance distribution??
The RADCAM only has one wavelength. (LOV has several, but not simultaneous)
The RADCAM & LOV cam are insensitive to polarization state (Ken Voss has POLRad with separate cameras, but long integration times)
And all of these are expensive, and unlikely to be widely available.
Life consists of tradeoffs.
More Practical Approaches
Diffuser weights incoming photons as \( \cos(\theta) \)

"Filter could be grating or prism or spectrally variable filter"

Detector could be 2 or 3 D array, e.g. CCD or CMOS

Mobley, 1994

\[
E_d(\vec{x}, t; \lambda) = \int_{\hat{\xi} \in \Xi_d} L(\vec{x}, t; \hat{\xi}, \lambda) |\cos \theta| d\Omega(\hat{\xi}) =
\]
Scalar Irradiance Sensor

Mobley, 1994
Irradiance Sensors

Chelsea Inst.

LiCor

Biospherical

Satlantic

Satlantic
Single Direction Radiance Sensors

Satlantic

Analytical Spectral Devices

GER
Really big radiance sensors...oops!

(Actually...it IS rocket science!)
RaDyO Benign Conditions Experiment
15 September, 2008; 11:09 Local; 18:09 Z
LATITUDE : 34°13.637' N
LONGITUDE : 119°38.110' W
Dalhousie HyperPro

Downwelling Spectral Irradiance

Upwelling Nadir Radiance

Downwelling Irradiance (µW cm⁻² nm⁻¹)

Upwelling Radiance (µW cm⁻² nm⁻¹ sr⁻¹)
RaDyO Benign Conditions Experiment
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Diffuse Attenuation Coefficient ($K_{ED}$ and $K_{LU}$); m$^{-1}$; Mean Upper 10 m +/- 1σ

Remote Sensing Reflectance (sr$^{-1}$)

Pure Water (M&M2001)
IOP’s can be independently measured ("a,b,c’s")

• Attenuation – c
  – ac meter
  – Transmissometer (BAM, c-Star, c-Rover)
• Absorption - a
  – ac meter
• Scattering - b
  – (bb, Hydroscat, Flintu, VSF)
• CTD
  – Conductivity, temperature, depth
Attenuation: theory to measurement

\[
\cos \theta \frac{dL(z, \theta, \varphi)}{dz} = -cL(z, \theta, \varphi) + \int \beta(\theta', \varphi' \to \theta, \varphi) L(z, \theta', \varphi')d\Omega' + \text{Other Sources}
\]

\[
c\Phi = -\frac{d\Phi}{dl}
\]

Differential Equation with solution:

\[
\Phi_\ell = \Phi_0 \exp\left(-\int_0^\ell cd\ell\right)
\]

After integration:

\[
\Phi_\ell = \Phi_0 e^{-\bar{c}\ell}
\]
Beam attenuation meter

Transmitter Housing

Receiver Housing

LED
Aperture
Beam Splitter
Pressure Window
Electronics
Lens
Detector
Bulkhead Connector

Measure of water clarity, POC, particles
Some things to think about….

• Acceptance angle – for C-Star, 1.2 degrees
  • *Important because one would like to exclude forward scattered light.*

• “Reference” or clear-water baseline – clear water is very difficult to “make”, transport, store

• “noise” (signal?) due to individual or aggregates of particles
Methods of measuring absorption in situ

• Collimated source, reflective sample cell with diffuser in front of wide area detector: WET Labs’ ac-s meter

• Capillary waveguide ("breve buster," Kirkpatrick et al. 2000)

• Integrating Sphere, e.g. Hobi Lab’s iSphere
Measuring absorption: Reflective tube method

Reflective tube absorption meter design

Forward scattered light from ~0 to 41.7 degrees is included in the signal measured by the detector.

Adapted from Zaneveld et al. (1992)
Practicalities in measuring absorption with a reflective tube

- Calibration and accuracy practicalities same as c measurement
- Scattered light from $\sim 41^\circ$-180° not measured
  - error usually $\sim 10\%$ of $b$ and there are correction schemes

Or expressed more accurately, there is a weighting function, $W(\theta)$, that defines the scattering error:

$$error = b_{TIR} = 2\pi \int_{\theta_{TIR}}^{180^\circ} \beta(\theta) \sin(\theta) d\theta$$

TIR = Total Internal Reflection

$$error = 2\pi \int_{0^\circ}^{180^\circ} W(\theta) \beta(\theta) \sin(\theta) d\theta$$
More Practicalities

The reflective tube detector does not collect all scattered photons.

A simple approach to correction is to subtract the signal at a longer wavelength (>700 nm) to bring absorption at the longer wavelength to zero.

There are two assumptions that would make this method valid: (1) the absorption is negligible at wavelengths >700 nm, and (2) the scattering error (and hence the absolute scattering) is wavelength-independent.

ac-9 and ac-S

Linear Variable Filters (LVFs)
Point-Source Integrating Cavity approaches (Kirk, 1997)

In principle, no scattering correction required.

PSI-Cam, Rudiger Roettgers

a-sphere, HOBI Labs
Liquid Capillary Waveguide Approaches

Fiber optic cells that combine an increased optical pathlength (50–500cm) with small sample volumes (125–1250µL). They can be connected a spectrophotometer and sensitive absorbance measurements can be performed in the ultraviolet (UV), visible (VIS) and near-infrared (NIR) to detect low sample concentrations.
Scattering

1. Full volume scattering function

2. Scattering at sub-sets of angles
Scattering of light by Sargasso Sea water

GUNNAR KULLENBERG*

(Received 5 February 1968)

This experimental investigation deals with the problem of the scatterance of light by very clear ocean water. The forward scatterance was measured close to a laser beam using a new measuring device. The forward particle scatterance was found to be virtually independent of wavelength, whereas the backward scatterance was dependent on the wavelength. The water investigated has a high degree of clearness compared with other areas. The ratio of scatterance at 45° to total scatterance over all angles was found to vary within narrow limits for different oceanic areas.
The (in)famous Petzoldt measurements (1972)
The “Ukrainian Instrument” MVSM
(as of 2014, Russian..ahem)

1. "Clean" Seawater
2. Kullenberg Sargasso Sea
3. Deionized "Nanopure" Water
4. Halifax Harbor Water

Lee and Lewis, 2003

Zhang et al., 2006
Wide range of variation in coastal, open ocean waters.
Multi-Angle Scattering Optical Tool (MASCOT)

Mike Twardowski, WETLabs
An Instrument for In Situ Measuring the Volume Scattering Function of Water: Design, Calibration and Primary Experiments
Cai Li,1 Wenxi Cao,1,* Jing Yu,2 Tiancun Ke,1 Guixin Lu,1 Yuezhong Yang,1 and Chaoying Guo1

State Key Laboratory of Oceanography in the Tropics, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China;
LISST instruments are based on the small-angle scattering method that is also known as laser diffraction. Scattering from a laser beam is observed at multiple angles. Particle size distributions are estimated from scattering models.
Stokes Vectors & Mueller matrices

If light is represented by Stokes vectors, optical components are then described with Mueller matrices:

\[
\begin{pmatrix}
I' \\
Q' \\
U' \\
V'
\end{pmatrix} =
\begin{pmatrix}
m_{11} & m_{12} & m_{13} & m_{14} \\
m_{21} & m_{22} & m_{23} & m_{24} \\
m_{31} & m_{32} & m_{33} & m_{34} \\
m_{41} & m_{42} & m_{43} & m_{44}
\end{pmatrix}
\begin{pmatrix}
I \\
Q \\
U \\
V
\end{pmatrix}
\]

where I represents the total intensity of the light; and, qualitatively, Q corresponds to the degree of linear polarization in the directions parallel to and vertical to the scattering plane; U to the degree of linear polarization at 45° to the parallel and vertical directions; and V to the degree of circular polarization. Each component of the Mueller matrix \(m_{ij}\) (i=1–4 and j=1–4) can be measured angularly.
Fixed angles in the backward direction - HobiLabs.

Hydroscat 2

Hydroscat 4

Hydroscat 6

Light Emitting Diode
Reference Photodiode
Prism
Instrument Face

Sampling Volume
Fixed angles in the backward direction - WetLabs.

BB-2F measures at 117 degrees at both 470 and 700 nm.

ECO VSF 3 measures the optical scattering at three distinct angles: 100, 125, and 150 degrees, and at wavelengths of 470, 530, and 660 nm.

BB-9 measures at 9 angles or 9 wavelengths or combinations.
How to get backscatter coefficient?

\[ b_b \equiv \int_{2\pi}^{4\pi} \beta(\Psi) d\Omega = 2\pi \int_{\pi/2}^{\pi} \beta(\theta) \sin \theta d\theta \]

Oishi (1990) showed from an analysis of measured and modeled VSF’s that

\[ G(\theta) = \frac{b_b}{\beta(\theta)} \]

changed little from 120 to 150 degrees, with the smallest variation at 120 degrees. Also see: Boss, E. and W.S. Pegau, Relationship of light scattering at an angle in the backward direction to the backscattering coefficient. Appl. Opt., 40, 5503-5507 (2001)
Closure – Bringing it all together

Inverse Problems ("given radiometric measurements of underwater or water-leaving light fields, determine the inherent optical properties of the water. This is very much an unsolved problem. Both conceptual and practical limits are encountered in inverse problems. Unfortunately, remote sensing is an inverse problem.")

Mobley, OceanOpticsWeb
Approach we took
Spectra of particulate backscattering in natural waters.

Howard R. Gordon\textsuperscript{1,*}, Marlon R. Lewis\textsuperscript{2,3}, Scott D. McLean\textsuperscript{3}, Michael S. Twardowski\textsuperscript{4}, Scott A. Freeman\textsuperscript{4}, Kenneth J. Voss\textsuperscript{1}, and G. Chris Boynton\textsuperscript{1}\textsuperscript{201} Optics Express 17: 16192-16208, 2010.

1. Measure, with great care, the vertical profile of hyperspectral downward irradiance, and upward radiance (HyperPro, Lewis and McLean).

2. Measure, with great care, the vertical profile of the absorption coefficient and the backscattering coefficient at several wavelengths (Twardowski and Freeman).

3. Without any tuning or adjustment, assimilate the irradiance and radiance into an advanced Monte Carlo inverse radiative transfer model to obtain high resolution spectra of the absorption coefficient ($a$) and the backscattering coefficient ($b_b$) of the water and its constituents. (Gordon, Boynton, Voss).

4. Compare derived IOP’s with direct measurements (all).
Results (depth profile)

Comparison of retrieved and in-situ vertical profiles of absorption (top at 443 nm) and backscattering (bottom at 462 nm) at the station off Lanai, Hawaii.
Results (hyperspectral)

Wow!! “Closure is in many ways is the Holy Grail of hydrologic optics – always sought, never achieved.” Mobley, 1994
Hindcast opportunities: Secchi Disk

Data available since late 1800’s! Inversely ~ to chlorophyll

South Pacific Gyre, Z~ 72m
Eyeball Optics

All of the things that one might think would interfere – the illumination conditions, sea-state, the nature of the disk, and human-to-human variability – actually have little effect since they are all contained inside the logarithm. The primary source of variability in the Secchi disk depth is the optical properties of the sea, specifically the attenuation of light.

\[ Z_{SD} = \frac{1}{\overline{c} + \overline{K}} \ln \left[ \frac{\zeta(A - R(0))}{R(0)C_l} \right] \]

Background reflectance just below surface
Reflectance of disk
Sea surface effects
Optical Properties of the Sea
Eyeball Response
Prediction skill (Case 1) not significantly different than algorithms that use precisely measured upwelling radiances!

\[ 1/\text{S.D.} \sim \varepsilon (c+K) \sim f(\text{Chl}) \]

Lewis, Kuring & Yentsch 1988

Eyeballs are pretty good.
Eyeball Optics (2): Spectral Resolution

The color of the sea shows a great deal of variability from the deep violet-blue of the open ocean to degrees of green and brown in coastal regions. Before the advent of sensitive optical instruments, color was determined by visual comparison against standard reference standards such as the Forel Ule Color scale.
Some More Results

Conclusions, part 1

In situ measurement of the radiative quantities and optical properties of the ocean is really hard to do well.

But through concerted efforts, the community has converged on a common set of standards and protocols for calibration, characterization and field deployments which have significantly advanced the field over the last 15 years.

At the same time, advanced numerical approaches to the solution (and inversion) of the radiative transfer equation have been well developed as well.

What is left to do?
Some thoughts

We still do not know what is responsible for backscattering light in the ocean.

Issues related to variation in the volume scattering function – and its effect on the full angular distribution of the radiance field are open.

In particular, the polarization variation (and its connection with biology) is largely unknown.

The optics of ice-covered seas are complex, and poorly understood.

Much work has gone into demonstrating the utility of optical observations in the prediction of ocean biogeochemical variability – we need to “operationalize” this (smaller, faster, cheaper…power of \( n^{-1/2} \)) (next).

And don’t forget….Life consists of trade-offs!
Part II: Statement of the Problem:

We would like to predict – in a *hindcast* (what did things look like before?), *nowcast* (what do things look like now?) and *forecast* (what will things look like in the future) sense – the three-dimensional fields of ocean biogeochemical properties and processes.

This includes both short (e.g. ocean weather) and long (climate) scales, and over a range of spatial scales. An example of the former might be harmful algal bloom prediction, and an example of the latter would be long-term secular changes in surface chlorophyll.

And we would like to do this with significant “skill”, that is, we wish to explain a significant fraction of the observed variance.
What do we need to do this?

Marine Environmental Prediction

Observations

Understanding

Prediction
Data assimilation

• The goal is to produce an atmospheric or ocean state as close as possible to reality and at the same time, dynamically consistent, taking into account all the available information: observed data, model, physical constraints, climatology.

• The tools: any type of objective (as opposed to subjective) data analysis: Optimal Interpolation, three-dimensional and/or four-dimensional variational assimilation (3D-VAR/4D-VAR), Kalman filter.

• The output is a set of meteorological or oceanographic fields on the model’s geometry (e.g. a geometrically regular grid or spectral coefficients, etc.) – the Analysis.

• Important aspect: cycling i.e. process of permanent assimilation of data.
Surface Pressure
An issue:

• Our real problem is that the ocean is severely undersampled with respect to the observations we require to develop predictions of ocean biogeochemistry.
But what does this have to do with optical observations?

We need many more of them.
Observational Approaches

- Observations of relevant biogeochemical properties, at relevant space and time scales, are necessary for prediction.
- Ships are too slow, and cost too much.
- Satellites provide a surface view; however, the dynamics that involve nutrient injection most assuredly involve vertical transport in some fashion.
- Fixed moorings capture the vertical and time domain, but not the synoptic, unless in arrays ($$...€ €$)
- Models are useful, but require observations for initialization, boundary conditions and assimilation.

*Autonomous platforms provide the third dimension, and can be deployed for long duration, at reasonable cost. But, few appropriate sensors are available.*
Sensors
on Autonomous / Lagrangian Platforms

Optical:
active and passive optical sensors
(radiometers, fluorometers, beam c,
backscattering, bioluminescence)

Chemical:
oxygen
nutrients on larger platforms

Other:
acoustics, turbulence, etc.

Credit: M.J. Perry
1st Bio-optical autonomous drifter...

• First deployment, Equatorial Pacific, 1994, dropped from aircraft (Satlantic + MetOcean).
• Lagrangian, surface drifter, ARGOS comms.
• Upwelling spectral radiance (“ocean color”), and downwelling irradiance at 490 nm.
• 100’s deployed now.
TEMPORAL VARIABILITY IN THE RELATIONSHIP BETWEEN SUNINDUCED FLUORESCENCE AND INCIDENT IRRADIANCE IN THE BERING SEA: AN EFFECT OF NUTRIENT AVAILABILITY?
Christina Schallenberg, Marlon R. Lewis, Dan E. Kelley and John J. Cullen. JGR, 2007
But...such surface drifters do not resolve vertical dimension. Profiling floats provide this capability.
Vertical gradient in irradiance (3 wavelengths) used to estimate diffuse attenuation coefficient ~ chlorophyll.
The Ocean Takes a Deep Breath
Arne Körtzinger, Jens Schimanski, Uwe Send, Douglas Wallace
Science, 2004
PRO-BIO (Satlantic + MARTEC + IFREMER + CNRS)

- 3-channel irradiance, beam-c, for chlorophyll, carbon, irradiance distribution.
- Requires Iridium satcomms solution.
Float Development w/LOV

SUNA Nitrate Sensor

Cal-Val Sensor Suite
BIODEGEOCHEMICAL SENSING SYSTEMS FOR AUTONOMOUS PROFILING FLOATS

Keith Browning, Diego Benitez-Pinales, Marion Lewis, Andrew Barnes, John Kongler, Casey Moore, Matthew Donato, Emmanuel Boss, Greg Greb, Hari Claustre

Satlantic LP, Halifax NS Canada; Dalhousie University, Halifax NS Canada

WET Labs Inc., Pismo Beach CA USA; WET Labs Europe, East Barnstaple MA USA

University of Maine, Orono ME USA; Stony Brook University, Stony Brook NY USA

Observatoire océanologique de Villefranche-sur-Mer, France

ABSTRACT

A bio-optical sensor system for profiling floats is being used to sample ocean color in the Gulf of Maine and the continental shelf of Canada. The floats are equipped with bio-optical sensors that measure chlorophyll fluorescence, photosynthetic pigments, and dissolved oxygen. The purpose of the system is to continuously monitor the biogeochemical processes occurring in the ocean, providing valuable insights into marine productivity and ecosystem health.

DESIGN GOALS

The system is designed to address the following goals:

- Robustness: The system is designed to withstand deployment in harsh oceanic environments.
- Sensitivity: The sensors are sensitive to minute changes in biological and chemical parameters.
- Flexibility: The system can be adapted to different sampling requirements and conditions.

ARCHITECTURE

The architecture of the bio-optical sensor system includes:

- Data collection: Sensors continuously collect data on chlorophyll fluorescence, photosynthetic pigments, and dissolved oxygen.
- Data transmission: Data is transmitted wirelessly to a receiver on the surface vessel.
- Data analysis: Data is analyzed on the surface vessel to extract meaningful information.

ENERGY CONSUMPTION

The system is designed to be energy-efficient, with sensors using minimal power to operate.

ACKNOWLEDGEMENTS

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REFERENCES

But...we still need the horizontal spatial dimension...

- Gliders couple the buoyancy regulation of floats with aerodynamics to allow platforms to “fly” horizontally through the ocean.
- Conceived by Henry Stommel based on Joshua Slocum’s (from Nova Scotia!) first solo voyage around the world on sailing ship Spray.
Currently several variants:

- Slocum (Webb Research)
- Spray (SIO)
- SeaGlider (iRobot)
- Sea-Explorer (ACSA)
- U.S. Navy
- Wave Glider (Liquid Robotics)
Chlorophyll Distribution, West Coast of U.S./Canada (SeaGlider + SeaWiFS)

Sackmann, Perry, Eriksen (2005)

Courtesy of Brandon Sackmann
Bio-optical Drifter Deployment at DyfaMed, 2004; Scattering coefficient reveals structure in POC. (Herve Claustre and Katarzyna Niewiadowska)
Powered AUV Platforms: REMUS

Brown, Huot, Cullen, Lewis, 2004
Conclusions (Part 2)

- In order to confirm changes in ocean biology for the future using ocean color satellite data, there is a strong requirement for ongoing vicarious calibration and characterization for all ocean color satellite sensors to ensure the development of long-term climate data records.

- Accurate and precise sea-going radiometry is required to achieve this.

- As well, sea-going radiometry and in situ IOP observations, coupled with data assimilating models, are essential to provide the third dimension and to bridge cloudy days.

- A widely distributed network of observations – encompassing buoys, autonomous profilers and ship observations - are needed, which can be objectively assimilated into a global synthesis for the entire constellation of ocean color satellites.

- And there will always be trade-offs.
But don’t trade off messing around in boats!

Merci, Thank you, спасибо, Danke, Obrigado, Gracias, 谢谢
감사합니다, Aitäh, cảm ơn bạn, धन्यवाद, dziękuję, grazie, na gode, Asante, ！