Sea-Bird Scientific radiometric measurements: Current evaluations and future opportunities for Ocean Color vicarious calibration and validation.

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Fiducial Reference Measurement Network for Satellite Ocean Colour
NPL, Teddington, London, UK
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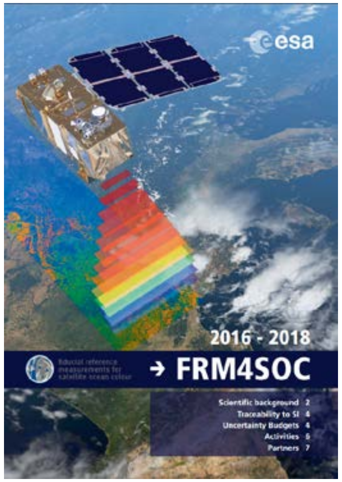
Overview

Sea-Bird Scientific has engaged in several efforts tied to SI traceable radiometric measurements, particularly w.r.t. Satellite Ocean Color calibration and product validation.

Topics Covered Today

1. Sea-Bird Scientific inter-laboratory radiometric calibration comparison exercise.
2. European Space Agency Fiducial Reference Measurements for Satellite Ocean Colour.
3. HyperNAV: An end-to-end system and strategy for ocean-color satellite calibration.

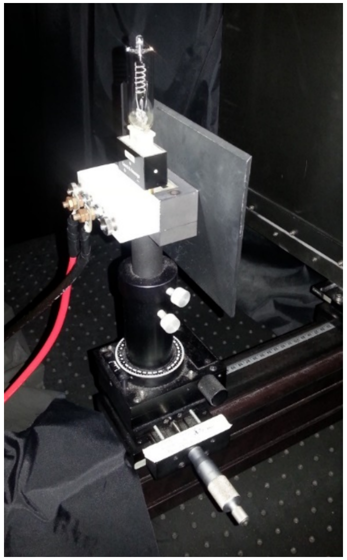


Each of these efforts share a common goal of producing detailed uncertainty values for in situ radiometric sensors.

1.) Inter-Laboratory Comparison Study

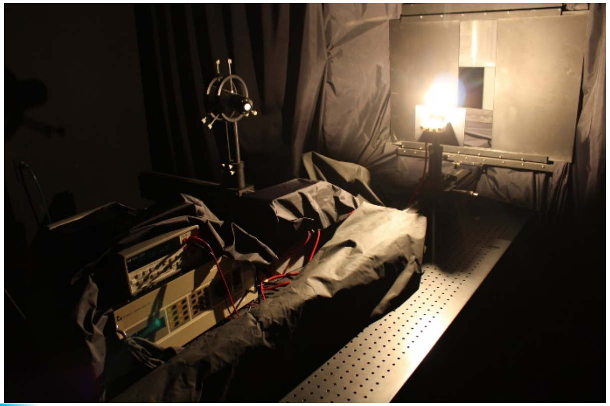
GOALS OF THE STUDY

In 2017, Sea-Bird Scientific transitioned the manufacturing and calibration of radiometric products from the facility located in Halifax (HAL), Nova Scotia CA to the facility located in Philomath (PHI), Oregon USA.

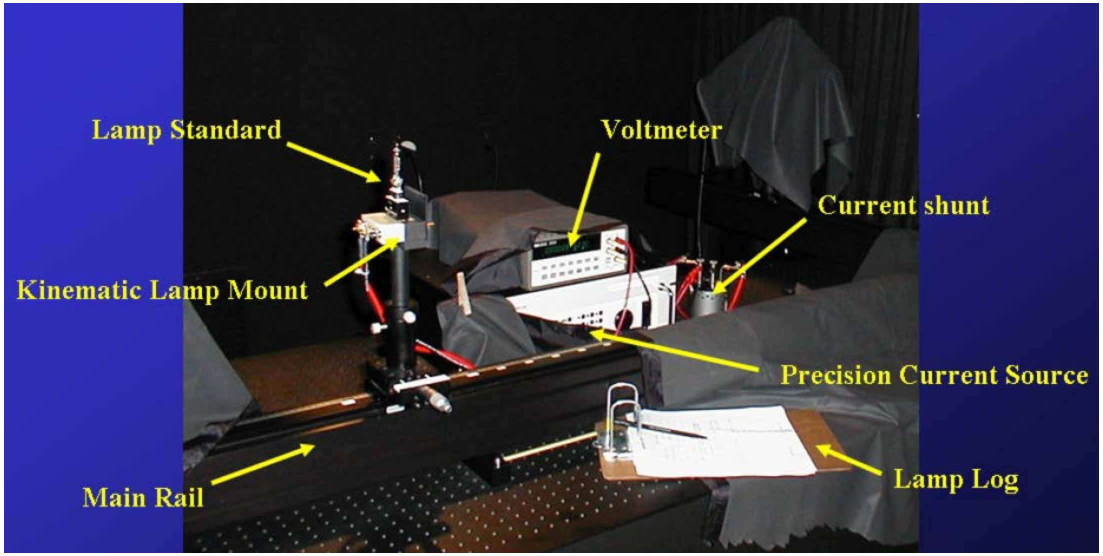


Sea-Bird Scientific conducted an extensive cross facility experiment to:

1. Quantify relative calibration uncertainties within and between Halifax and Philomath laboratories;
2. Quantify differences in repeatability relative to Halifax (established standard);
3. Compare relative laboratory calibration uncertainties to budget of estimated uncertainty sources;
4. Verify successful transfer of build and calibration processes at Philomath site.



1.) Inter-Laboratory Comparison Study



- Calibration labs: Halifax, Nova Scotia and Philomath, Oregon.
- FEL lamps and Spectralon plaques.
- All equipment including supplies, shunts, meters, have SI traceable calibration and are regularly recalibrated.
- Clean rooms: HEPA filtered, temperature controlled, positive air pressure, humidity controlled.
- The Halifax lab participated in the NASA SIRREX-7[1] round-robin experiment, with extensive calibration characterization and uncertainty estimation.

[1] *Hooker, Stanford, Elaine Firestone, eds. (2002) "SeaWiFS Postlaunch Technical Report Series. Volume 17, The Seventh SeaWiFS Intercalibration Round-Robin experiment (SIRREX-7), March 1999." NASA Goddard Space Flight Center Tech. Memo. 2002-206892 vol 17. 39 pp.*

1.) Inter-Laboratory Comparison Study

Utilized a series of “reference” radiometers

1 year study: several repeated calibrations were conducted at both sites following standard methods (e.g. Banks et al 2017).

Long-term experiments: included several FEL lamps, plagues, and power supplies/shunts.

Short-term experiments: Used same equipment at both sites, shorter time periods.

Data were used:

- Quantify reproducibility within each lab and compared to uncertainty budgets.
- Site to site comparisons – percent difference relative to HAL lab.

Model	Type	Description	Model	S/N
OCR-507	ICSA	Irradiance Cosine in Air	OCR-507	350
OCR-507	ICSA	Irradiance Cosine in Air	OCR-507	351
OCR-507	ICSW	Irradiance Cosine in Water	OCR-507	352
OCR-507	ICSW	Irradiance Cosine in Water	OCR-507	353
OCR-507	R08A	Radiance 08 deg Half-Angle Air	OCR-507	150
OCR-507	R08A	Radiance 08 deg Half-Angle Air	OCR-507	151
HOCR-HPE	ICSW	Irradiance Cosine in Water	HOCR-HPE	306
HOCR-HSE	ICSA	Irradiance Cosine in Air	HOCR-HSE	451
HOCR-HPL	R08W	Radiance 08 deg Half-Angle Water	HOCR-HPL	611
HOCR-HSL	R03A	Radiance 03 deg Half-Angle Air	HOCR-HSL	446

1.) Inter-Laboratory Comparison Study

Expected uncertainties – Short-term reproducibility, using same equipment

Sensor	Uncertainty components	350 nm	500 nm	650 nm	800 nm	Reference
Both	Power supply	0.05%	0.02%	0.02%	0.02%	
Both	Lamp ageing, 20 h	0.10%	0.10%	0.10%	0.10%	Bernhard and Seckmeyer (1999)
Both	Lamp alignment	0.10%	0.10%	0.10%	0.10%	
Both	Thermal responsivity	0.10%	0.10%	0.10%	0.10%	Kuusk *et al.* (2017)
Irradiance	Lamp-sensor distance	0.16%	0.16%	0.16%	0.16%	
Irradiance	Sensor angular alignment	0.10%	0.10%	0.10%	0.10%	Kuusk *et al.* (2017)
Radiance	Lamp-plaque distance	0.06%	0.06%	0.06%	0.06%	
Radiance	Plaque alignment	0.10%	0.10%	0.10%	0.10%	
Radiance	Sensor angular alignment	0.10%	0.10%	0.10%	0.10%	Kuusk *et al.* (2017)
Irradiance	**Expanded Uncertainty, *k*=2**	**0.5%**	**0.5%**	**0.5%**	**0.5%**	**Same Equipment**
Radiance	**Expanded Uncertainty, *k*=2**	**0.5%**	**0.5%**	**0.5%**	**0.5%**	**Same Equipment**

Expected uncertainties – Long-term reproducibility, includes use of different equipment

Sensor	Uncertainty components	350 nm	500 nm	650 nm	800 nm	Reference
Both	NIST FEL, k=1	0.65%	0.40%	0.35%	0.30%	Yoon and Gibson (2011)
Both	G&H FEL additional, k=1	0.50%	0.50%	0.50%	0.50%	Calibration certificate, G&H
Both	Lamp aging, 50 h, k=1	0.29%	0.29%	0.29%	0.29%	Bernhard and Seckmeyer (1999)
Both	Lamp optical center, k=1 (Radiance only)	0.07%	0.07%	0.07%	0.07%	Yoon *et al.* (2012)
Radiance	Plaque 0/45 reflectance, k=1	1.00%	0.80%	0.80%	1.50%	Calibration certficate, Labsphere
	Table 13, k=1 (-ageing)	0.20%	0.20%	0.20%	0.20%	
Irradiance	**Expanded Uncertainty, *k*=2**	**1.8%**	**1.5%**	**1.4%**	**1.4%**	**Different Equipment**
Radiance	**Expanded Uncertainty, *k*=2**	**2.7%**	**2.2%**	**2.2%**	**3.3%**	**Different Equipment**

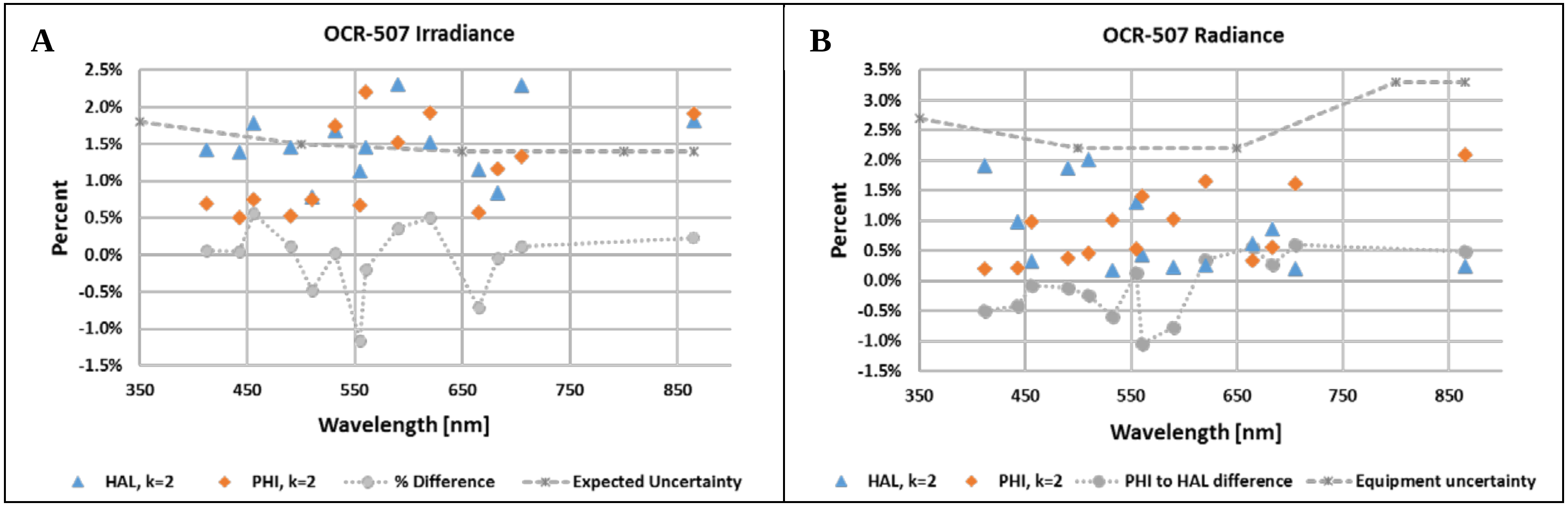
The Halifax lab participated in the NASA SIRREX-7 round-robin experiment

Provided targets for reproducibility for study

Expanded Uncertainty (k=2)

1.) Inter-Laboratory Comparison Study

Multi-spectral (OCR 500 series) sensors



Reproducibility uncertainty: HAL (blue triangle) and PHI (orange diamond). Expected uncertainties for use of the same equipment (gray asterisks). The % difference of PHI to HAL calibration coefficients (gray dots).

UNCERTAINTY RESULTS – Long-term

IRRADIANCE:

Reproducibility: HAL < 2.3 %, PHL < 2.2 %

% difference between labs: generally within 1%, no spectral trends

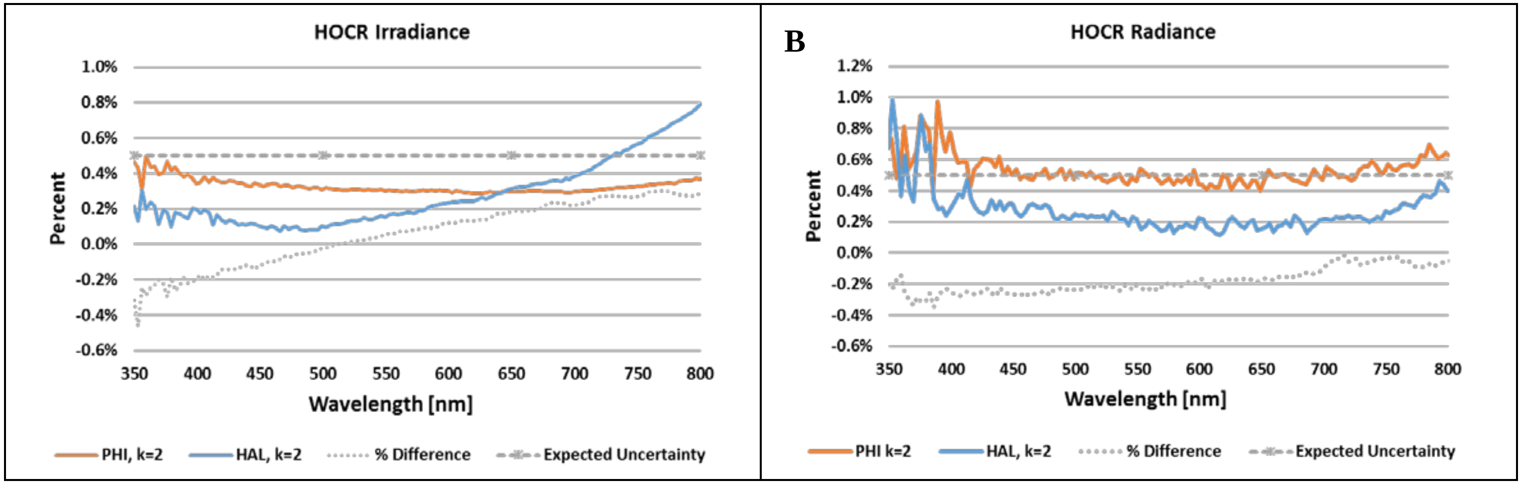
RADIANCE:

Reproducibility: HAL < 2.0 %, PHL < 2.1 %

% difference between labs: generally within 1%, slight spectral trend

1.) Inter-Laboratory Comparison Study

Hyperspectral (HOCR) sensors



Reproducibility uncertainty: HAL (blue triangle) and PHI (orange diamond). Expected uncertainties for use of the same equipment (gray asterisks). The % difference of PHI to HAL calibration coefficients (gray dots).

UNCERTAINTY RESULTS – Short-term

IRRADIANCE:

Reproducibility: HAL < 0.3 % (350-650nm), up to 0.8 % IR, PHL < 0.5 % spectrally flat
% difference between labs: spans -0.3 % to 0.3 %, spectral trend

RADIANCE:

Reproducibility: HAL < 0.5 % (except 350-400nm), PHL ~0.5 % (except 350-400nm)
% difference between labs: spans -0.3 % to 0%, spectral trend, PHL<HAL

1.) Inter-Laboratory Comparison Study

CONCLUSIONS

Sea-Bird Scientific successfully transitioned the manufacturing, servicing and calibration of radiometric products to Philomath, Oregon USA.

1. Both Labs achieved target performance, with both long-term and short-term reproducibility uncertainty values below or close to target values.
2. Differences in calibration coefficients between Labs were small (1% or less) even when different equipment was used and over longer periods.
3. Some spectral trends were observed between Labs for Hyperspectral sensors (HOCR), we believe are due to lab conditions (ongoing investigation).
4. This study and from a series of new production built sensors (PHL) verified that the new Philomath Lab is performing within expected uncertainties.

See Poster #185 at Ocean Optics 2018 Conference: ***Calibration Uncertainty Budget for Sea-Bird Scientific Radiometers*** – C. Orrico, R. Van Dommelen, A. Barnard, R. Lamb, J. Foesenek, S. Muhammad, K. Brown, M. Dewey, A. Crisp, W. Strubhar, C. Moore.

2.) FRM4SOC

Sea-Bird Scientific participated in several FRM4SOC activities

Opportunity to contribute to the Ocean Color Community as industry – uncertainty characterizations

Opportunity to independently evaluate our processes and sensors. Learn and continuous improvement.

Leverages our Inter-Laboratory Comparison Study.

We gratefully thank all of the FRM4SOC members, team, supporting agencies for their work.

SI-traceable Laboratory inter-comparison experiment – LCE-1

European Space Agency organized SI-traceable laboratory inter-comparison experiment LCE –1, for ocean colour radiometry reference irradiance & radiance calibration targets, in two stages: 1. "Verification of reference irradiance sources" on 3 – 7 April 2017 at the National Physical Laboratory (NPL), London, UK; 2. "Verification of reference radiance sources" Read more ...

SI-traceable Laboratory inter-comparison experiment – LCE-2

European Space Agency organized on 8 – 13 May 2017 in Tartu Observatory, Estonia SI-traceable Laboratory inter-comparison experiment LCE – 2 for verification of Fiducial Reference Measurement (FRM) Field Ocean Colour Radiometers (OCR) Read more ...

Fiducial Inter-Comparison Experiment for Sentinel-3 – FICE-AAOT

European Space Agency is organizing Fiducial Inter-Comparison Experiment for Sentinel-3 at the Acqua Alta Oceanographic Tower in July 2018. The Acqua Alta Oceanographic Tower (AAOT) off the Gulf of Venice, Italy, in the northern Adriatic Sea is a purpose built steel tower with a platform containing an instrument house to facilitate the measurement of ocean properties under exceptionally stable conditions. Read more ...

International workshop on OCR Vicarious Adjustment Infrastructure

European Space Agency organized on 21 – 23 February 2017 an international workshop on OCR Vicarious Adjustment Infrastructure in ESRIN, Italy to evaluate the options for future European satellite OCR vicarious adjustment infrastructure for the Sentinel-3 OLCI and Sentinel-2 MSI series. Read more ...

2.) FRM4SOC

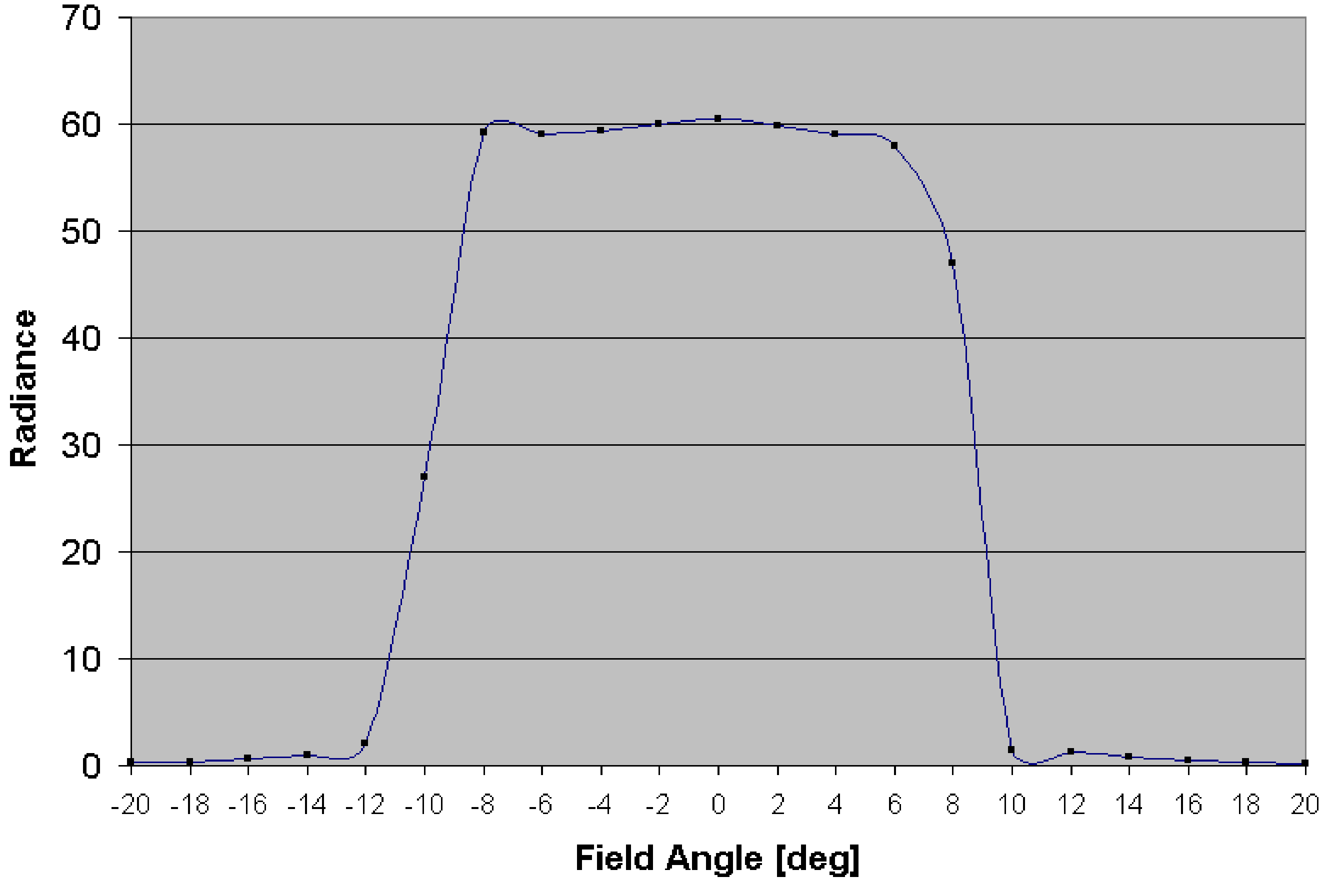
HyperOCR FOV Clarification

Sea-Bird Scientific acknowledges that existing literature was not clear or is confusing w.r.t. the FOV for HyperOCR radiance sensors

Sea-Bird Scientific manufactures two versions of HyperOCR sensors

- HSL: Hyperspectral SURFACE Radiance sensors: specifically for above-water sky and total radiance measurements (commonly used with HyperSAS systems). These sensors have 3^o (half angle) FOV (6^o full angle).
- HPL: Hyperspectral PROFILING Radiance sensors: specifically for IN WATER profiling applications (commonly used on a HyperPro series system). These sensors have a 8^o (half angle) FOV.
- HPL versions, when used in air the FOV changes to 11.5^o (half angle). Thus, in air, these sensors have a 23^o FOV.
- Literature on website did not accurately delineate between these two versions. Literature has been updated.

2.) FRM4SOC



Measured FOV for HyperOCR HPL series sensors

Working to verify FOV HOCR sensors used in LCE-2 (Univ. Victoria, PML)

2.) FRM4SOC

KEY TAKEAWAYS – LEARNINGS

- While results of FRM4SOC activities demonstrated that radiometric uncertainties are below or close to requirements, further improvement is still needed.
- We support activities such as FRM4SOC to both define existing and future requirements, but also to work with industry to work in collaboration to verify uncertainties and make recommendations for improvements.
- Sea-Bird Scientific is currently building additional facilities at the Philomath site to measure the cosine response for irradiance sensors (replicating Halifax capabilities) as well as facilities to quantify the immersion coefficients of radiometers.
- Expected completion: early 2019
- Additional improvements in future: thermal corrections.

3.) HyperNAV

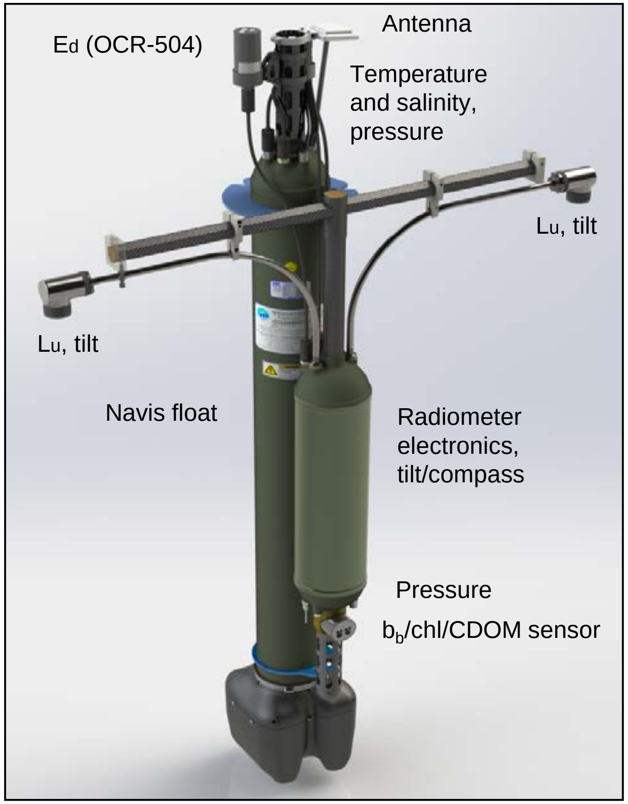
Autonomous hyperspectral radiometer for satellite vicarious calibration

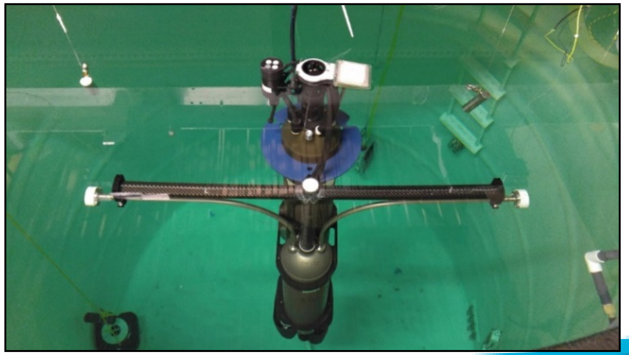
Goals

- Next-generation hyperspectral radiometric sensors for calibration/validation.
- Utilize autonomous floats as a platform to collect hyperspectral radiometric to minimize uncertainty.
- Develop an end-to-end system/strategy for new ocean-color satellite calibration – including float deployment, radiometric data quality assurance, data delivery and satellite inter-comparison.

HyperNav autonomous float system advantages

- Risk reduction approach to the vicarious calibration program for PACE and other missions.
- Deployment floats at the start of a satellite mission - rapid characterization of in flight satellite radiometer.
- Provide radiometric measurements across a broader range of solar angles and geographic regions, to assess the satellite dependencies on out-of-band response, BDRF, etc.
- Augments other moored cal/val sites throughout satellite lifetimes, enables rapid collection of vicarious calibration data.

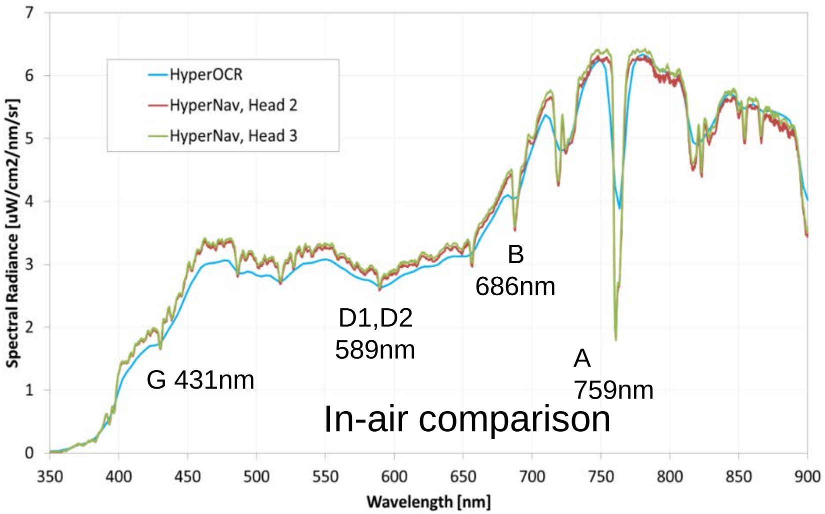




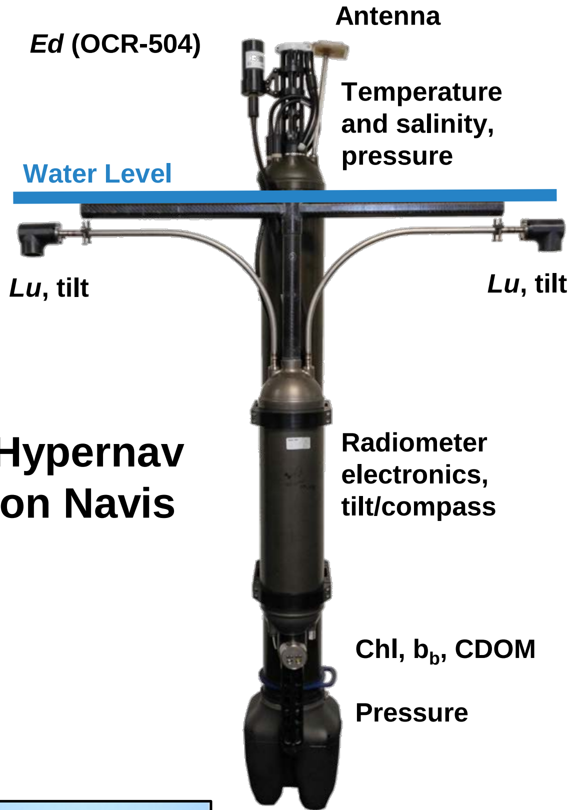
3.) HyperNAV

Design of Radiometric System

1. Dual radiance heads -> sun-side radiometer & intercomparison.
2. Heads on arms reduce self-shading.
3. Right-angle design -> near surface.
4. Reduced errors in extrapolation to Lu(0-).
5. Tilt sensors for alignment and to monitor position.
6. Shutters for collecting darks.
7. Depolarizer to remove uncertainty in the fore optics.
8. 2.2 nm nominal resolution, 350-900 nm



3.) HyperNAV

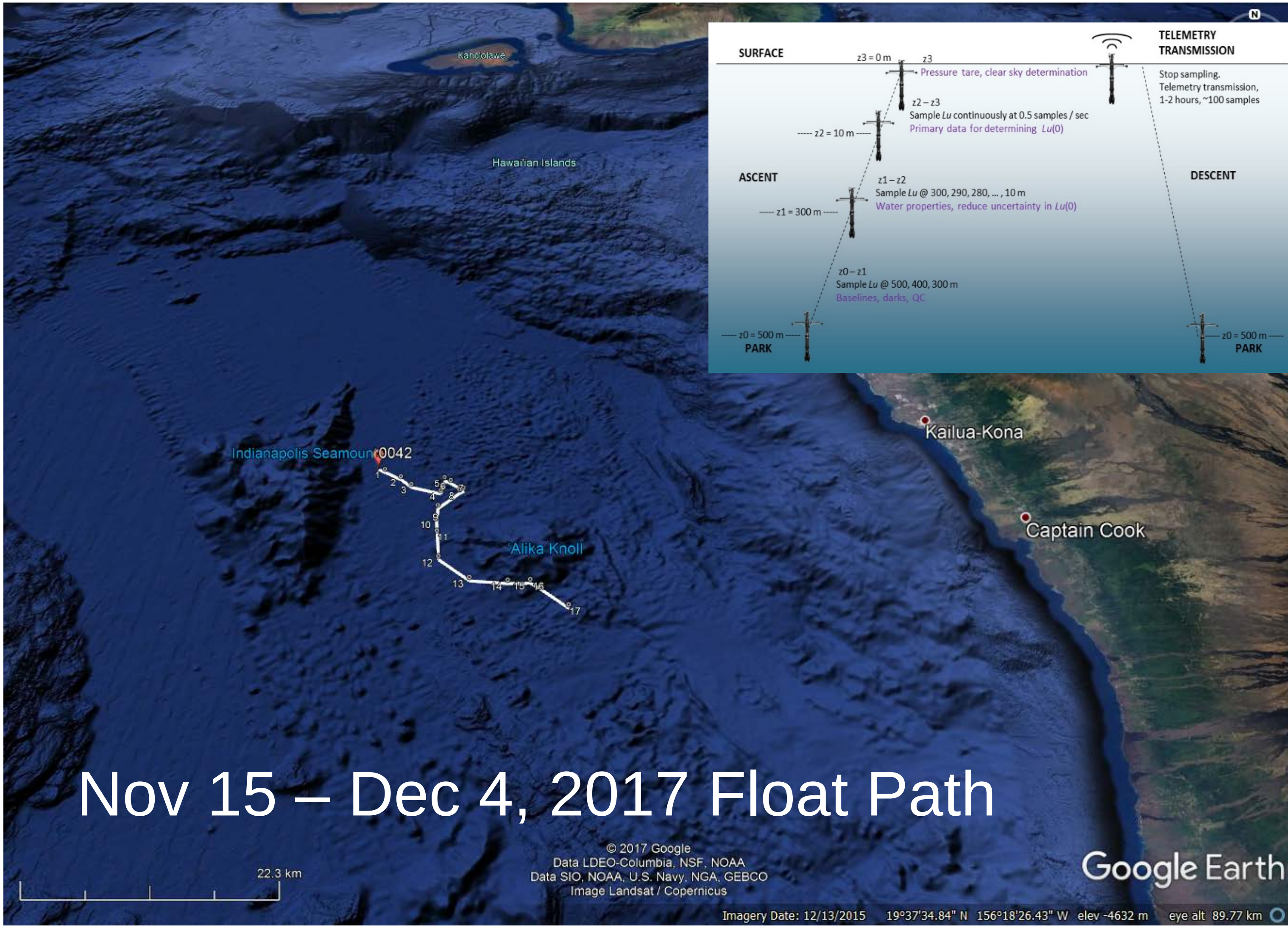


Hypernav on Navis

Capability Highlights

- Dual *Lu* heads, extended arms, <2.5 nm resolution, 350-900 nm.
- Lu very close to surface (~10-20 cm)
- Characterized for polarization, thermal, linearity, stray light, self shading (NIST characterizations of linearity & stray light).
- Overall uncertainty < 4% in blue-green, < 6% in red regions
- Radiometer can operate in cabled freefall mode with fins.
- Pressure rated to ~ 1000m
- Minimization of self shading
- Ability to extend at surface acquisition time
- Autonomous operation demonstrated in Hawaii fall 2017.

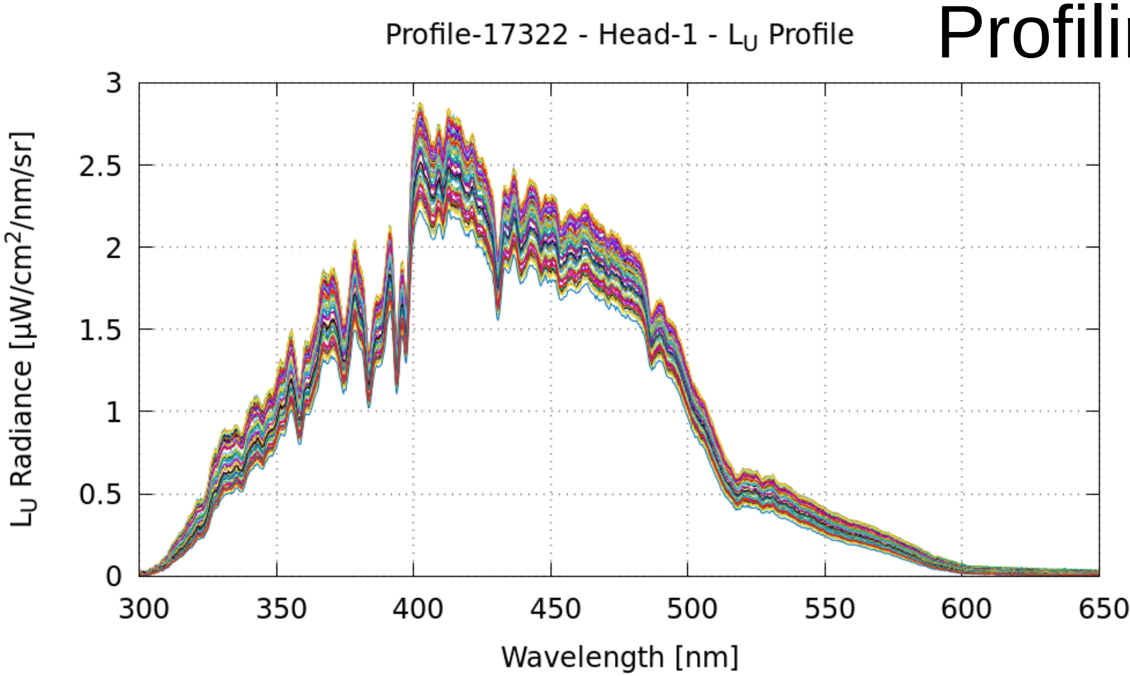
3.) HyperNAV



SURFACE
z3 = 0 m
z3
Pressure tare, clear sky determination
TELEMETRY
TRANSMISSION
Stop sampling.
Telemetry transmission,
1-2 hours, ~100 samples
z2 – z3
Sample Lu continuously at 0.5 samples / sec
Primary data for determining Lu(0)
z2 = 10 m
ASCENT
DESCENT
z1 – z2
Sample Lu @ 300, 290, 280, ... , 10 m
Water properties, reduce uncertainty in Lu(0)
z1 = 300 m
z0 – z1
Sample Lu @ 500, 400, 300 m
Baselines, darks, QC
z0 = 500 m
PARK
z0 = 500 m
PARK
Kaho'olawe
Hawaiian Islands
Indianapolis Seamount
0042
'Alika Knoll
Kailua-Kona
Captain Cook
Nov 15 – Dec 4, 2017 Float Path
22.3 km
© 2017 Google
Data LDEO-Columbia, NSF, NOAA
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Google Earth
Imagery Date: 12/13/2015 19°37'34.84" N 156°18'26.43" W elev -4632 m eye alt 89.77 km

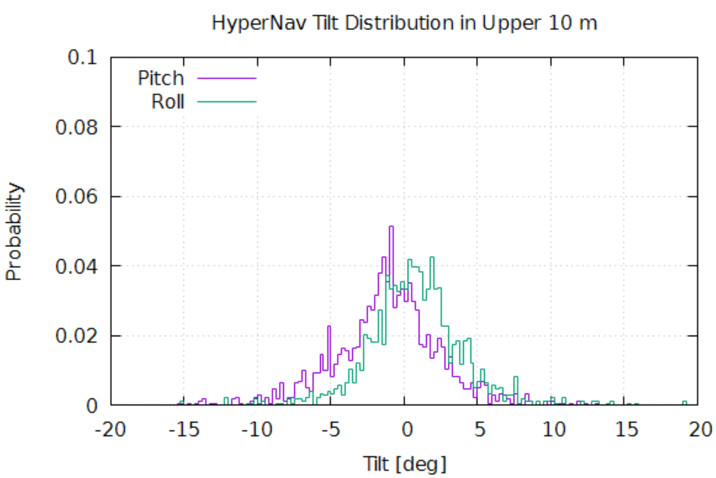
3.) HyperNAV

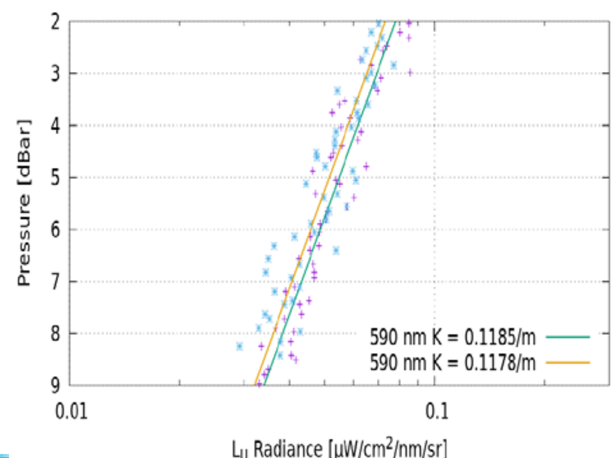
Profiling Float - Spectra



Spectra from the upper 10 m and at the surface.

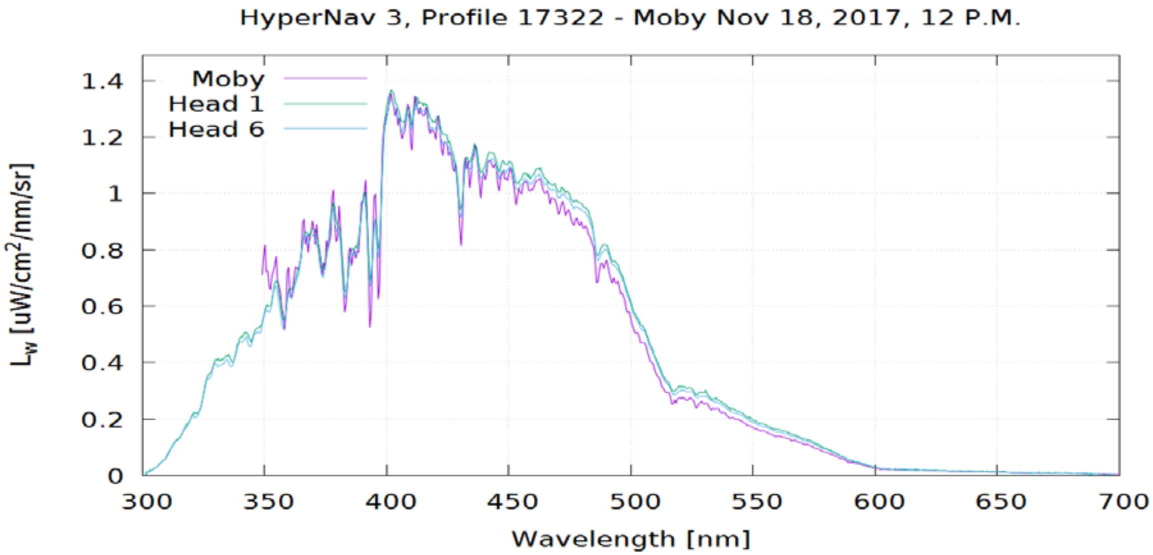
Surface data not filtered for tilt.





3.) HyperNAV

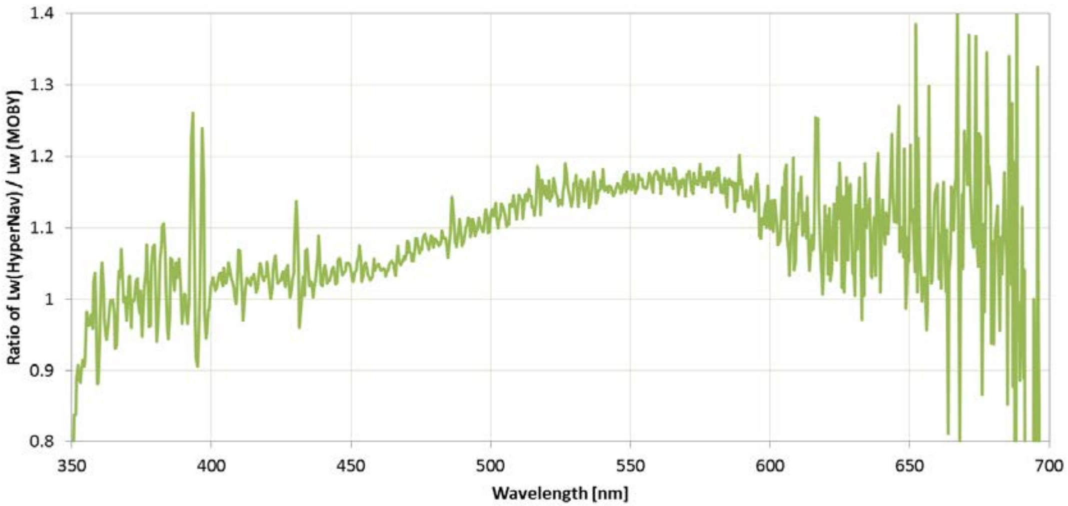
Comparison with MOBY



Nov 18, 2017

Hypernav float system located some 70 miles or so apart.

Matchup with satellite data in progress.



Hypernav Lw data calculated by best fit of the 1-5m profile data to constant k, then extrapolated to surface and transmitted through water surface (Quan & Fry, 1995)

Note: Minimal corrections have been applied (stray light, linearity, etc).

3.) HyperNAV

Hypernav Uncertainties Matrix

Source	380nm	412nm	443nm	490nm	510nm	550nm	665nm
Calibration							
Irradiance Standard	0.55	0.51	0.48	0.44	0.42	0.40	0.34
Reflectance Target	1.1	1.1	1.0	0.9	0.8	0.8	0.9
Geometric Effects	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Reproducibility	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Instrument							
Polarization	0.9	0.5	0.4	0.1	0.06	0.07	0.5
Thermal	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Immersion	0.43	0.45	0.45	0.36	0.40	0.39	0.30
Integration Time Linearity	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Counts Linearity	0.00	0.00	0.00	0.00	0.01	0.03	1.0
Stray Light	0.12	0.1	0.09	0.08	0.05	0.04	0.09
Wavelength @ Cal	0.19	0.15	0.13	0.09	0.08	0.06	0.03
Wavelength @ Field	1.0	0.1	0.1	0.2	0.5	0.2	0.1
Field							
Self-shading (corrected)	0.3	0.26	0.22	0.24	0.32	0.56	2.7
Tilt Effects	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Biofouling	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Wave Focusing	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Depth Uncertainty	0.70	0.56	0.54	0.54	0.82	1.14	4.0
Surface Transmittance	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**3.5**	**3.2**	**3.2**	**3.1**	**3.2**	**3.3**	**5.8**

<4% uncertainty in the UV to green region, 5-6% in the red region

3.) HyperNAV

Accomplishments

- Radiance: 350 -> 900 nm spectral range, ~2.2 nm resolution, < 0.45 nm channel spacing.
- Radiometric uncertainty < 4% blue-green & ~5% in red spectral regions.
- Autonomous in-water filed operation demonstrated off Hawaii.
- Good comparison with MOBY data. Satellite data comparisons ongoing.
- Fully characterized radiance measurement system – uncertainty budget.
- SI traceable radiometric calibrations – NIST linearity and stray light.
- HyperNAV demonstrated Technology Readiness Level 7 (TRL-7).

Conclusions & Recommendations

- Rigorous, sustained uncertainty analyses of in situ data is key to sustaining and implementing a robust traceable set of measurements to validate Ocean Color data and products.
- Sea-Bird Scientific is dedicated to producing high quality, robust in situ radiometric sensors to support existing and future needs for Ocean Color.
- Sea-Bird Scientific is also looking to the future advancing the state of the art in radiometric measurements and in developing the next set of tools for accurate, cost effective satellite ocean color calibration/validation using autonomous floats.

See Poster #13 at Ocean Optics 2018 Conference: ***A New Paradigm For Ocean Color Satellite Calibration and Validation: Accurate Measurements of Hyperspectral Water Leaving Radiance From Autonomous Profiling Floats (HyperNAV)*** – A. Barnard, R. Van Dommelen, E. Boss, B. Plache, V. Simontov, C. Orrico, D. Walter, M. Lewis, D. Carlson.

Thank You