Great Pyrenees Optical Experiments
A Morning Wave Experiment
Principal RaDyO Applied Problem

How can objects be ‘observed’ from above and from below the sea surface?

Above- and below-surface images using RadCam on MASCOT – Images provided by Marlon Lewis’ group.
Over 65 investigators, 12 nations, and 20 institutions.

**Principal Investigators**

Michael Banner (LDEO), Tim Boyd (SAMS), Grace Chang (Sea Engineering), Tommy Dickey (UCSB), David Farmer (URI), Johannes Gemmrich (Univ. of Victoria), George Kattawar (Texas A&M), Luc Lenain (SIO), Marlon Lewis (Dalhousie), Yi Liu (JHU), Yuming Liu (MIT), Ken Melville (SIO), Russel Morison (Univ. of New South Wales), Scott Pegau (OSU), Howard Schultz (U. Massachusetts), Lien Shen (Johns Hopkins), Dariusz Stramksi (SIO), Mike Twardowski (WETLabs), Svein Vagle (IOS, BC), Ken Voss (Miami), Hemantha Wijesekera (NRL), Yu You (Texas A&M), Dick Yue (MIT), Ron Zaneveld (WETLabs), Chris Zappa (LDEO)

**Other Funded Investigators**

M.-C. Alboussiere, Puru Bhandari (U. Miami), M. Cimomo, Helen Czerski (URI), Mirek Darecki (PAS), Scott Freeman (WET Labs), Jules Jaffe (SIO), **Song Jiang (UCSB)**, Luke Logan (Miami), **Derek Manov (UCSB)**, Scott McLean (Satlantic), Mark Moline (Cal Poly), Francesco Nencioli (UCSB), Nick Patch-Hall (SIO), B. Reineman, Matt Slivkoff (WET Labs), Masaya Shinki, (IOS), Jen Sirak (UCSB), Maciej Sokolski (PAS), Frank Spada (Sea Engineering), Nick Statom (SIO), Peter Sutherland (SIO), Fernando Simonett (SIO), Eric Terrill (Scripps), Ronnie Van Dommelen (Satlantic), Jenwei Wei (Satlantic), Oliver Wurl (IOS, BC), Selda Yildiz (SIO)

**Collaborating Investigators**

Leila Carvalho (UCSB), Yi Chao (JPL), Charles Dong (UCLA), Eric Firing (U. Hawaii), Adilson Gandu (Sao Paulo), Ben Holt (JPL), Jules Hummon (U. Hawaii), Charles Jones (UCSB), Ian Robbins, (Cal Poly), Ruediger Roettgers (GKS, Germany), Dave Siegel (UCSB), Libe Washburn (UCSB)
Examples of Related Interdisciplinary Problems

1. Prediction of underwater light field statistics given wave structure plus other factors (forward model-based).

2. Prediction of wave structure from subsurface light field statistics (inverse model).

3. Particle characterization with optics for remote sensing, photosynthesis, photo-oxidation, biogeochemistry, etc.


5. How do solar zenith angles, winds, surface waves and upper ocean optical properties affect ocean surface albedo and upper ocean heat fluxes and budget on seconds to climate time scales?
Fundamental Problem: What is the fate of sunlight?
Light reflects from sea surface

\[ \text{Albedo} = \frac{\text{Reflected}}{\text{Incident}} = \frac{I_r}{I_0} \]

Relative incident angle on rapidly changing, spatially complex ocean surface matters!
Waves, roughness, foam, etc.

Albedo fcn (angle, wind, atmos. optics, ocean optics)
Light also refracts across sea surface and enters ocean.

Fresnel Equations
French Commissioner of Lighthouses
Royal Society of London
Rumford Medal

"All the compliments that I have received from Arago, Laplace and Biot never gave me so much pleasure as the discovery of a theoretic truth, or the confirmation of a calculation by experiment".

Augustin-Jean Fresnel 1788-1827

Willebrord Snellius 1580-1626

Ibn Sahl 940-1000
Light interactions with oceanic materials

Scales of interest from 400 nm to meters (Spanning 6 orders of mag.)

Schematic by Dariusz Stramski
Light from the sun and the atmosphere (sky irradiance)

Waves

Pure Water molecules

Bubble Clouds

Phytoplankton, Detritus and Non-Algal Particles

Coloured Dissolved Organic Matter (CDOM) from land

Microlayer
Light from the sun and the atmosphere (sky irradiance)

Waves

Pure Water molecules

Bubble Clouds

Phytoplankton, Detritus and Non-Algal Particles

Coloured Dissolved Organic Matter (CDOM) from land
Light from the sun and the atmosphere (sky irradiance)

Waves

Pure Water molecules

Bubble Clouds

Phytoplankton, Detritus and Non-Algal Particles

Coloured Dissolved Organic Matter from land
Light scatters from ocean water, particles & organisms & exits sea.

Exiting light can be seen above water surface; sensed by airplanes and satellites.
Light scatters from ocean water, particles & organisms & is absorbed.

Instruments in water needed for light measurements here.
Light scatters from ocean water, particles & organisms & is absorbed.

Absorption by water, particles & organisms.
Light scatters from ocean water, particles & organisms & is absorbed

\[ \rho c_p \Delta T + \rho c_p \Delta [\langle w'T' \rangle] = \Delta [I(z)] \]

Simple Model: \( I(z) = I_0 \exp(-Kz) \)

\( K = K_w + K_{\text{part}} + K_{\text{diss}} \)

Note \( K = K(\lambda) \)
Light scatters from ocean water, particles & organisms & is absorbed.

Absorption

Heating

Algal Cells (Photosynthesis + Fluorescence)
Light scatters from ocean water, particles & organisms & is absorbed.

Absorption

Heating
Algal Cells (Photosynthesis + Fluorescence)
Re-emission (Raman Scattering) (Biolumin. source)
Processes & Factors Affecting Near Surface Optics (e.g., optical water depth for climate models)

* Wind forcing and incident solar radiation
* Surface gravity and capillary waves
* Internal gravity waves
* Boundary layers on both sides of the interface
* Surfactants
* Whitecaps and bubbles
* Ocean circulation, water motion, turbulence
* Inherent and apparent optical properties
* Light absorption, scattering, polarization
* Bioluminescence
* Radiative transfer at air-sea interface and within the water column
RaDyO Approaches
Coupled Physical & Optical Modeling for Synthesis and Prediction

New Optical Technologies for Science and Modeling

Scales down to msec's and mm's

Fast sampling

Large dynamic ranges

Multi-angle

Multi- and hyperspectral

Polarigraphic
Multi-scale Observations

Photographs provided by RaDyO investigators
Field Experiments

Scripps Pier Experiment
Goal: Test instrumentation
(Jan. 6-28, 2008)

Santa Barbara Channel Experiment
Goal: Benign wave conditions
(Sept. 3-25, 2008)

Hawaii Experiment South of Big Island
Goal: High sea-state conditions
(Aug. 24-Sept. 15, 2009)
Hawai’i FLIP drift and regional SST, wind, and color maps.
Note northeasterly trade winds and east-west and north-south SST grad.
SB Channel with RaDyO Site and Other Platforms
Channel is ~40 X 100 km, max. depth up to ~600 m, ~170 m at site

KM at 34° 13.3' N, 119° 37.7' W (173 m depth) or
1 nt mi north of FLIP at 34° 12.31' N, 119° 34.71' W

Night site for KM was ~8 nt mi W
Satellite observations included SST, color, wind stress, and SAR. A small aircraft carrying a Lidar system was also flown by SIO group.
Regional Setting for RaDyO SBC

SAR images, Ben Holt
3 Wind Regimes

Wind Speed from KM (Blue) and FLIP (red), mean values are calculated from KM data.

- KM Wind Speed Mean: 5.182
- KM Wind Speed STD: 2.780

Wind Stress from KM (Blue) and FLIP (red), mean values are calculated from KM data.

- KM Wind Speed Mean: 5.182
- KM Wind Speed STD: 2.780

Wind Speed Spectra (KM), Sept. 8-22, 2008

- Diurnal

Wind Speed Spectra (FLIP), Sept. 13-23, 2008

- OPL and Chris Zappa Data
MLD ~10-20 m (diurnal), then >20 m, and ~10 m. OPL and Mike Twardowski Data
Multi-scale sampling 1sts
2-D slope field meas. cap.-grav. waves w/ polarimeter. IR anal. of μ-scale breaking. Meas. detailed response of underwater radiance to sfc. Obs. wave field including breaking at all scales.
Interfacial + near surface meas. to quantify microlayer and near surface processes including chemical and bubble effects (Vagle et al.) – obs. enhancement of part. conc. + increase in particle absorp. and scatt.
Right. MASCOT used for 1st comprehensive scattering (incl. 17 angles), absorption, CTD, and optical bubble observations. Also, linear polarization elements of VSF.

Left. Acoustic resonator used to measure bubble distributions in range of 5 - 100 microns in diam. Bubble plumes meas. under breaking waves.

Twardowski et al.

Vagle, Farmer, Czerski
The number of bubbles with a radius of 40 µm as a function of time, measured by both optical and acoustical techniques. $N$ is the number of bubbles per cubic meter per µm radius increment. These are the raw results, uncorrected for the presence of coatings. It can be seen that there is general agreement in $N$ with time, but that these uncorrected time series do not show detailed agreement. The chosen “active period” is between 63 and 78 min. Czerski et al. JGR 2012
HyperPro and Radcam
Vertical profiles of full radiance with 0.25 m resolution;
Resolve full radiance distr. at high freq.; $10^6$ dyn. range; both hemispheres.

Photos by Marlon Lewis group
Irradiance from RadCam (Lewis et al. 2011)

(a) Pacific Ocean off Big Island, Hawaii, (b) Santa Barbara Channel, (c) Bedford Basin, N.S.
Inherent Optical Properties from RadCam

a. Hawaii, b. SB Channel, c. Bedford Basin (Lewis et al. 2011)
Below. NPOL meas. full downwelling polarized spectral radiance distribution

Right. Porcupine measures high intensity, msec scale flashes of 3000 W m\(^{-2}\) (over 10 times greater than ave.) spectrally

Ken Voss group

Dariusz Stramski group
Example fluctuations in radiance at a near-surface depth of 0.93 m for different zenith angles of radiance observation $\theta$ (as indicated) within the solar principal plane, more specifically the half plane facing the sun. The time series data are shown for the normalized radiance, $L(t)/L$. The measurements were made with the Porcupine radiance sensors equipped with the interference filter centered at 532 nm in the Santa Barbara Channel on September 18, 2008 at 12:20 P.M. local time under sunny conditions, solar zenith angle $\theta_s = 33^\circ$, mean zenith angle of solar beam in water $\theta_{sw} = 24^\circ$, wind speed $W = 7.0$ m s$^{-1}$, and the beam attenuation coefficient of seawater at 555 nm, $c(555) = 0.65$ m$^{-1}$. The azimuthal orientation of the radiance sensors varied within $\pm 5^\circ$ during the time series measurement.

The brightest flashes of irradiance or radiance can exceed the time-averaged irradiance or radiance by an order of magnitude and the duration of flashes is typically on the order of milliseconds to tens of milliseconds.

M. Darecki, D. Stramski, and M. Sokólski, JGR 2011
Modeling Highlight Firsts

Kattawar and You

Num. 3D model for fast, accurate polarized light fields in coupled atm.-ocean system – emulates dynamic light field beneath roughened sea surface.

Calculations using instantaneous wave slopes simulating complete underwater polarized light.

Yue and Shen

Direct simulation developed for linear and nonlinear waves, turbulence and surfactants and coupled to optical model.

Radiative transfer simulated via 3-D coupled atmosphere-ocean Monte Carlo method with realistic sfc. deformations and IOPs.
Summary of SBC Results

Regional and Channel Scales

* Upwelling along coast, Point Conception and north
* 3 wind regimes during experiment
* Strong diurnal sea-land breeze winds
* Eddy features in SBC (tracking done)

RaDyO Site

* MLD deepening and shoaling
* Optical properties changed in response to wind mixing and currents

Project highlights at
http://www.opl.ucsb.edu/radyo/docs/RaDyO_Highlights.pdf
Parameterizations of Ocean Surface Albedo for Climate Models
(See Jin et al., 2004; Li et al, 2006)

1. Dependence on solar zenith angle
2. Dependence on wind speed
3. Dependence on atmospheric optical depth
4. Dependence on oceanic optical depths

Uses look up tables based on coupled ocean-atmosphere radiative transfer code. Tables for 4 and 24 spectral bands and broadband.
Further Reading


See RaDyO links at www.opl.ucsb.edu. This talk (Climate Optics) will be on menu.
Evolution of Surface Currents

Libe Washburn’s HF Radar 1 day data on 1 km grid ave.; data assimilation model run by Yi Chao.

New eddy tracking algorithm to be applied (Nencioli et al., in press)
KM ADCP Currents
Hawaii FLIP configuration
Hawai’i
Time-series for Wind, SST, Sal., Chlor., Backscatt.
Hawai’i
Time-series for Wind, SST, Sal., Chlor., Backscatt.
Transition from cool salty to warm fresh water as FLIP drifted westward south of Hawai’i
Shift in vert. structures of physical & optical properties. Comparison of YD 242-250 (blue) and YD 253-258 (red) during Hawai’i RaDyO experiment.