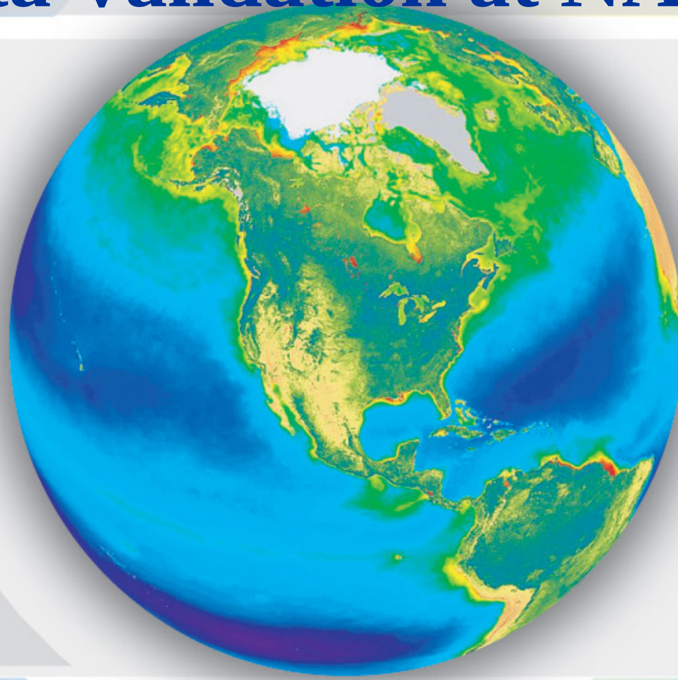
The Importance of Fiducial Reference Measurements (FRM) in Ocean Color Satellite Data Validation at NASA



Paula Bontempi and Sean Bailey (with Chris Proctor)
(NASA Headquarters & NASA GSFC)

ESA FRM4SOC Workshop – NPL, Teddington, UK
4-5 October 2018

FRM at NASA Has a Long History

- CZCS validation – early 1980s
- SeaWiFS Project cal/val program – early1990s
  - SeaBASS
  - Support for MOBy
- SIMBIOS Program – late 1990s/early 2000s
- Participation in the CEOS OCR-VC / INSITU-OCR activities – early 2000s-2010s
- PACE – NOW!

SIMBIOS Lessons Learned and Addition of Possible Follow-on to CEOS OCR-VC

Sensor Intercomparison & Merger for Biological & Interdisciplinary Ocean Studies

- Ensure development of internally consistent research products and time series from multiple satellite ocean color data sources
- Develop methodologies for cross-calibration of satellite ocean color sensors
- Develop methodologies for merging data from multiple ocean color missions
- Promote cooperation between ocean color projects

- Conceived in 1994 by NASA HQ as an alternative to the EOS Color mission. SIMBIOS Program ended in December 2003

- What are lessons learned, and would there be any advantages to having a follow on program that could be part of the OCR-VC?

SIMBIOS Program Activities

- **Global bio-optical & atmospheric *in situ* data collection (NRA's)**
- **Bio-optical & atmospheric database development (SeaBASS)**
- **Field measurement & data processing protocol development**
- **Traceability of laboratory calibration sources to standards (R/R)**
- **R&D of new instruments & instrument pool**
  - **SeaPRISM (AERONET-OC)**
  - **SIMBAD(A)**
- Prelaunch sensor calibration & characterization protocols
- On-orbit calibration evaluation & methodology development
- Instrumented calibration sites (MOBY)
- Bio-optical & atmospheric correction algorithm development + product accuracy evaluation & methodology development
- **Data merger algorithm development & data processing**
- High volume data processing capabilities
- Multi satellite data processing software (SeaDAS)
- **Systematic documentation (NASA TMs and publications)**
- **International collaborations and Science Team**

PS/GF lead
SeaWiFS lead
SIMBIOS

Satellite Data from Calibrated Sensors (2003)

Mission Feedback

•Science community input

•Comparison with other appropriate products

•New Mission

•Protocol development

Calibration Strategy

•Prelaunch

Lab. characterization & calibration (NIST traceable)

Solar calibration (transfer-to-orbit)

•Postlaunch (operational adjustments)

Solar calibration (daily)

Lunar calibration (monthly)

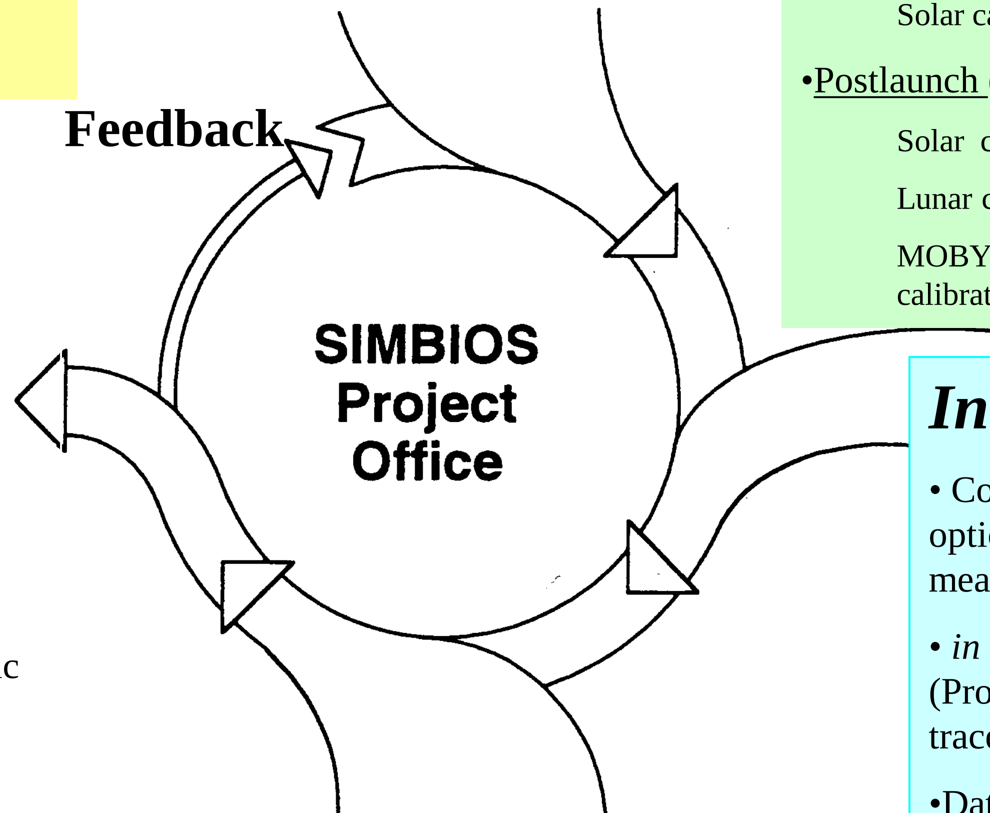
MOBY L_{wn} time series for vicarious calibration

Improved Products &Algorithms

• Reprocessing due to improvements in calibration, masks, binning schemes, product compatibilities, etc.

•New products from bio-geochemical fields, atmospheric fields, etc.

•Data distribution interface



In Situ Data

• Collection of required bio-optical and atmospheric measurements (SIMBIOS PIs)

• *in situ* instrument calibration (Project round robin NIST-traceable)

•Data collection following NASA Ocean Optics protocols

•Maintenance of an archive of calibrated QC *in situ* data (SeaBASS)

•Calibrated instrument pool

SeaDAS

• Satellite data processing software (CZCS, MOS, SeaWiFS, OCTS, OSMI and MODIS)

Product & Algorithm Validation

•Atmospheric & bio-optical algorithm validation and development (SIMBIOS PIs and project staff)

•Match-up analysis, satellite QC, time series evaluation, etc.

SIMBIOS *In situ* Field Lessons Learned:

- Accurately sample relevant measurements
- Regularly review how well they can be measured
- Make observations across wide range of biological/biogeochemical provinces
- Sample *in situ* observations according to agreed upon protocols and relate observations to community measurement standards
- Compare vicarious instrument calibration results with on-orbit methods
- Push advanced instrumentation development & ongoing instrument performance evaluations;
- Support calibration and data analysis round robins
- Provide these data to a centralized data center.

- Field training/certification for QA/QC

Consistent Series of Daily Global Ocean Color Data Sets

Thorough multi-sensor ***data validations***:

- estimate discrepancies between the products,
- extract disparate temporal trends, scan-angle dependencies, and other sensor differences,
- eliminate these trends by data cross-calibrations,
- define product accuracy levels (match ups, time series analysis by regions)
- choose the most suitable merger algorithm.

- Example: cross-calibration to eliminate scan-angle dependencies in MODIS-Terra data improved the matchups between MODIS and SeaWiFS chlorophyll

Overall SIMBIOS Lessons Learned:

- The calibration and validation programs for individual missions had a wide range of approaches and methodologies
  - International cooperation is imperative to ensure high **quality global climate data**.
- Long-term, high quality measurements are needed for global climate research.
- Data stability should be addressed in terms of :
  - sensor characterization, calibration, traceability to standards and data product validation;
  - Requirements for and approaches to data continuity, and
  - data systems (long-term archiving, data reprocessing capability, careful metadata and documentation, algorithm development in a open, peer-review process, etc.)
- Long-Term, consistent data sets should be addressed in terms of:
  - overlapping observations
  - cross-calibration
  - evolution, reprocessing, and multiple versions of data sets

The SIMBIOS Project, including it's Science Team, was a success story on how to tackle these issues while engaging the international ocean color community.

SeaBASS data collection & sources

SeaBASS is a permanent, publicly available archive of data from around the globe. It was originally formed to support the SeaWiFS mission, and since then it has archived data collected under NASA's:

- SeaWiFS Project
- SIMBIOS Program
- Ocean Biology and Biogeochemistry (OBB) Program
- Earth Venture projects & voluntary submissions

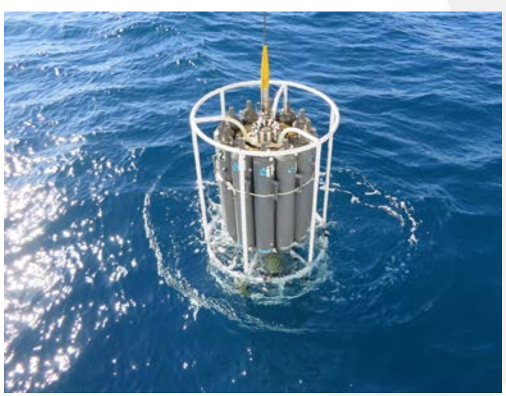
http://seabass.gsfc.nasa.gov

SeaBASS data types

Data archived in SeaBASS are collected from ships, moorings, autonomous buoys and other platforms. Measurements come from a variety of instruments, such as profilers, hand-held sensors, and laboratory analyzers.

Diverse data types include:

- **apparent optical properties / radiometry**
- inherent optical properties
- phytoplankton pigments
- carbon stocks
- hydrography
- other biogeochemical & atmospheric measurements



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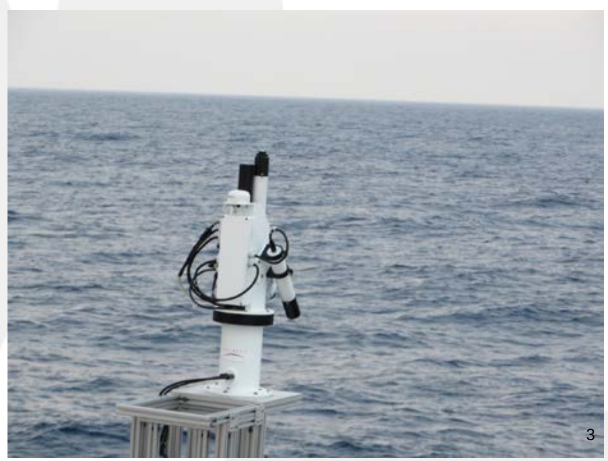

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Images provided by Javier Concha[1,2,3] and Chris Proctor[4]

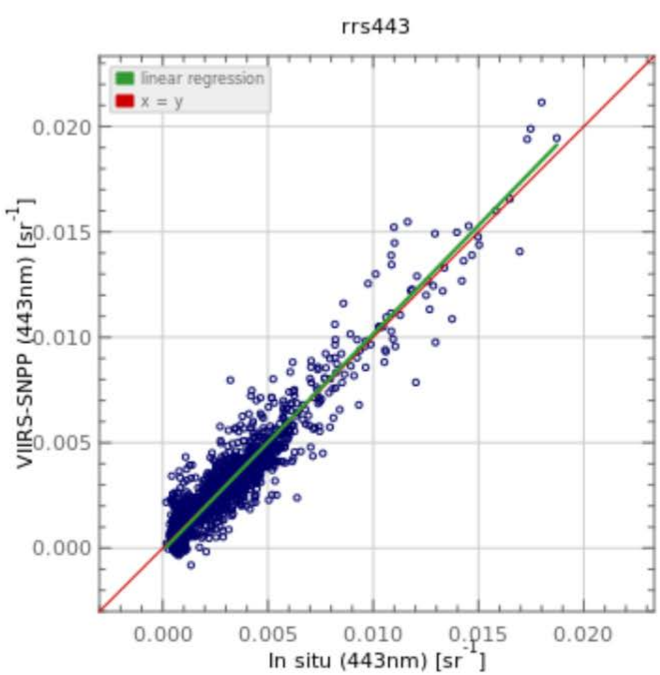
SeaBASS web-based Level-2 Validation Search

(https://seabass.gsfc.nasa.gov/search#val)

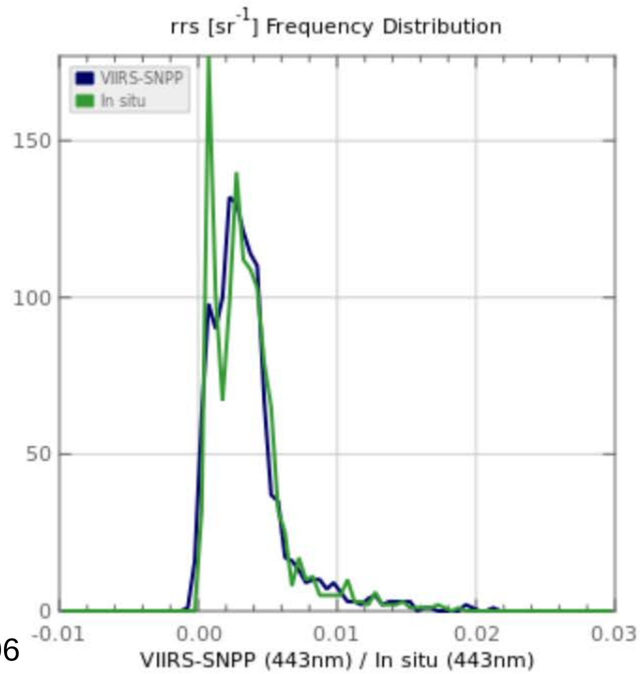
Data values and statistics for where successful coincident match-ups were calculated between *in situ* and satellite ocean color sensors measurements

Statistics | Data

Product Name	#	Mean Bias	Mean Absolute Error (MAE)	VIIRS-SNPP Range	In situ Range
rrs410	1249	-0.00025	0.00099	-0.00319 - 0.01614	0.00000 - 0.01527
rrs443	1247	-0.00002	0.00072	-0.00081 - 0.02115	0.00017 - 0.01871
rrs486	1250	-0.00062	0.00083	0.00040 - 0.02595	0.00058 - 0.02530
rrs551	1240	-0.00071	0.00083	0.00095 - 0.02455	0.00128 - 0.02633
rrs671	1250	-0.00022	0.00030	-0.00022 - 0.00977	-0.00000 - 0.01022



Bailey and Werdell, 2006



NASA Ocean Biology & Biogeochemistry Program

Field data collected under research proposals funded by the NASA OBB program are required to be submitted to SeaBASS.

field work funded by OBB Program

QA/QC

by data contributor

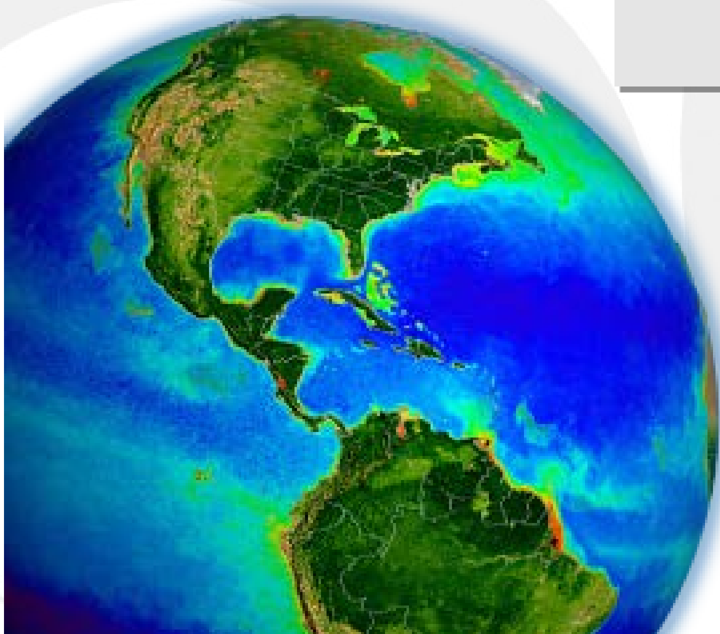
in situ data submitted to NASA SeaBASS within 1-year of measurements

by NASA

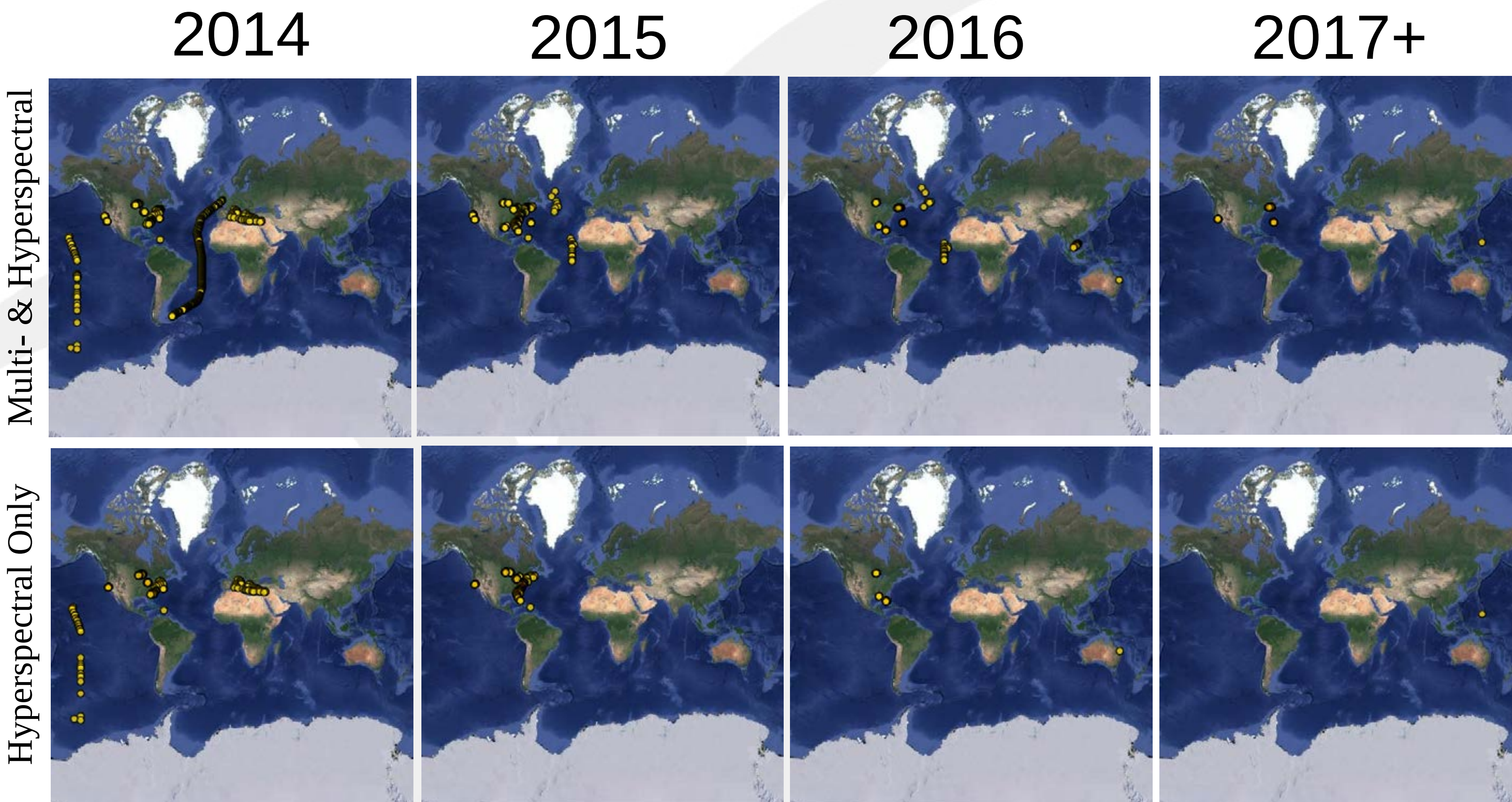
in situ data publicly released

by NASA

in situ data used to validate satellite data products & to develop / evaluate algorithms



SeaBASS AOP Holdings by Year (candidates for validation processing)



SeaBASS submissions only, i.e., excludes external data sources like AERONET-OC

SeaBASS Validation External Sources

Aerosol Robotic Network - Ocean Color

- Currently SeaBASS match-ups only made with Level 2.0 AERONET-OC data (cloud cleared, fully calibrated, and manually inspected)
- New and updated data are processed when new L2.0 data become available (e.g., annually)

Zibordi et al. (2009)

R_{rs} validation results & numbers

Quick summary of MODIS-Aqua validation results

SeaBASS-only

Product Name	#	Mean Bias	Mean Absolute Error (MAE)
rrs412	394	-0.00012	0.00121
rrs443	595	-0.00008	0.00091
rrs488	606	-0.00035	0.00073
rrs531	123	-0.00032	0.00080
rrs547	62	-0.00060	0.00121
rrs555	435	-0.00054	0.00063
rrs667	487	-0.00004	0.00014
rrs678	19	-0.00002	0.00022

SeaBASS + AERONET-OC

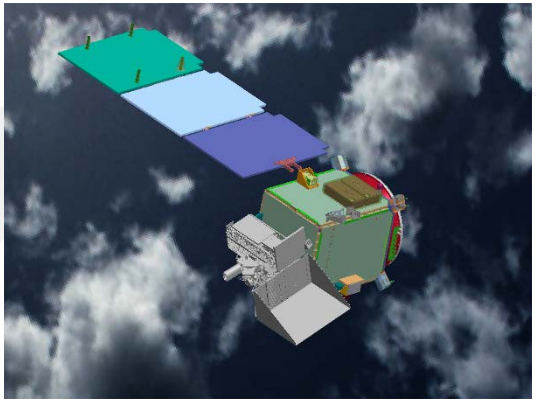
Product Name	#	Mean Bias	Mean Absolute Error (MAE)
rrs412	4529	0.00002	0.00100
rrs443	4732	0.00006	0.00076
rrs488	4319	-0.00053	0.00078
rrs531	2563	-0.00057	0.00078
rrs547	4200	-0.00050	0.00077
rrs555	4067	-0.00078	0.00092
rrs667	4115	-0.00016	0.00029
rrs678	535	-0.00016	0.00033

*Includes land bands

Including AERONET-OC results increases # of successful match-ups by more than 10x for some bands

Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission: new requirements & data needs

PACE



Spectrometer from UV to near-infrared: 345 (320 goal) – 885 nm at no greater than 5 nm resolution, plus discrete SWIR bands centered on 940, 1038, 1250, 1378, 1615, 2130, and 2260 nm

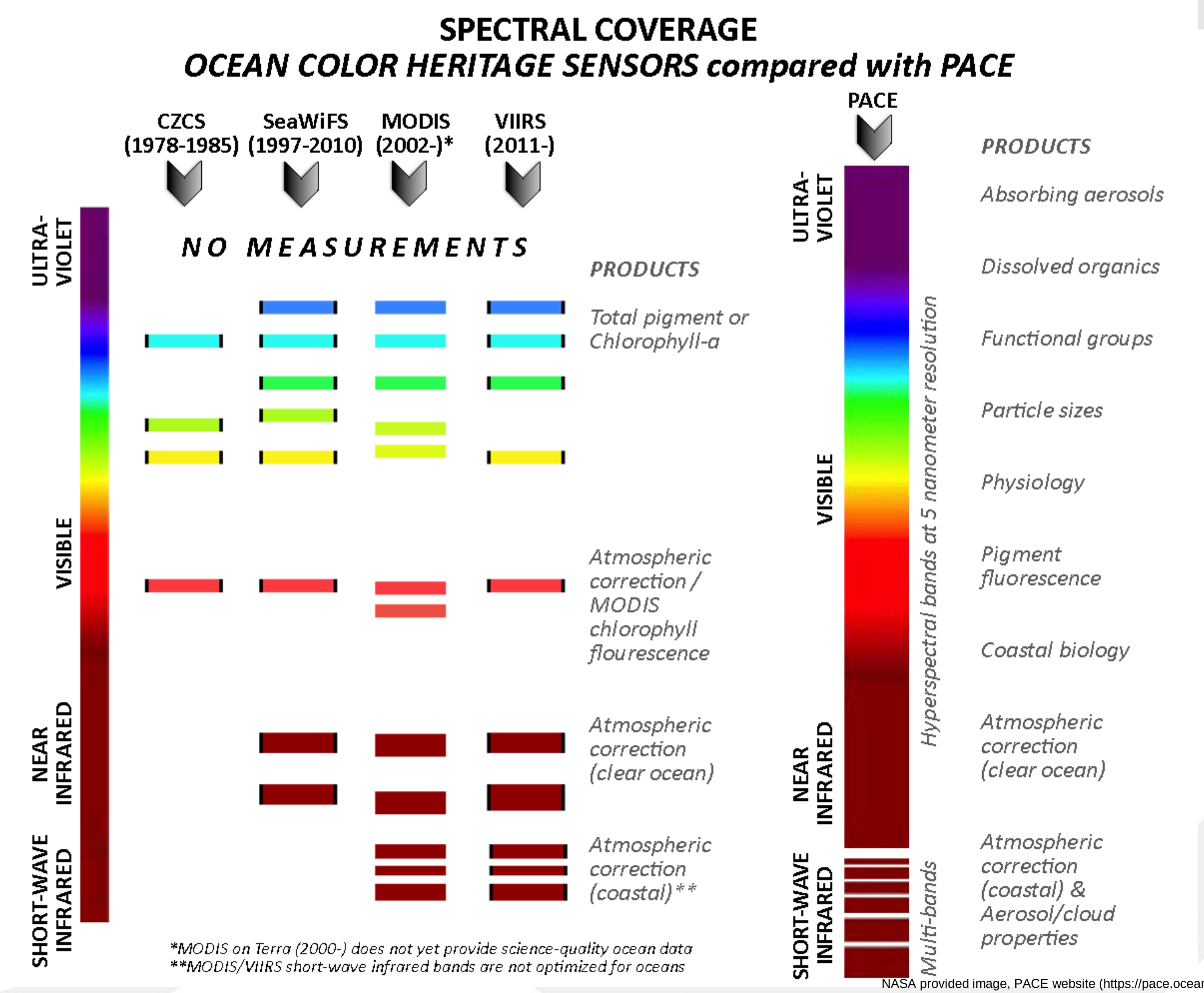
- 1 km spatial resolution
- 2-day global coverage to solar zenith angle of 75-deg and sensor zenith angle of 60-deg
- Sun-synchronous, polar orbit with a local Equatorial crossing time of ~13:00

Launch: 2022

Additional sources of high quality hyperspectral data (e.g., WATERHYPERNET) are needed for PACE validation

NASA provided images, PACE website (https://pace.oceansciences.org/)

PACE spectral coverage continued



NASA provided image, PACE website (https://pace.oceansciences.org/)

Progress: Vicarious Calibration of Ocean Color

- ROSES 2014 A.3 Ocean Biology and Biogeochemistry: three selections made (2015)
    - Hyperspectral radiometric device for accurate measurements of water leaving radiance from autonomous platforms for satellite vicarious calibrations (Hypernav)
        - Andrew Barnard – SeaBird Scientific, Inc.
        - $1.35M/3 years
    - Hybrid-spectral Alternative for Remote Profiling of Optical Observations for NASA Satellites (HARPOONS)
        - Carlos Del Castillo – NASA Goddard Space Flight Center
        - $2.8M/3 years
    - Developing a MOBY-NET instrument, suitable for a federation network for Vicarious Calibration of Ocean Color Satellites
        - Ken Voss – University of Miami
        - $2.8M/3 years

Hyperspectral radiometric device for accurate measurements of water leaving radiance from autonomous platforms for satellite vicarious calibrations (aka HYPERNAV)

PI: Andrew Barnard, Sea-Bird Scientific

Co-PI: Emmanuel Boss, University of Maine

Ronnie Van Dommelen, Keith Brown, Marlon Lewis, Burkhard Plache, Jamie Hutchins, Scott Feener, Joel Reiter, Daryl Carlson, Alex Derr, Nils Haentjens

HyperNav: Autonomous hyperspectral radiometer for satellite vicarious calibration

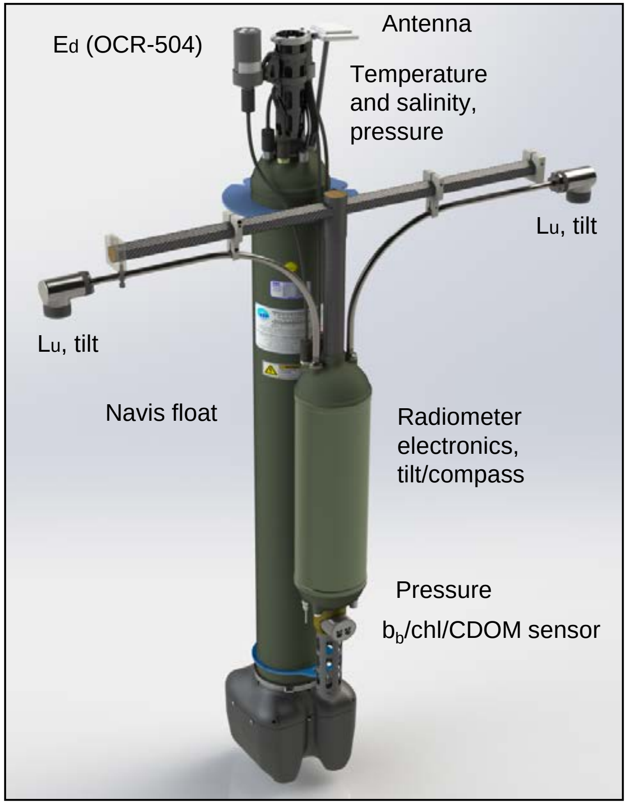
PI: Andrew Barnard

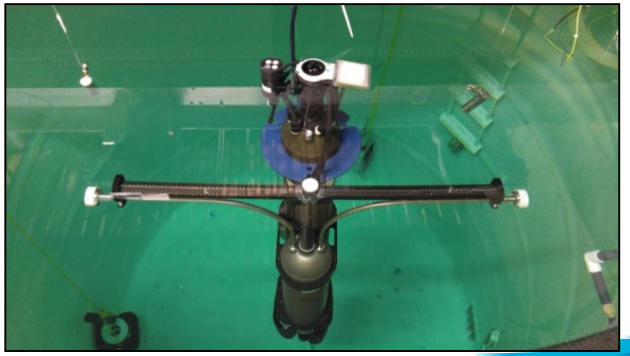
Goals

- 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.





HARPOONS Hybridspectral (SiP, InGaAs, and CCD) Above- and In-Water Autonomous Data Collection

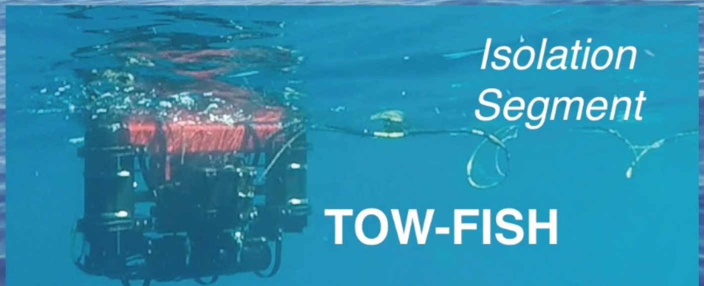
Sun Photometer with Reference

Autonomous Shore Measurements Improve Atmospheric Correction

Sea cable with high visibility floats, isolation segment to reduce towing effects, plus primary and secondary strength members.

SV3 Wave Glider

Autonomous At-Sea Measurements from SV3 with Reference Towing an Optical Profiler (TOW-FISH)



Digital thrusters allow stable up and down $E_d(\lambda)$ and $L_u(\lambda)$ profiles with all data products derived in upper 2 m.

HARPOONS is Ready to Support a Future Mission with Verified Data Quality and Uncertainties

A.3 requirements have been, or will soon be, met or *exceeded* for PACE or SGLI:

1. The above- and in-water combined spectral range is 320 – 1,640 nm (10 nm SiP and 15 – 30 nm InGaAs bands), plus 190 – 1,000 nm CCDs (≤2.2 nm resolution);
2. Radiometric uncertainty below 4% in blue-green and approximately 5% in red;
3. Stability of 1% per deployment with NIST traceability;
4. Autonomous in-water field operation demonstrated 4 times (Kawaihae, Lana'i, Monterey Bay, and Puerto Rico) with the longest lasting more than 7 days;
5. Internal calibration for 5 y with 4 transfer radiometers, NIST-traceable lamp library (19 FELs), plus LED portable source;
6. Deployed systems are commercial-off-the-shelf (COTS) sustainable , and field maintenance demonstrated;
7. Complementary field work to verify data quality and uncertainties demonstrated;
8. Instruments are field and laboratory characterized;
9. Fully autonomous data delivery, in the proper format, fidelity, and latency, to enable NASA mission science;
10. Calibration (oligotrophic), validation (mesotrophic), and research (eutrophic red tide) SV3 data collection demonstrated; and
11. TRL advanced to a fully tested, field deployable instrument *beyond* required TRL 6.

Developing a MOBY-NET instrument, suitable for a federation network for Vicarious Calibration of Ocean Color Satellites

(Ken Voss – UMiami, Carol Johnson-NIST, Mark Yarbrough-MLML, Art Gleason-UMiami)

The Specific goals are

A) A MOBY structure that can fit in a 40' container and be able to accept a modular optical system.

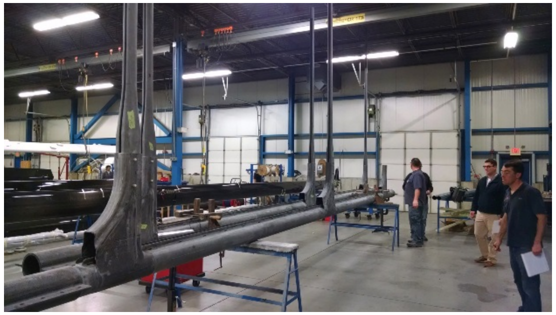
B) A modular, stable, optical system allowing installation and removal from buoy hull as one intact piece.

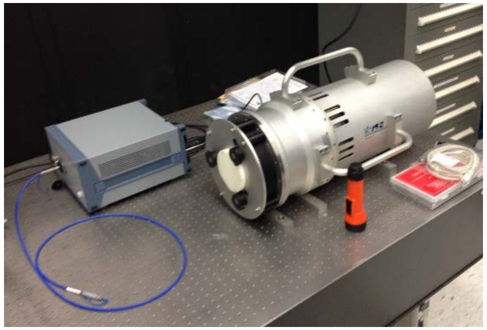
C) A separate stable source and radiometer, with sufficient stability to verify system performance pre/post deployment at the chosen remote site.

Meets IOCCG White paper OC-VCAL requirements!

The idea of MOBY-Net is to develop the techniques and equipment to be able to support an additional remote field site with instrumentation consistent with the Hawaiian location, and common calibration.

Requires: Structure that allows optics to be installed and removed intact…new carbon fiber structure, with arms designed for installation and removal of collectors.





Source and monitor to verify performance before and after deployment.

Satellite Data from Calibrated Sensors (2010)

Mission Feedback

•Science community input

•Comparison with other appropriate products

•New Mission

•Protocol development

Calibration Strategy

•<u>Prelaunch</u>

Lab. characterization & calibration (NIST traceable)

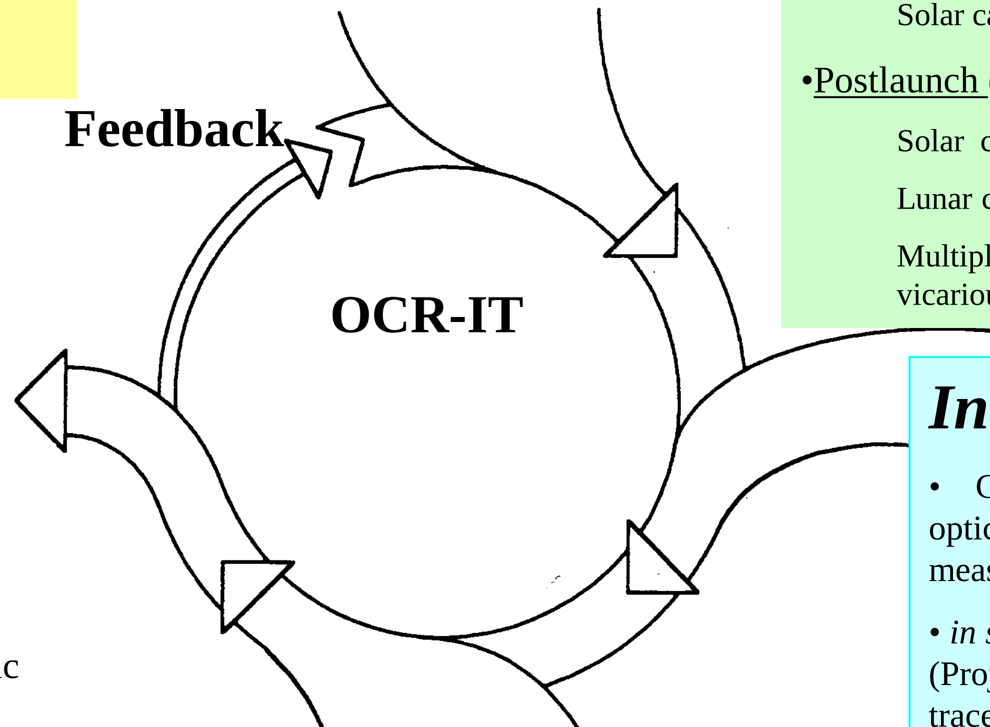
Solar calibration (transfer-to-orbit)

•<u>Postlaunch</u> (operational adjustments)

Solar calibration (daily)

Lunar calibration (monthly)

Multiple sites L_{wn} time series for vicarious calibration – ISRO, MOBY C



Improved Products &Algorithms

• Reprocessing due to improvements in calibration, masks, binning schemes, product compatibilities, etc.

•New products from bio-geochemical fields, atmospheric fields, etc.

•Data distribution interface

In Situ Data

• Collection of required bio-optical and atmospheric measurements (SIMB II PIs)

• *in situ* instrument calibration (Project round robin NIST-traceable, IOPs, AOPs)

•Data collection following NASA Ocean Optics protocols

• Archive of calibrated QC *in situ* data (SeaBASS)

•Calibrated instrument pool

• Development of new instrumentation

SeaDAS

• Satellite data processing software (ACE, OCM-2, MERIS, OLCI, SGLI, GOCI, GEO-CAPE, etc.)

Product & Algorithm Validation

•Atmospheric & bio-optical algorithm validation and development (SIMBIOS PIs and project staff)

•Match-up analysis via Aeronet OC sites, satellite QC, time series evaluation, Bio-Argo etc.

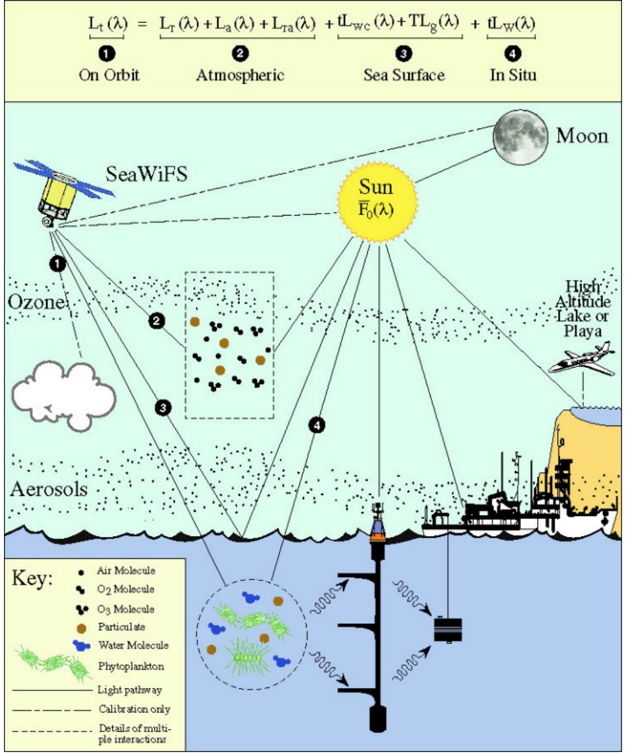
• **Earth System/Climate Model data assimilation**

Backup Slides

Functional Structure

- **SIMBIOS Science Team:** 1997 - Nov. 2003
  - NRA-96 (1997-2000): 21 US & 5 international investigations
  - NRA-99 (2001-2003): 21 US & 14 international investigations
  - MODIS Oceans Team ~$3.2 M/year
- **SIMBIOS Project Office:** 1996 - Nov. 2003
  - Co-located with SeaWiFS, technical & program management (budgets, staff, tasks, etc.), science team coordination, contract negotiations and revisions, and NRA coordination with HQ
  - Technical interface and MOUs with international space agencies (e.g., NASDA, CNES, ESA, KARI), other organizations (e.g., NIST, IOCCG, JRC, DLR), and programs (e.g., EOS, AERONET)
  - Specific research activities ~$1.3 M/year

"We worked in the meso to large scale and tried to developed long-term, high quality data for climate research"



1) SIMBIOS funded through contracts the collection of global *in situ* bio-optical and atmospheric data (and related oceanographic measurements). Augmented data with CIMEL stations and instrument pool;

2) Research areas were targeted by Project. Had a coordinated data collection;

3) All investigators followed NASA standardized protocols and participated in RRs (radiometric & measurements);

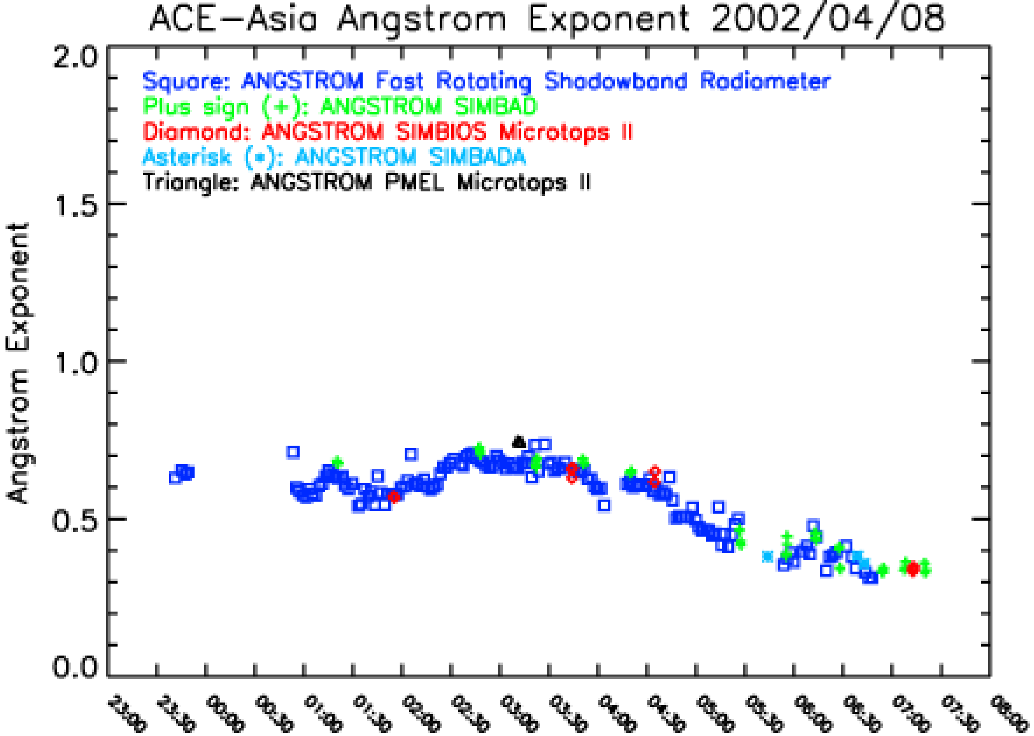
4) Bio-optical & atmospheric database development (SeaBASS);

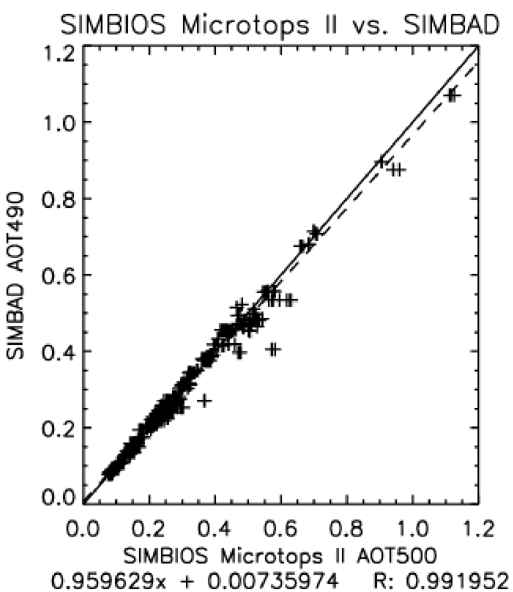
5) R&D technology evaluation (Simbad/Simbada, SQM, PREDE, Lidar).

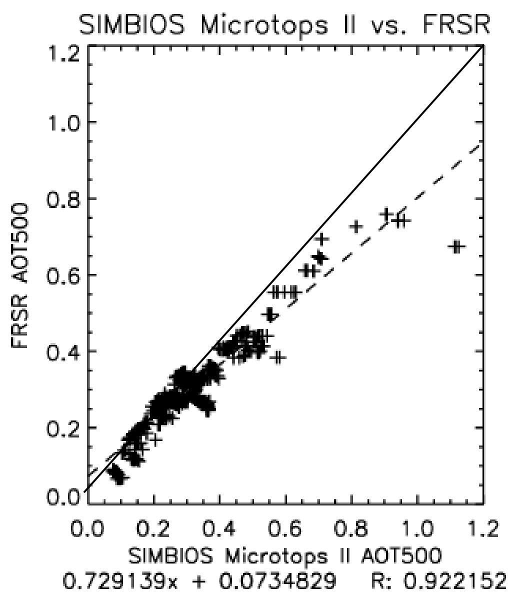
6) Worked with community to have up-to-date protocols

Lessons learned: High quality data are needed for **both vicarious calibration and product validation**. These data must follow sampling, analysis, QC and protocol methods approved by the community.

We worked in the **meso-large scale**







SIMBIOS deployed multiple instruments and collected continuous data over the oceans

- SIMBIOS Project deployed an interdisciplinary team
- ACE-Asia was ideal for sun photometer validation
  - **Encountered a variety of aerosol conditions**
  - **FRSR, SIMBAD, SIMBADA and 2 Microtops II's**
  - **Calibration was performed by a variety of means**
- Hand held sun photometer AOT and Angstrom Exponent values agree within uncertainties in all situations.

Sensor Cross-Comparisons Lessons Learned

- Important to identify user applications on how the merged data can meet their requirements better than any-single sensor datasets (interest in "coastal" zones)
- SIMBIOS goal was to create high quality, long-term, multi-sensor ocean color data sets (mesoscale to large scale):
  - Bring all multi-sensor data to a common, consistently calibrated and jointly validated ocean color baseline.
  - Accomplish it through sensor intercomparisons, validations, cross-calibrations, and "intelligent" data merger.
  - Integrate data on the level of chlorophyll, nLw, and radiances at the top-of-the-atmosphere.
- Small erroneous trends in sensor calibration can be misinterpreted as real signal from interannual oscillation.

SIMBIOS Lessons Learned and Addition of INSITU-OCR (International Network for Sensor InTer-comparison and Uncertainty assessment for Ocean Color Radiometry) to CEOS OCR-VC

Sensor Intercomparison & Merger for Biological & Interdisciplinary Ocean Studies

- Ensure development of internally consistent research products and time series from multiple satellite ocean color data sources
- Develop methodologies for cross-calibration of satellite ocean color sensors
- Develop methodologies for merging data from multiple ocean color missions
- Promote cooperation between ocean color projects

- Research Announcements could be drafted and released together
- Agencies could target specific scientific problems of interest, supporting what is most relevant
- Centralized database like SeaBASS, QA/QC and data submission requirements (e.g., 3 months for data submission), protocol development, exchange of personnel possible, connectivity to Round Robins

Field Summary

- **Field support**
  - Satellite overflight & coverage info, real-time data
  - **Over 390 field** experiments supported
- **International field experiments**
  - INDOEX (1999)
  - ACE-Asia (2001)
  - R/V Akademik Ioffe (Atlantic Ocean and Antarctica, 2001-2002)
  - R/V Urania (Mediterranean Sea, 2002)
  - R/V Revelle (California Current, March 2003)- GLI calibration cruise
- **Bio-optical data archival & distribution**
  - SeaBASS (reconfiguration of SeaBASS database system 1999-2000)
  - NODC (data at the end of each SIMBIOS Team contract)
- **Sunphotometer deployment, calibration, maintenance, data processing**
  - 14 Coastal Cimel stations (stations given to AERONET in 2003)
  - Instrument pool: PREDE MKII, SIMBAD, SIMBADA, MicroTops and MPL

Field Summary (continued)

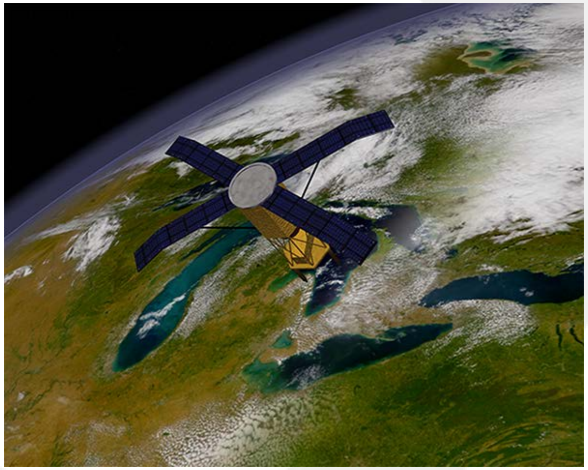
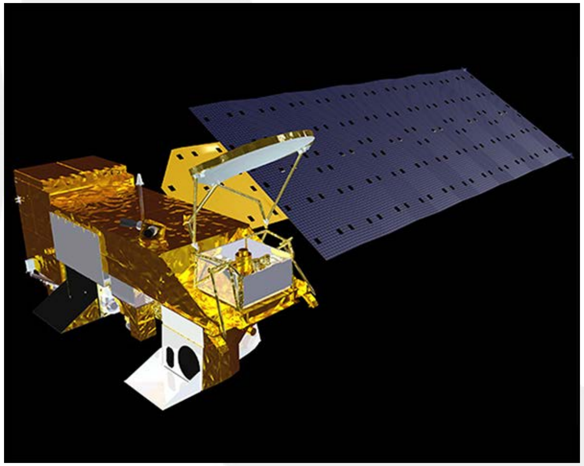
- **Radiometric round-robin**
  - 1997: NASA/GSFC, PML (UK), JRC (Italy), SDSU, Biospherical Instruments Inc., UCSB, NRL, DLR (Germany), NASA/WFF, Satlantic Inc. (Canada)
  - 2001: GSFC, Satlantic Inc., Biospherical Instruments Inc., HOBI Labs, UCSB, NRL, SIO
  - 2002: GSFC, Satlantic Inc., Biospherical Instruments Inc., UCSB, NRL, SIO, MOBY,USF, RSMAS, Wallops & Stennis
- **Chlorophyll round-robin**
  - 2000: ONR, UMD, SIO, SDSU, Bigelow, USF, NOAA & NASA/SSC
  - 2001: SDSU, UMD, CNR (Italy), LODYC (France) and BBRS
- **Technology development**
  - The SeaWiFS Transfer Radiometer (SXR-II) with NIST
  - SQM: Satlantic & Yankee Environmental Instruments; SIMBAD/SIMBADA (UCSD)
- **Protocol development & updates with science community (REVISIT)**
  - Mueller & Austin 1995, Volume 25 in the SeaWiFS Technical Report Series.
  - Fargion & Mueller 2000, Revision 2, NASA TM 2000-209966
  - Fargion et al., 2001, AOT Protocols, NASA TM 2001-209982
  - Mueller et al. 2002, Revision 3, NASA TM 2002-21004 (Vols 1 & 2)
  - Mueller et al. 2003, Revision 4, NASA TM 2003-211621 (Vols 1, 2, 3, 4 & 5)

SeaBASS validation support

In addition to providing public distribution of datasets, SeaBASS supports:

- satellite data product validation
- satellite algorithm development & the NOMAD data set
- satellite instrument calibration
- time series analysis

Sensor	Reprocessing Version
VIIRS-SNPP	R2018.0
MODIS-Aqua	R2018.0
MODIS-Terra	R2018.0
SeaWiFS	R2018.0
MERIS	R2012.1
OCTS	R2014.0
CZCS	R2014.0


NASA provided images

Validation details, in situ Rrs data processing

https://seabass.gsfc.nasa.gov/wiki/validation_description

A guiding philosophy for the validation system is to select the best available comparison between each satellite observation and a corresponding ground truth measurement per time and location

To accomplish this principle, the validation dataset is built by reducing measurements made at a given station to one representative sample (Werdell & Bailey, 2005)

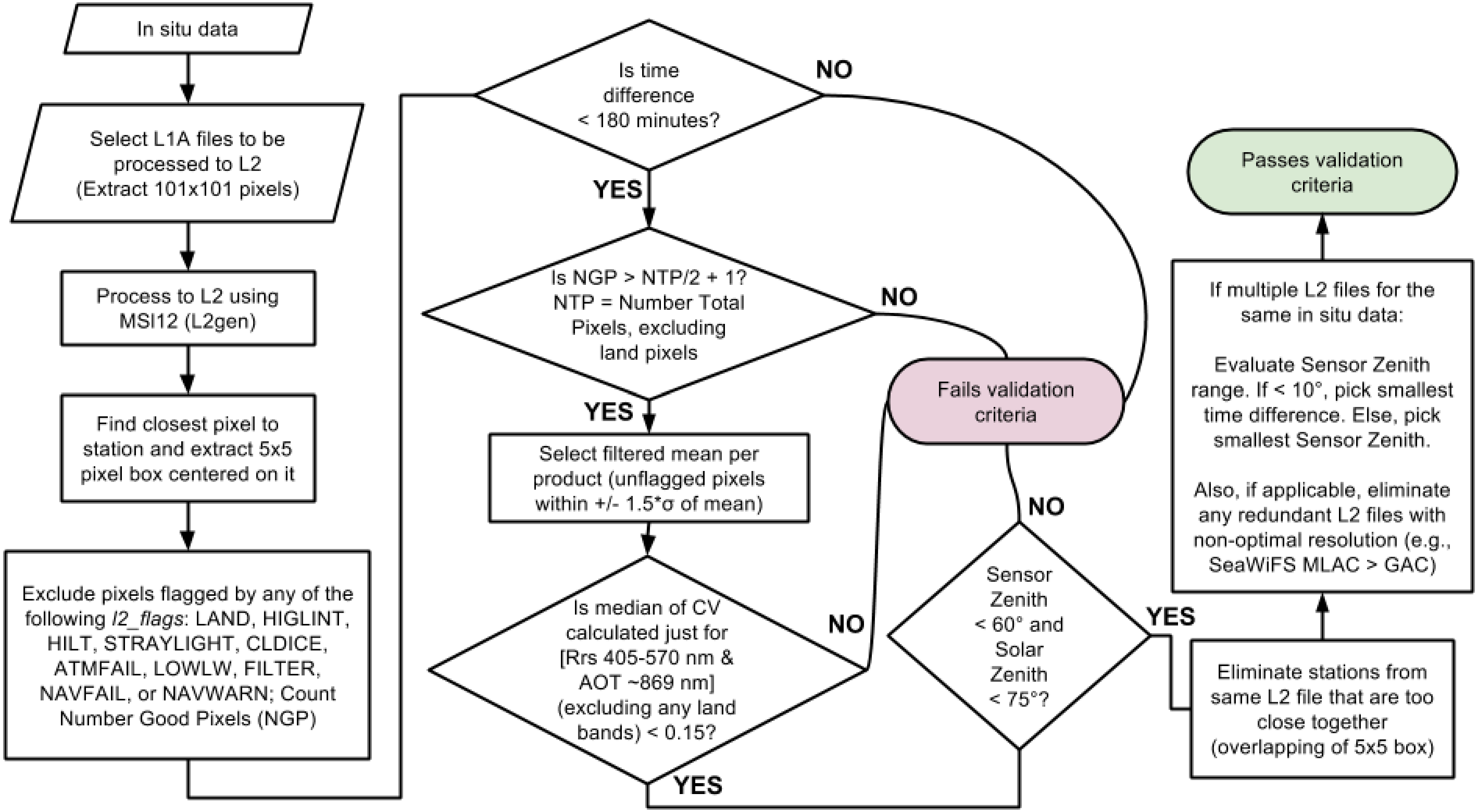
This reduction follows the calculation of water leaving values (e.g., from profiles of radiometric measurements). A single spectrum is selected (if there were repeated measurements)

To simplify the use of wavelength-specific in situ measurements:

- Multispectral measurements: within ±3 nm of a nearby satellite band center are generalized and reassigned to the satellite wavelength (i.e., without transforming the data)
- Hyperspectral measurements: 11 nm bandpass imposed, based on satellite bandcenters

BRDF: The bidirectional reflectance distribution function (BRDF) is calculated for in situ Rrs validation measurements to obtain the "exact" normalization as described by Morel and Gentili (1991, 1993, 1996) with alterations described by Gordon (2005). This BRDF correction is applied for consistency with the satellite product, using the same look-up tables and approach as the satellite processing code (Bailey and Werdell, 2006)

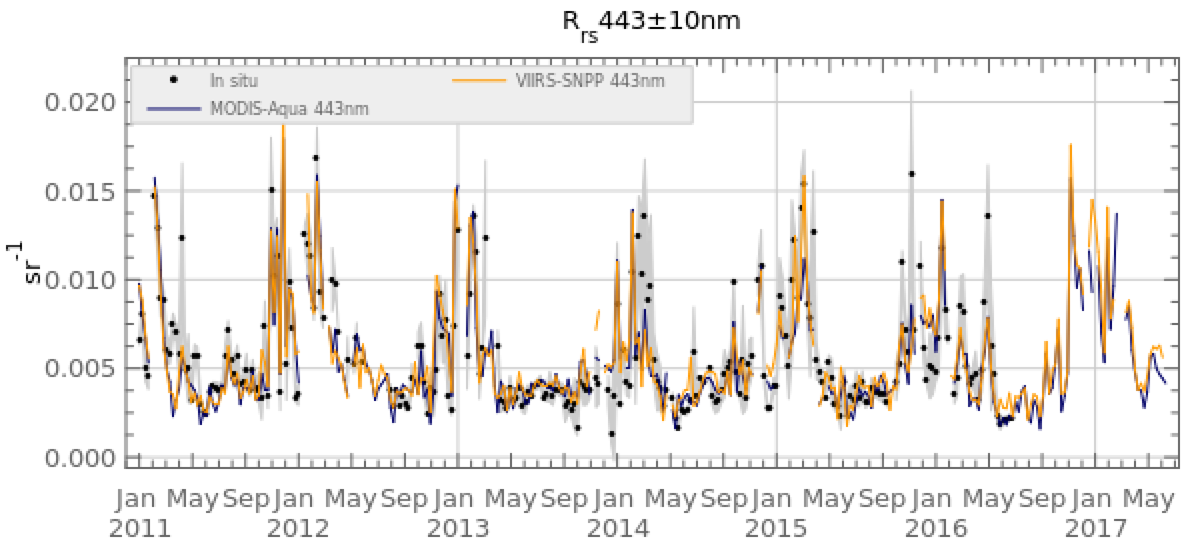
Level-2 match-ups
General processing / exclusion criteria

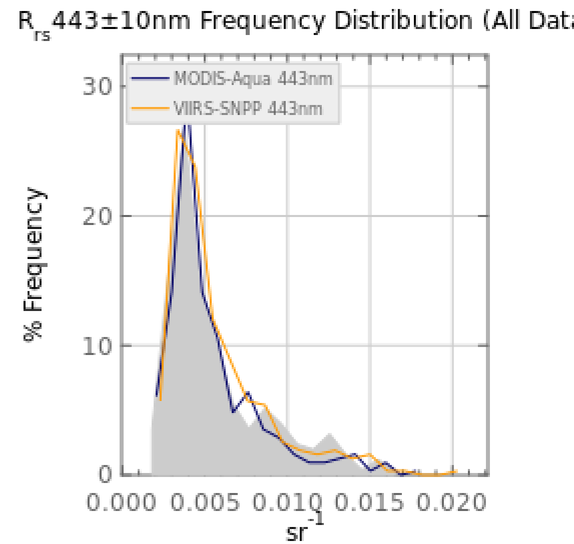


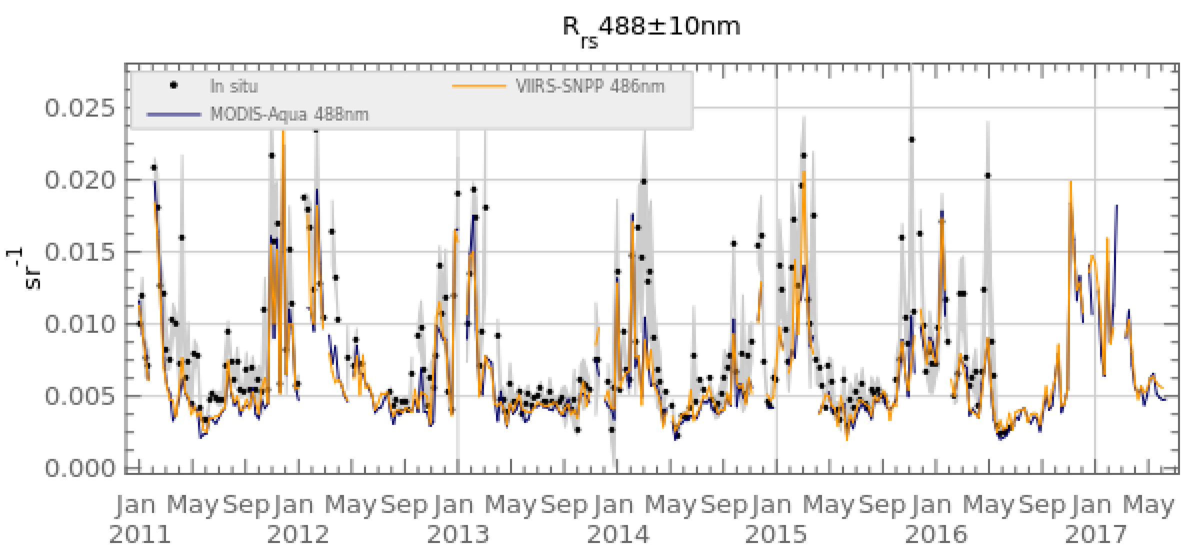
S.W. Bailey and P.J. Werdell, "A multi-sensor approach for the on-orbit validation of ocean color satellite data products," Rem. Sens. Environ. 102, 12-23 (2006).

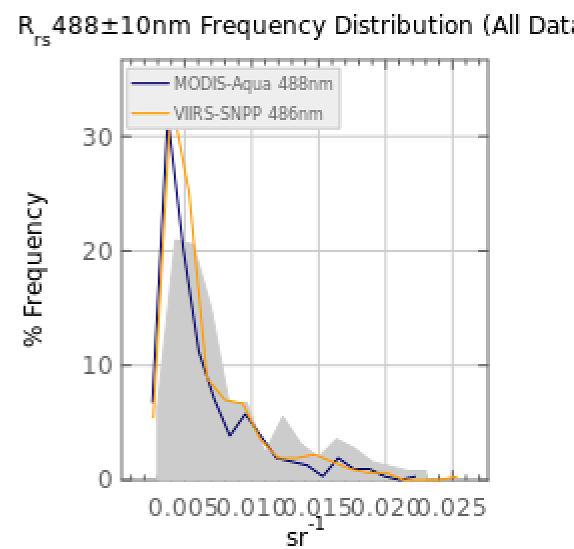
A new Level-2 regional time-series validation tool

time series for multi-sensor & in situ measurements at over 27 sites



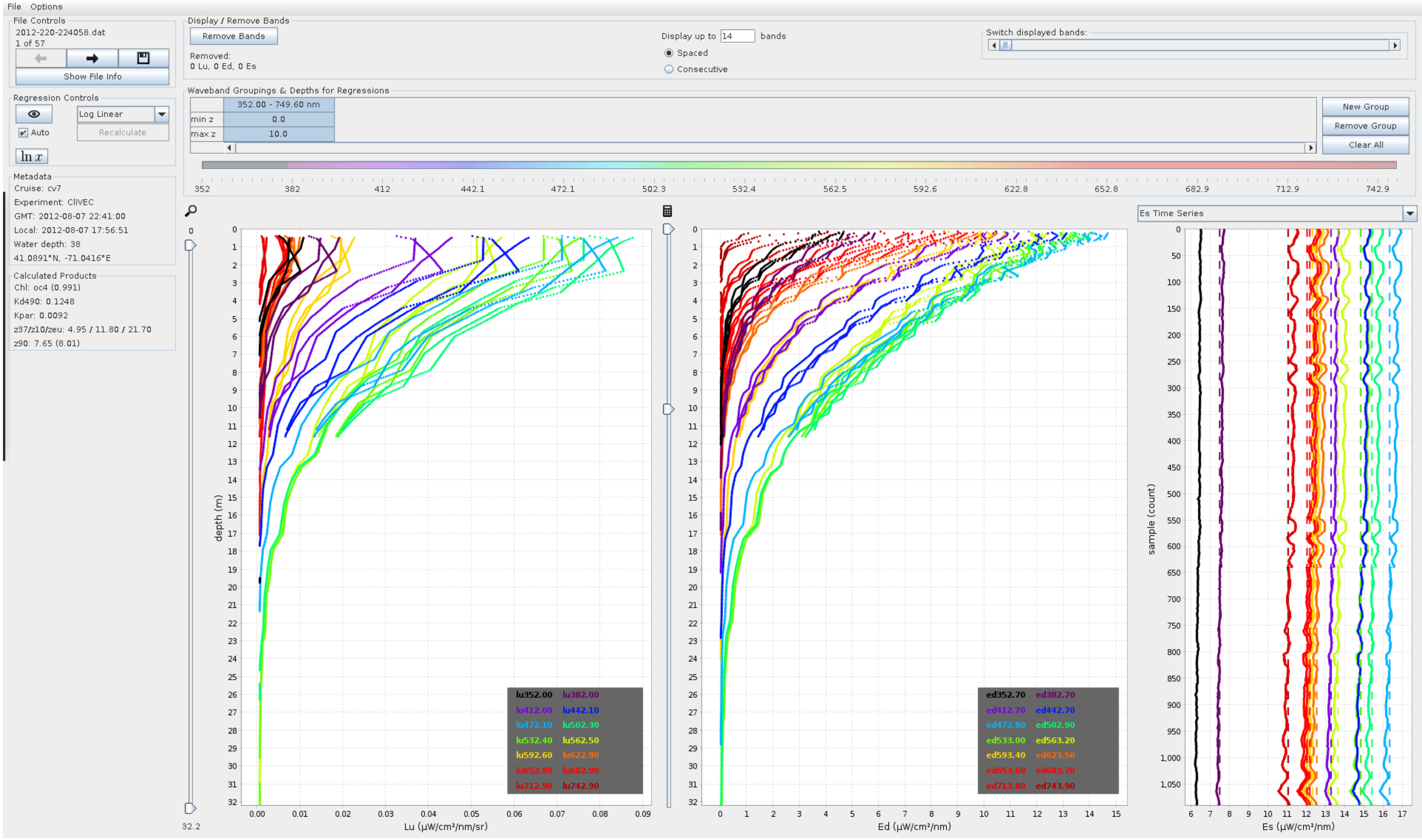






http://seabass.gsfc.nasa.gov

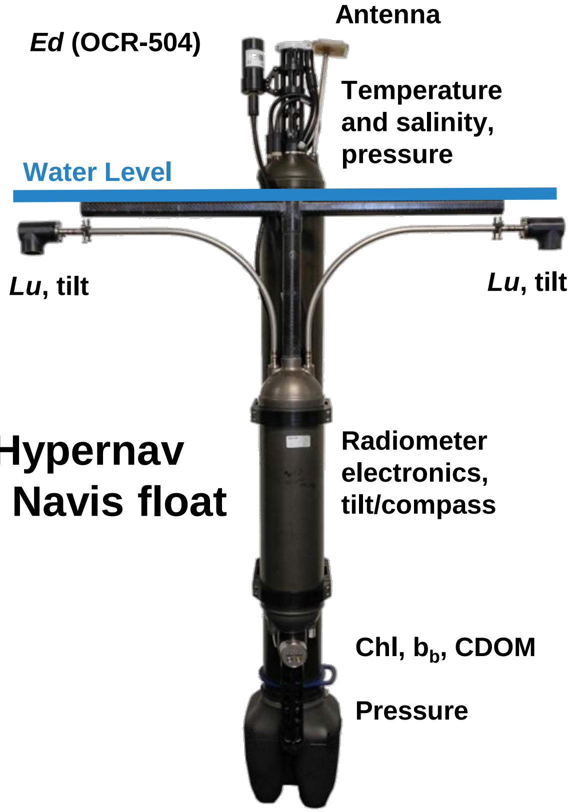
AOP / Radiometry Data Analysis & Processing
Lu(z,λ), Ed(z,λ) → Lw(λ), Ed(0+,λ)



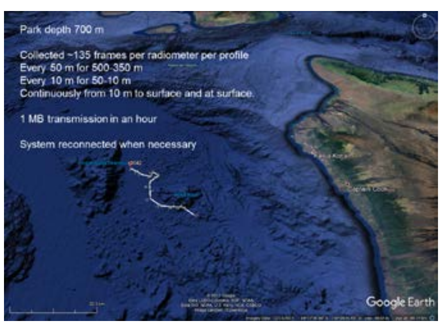
In house SeaBASS "Visual SeaBASS" software

HyperNav: Autonomous hyperspectral radiometer for satellite vicarious calibration

PI: Andrew Barnard

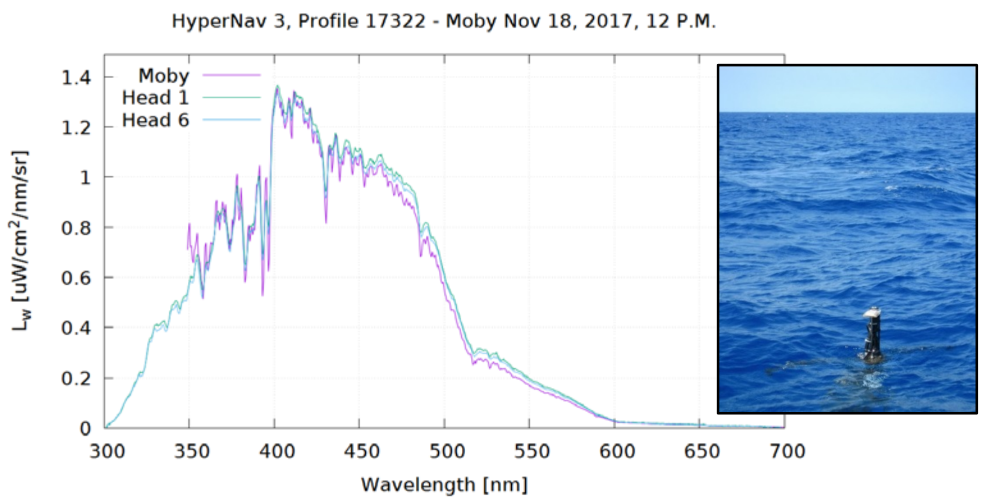


Hypernav on Navis float



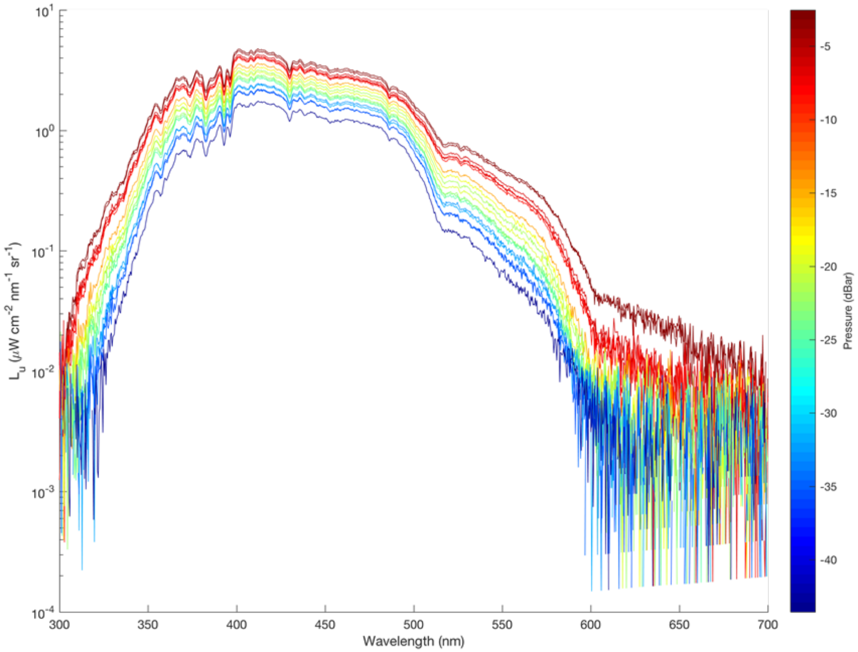
Capability Highlights

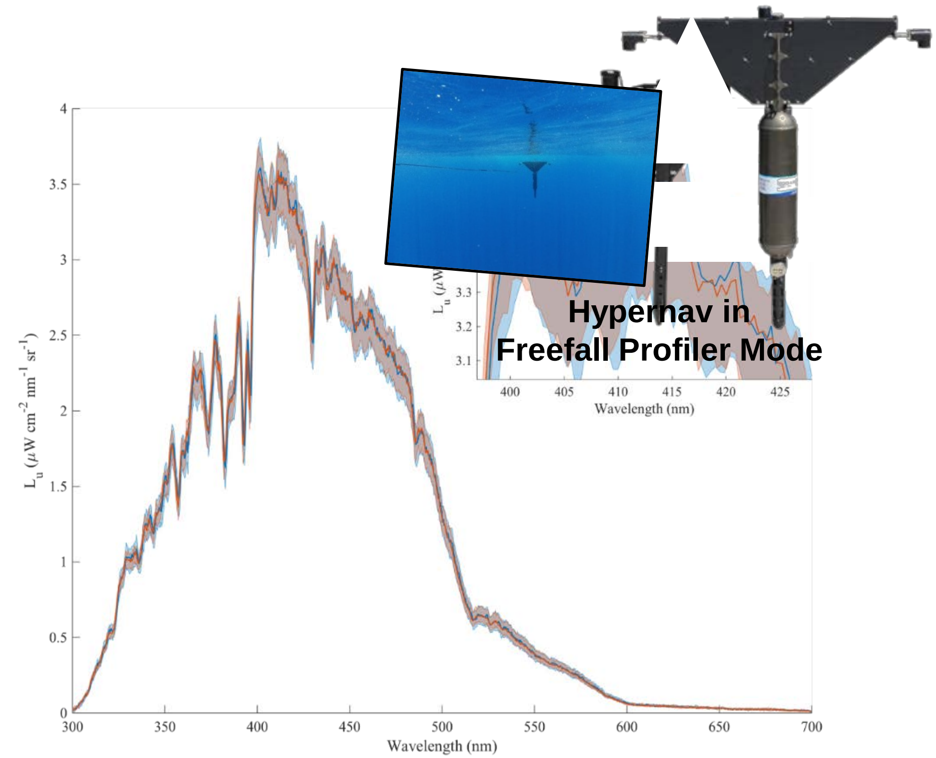
- Dual *Lu* heads, extended arms, <2.5 nm resolution, 350-900 nm.
- Characterized for polarization, thermal, linearity, stray light, self shading (NIST characterizations of linearity & stray light).
- Overall uncertainty < 4% in blue-green, < 6% in red regions
- Radiometer can operate in cabled freefall mode with fins.
- Autonomous operation demonstrated in Hawaii fall 2017.
- Leverages our participation in FRM4SOC efforts (LCE-1 and LCE-2)



SURFACE: $L_w(\lambda)$ spectrum obtained from Hypernav+ Navis system. Comparison with $L_w(\lambda)$ spectrum obtained from MOBY mooring (located ~ 81 nautical miles from deployment site). Hypernav data are uncorrected for stray light.

HyperNav Profile Data





PROFILE: $L_u(\lambda)$ spectrum as function of depth. Deep cast from sensor 2 of HyperNav 1 on August 8, 2017 at 14:06 local. Data with a tilt > 3º is ignored.

SURFACE: $L_u(\lambda)$ spectrum. Median, 5 and 95 percentiles of L_u tilt > 3º is excluded.

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**

The new blue spectrometers have been installed for testing on each deployment of the operation MOBY since August 2016.

This instrument was deployed in August 2016.

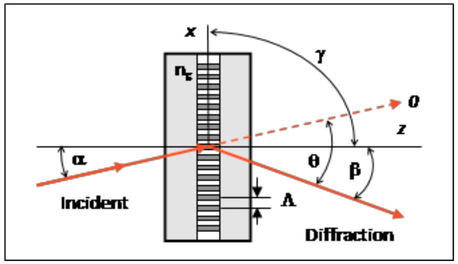
Photo shows new blue spectrometer in place on MOBY.

MOBY spars/hull parts fit in container with room to spare

Inside of 40’ container with two MOBY hulls inside. Main spars are hanging on the side, the arms are on the floor (out of site), towards the back are the two floats, while the instrument cradles have not been assembled, but are towards the back of the container.

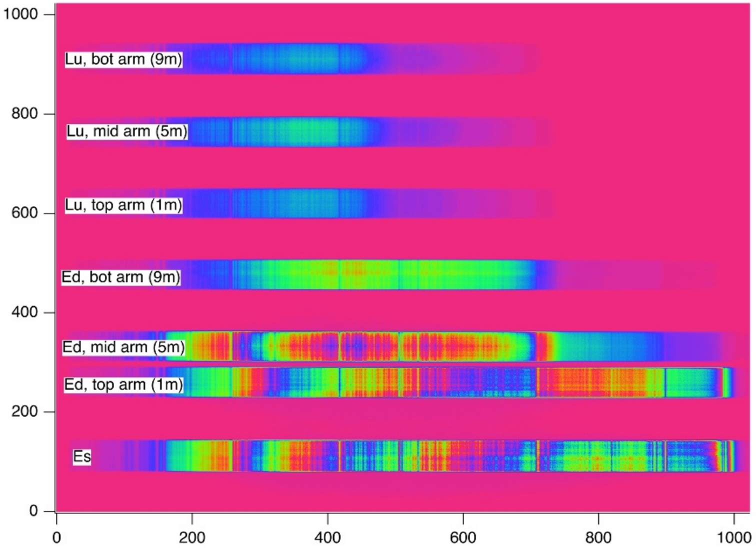
Plenty of room for a mooring buoy and the optical systems.

New 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

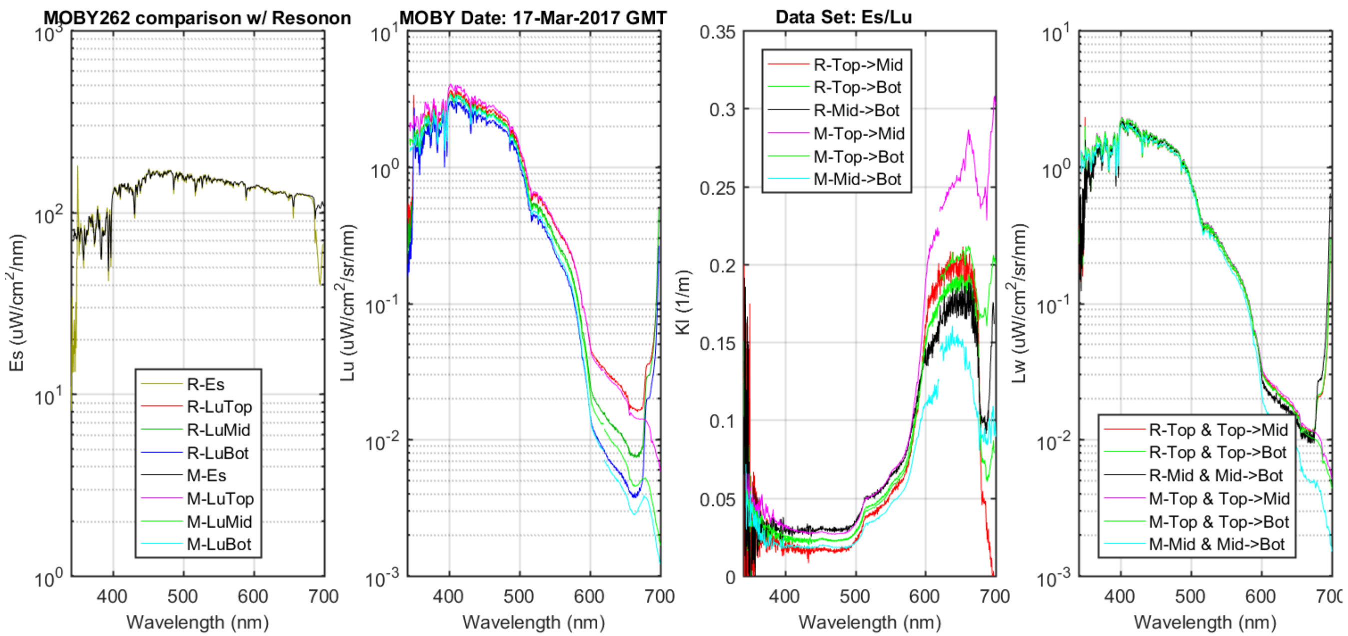


The new blue spectrometers have been installed for testing on each deployment of the operation MOBY since August 2016. The dual spectrometer was installed for the deployment on May 2018

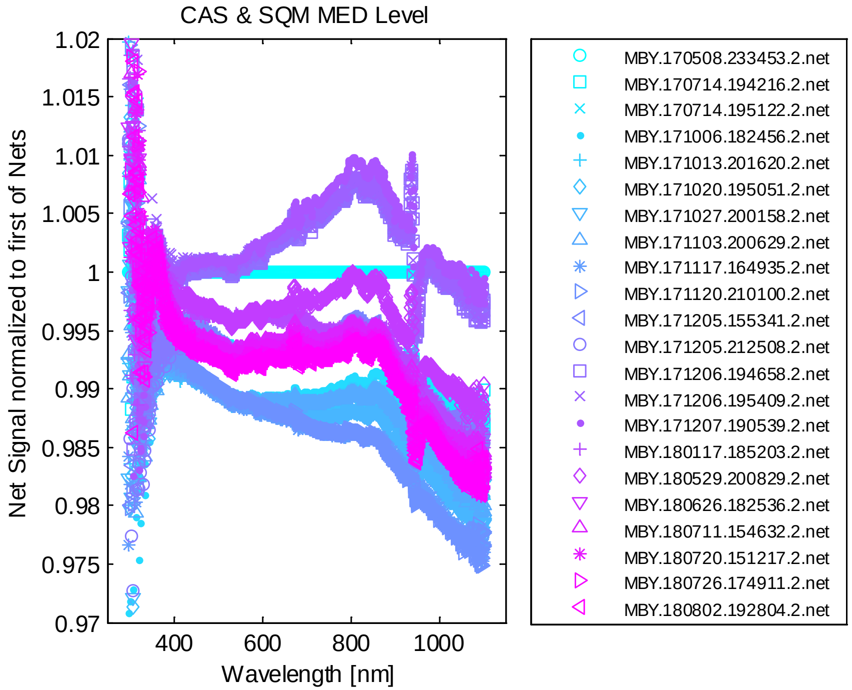
Photo shows new blue spectrometer in place on MOBY.

Red/Blue spec on the side of MOBY.

Comparison with MOBY-Heritage



Very good agreement, at least early in the deployment. Divergences at high and low wavelengths driven by lack of stray light correction and uncorrected (at this point) second order light.



We monitor the output of the Satellite Quality Monitor (SQM, Yankee Engineering) stability source with a CAS140 fiber coupled spectroradiometer (Instrument Systems) using a custom radiance head. The head is mounted kinematically to the SQM, similar to the SeaWiFS Quality Monitor protocol.

The plot shows the CAS output normalized to the initial data for 08-May-2017 and run through 02-Aug-2018. The time series includes two shipping events (Honolulu and Miami from Gaithersburg) and swapping of the radiance head and fiber optic cable with the complementary irradiance hardware.

Ancillary data establish that the variability is from the CAS, not the SQM.

Results from tests to date

Spectral stability has been very good, latest deployment within 0.1 nm over 5 months (verified with Fraunhofer lines).

Simultaneous acquisition of all 3 Lu measurements and Es allows much better determination of KL for propagation of Lu to surface even in unstable conditions.

Our stability source and monitor system are working at the 2% level, we are trying to improve beyond this.

Results from tests to date

Spectral stability has been very good, latest deployment within 0.03 nm over 2 months (verified with Fraunhofer lines).

Simultaneous acquisition of all 3 Lu measurements and Es allows much better determination of KL for propagation of Lu to surface even in unstable conditions.

Our stability source and monitor system are working at the 2% level, we are trying to improve beyond this.

The first dual (red/blue spectrometer system) will be deployed along with the operational system in April.