MOBY
vicarious calibration site

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Acknowledgments: The MOBY Team

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• Mark Yarbrough	MLML *(HI)*	Project Manager, Engineer
• Mike Feinholz	MLML *(HI)*	Calibrations
• Terrence Houlihan	MLML *(HI)*	Hardware, Mooring, Diver
• Stephanie Flora	MLML *(CA)*	Data Processing
• Darryl Peters	MLML *(CA)*	Data processing, Diver

Data availability websites:

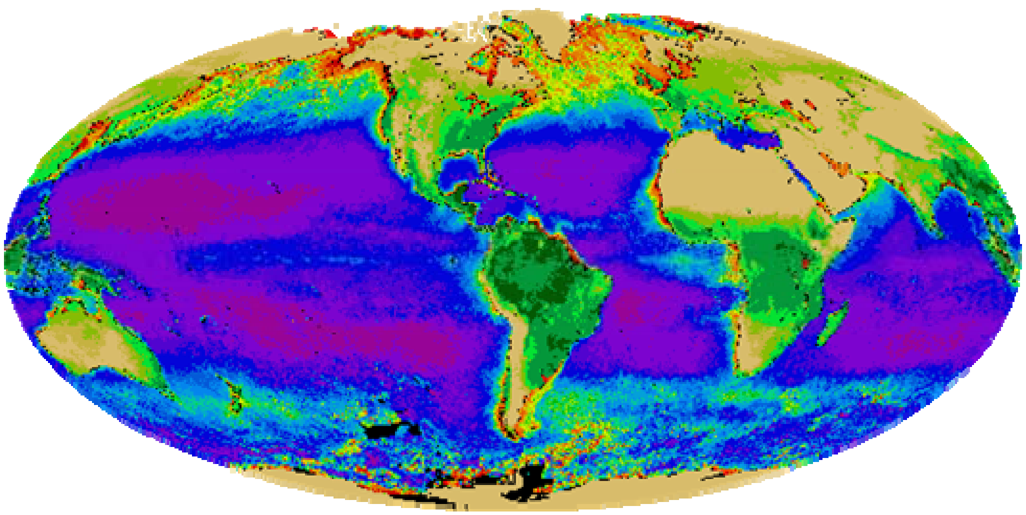
http://moby.mlml.calstate.edu/

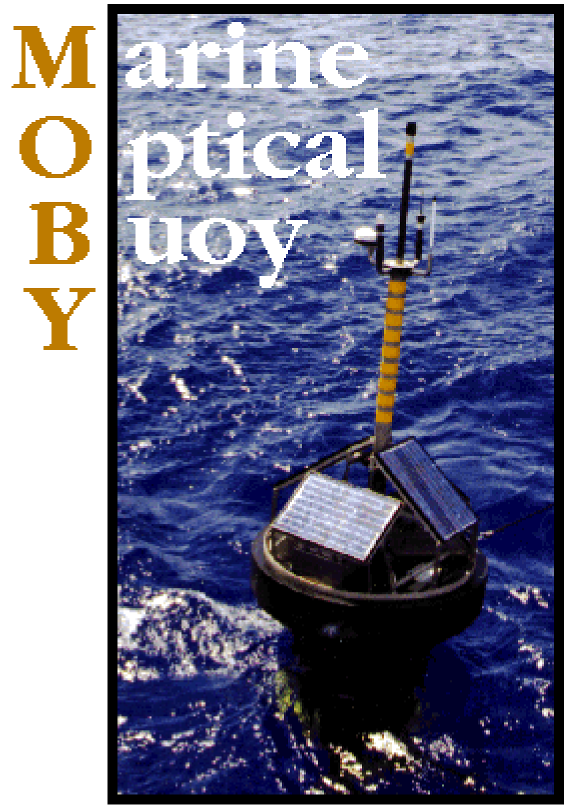
http://coastwatch.noaa.gov/moby/gold/index.html

Project transferred from NASA research to NOAA operations on 01-Apr-2007

Outline

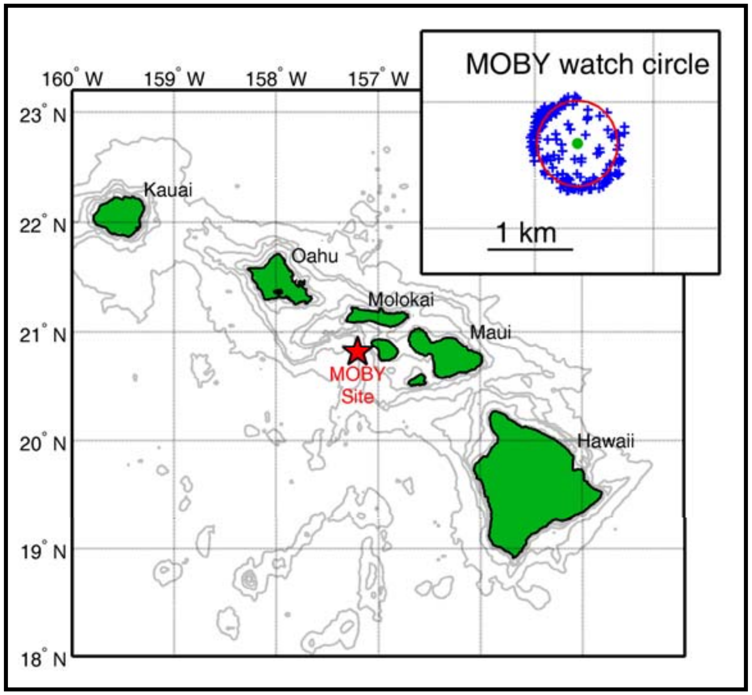
1. System Overview
2. Products, Applications, Uncertainties
3. Challenges
4. Ways to go forward





Marine Optical Buoy (MOBY)

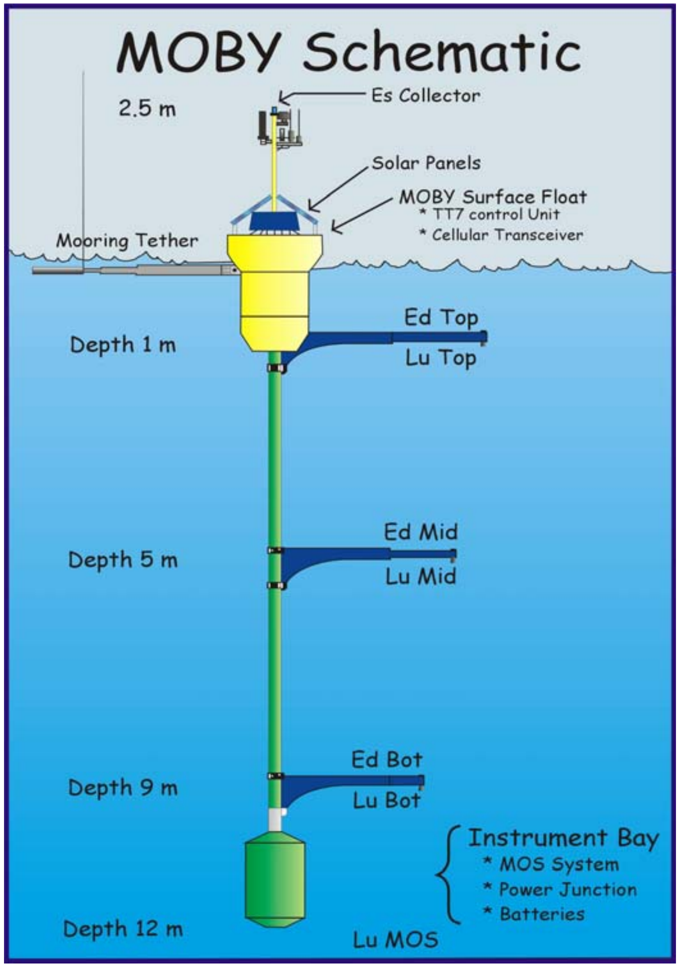
Ocean Color Calibration / Validation



MOBY operations: Univ. of Hawaii Marine Center, Honolulu HI

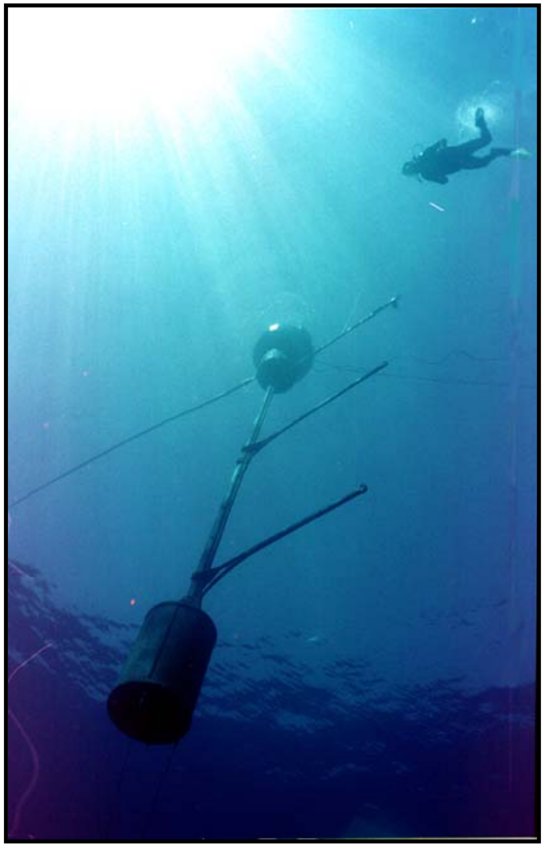
- **Oligotrophic water** – low horizontal gradients, optically deep, high blue signal
- **Maritime atmosphere** – small aerosol component
- **Characterized** – physical, biological, optical, BRDF measurements & models
- **Servicibility** – pier-side support (ship, cranes, machine shop), small boat & diver safety
- **In-water sensor** – measures water-leaving spectral radiance Lw(λ)
- **Time series** – long term (13 years, 1997 – present), consistent, calibrated
- **3 daily profiles** – timed to coincide with satellite overpasses (20, 22, 23:00 h GMT)

Clark *et. al*. 2003, Ocean Optics Protocols for Satellite Ocean Color Validation, Rev.4 Vol.6



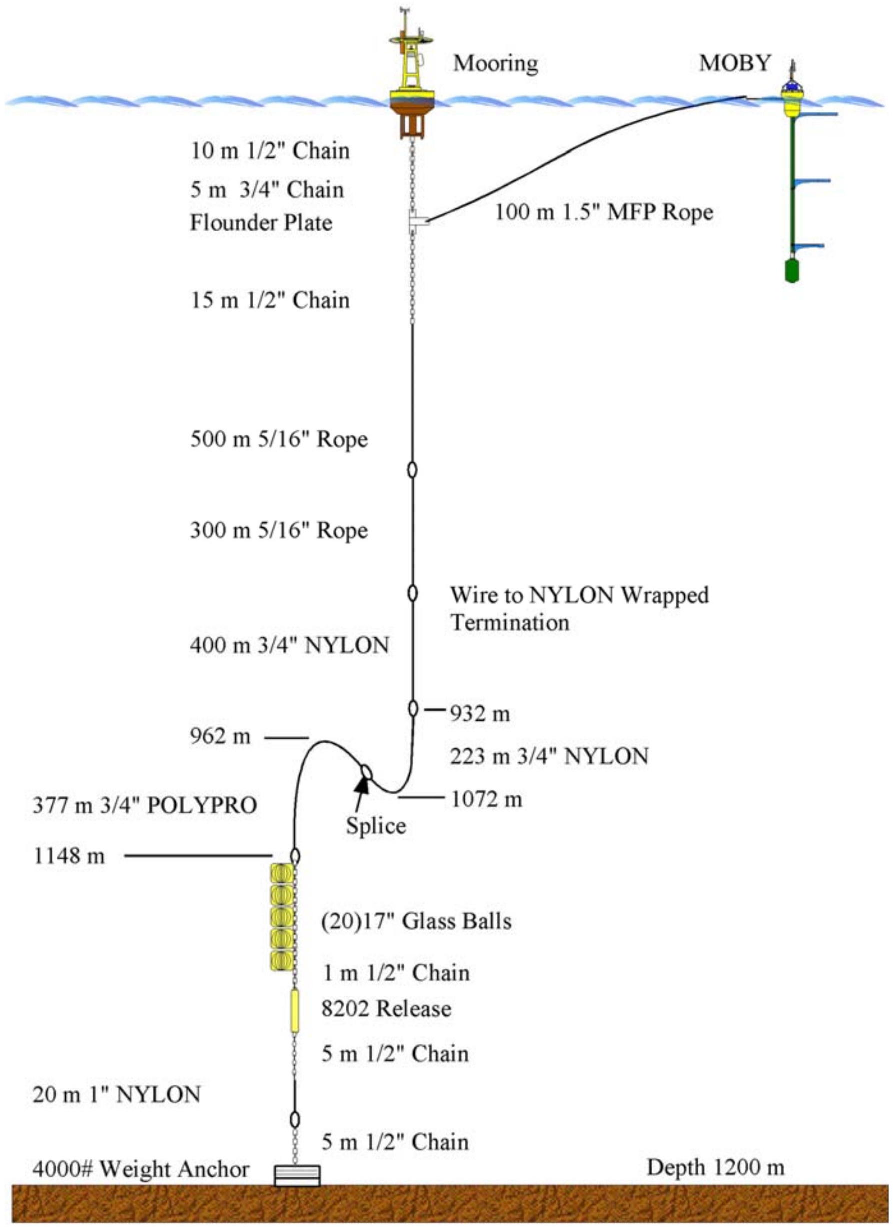
Marine Optical Buoy

Spar buoy,
slack-line tethered
to moored buoy.
Instrument bay houses
Marine Optical System
and optical multiplexer,
with fiber optic connection
to optical collector heads.



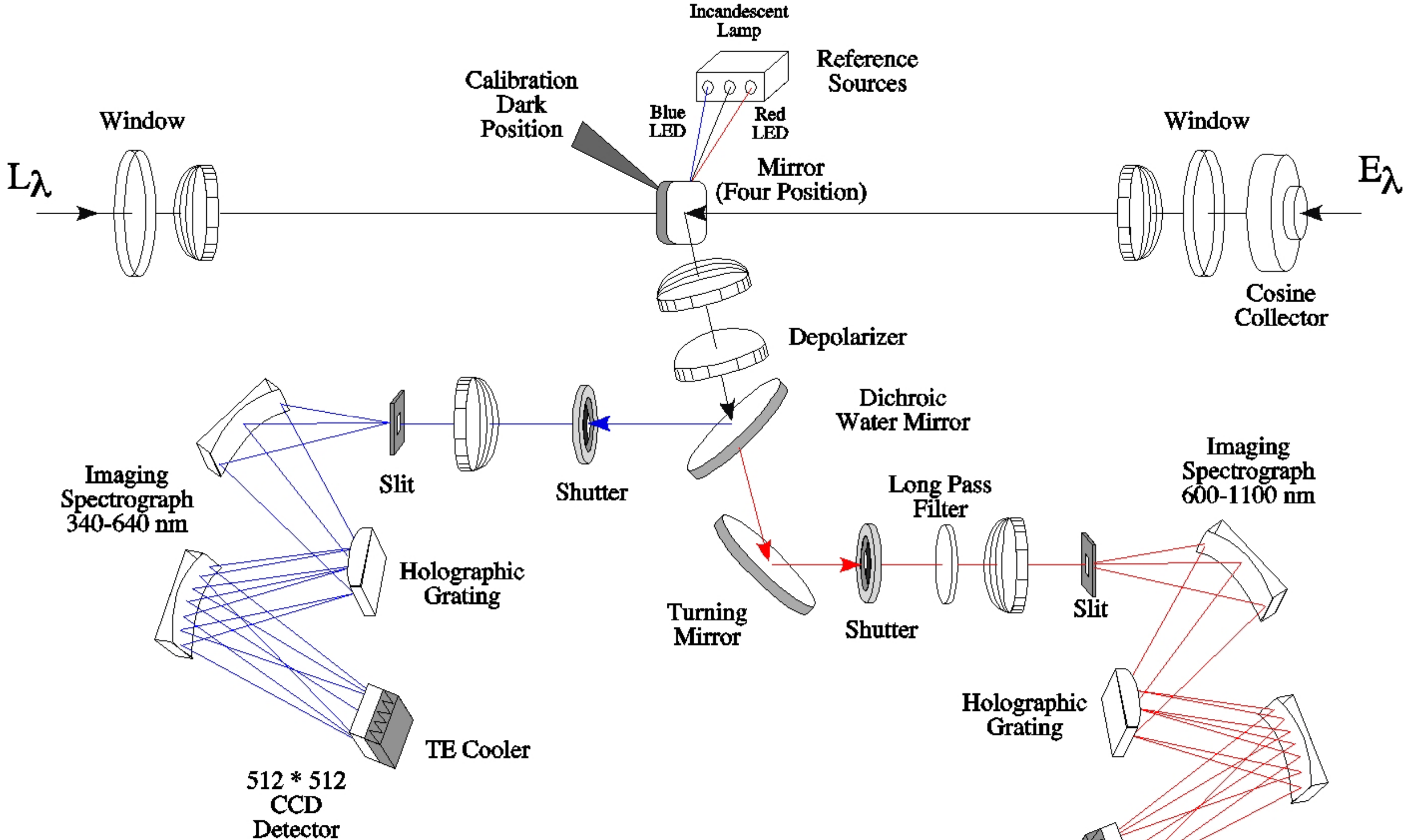
- Optical – high spectral resolution, large spectral range, temperature stabilization, on-board reference lamps for stability monitoring
- Calibration – NIST traceability & collaboration
- Characterization – stray light, thermal, linearity, shadow correction modeling
- Buoy – stable (small tilt angles), minimized shadowing (small buoy, sm. collectors, standoff arms)
- Reliability – 3-to-4 month deployments, diver cleaning & cals minimize bio-fouling, three systems: 1 = deployed, 2 = being refurbished, 3 = spare

Ocean Mooring



Instrumentation:
PAR, wind speed, air °C, %RH, atm. press., CTD, solar panels, batteries, night-light, radar-reflect.

Marine Optical System - Dual Spectrographs



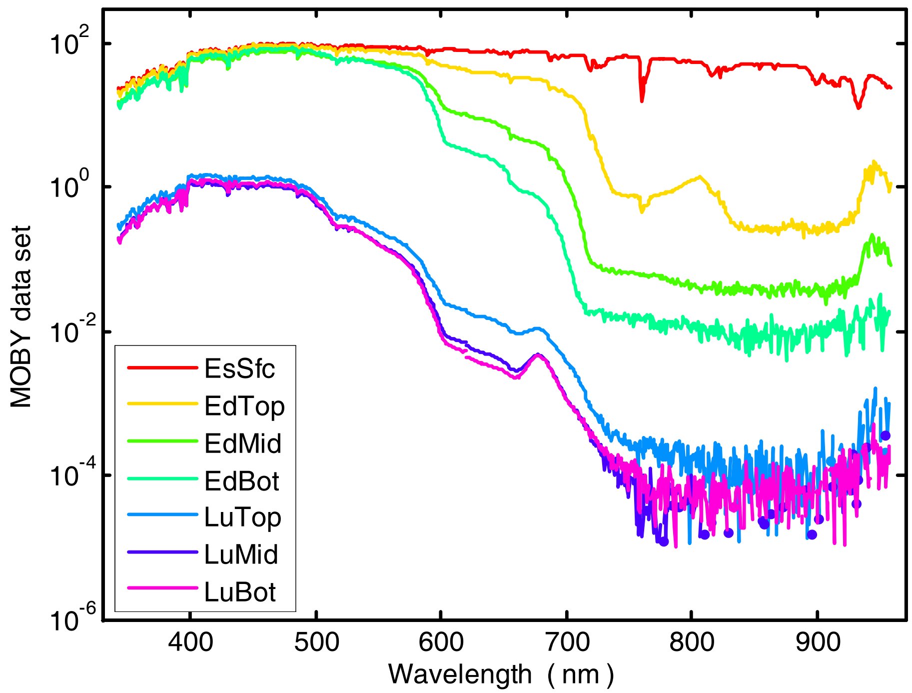
Spectrograph	Blue	Red
Spectral range	340 – 640 nm	550 – 955 nm
Bandpass FWHM	0.91 nm	1.17 nm
Pixel spacing	0.58 nm	0.81 nm
Spectral overlap	550 – 640 nm	

Data Analysis

- Surface-incident spectral irradiance Es(λ)
- Downwelling irradiance, Ed(λ) at 1, 5, 9 m depths
- Upwelling radiance, Lu(λ) at 1, 5, 9, 12 m depths
- Sequential sampling: Es, Ed(z1), Es, Lu(z1), Es, Ed(z2), Es, Lu(z2) ...

includes: dark scans, LED scans, 7 x °C, %RH, Volts, amps, coolant flow, position, date, time, X & Y tilt (inclination), heading, depth

- **MATLAB *MLDbase* Data Processing:**
- Radiance attenuation coefficient, Kl(λ)
- Water-leaving radiance, Lw(λ)
- Band averaging *(full-band response includes out-of-band)*
- Quality Control *(Lw consistency, Kl vs clear water, CIE coordinates)*



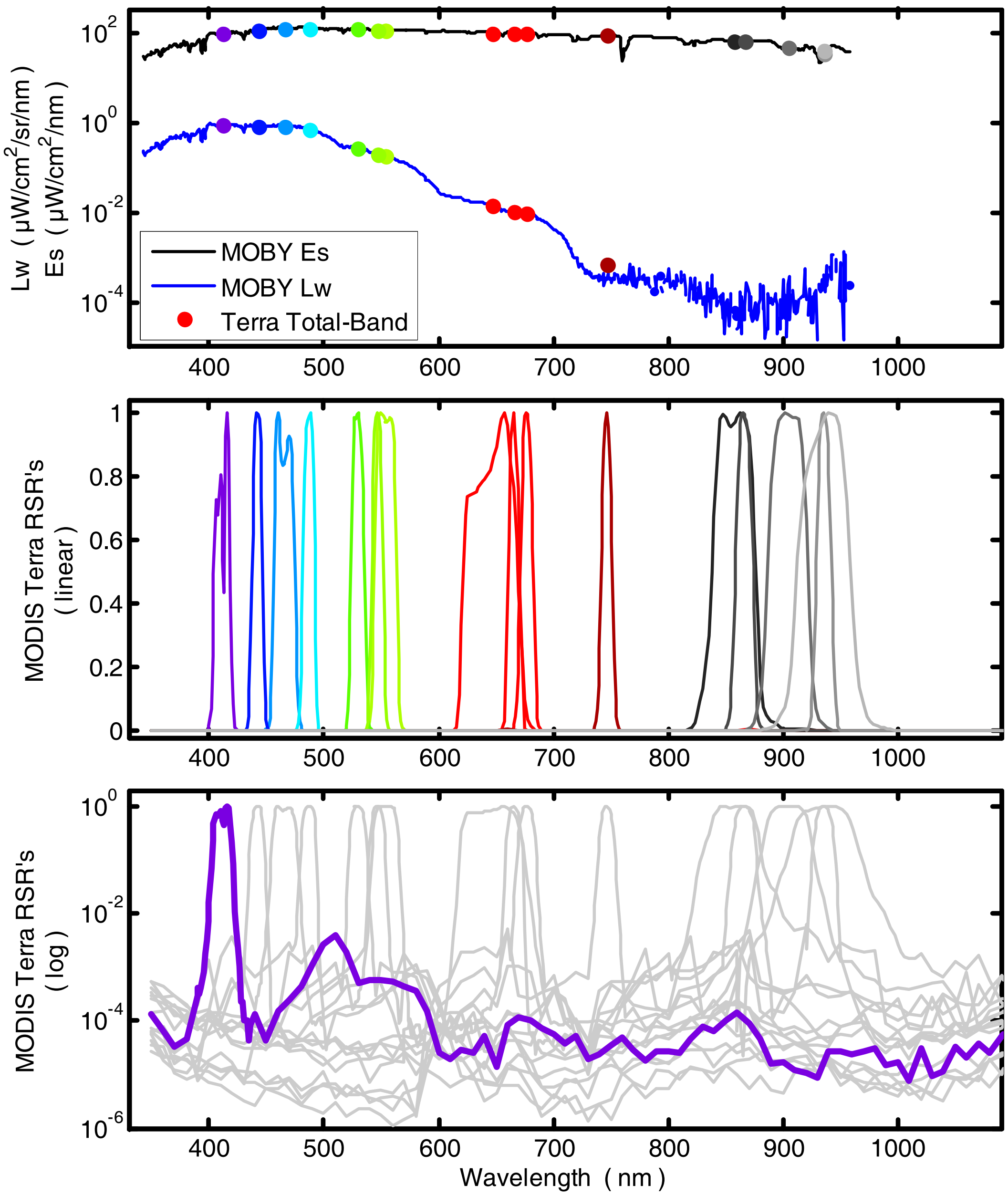
$$K_L(\bar{z}_{ij},\lambda) = \frac{1}{z_j - z_i} \ln\left[\frac{L_u(z_i,\lambda,t_i)\,E_s(0,\lambda,t_j)}{L_u(z_j,\lambda,t_j)\,E_s(0,\lambda,t_i)}\right]$$

$$L_u(0^-,\lambda) = L_u(z,\lambda)\exp\left[K_L(\bar{z}_{ij},\lambda)\,z\right]$$

$$L_w(\lambda) = \frac{1-\rho}{n_w^2} L_u(0^-,\lambda)$$

$$\frac{1-\rho}{n_w^2} \equiv 0.543$$

Products: Sensor Spectral Band Matching



Relative Spectral Response, RSR
Band-Averaged Radiance, BAL

$$BAL = \frac{\int RSR(\lambda)\, Lw(\lambda)\, d\lambda}{\int RSR(\lambda)\, d\lambda}$$

Applications: Satellite matchups

Ocean Color Sensors Supported by MOBY

- China - MERSI
- Europe - MERIS
- France - POLDER 1 & 2
- India - OCM-2
- Japan - OCTS, GLI
- US - SeaWiFS
- US - MISR (Terra)
- US - MODIS (Terra and Aqua)

Example: SeaWiFS sensor + algorithm system 5x5 pixel data vs MOBY Lw:

- **MOBY provided 1450 matchups over 9 years**, coincident with satellite overpass
  i.e. 1450 *after* MOBY's *in situ* observation quality screening, including:
  significant buoy tilt, Es & Kl & Lw stability, Instrument problems
- **150 passed OBPG screening process** (~10%), including:
  Atmos. correction contamination -
  land, clouds, cloud shadow, stray light
  Navigation error, Chl-*a* > 0.2 mg/m^3,
  NIR τ-aerosol > 0.15,
  Sensor θ > 56°, Solar θ > 70°
  Lw via Lu-Top vs Mid differ > 5%
  Es vs model differ > 10%

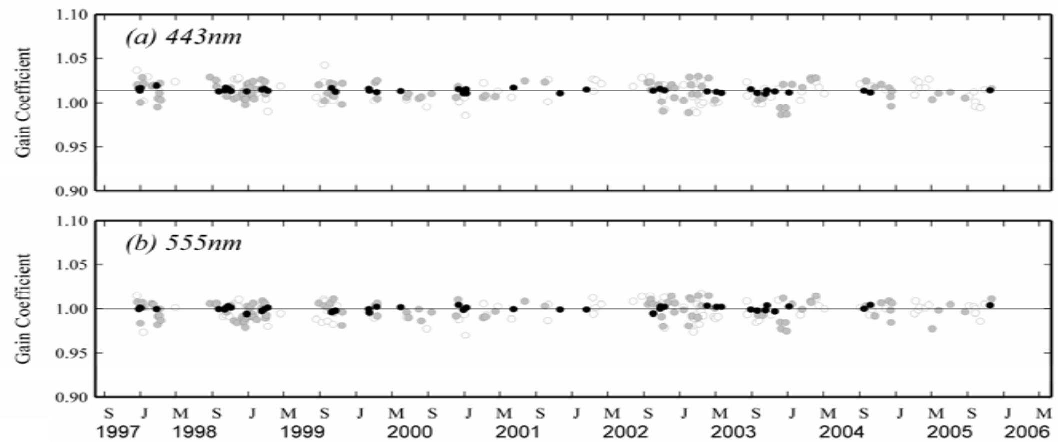


Table 2. SeaWiFS Vicarious Gain Coefficients

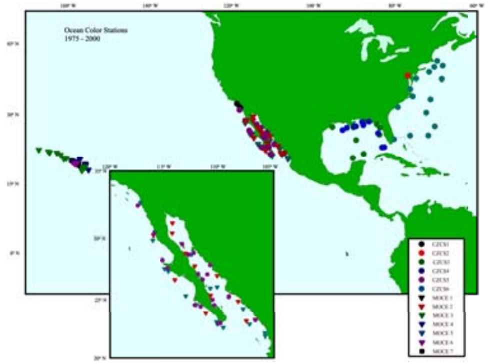
λ	412	443	490	510	555	670	765	865	N^a
$\bar{g}$	1.0377	1.014	0.9927	0.9993	1.000	0.9738	0.9720	1.000	150 (97)
σ^b	0.009	0.009	0.008	0.009	0.008	0.007	0.010	0.0	
$S_E{}^c$	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0011	0.0	

[a]Number of gain samples, g_i, used to compute the mean gain, $\bar{g}$, for $\lambda < 765$ ($\lambda = 765$).
[b]Standard deviation of the distribution of g_i about $\bar{g}$.
[c]Standard error on the mean, $\bar{g}$, computed as σ/sqrt(N).

Franz *et. al.* 2007
Appl. Opt.46, 5068-5082
Fig. 3 & Table 2

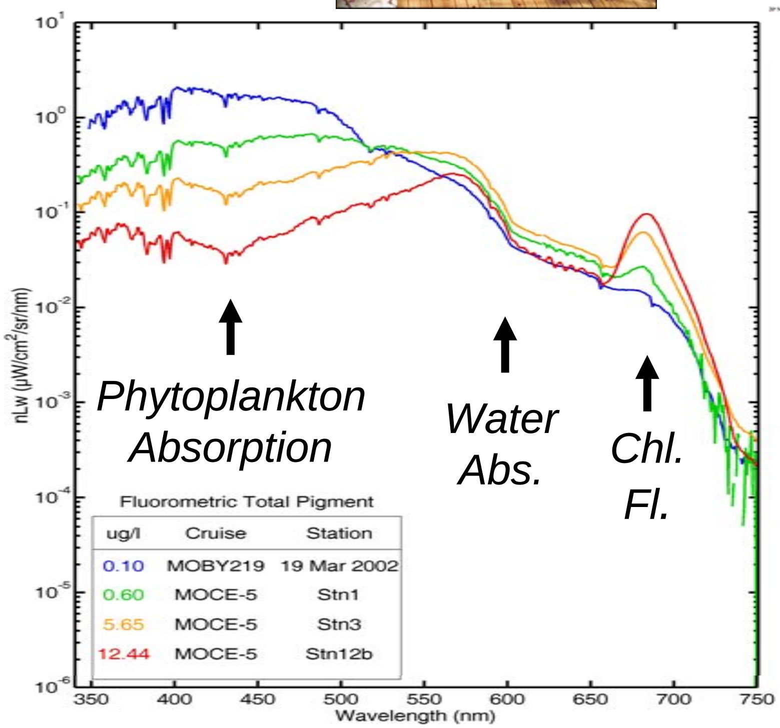
Applications: Bio-Optical Algorithms

Deployments of the MOS profiler were used in conjunction with analytical sampling to compile a hyperspectral Ocean Color Database, which was used to develop bio-optical algorithms for MODIS.

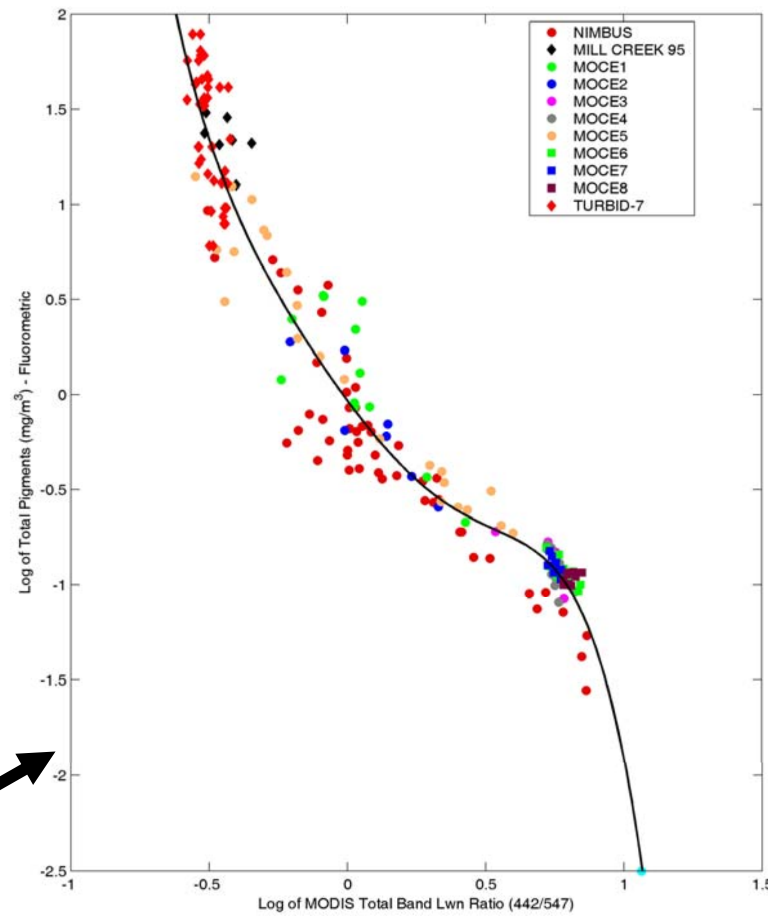


some MODIS Terra Products

- CZCZ_pigment – Fl determined
- Chlor_MODIS – HPLC determ.
- Pigment_cl_total – HPLC
- TSM – dry weight
- K_490 – SeaWiFS Ed



CZCS Pigments MODIS-Terra

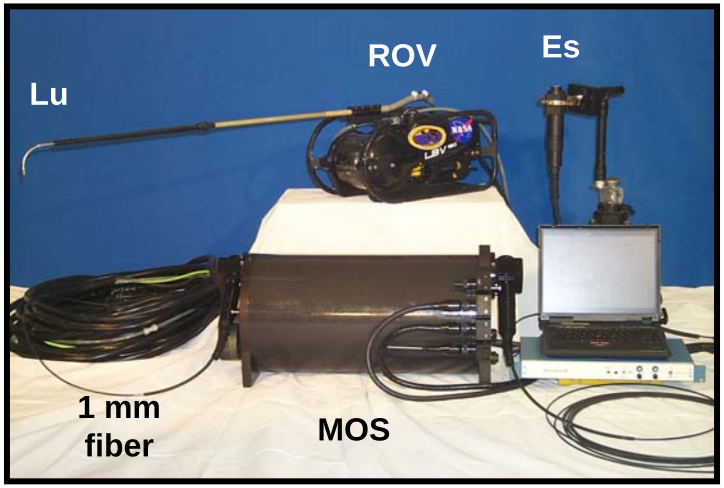


Generalized form for product computation:

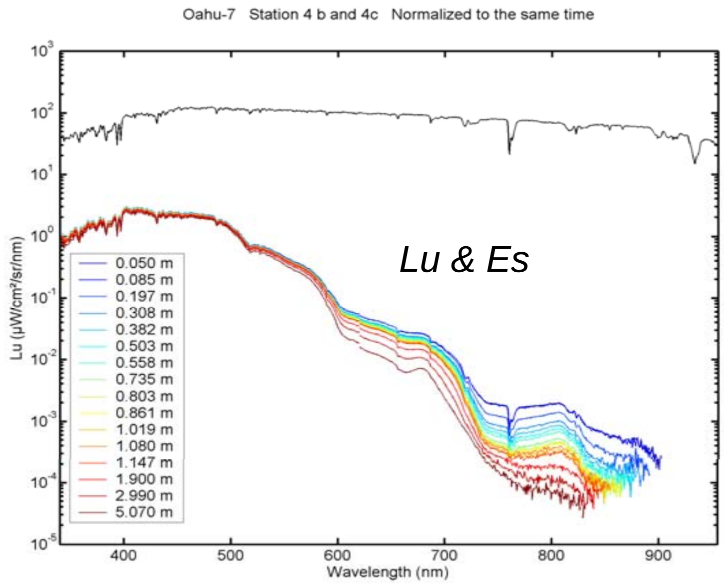
Log Product = [A(Log X)^3 + B(Log X)^2 + C(Log X) + D] / E

where X = nLw(band 9) / nLw(band 12)

Applications: ROV

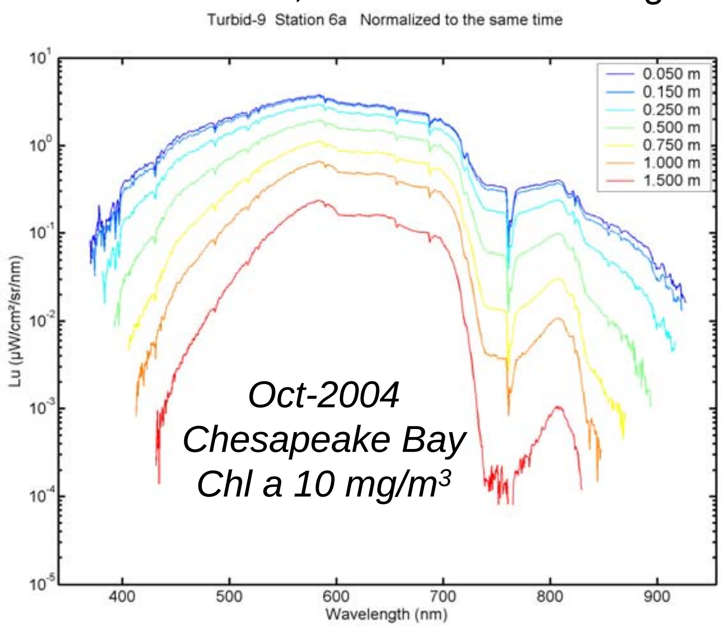


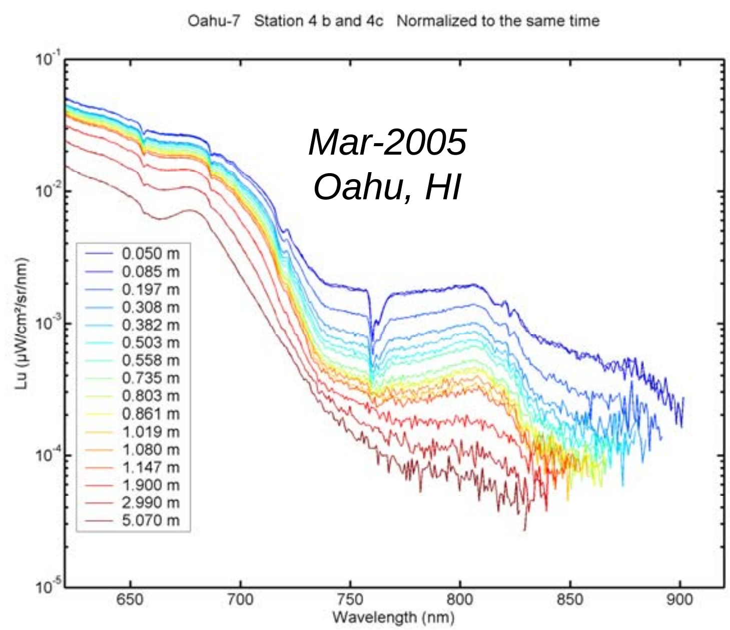
Seabotix LBV-150 ROV
1 mm fiber optic to MOS
1 m collector standoff
Lu shadowing dia < 5 mm
Depth control 1 to 10 cm
Azimuth control 1 deg



High depth-resolution vertical profile

Turbid water, Low / ~no shadowing





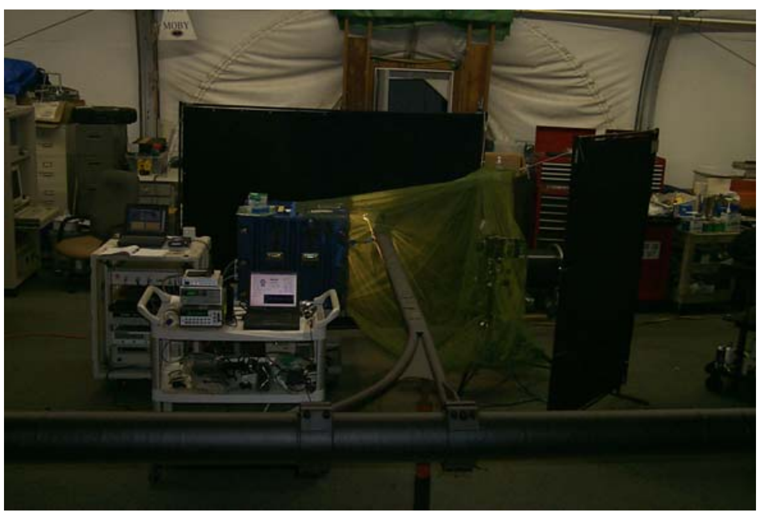
Yarbrough *et. al.* 2007, Proc. SPIE 6680, 66800I1 to 66800I-12

Radiometric Calibration

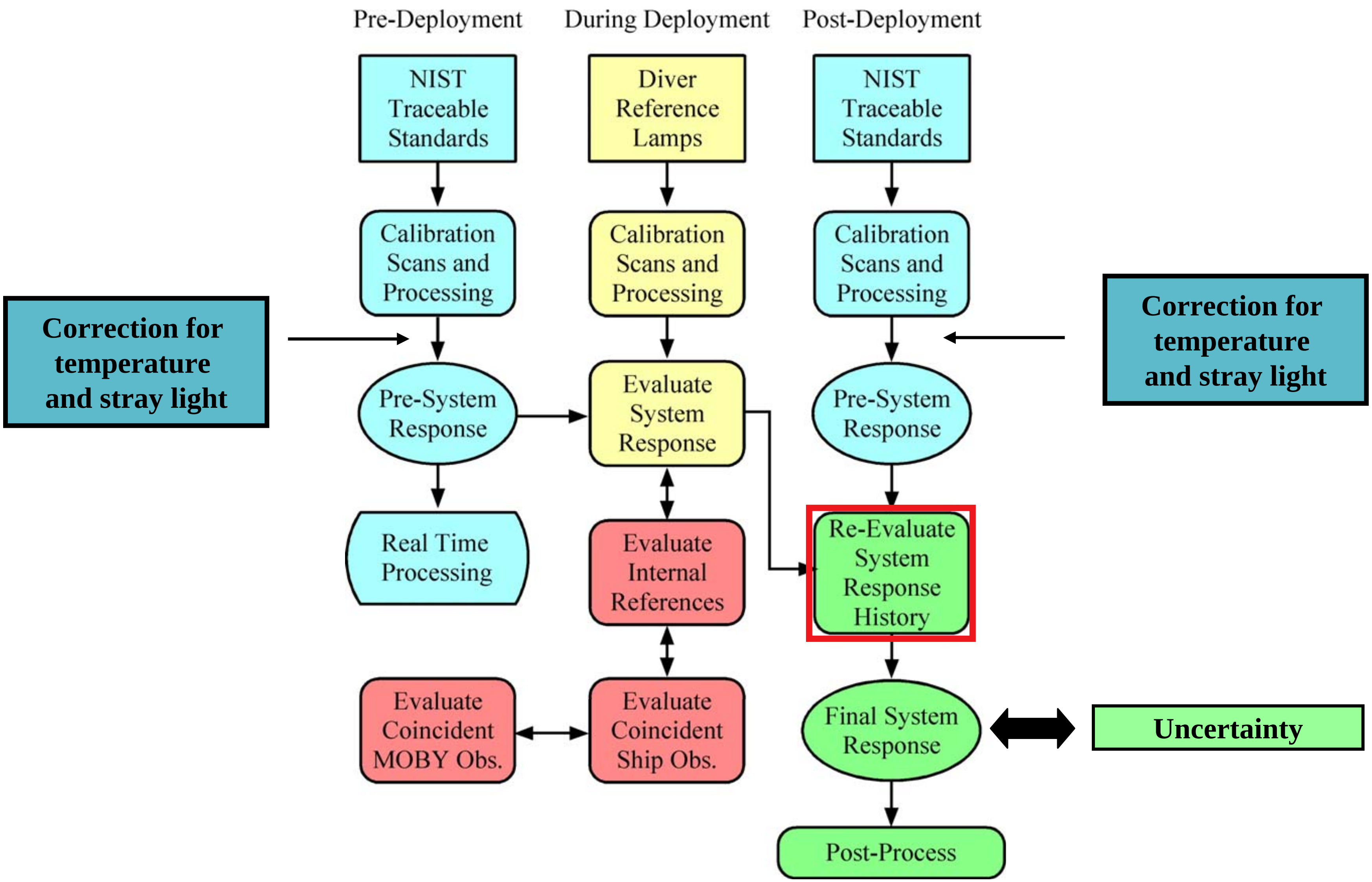
- System level calibrations of Es, Ed, Lu, λ
- Pre & Post-deployment calibrations
- Traceability to SI reference standards
- 50 hr standard lamp NIST calibrations
  (beginning and end-of-life calibrations)
- Standard Lamp Monitors (SLM)
  (412 & 872 nm, Ir/Radiance)
- Housekeeping data: Volts, Amps, °C, %RH
- MOS internal reference sources scanned
- Annual on-site NIST intercomparisons
- Stray Light Characterization (SLC)
- Thermal Characterization
- Goniometric Characterization
- Linearity, Integration Time, Bin Factor

HI Lab (van) 2001: OL420 SLM SXR VXR

HI Tent 2000: MOBY NPR VXR



Calibration Approach

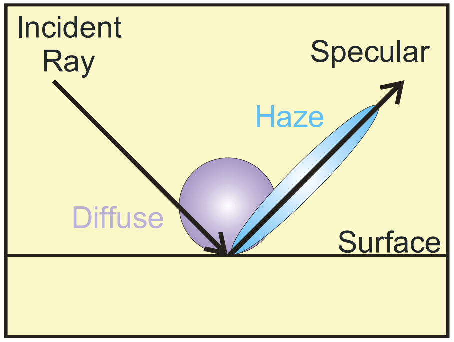


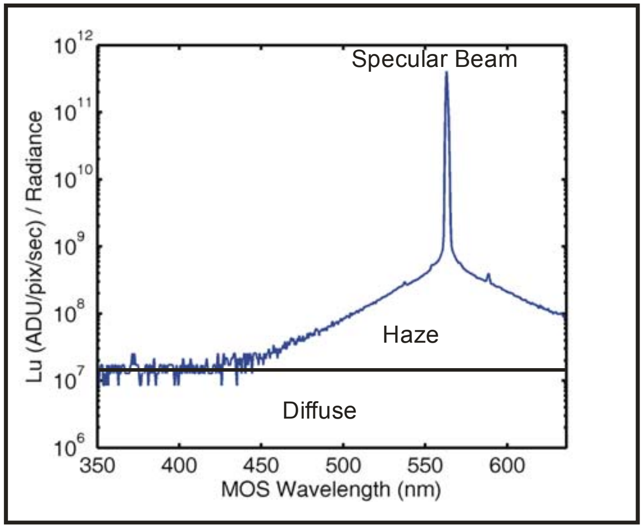
MOBY Lu uncertainty components for one deployment	**MODIS Terra Band** (k=1) [%]					
	8	9	10	11	12	13
	411.8 nm	442.1 nm	486.9 nm	529.7 nm	546.8 nm	665.6 nm
Radiometric Calibration Source						
Spectral Radiance	0.65	0.60	0.53	0.47	0.45	0.35
Stability	0.41	0.46	0.51	0.53	0.53	0.48
Transfer to MOBY						
Interpolation to MOBY wavelengths	0.20	0.15	0.03	0.03	0.03	0.03
Reproducibility	0.37	0.39	0.42	0.44	0.42	0.30
Wavelength accuracy	0.29	0.08	0.04	0.03	0.01	0.04
Stray Light	0.66	0.29	0.13	0.21	0.36	0.64
Temperature	0.25	0.25	0.25	0.25	0.25	0.25
MOBY stability during deployment						
System Response	1.59	1.30	1.19	1.11	1.08	0.92
In-water internal calibration	0.43	0.42	0.44	0.46	0.51	0.55
Immersion Coefficient (*est.*)	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*
Wavelength stability	0.13	0.14	1.12	0.82	1.37	0.65
Environmental						
Type A (good days only)	0.80	0.83	0.87	1.02	0.64	1.31
Temporal overlap	0.3	0.3	0.3	0.3	0.3	0.3
Self-shading (uncorrected)	1	1	1.2	1.75	2.5	12
Self-shading (corrected)	0.20	0.20	0.24	0.35	0.50	2.4
In-water bio-fouling	1	1	1	1	1	1
Combined Standard Uncertainty- shading uncor.	2.6	2.4	2.6	2.9	3.5	12.2
Combined Standard Uncertainty- shading corr.	2.4	2.2	2.4	2.3	2.4	3.3

Brown, *et.al.* 2007, Proc. SPIE 6744, 67441M1-67441M12

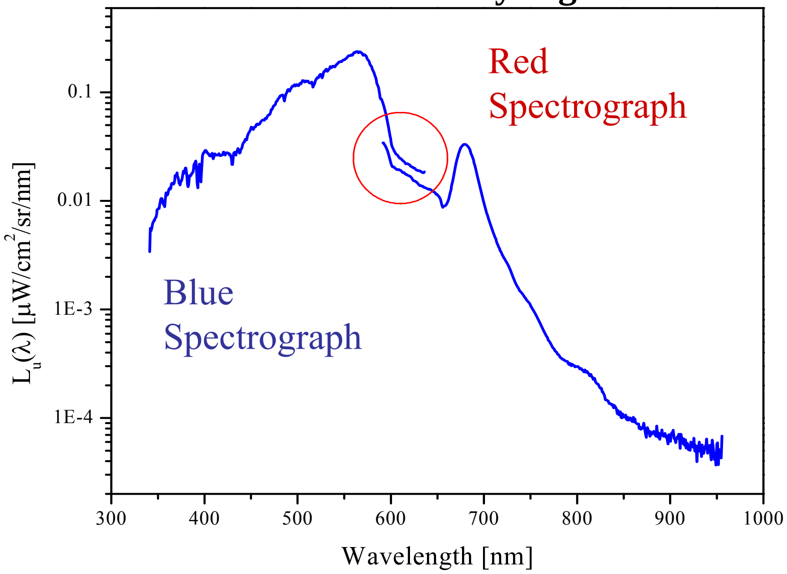
Stray Light Correction

- Stray Light is light scattered off optical surfaces.
- 3 Factors: Diffuse, Haze, Reflections
- Monochromatic spectral line source (ex. Laser) light tells us how single λ Input effects all CCD detector pixels

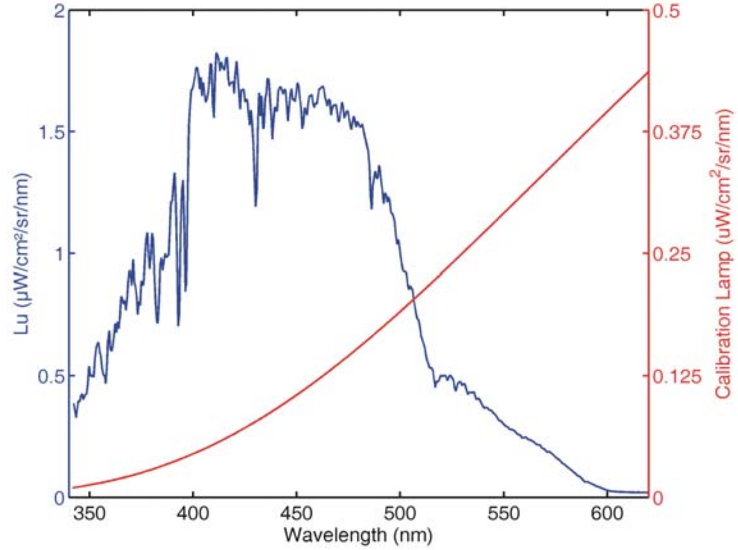




MOBY measurements did not agree in the spectrograph overlap region … because of stray Light



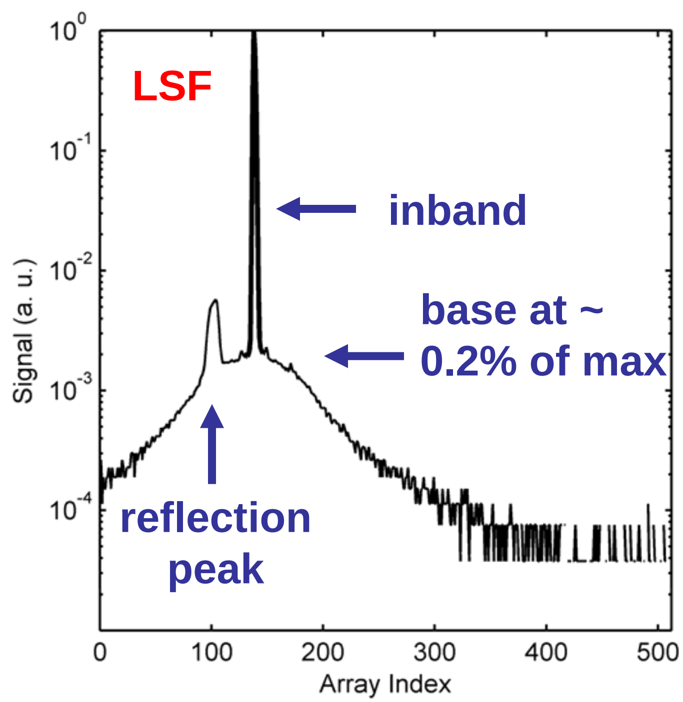
Source spectral power mis-matched: Calibration via red-rich incandescent lamp, Field measurements of blue water



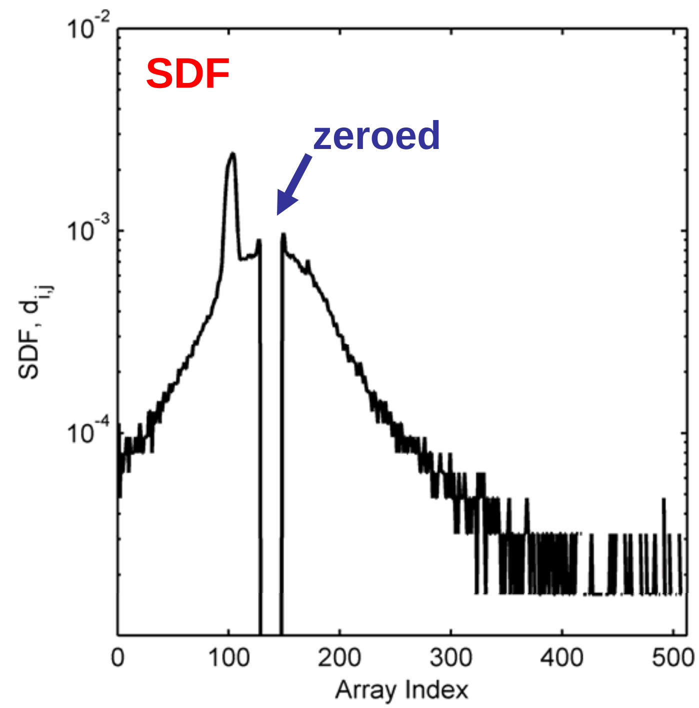
Zong *et. al.* 2006, Appl. Opt. 45, 1111-1119

SLC …continued…

1.) Spectral line spread function, LSF
describes spectrometer's response
to fixed monochromatic excitation



2.) divide LSF by inband area and
set inband pixels to zero, gives
relative fractional amount of incident radiation scattered onto other elements, called
stray light distribution function, SDF



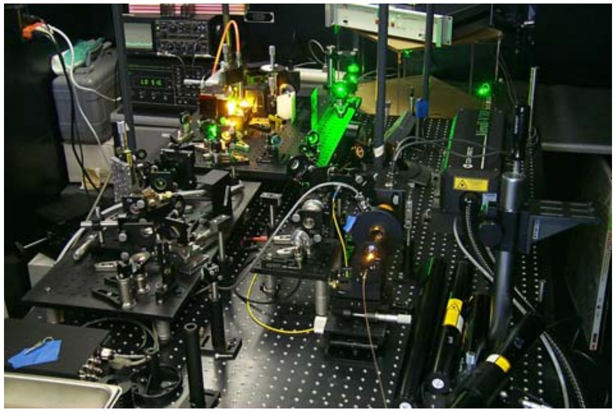
3.) Measure many λ's, interpolate & extrapolate to fill all detector elements (MOBY n = 512)

4.) Compile a 2-dimensional n x n matrix of SDF's = D, where each column of D is an individual SDF, then, each row of D is the relative stray light response function, which is **the relative amount of light scattered onto that element of the detector from all other elements**.

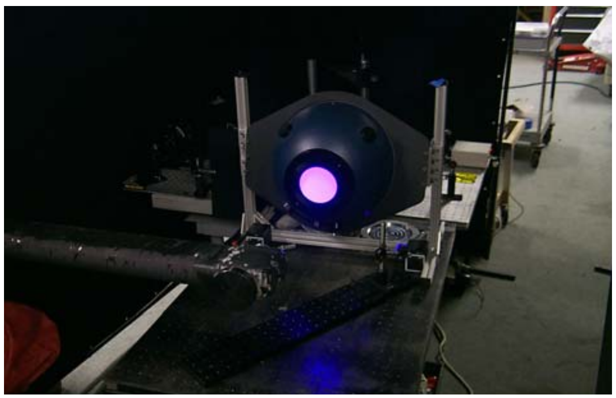
5.) Matrix math correction applied to both the system response and measured ir/radiance

Feinholz *et. al.* 2009, J. Atmos. & Oceanic Tech. 26, 57-73

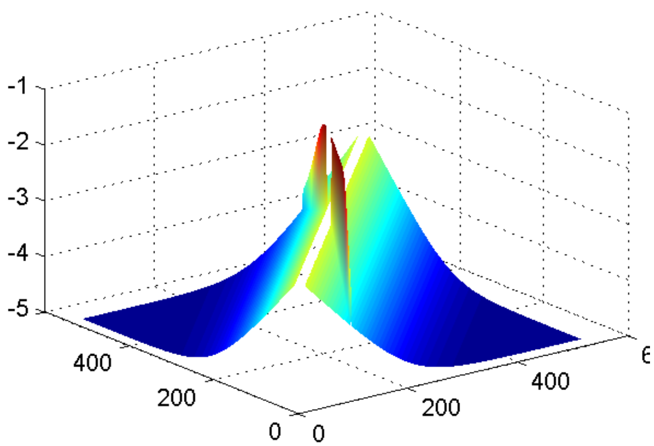
Traveling SIRCUS in HI van



… and at MOBY arms in HI tent



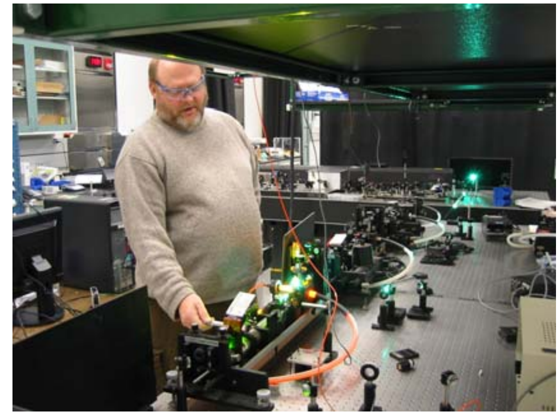
Modeled - Even - BSG - fibered



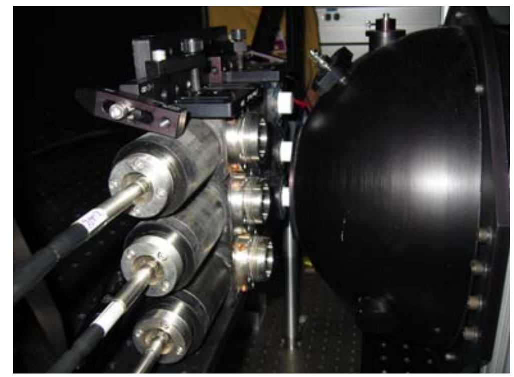
<u>2001-02:</u>
Limited number of tunable laser wavelengths brought to MOBY in Hawaii

<u>2008:</u>
Full SIRCUS laser capability with MOBY brought to NIST in Maryland

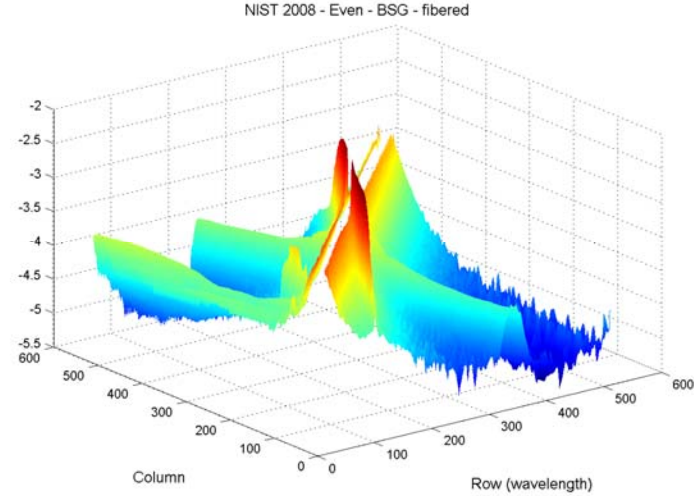
SIRCUS at NIST, MD



MOBY collector heads at SIRCUS

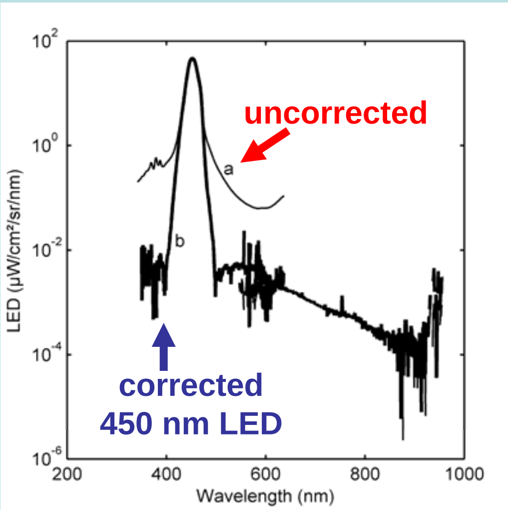


NIST 2008 - Even - BSG - fibered



Stray Light Impact

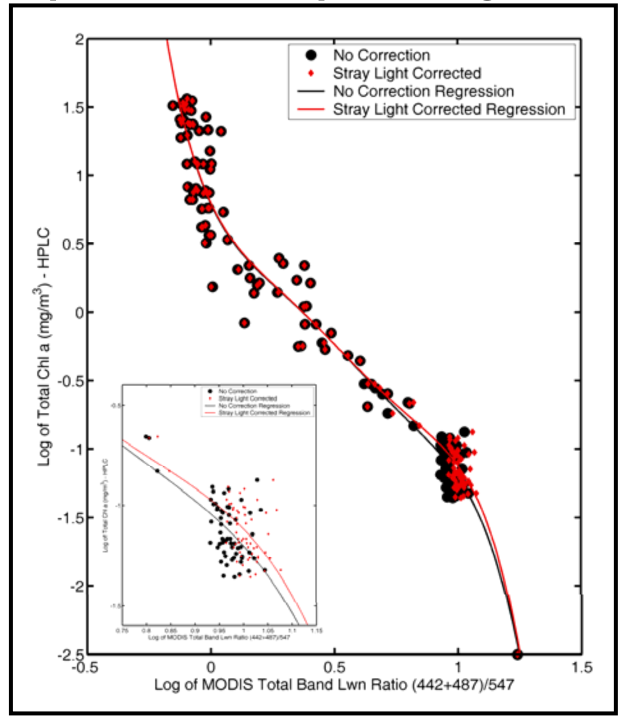
SCL validation via colored sources:



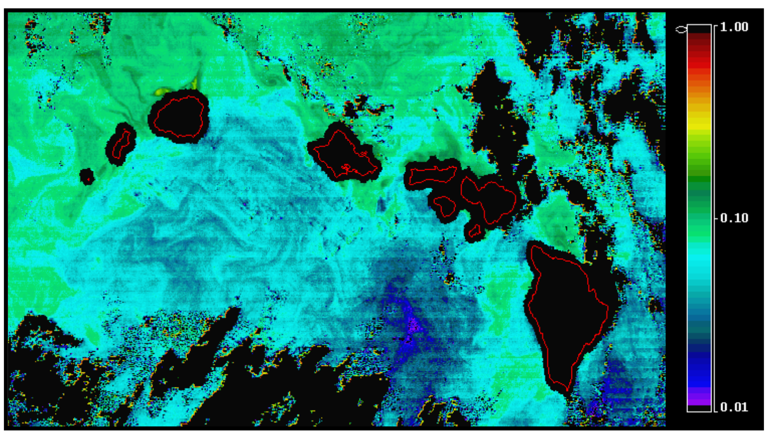
Stray light is a **systematic bias** – will not average out via repeat measurements

MODIS band nm	Avg. Lw Corr. Factor	LuTop SLC Uncertainty
411.8	+ 9.6 %	0.66 %
442.1	+ 3.6 %	0.29 %
486.9	+ 1.4 %	0.13 %
529.7	- 3.7 %	0.21 %
546.8	- 4.0 %	0.36 %
665.6	+ 2.3 %	0.64 %

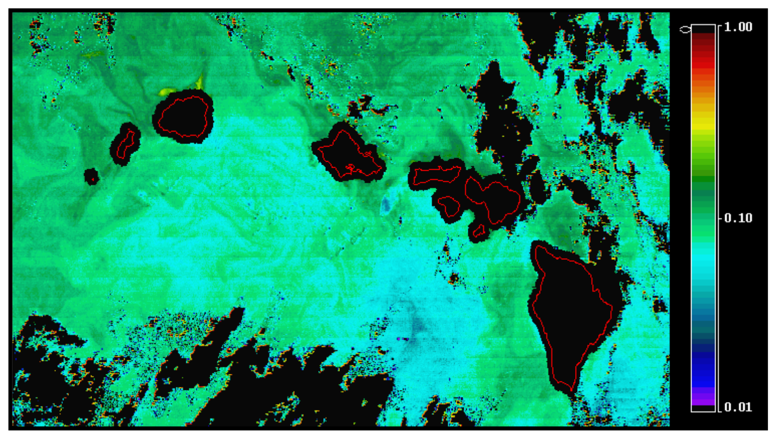
Impact on bio-optical algorithm



Application to MODIS image



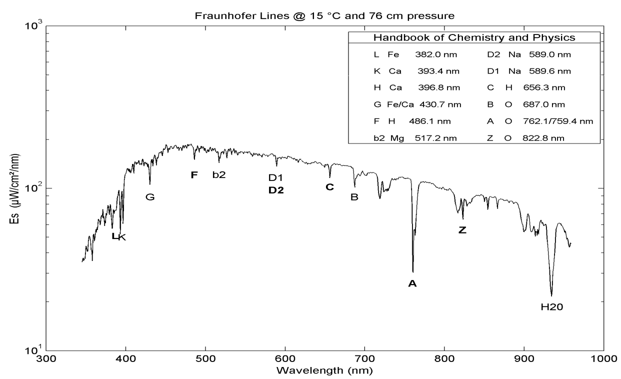
Before stray light correction



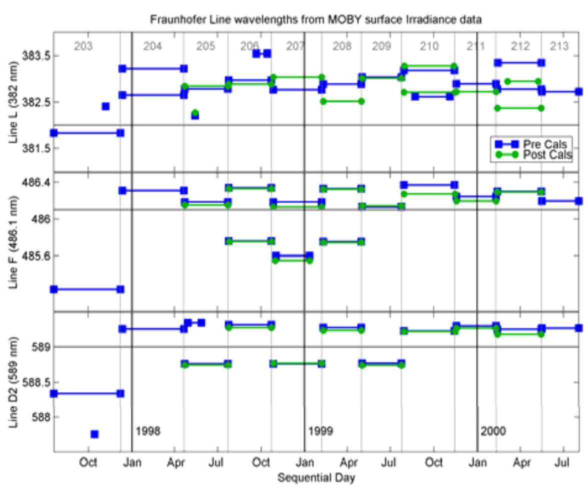
After stray light correction

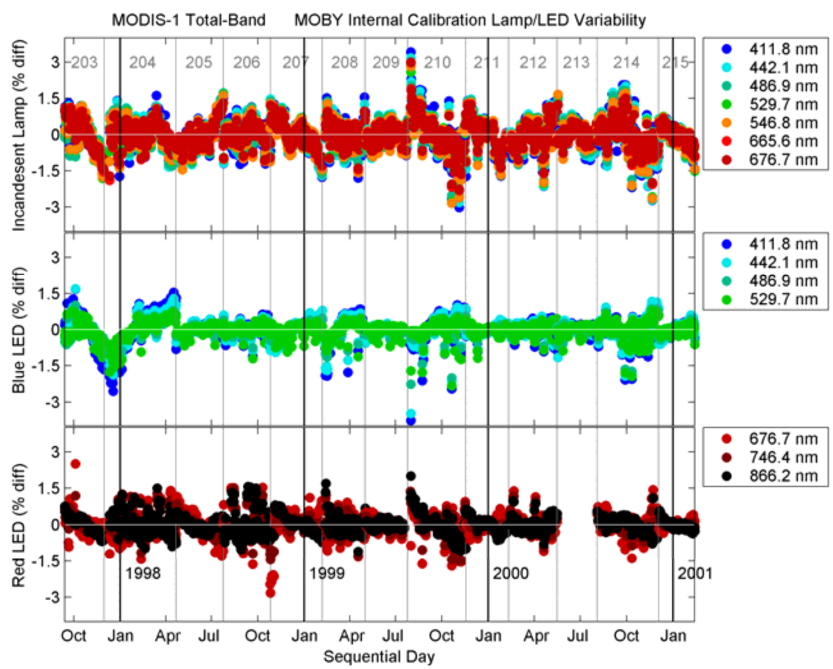
Tracking long term stability

- Fraunhofer solar absorption lines
- Internal reference lamps
- Underwater diver Lamps
- Pre vs Post-Deployment lab calibrations
- Standard Lamp Monitors (SLM)



BSG λ approx. ± 0.6 nm





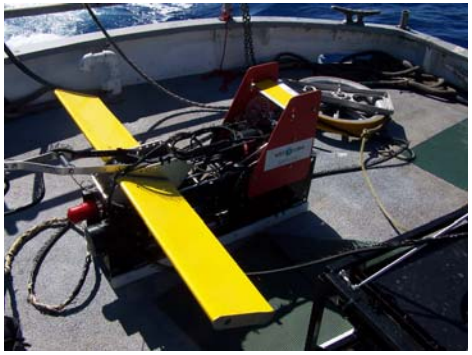
Inter-comparisons

- 1992-96 ***SIRREX –*** *SeaWiFS Intercalibration Round-Robin Experiment*
- 2002 ***SIMRIC –*** *SIMBIOS Radiometric Intercomparison*
  SIMBIOS - *Sensor Intercomparison & Merger for Biological & Interdisciplinary Ocean Studies*
- 2007 ***SORTIE -*** *Spectral Ocean Radiance Transfer Investigation and Experiment*

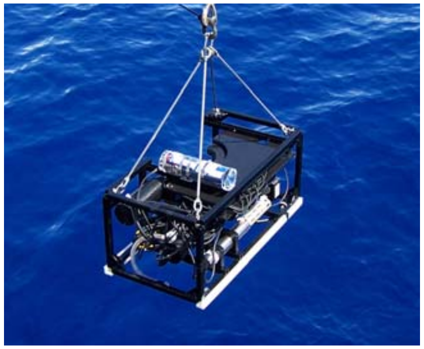
C.Trees, A.Barnard, M.Twardowski, K.Voss, R.Zaneveld, C.Johnson, MOBY team

- AOP's – MOBY & Satlantic HyperPro: Lu(z), Ed(z), Es, $L(\theta,\phi)$
- IOP's – towed & profiling = absorption, attenuation, backscattering
  DOLPHIN (ACS AC9 ECOVSF ECOBB3), MASCOT (AC9 VSF AUVB SAM CTD)
  NuRADS – Upwelling Radiance Distribution: BRDF
- Blind calibration intercomparison – Lu, Ed via NIST sources & VXR

HyperPro



DOLPHIN (tow, profile)



MASCOT (profile)

NuRADS

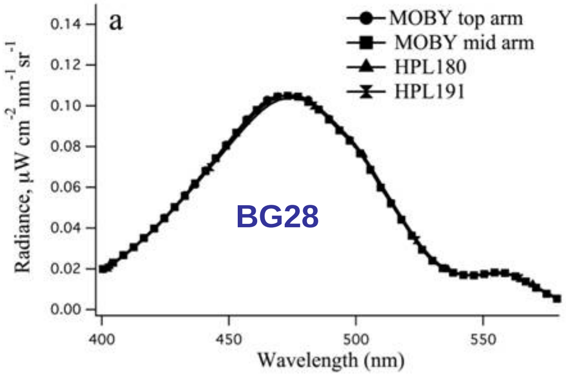
Voss *et. al*. Oct-2010, J. Atmos. & Ocean Tech. 27-10, 1747-1759

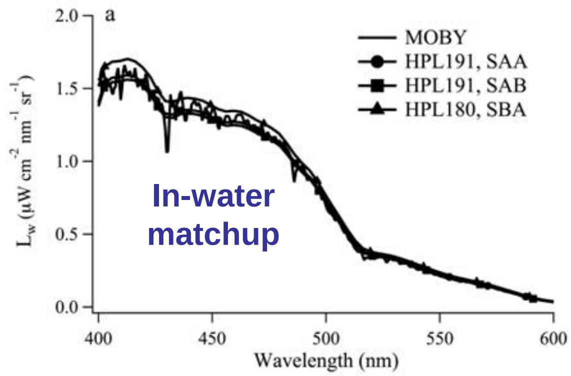
SORTIE - 2007

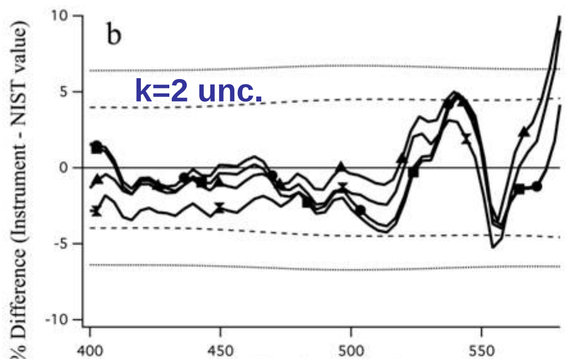
NIST OL420

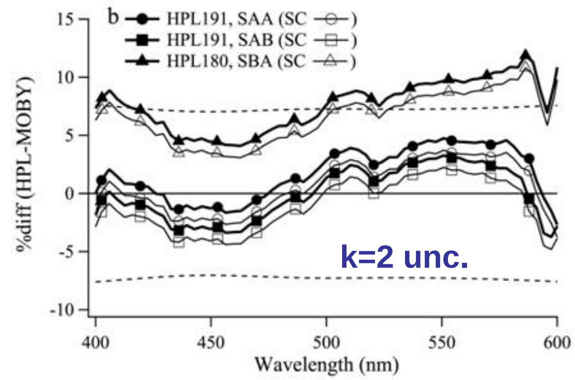
HPL SLM MOBY VXR

Laboratory Intercomparison

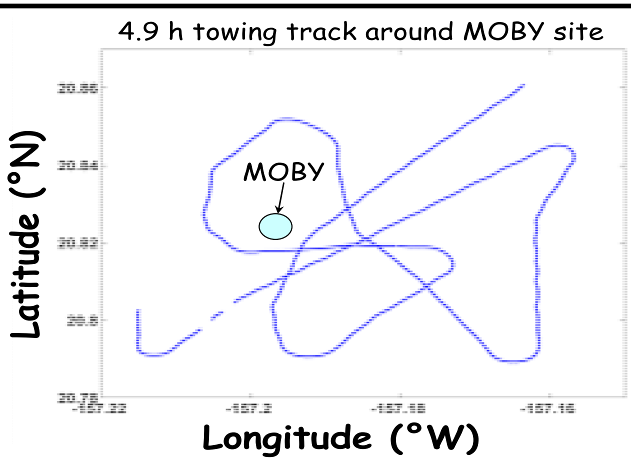


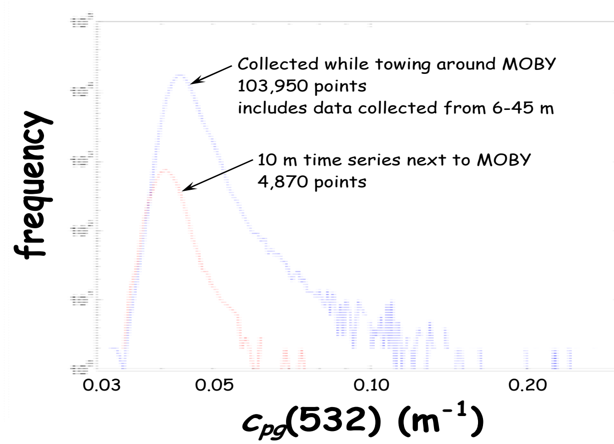






DOLPHIN towed survey around MOB



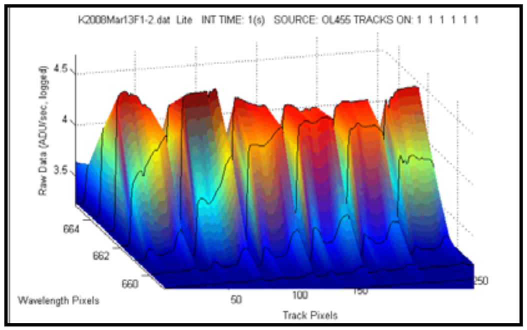


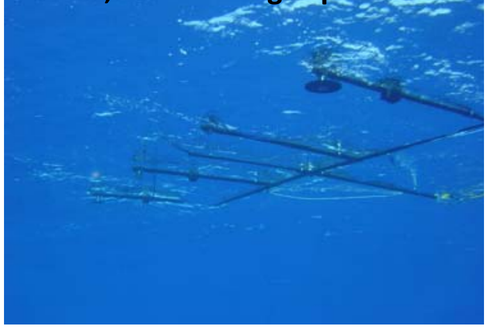
Dr. Ken Voss, U.Miami

Future Goals: MOBY-C

- Multi-channel fiber-coupled hyperspectral imaging spectrograph
- Simultaneous measurements – reduce environmental source of uncertainty
  (solar zenith angle, atmospheric conditions, depth, wave focusing)
- Relocate power to mooring
  (reduce size of optical buoy)

Simultaneous Observations with 6 inputs





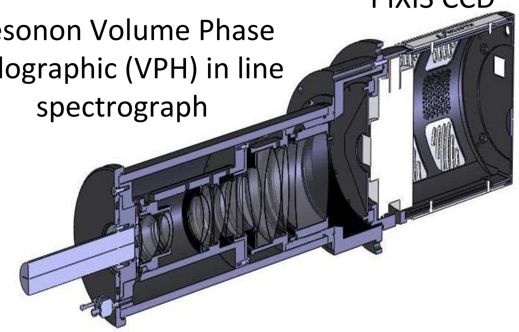
2007, Self Shading Experiments

2006, Field-testing a suitable MOBY Replacement

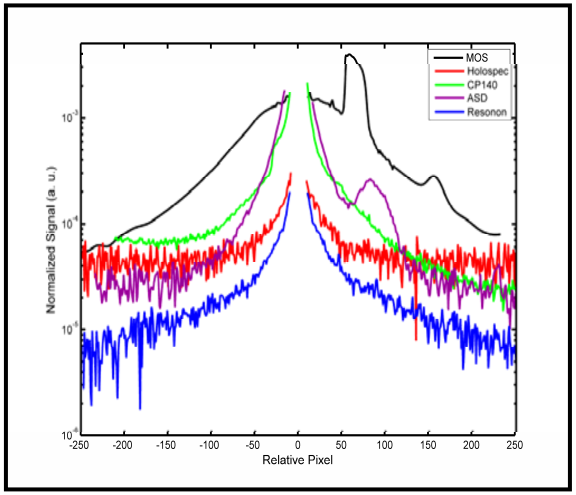
Key parameters of Imaging Spectrometers		
Parameter	**Blue**	**Red**
Size (cm)	13.7 x 41.7	13.7 x 43.2
Spectral coverage (nm)	370 – 720	500 – 900
Spectral resolution (nm)	0.34	0.39
Img at focal plane (mm)	13 x 13	13 x 13
Slit dimensions (mm)	13 x 0.025	13 x 0.025
Thermal effect (pix/°C)	< 0.05 pixel	< 0.05 pixel
Throughput (%)	75 at 430nm	73 at 700nm
Ghosting / Stray Light	<0.5%420nm	<0.6%520nm

Princeton Instrument PIXIS CCD

Resonon Volume Phase Holographic (VPH) in line spectrograph



Romack 14 fiber input

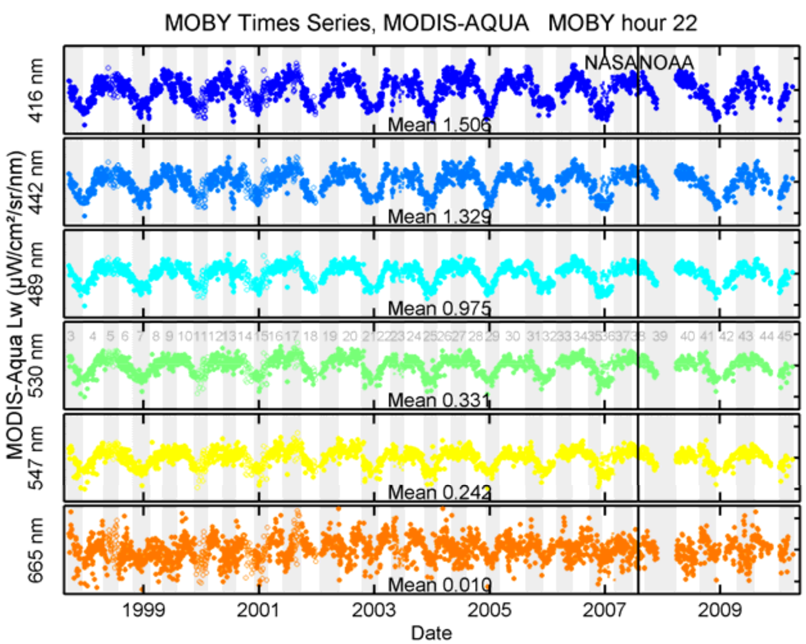


Resonon stray light , 20x better than MOS

Report on Blue and Red Imaging Spectrograph for MOBY (2009) M.Kehoe & C.Dodge, Resonon Inc.

Future Goals – Uncertainty Analysis

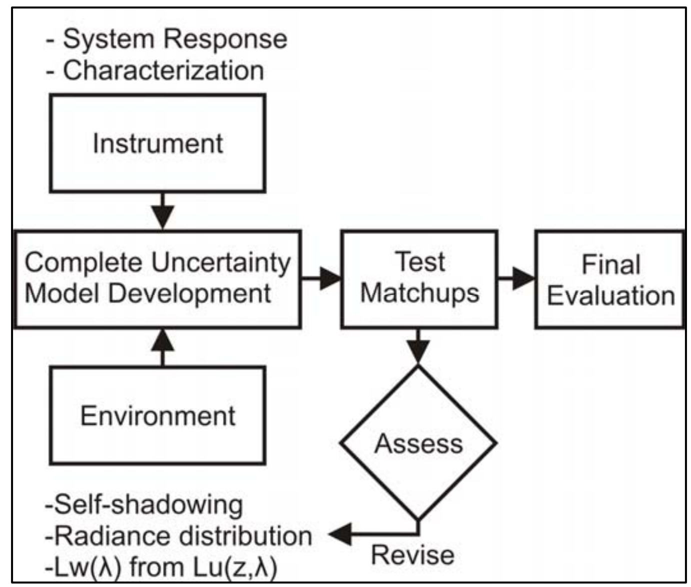
- *Search for & identify sources of bias*
- *Develop correction algorithms*
- *Validate corrections, where possible*
- *Produce time-dependent unc. product*
- *Sensitivity study – impact of MOBY unc. on ocean color time-series*



The MOBY data set from 1997 to present, band-averaged via MODIS aqua RSRs.

To-Do List:

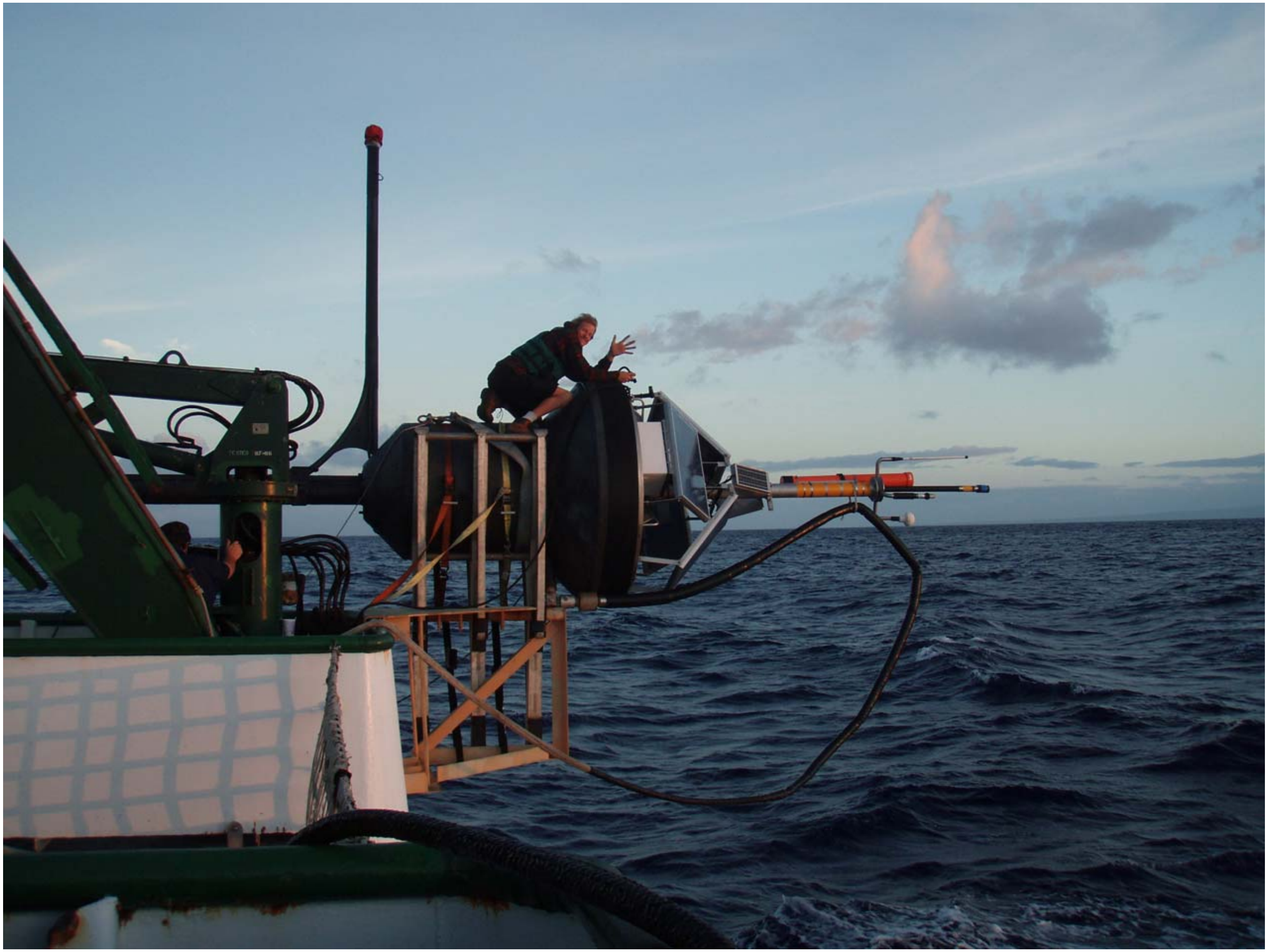
Reduce cal lamp unc. via SLM & VXR
SLC deployments prior to 2008
Thermally characterize *odd* MOS
Mueller Shadowing Model corrections
Goniometric corrections to Es data
Immersion coefficient uncertainties
Upwelling Radiance distribution model
Extrapolation through sea surface unc.
Evaluate time-series for trends



The MOBY uncertainty model approach: the backbone is the uncertainty model

ref: ROSES 2010 proposal: B.C.Johnson, D.K.Clark, B.A.Franz

Thank You – Grazie Mille !

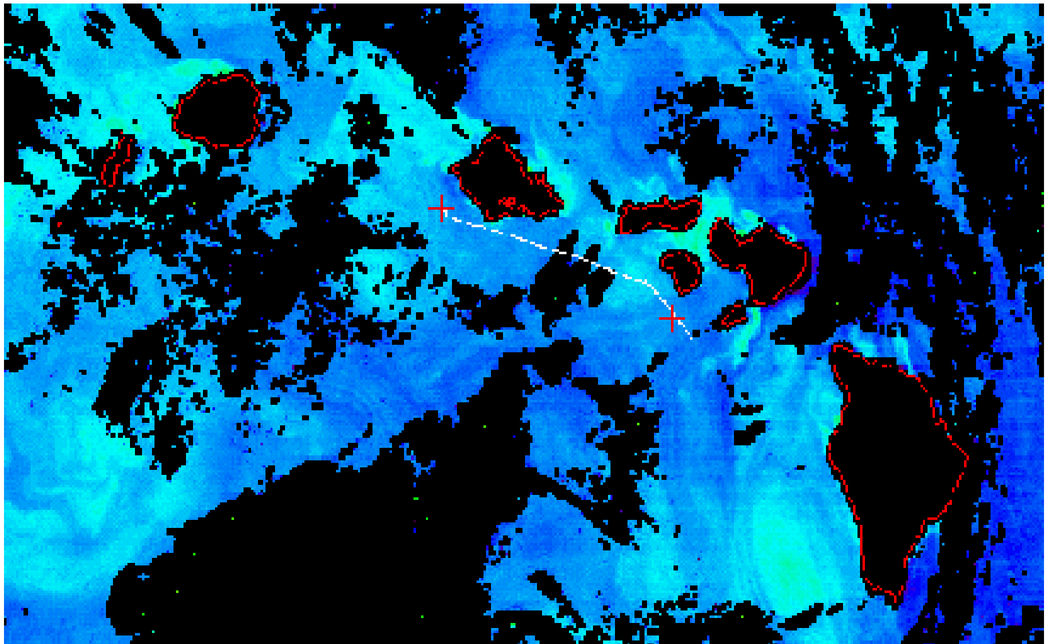


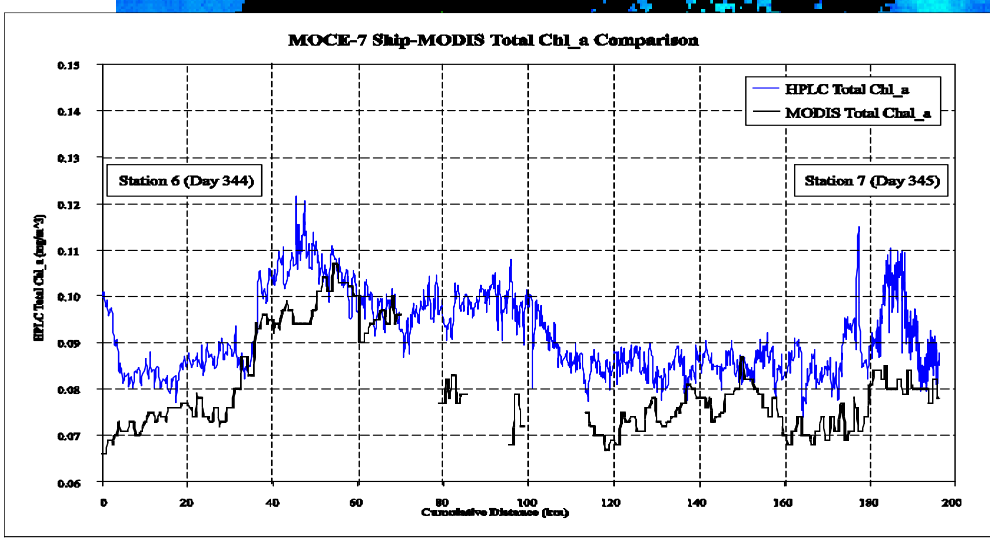
Backup Material

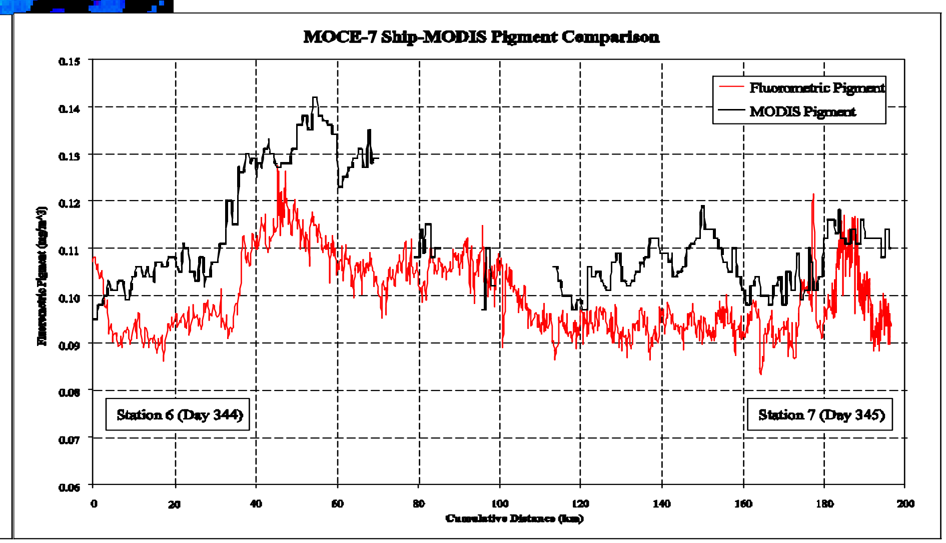
Site Characterization (example #1)

Dec-2000 MOCE-7: MODIS Day 345 ship track

Station 7 Station 6

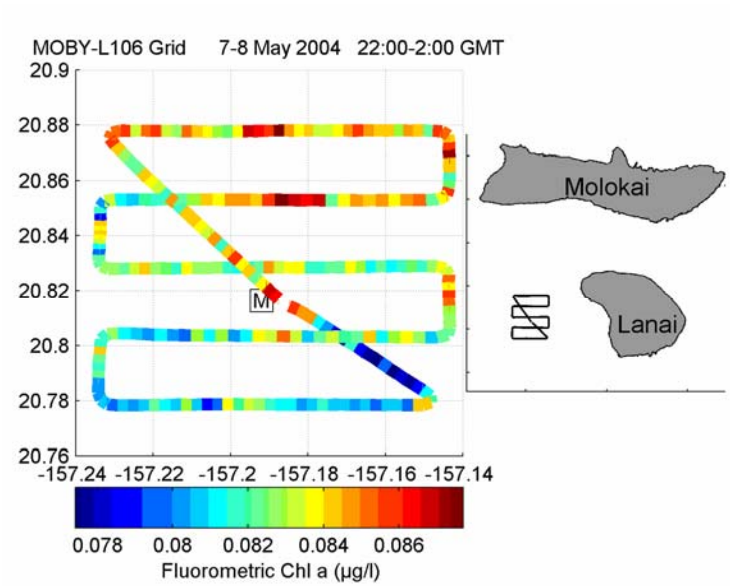


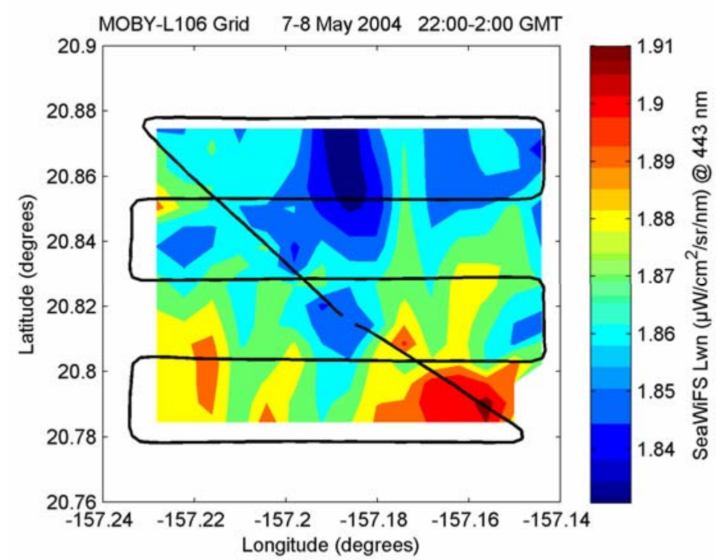




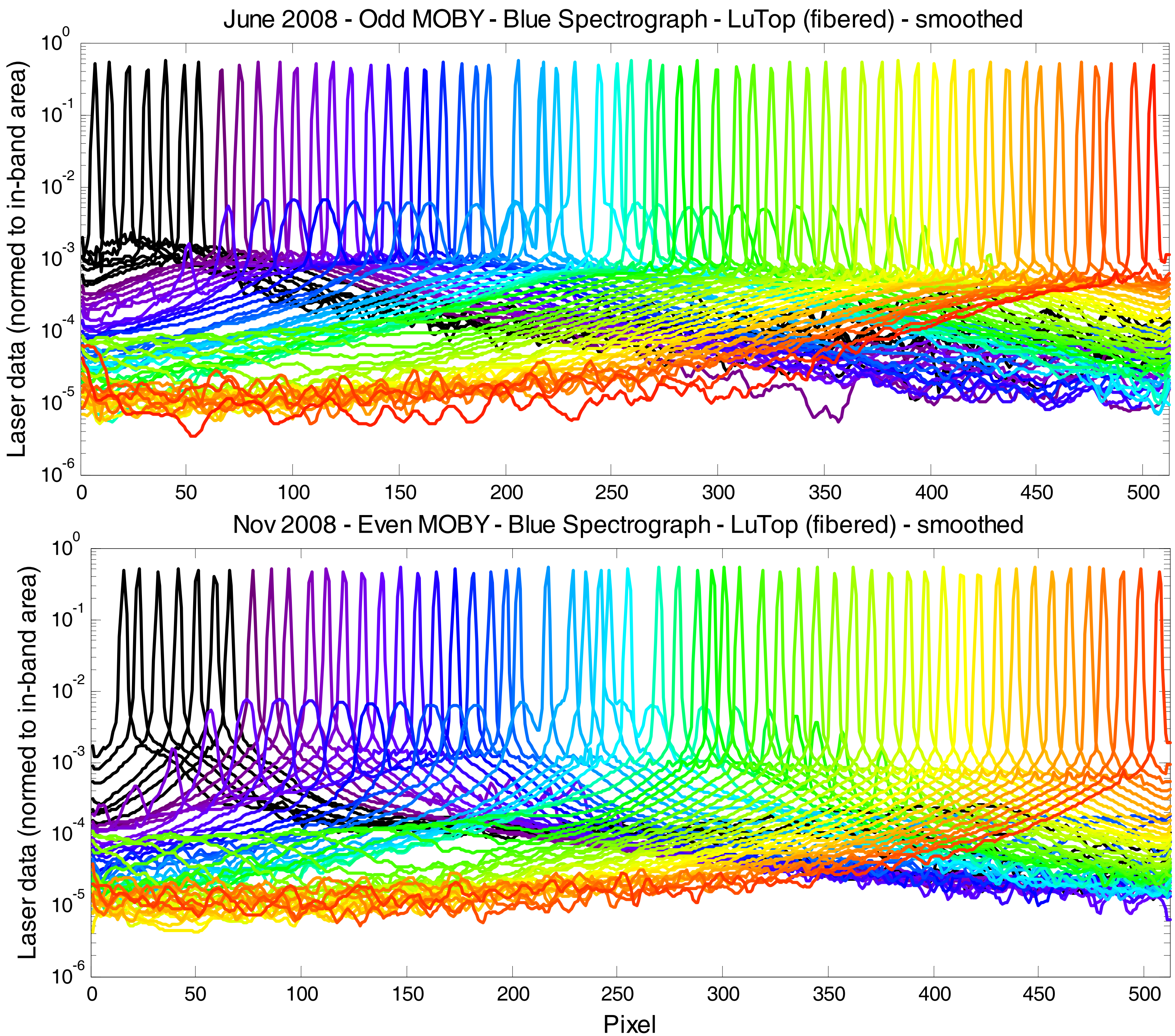
Site Characterization (example #2)

May 2004: 10 x 12 km grid of fluorometrically determined chl-*a* at MOBY coincident with MODIS Aqua overpass: mean 0.083 mg/l, stdev 2.5 %. Converted to Lw(443) = 1.87 mW/cm^2/sr/nm, stdev = 0.98 %.





The MODIS Aqua chl-*a* product extracted for the grid coordinates (excluding duplicate measurements, clouds, measurements near clouds) mean = 0.07 mg/l, stdev = 37%, for 20 matchups.



June 2008 - Odd MOBY - Blue Spectrograph - LuTop (fibered) - smoothed
Laser data (normed to in-band area)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
50
100
150
200
250
300
350
400
450
500
Nov 2008 - Even MOBY - Blue Spectrograph - LuTop (fibered) - smoothed
Laser data (normed to in-band area)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
50
100
150
200
250
300
350
400
450
500
Pixel

Changes in the MOS204 stray light performance are associated with instrument relative humidity, with a single event resulting in a permanent effect.