The Metrological Basis for MOBY

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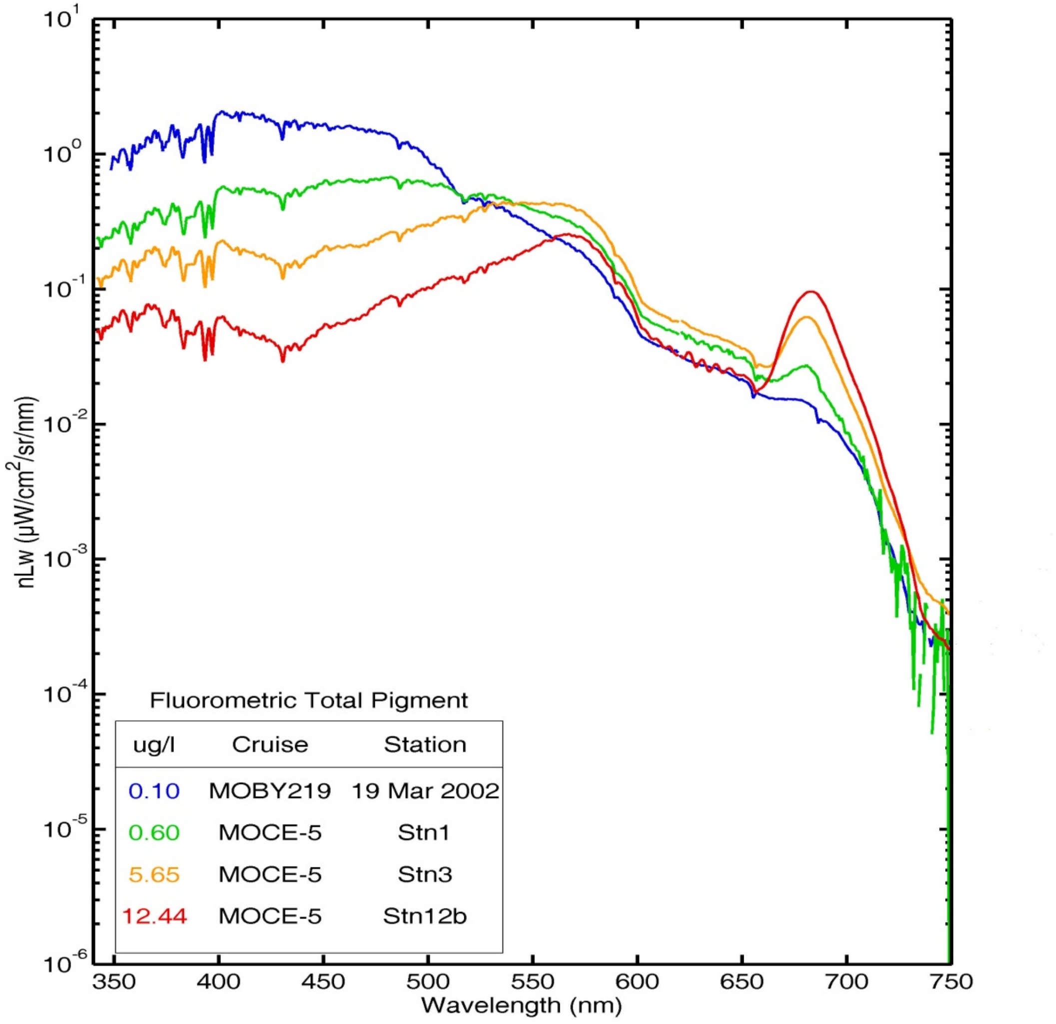
Outline

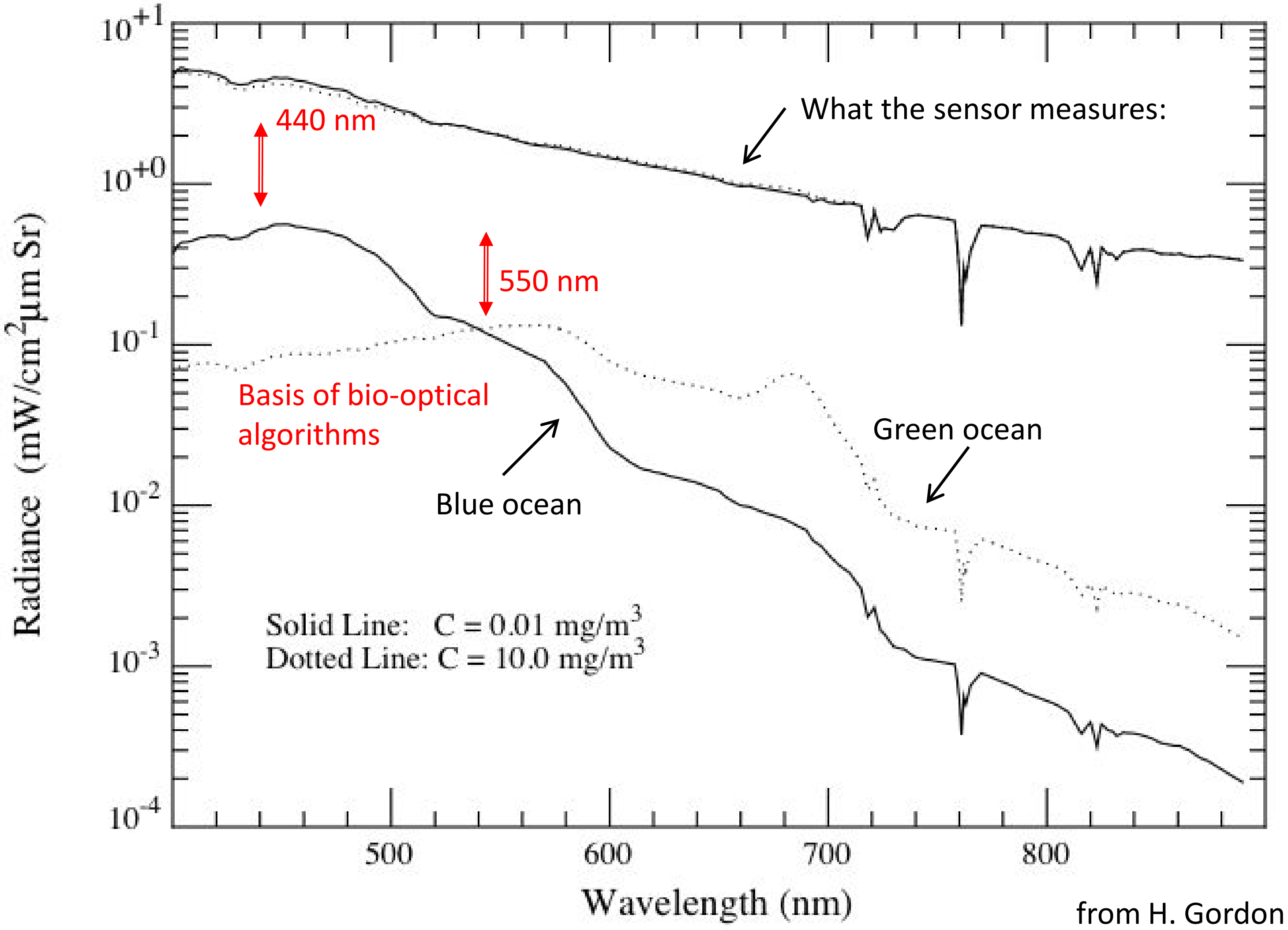
- Why System Vicarious Calibration (SVC)
- MOBY Basics
- Radiometric Traceability
- Uncertainty Estimates
- Maintenance of Quantities; Reprocessing
- Briefly: Heritage, Refresh, NET

The concentration of chlorophyll (and other material) in marine waters affects the spectral shape and magnitude of the backscattered radiant flux. Clarke, Ewing and Lorenzen's aircraft measurements (Science, 1970) first suggested a path forward for oceanic studies from space.



MOBY Team measurements of normalized water-leaving spectral radiance for marine waters with different fluorometric total pigment (MOBY site & Gulf of California)

Why SVC



from H. Gordon

Using satellites, the uncertainty goal is 5% in Lw and 0.5% radiometric stability over 10 years in the blue spectral region for oligotrophic waters.

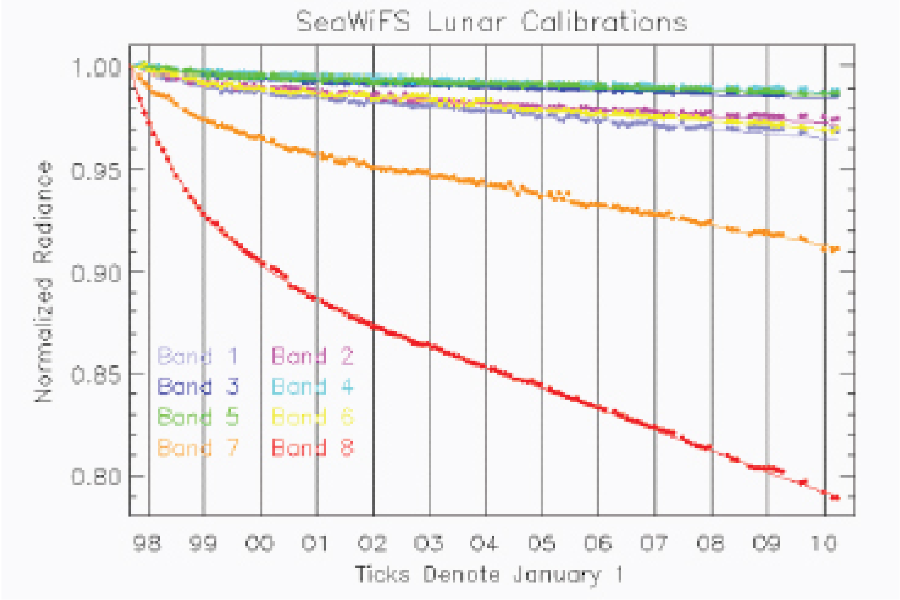
Lw is a small fraction of the at-satellite spectral radiance Lt, requiring ≈<0.5% sensor calibration and atmospheric correction.

SVC solves the calibration problem via highly accurate ground measurements timed with overpasses & TOA calculations using the same atmospheric correction as in the Lw retrieval processing.

Reminder: more than SVC is required

- SVC facilities
  - because the uncertainty in the pre-flight calibration & atmospheric correction is too large to meet the required product uncertainties
- Well-characterized & calibrated sensor
  - because there are many influencing parameters and the measurement configuration cannot be duplicated in the laboratory
- On-orbit stability monitor(s)
  - because the sensor cannot be guaranteed to be stable
- Measurement equations that model the actual physics, with correct ancillary data
  - because the water-leaving radiance is a small fraction of the total radiance the satellite sensor measures

SeaWiFS Lunar Calibrations



Source: Ocean Color Biology Group, NASA/GSFC

Coastal Zone Color Scanner (CZCS) used ship measurements for SVC, demonstrating the need for a MOBY like system (D. Clark & colleagues)

- CZCS launched 10/24/1978
- Required on-orbit calibration
- 3 post launch SVC cruises
  - Gulf of Mexico, R/V Athena (14 days)
  - Baja California, Gulf of California, R/V Velero IV (22 days)
  - East Coast US, R/V Athena (25 days)
- Total 61 days of ship time with 55 stations, resulting in only 9 stations suitable for SVC

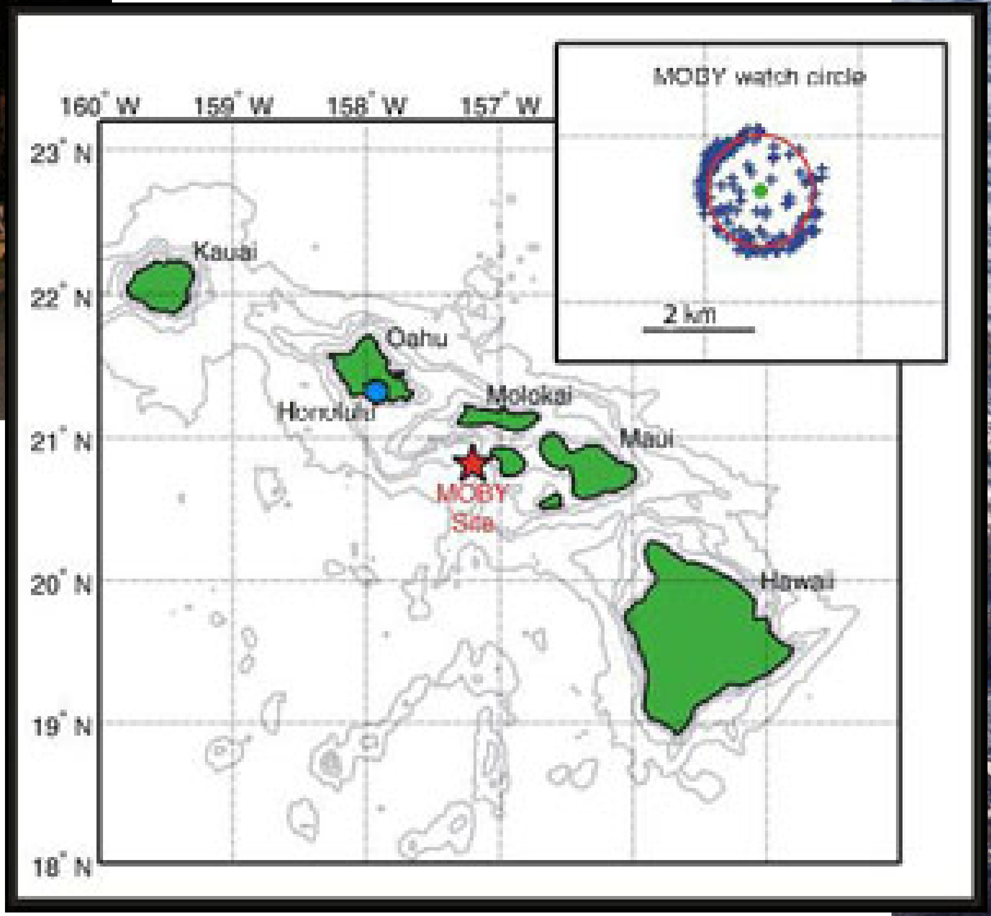
Navy patrol gunboat USS Chehalis prior to conversion to R/V Athena

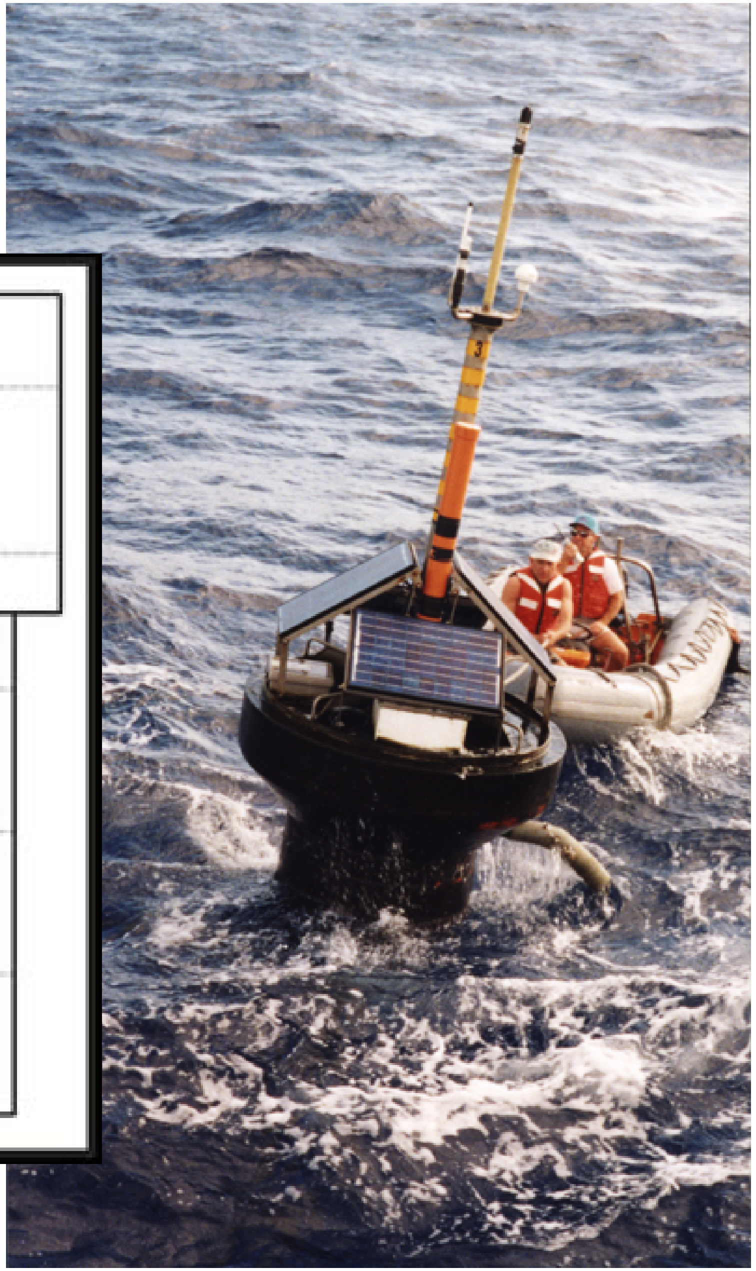
R/V Athena on turbine

- Source attributes
  - calibrated and characterized (continuous in situ radiometric instrumentation and ancillary AOP, IOP data);
  - any biases are known and quantified (e.g., in the instrument and in the overall approach);
  - representative (of the Earth's oceans);
  - and is available for use (daily measurements at overpass times)
- Program elements
  - team to maintain laboratory and in situ facilities, instruments, radiometric scales, data analysis, assess results, research improvements, disseminate results, etc.
  - logistical support includes ship or small boat, method of data transfer, access to field site (e.g., weather conditions, distances)

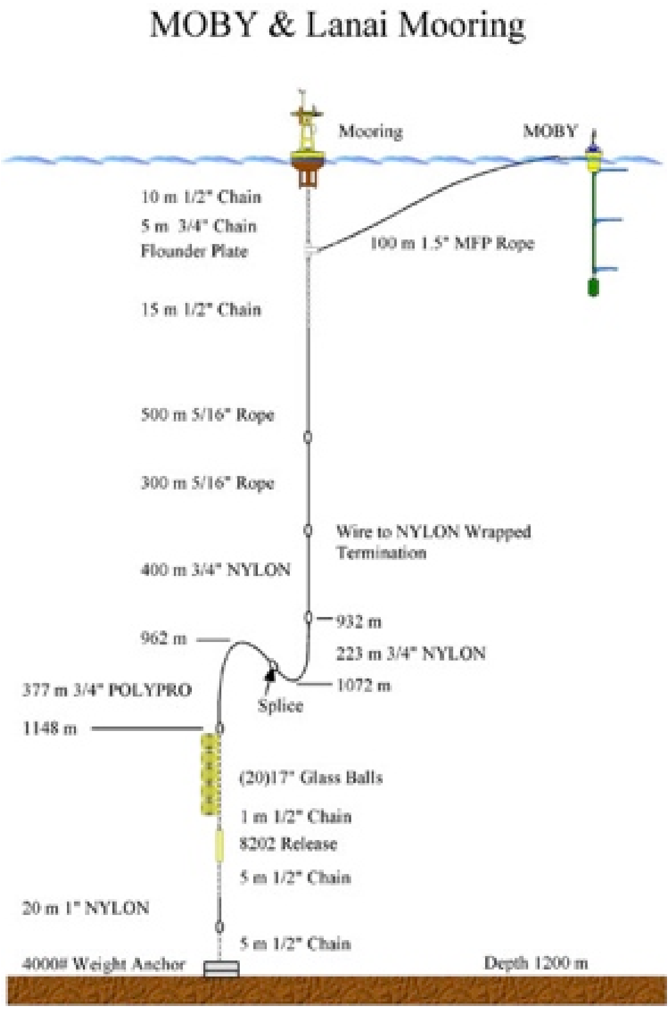
- Oligotrophic water (1.2 km depth), uniform optical properties, BRDF measured, clean marine atmosphere
- Clear skies – cloud formation is mostly afternoon
- NIST participation; SI traceable values
- Multiple redundancies in radiometry & other key parameters
- Daily measurements, timed for nominal satellite overpass (VIIRS SNPP & JPSS 1, MODIS Aqua, S3A OLCI)
- Communication daily – cell phone allows for more data volume
- High resolution, hyperspectral, 380 – 950 nm – allows for SVC of different OC satellite missions
- Accessible for servicing (buoy rotations, monthly diver cleaning & radiometric stability checks)
- Support facilities at U. Hawaii, ships from UH & commercial
- Stable, expert team
- System location security (ARGOS, Iridium satellite-based beacons (new); help from local fisherman)
- Uncertainty analysis
- Sun glint is an issue in the summer for non-tilting sensors
- Heritage MOBY - sequential acquisition of Es, Lu collectors; Refresh & NET – simultaneous acquisition

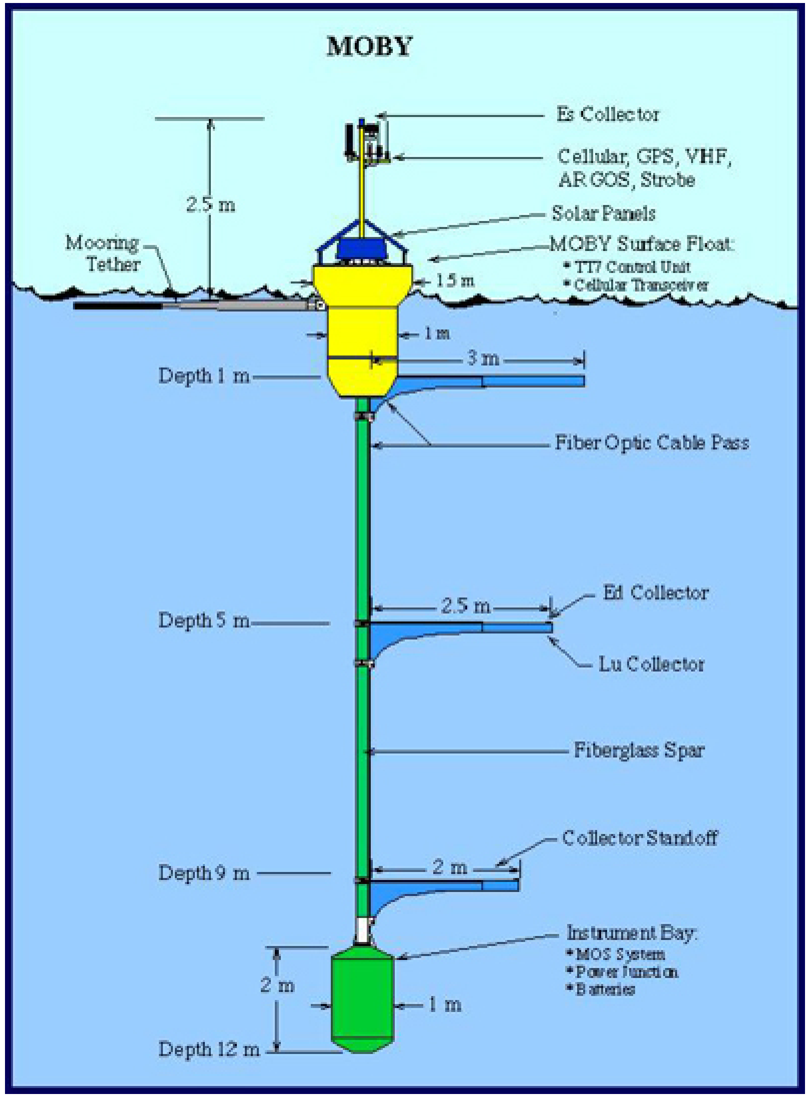
Hawaii Works

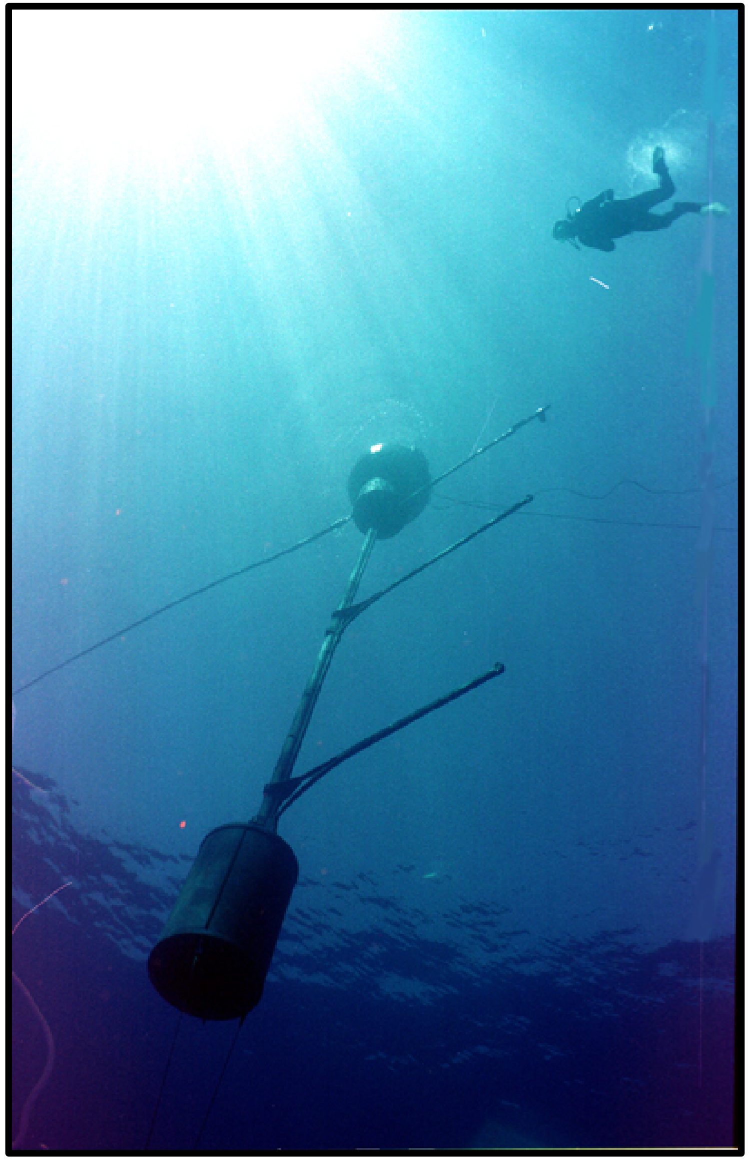




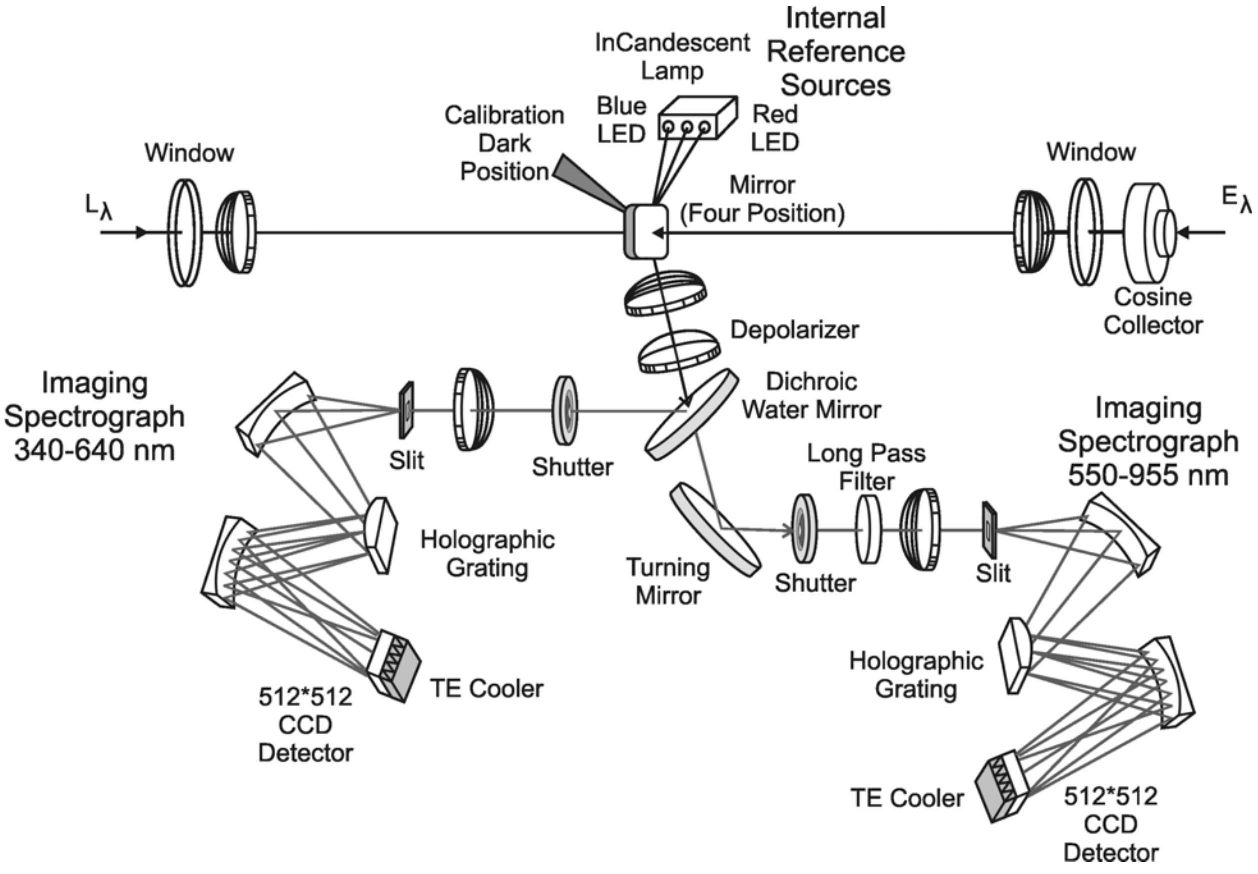
Heritage MOBY Instrument







Heritage MOBY Spectrograph Design



Marine Optical System (MOS)

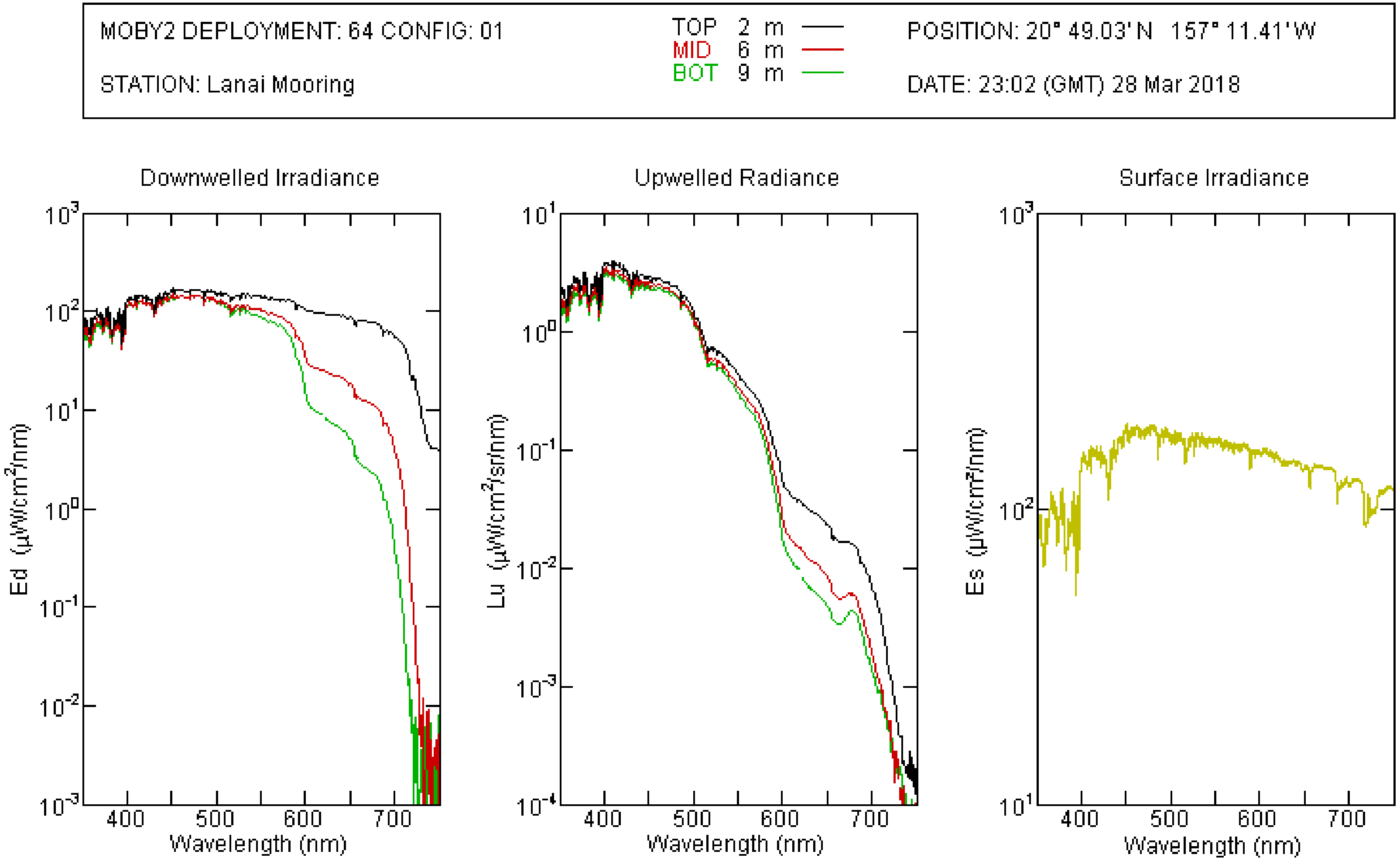
Dual Spectrographs
Dichroic Beamsplitter
0.6 nm to 0.9 nm spacing
0.8 nm to 1.0 nm FWHM
Internal Reference Sources
Internal Shutter

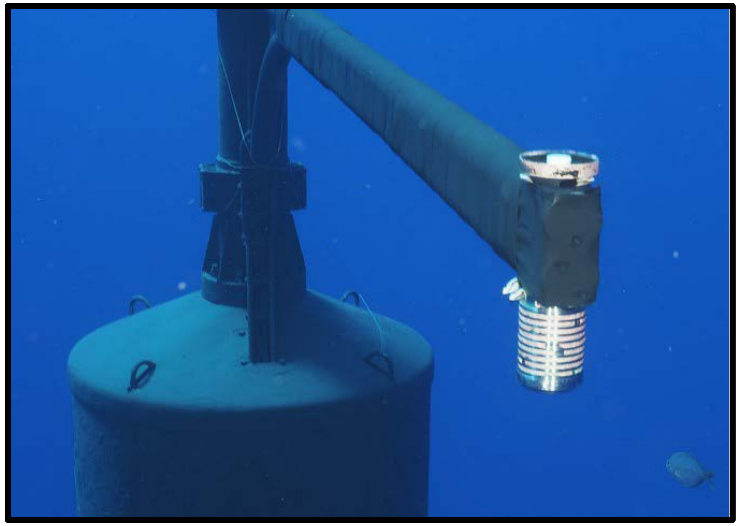
Different measurements must be done sequentially

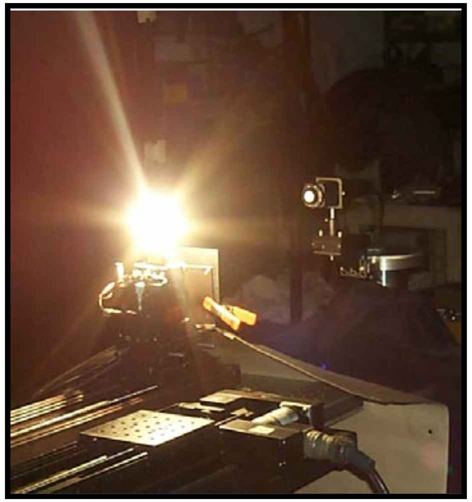
Illustrated: profiling version; in MOBY the Es(λ) path is replaced by an optical multiplexer that relays the different collectors

Typical MOBY DATA

In-water: downwelled irradiance Ed; upwelled radiance Lu. In-air: downwelled sky irradiance Es. Lu and Es are used to produce Lw. For data, see https://www.star.nesdis.noaa.gov/sod/moby/





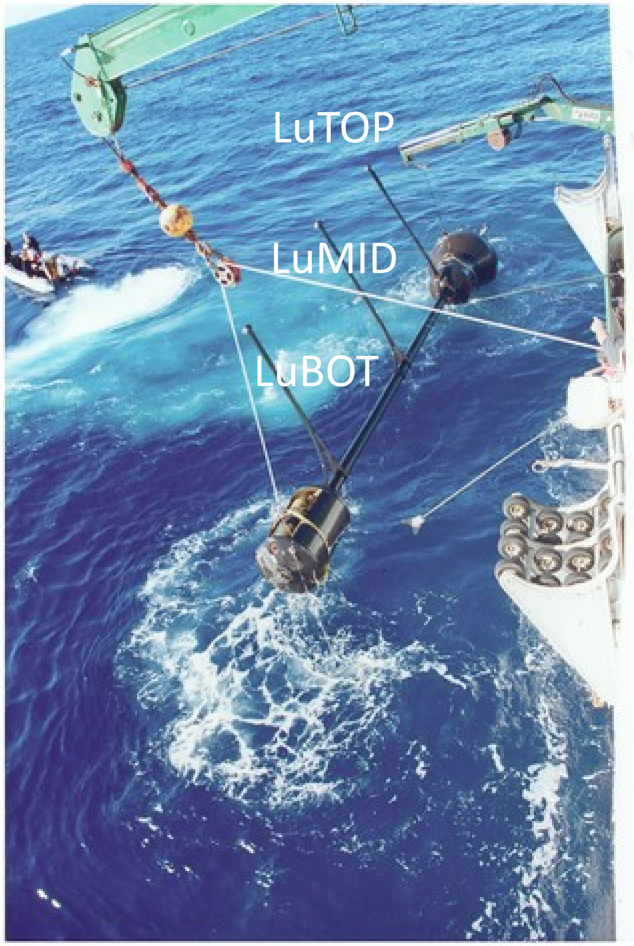


Measurement Equations

MOBY intermediate and final products are derived from the Lu and Es data sets. Three variations possible, using different arm pairs, e.g. Lw1 uses LuTOP and KL(TOP,MID).

Diffuse upwelling radiance attenuation, KL(λ)

$$KL(z_1, z_2, \lambda) = \frac{1}{z_2 - z_1} \ln\left[\frac{Lu(z_1,\lambda)}{Lu(z_2,\lambda)}\right], \quad z_2 > z_1$$



Water-leaving spectral radiance, Lw(λ)

$$Lw(\lambda) = Lu(z_i,\lambda)\frac{t(\lambda)}{n^2(\lambda)}\exp\left[KL(z_1,z_2,\lambda)\right]$$

Normalized water-leaving spectral radiance, Lwn(λ)

$$Lwn(\lambda) = \frac{Lw(\lambda)}{Es(\lambda)} F_0(\lambda)$$

Other quantities, $t(\lambda), n^2(\lambda), F_0(\lambda)$,

are the surface transmittance, index of refraction of water, and extraterrestrial solar irradiance

- Metrological Traceability
  - “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty” Bureau International des Poids et Mesures (BIPM)
  - Some features
    - Values are traceable, not instruments or institutions
    - Required to establish the calibration hierarchy
    - Reference is fully specified, including all metrological information (e.g. dates)
    - If multiple quantities are involved in the result, traceability requirements apply to all, separately
    - Existence of traceability is not a guarantee the uncertainty is adequate nor mistakes don’t exist
    - Stricter interpretations exist (see International Laboratory Accreditation Cooperation (ILAC) ILAC P-10:2002)
    - NIST’s policy
      - Adopts the International Vocabulary of Metrology (VIM) definition, 2.4.1
      - The provider of traceability claim is responsible for supporting the claim; the user is responsible for validating the claim;
      - NIST does not define, specify, assure, or certify metrological traceability

Radiometric Traceability for MOBY Lu Values, Chain of Calibrations

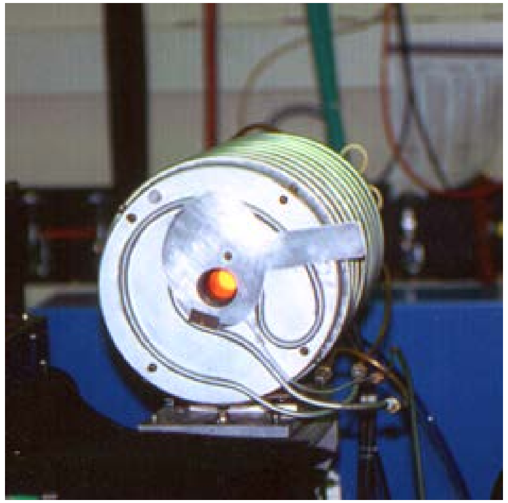
Artifact	Type	Method	Wavelength	Notes
Gold Point Blackbody	Realization	Planck's Law & ITS-90	654.6 nm	$T \equiv 1337.33$ K

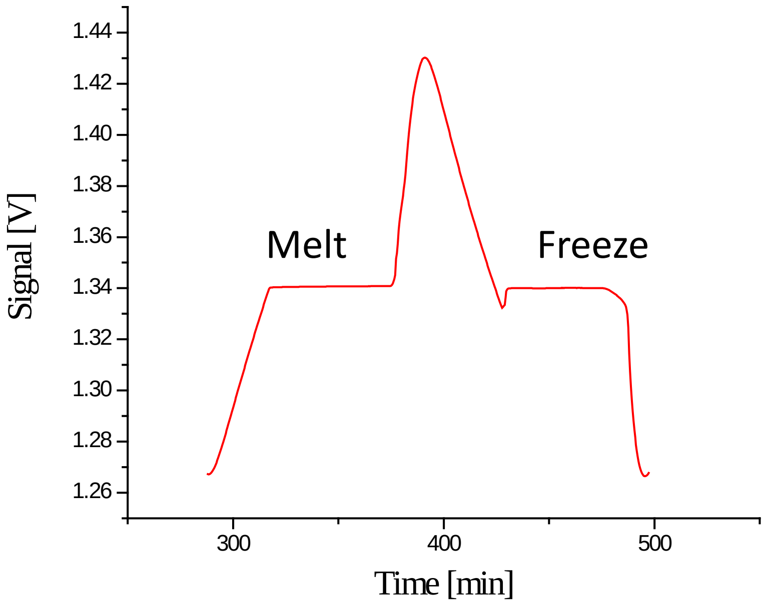
Artifact 1	Artifact 2	Type	Method	Wavelength	Notes
GPBB	Vacuum W lamp	Source/Source	Transfer w Cary14	654.6 nm	$T_\lambda \approx 1530$ K
Vacuum W lamp	Gas W lamp	Source/Source	Transfer w Cary14	654.6 nm	$T_\lambda \approx< 2470$ K
Gas W lamp	VTBB	Source/Source	Transfer w Cary14	250 to 2500 nm	$T \approx 2060$ K
VTBB	MLML Sphere Source	Source/Source	Transfer w Cary14	300 to 1100 nm	$L(\lambda)$ values w calibration report
MLML Sphere Source	MOBY Lu arms & MOS port	Source/Detector	Calibrate MOBY	350 to 950 nm	DN/pxl/sec/$L(\lambda)$
MOBY Lu arms & MOS port	Marine Waters, MOBY site	Detector/Source	Use MOBY & Immersion Coefs.	350 to 950 nm	$Lw(\lambda)$ values
Marine Waters, MOBY site	OC Sensor, on orbit	Source/Detector	SVC	Satellite Bands	Corrections to pre flight responsivity
OC Sensor, on orbit	Global OC	Unknown Source	Use OC Sensor	Satellite Bands	$Lw(\lambda)$ values

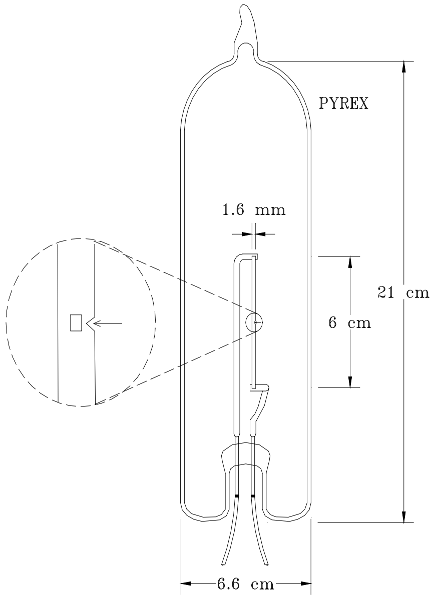
Reference: NBS SP250-1, "Spectral Radiance Calibrations"

Images – Spectral Radiance

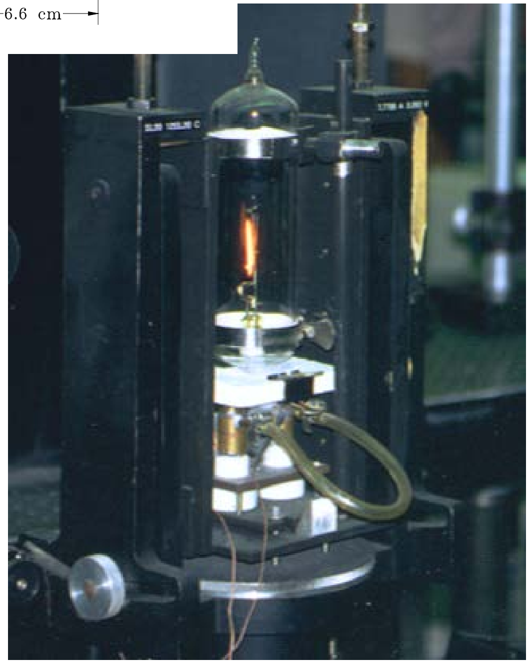
Gold-Point Blackbody

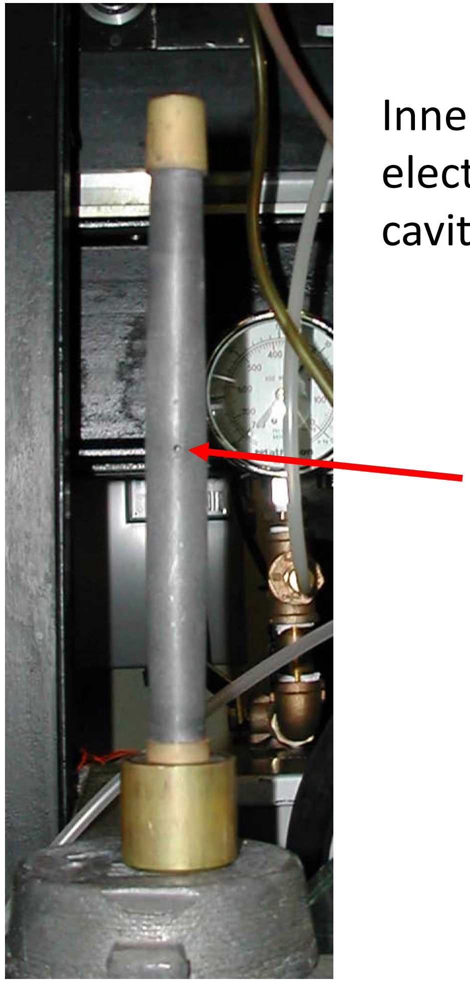






Tungsten Strip Lamp (Quartz Snout for UV)



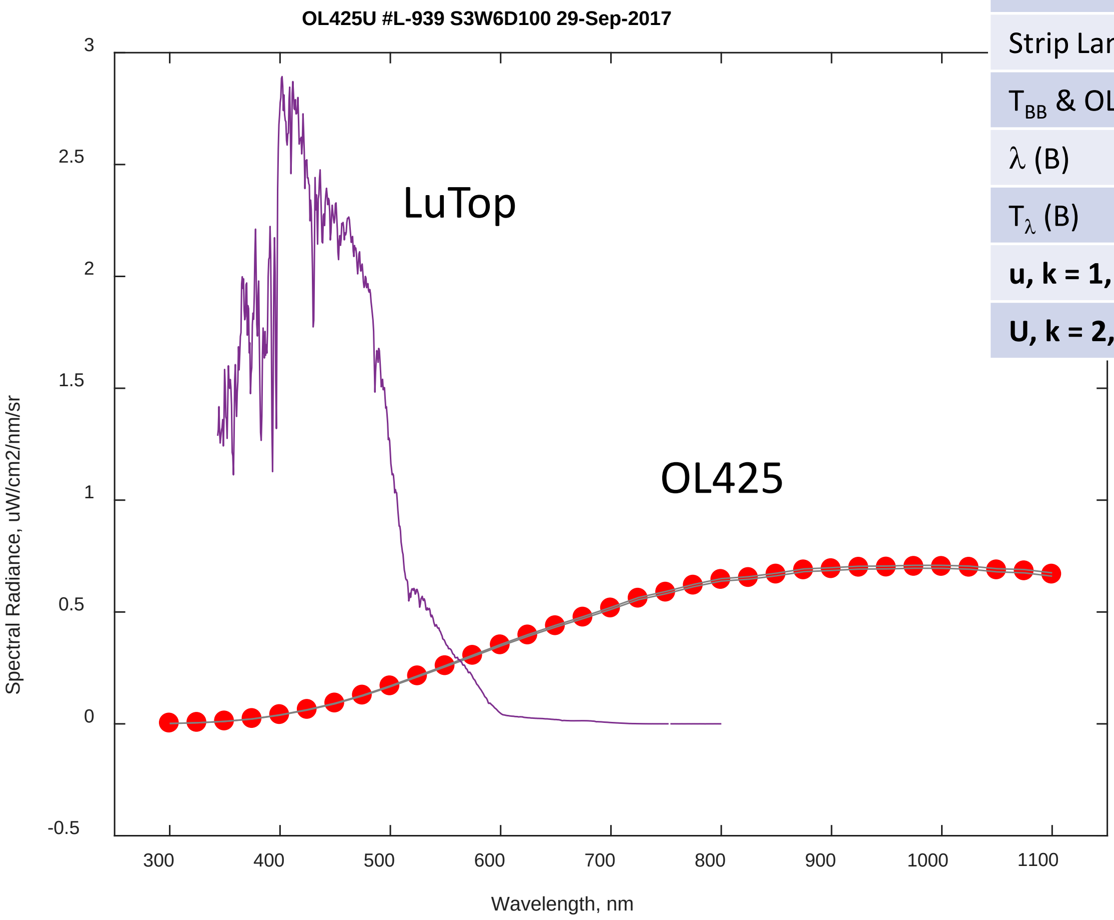


Inner electrode & cavity of VTBB

2 mm dia opening

NOTE: All these source areas are SMALL – means the MLML sphere sources are calibrated over a 0.6 mm x 0.8 mm area!

MLML OL425 values and FASCAL uncertainty budget



Effect	300	400	500	600	700	800	900	1000	1100
BB Quality (B)	0.06	0.03	0.01	0	0	0	0.02	0.02	0.02
Strip Lamp (B)	0.17	0.14	0.11	0.09	0.07	0.06	0.06	0.05	0.05
T_{BB} & OL425 (A)	1.12	0.79	0.53	0.47	0.42	0.41	0.44	0.46	0.55
λ (B)	0.06	0.05	0.04	0.03	0.02	0.02	0.02	0.02	0.02
T_{λ} (B)	0.29	0.23	0.18	0.15	0.13	0.12	0.1	0.1	0.09
u, k = 1, %	**1.17**	**0.84**	**0.57**	**0.5**	**0.45**	**0.43**	**0.45**	**0.47**	**0.56**
U, k = 2, %	**2.34**	**1.67**	**1.14**	**1**	**0.89**	**0.85**	**0.9**	**0.95**	**1.12**

NOTES:

- The Gold-Point BB is used infrequently; the vacuum strip lamp holds the scale;
- The expanded uncertainties for the OL425 are the gray lines in the figure;
- A representative MOBY LuTOP is included – the spectral radiance is very different (blue rich, red poor) compared to the calibration standard.

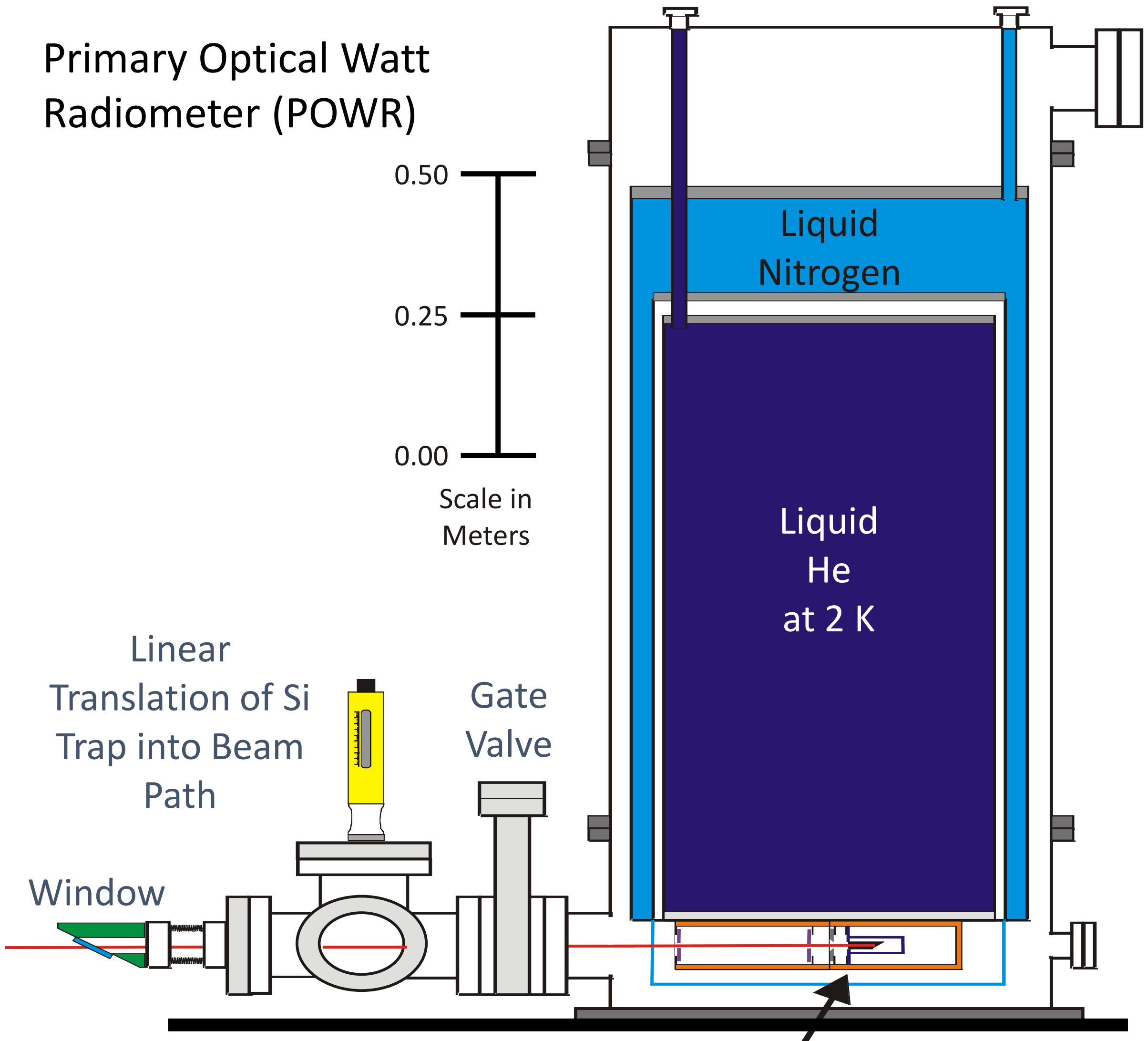
Radiometric Traceability for MOBY Es Values, Chain of Calibrations

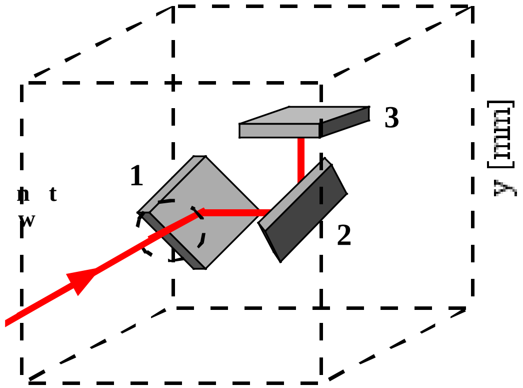
Artifact	Type	Method	Wavelength	Notes
Cryogenic Radiometer	Realization	Electrical Substitution	Tunable Lasers	$\Phi \approx 1$ mW

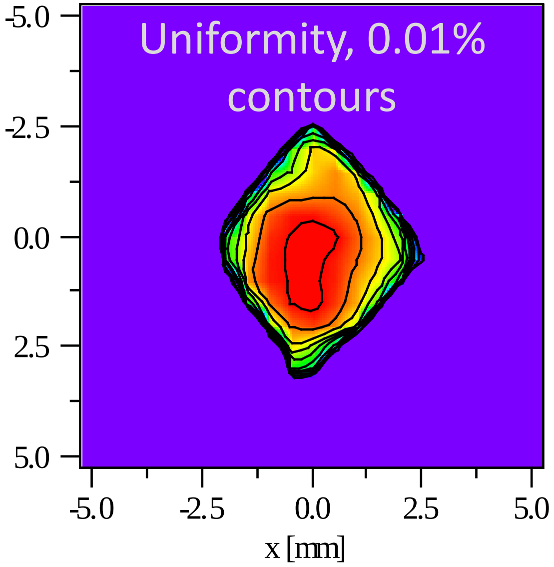
Artifact 1	Artifact 2	Type	Method	Wavelength	Notes
Cryogenic Radiometer	Si Trap Detectors	Detector/Detector	Lasers	Tunable Lasers	A/W values
Si Trap Detectors	Reference Detectors	Detector/Detector	Cary14 & lamp	350 to 1800 nm	A/W values
Reference Detectors	Filter Radiometers	Detector/Detector	Cary14 & lamp Aperture Area Facility Amplifier Gain Facility	350 to 1200 nm	A/W values A/W/cm^2 values V/W/cm^2 values
Filter Radiometers	High Temperature Blackbody (HTBB)	Detector/Source	Planck's Law w FR's Aperture Area Facility Aperture Separation	Filter Bands	$T_{BB} \approx 3000$ K $L_{BB}(\lambda)$ values $E(\lambda)$ values
HTBB	Czerny-Turner	Source/Detector	Cal Czerny-Turner	200 to 2500 nm	Output / $E(\lambda)$
Czerny-Turner	FEL check standards	Detector/Source	Cal the FELs	200 to 2500 nm	$E(\lambda)$ values
FEL check standards	FEL working standards	Source/Source	Czerny-Turner	200 to 2500 nm	$E(\lambda)$ values
FEL working standards	MLML FELs	Source/Source	Czerny-Turner	250 to 1600 nm	$E(\lambda)$ values
MLML FELs	MOBY Es, Ed	Source/Detector	Calibrate MOBY	350 to 950 nm	DN/pxl/sec/$E(\lambda)$
MOBY Es, Ed	In Situ Es, Ed	Detector/Source	Use MOBY & Immersion Coeffs	350 to 950 nm	$Es(\lambda)$ values $Ed(\lambda)$ values

Reference: NBS SP250-89, "Spectral Irradiance Calibrations" and NIST SP250-41, "Spectroradiometric Detector Measurements"

Images – Spectral Irradiance

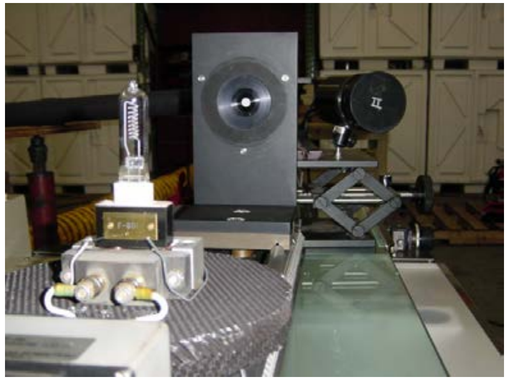




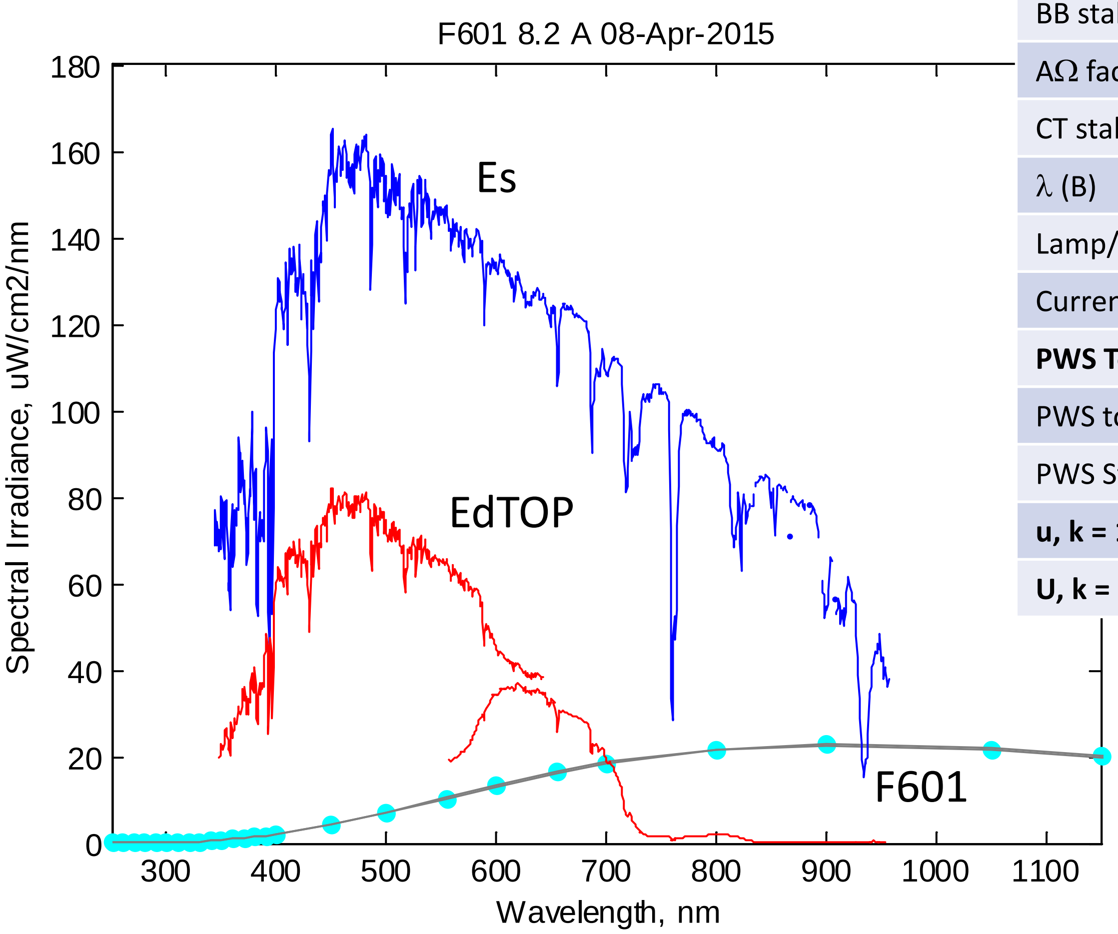


FASCAL II

FEL during setup at MOBY



MLML FEL values and typical uncertainty budget



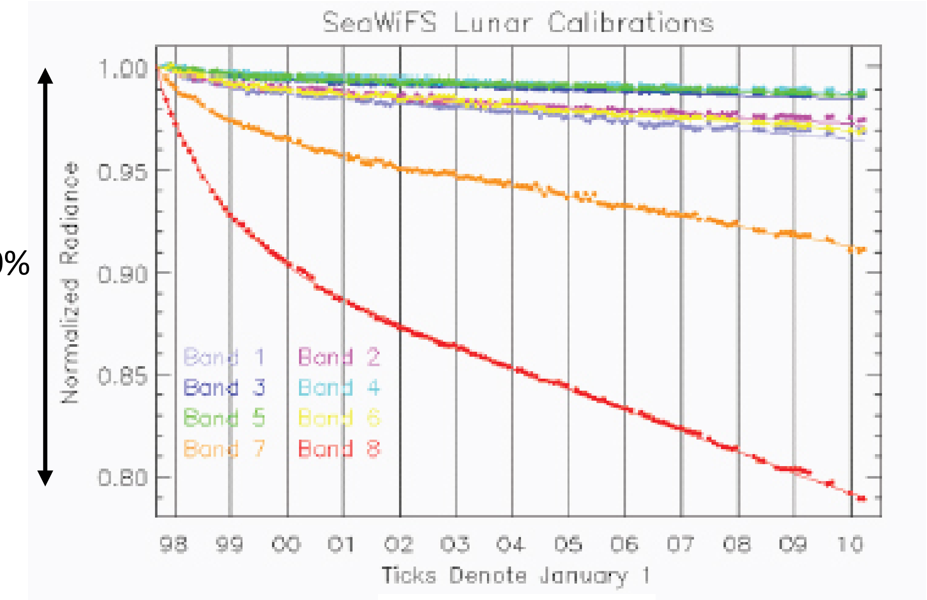
Effect	250	350	450	555	654.6	900	900	1000
T_{BB} (B)	0.28	0.2	0.16	0.13	0.11	0.08	0.05	0.28
ε_{BB} (B)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
BB x,y unif. (B)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
BB stability (B)	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.03
AΩ factors (B)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
CT stability (B)	0.3	0.3	0.15	0.15	0.15	0.15	0.15	0.3
λ (B)	0.29	0.13	0.06	0.04	0.02	0	0.01	0.29
Lamp/CT xfer (B)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Current Stability (B)	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.03
PWS Total Unc (B)	**0.52**	**0.4**	**0.25**	**0.23**	**0.21**	**0.2**	**0.19**	**0.52**
PWS to Lamp (A)	0.25	0.15	0.1	0.1	0.1	0.1	0.1	0.25
PWS Stability (B)	0.66	0.47	0.36	0.3	0.25	0.18	0.1	0.66
u, k = 1, %	**0.87**	**0.63**	**0.45**	**0.39**	**0.34**	**0.29**	**0.24**	**0.87**
U, k = 2, %	**1.74**	**1.26**	**0.91**	**0.77**	**0.69**	**0.57**	**0.47**	**1.74**

NOTES:

- The HTBB is used infrequently; the primary working standard (PWS) lamps hold the scale;
- The expanded uncertainties for the F601 are the gray lines in the figure;
- A representative MOBY Es and EdTOP is included – these spectra are very different compared to the calibration standard.

Pause for Comments on Uncertainty Lexion (see the VIM)

20%

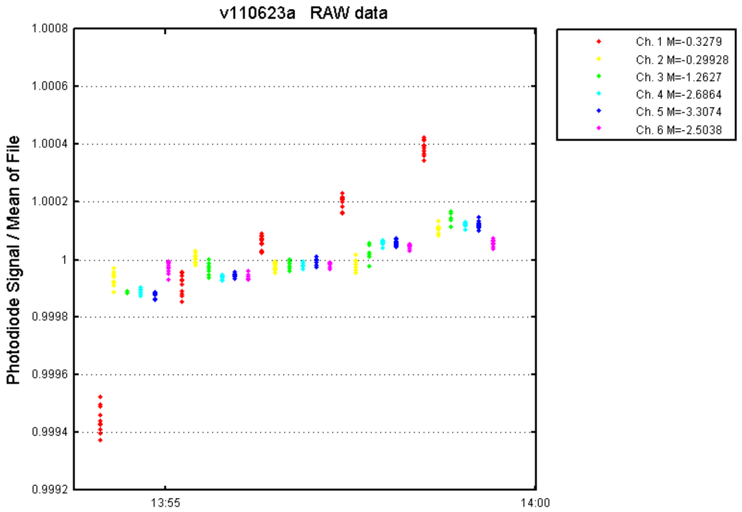


12 years

SeaWiFS Lunar Calibrations
OCBG, NASA

0.16%

Filter Radiometer and Reference
Integrating Sphere Source



5 min

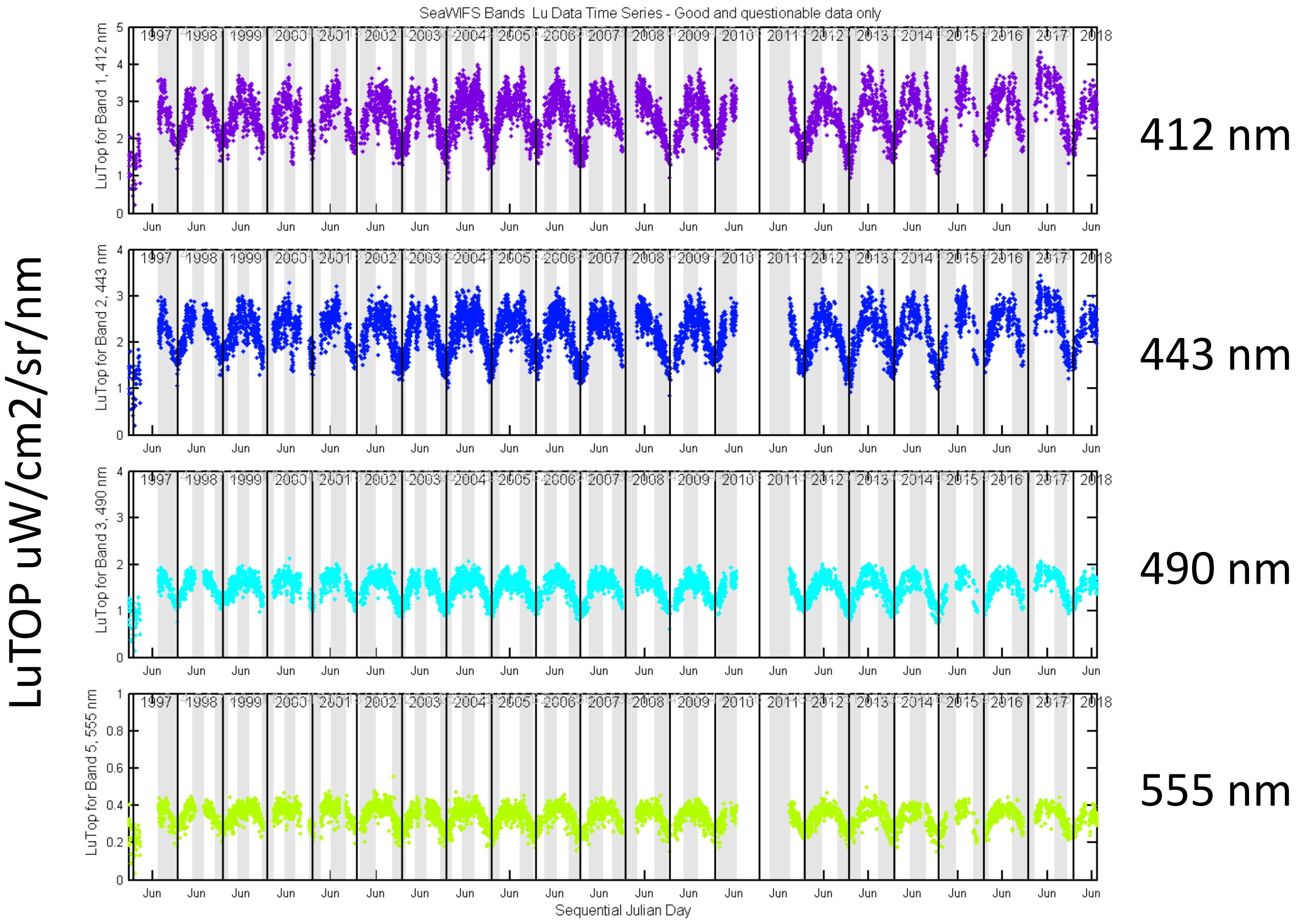
MEASUREMENT PRECISION: Measure exactly the same thing, what is the agreement?

Be careful to use the term “measurement precision” only when the measurements are truly replicates using the same or similar objects, taken under specified conditions. Stability, repeatability may be more appropriate descriptors of the observed agreement, especially for in situ.

ACCURACY: Does the measurement result agree with the true value?

We will never know the true value. So we speak of measurement uncertainty instead of accuracy. Offsets from the truth are biases, which may be unknown to us. You cannot reduce bias (systematic effects) by repeating the measurement. Scatter (random effects) about the value when measuring the same thing can be decreased by repeating the measurement.

Note: Uncertainties are not determined by differences observed in validation experiments. But such comparisons may reveal that biases exist.



MOBY time series, 1997 to 2018 (21 Years)

Progress on Corrections for Biases

- Correction to KL for inelastic light
  - No bias in Lw below 575 nm, up to 50% bias at 700 nm
  - Correction is implemented in the MOBY data
  - Uncertainty in correction ($\approx$0.01 to 0.02m^{-1}, λ>575nm) from sensitivity studies in modeling correction
  - Voss et al., “A method to extrapolate the diffuse upwelling radiance attenuation coefficient to the surface as applied to the Marine Optical Buoy,” J Atm. & Oceanic Tech. (2017)
- Correction to water-air transmission coefficient
  - Spectrally varying bias, 1% to 3% between 350 nm to 700 nm
  - Correction not yet implemented in the MOBY data
  - Uncertainty in correction of 0.1% using time series of salinity and temperature at MOBY
  - Voss & Flora, “Spectral dependence of the seawater-air radiance transmission coefficient,” J. Atm. & Oceanic Tech. (2017)
- Correction to Es for non-cosine response and buoy tilt
  - Small bias (<0.5%), corrections vary by ±2% depending on geometry (solar zenith angle, buoy tilt, wavelength)
  - Correction is not yet implemented or in the literature
  - Uncertainty in correction is <0.5%, from Monte Carlo simulations (know cosine response, tilt statistics, models of sky radiance)
- Immersion Coefficient (correction) validated
  - Air to water correction factor is large, e.g. 1.72 at 490 nm
  - Correction is implemented (always has been) in the MOBY data set
  - Uncertainty in correction is 0.1% from theory and experiment
  - Feinholz et al., “Immersion coefficient for the Marine Optical BuoY (MOBY) radiance collectors,” J. Res NIST (2017)

- Correction to buoy tilt and BRDF of MOBY site waters
  - No bias, but correction is ±0.4%
  - Correction is not yet implemented in the MOBY data
  - Uncertainty in correction around 0.1% from Monte Carlo analysis
- Correction for arm depth change from tilts
  - No bias, correction negligible in blue and no larger than 2% in the red
  - Uncertainties will be estimated using Monte Carlo
- Correction for Shadowing
  - Bias is small for most viewing geometry; bias is spectral
  - When the relative azimuth between buoy arm and Sun is less than ±25° a correction is necessary
  - Monte Carlo method for uncertainty in correction
- Polarization Effects
  - Buoy259 and earlier had polarization sensitivity, but had negligible impact
  - Buoy260 and later have depolarizers installed

- Buoy Radiometric Calibrations
  - Pre- and Post Deployment, including wavelength calibrations
  - Sphere sources re-cal’d at NIST every 50 hours; lamps changed
  - FELs re-cal’d or re-issued every 50 hours
  - Sources monitored with NIST designed, calibrated dual mode filter radiometers
  - Sources validated ≈ annually by NIST at MOBY facility
- Buoy Radiometric Characterizations
  - Bin factor, integration time, linearity, image of slit on CCD
  - Wavelength calibration, stability (pen lamps & Fraunhofer lines)
  - Sensitivity to ambient temperature
  - Many laser images for stray light matrix & stray light correction (SLC)
  - Polarization sensitivity, cosine response, immersion coefficients
  - On-board internal sources (blue, red LED, incandescent lamp)
  - ≈ monthly diver cleaning and testing with stable sources, in situ
  - Validation of buoy attitude (compass for arm direction, arm depth, tilt sensors)

MOBY Uncertainties k = 1, In Progress

Calibration, stability of responsivity, and stray light correction dominate the Lu uncertainty budget

Lu Product						
Component	Type	Uncertainty Source	443 nm	555 nm	670 nm	Acts As
Reference Source (RS)	B	Calibration Report	0.72	0.53	0.46	Systematic
RS drift	B	Repeat of NIST Cals	0.46	0.53	0.48	Systematic
RS uniformity	B	Horiz Scan during cal	0.20	0.20	0.20	Systematic
Integration Time Corr	A	Fit to Characterization Data	0.15	0.15	0.15	Systematic
Ambient Temperature	A	Fit to Characterization Data	0.16	0.16	0.16	Systematic
Interp to MOBY λ	B	Sensitivity to Method	0.15	0.03	0.03	Systematic
Pre/Post Cals	B	Mean ratio + 1 std dev	1.12	0.86	0.74	Systematic
Wavelength (0.1 nm)	B	Taylor expansion	0.29	0.14	0.06	Systematic
Immersion Coef	B	Theory & Experiment	0.10	0.10	0.10	Systematic
Stray Light Corr	A	Monte Carlo	0.60	0.55	0.39	Systematic
Meas Unc, Cal	A	Standard Deviation	0.21	0.22	0.10	Random
Meas Unc, in situ	A	Standard Deviation	0.74	0.76	1.66	Random
Arm Depth from Tilting	A	Monte Carlo	≈ 0	≈ 0.10	0.20	Random
BRDF from Tilting	A	Monte Carlo	≈ 0.10	≈ 0.10	≈ 0.10	Random
Polarization	B	Modeling w Experiment Data	Pre B260, negligible; B260, depolarizers installed			Systematic
Shadowing, restricted RA	B	Theory and Experiment	In progress, small unless relative azimuth to sun w/in ±25°			Systematic
Combined, k = 1			≈ 1.8	≈ 1.6	≈ 2.0	

MOBY Uncertainties k = 1, In Progress

In situ measurement uncertainty, calibration, and stability of responsivity dominate the Es uncertainty budget

Es Product						
Component	Type	Uncertainty Source	443 nm	555 nm	670 nm	Acts As
Reference Source (RS)	B	Calibration Report	0.46	0.39	0.34	Systematic
RS drift	B	Repeat of NIST Cals	0.75	0.67	0.34	Systematic
Gamma Bench	B	Comparison Data	0.49	0.49	0.49	Systematic
Integration Time Corr	A	Fit to Characterization Data	0.15	0.15	0.15	Systematic
Ambient Temperature	A	Fit to Characterization Data	0.16	0.16	0.16	Systematic
Interp to MOBY λ	B	Sensitivity to Method	0.10	0.10	0.10	Systematic
Pre/Post Cals	B	Mean ratio + 1 std	0.92	0.76	0.52	Systematic
Wavelength (0.1 nm)	B	Taylor expansion	0.25	0.12	0.05	Systematic
Stray Light Corr	A	Monte Carlo	0.35	0.05	0.27	Systematic
Meas Unc, Cal	A	Standard Deviation	0.14	0.06	0.06	Random
Meas Unc, in situ	A	Standard Deviation	2.51	2.67	2.72	Random
Cosine Response	A	Monte Carlo	<0.50	<0.50	<0.50	Systematic
Combined, k = 1			<2.95	<2.98	<2.92	

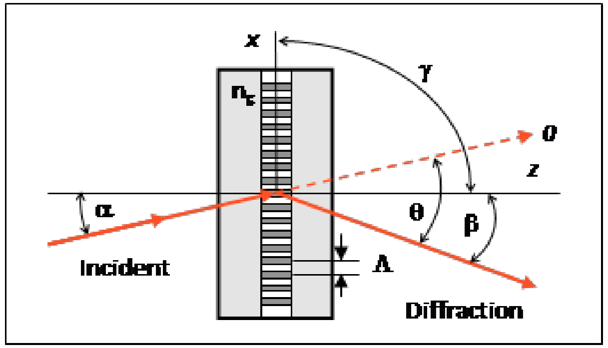
Note: for both Lu and Es, the in situ measurement uncertainty (e.g. COV) includes environmental noise/variability

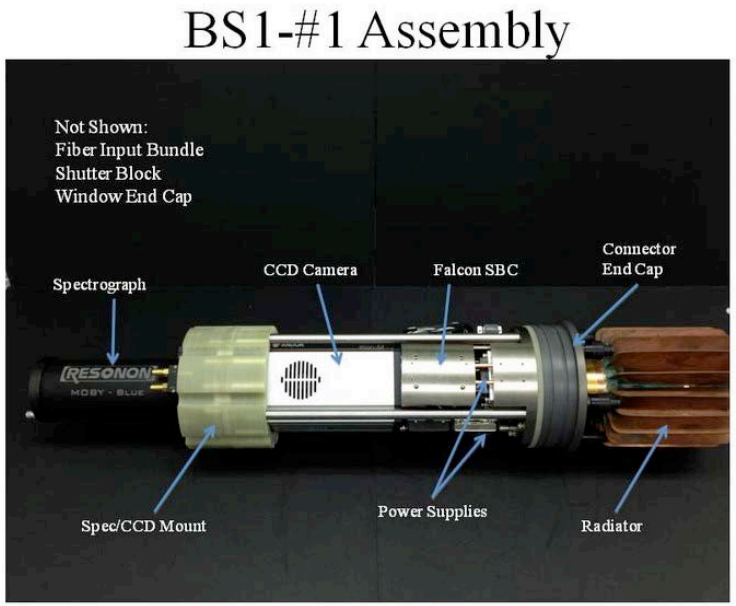
Quality Control & (re)processing

- Data Flow
  - Cell modem link to Miami servers to MLML servers
  - Inspect for irregularities, pull in associated data such as GOES images
  - Process data, remove data spectral spikes, assign quality (good, bad, questionable)
  - Post to CoastWatch, latency 1 to 2 days https://www.star.nesdis.noaa.gov/sod/moby/
  - After deployment, use post calibration to improve deployment products, latency 12→4 months
  - After end of life (EOL) NIST calibration of standard, reevaluate and reprocess
  - Specific reprocessings occur as corrections are implemented
- Quality Assurance Criteria
  - GOES imagery (cloud contamination)
  - Remove spectral spikes (must be done manually)
  - Discard outliers in the Lu/Ed/Es set (typical is dark, 3 or 5 lights, dark)
  - Evaluate Es changes before and after each Lu or Ed acquisition
  - Compare the KLs derived from different arm pairs
  - Compare to historical values
  - Examine differences in the overlap region of the two spectrographs (after thermal and SLC)
  - Alert team to anomalies, adapt schedule of diver cleaning if necessary

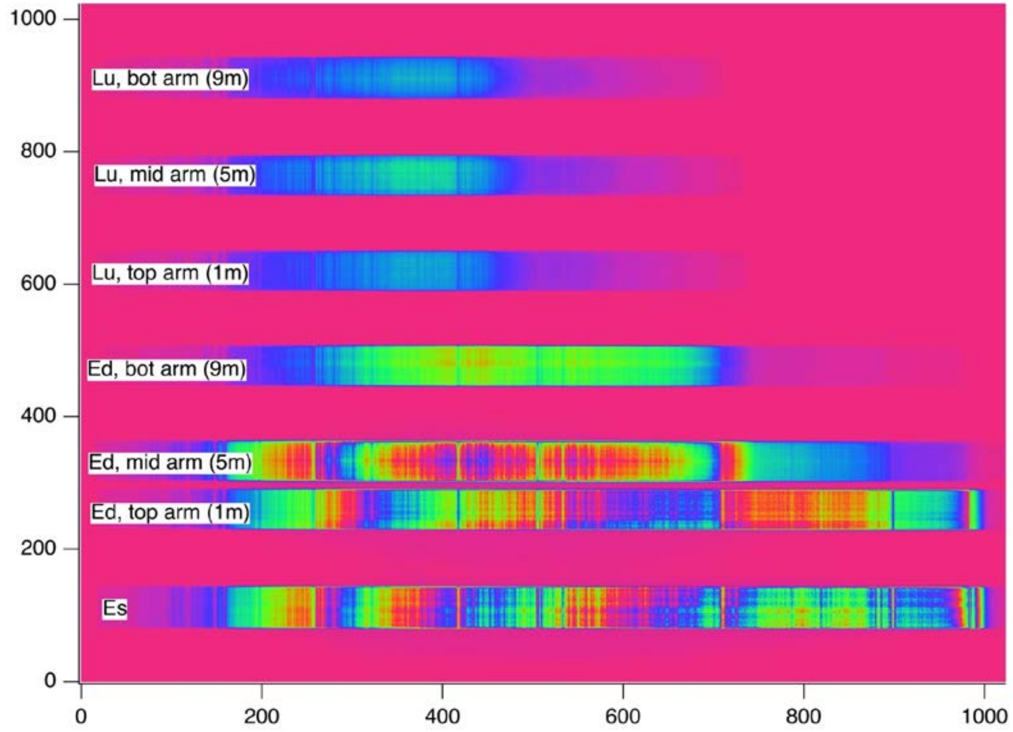
The MOBY-Refresh (NOAA supported) and MOBY-Net (NASA supported) optical system consists of dual in-line volume phase holographic grating systems. Allows simultaneous spectra to be acquired.

From http://www.bayspec.com/technical-support/definitions/vpg/

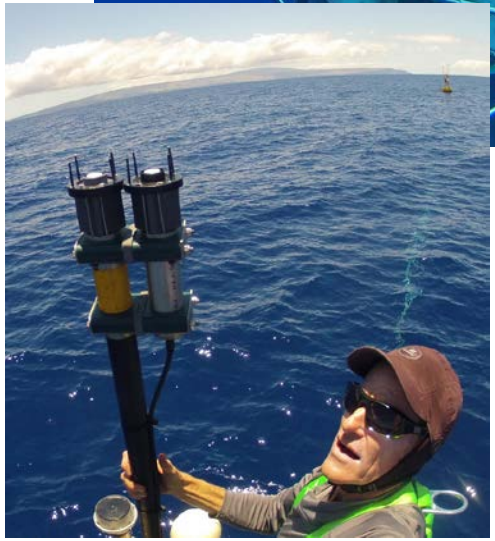




Example spectra from field measurements with blue spectrometer

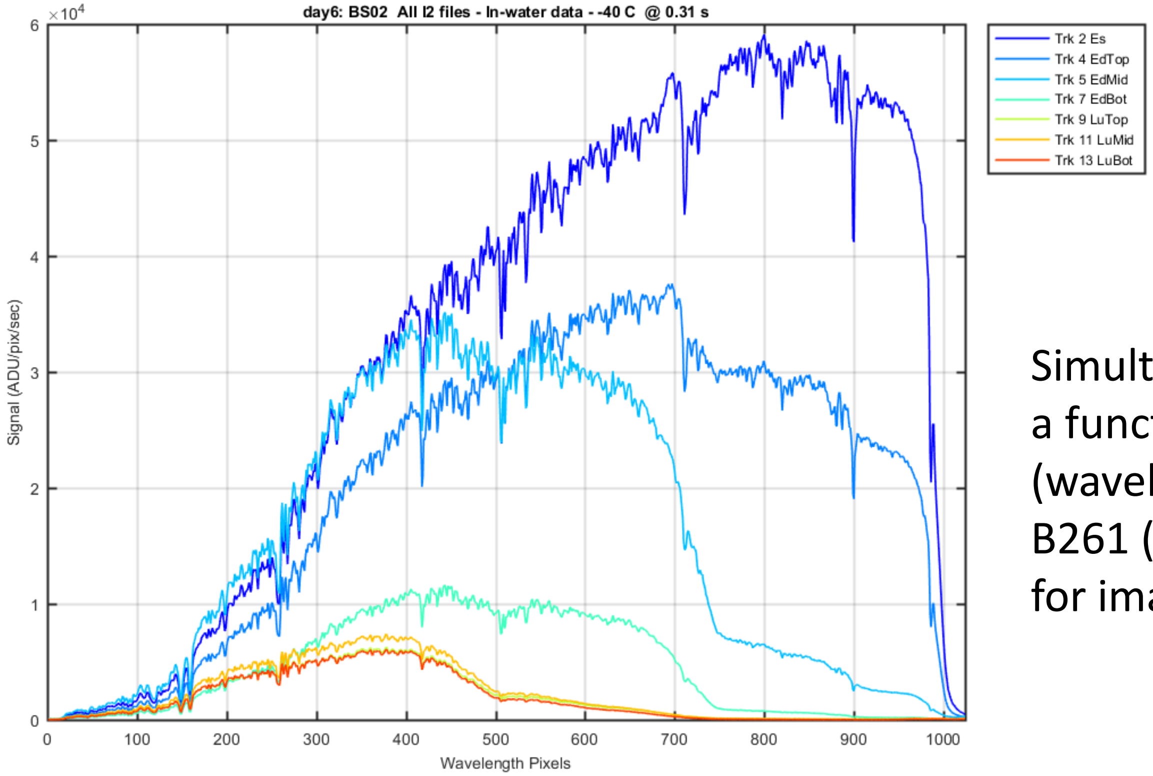


MOBY Refresh and MOBY NET



Heritage MOBY and Refresh have been run in the water together starting in August 2016

- Deployment History
  - M261, BS02
  - M262, BS01
  - M263, BS03
  - M264, BS04
  - M265, BS03/RS04



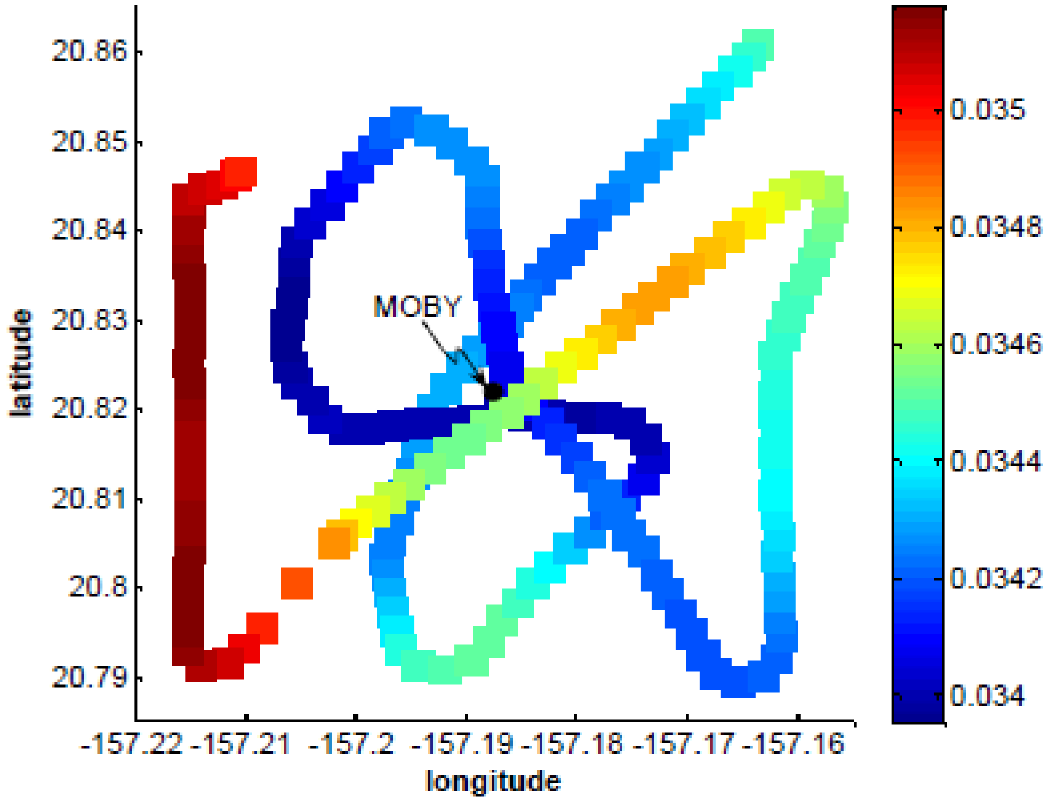
Simultaneous output as a function of CCD pixel (wavelength), BS02 on B261 (see previous slide for image on CCD)

- MOBY Lu, Es, and Lw values are traceable to NIST via source and detector reference standards
- Corrections to the data are well along, goal is to implement all in 2019 for the MOBY Heritage time series.
- Uncertainty budget is well along; goal is to assign uncertainty to each hour file’s products and this will take additional effort
- Substantial data for the Refresh/NET optical design exists, especially for in water; current focus is on understanding sources of unexplained variability

Backup

Spatial uniformity of optical properties

$$\frac{b_{bt}(460)}{b_{bt}(460)+a_t(460)}$$ as a function of position at the MOBY site

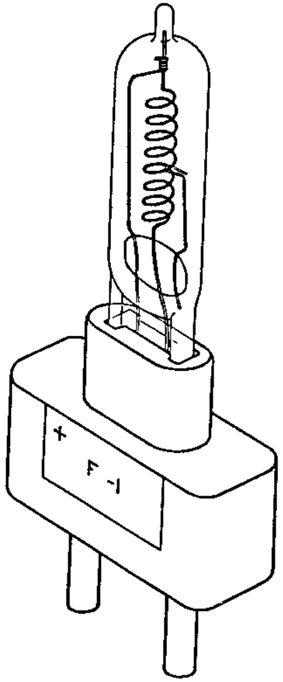


Results from a towed instrument measuring IOP's at the MOBY site. $b_{bt}(460)$ is the total backscattering at 460 nm and $a_t(460)$ is the total absorption at 460 nm.

Results show patchiness with standard deviation less than 2% of the mean value. There is also a trend of steadily decreasing values during the tow, reaching a minimum of about 4 % less than values at the beginning of the tow.

Scale: diagonal of map is 10km.

Voss et al., "An example crossover experiment for testing new vicarious calibration techniques for satellite ocean color radiometry," JTECH (2010).



Irradiance Calibration Geometry at NIST