Measurement of in-situ optical properties

Marlon R. Lewis

Professor and Chair, Department of Oceanography
Dalhousie University
Halifax, Nova Scotia, Canada   B3H 1J2
Marlon.Lewis@dal.ca

& Founder/Chief Scientist, Satlantic LP/SeaBird Scientific.

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

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Simply messing around in boats…

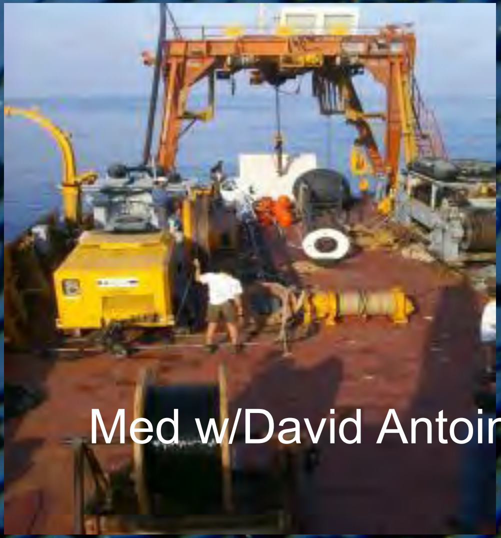

Lac LaBiche, w/ Dave Schindler


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.

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(Scientific) Background

- The fundamental radiometric quantity is the spectral radiance distribution ($L(z,x,y,t,\theta,\varphi,\lambda)$), 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

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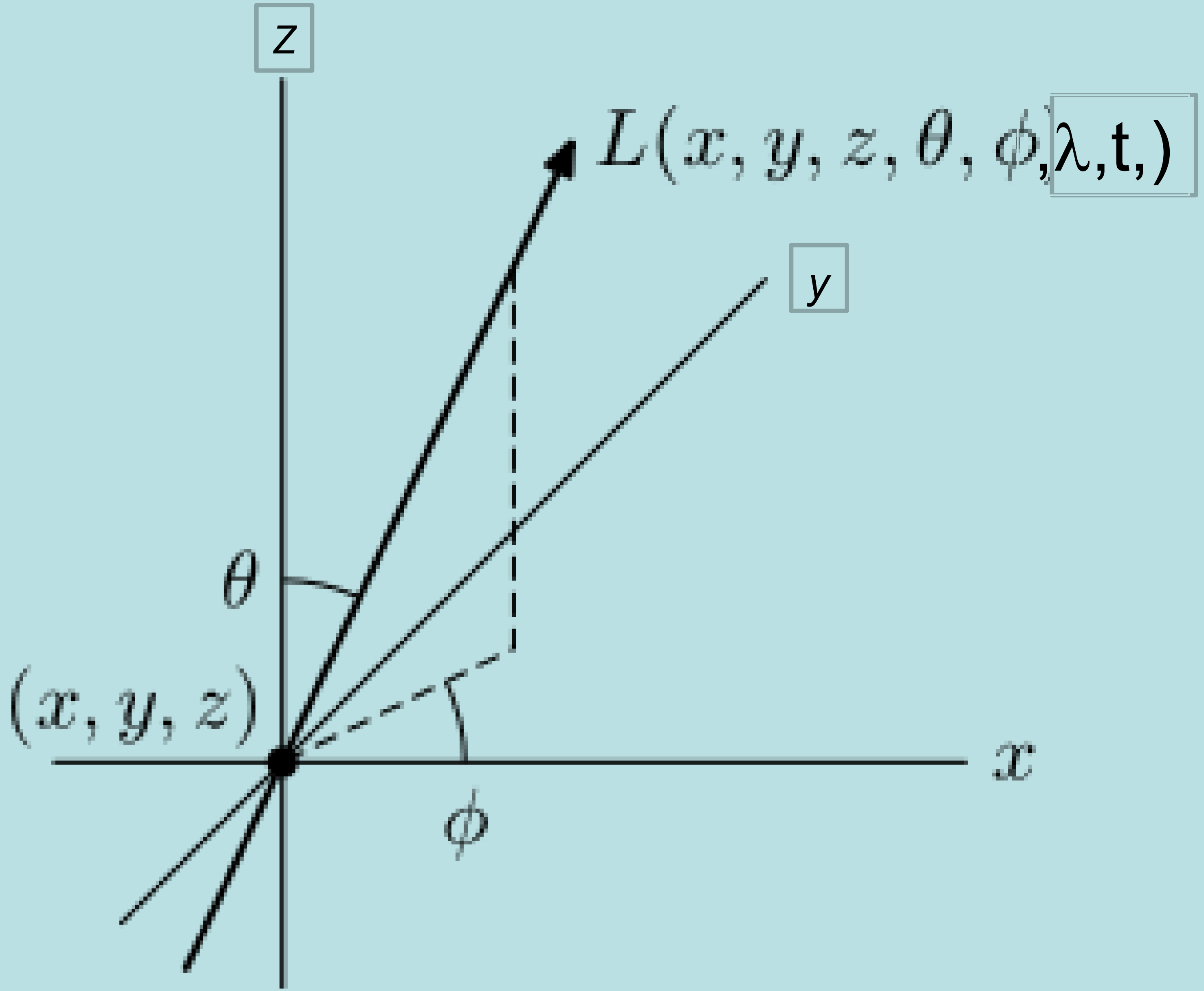
z
L(x, y, z, θ, φ,λ,t,)
y
θ
(x, y, z)
x
φ

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)

Do Radiance Right

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And if you need another good reason…

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Background

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

A caveat: Life consists of trade-offs.

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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).

$L(z,\theta,\varphi)$

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

θ',φ'

θ,φ

$\cos \mathrm{d}r = \mathrm{d}z$

$\mathrm{d}r$

Losses due to absorption & scattering ($c=a+b$).

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

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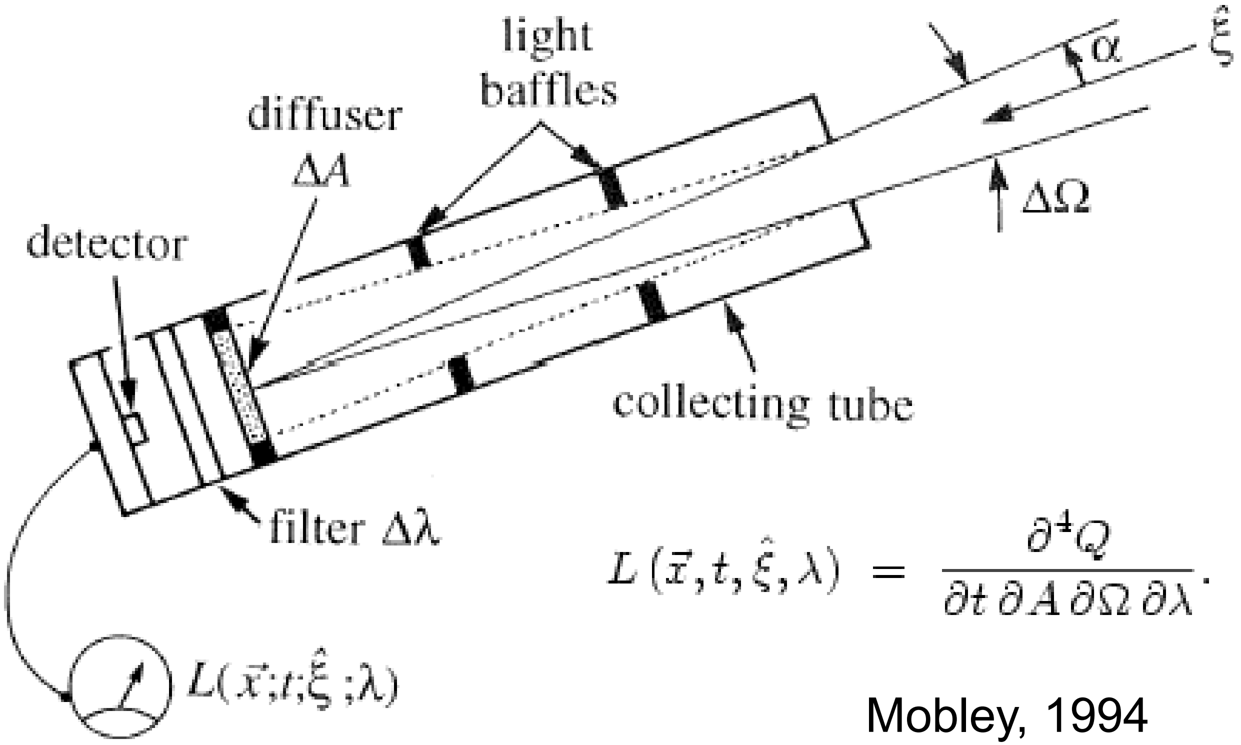
Some good reasons for measuring variability in the full radiance field,

- 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.

Measurement of the Radiance Distribution.

- 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



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

Mobley, 1994

The Gershun Tube

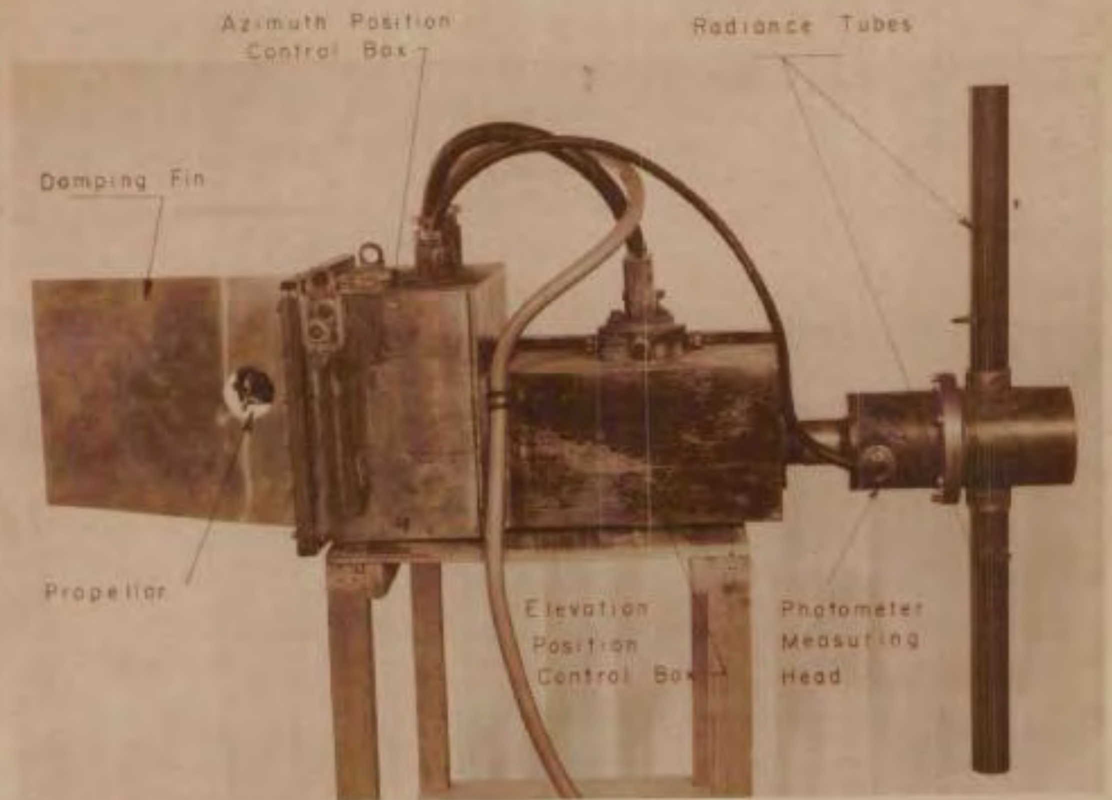


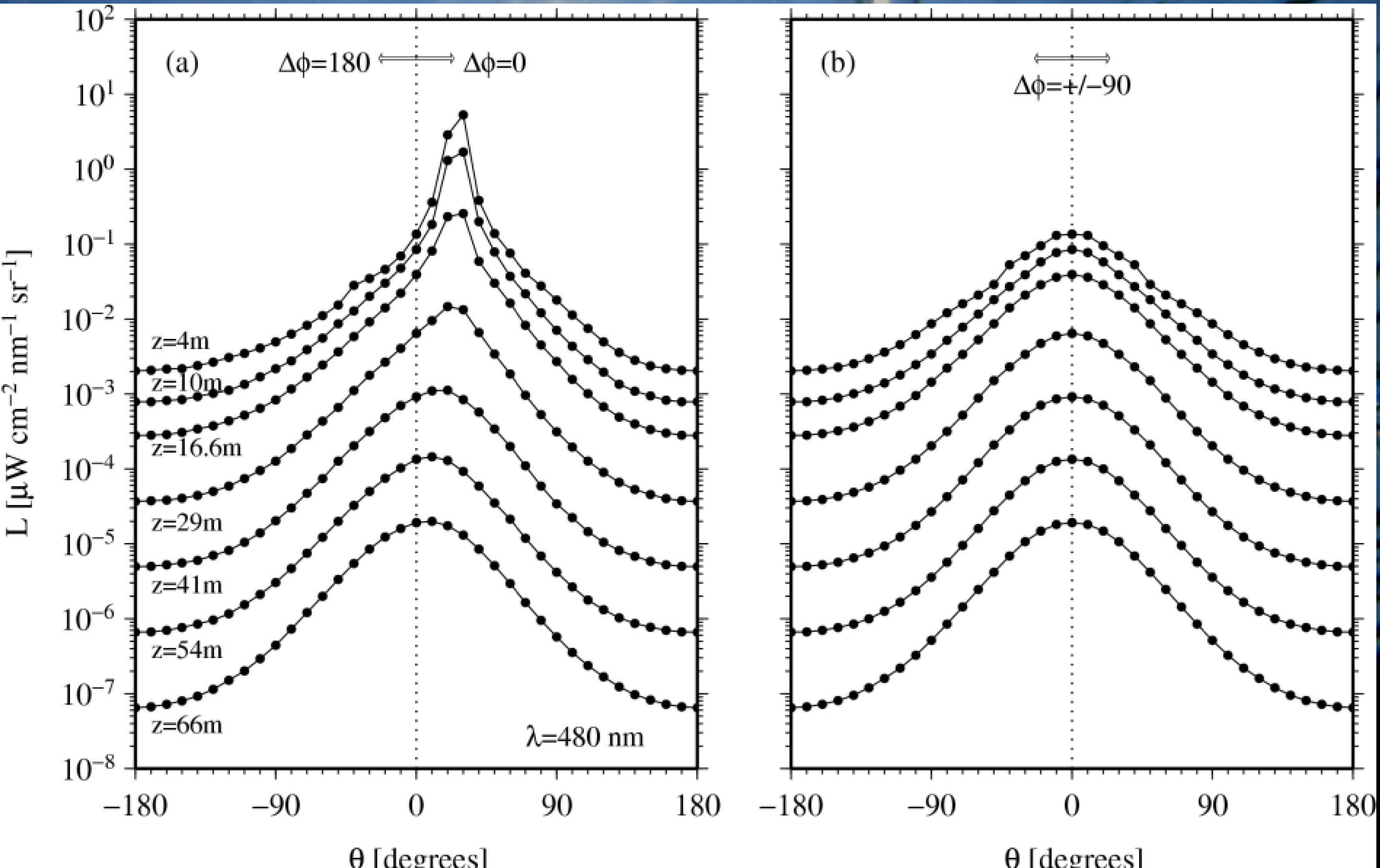
Figure 2

Underwater Photometer

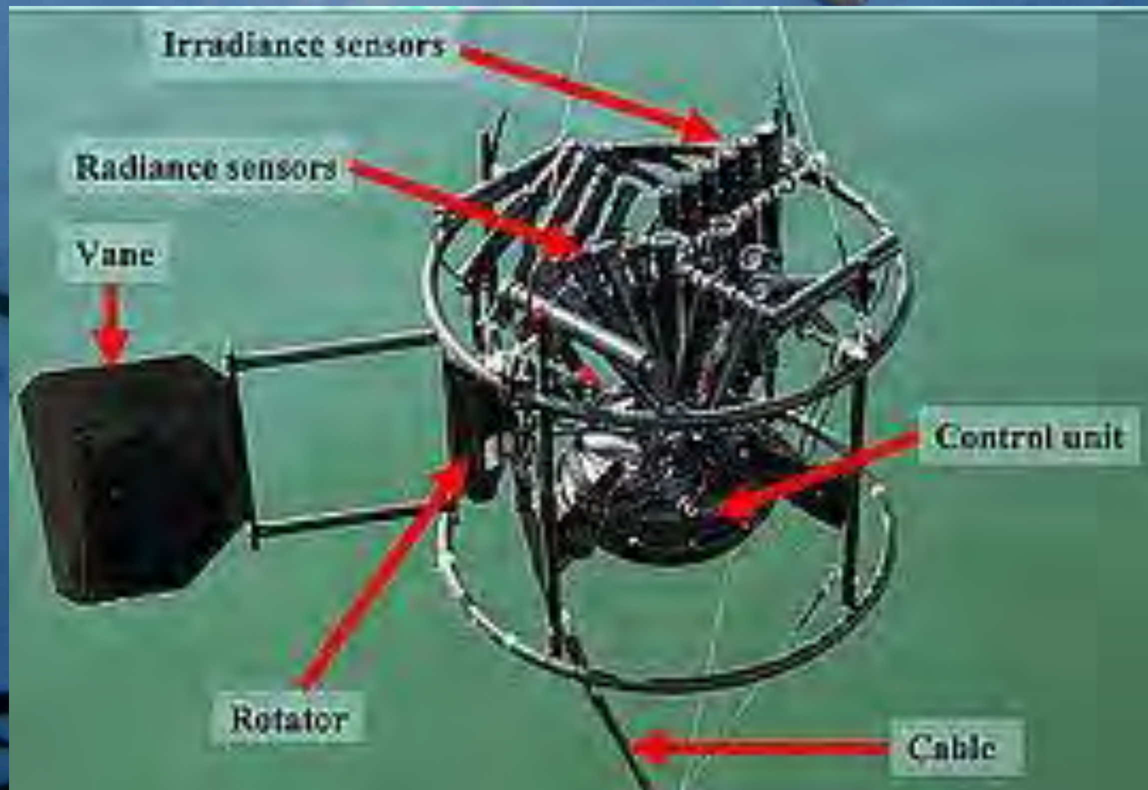
Duntley, Tyler

* Measuring Head and Positioning Equipment

Data from Tyler



Porcupine



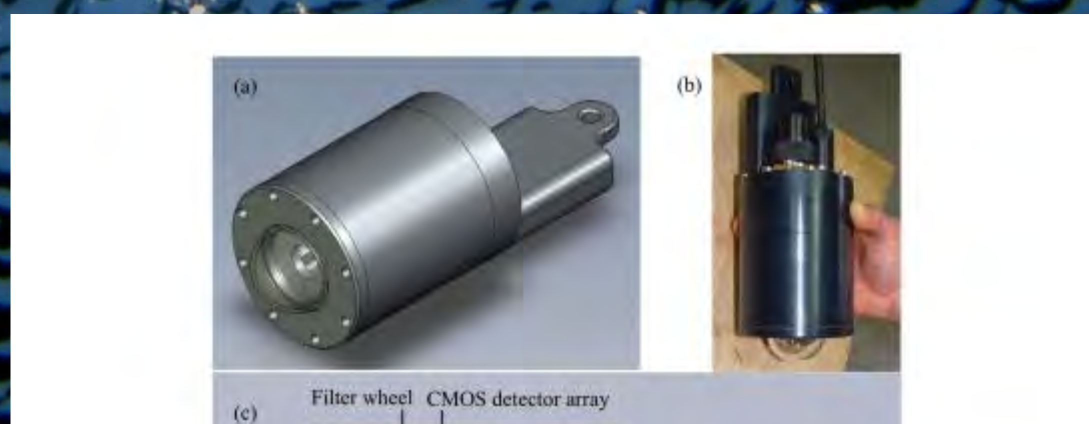
Miroslaw Darecki

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



RADCAM

- 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 ~ 10^6-10^7.

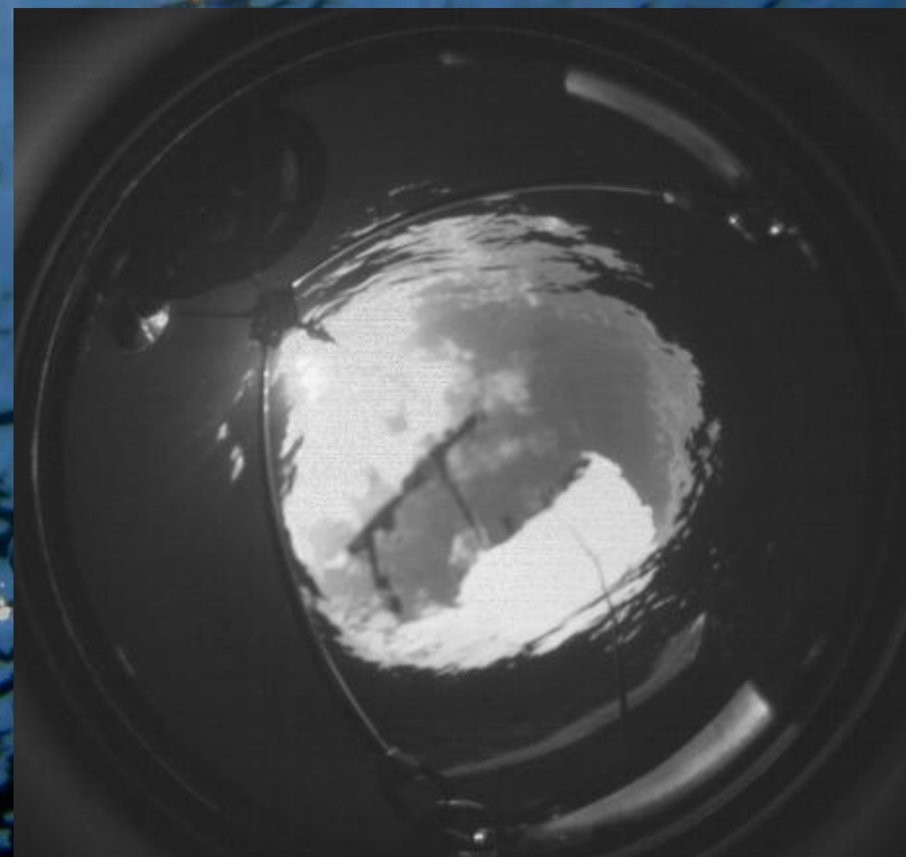
Off Hawaii

Joys of being a graduate student

R/V Kilo Moana

Free-falling

Above and below surface downward radiance field



Optical manhole

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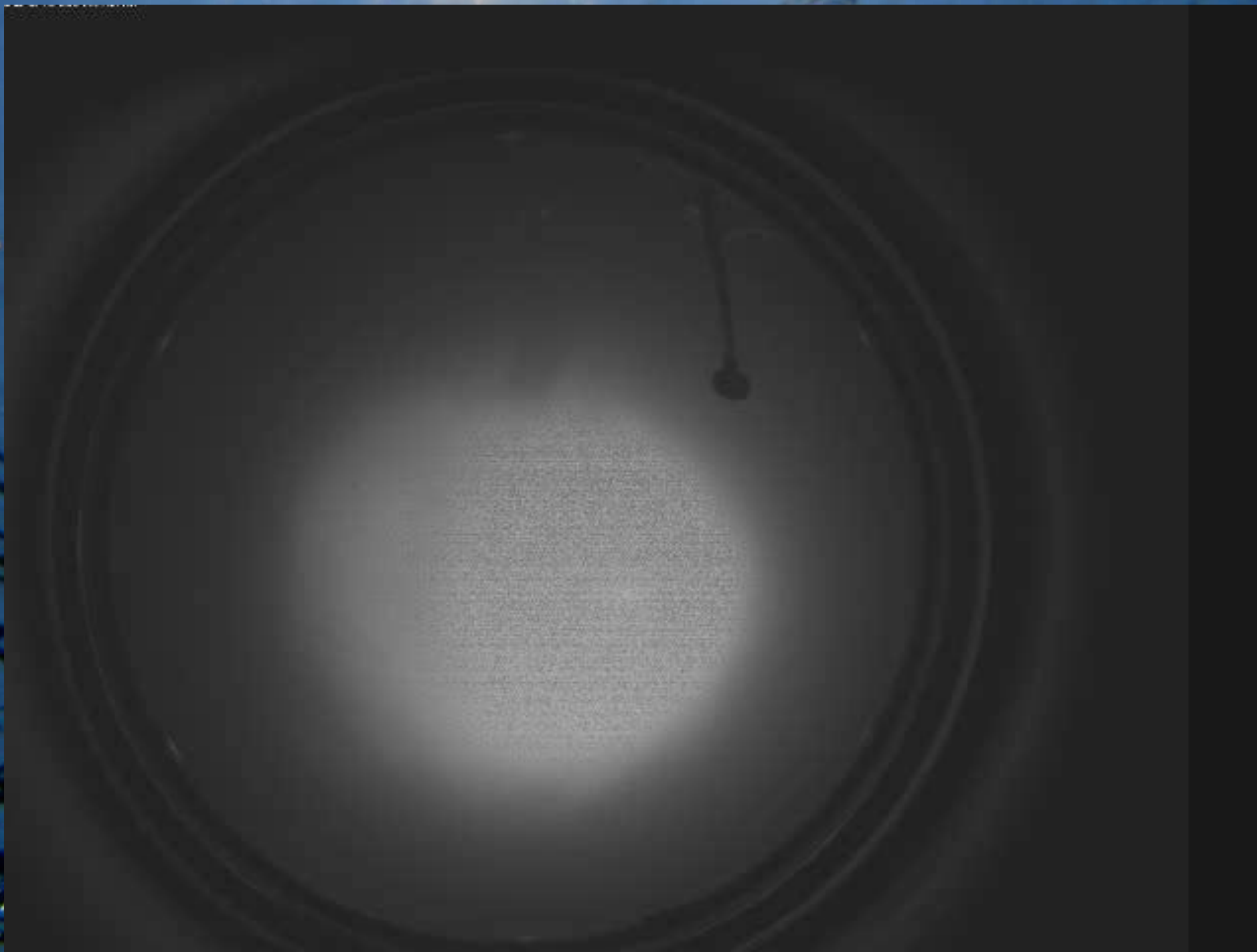
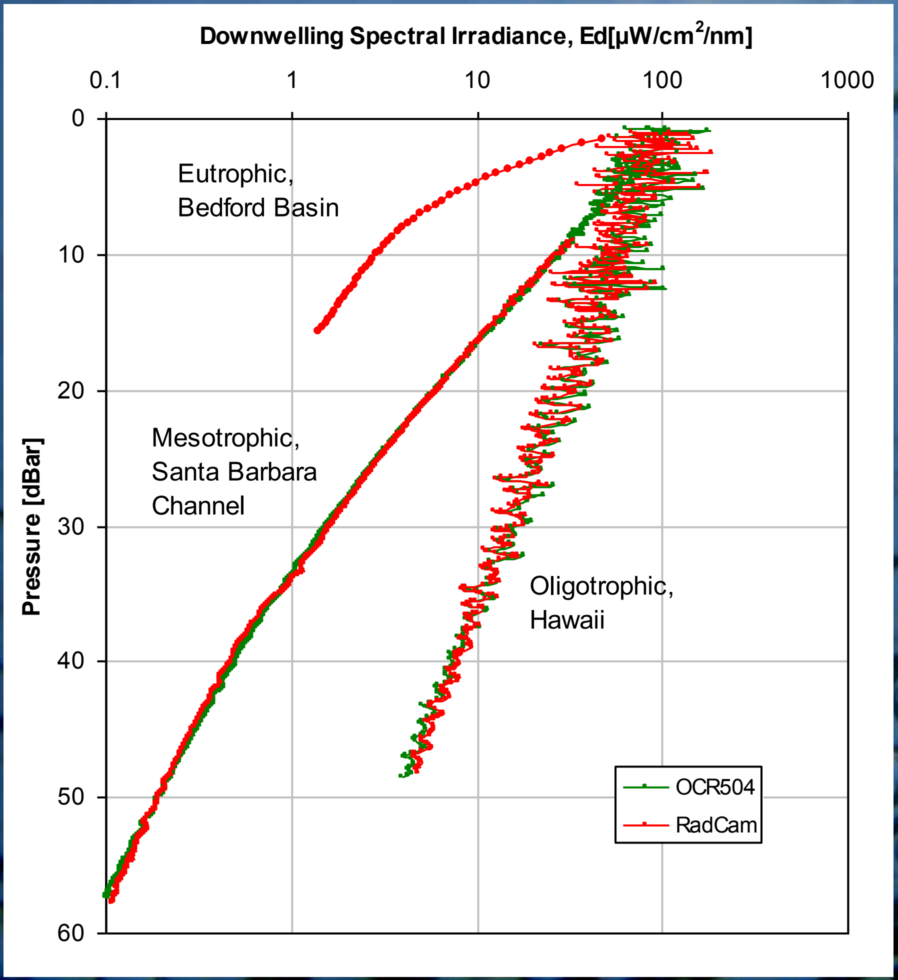
Surface and Dive



Three primary deployments for the measurement of variability in the underwater radiance distribution



Hawaii, Oligotrophic, Large Waves

Santa Barbara, Mesotrophic, Small Waves

Bedford Basin, Eutrophic, Calm

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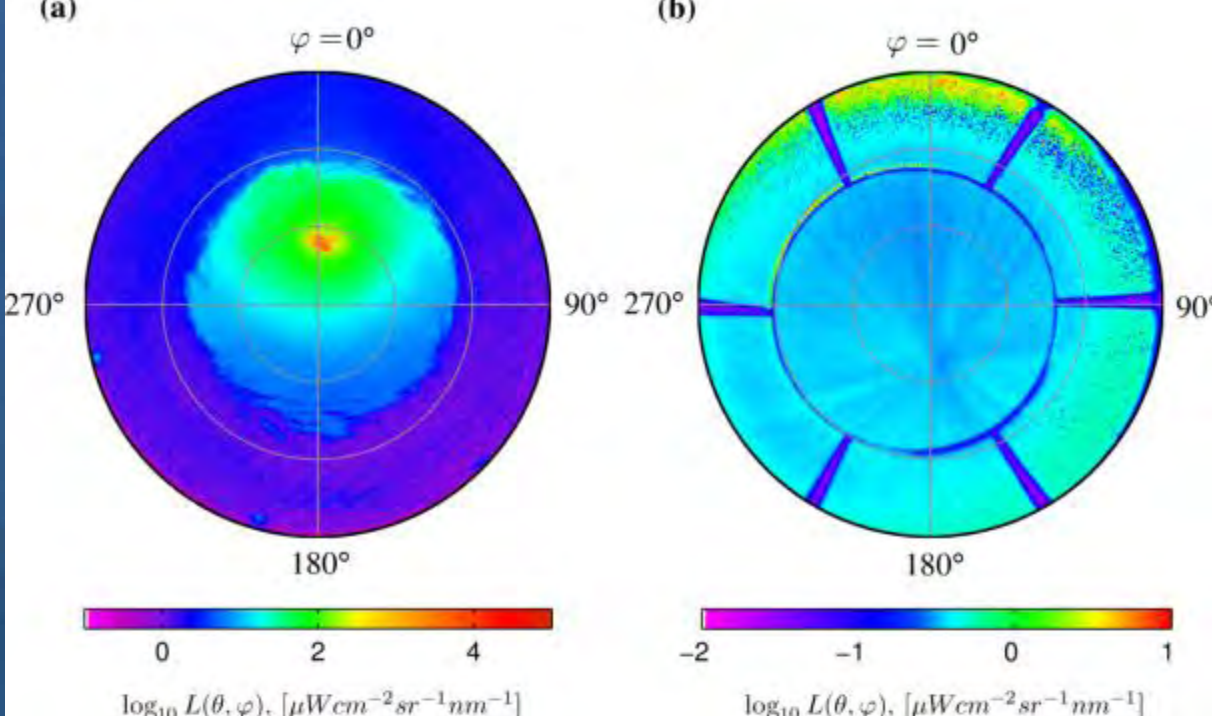
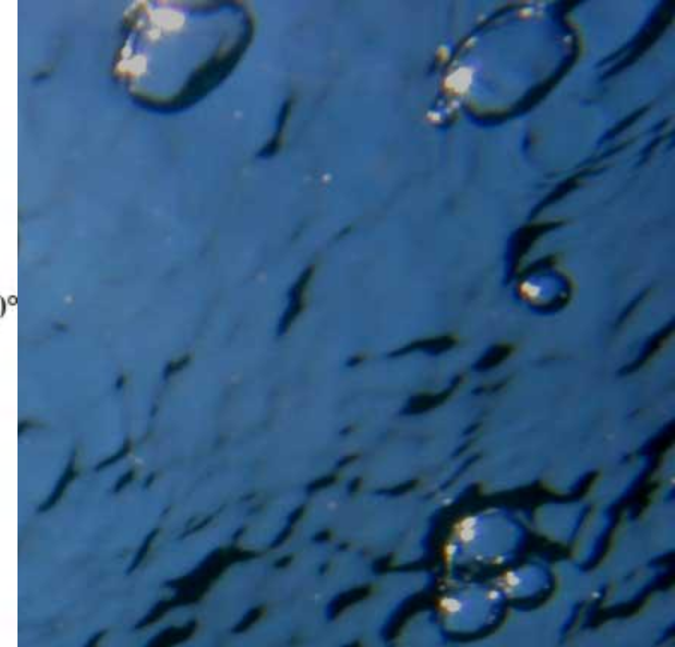
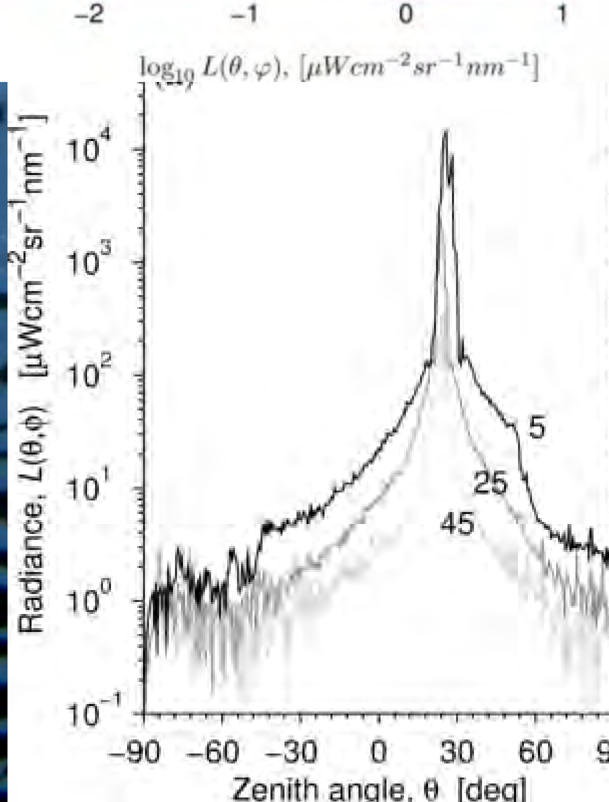
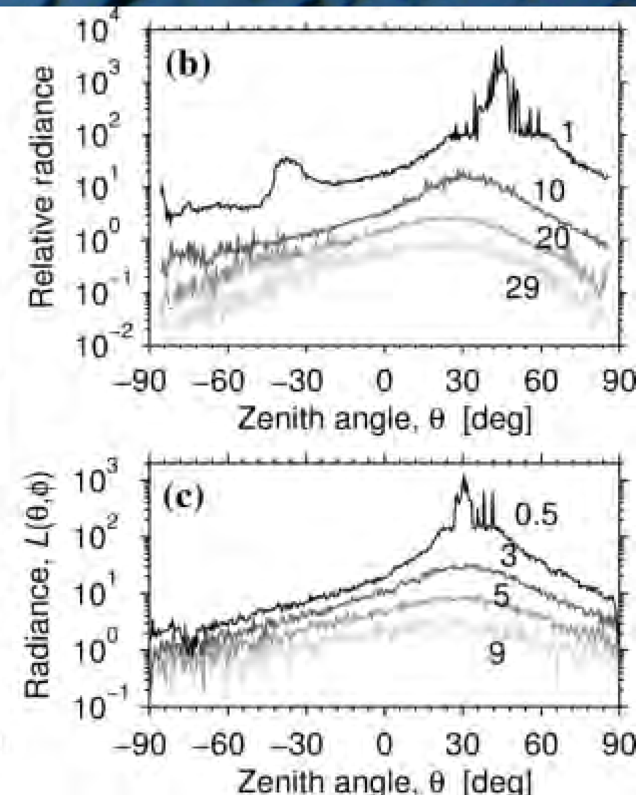
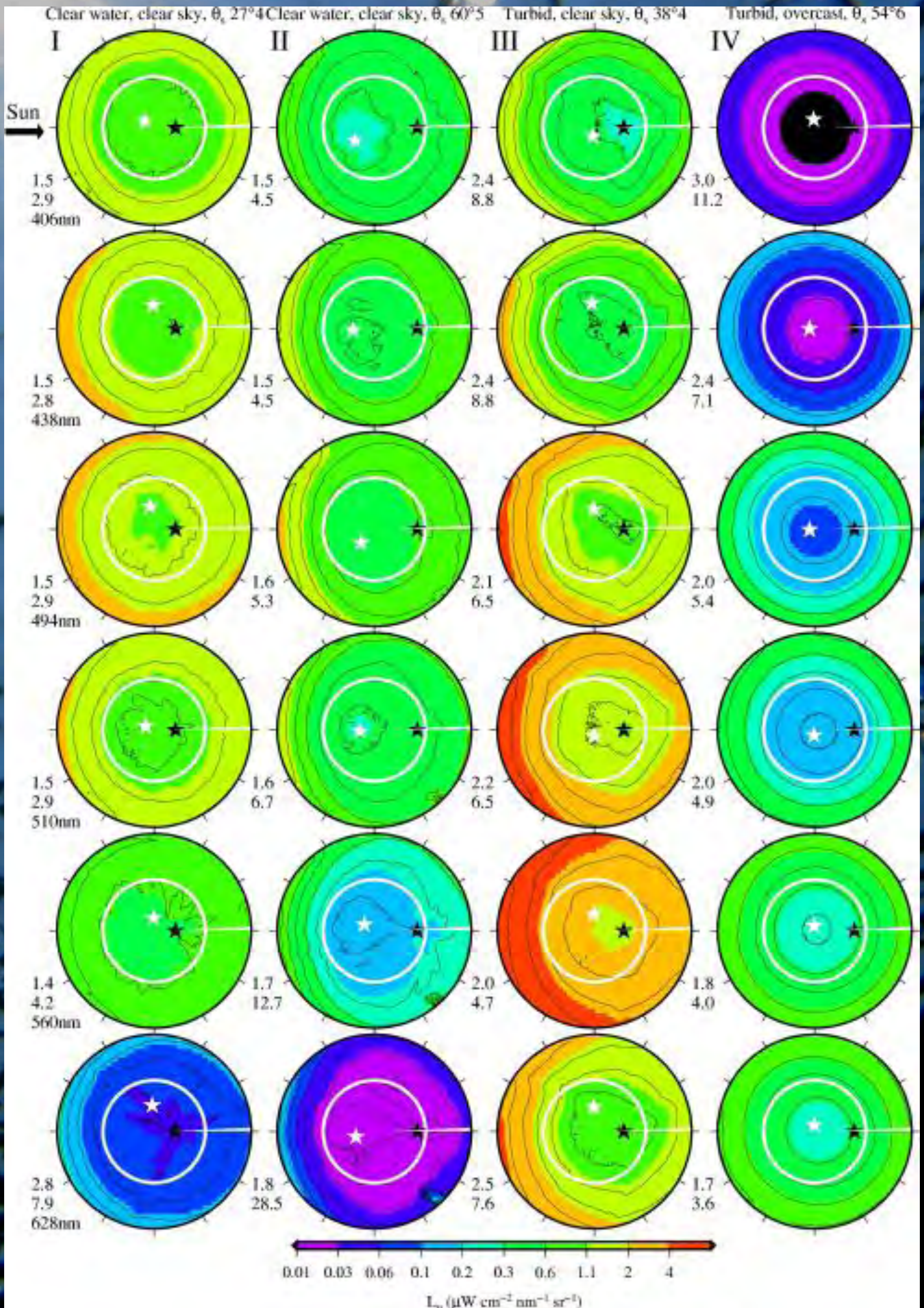

(a)
(b)
$\varphi = 0°$
270°
90°
180°
0
2
4
−2
−1
0
1
$\log_{10} L(\theta, \varphi)$, $[\mu W cm^{-2} sr^{-1} nm^{-1}]$
$\log_{10} L(\theta, \varphi)$, $[\mu W cm^{-2} sr^{-1} nm^{-1}]$




Radiance, $L(\theta,\phi)$ $[\mu W cm^{-2} sr^{-1} nm^{-1}]$
Zenith angle, θ [deg]
5
25
45

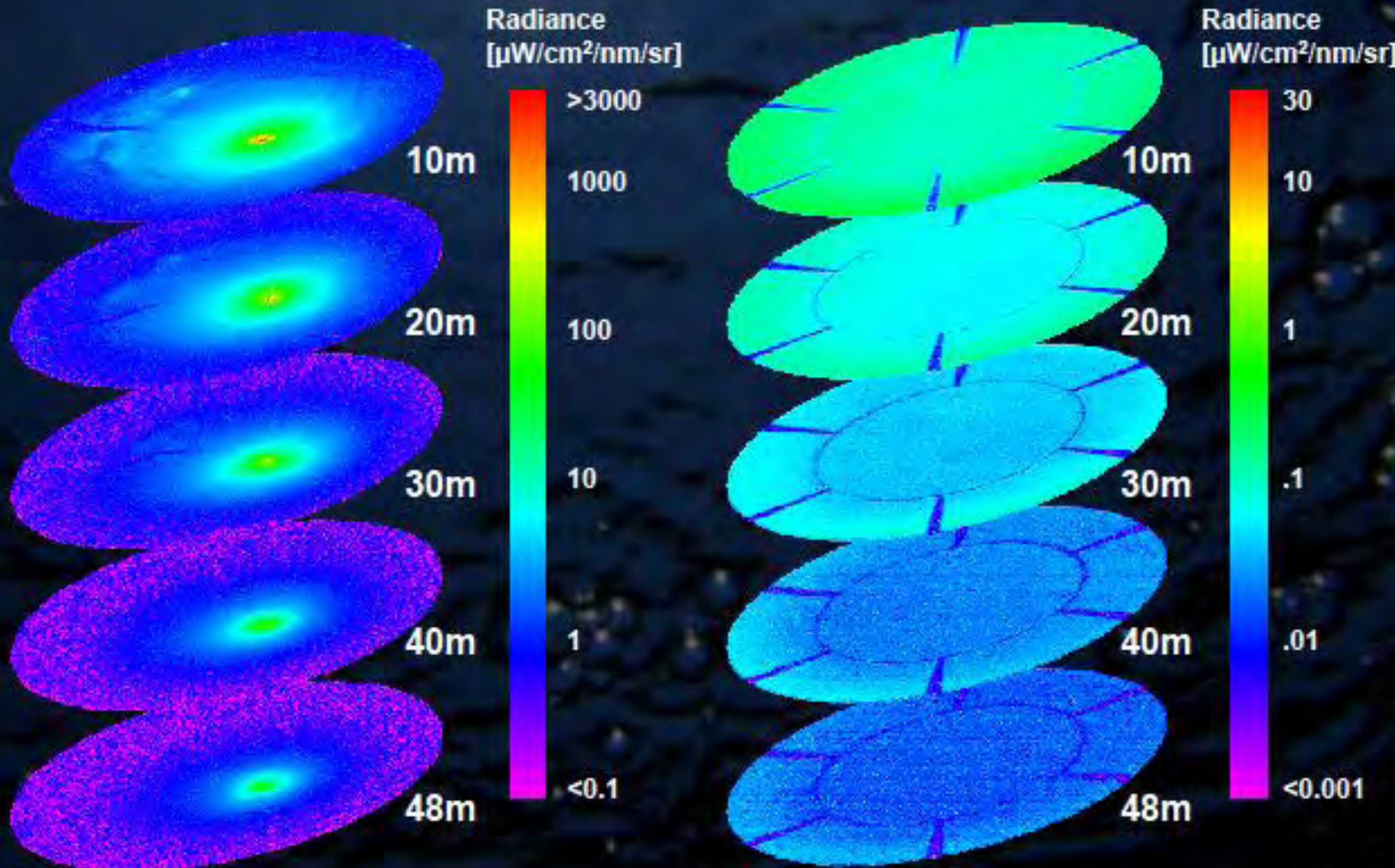

(b)
Relative radiance
1
10
20
29
Zenith angle, θ [deg]
(c)
Radiance, $L(\theta,\phi)$
0.5
3
5
9
Zenith angle, θ [deg]

Upwelling spectral radiance distributions, 4 environments (Antoine et al. 2012)

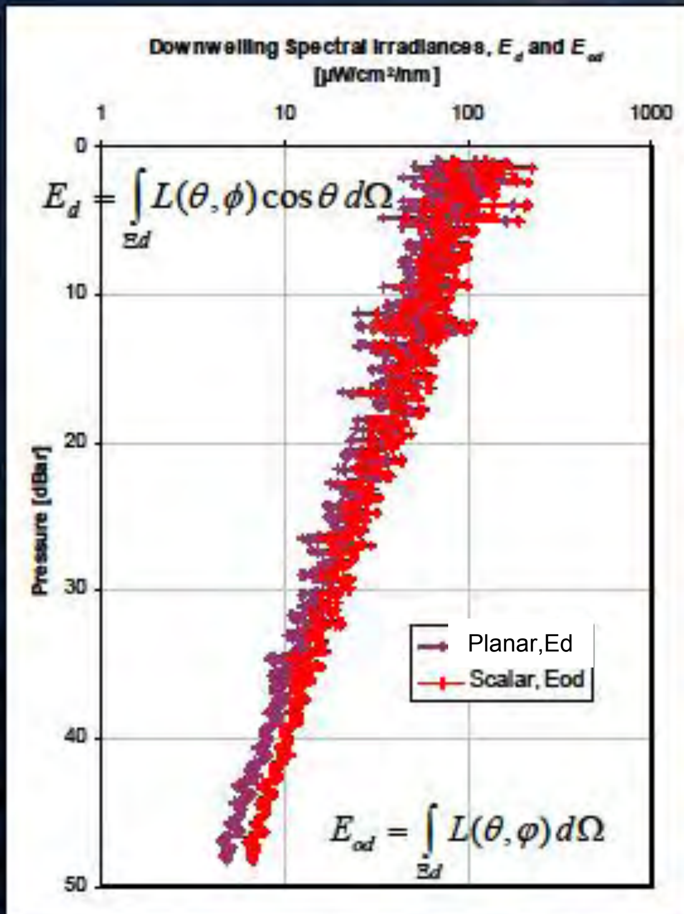


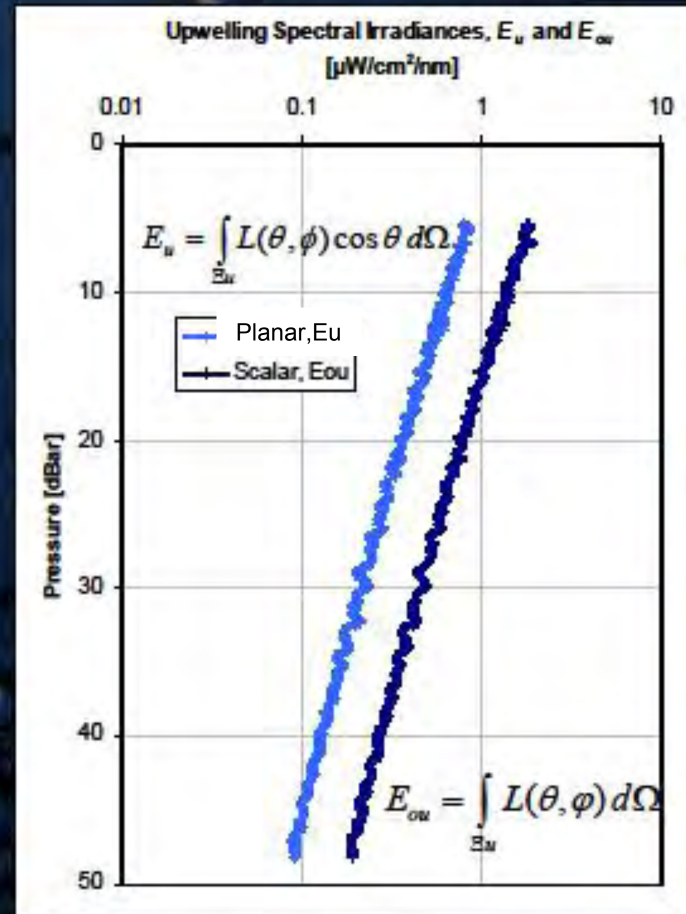
Oligotropic Environment

Hawaii - Clear Sky



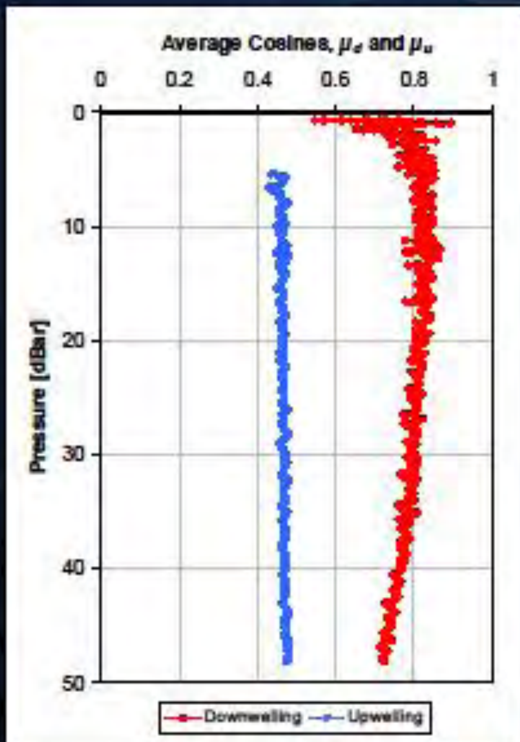
Oligotropic Environment

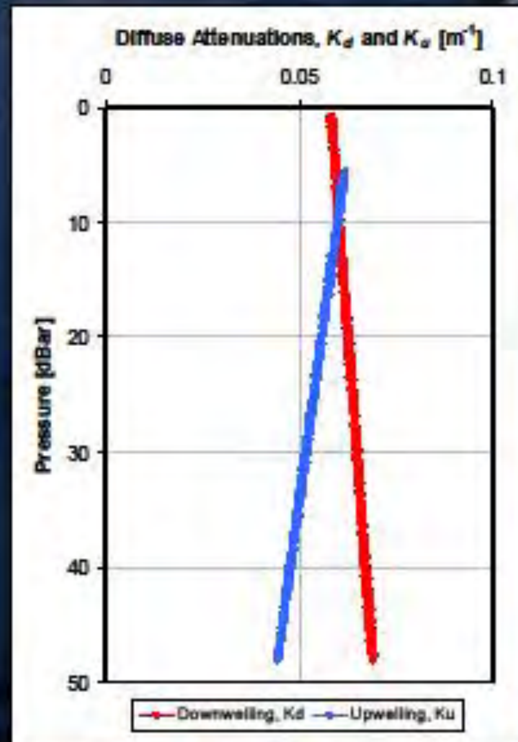


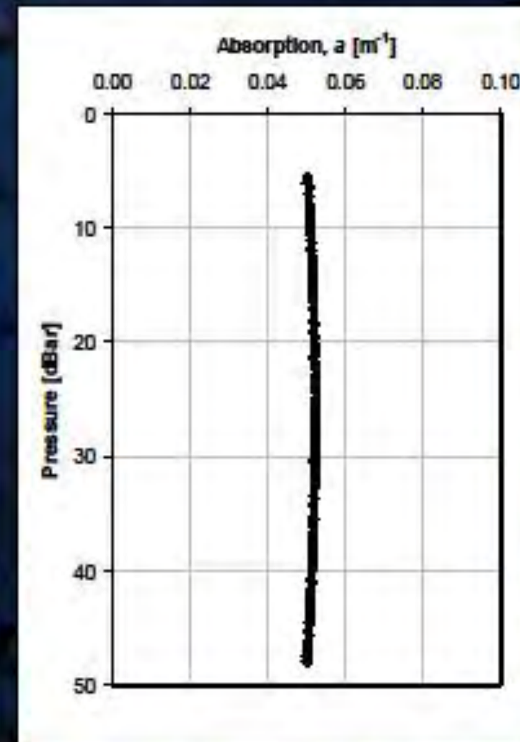


Irradiances found by integrating radiance fields

Oligotropic Environment







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

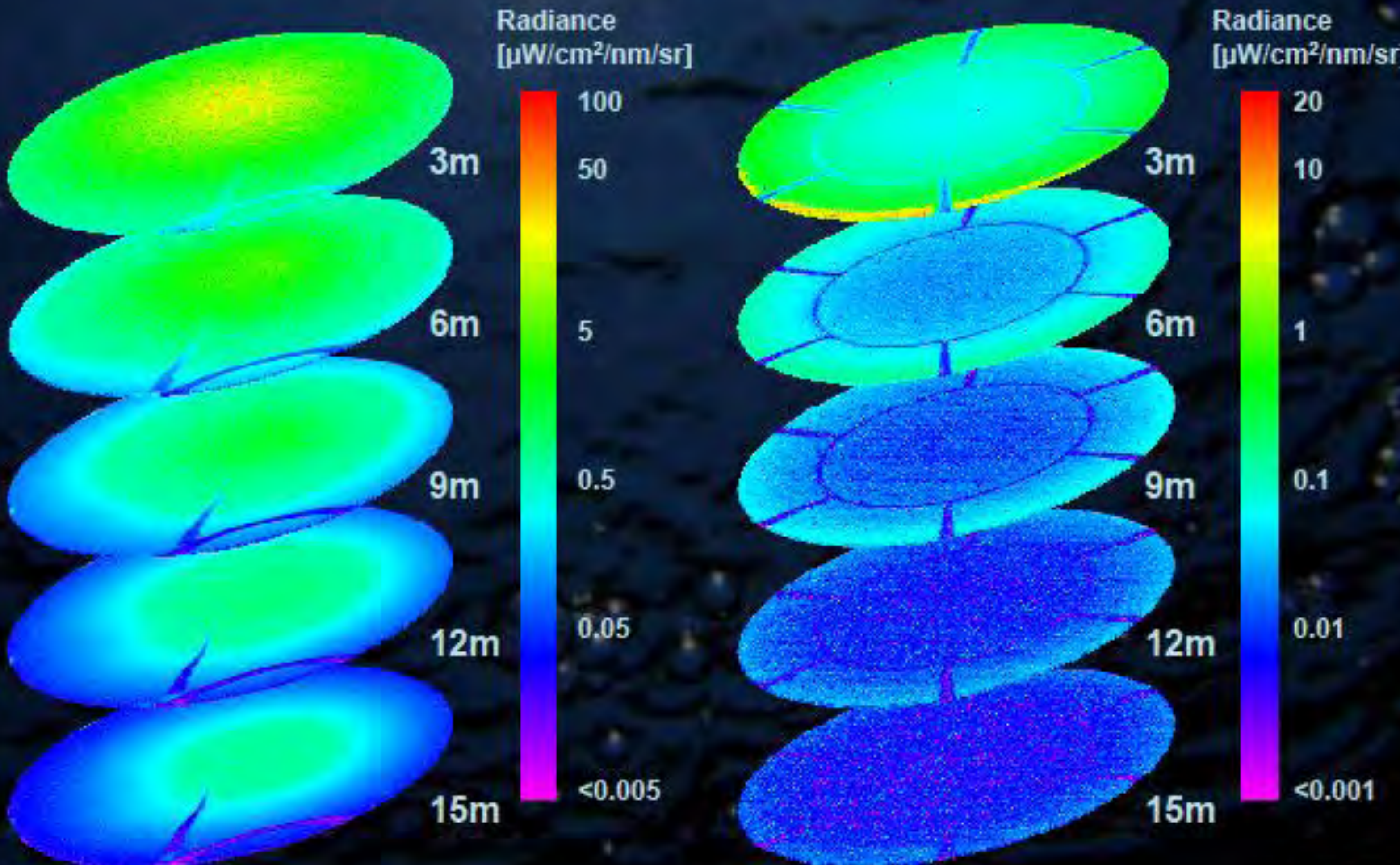
$$\frac{1}{E_n(z)}\frac{d(E_n(z))}{dz} = -K_n(z)$$

$$\nabla \bullet \mathbf{E} = -aE_o + Sources$$

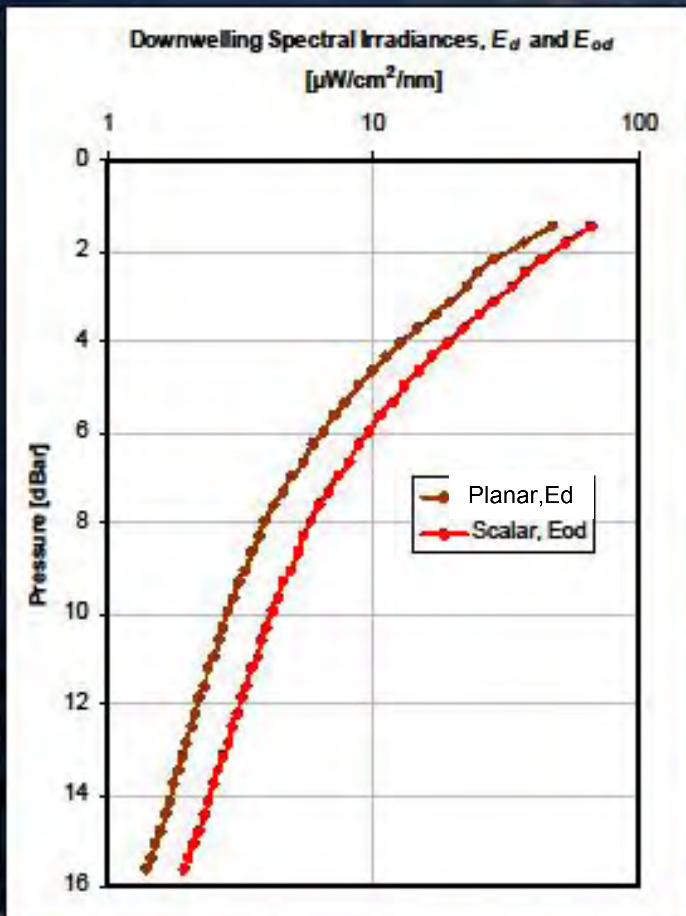
All quantities calculated from radiance fields

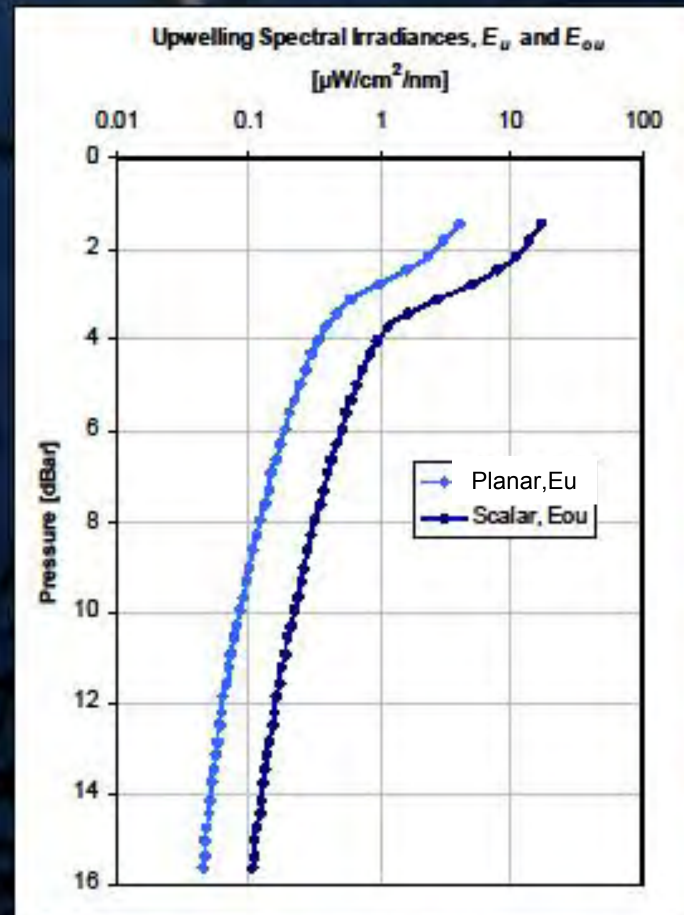
Eutrophic Environment

Bedford Basin, Nova Scotia



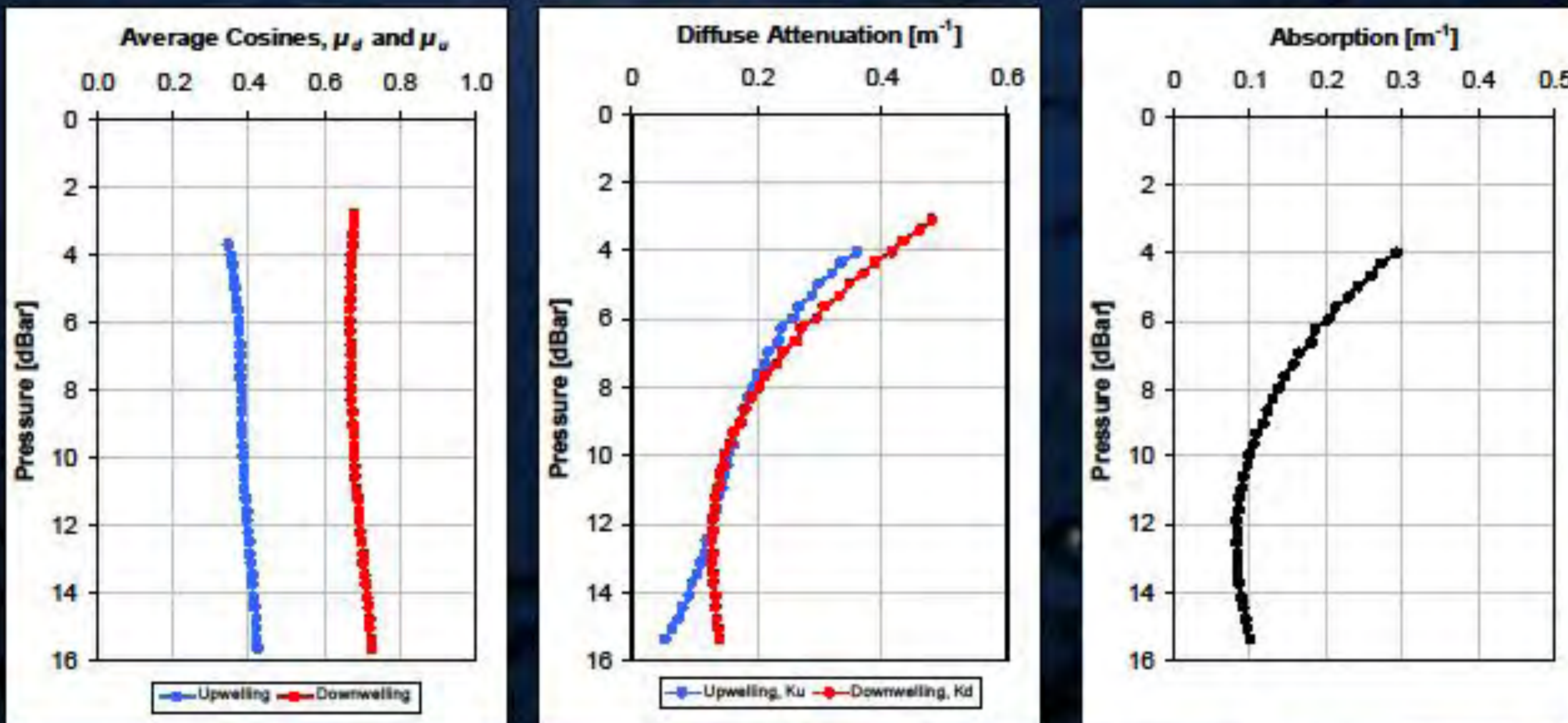
Eutrophic Environment





Irradiances found by integrating radiance fields

Eutrophic Environment



All quantities calculated from radiance fields

Time dependency

Profile, Downwelling

Profile, Upwelling

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

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

Zaneveld and Pak, 1972?

Other (analytical, numerical) approaches?

Or can we do something really useful???

Measurement of in-situ optical properties (contd)

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Dalhousie University
Halifax, Nova Scotia, Canada B3H 1J2
Marlon.Lewis@dal.ca

& Founder/Chief Scientist, Satlantic LP/SeaBird Scientific.

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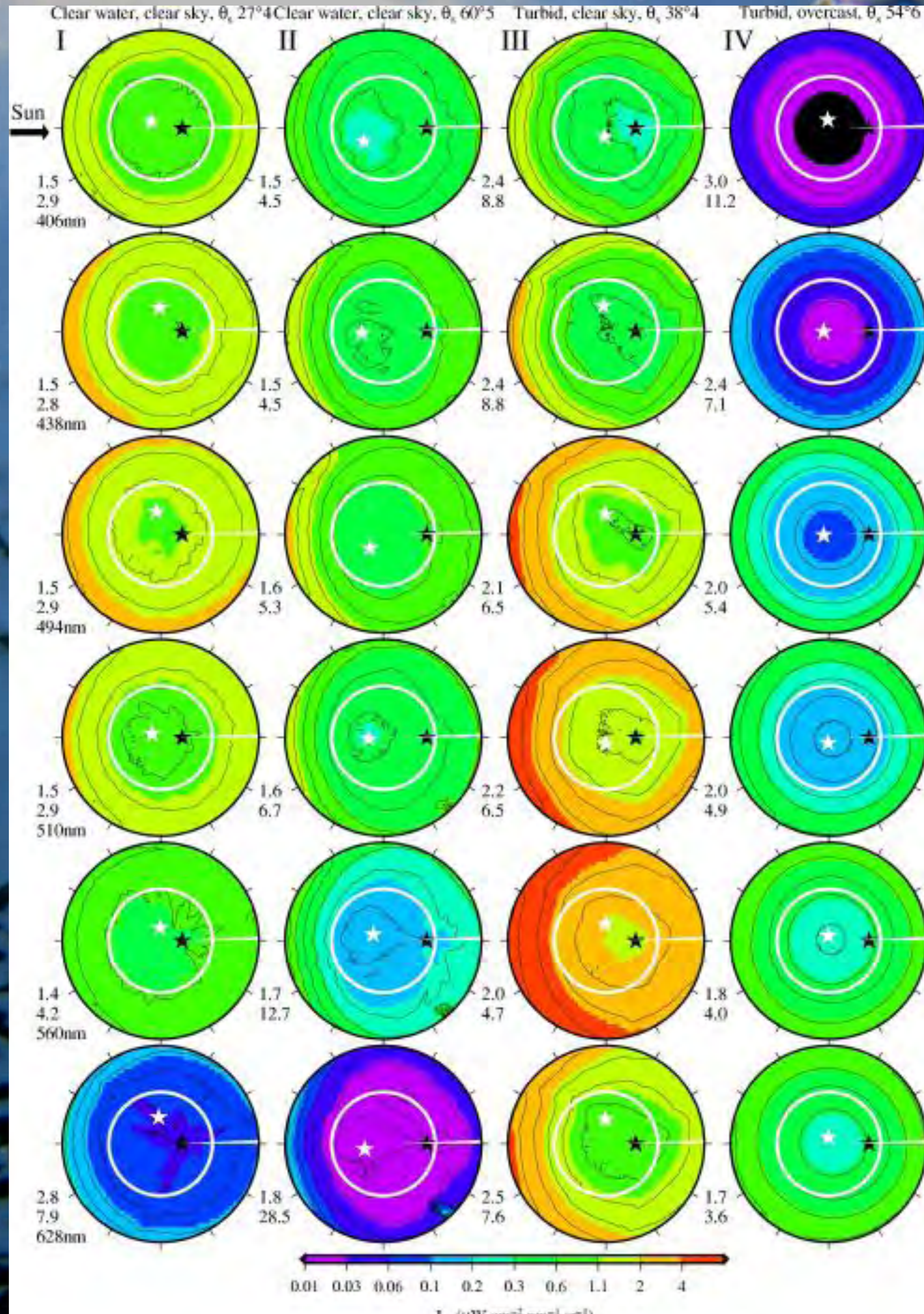
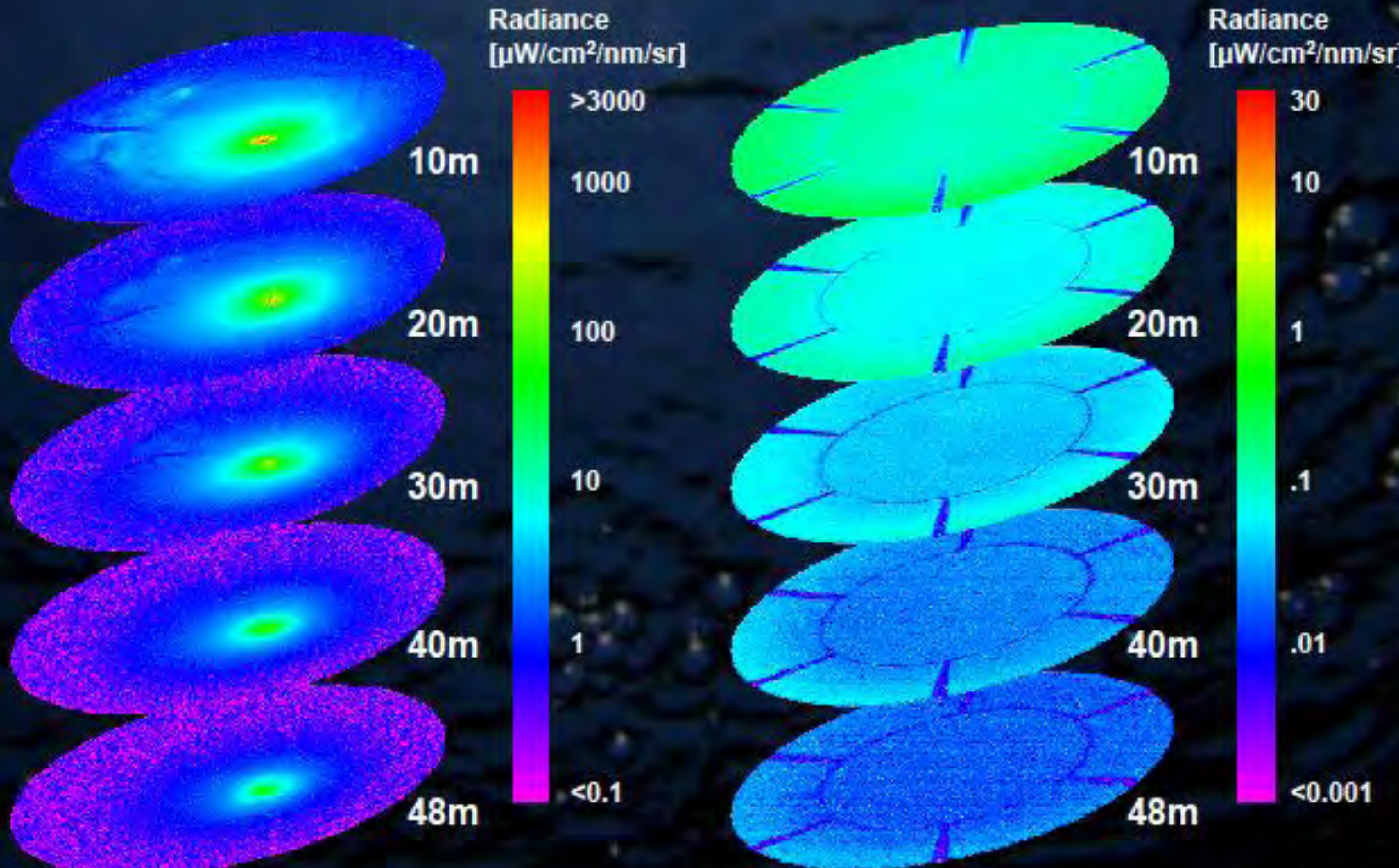


Clear water, clear sky, θs 27°4
Clear water, clear sky, θs 60°5
Turbid, clear sky, θs 38°4
Turbid, overcast, θs 54°6
I
II
III
IV
Sun
1.5 2.9 406nm
1.5 4.5
2.4 8.8
3.0 11.2
1.5 2.8 438nm
1.5 4.5
2.4 8.8
2.4 7.1
1.5 2.9 494nm
1.6 5.3
2.1 6.5
2.0 5.4
1.5 2.9 510nm
1.6 6.7
2.2 6.5
2.0 4.9
1.4 4.2 560nm
1.7 12.7
2.0 4.7
1.8 4.0
2.8 7.9 628nm
1.8 28.5
2.5 7.6
1.7 3.6
0.01 0.03 0.06 0.1 0.2 0.3 0.6 1.1 2 4
Lu (μW cm−2 nm−1 sr−1)

Oligotropic Environment

Hawaii - Clear Sky



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.

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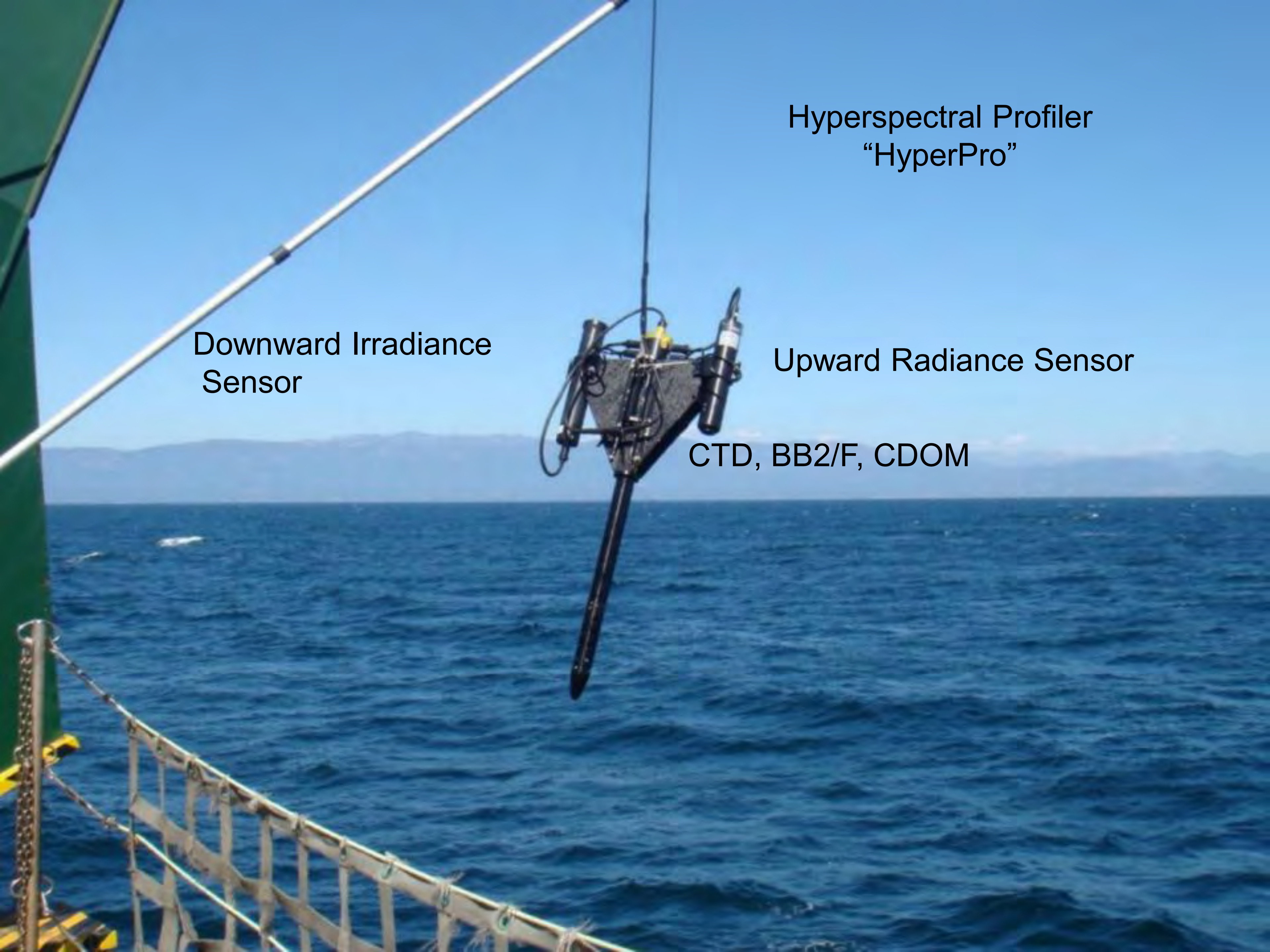
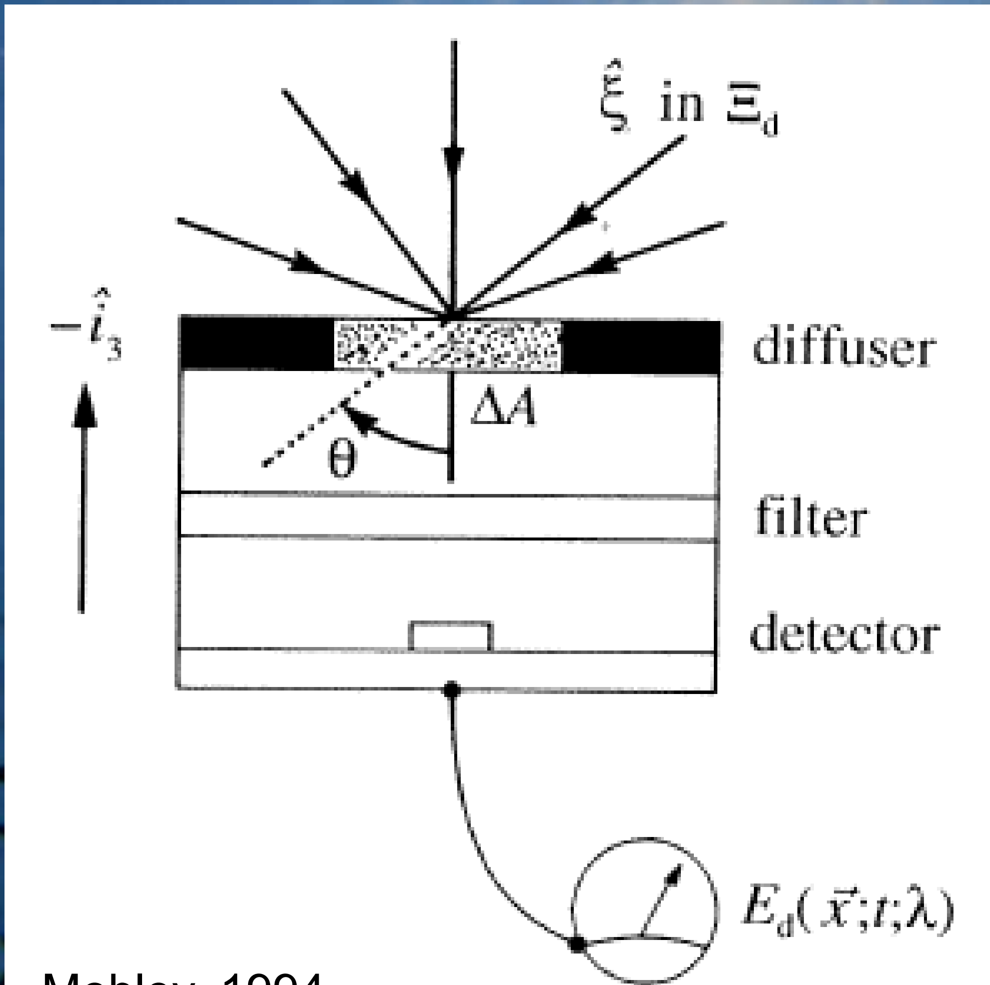
More Practical Approaches


Hyperspectral Profiler
“HyperPro”
Downward Irradiance
Sensor
Upward Radiance Sensor
CTD, BB2/F, CDOM


DYNAMIC
STATIC
DATE TESTED

Planar Irradiance Sensor – "Built – in" integration



Mobley, 1994

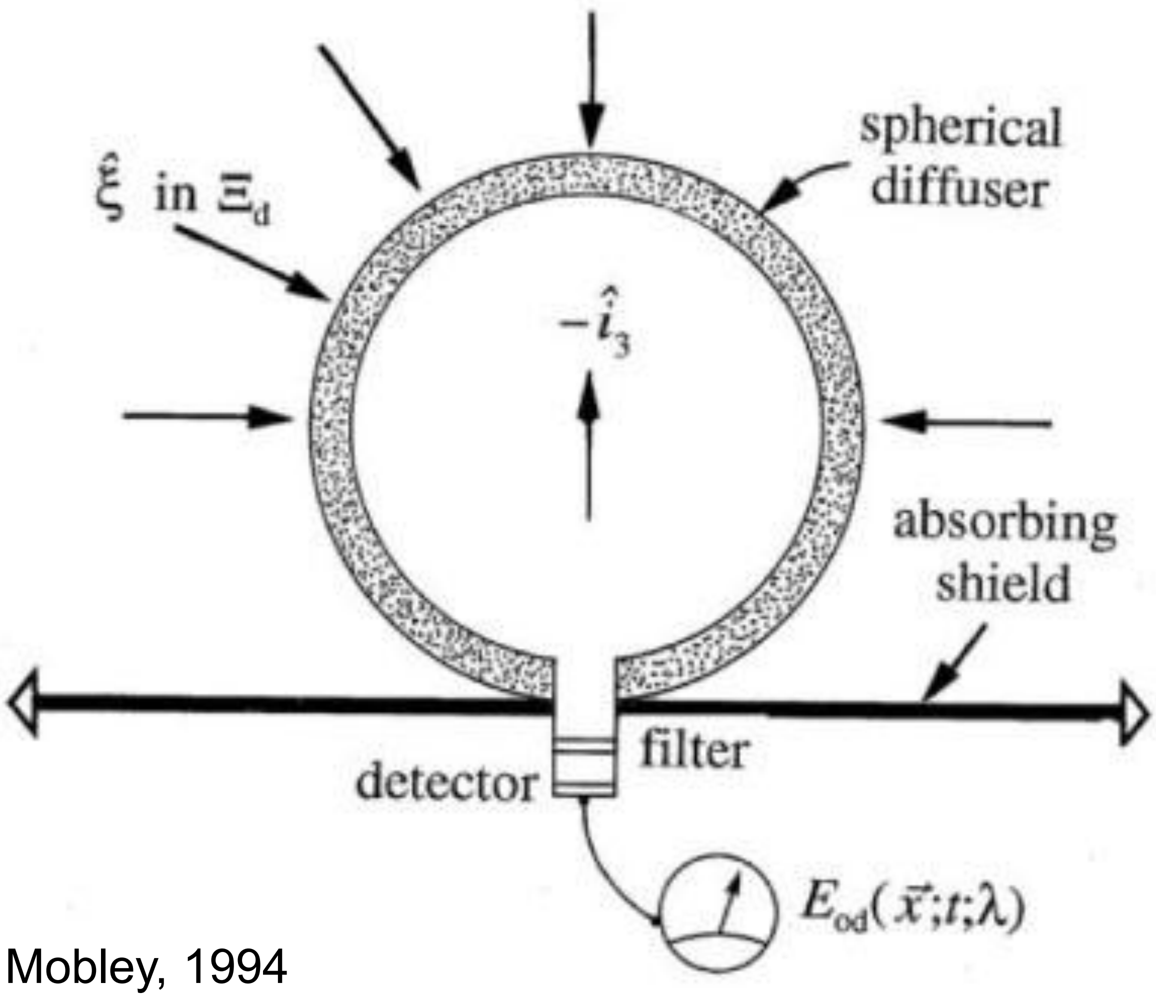
Diffuser weights incoming photons as cos (θ)

"Filter could be grating or prism or spectrally variable filter

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

$$E_d(\vec{x},t,\lambda) = \int_{\hat{\xi}\in\Xi_d} L(\vec{x},t,\hat{\xi},\lambda)\,|\cos\theta|\,d\Omega(\hat{\xi}) =$$

Scalar Irradiance Sensor



Mobley, 1994

Irradiance Sensors


Chelsea Inst.


LiCor


Satlantic


Biospherical


Satlantic

Single Direction Radiance Sensors

Satlantic

Analytical Spectral Devices

GER

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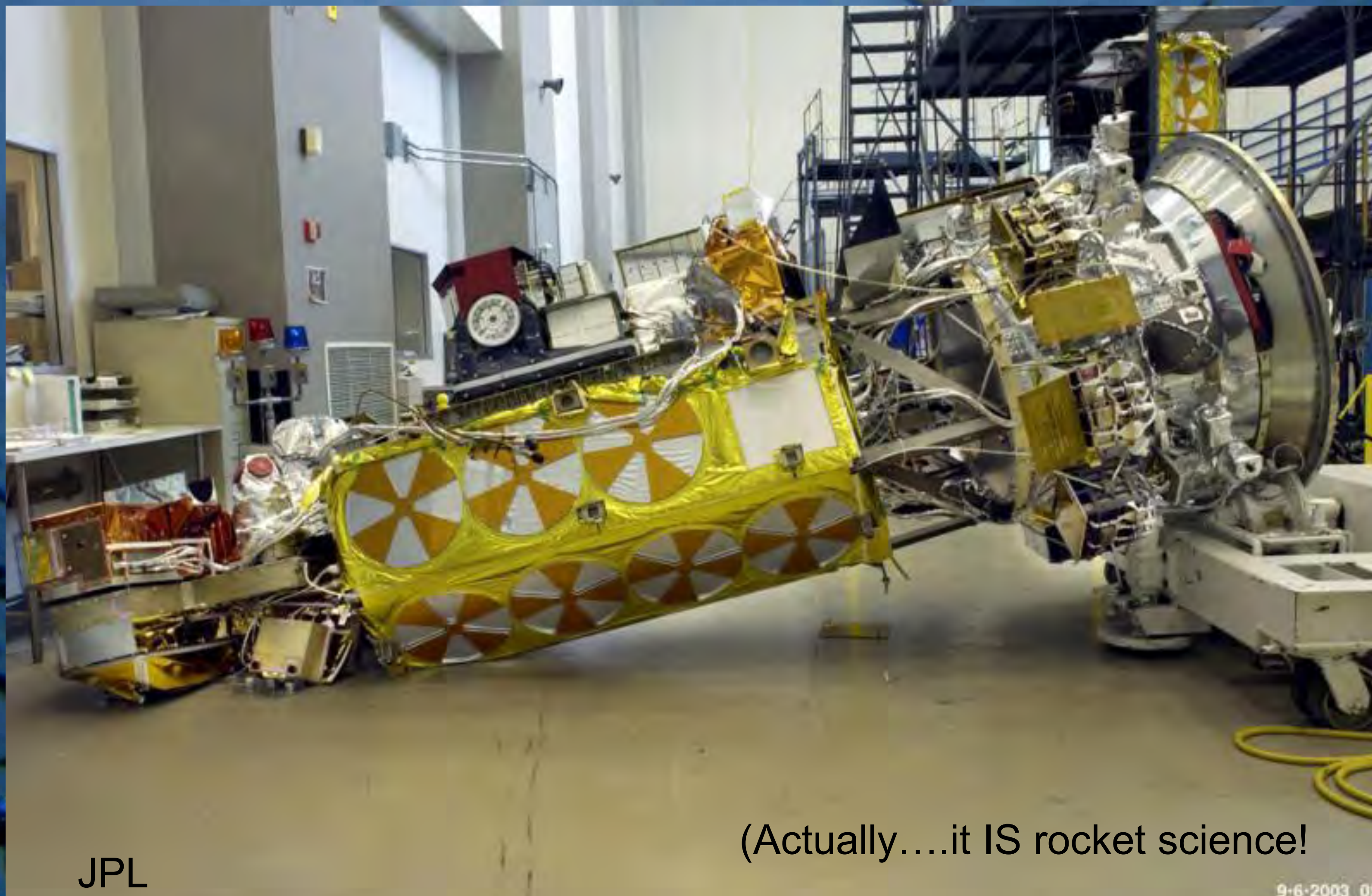
Really big radiance sensors…oops!



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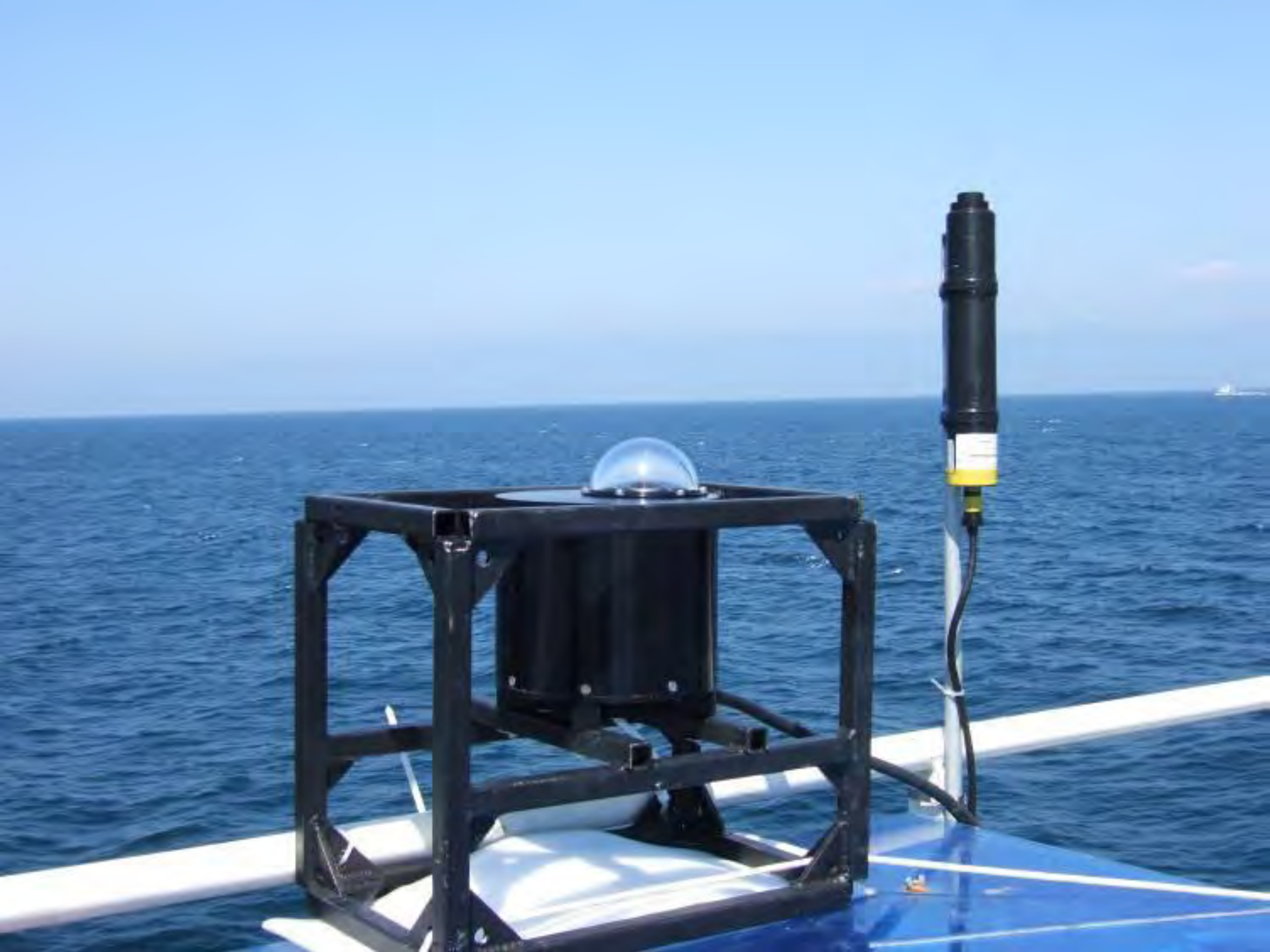
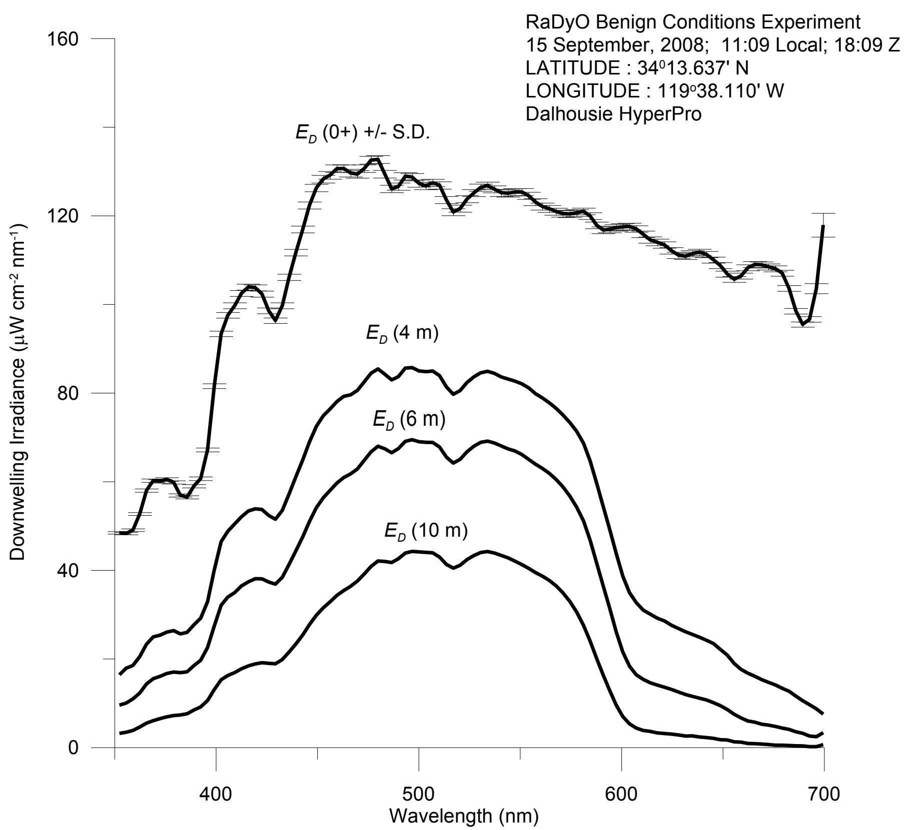
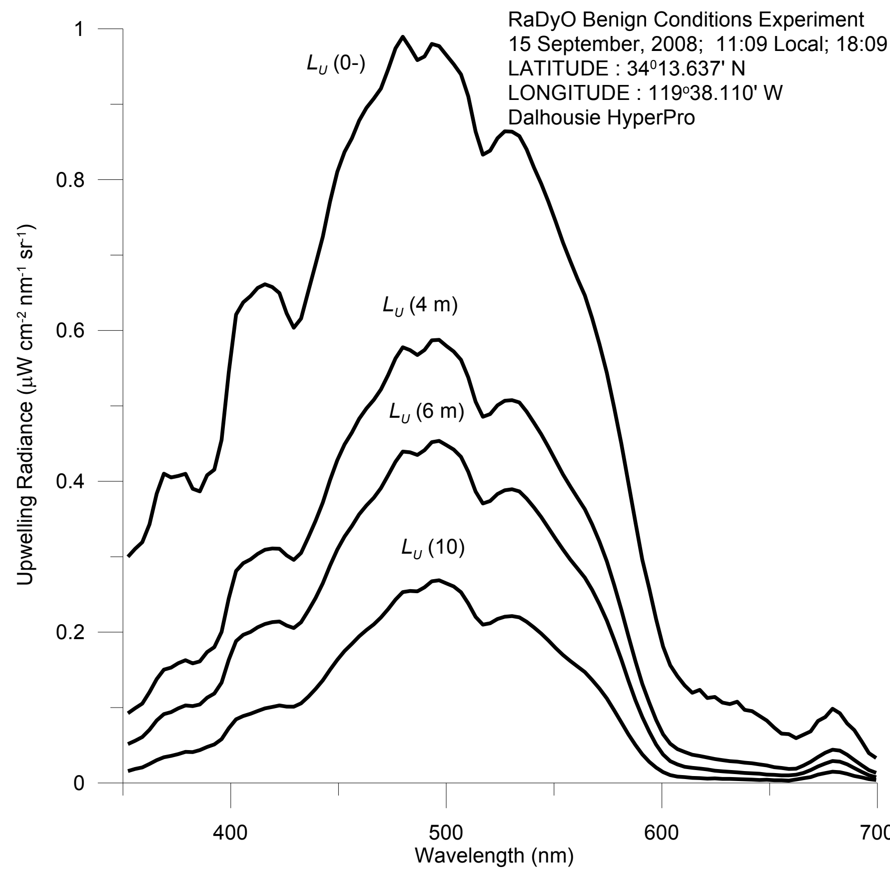
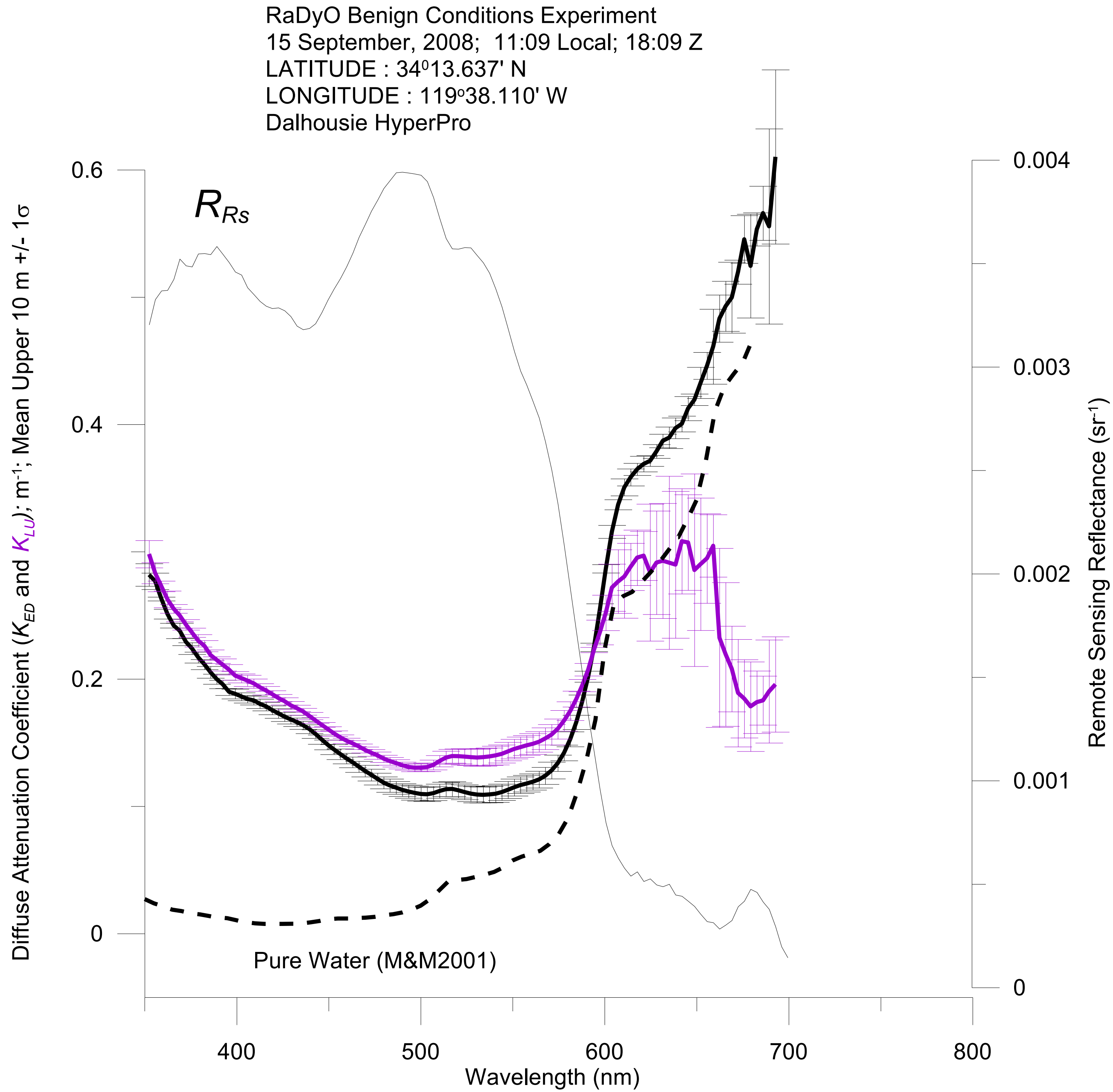


Downwelling Spectral Irradiance



Upwelling Nadir Radiance

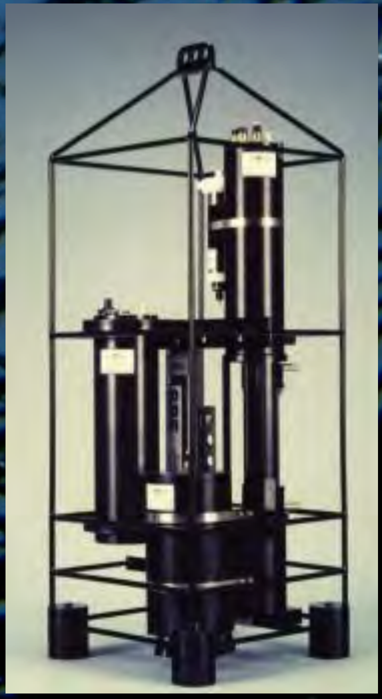




RaDyO Benign Conditions Experiment
15 September, 2008; 11:09 Local; 18:09 Z
LATITUDE : 34°13.637' N
LONGITUDE : 119°38.110' W
Dalhousie HyperPro
R_{Rs}
Diffuse Attenuation Coefficient (K_{ED} and K_{LU}); m^{-1}; Mean Upper 10 m +/- 1σ
Remote Sensing Reflectance (sr^{-1})
Pure Water (M&M2001)
Wavelength (nm)
0
0.2
0.4
0.6
0
0.001
0.002
0.003
0.004
400
500
600
700
800

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, Flntu, VSF)
- CTD
  - – Conductivity, temperature, depth

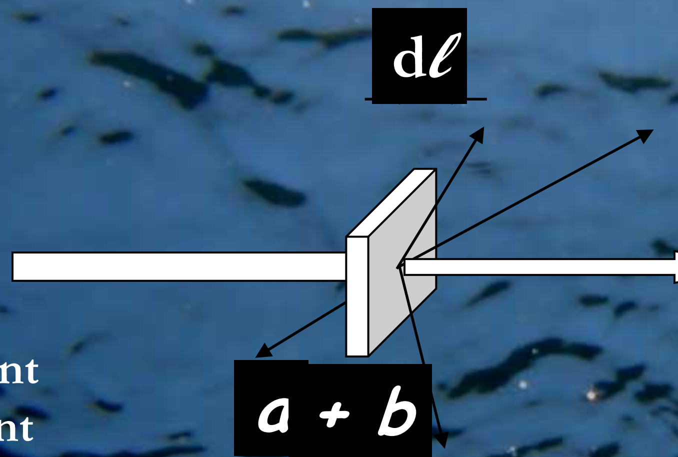


Attenuation: theory to measurement

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

Φ_o

Incident Radiant Power (W)



Φ_ℓ

Transmitted Radiant Power (W)

$$c \equiv a + b$$

$$c\Phi = -\frac{d\Phi}{d\ell}$$

Differential Equation with solution:

$$\Phi_\ell = \Phi_0 \exp\left(-\int_0^\ell c\, d\ell\right)$$

After integration:

$$\Phi_\ell = \Phi_0 e^{-\bar{c}\ell}$$

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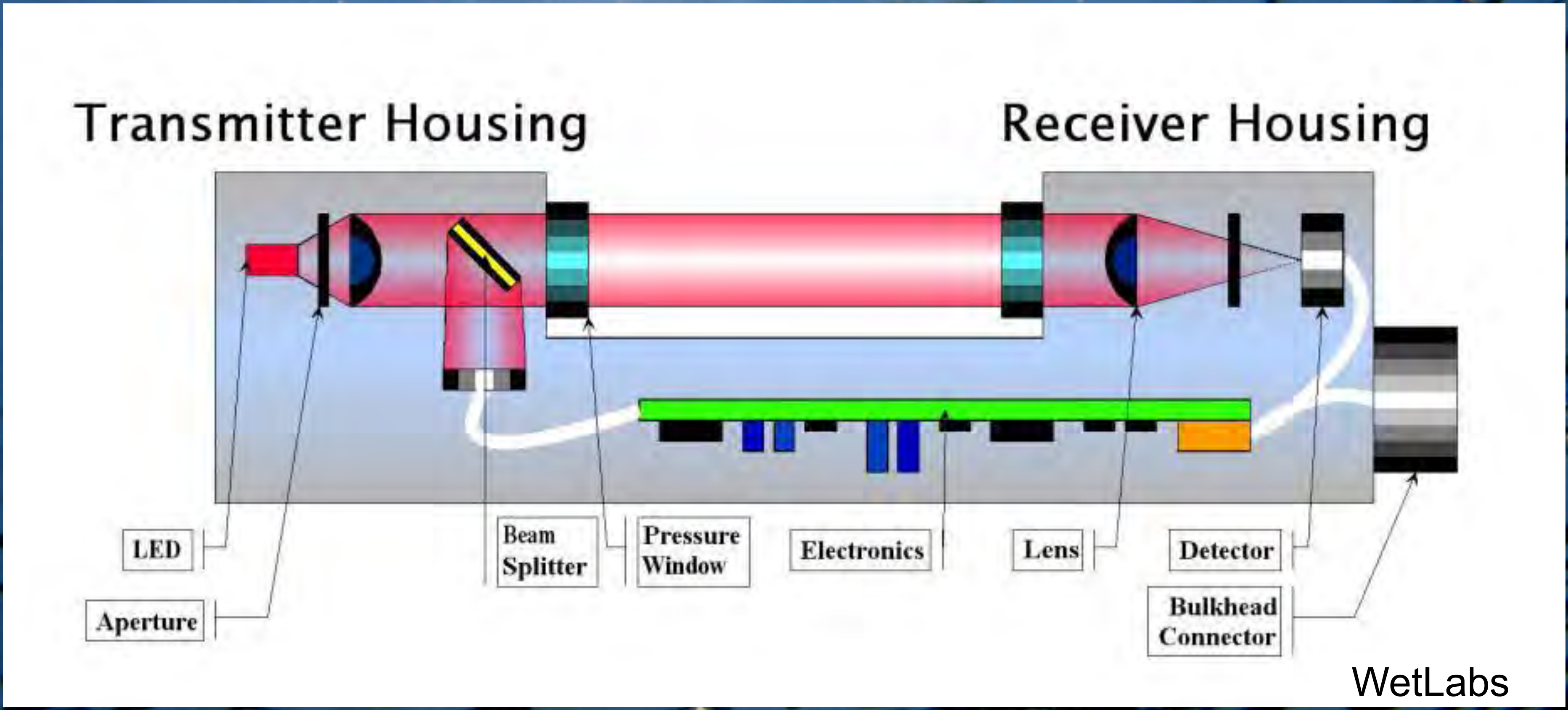
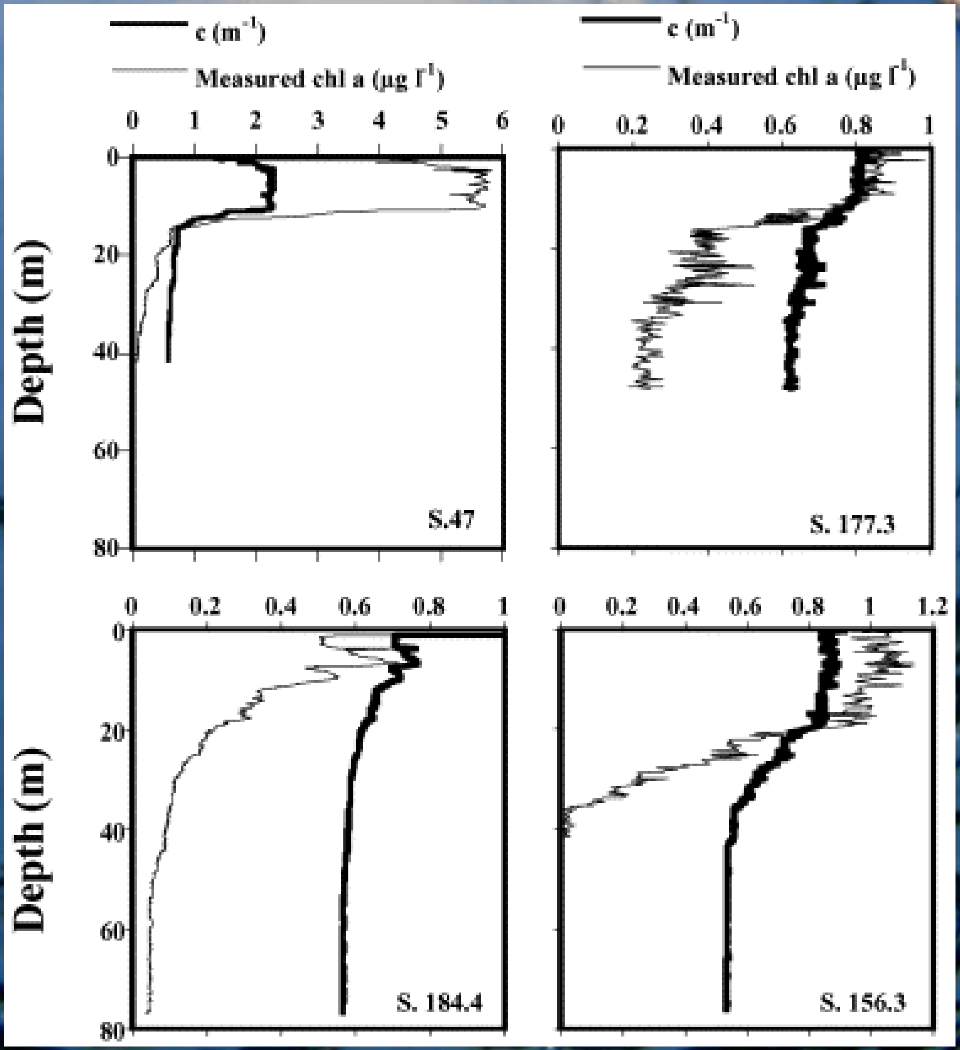
Beam attenuation meter



Measure of water clarity, POC, particles

Some things to think about….

- Acceptance angle – for C-Star, 1.2 degrees
- “Reference” or clear-water baseline – clear water is very difficult to “make”, transport, store
- “noise” (signal?) due to individual or
  aggregates of particles



Figuero 2002

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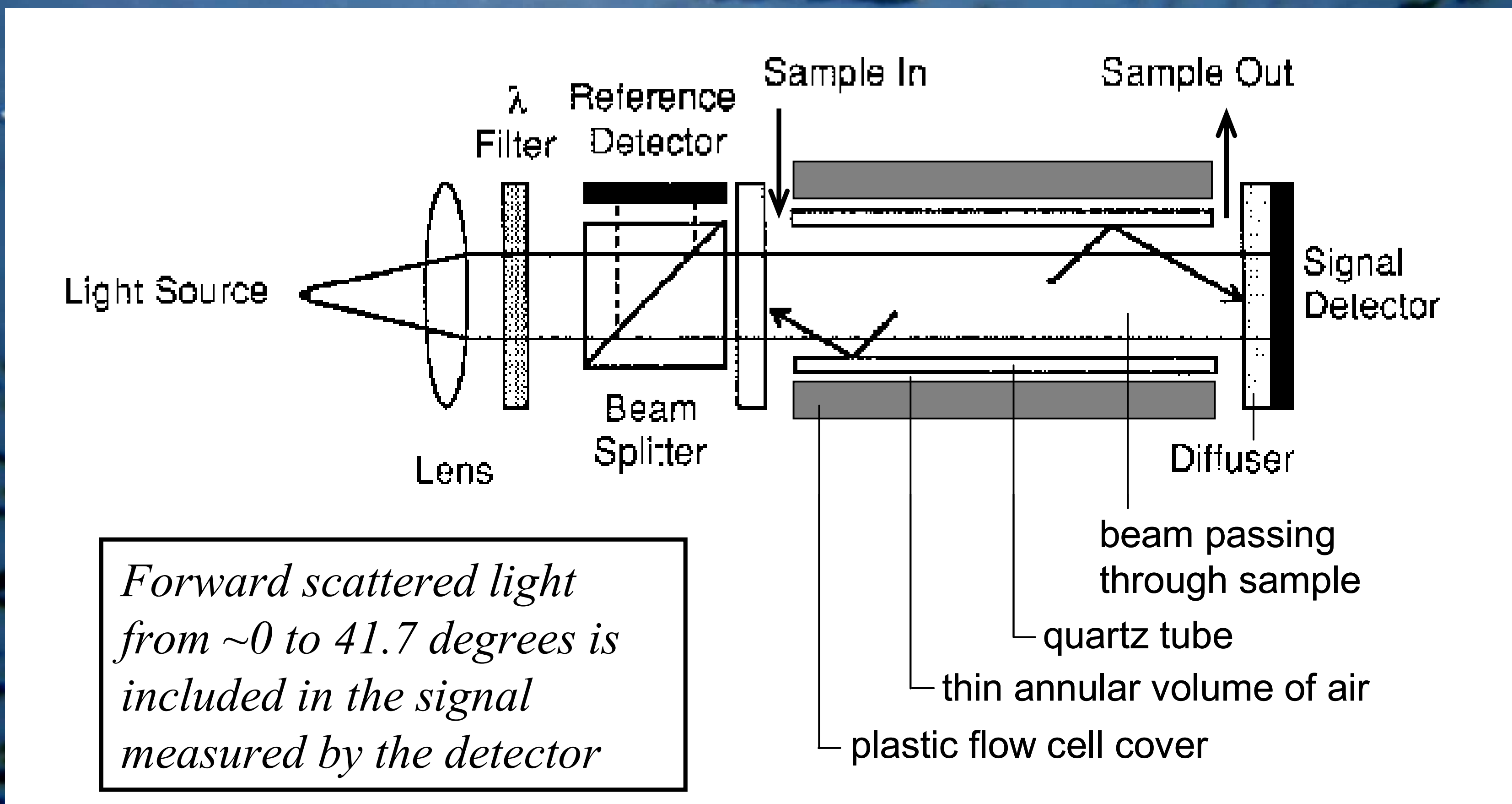
Methods of measuring absorption in situ

- 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



Adapted from Zaneveld et

adapted

Practicalities in measuring absorption with a reflective tube

- Calibration and accuracy practicalities same as *c* measurement
- **Scattered light from ~41°-180° not measured**
  - error usually ~10% of *b* and there are correction schemes (

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

TIR=Total Internal Reflection

Or expressed more accurately, there is a weighting function, *W(θ)*, that defines the scattering error:

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

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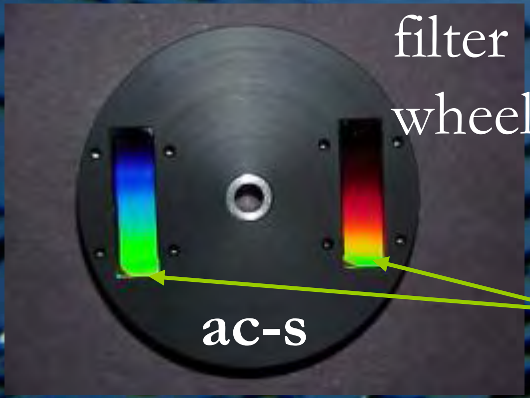
ac-9 and ac-S



Linear Variable Filters (LVFs)

Point-Source Integrating Cavity approaches(Kirk, 1997)

PSI-Cam, Rudiger Rottgers

a-sphere, HOBI Labs

Liquid Capillary Waveguide Approaches

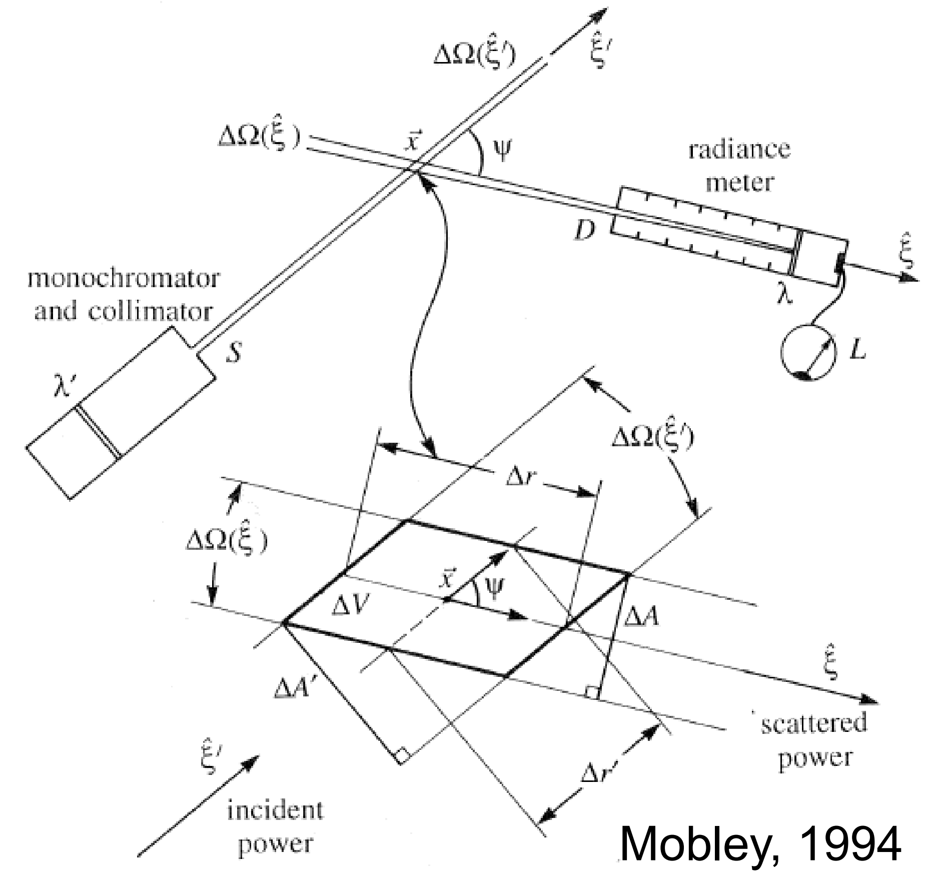
Fiber optic cells that combine an increased optical pathlength (50–500cm) with small sample volumes (125–1250μL). They can be connected a spectrophotometer and sensitive absorbance measurements can be performed in the ultraviolet (UV), visible (VIS) and near-infrared (NIR) to detect low sample concentrations.

World Precision Instruments

Scattering

1. Full volume scattering function

2. Scattering at sub-sets of angles



Mobley, 1994

Volume Scattering Function

Deep-Sea Research, 1968, Vol. 15, pp. 423 to 432.

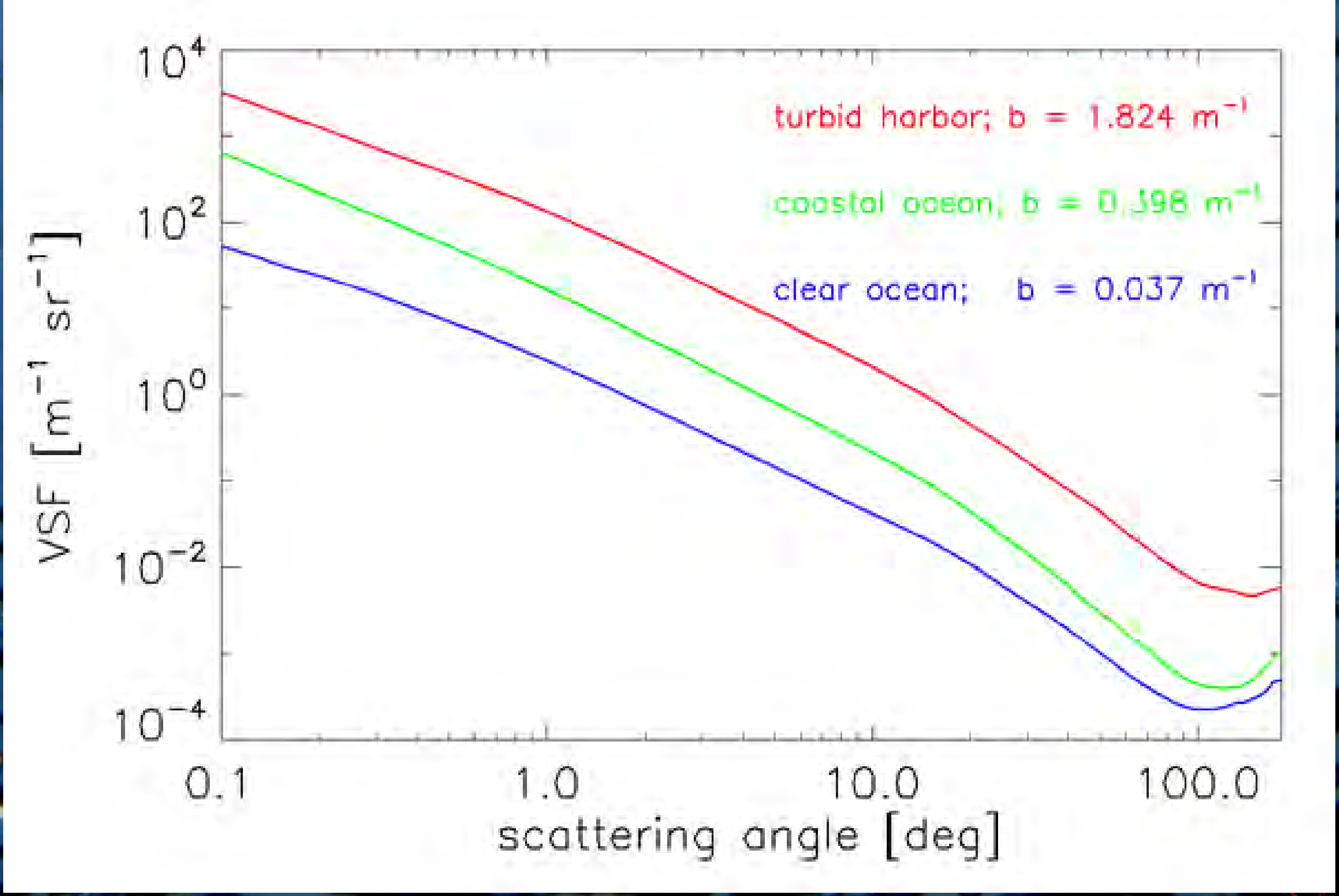
Scattering of light by Sargasso Sea water

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.

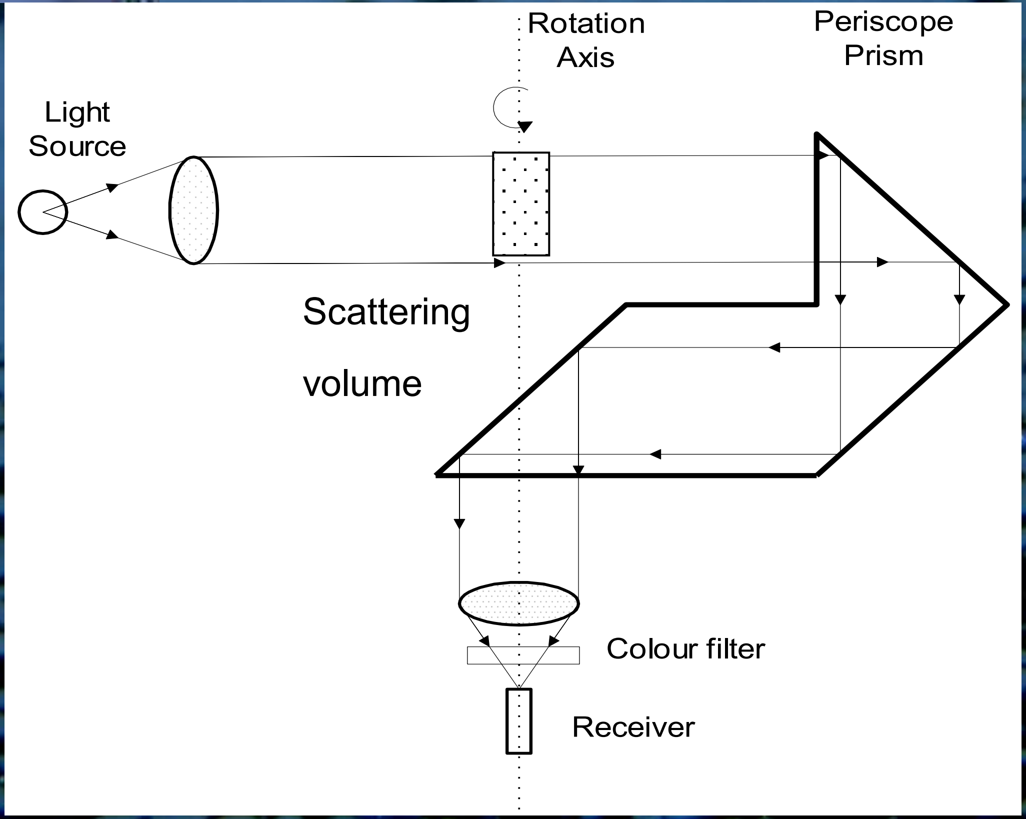
The (in)famous Petzold measurements (1972)



SATLANTIC

The “Ukrainian Instrument” MVSM

Lee, M., and M.R. Lewis. 2003. A new method for the measurement of the optical volume scattering function in the upper ocean. *J. Atmos. Oceanic Tech.* 20: 563-571



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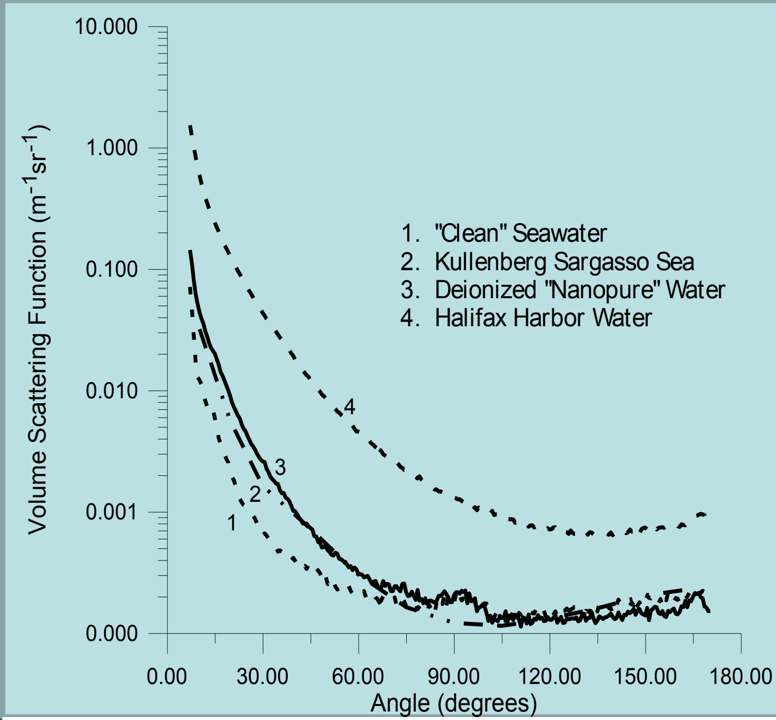
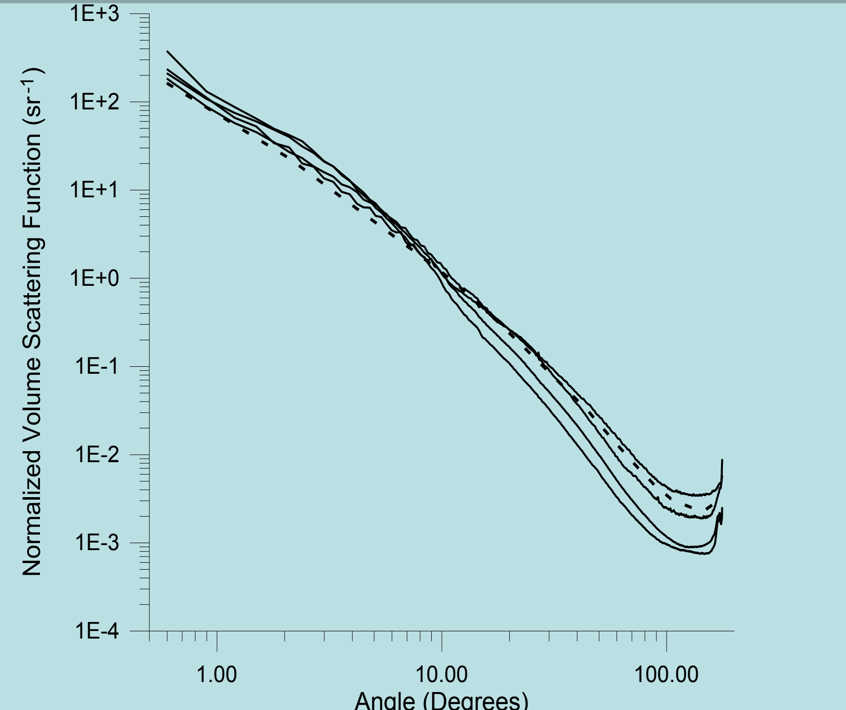
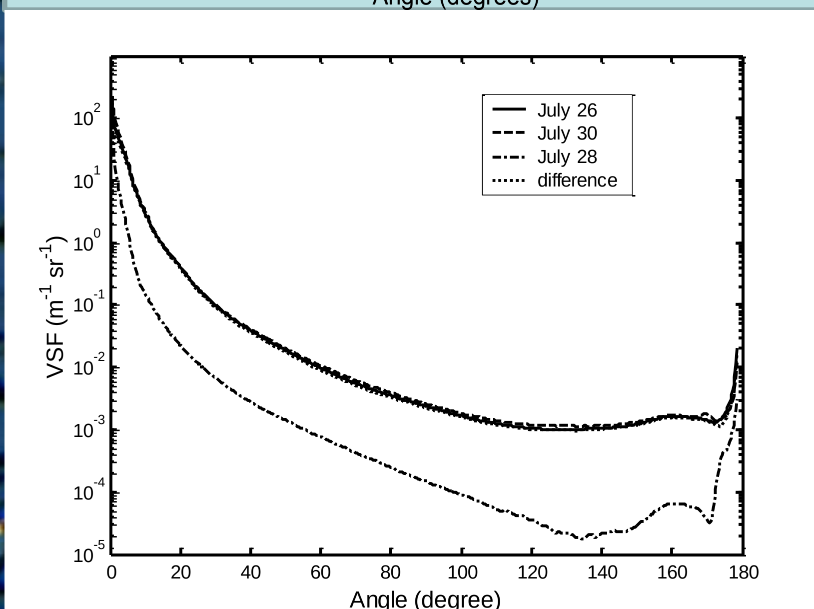


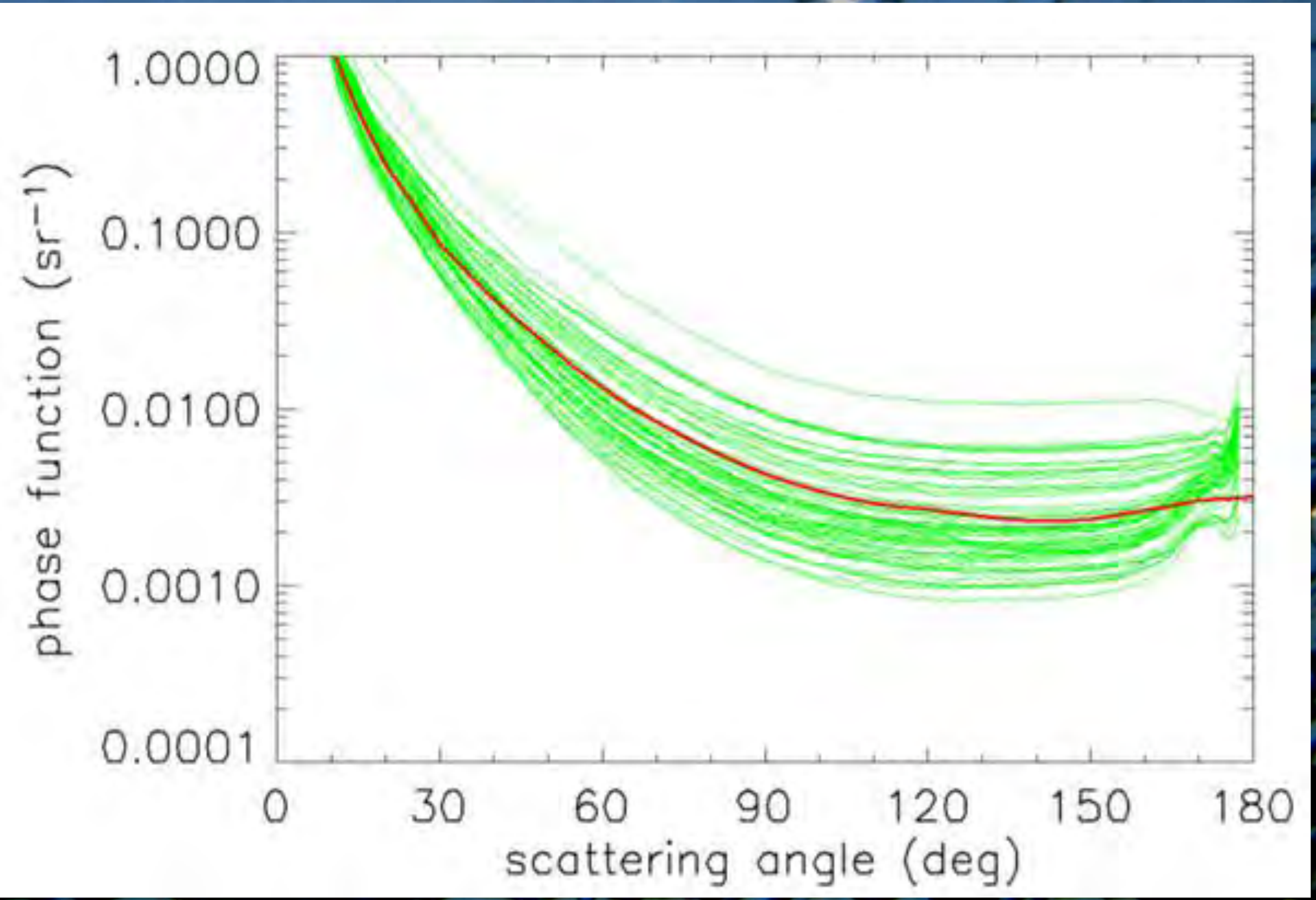


Lee and Lewis, 2003



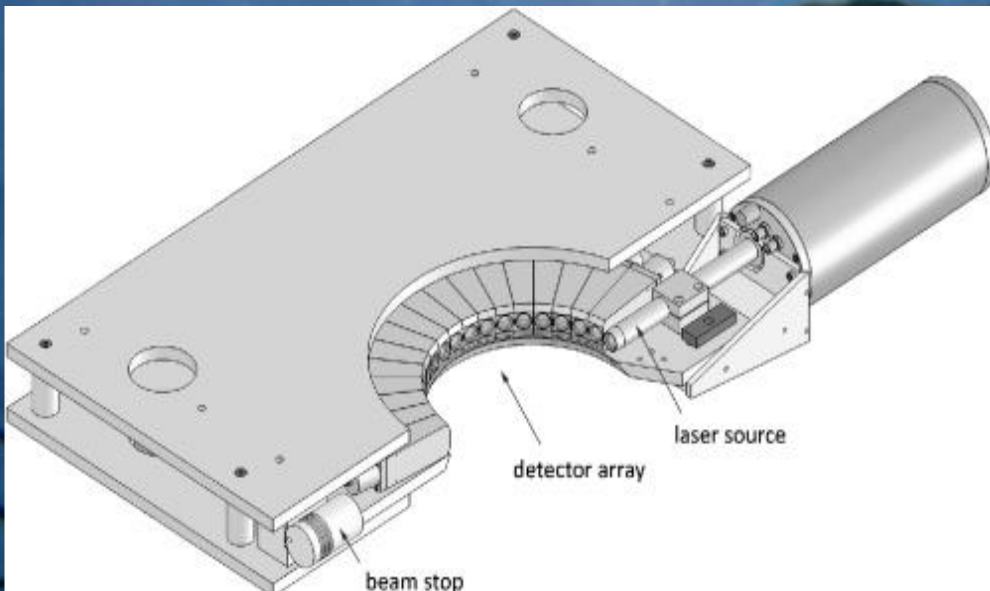
Zhang et al., 2006

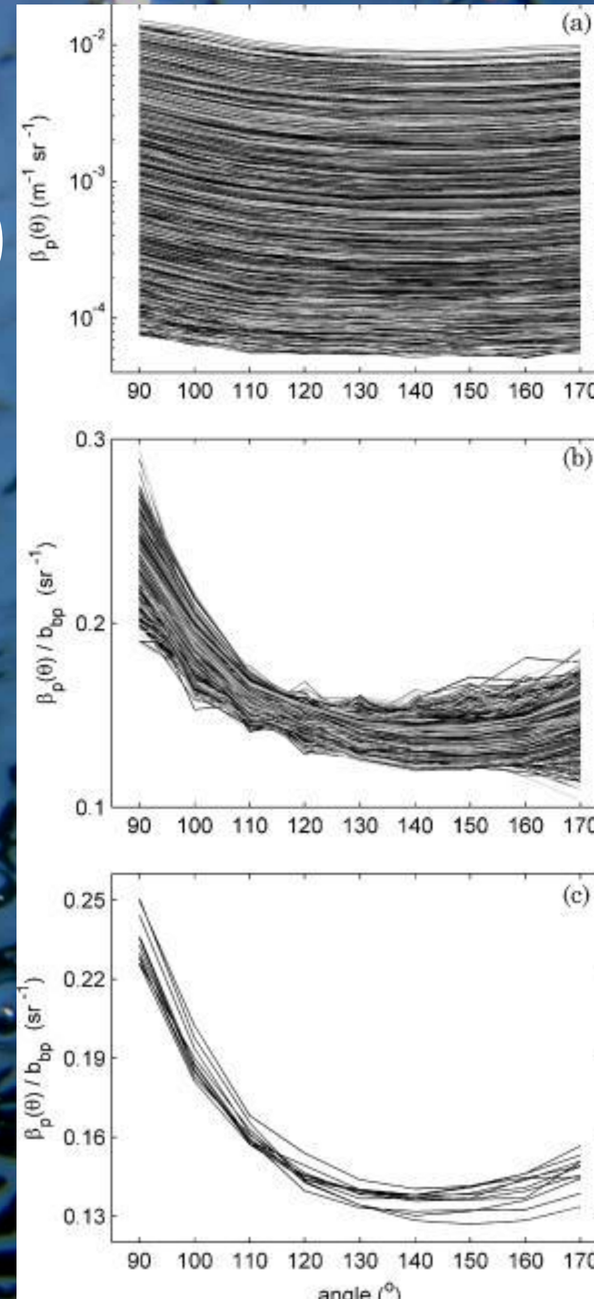
Wide range of variation in coastal,open ocean waters.



ATLANTIC

Multi-Angle Scattering Optical Tool (MASCOT)





Mike Twardowski, WETLabs

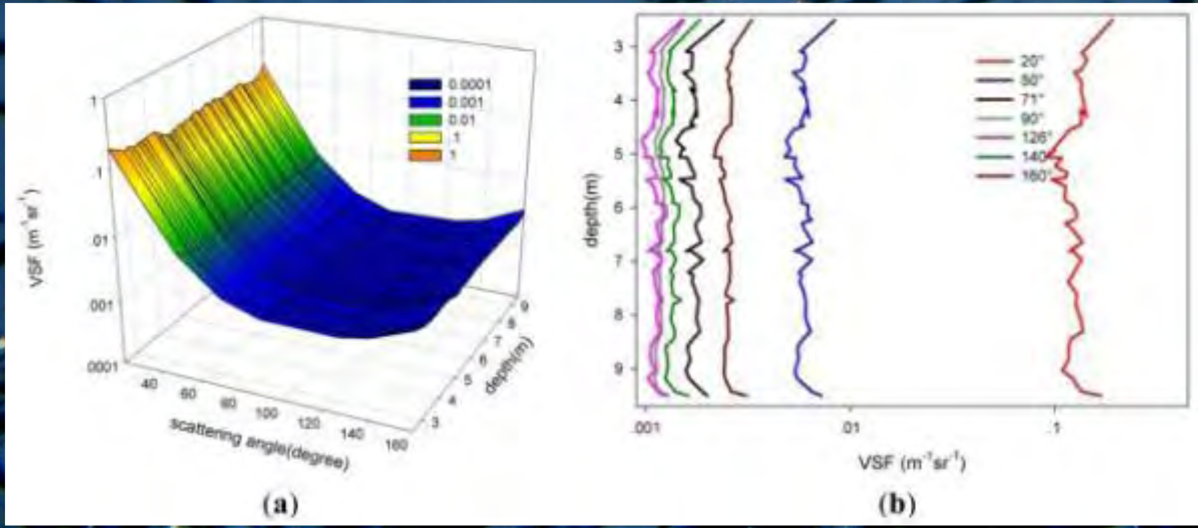
A new one!

Published online 2012 April 10. doi: 10.3390/s120404514
PMCID: PMC3355425

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 Guo[1]

State Key Laboratory of Oceanography in the Tropics, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China;



Forward angle scatter

New – forward + wide angle + pol

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.

Sequoia Instruments

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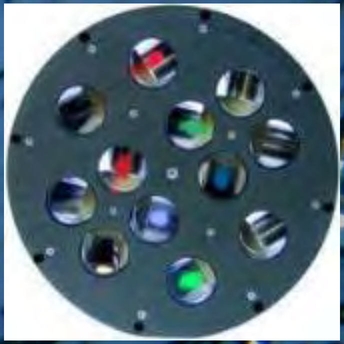
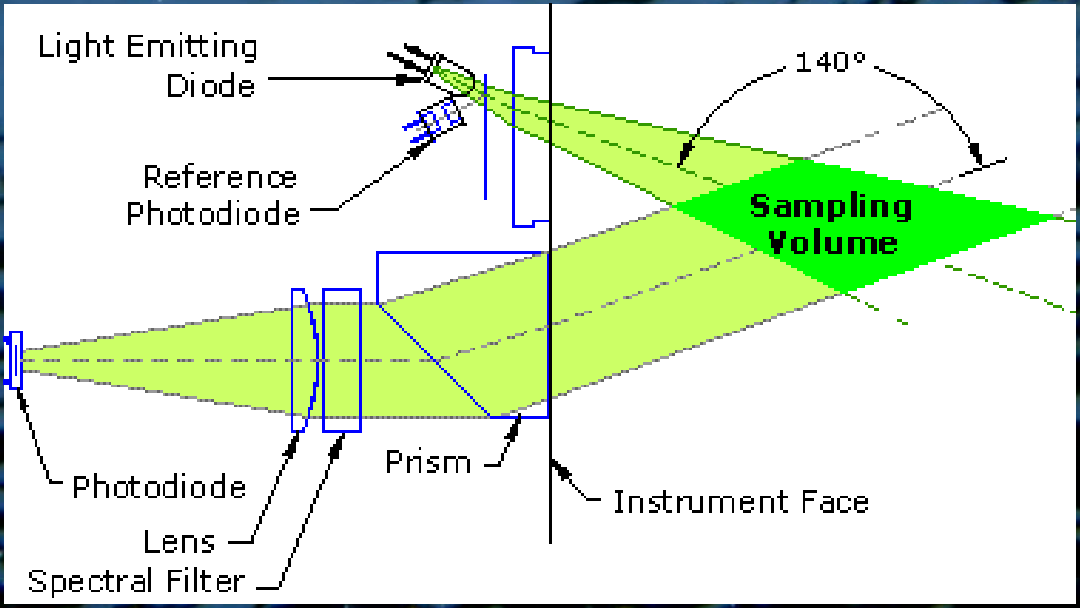
Fixed angles in the backward direction - HobiLabs.

Hydroscat 2

Hydroscat 4

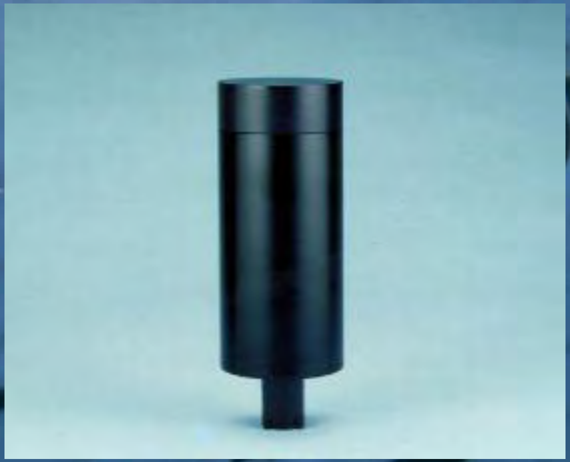


Hydroscat 6



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

BB-9 measures at 9 angles or 9 wavelenghts or combinations

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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[1,*], Marlon R. Lewis[2,3], Scott D. McLean[3], Michael S. Twardowski[4],Scott A. Freeman[4], Kenneth J. Voss[1], and G. Chris Boynton[1]

Optics Express 17: 16192-16208, 2010.

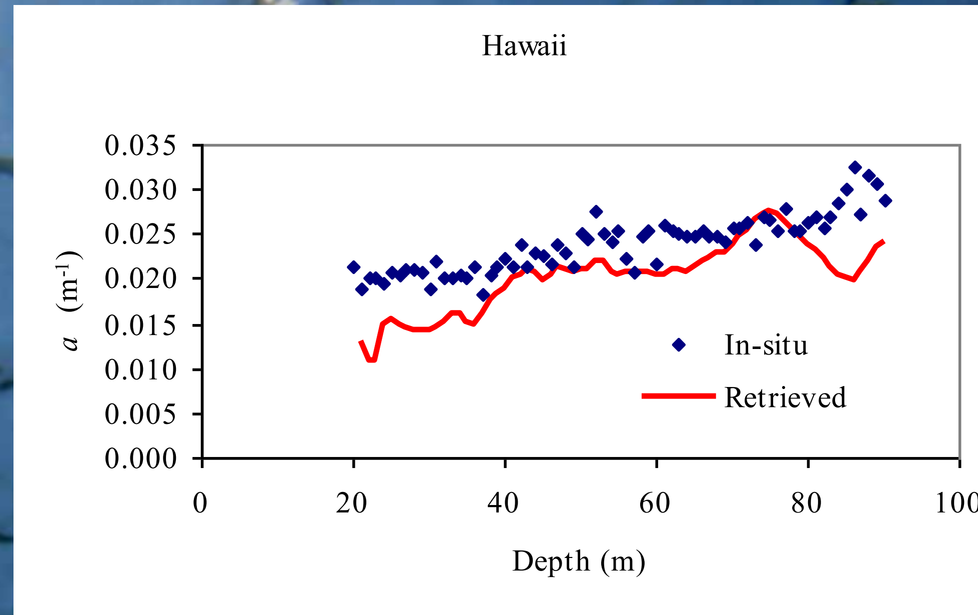
1. Measure, with great care, the vertical profile of hyperspectral downward irradiance, and upward radiance (HyperPro, Lewis and McLean).

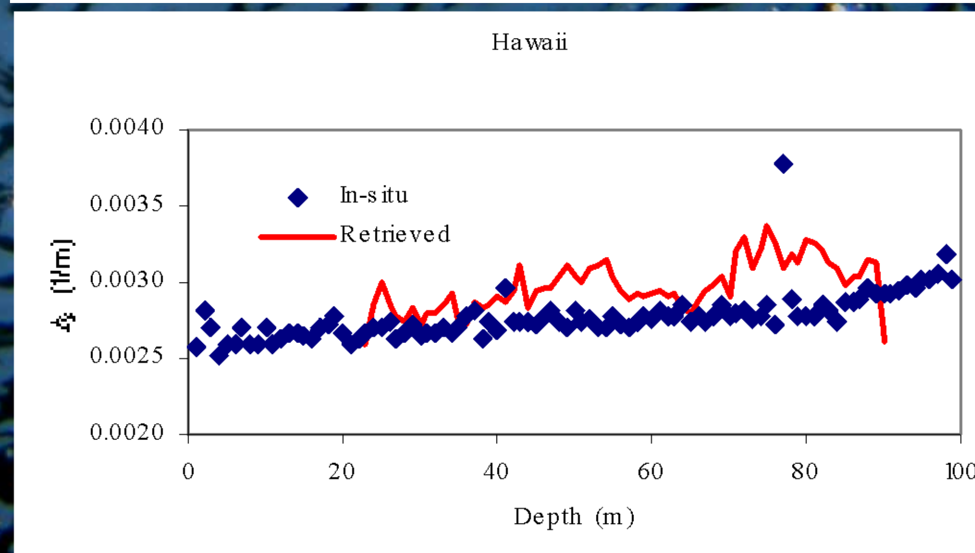
2. Measure, with great care, the vertical profile of the absorption coefficient and the backscattering coefficient at several wavelengths (Twardowski and Freeman.

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).

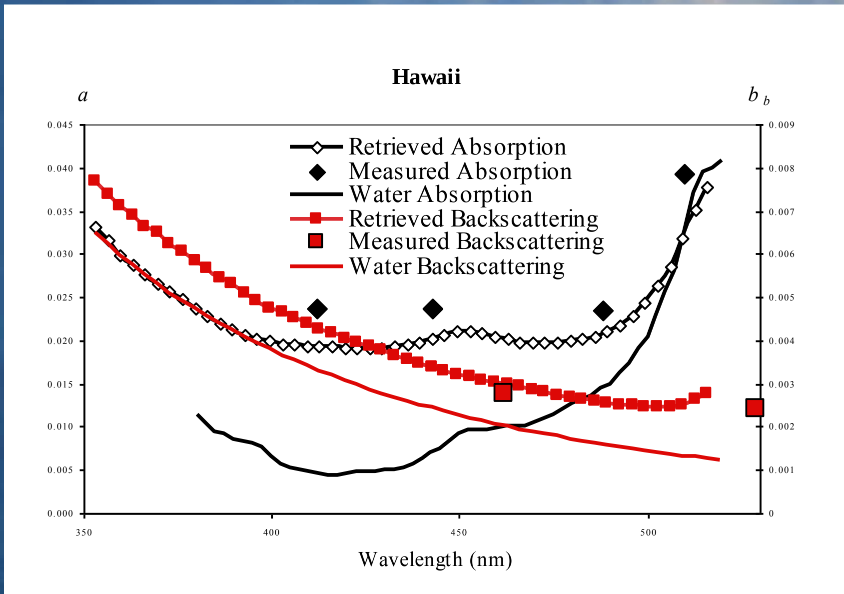
Results (depth profile)

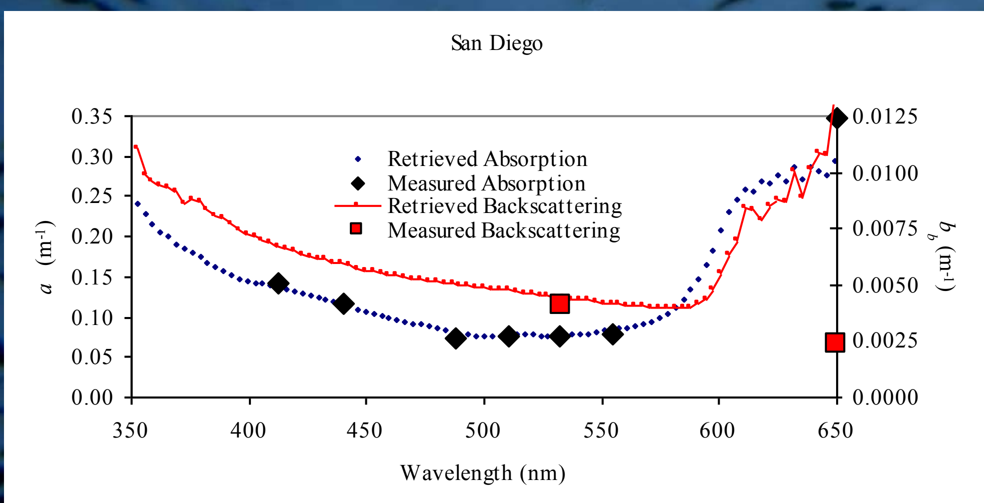




Comparison of retrieved and *in-situ* vertical profiles of absorption (top at 443 nm) and backscattering (bottom at 462 nm) at the station off Lanai, Hawaii.

Results (hyperspectral)





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

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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?

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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:

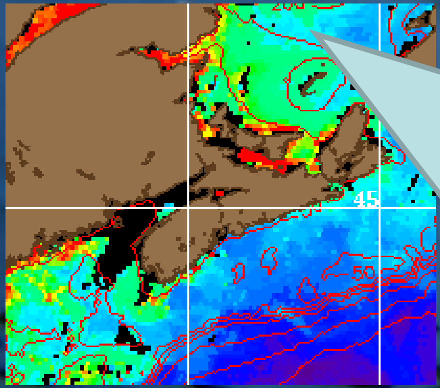
We would like to predict – in a *hindcast* (what did things look like before?), *nowcast* (what do things look like now?) and *forecast* (what will things look like in the future) sense – the three-dimensional fields of ocean biogeochemical properties and processes.

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.

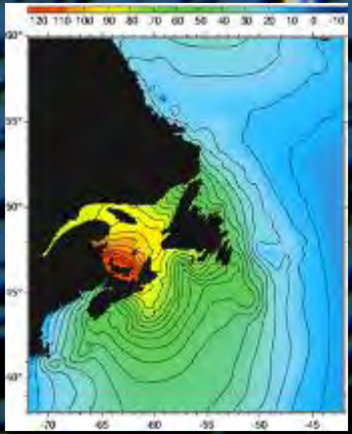
And we would like to do this with significant "skill", that is, we wish to explain a significant fraction of the observed variance.

What do we need to do this? : Marine Environmental Prediction

Observations



Understanding

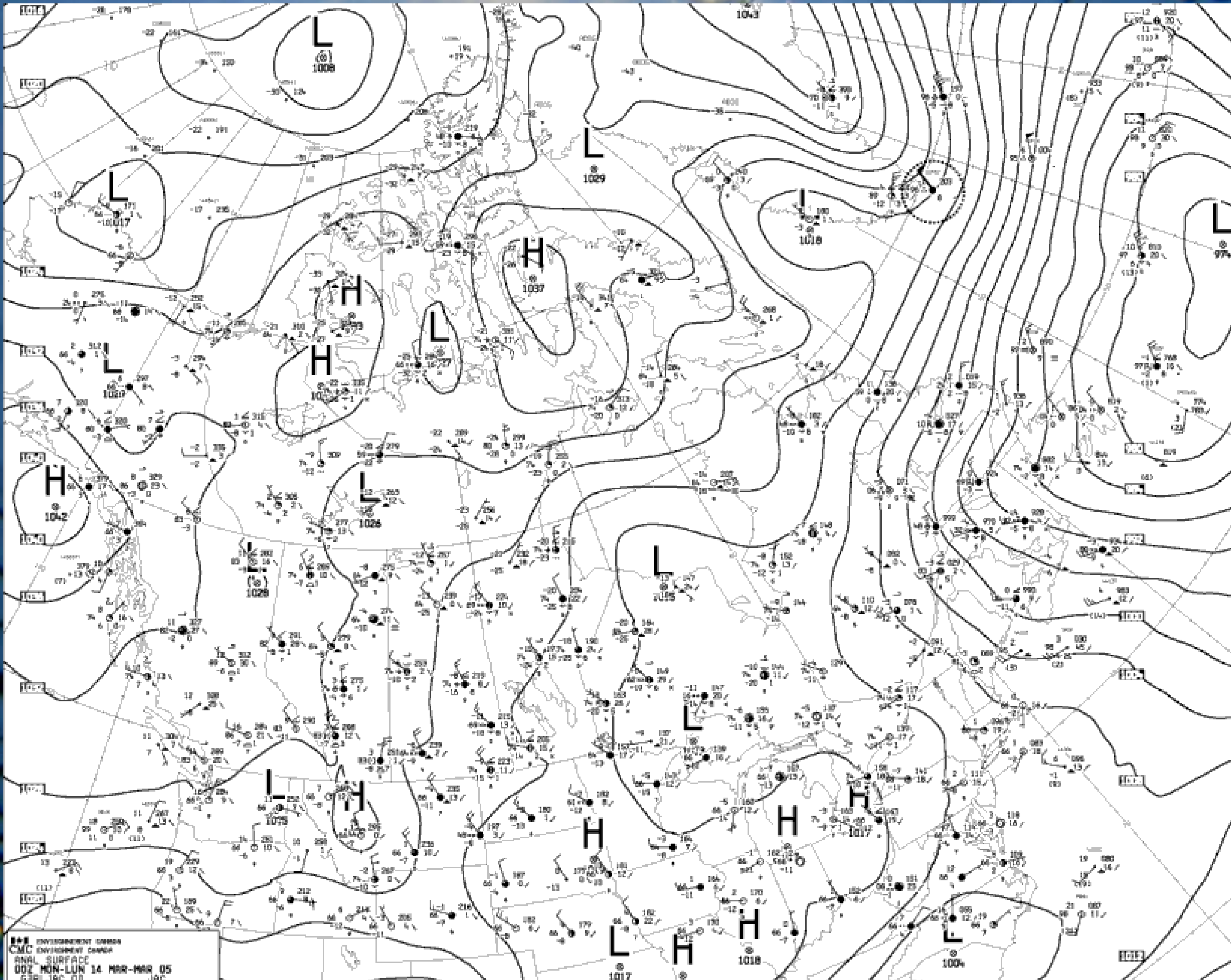


Prediction

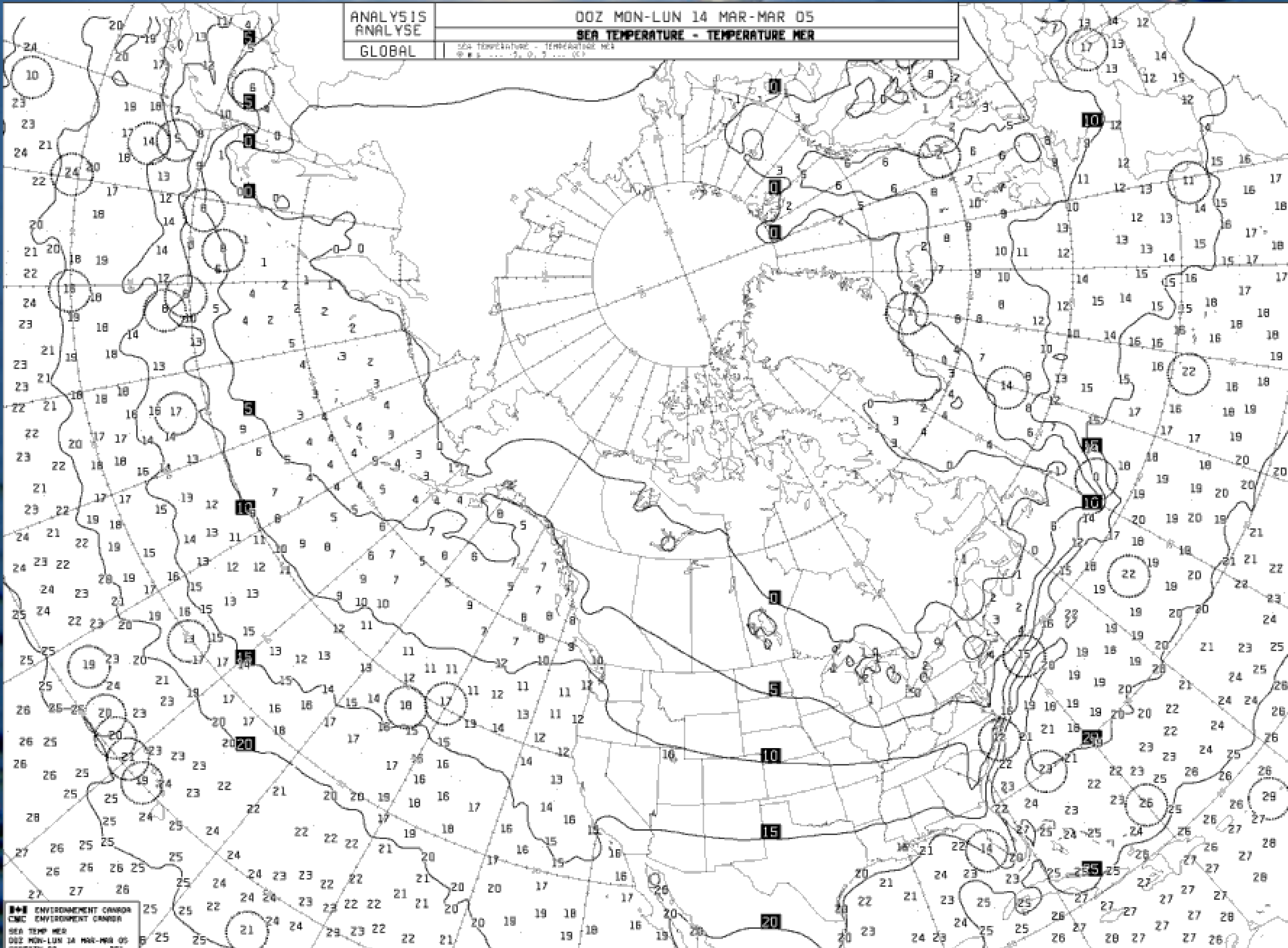
Data assimilation

- 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



Sea Surface Temperature



Sometimes….data is just not enough…nor are models sufficient.

- The basic objective information that can be used to produce the analysis is a collection of observed values provided by observations of the true state.
- If the model state is overdetermined by the observations, then the analysis reduces to an interpolation problem. In most cases the analysis problem is under-determined because data is sparse and only indirectly related to the model variables.
- In order to make it a well-posed problem it is necessary to rely on some *background* information in the form of an a priori estimate of the model state. Physical constraints on the analysis problem can also help.

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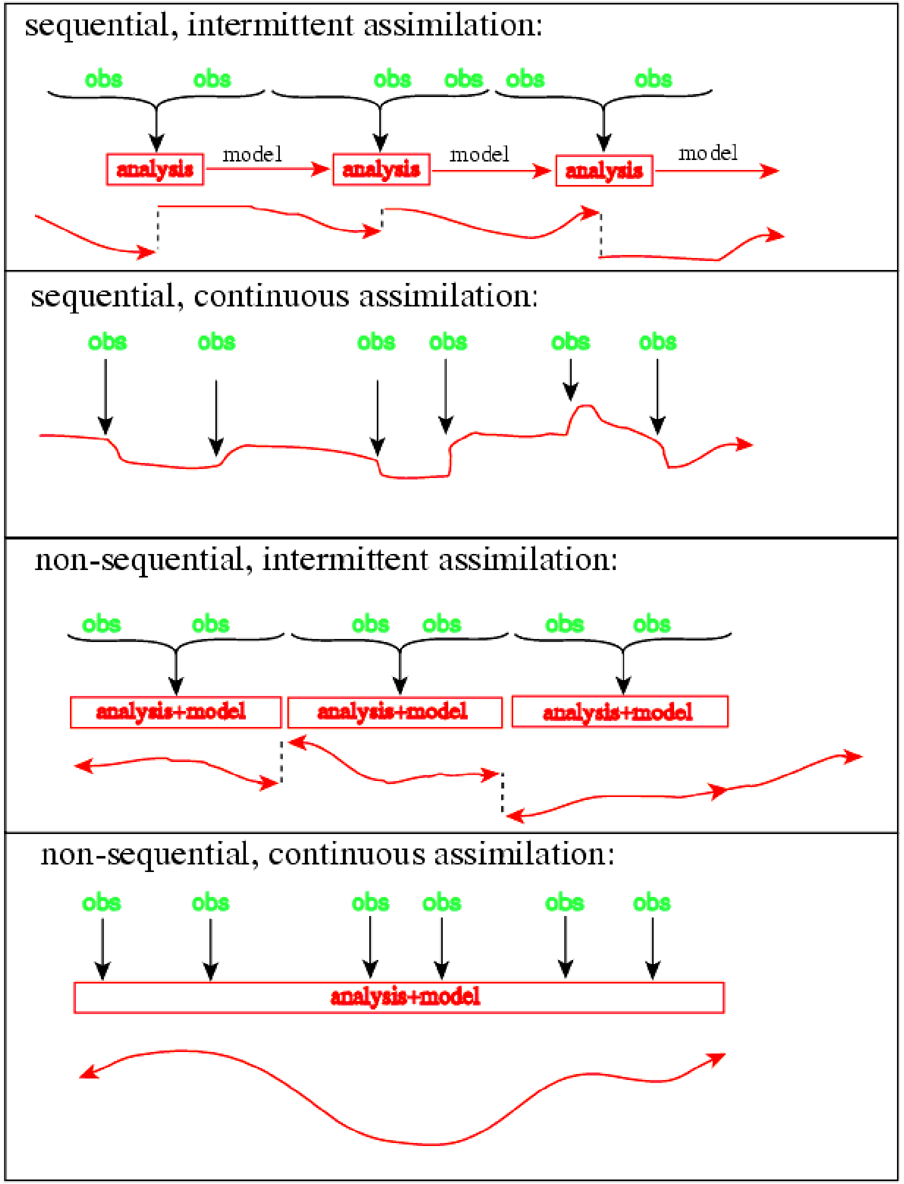
Data Assimilation

Data assimilation : analysis technique in which the observed information is accumulated into the model state by taking advantage of consistency constraints with laws of time evolution and physical properties.



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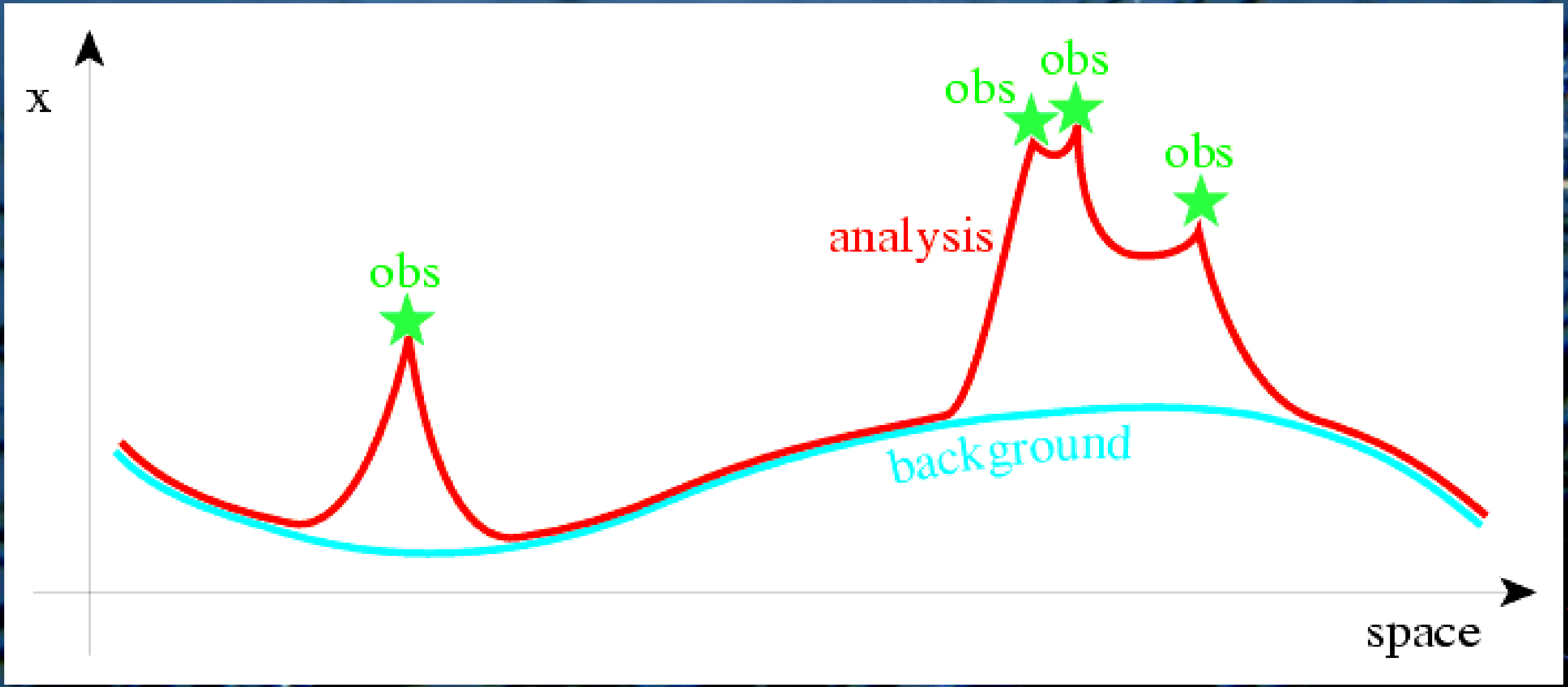
The Cressman approach is a (still used) data assimilation scheme used to merge models and data. Note that more weight can be given to the model (or climatology) by setting the weights less than one for *i=j* – this is termed the "successive correction method" (SCM). Essentially, this is then a weighted average between the background and the observation. It "works" pretty well.



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 and assimilation.

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

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Sensors on Autonomous / Lagrangian Platforms

Optical:

- active and passive optical sensors (radiometers, fluorometers, beam c, backscattering, biolumінesence)

Chemical:

- oxygen
- nutrients on larger platforms

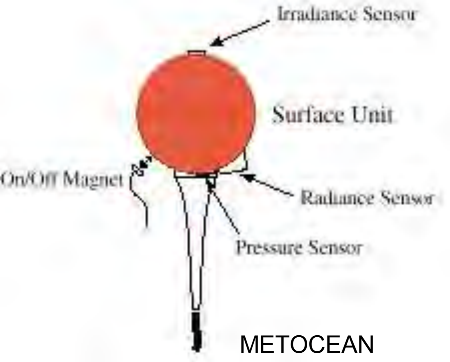
Other:

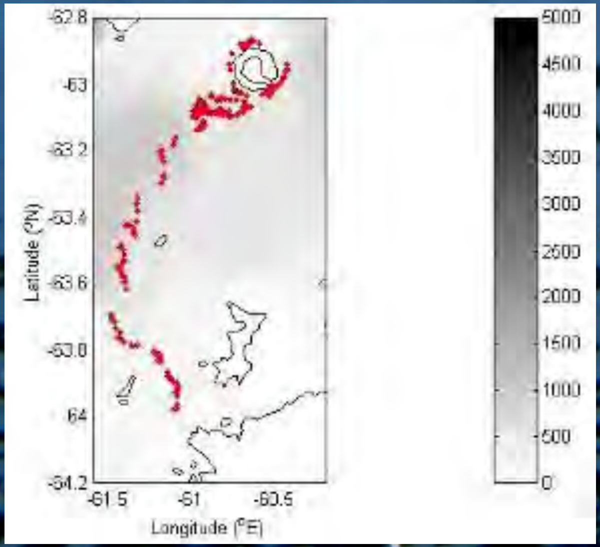
- acoustics, turbulence, etc.

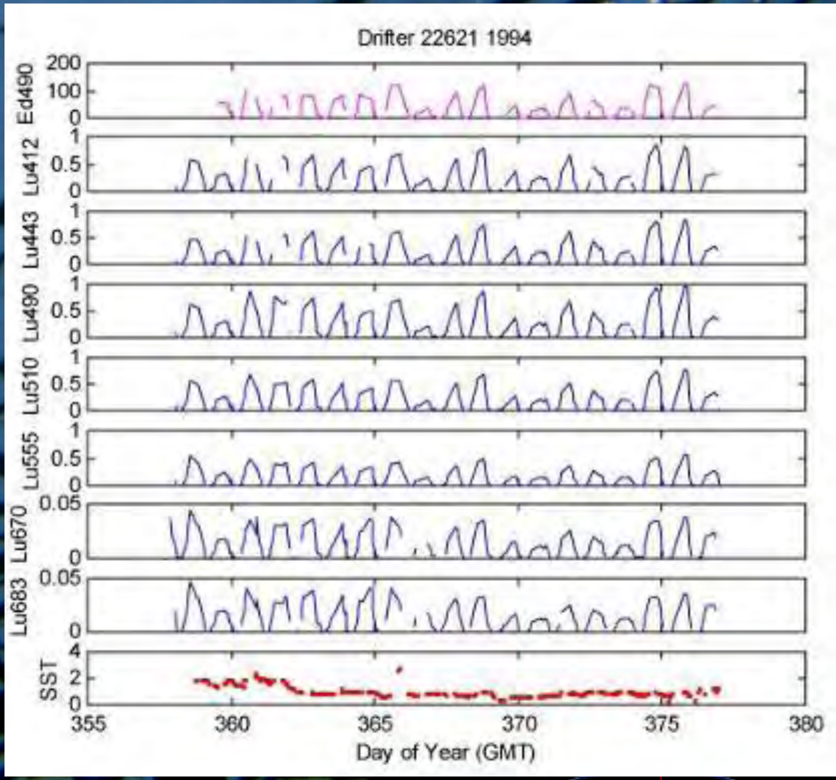
Credit: M.J. Perry

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.

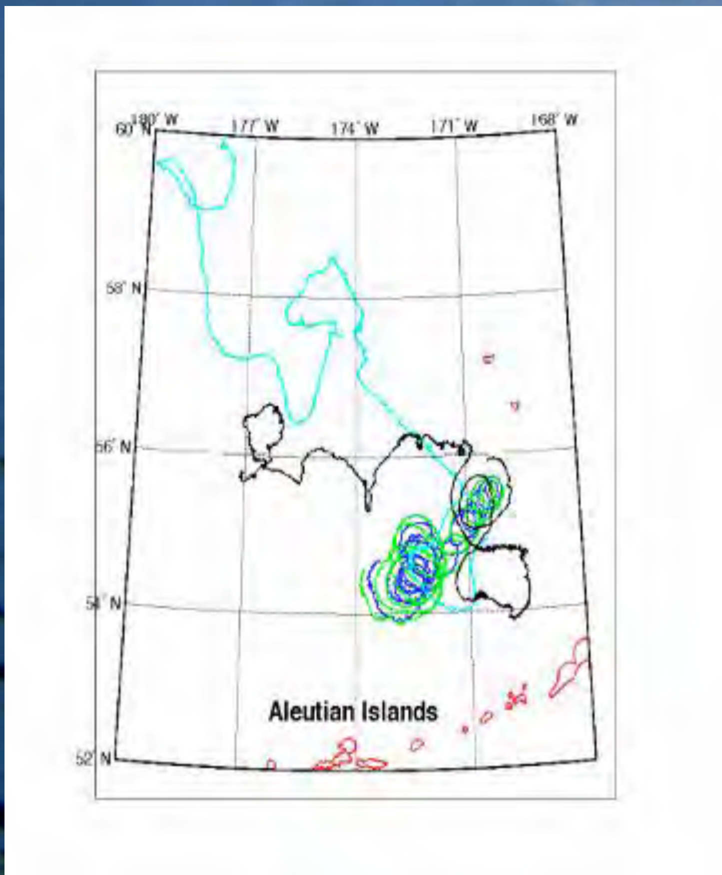


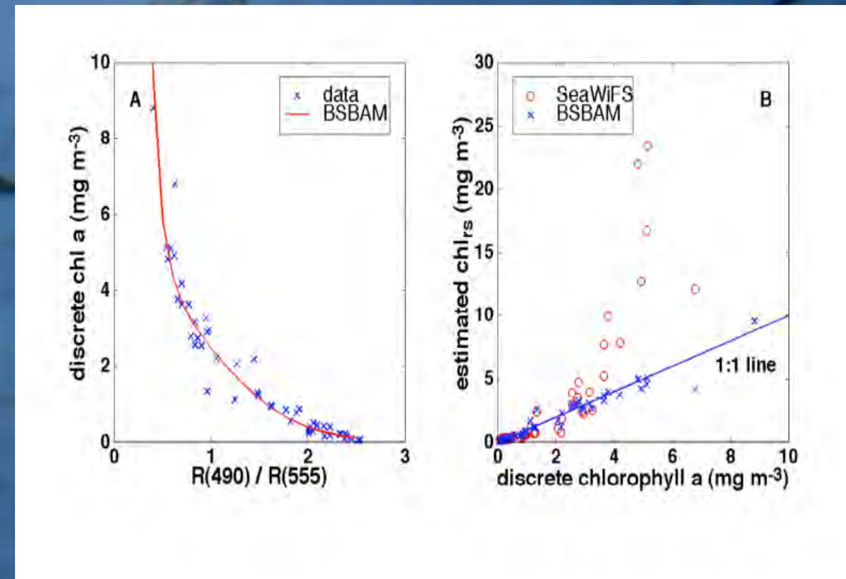


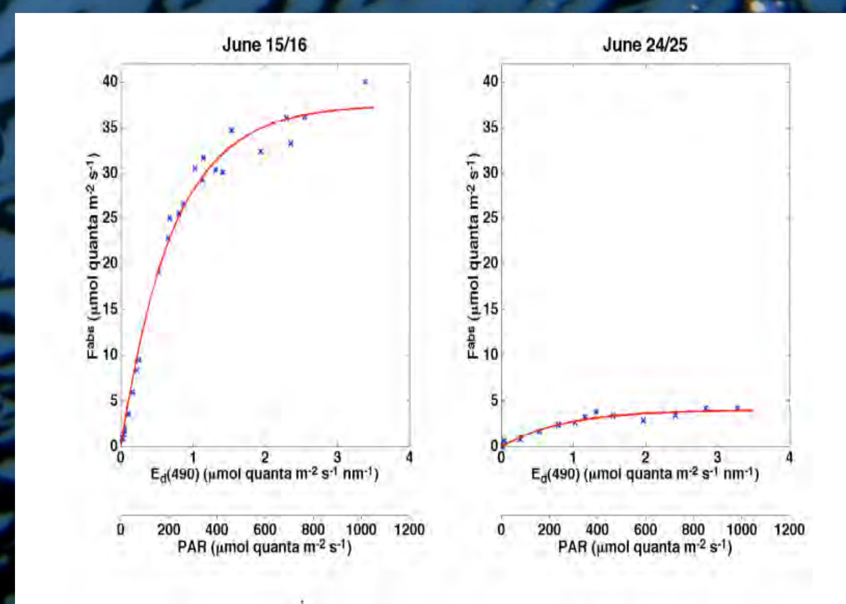


TEMPORAL VARIABILITY IN THE RELATIONSHIP BETWEEN SUNINDUCED FLUORESCENCE AND INCIDENT IRRADIANCE IN THE BERING SEA: AN EFFECT OF NUTRIENT AVAILABILITY?

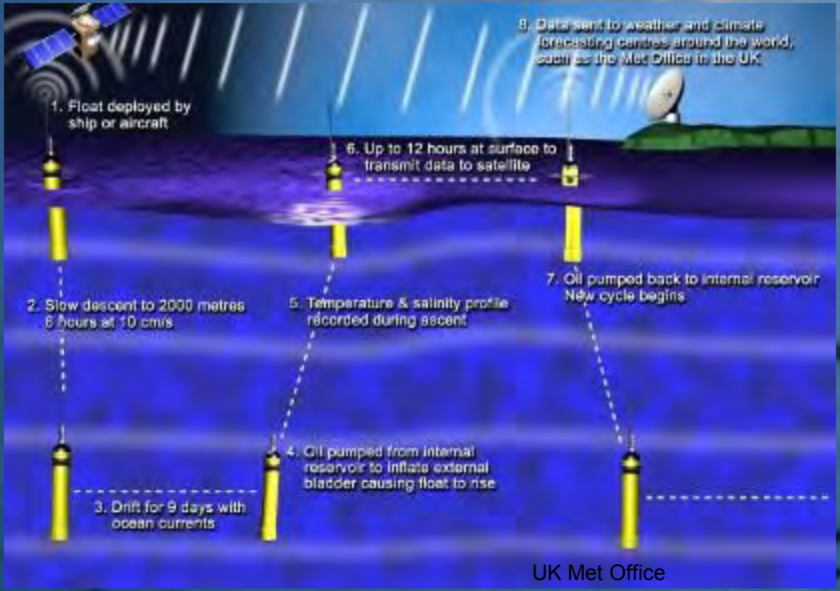
Christina Schallenberg, Marlon R. Lewis, Dan E. Kelley and John J. Cullen. JGR, 2007

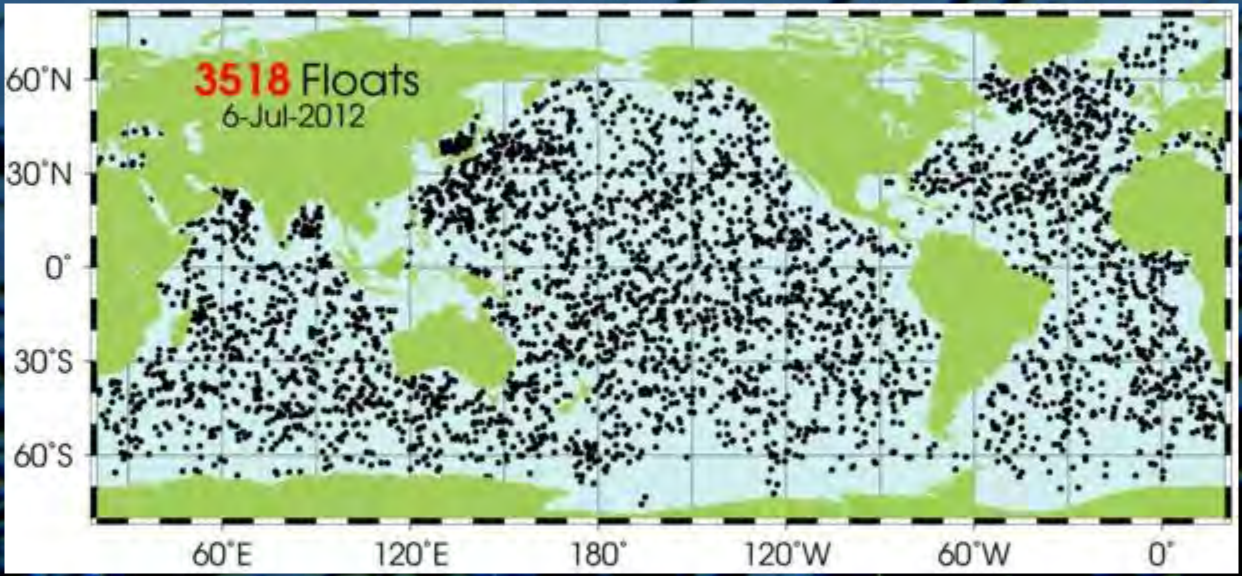






But….such surface drifters do not resolve vertical dimension. Profiling floats provide this capability.





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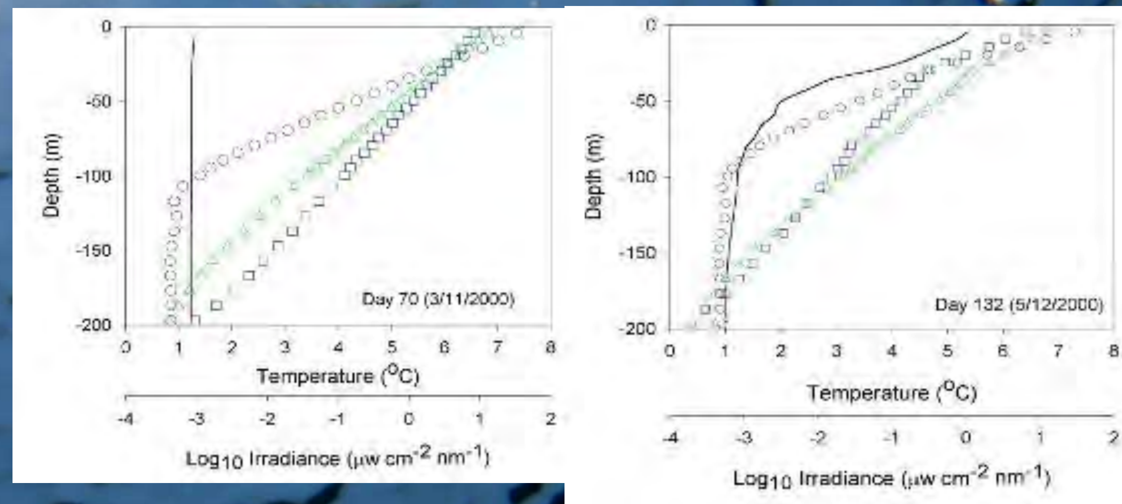
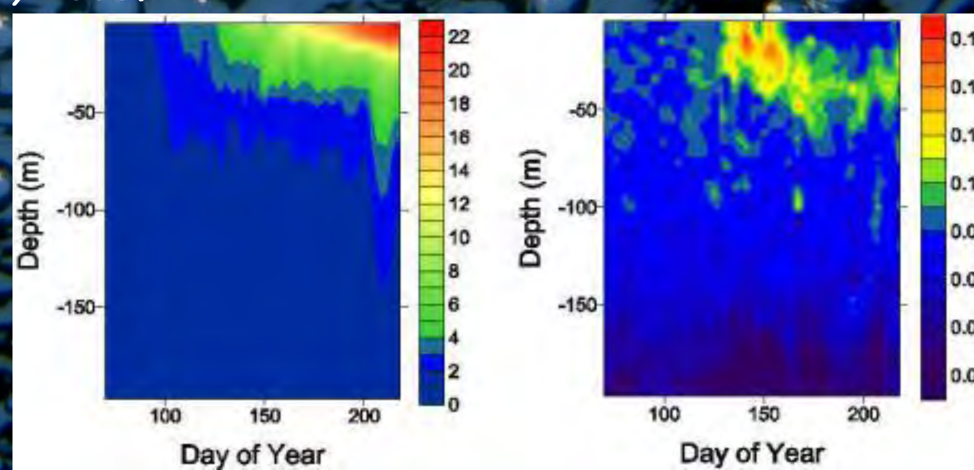
K-solo, Mitchell et al. 2001

Vertical gradient in irradiance (3 wavelengths) used to estimate diffuse attenuation coefficient ~ chlorophyll.



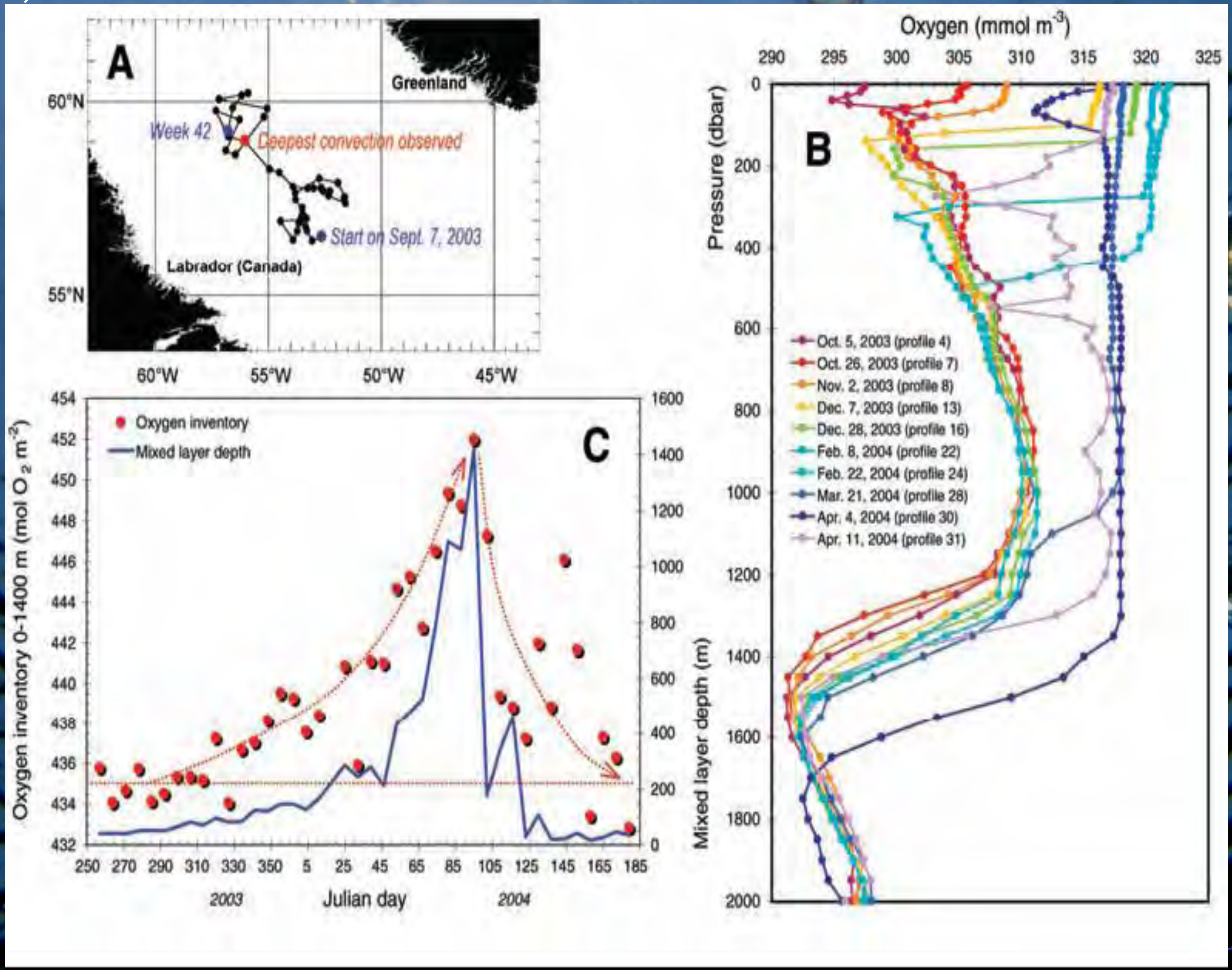
Vertical profiles of temperature (__) and irradiance at three wavelengths (380 m - ○; 490 nm - □; 555 nm - △) transmitted by KSOLO for A. March 11 and B. May 12, 2000.

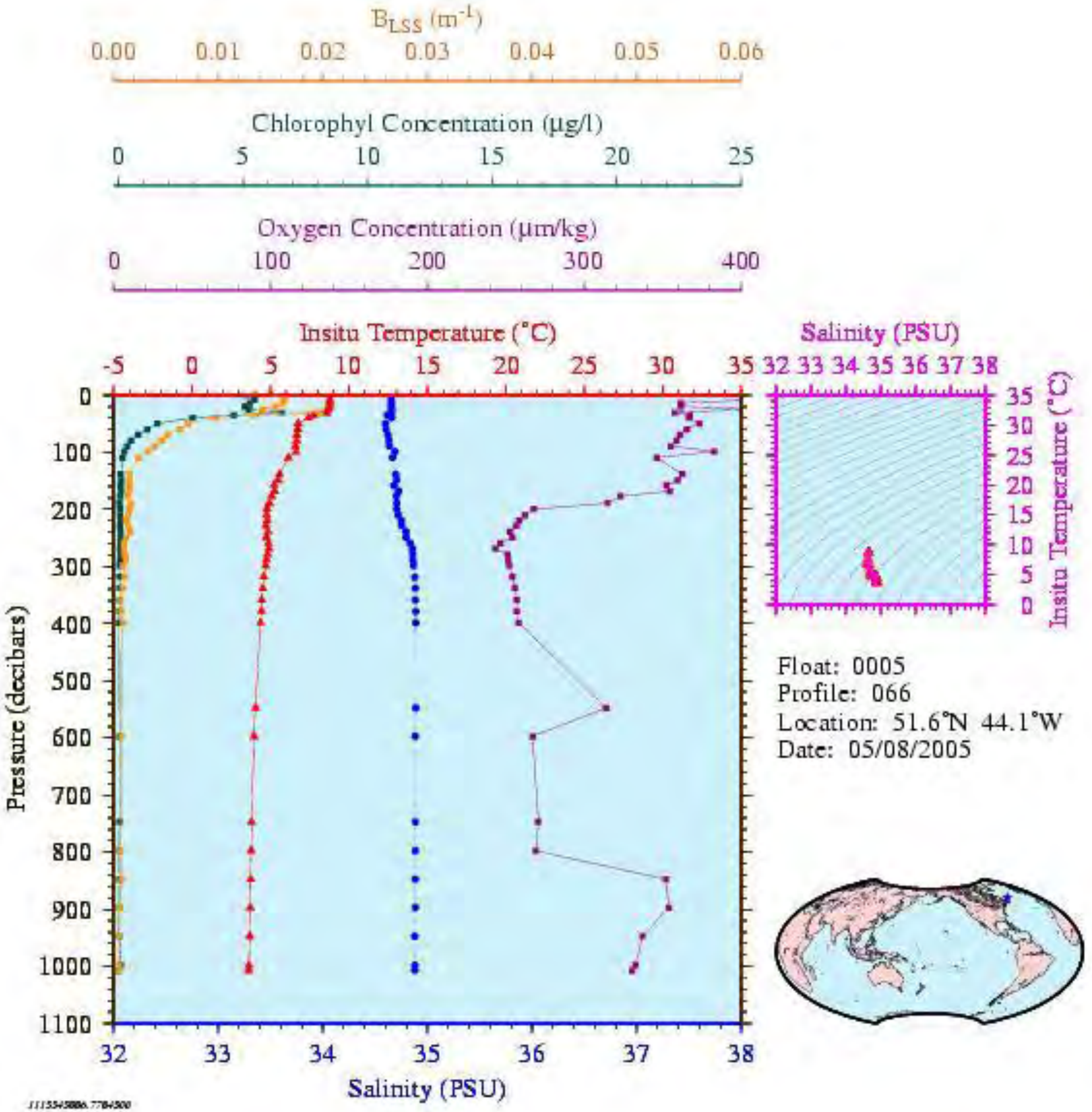


The Ocean Takes a Deep Breath

Arne Körtzinger, Jens Schimanski, Uwe Send, Douglas Wallace

Science, 2004





Emmanuel Boss

PRO-BIO (Satlantic + MARTEC + IFREMER +CNRS)

- 3-channel irradiance, beam-c, for chlorophyll, carbon, irradiance distribution.
- Requires Iridium satcomms solution.

+ radiomètre

$Ed(\lambda)$

+ Transmissiomètre

$c(660)$

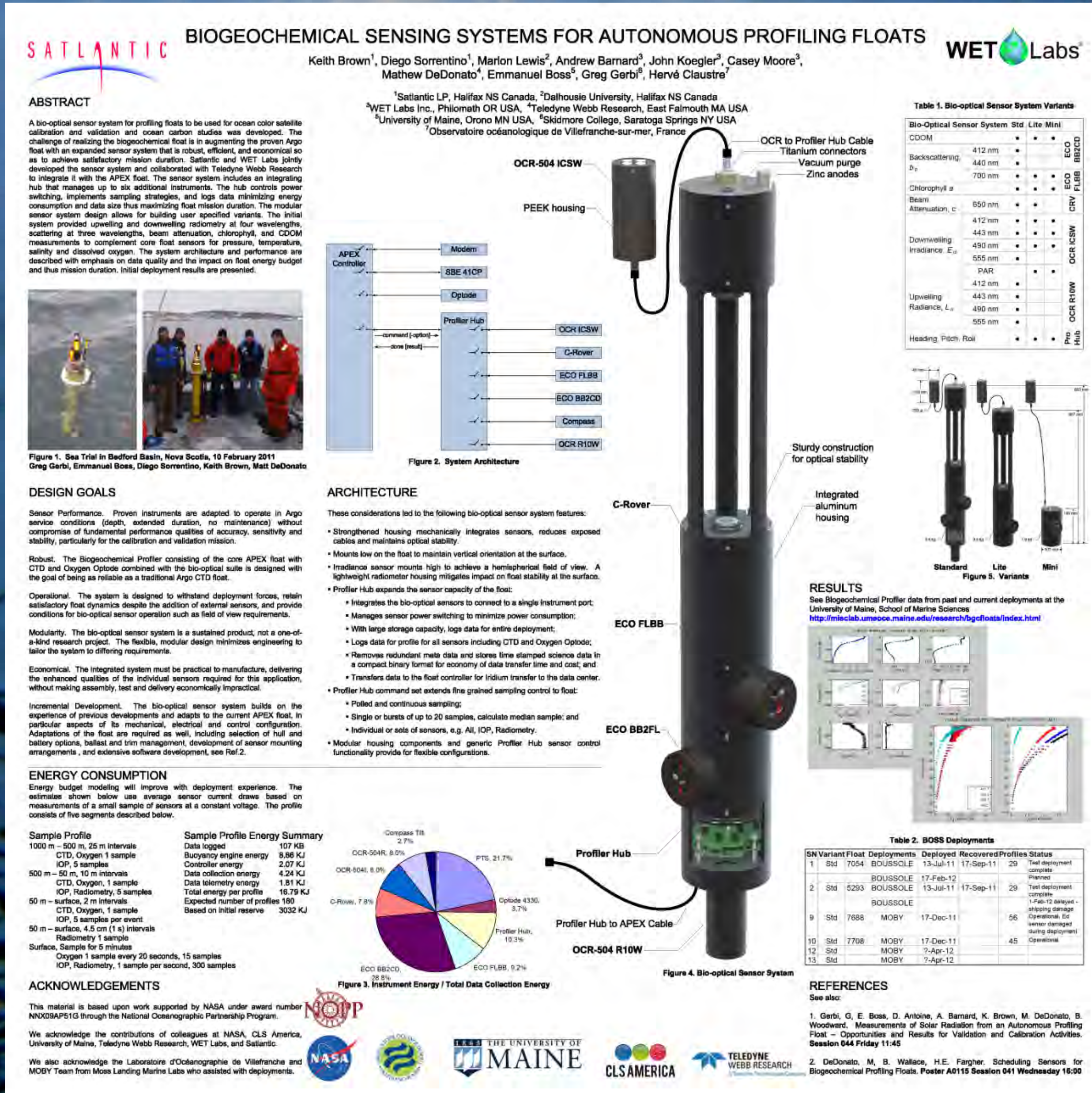
Float Development w/LOV

SUNA Nitrate Sensor

Cal-Val Sensor Suite

SATLANTIC

Float Development w/U Maine



BIOGEOCHEMICAL SENSING SYSTEMS FOR AUTONOMOUS PROFILING FLOATS

Keith Brown[1], Diego Sorrentino[1], Marlon Lewis[2], Andrew Barnard[3], John Koegler[3], Casey Moore[3], Mathew DeDonato[4], Emmanuel Boss[5], Greg Gerbi[6], Hervé Claustre[7]

[1]Satlantic LP, Halifax NS Canada, [2]Dalhousie University, Halifax NS Canada
[3]WET Labs Inc., Philomath OR USA, [4]Teledyne Webb Research, East Falmouth MA USA
[5]University of Maine, Orono MN USA, [6]Skidmore College, Saratoga Springs NY USA
[7]Observatoire océanologique de Villefranche-sur-mer, France

ABSTRACT

A bio-optical sensor system for profiling floats to be used for ocean color satellite calibration and validation and ocean carbon studies was developed. The challenge of realizing the biogeochemical float is in augmenting the proven Argo float with an expanded sensor system that is robust, efficient, and economical so as to achieve satisfactory mission duration. Satlantic and WET Labs jointly developed the sensor system and collaborated with Teledyne Webb Research to integrate it with the APEX float. The sensor system includes an integrating hub that manages up to six additional instruments. The hub controls power switching, implements sampling strategies, and logs data minimizing energy consumption and data size thus maximizing float mission duration. The modular sensor system design allows for building user specified variants. The initial system provided upwelling and downwelling radiometry at four wavelengths, scattering at three wavelengths, beam attenuation, chlorophyll, and CDOM measurements to complement core float sensors for pressure, temperature, salinity and dissolved oxygen. The system architecture and performance are described with emphasis on data quality and the impact on float energy budget and thus mission duration. Initial deployment results are presented.

Figure 1. Sea Trial in Bedford Basin, Nova Scotia, 10 February 2011
Greg Gerbi, Emmanuel Boss, Diego Sorrentino, Keith Brown, Matt DeDonato

DESIGN GOALS

Sensor Performance. Proven instruments are adapted to operate in Argo service conditions (depth, extended duration, no maintenance) without compromise of fundamental performance qualities of accuracy, sensitivity and stability, particularly for the calibration and validation mission.

Robust. The Biogeochemical Profiler consisting of the core APEX float with CTD and Oxygen Optode combined with the bio-optical suite is designed with the goal of being as reliable as a traditional Argo CTD float.

Operational. The system is designed to withstand deployment forces, retain satisfactory float dynamics despite the addition of external sensors, and provide conditions for bio-optical sensor operation such as field of view requirements.

Modularity. The bio-optical sensor system is a sustained product, not a one-of-a-kind research project. The flexible, modular design minimizes engineering to tailor the system to differing requirements.

Economical. The integrated system must be practical to manufacture, delivering the enhanced qualities of the individual sensors required for this application, without making assembly, test and delivery economically impractical.

Incremental Development. The bio-optical sensor system builds on the experience of previous developments and adapts to the current APEX float, in particular aspects of its mechanical, electrical and control configuration. Adaptations of the float are required as well, including selection of hull and battery options, ballast and trim management, development of sensor mounting arrangements , and extensive software development, see Ref.2.

APEX Controller
Modem
SBE 41CP
Optode
Profiler Hub
command [option]
done [result]
OCR ICSW
C-Rover
ECO FLBB
ECO BB2CD
Compass
OCR R10W

Figure 2. System Architecture

ARCHITECTURE

These considerations led to the following bio-optical sensor system features:

- Strengthened housing mechanically integrates sensors, reduces exposed cables and maintains optical stability.
- Mounts low on the float to maintain vertical orientation at the surface.
- Irradiance sensor mounts high to achieve a hemispherical field of view. A lightweight radiometer housing mitigates impact on float stability at the surface.
- Profiler Hub expands the sensor capacity of the float:
  - Integrates the bio-optical sensors to connect to a single instrument port;
  - Manages sensor power switching to minimize power consumption;
  - With large storage capacity, logs data for entire deployment;
  - Logs data for profile for all sensors including CTD and Oxygen Optode;
  - Removes redundant meta data and stores time stamped science data in a compact binary format for economy of data transfer time and cost; and
  - Transfers data to the float controller for Iridium transfer to the data center.
- Profiler Hub command set extends fine grained sampling control to float:
  - Polled and continuous sampling;
  - Single or bursts of up to 20 samples, calculate median sample; and
  - Individual or sets of sensors, e.g. All, IOP, Radiometry.
- Modular housing components and generic Profiler Hub sensor control functionality provide for flexible configurations.

ENERGY CONSUMPTION

Energy budget modeling will improve with deployment experience. The estimates shown below use average sensor current draws based on measurements of a small sample of sensors at a constant voltage. The profile consists of five segments described below.

Sample Profile
1000 m – 500 m, 25 m intervals
CTD, Oxygen 1 sample
IOP, 5 samples
500 m – 50 m, 10 m intervals
CTD, Oxygen, 1 sample
IOP, Radiometry, 5 samples
50 m – surface, 2 m intervals
CTD, Oxygen, 1 sample
IOP, 5 samples per event
50 m – surface, 4.5 cm (1 s) intervals
Radiometry 1 sample
Surface, Sample for 5 minutes
Oxygen 1 sample every 20 seconds, 15 samples
IOP, Radiometry, 1 sample per second, 300 samples

Sample Profile Energy Summary

Data logged	107 KB
Buoyancy engine energy	8.66 KJ
Controller energy	2.07 KJ
Data collection energy	4.24 KJ
Data telemetry energy	1.81 KJ
Total energy per profile	16.79 KJ
Expected number of profiles	180
Based on initial reserve	3032 KJ

Compass Tilt 2.7%
OCR-504R, 8.0%
OCR-504I, 8.0%
C-Rover, 7.8%
PTS, 21.7%
Optode 4330, 3.7%
Profiler Hub, 10.3%
ECO FLBB, 9.2%
ECO BB2CD, 28.8%

Figure 3. Instrument Energy / Total Data Collection Energy

OCR to Profiler Hub Cable
Titanium connectors
Vacuum purge
Zinc anodes
OCR-504 ICSW
PEEK housing
Sturdy construction for optical stability
Integrated aluminum housing
C-Rover
ECO FLBB
ECO BB2FL
Profiler Hub
Profiler Hub to APEX Cable
OCR-504 R10W

Figure 4. Bio-optical Sensor System

Table 1. Bio-optical Sensor System Variants

Bio-Optical Sensor System		Std	Lite	Mini	
CDOM		•	•	•	ECO BB2CD
Backscattering, b_b	412 nm	•			ECO BB2CD
	440 nm	•			ECO BB2CD
	700 nm	•	•	•	ECO FLBB
Chlorophyll a		•	•	•	ECO FLBB
Beam Attenuation, c	650 nm	•	•		CRV
Downwelling Irradiance, E_d	412 nm	•	•	•	OCR ICSW
	443 nm	•	•	•	OCR ICSW
	490 nm	•	•	•	OCR ICSW
	555 nm	•			OCR ICSW
	PAR		•	•	OCR ICSW
Upwelling Radiance, L_u	412 nm	•			OCR R10W
	443 nm	•			OCR R10W
	490 nm	•			OCR R10W
	555 nm	•			OCR R10W
Heading, Pitch, Roll		•	•	•	Pro Hub

Standard Lite Mini

Figure 5. Variants

RESULTS

See Biogeochemical Profiler data from past and current deployments at the University of Maine, School of Marine Sciences
http://misclab.umeoce.maine.edu/research/bgcfloats/index.html

Table 2. BOSS Deployments

SN	Variant	Float	Deployments	Deployed	Recovered	Profiles	Status
1	Std	7054	BOUSSOLE	13-Jul-11	17-Sep-11	29	Test deployment complete
			BOUSSOLE	17-Feb-12			Planned
2	Std	5293	BOUSSOLE	13-Jul-11	17-Sep-11	29	Test deployment complete
			BOUSSOLE				1-Feb-12 delayed - shipping damage
9	Std	7688	MOBY	17-Dec-11		56	Operational, Ed sensor damaged during deployment
10	Std	7708	MOBY	17-Dec-11		45	Operational
12	Std		MOBY	?-Apr-12			
13	Std		MOBY	?-Apr-12			

ACKNOWLEDGEMENTS

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We also acknowledge the Laboratoire d'Océanographie de Villefranche and MOBY Team from Moss Landing Marine Labs who assisted with deployments.

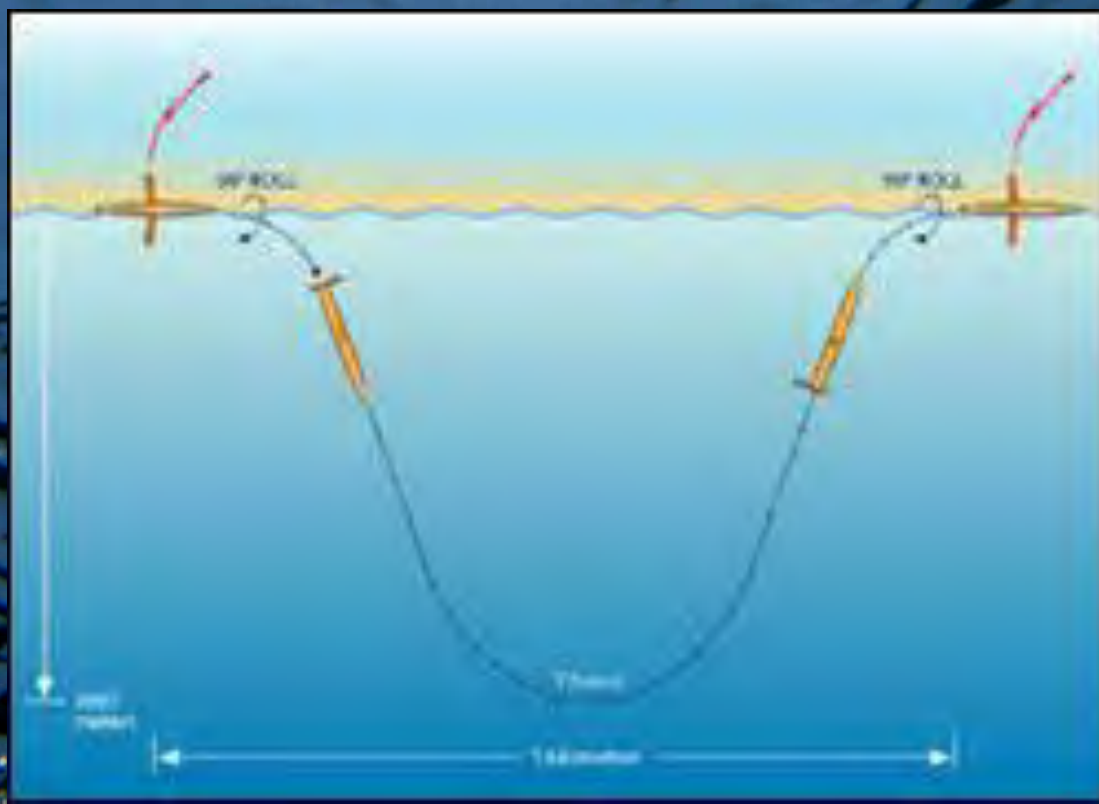
REFERENCES
See also:

1. Gerbi, G, E. Boss, D. Antoine, A. Barnard, K. Brown, M. DeDonato, B. Woodward. Measurements of Solar Radiation from an Autonomous Profiling Float – Opportunities and Results for Validation and Calibration Activities. **Session 044 Friday 11:45**

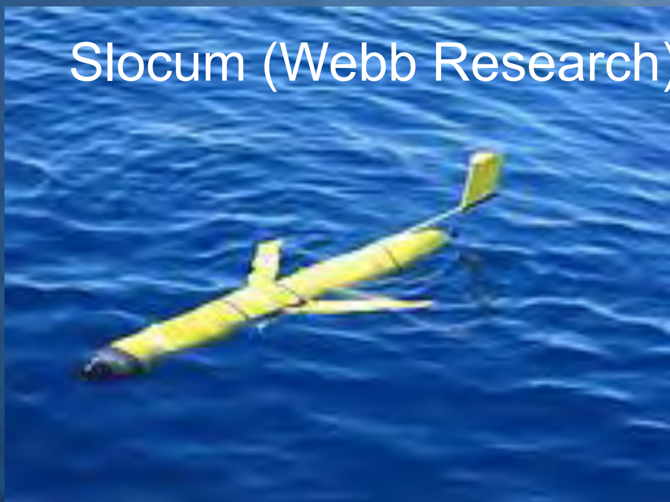
2. DeDonato, M, B. Wallace, H.E. Fargher. Scheduling Sensors for Biogeochemical Profiling Floats. **Poster A0115 Session 041 Wednesday 16:00**

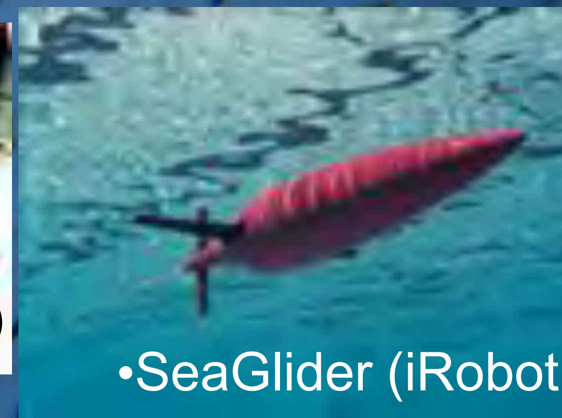
But….we still need the horizontal spatial dimension…

- 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.

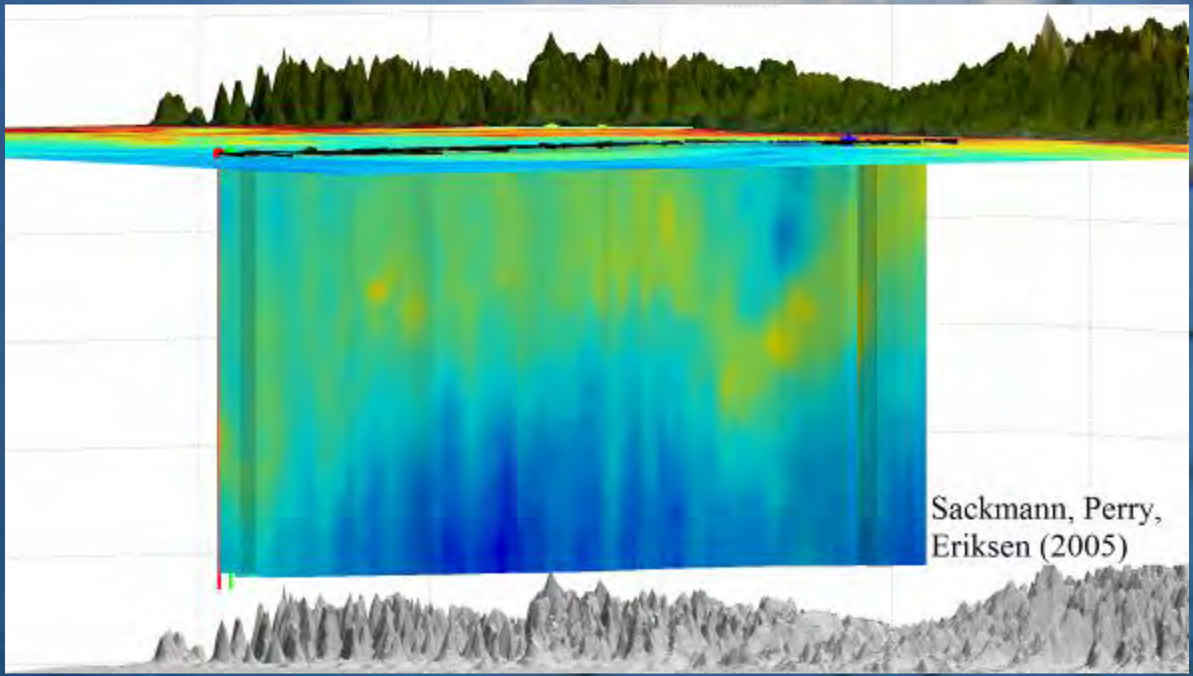


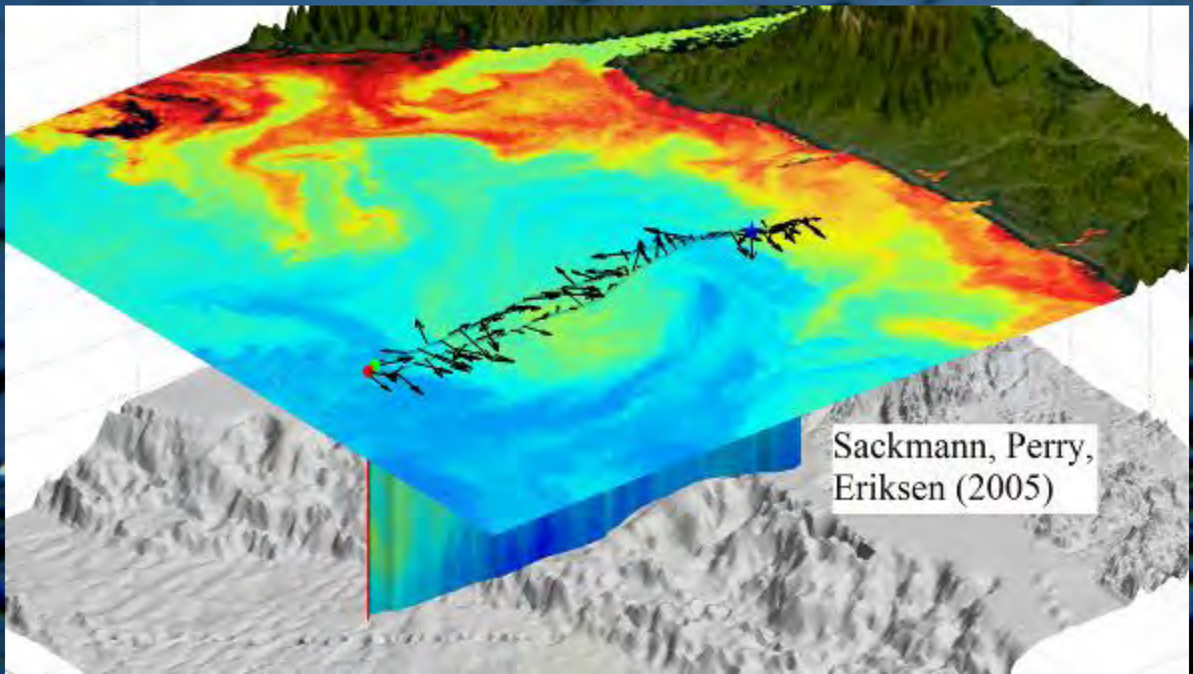
•Currently several variants:





Chlorophyll Distribution, West Coast of U.S./Canada (SeaGlider + SeaWiF





Courtesy of Brandon Sackmann

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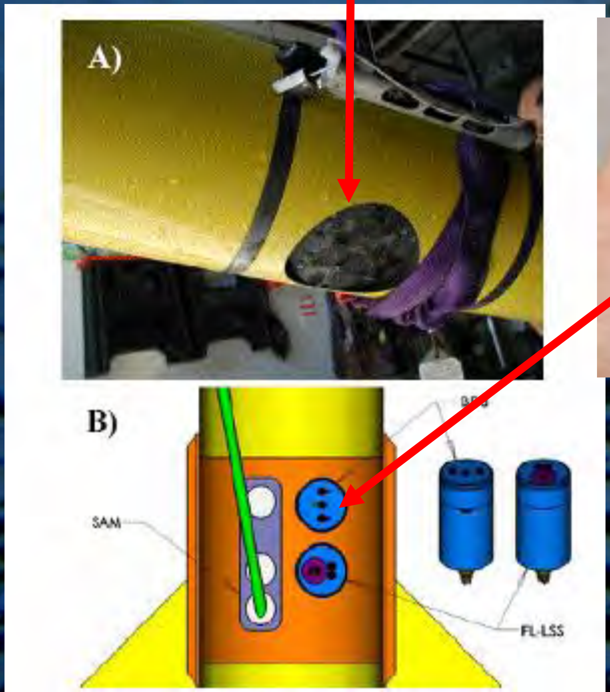
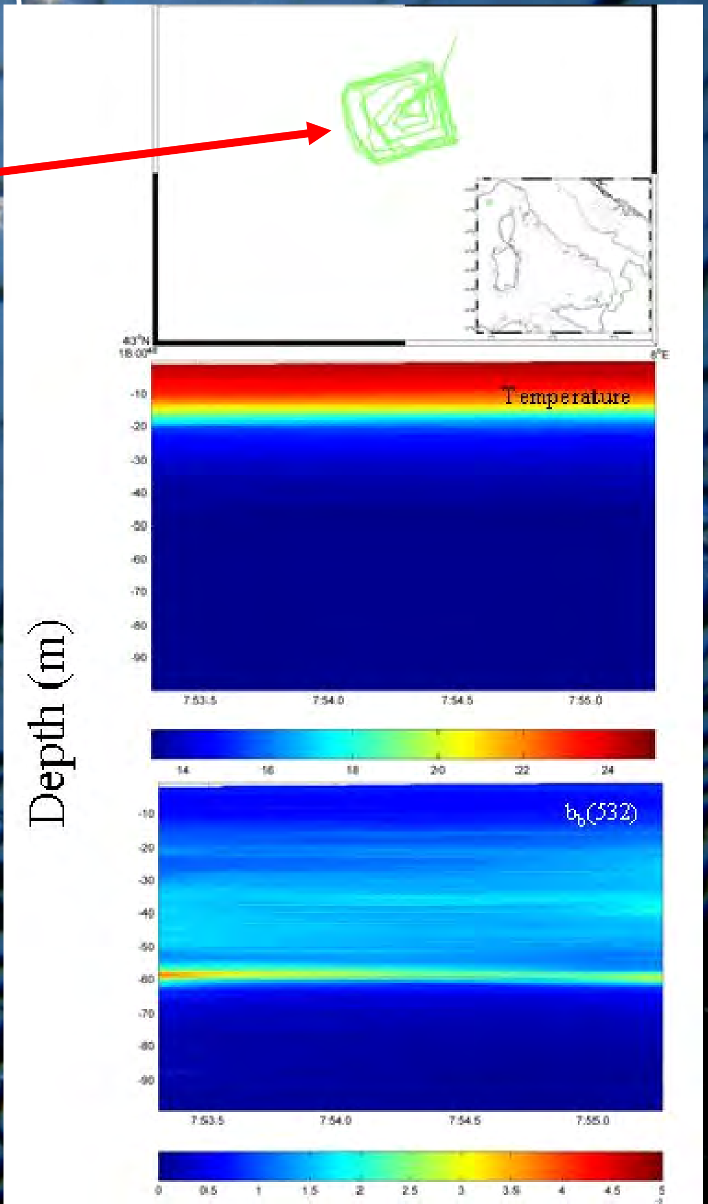
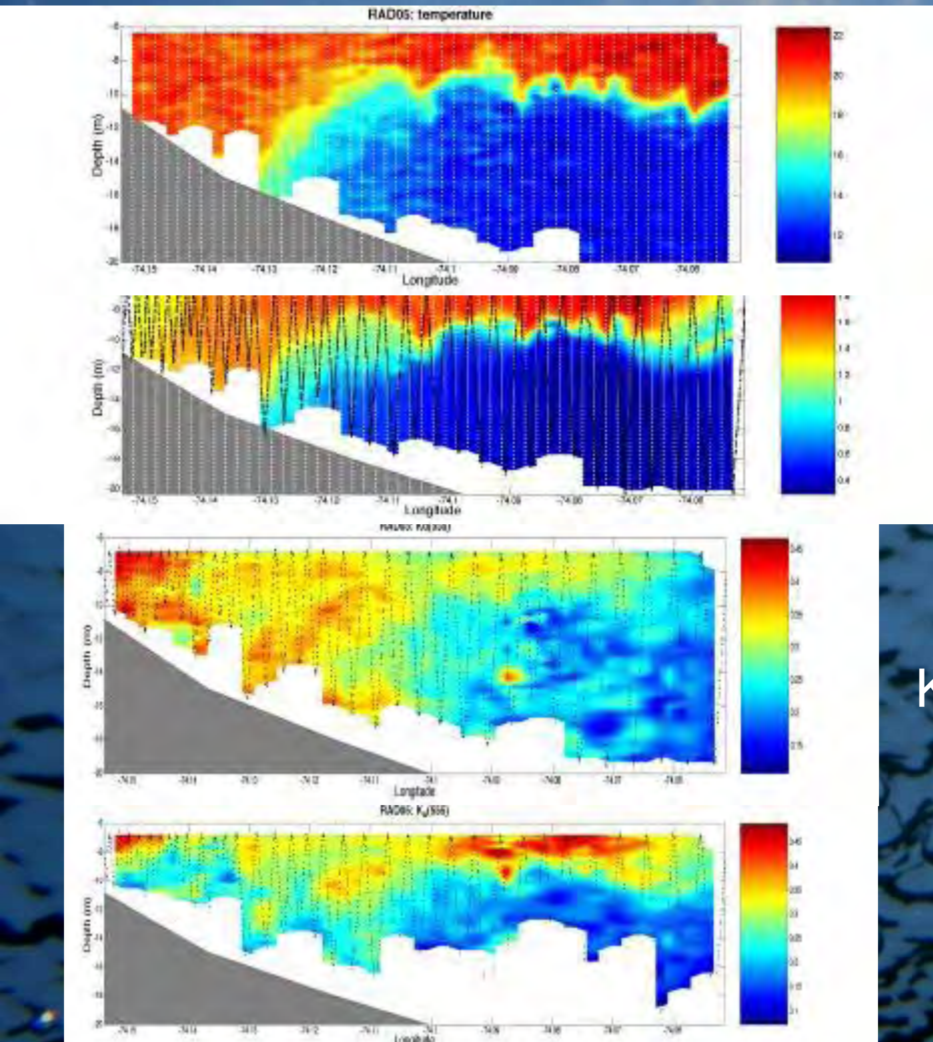
Webb (Slocum) Glider:

Bio-optical Drifter Deployment at DyfaMed, 2004; Scattering coefficient reveals structure in POC. (Herve Claustre and Katarzyna Niewiadomska)





Powered AUV Platforms: REMUS

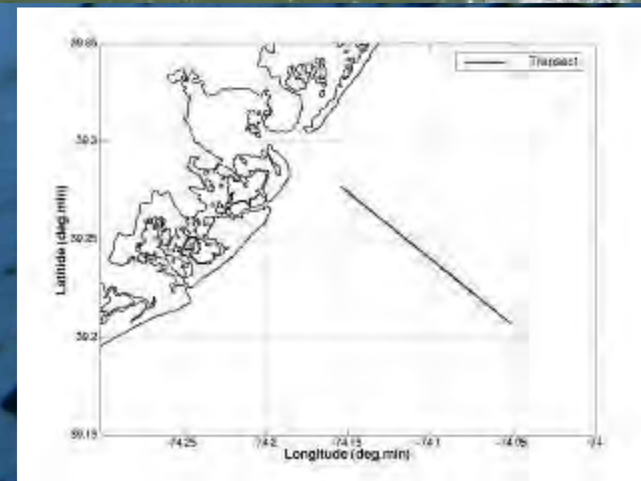


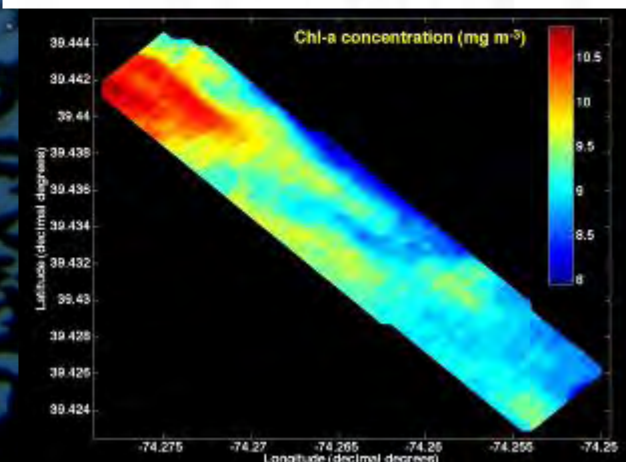
Temp.

Fluoro.

$K_D(555)$

$K_{Lu}(555)$

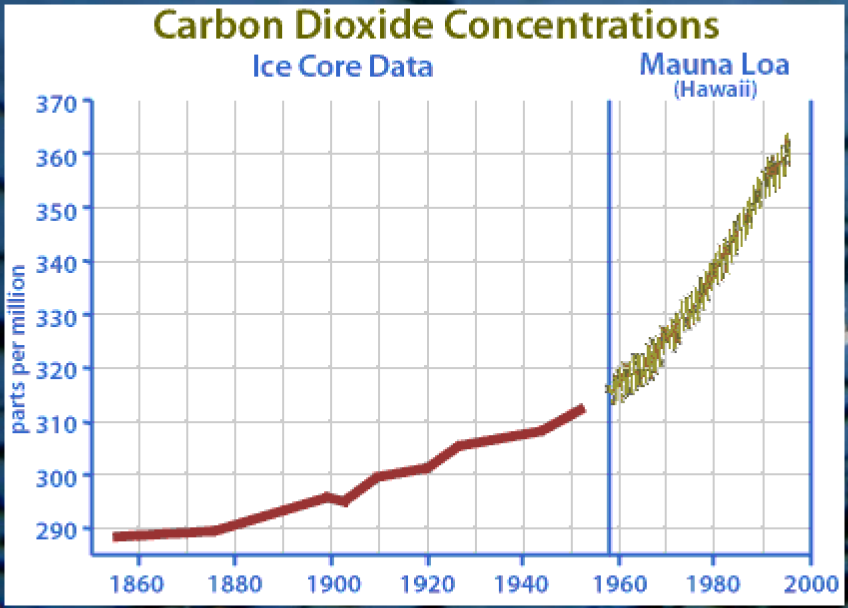


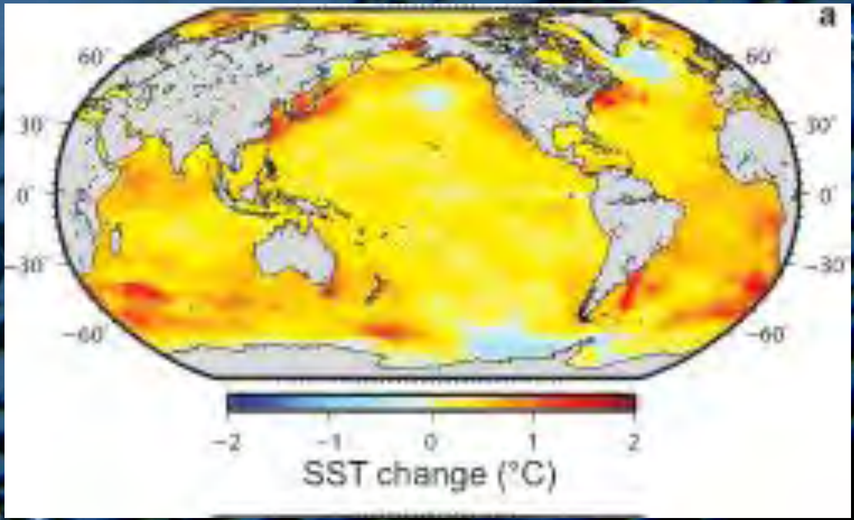


Brown, Huot, Cullen, Lewis, 2004

A Hindcast Problem: Sea of Change

- The atmosphere and oceans are undergoing a wide range of rapid change on a global basis.
- As phytoplankton are largely at the mercy of their physical environment, there is concern that they are being affected as well – and as a result, changing the nature of marine food webs, upper ocean thermal structure, and geochemical fluxes.





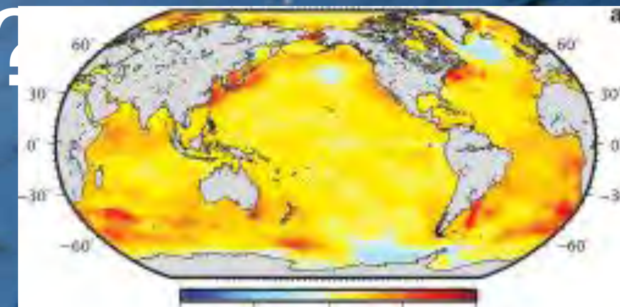
Boyce, Lewis, Worm, 2010

Adapted from an image courtesy of the White House Initiative on Global Climate Change.

What might cause changes in phytoplankton ???

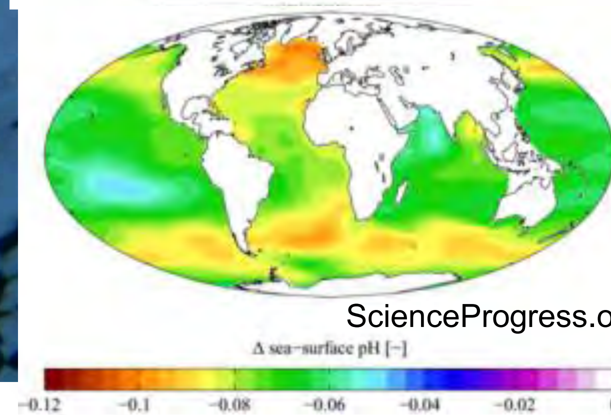
The surface oceans are measurably:

1. Warming as a result of radiative forcing (~0.5-1 degree over the last century)



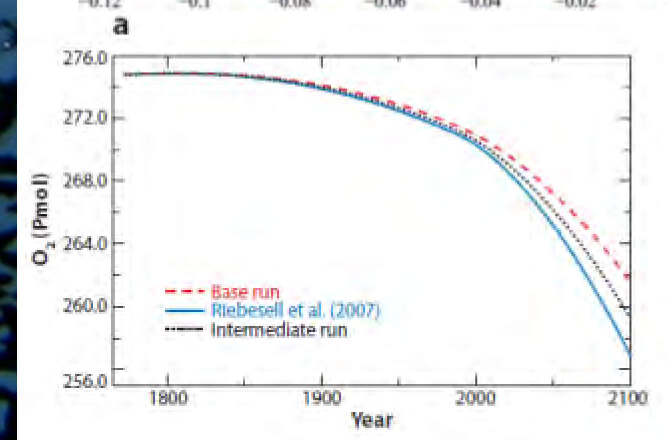
Boyce, Lewis, Worm, 201

2. Acidifying as a result of increased CO_2 flux into the ocean ("the other CO_2 problem"; ~ 0.1 unit in North Atlantic)



ScienceProgress.or

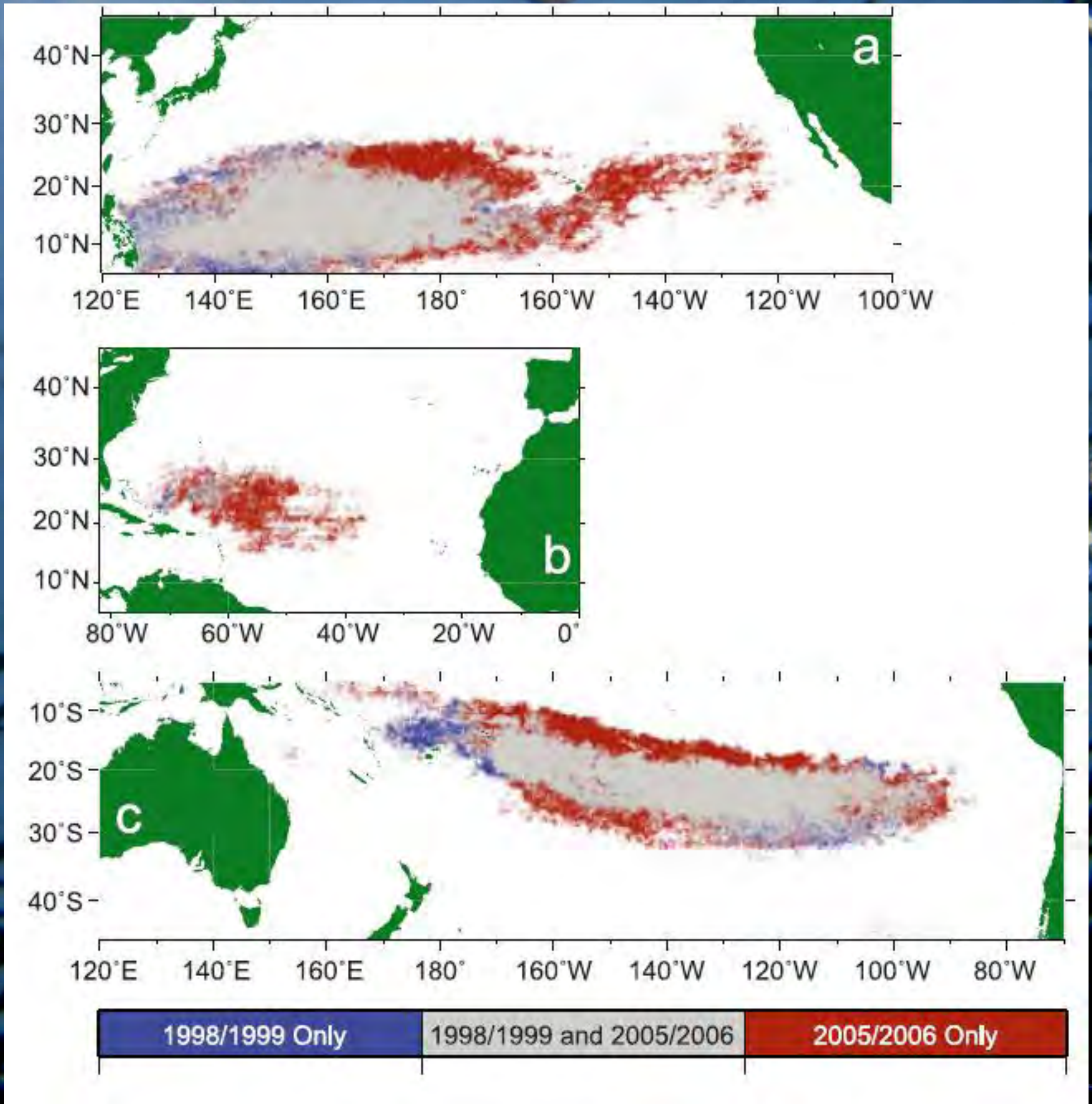
3. Deoxygenating, perhaps as a result of increased stratification due to surface warming



Warm, Sour and Putrid:
The "Angry Ocean" – Ken Denman

Expanding ocean deserts?

- 1998-2006 SeaWiFS
- Low-Chl regions expanding at 1-4% yr^{-1}



Source: Polovina et al. (2008) Geophys Res Lett 35:L03618

Conflicting Results

- "…changes in global ocean chlorophyll from the CZCS (1979–1986) and SeaWiFS (1997–2000) records. Global spatial distributions and seasonal variability of ocean chlorophyll were similar, but **global means decreased** over the two observational segments." *Gregg et al. GRL 2002*
- "Satellite-in situ blended ocean chlorophyll records indicate that **global ocean annual primary production has declined more than 6% since the early 1980's.** Nearly 70% of the global decadal decline occurred in the high latitudes." *Gregg et al. GRL 2003*
- "The analysis of decadal changes from the CZCS to the SeaWiFS era **shows an overall increase of the world ocean average chlorophyll** concentration by about 22..." *Antoine et al. JGR; 2005*
- "The **period is dominated by an initial increase in NPP of 1,930 teragrams of carbon a year (Tg C yr^{-2}), followed by a prolonged decrease** averaging 190 Tg Cyr^{-2}." *Behrenfeld et al. Science 2006*

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More…

- "…multidecadal changes in global phytoplankton abundances are related to basin-scale oscillations of the physical ocean, specifically the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation…" (*Martinez et al. Science, 2009*)

- "while the ocean's most extreme deserts are increasing at an accelerating rate, some oligotrophic areas are simultaneously shrinking….in phase with the Pacific Decadal Oscillation Index from 1998–2007. (*Oliver and Irwin, GRL, 2009*)

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“These results emphasize that it is difficult to draw unequivocal conclusions about long-term trends of biogeochemical properties in the oceans with the current relatively short bio-optical records.”

ZhongPing Lee, Shaoling Shang, Chuanmin Hu, Marlon Lewis, Robert Arnone, Yonghong Li, and Bertrand Lubac, 2010.

Time series of bio-optical properties in a subtropical gyre: Implications for the evaluation of interannual trends of biogeochemical properties. Journal of Geophysical Research 115, C09012, doi:10.1029/2009JC005865, 2010

A stronger statement

- “We find that detection of climate change-driven trends in the satellite data is confounded by the relatively short time series and large interannual and decadal variability in productivity. Thus, recent observed changes in chlorophyll, primary production and the size of the oligotrophic gyres cannot be unequivocally attributed to the impact of global climate change. Instead, our analyses suggest that a time series of ~40 years length is needed to distinguish a global warming…”

- Henson, S. A.; Sarmiento, J. L.; Dunne, J. P.; Bopp, L.; Lima, I. D.; Doney, S. C.; John, J.; Beaulieu, C. 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. Biogeosciences 7 (2010): 621-640, doi:10.5194/bg-7-621-2010

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A problem

While satellites provide complete global coverage every several days, they have only been operating on a continuous basis since 1997 with the launch of SeaWiFS (the Coastal Zone Color Scanner operated sporadically from 1978 to 1986).

This is too short a record to evaluate climate-scale trends.

What to do?

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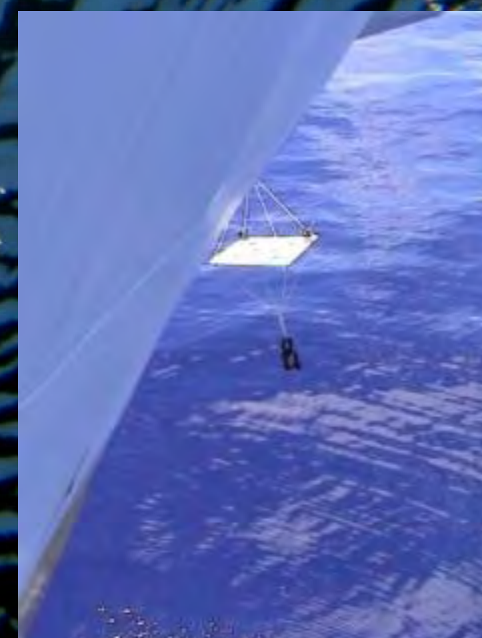
A possible solution: Secchi Disk

Baltic Sea, Z ~ 0.5 m

South Pacific Gyre, Z~ 72m



Off Halifax, CBC, 2010

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

Eyeball Optics

Background reflectance just below surface

Reflectance of disk

Sea surface effects

$$Z_{SD} = \underbrace{\frac{1}{\bar{c}+\bar{K}}}_{\text{Optical Properties of the Sea}} \ln\left[\frac{\varsigma(A-R(0))}{R(0)C_l}\right]$$

Optical Properties of the Sea

Eyeball Response

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.

Eyeballs are pretty good.

Lewis, Kuring & Yentsch 1988

$$1/\mathrm{S.D.} \sim \varepsilon\,(c+K) \sim f(\mathrm{Chl})$$

Prediction skill (Case 1) not significantly different than algorithms that use precisely measured upwelling radiances!

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.

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Another piece of the puzzle: direct measurement of surface chlorophyll concentrations, both extracted and in situ fluorescence

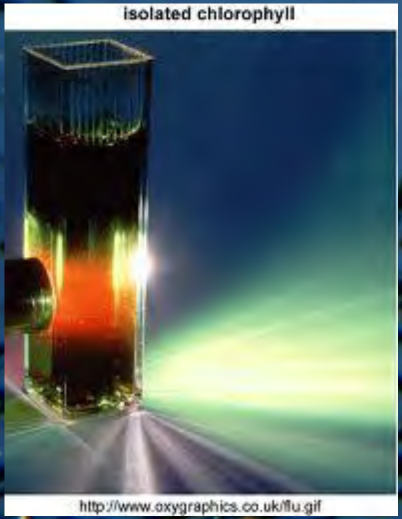

Image courtesy of 2007: Ex... Janet Spa... Cel...

So….have phytoplankton already decreased?

Yes, in 8 out of 10 ocean basins examined over the time period 1900 to the present.

(Boyce, D.G., M.R. Lewis, B. Worm, 2010. Global phytoplankton decline over the past century. *Nature*, 466: 591-596; Boyce, Lewis, Worm, *Nature*)

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Approach: Observational Bases

- Collect all available Secchi disk and chlorophyll observations.
- Carry out comprehensive quality control.
- Remove all records for waters <25 m deep and <1 km from shore.
- Remove all records for chlorophyll observations >20 meters.
- Compute Chl concentration from Secchi disk using established relationships (Lewis et al., 1988, Falkowski and Wilson, 1992)
- Convince ourselves and others that the measurements provide observations that are statistically similar enough to combine.
- Resulted in 450,000 data points (compare to >300,000,000 *per day* with satellite!)

Approach: Analysis

- Used Generalized Additive Model (GAM's) to estimate Chl trends.
- These are extensions of Generalized Linear Models that do not require prior knowledge of the shape of the response function.
- Trends were estimated at local, regional and global scales.

$$\eta(\mu_i) = B_0 + B_1 Year_i + B_2 Bathymetry_i + f_2 Latitude, Longitude_i + f_3 day_i + \epsilon_i$$

$\eta(\mu_i)$ is the monotonic link function of the expected mean Chl conc.,
B_o is the intercept
B_i and f_i are parametric and non-parametric effects estimated from the data
ϵ_i is an error term.

Hastie, T. J. and Tibshirani, R. J. (1990). *Generalized Additive Models*. Chapman & Hall/CRC. ISBN 9780412343902.

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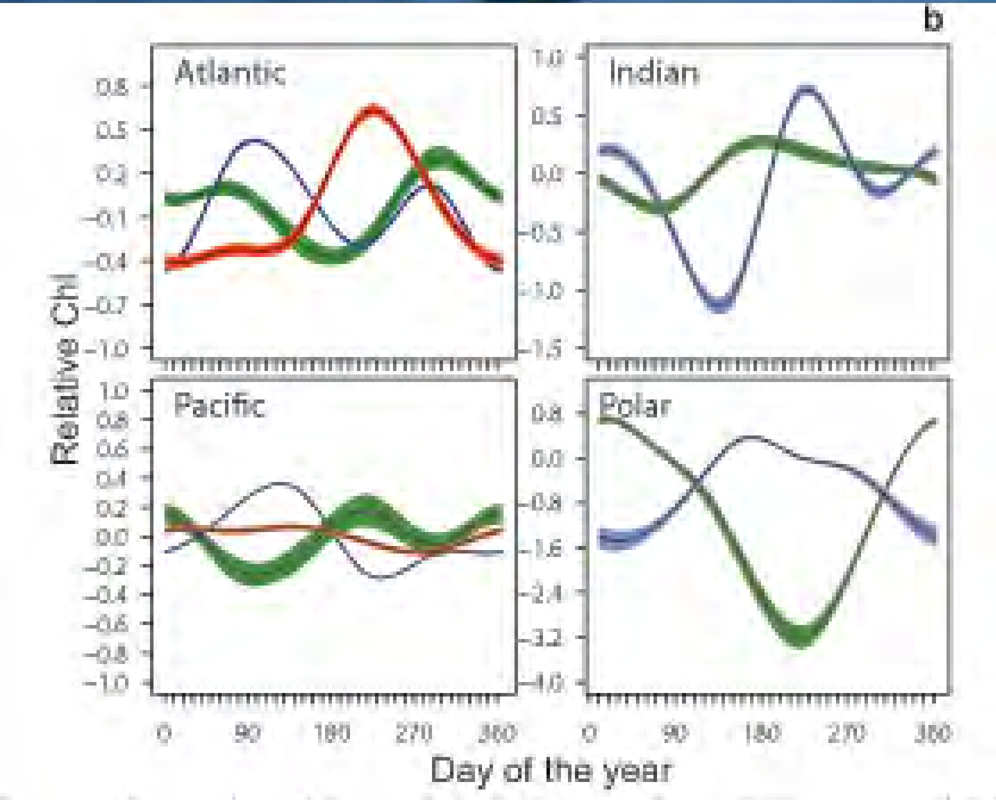
The analysis did a beautiful job of reproducing seasonal cycles at basin scales.



Blue is Northern
Red is tropical
Green is southern

Envelope is approx. 95% Bayesian credible limits.

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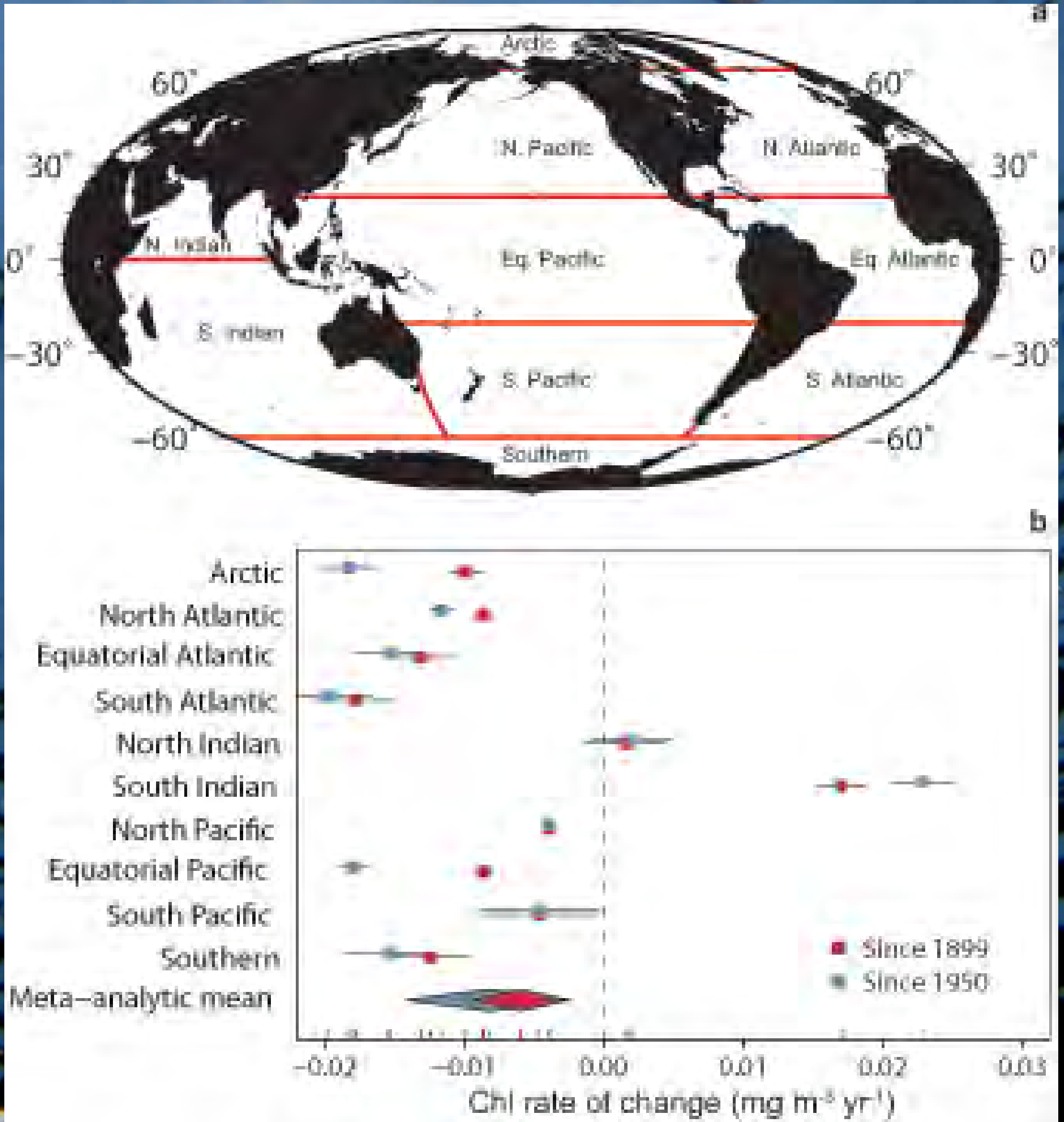
But the long term trends are a bit frightening



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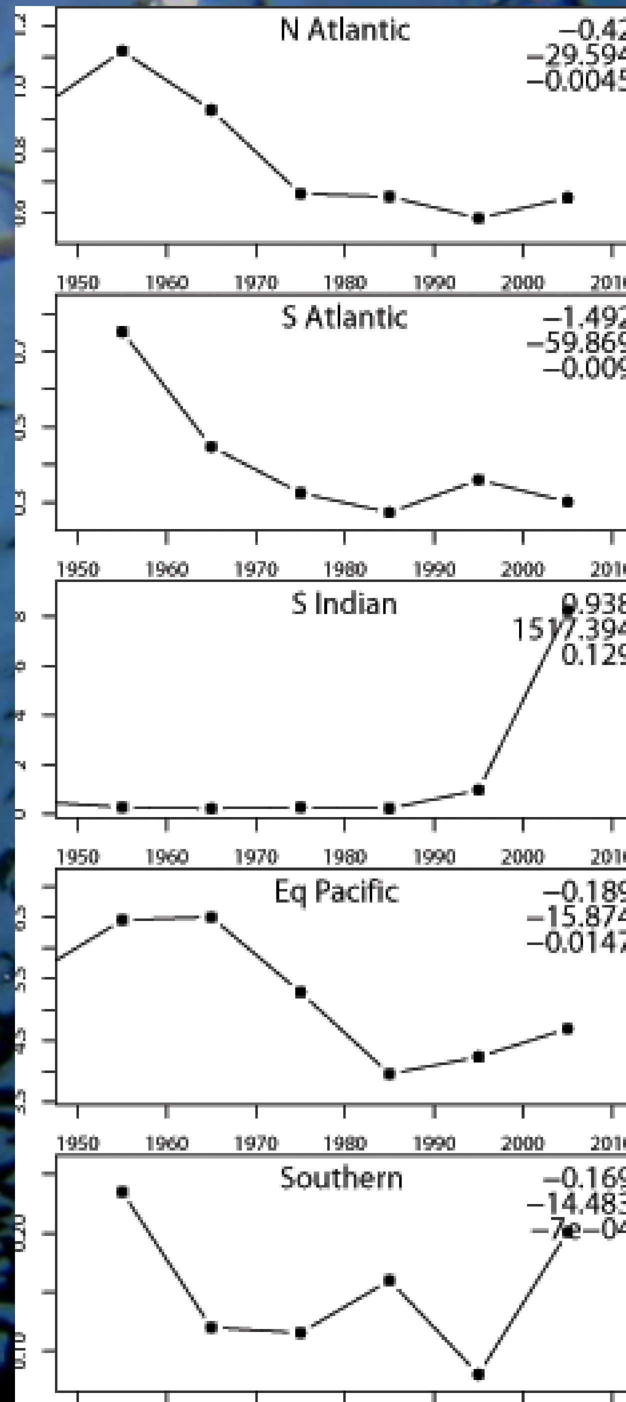
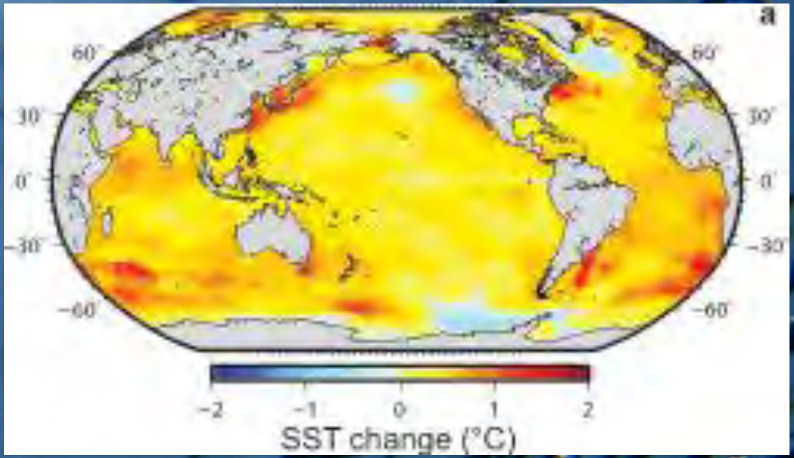
Time trend, decadal means, last 50 years

It is a somewhat complicated, but overall, in a meta-analytic mean sense, concentrations have declined ~40% of the global median over the last 50 years.



Why?

We examined a number of different variables to look for correlates with the observed declines in chlorophyll.

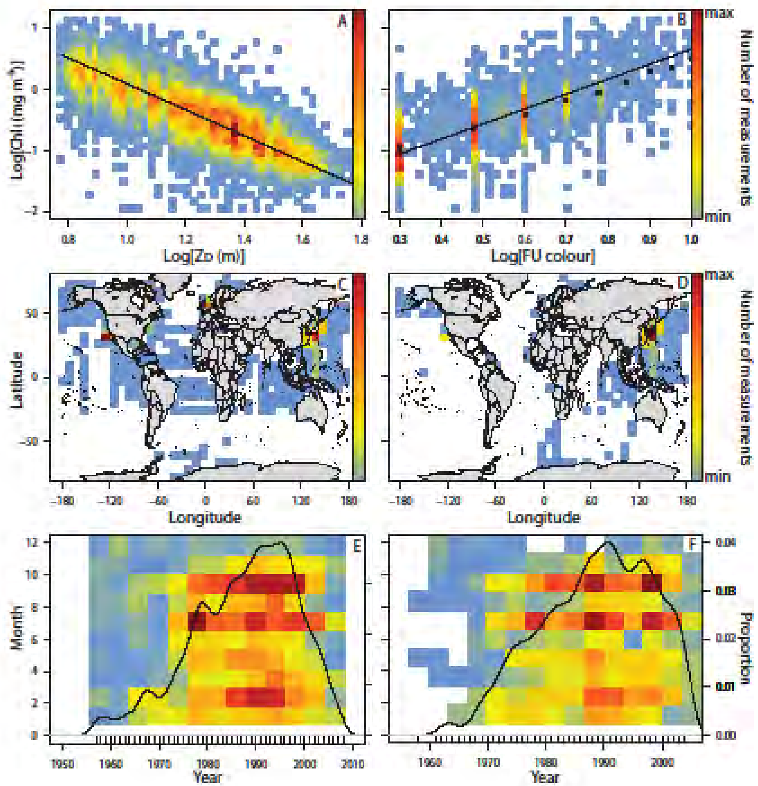


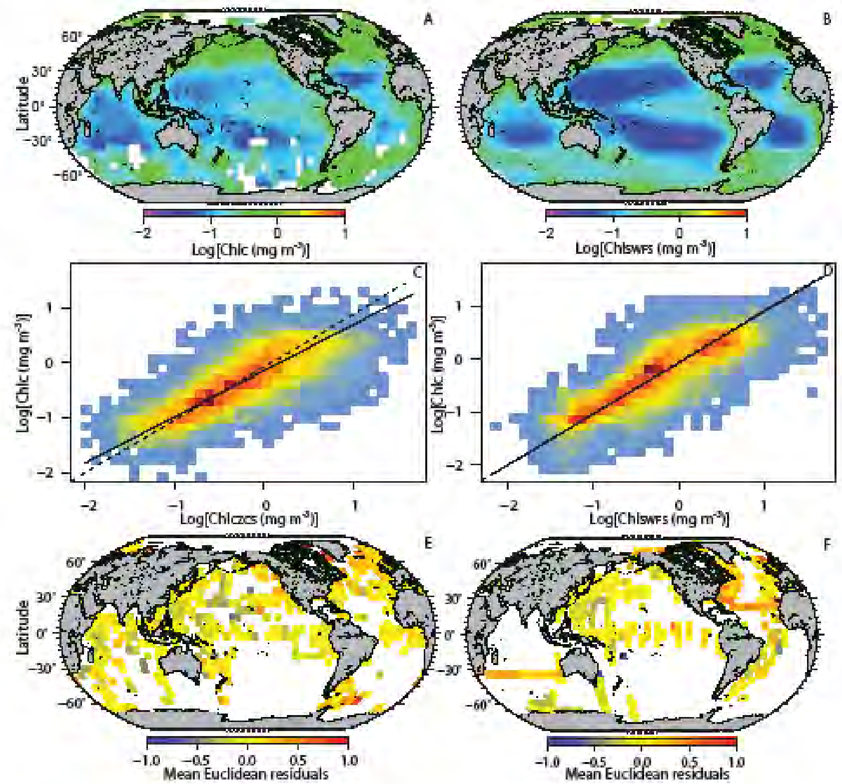
Result from GAM

The most consistent ‘predictor’ was SST:

Rising SST was associated with declining Chl in 8 of 10 regions examined (-0.21to -0.019 mg m^{-3}(^{o}C)$^{-1}$)

Recent Results





Integrating global phytoplankton data from 1890 to 2010. Daniel G. Boyce, Marlon Lewis, and Boris Worm, Limnol. Oceanogr. Methods, in press

Future Goal to establish conclusive climate trends: Climate Data Records

- *"….the committee defines a climate data record as "a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change."*

  Climate Data Records from Environmental Satellites: Interim Report. National Academies Press, 2004

- Note:

  1. Sufficient Length
  2. Sufficient Consistency
  3. Sufficient Continuity

Can we do this with satellite ocean color observations?

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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, autonmous 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.

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But don’t trade off messing around in boats!

Merci, Thank you, спасибо, Danke, Obrigado, Gracias,谢谢
감사합니다, Aitäh , Asante !

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