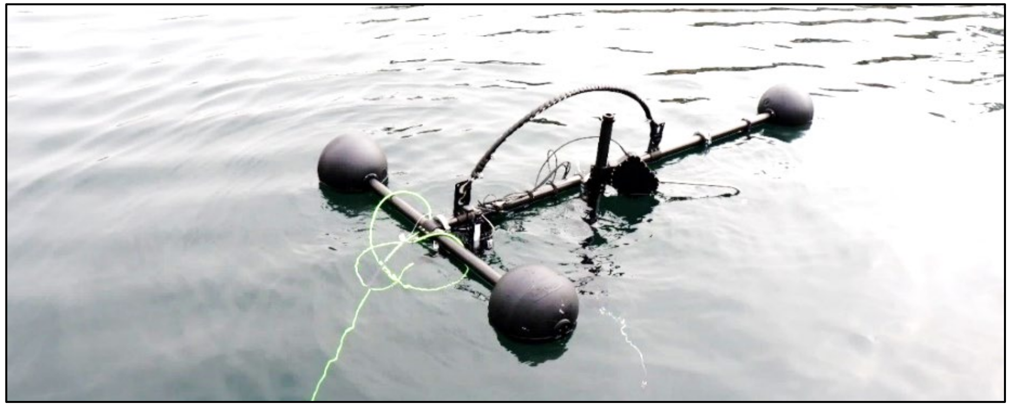
AquaFloat: A near-surface hyperspectral radiometer system for ocean color measurements in the UV-VIS-NIR spectral region



AquaFloat development under NASA SBIR program.

We thank Jeremy Werdell and John Moisan for monitoring the project and Laura Lorenzoni and NASA OBB program for supporting Phase III of the project.

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NOAA Ocean Color Coordinating Group Seminar
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Overarching goal

- A novel radiometric system "AquaFloat" for in-situ determinations of *hyperspectral* ($\Delta\lambda$~1 nm) water-leaving radiance and remote-sensing reflectance over a *broad spectral range* from the UV to NIR (~300 – 1000 nm).

Specific objectives

- Hyperspectral measurements of underwater upwelling radiance, $L_u(z,\lambda)$, *simultaneously at multiple (adjustable) near-surface depths within the top ~1 m layer)* for extrapolation-based determination of water-leaving radiance, $L_w(z=0^+,\lambda)$.
- Simultaneous hyperspectral measurements of above-water downwelling plane irradiance, $E_d(z=0^+,\lambda)$, required for determination of remote-sensing reflectance, $R_{rs}(\lambda)$.
- High measurement accuracy and fidelity; non-moored and non-profiling deployment of the instrument.
- Support for the algorithm development, validation, and applications of ocean color remote sensing including hyperspectral (PACE-OCI) and multispectral (e.g., VIIRS, OLCI) satellite missions.

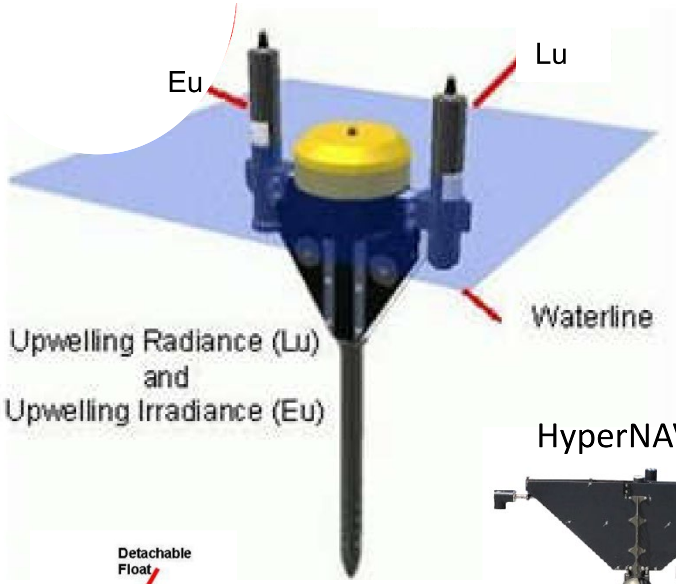
Example in-water radiometric systems

Commercial systems for underwater L_u measurements at a single near-surface depth or non-simultaneous (profiling) measurements at multiple depths

Specialized systems for underwater L_u measurements simultaneously at a few depths.
The shallowest depth ≥ 1 m.

HyperPro system
in profiling mode

HyperPro system
in surface mode

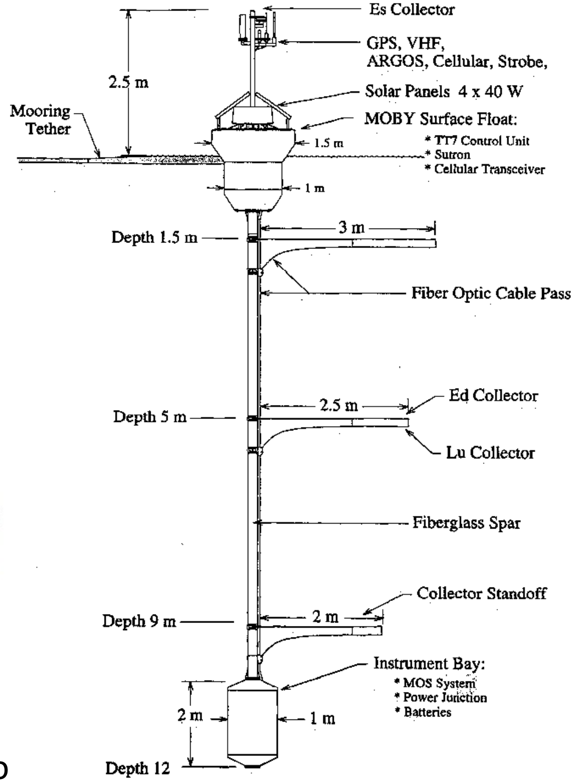


HyperNAV

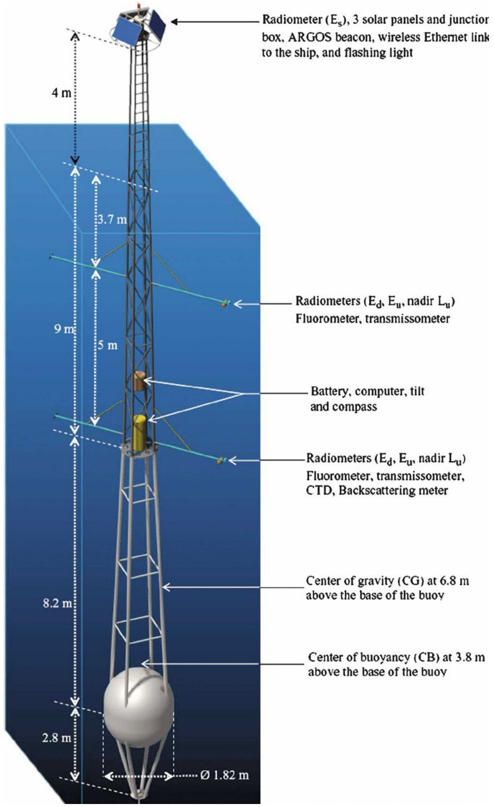
(Sea-Bird Scientific)

HyperPro

Marine Optical Buoy (MOBY)
(Clark et al. 1997)



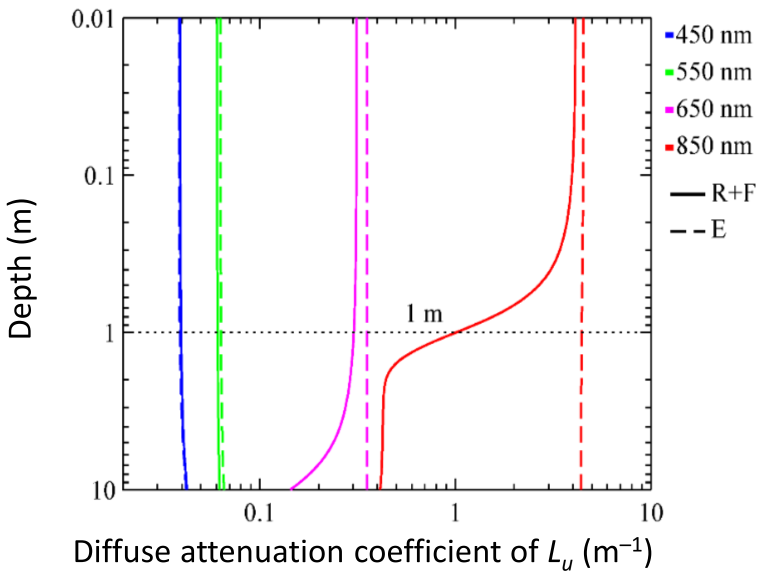
BOUSSOLE Buoy
(Antoine et al. 2008)

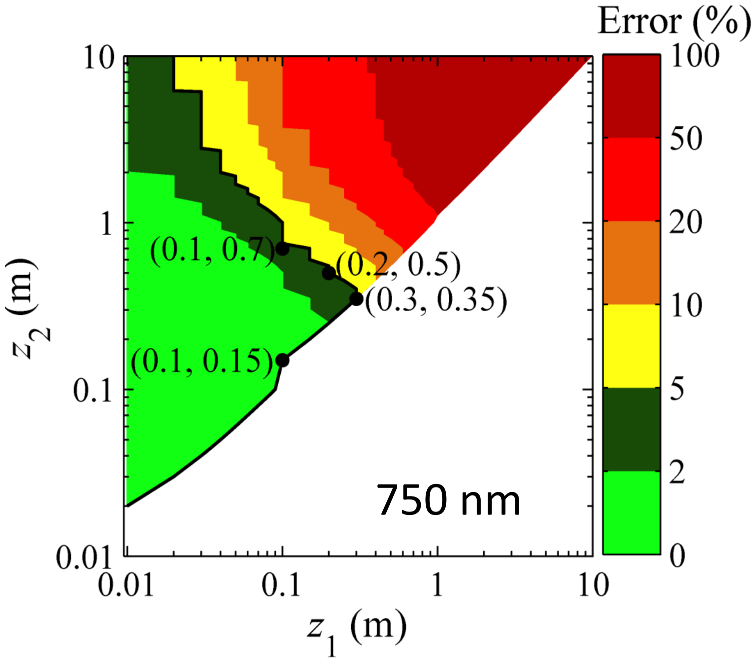


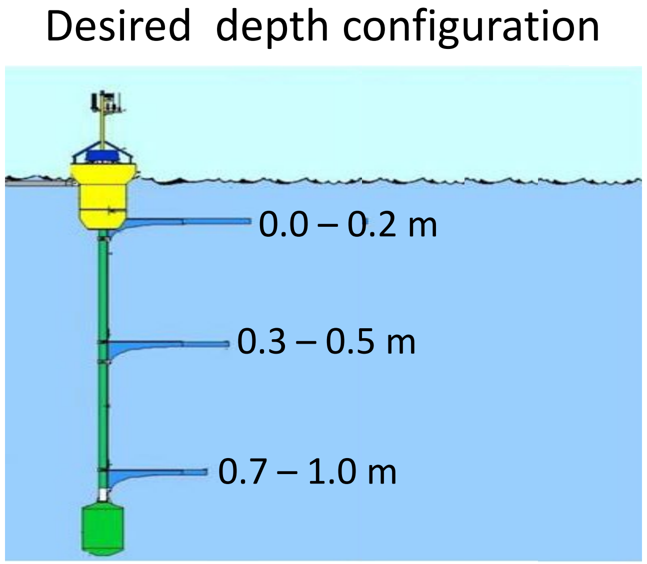
Scientific motivation

Simultaneous multi-depth measurements at near-surface depths are needed even in optically homogeneous water column to address the extrapolation issues caused by inelastic radiative processes, especially the impact of Raman scattering by water molecules in the red and near-infrared spectral regions

- Depth profiles of K_{Lu} at selected wavelengths with (solid lines) and without (dashed lines) inelastic processes indicate significant variations in K_{Lu} at shallow depths within optically uniform water column for spectral regions strongly influenced by Raman scattering. (Left panel: R+F with Raman scattering and CDOM and Chl-a fluorescence; E- elastic scattering only)
- To achieve errors of < 5% for water-leaving radiance (green shaded areas) in the red-NIR regions, measurements of L_u should be made at depths less than 1 m, indicated by the example depth pairs z_1 and z_2 (middle panel)





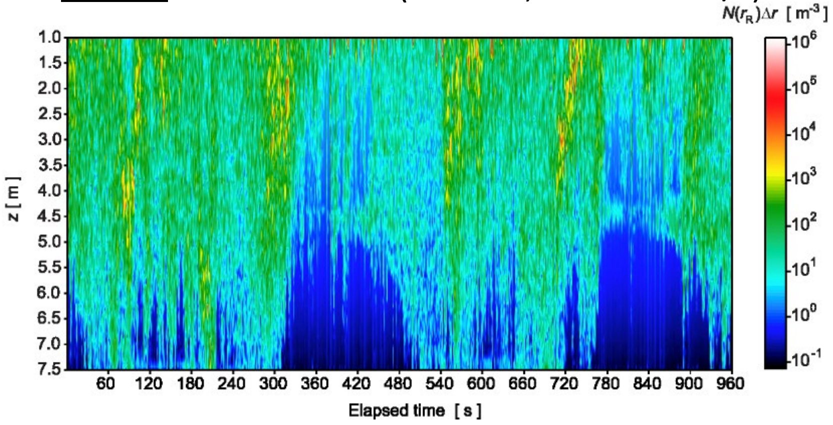


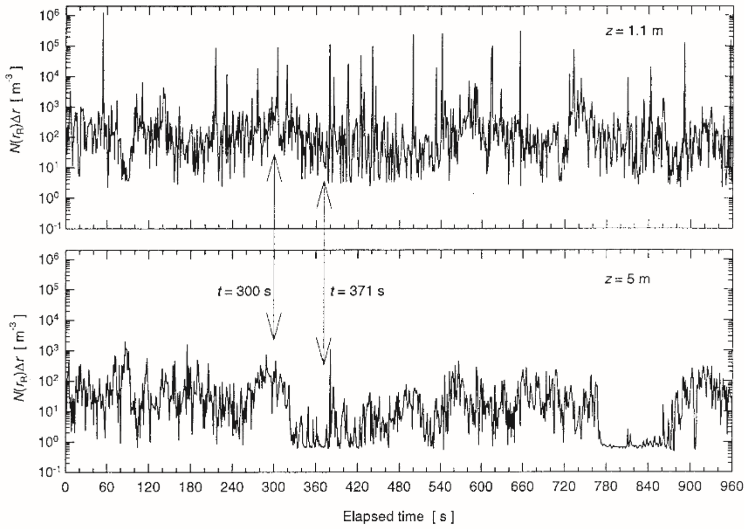
Li, L., D. Stramski, and R. A. Reynolds. (2016). *Appl. Opt.*, 55, 7050-7067.

Scientific motivation

Simultaneous multi-depth measurements at near-surface depths are needed to account for vertical changes and temporal fluctuations in the inherent optical properties of water within the extrapolation surface layer

Vertical changes and temporal fluctuations in ***bubble*** concentration (Atlantic, wind ~10 m/s)

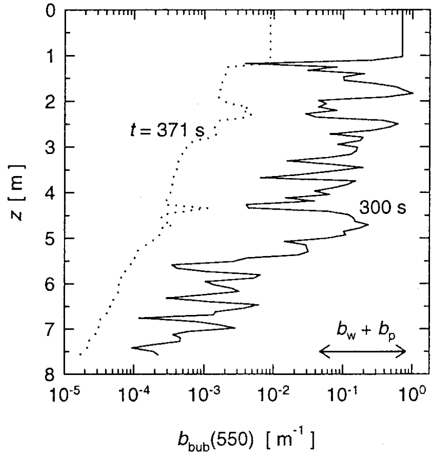




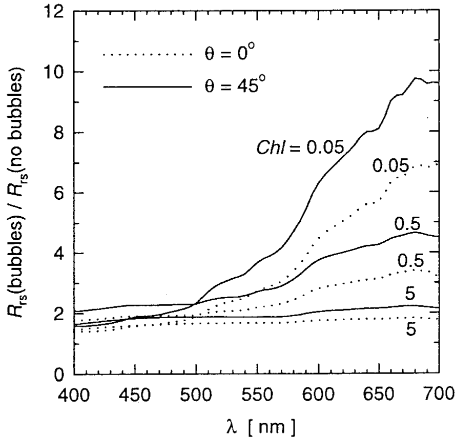
Very large effect on scattering IOPs, radiometric quantities (e.g., L_u), and AOPs (e.g., K_{Lu} and R_{rs})

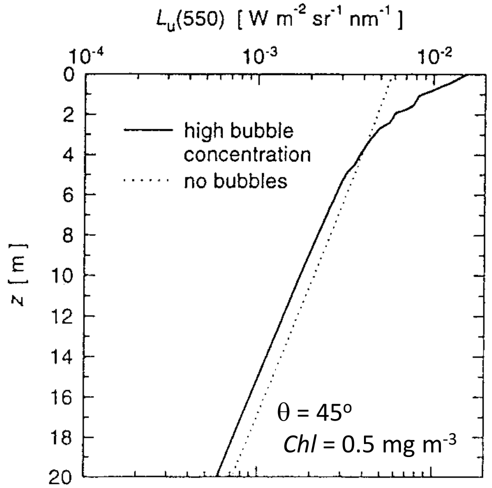
Note:
At t = 300 s the maximum void fraction is 2.2 × 10^{-5} at z = 1.8 m which produces b_{bub} = 1 m^{-1}.
At t = 371 s, the bubble concentration is lower by 3-4 orders of magnitude.

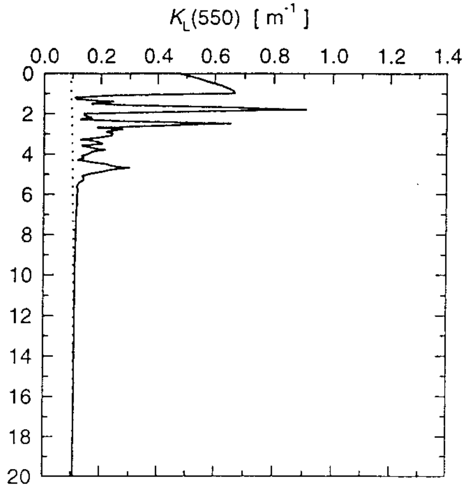
Scattering
~1 to >2 orders of magnitude



Remote-sensing reflectance
~1.5-10-fold effect





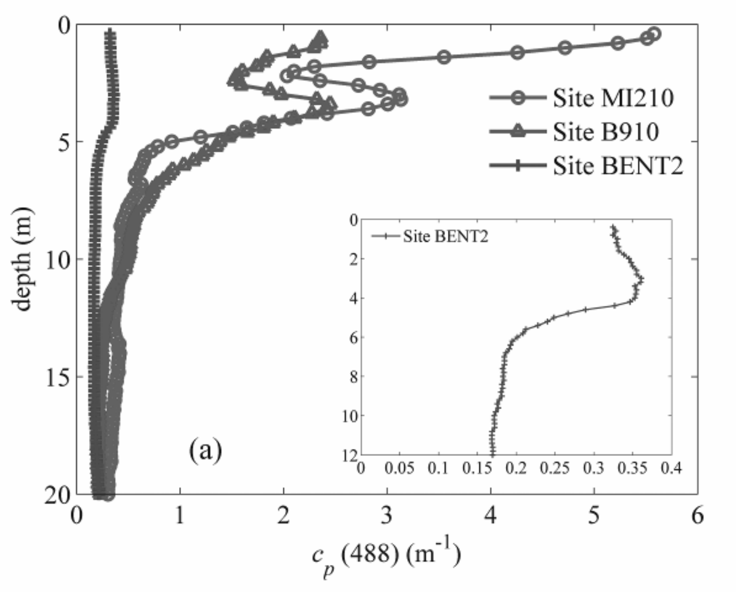


Stramski, D. and J. Tęgowski. (2001). *J. Geophys. Res.*, 106, 31345-31360.

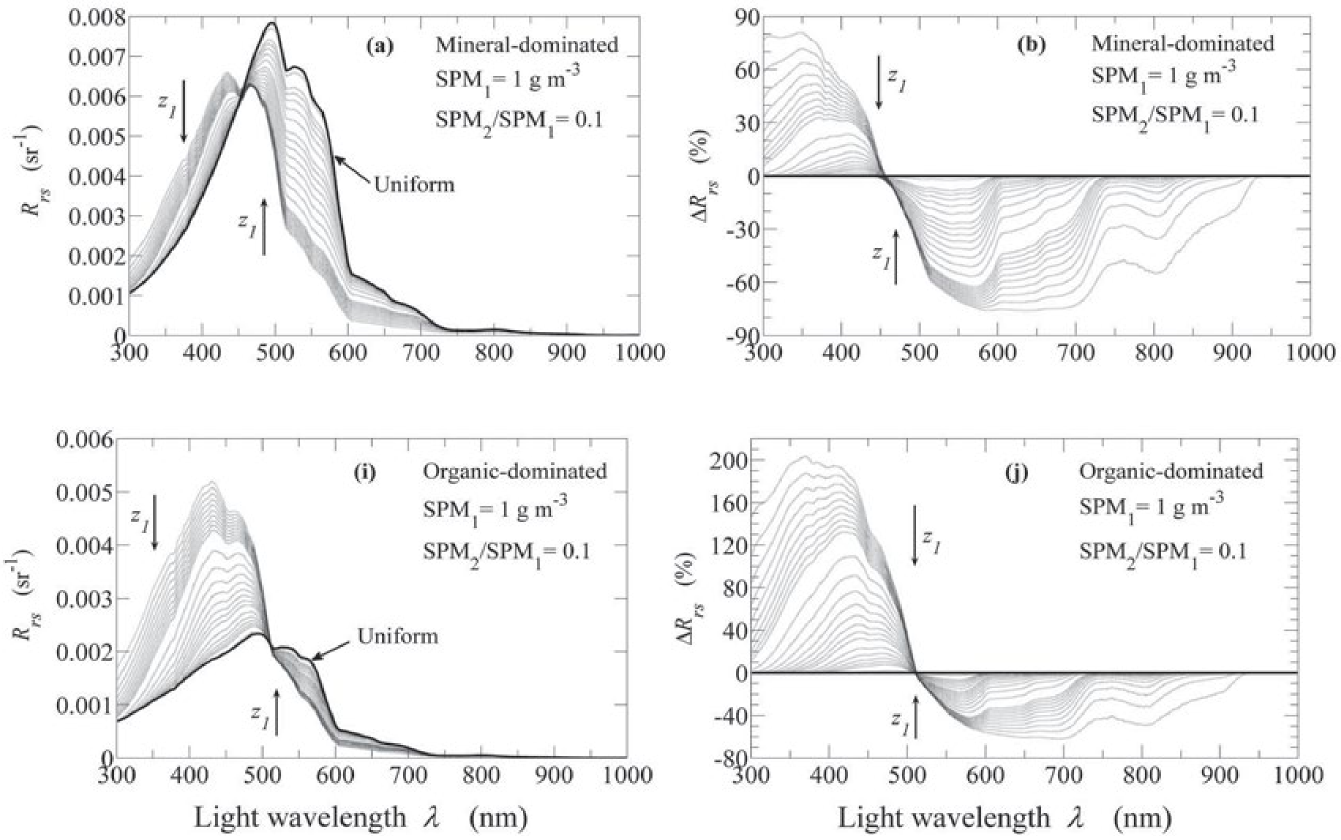
Scientific motivation

Simultaneous multi-depth measurements at near-surface depths are needed to account for vertical changes in the inherent optical properties of water within the extrapolation surface layer

Near-surface vertical changes
in particulate beam attenuation
(Kongsfjord, Spitsbergen)



Near-surface changes in particulate concentration and IOPs have strong effect on reflectance, which depends on the vertical extent of near-surface turbid layer and contrast with an underlying layer

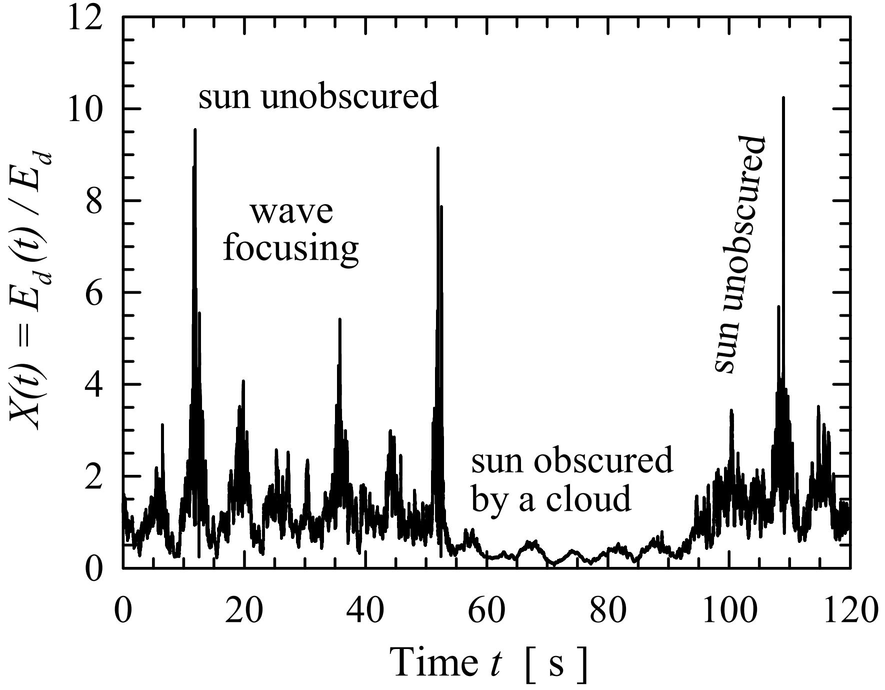


Yang, Q., D. Stramski, and M-X. He. 2013. *Appl. Opt.*, 52, 359-374.

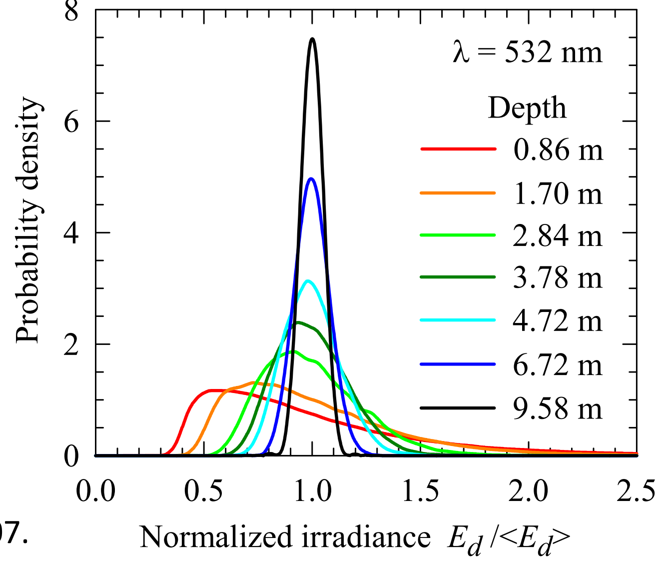
Scientific motivation

Simultaneous multi-depth measurements at near-surface depths are needed to address short-term temporal fluctuations in near-surface light field

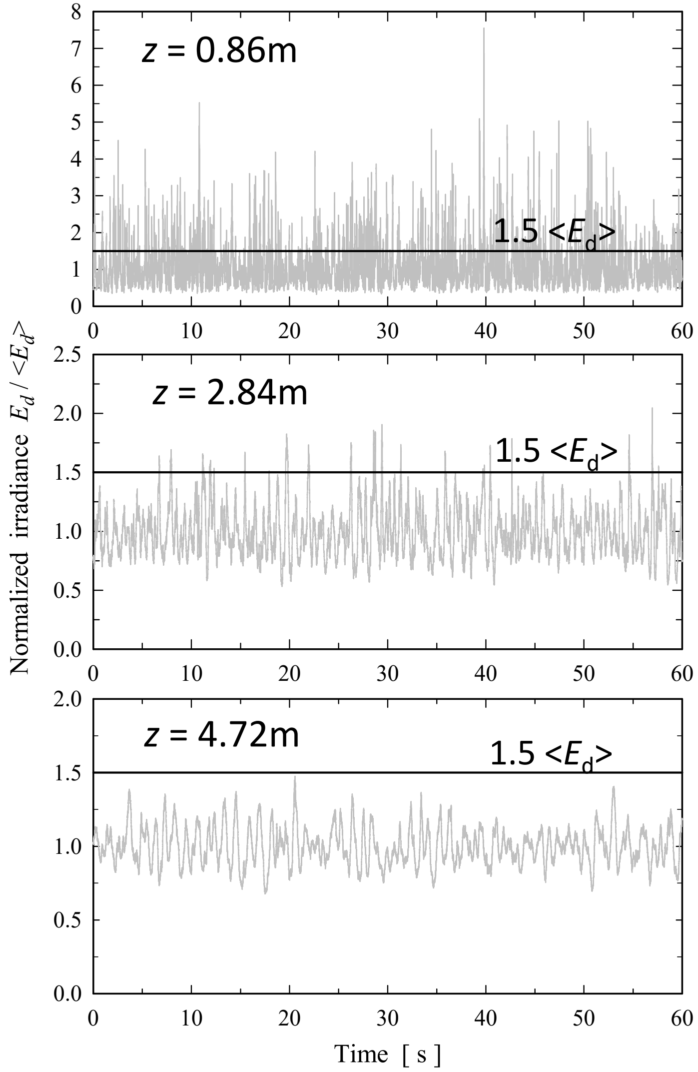
Cloud and wave-induced fluctuations in near-surface light field (south of Hawaii Islands, z = 1.7 m). Temporal scales from milliseconds to minutes.



Non-Gaussian distribution of near-surface $E_d(t)$

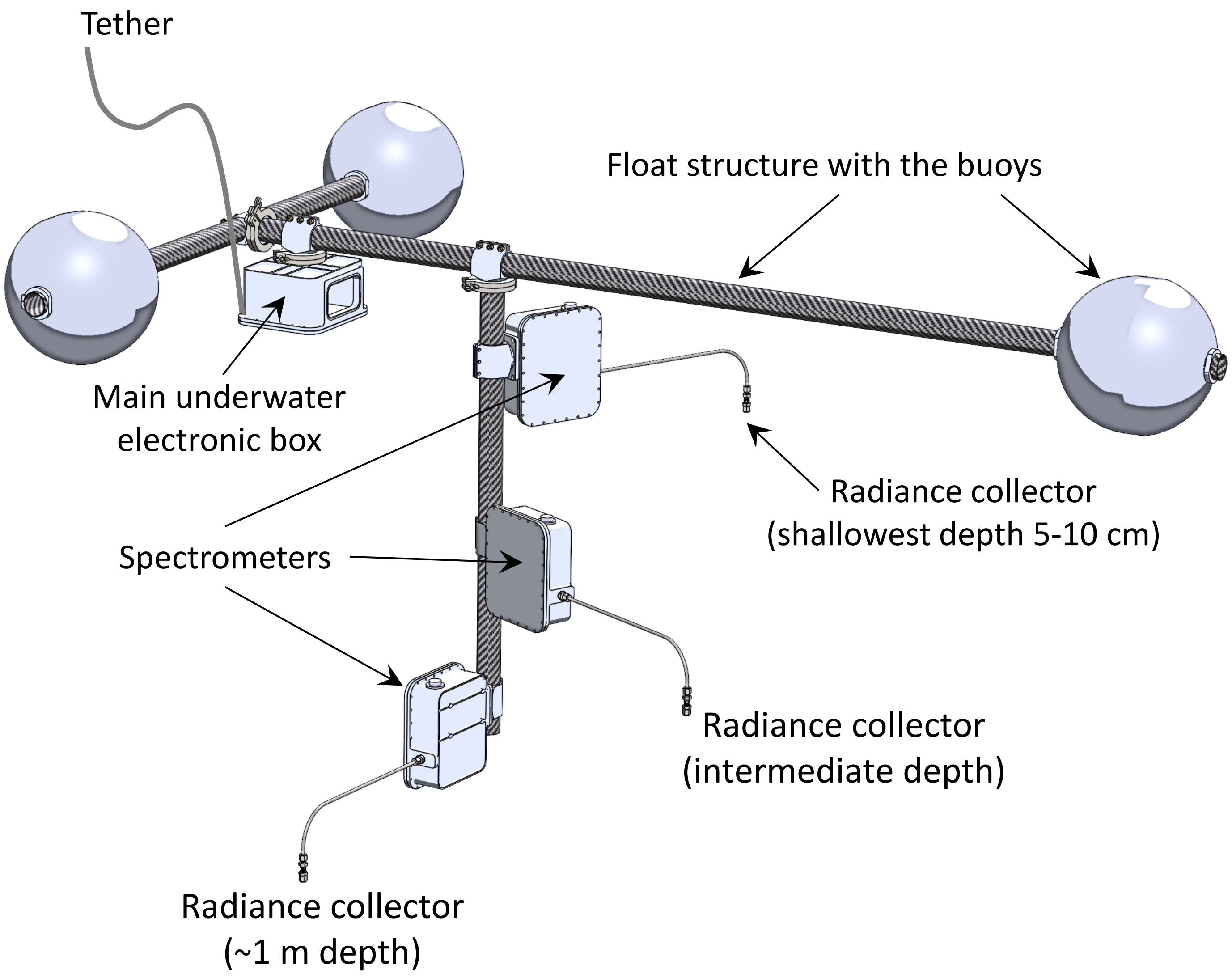


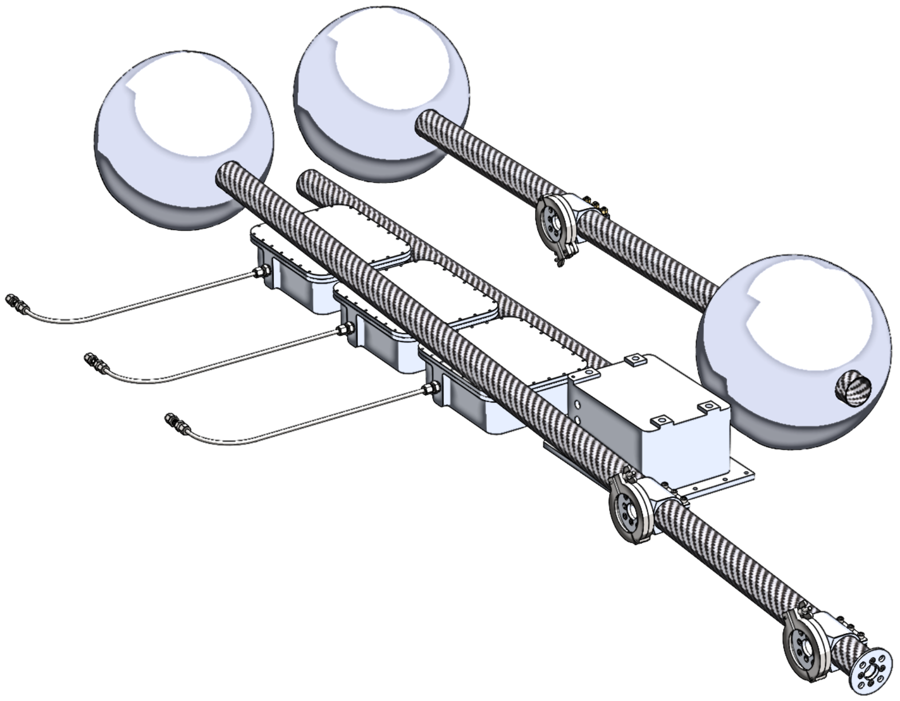
Clear skies, Santa Barbara Channel



Gernez, P., D. Stramski, and M. Darecki. 2011. *J. Geophys. Res.*, 116, C00H07.
Darecki, M., D. Stramski, and M. Sokólski. 2011. *J. Geophys. Res.*, 116, C00H09.

General schematic of AquaFloat





Key specifications

FLOAT	
OPTICAL	
Upwelling Radiance Sensors	3
Upwelling Sensor Depths	Adjustable; min: 5 cm; max: 100 cm; typical: 5, 50, 100 cm
Depolarizers in Upwelling Sensors	Yes
Immersion Factor Correction	Yes
Field of View (full angle)	3.9° (in water)
Auxiliary Sensors	Inclinometers, Magnetometer, Depth Sensor, Out of Water Switch, GPS
MECHANICAL	
Float Frame Material	Carbon Fiber
Float Size, Assembled	272 cm × 163 cm × 158 cm
Float Weight, Assembled	28 kg (62 lb.)
Weight of Single Spectrometer	3.2 kg (7 lb.)
Communication Box Size	49 cm × 35 cm × 18 cm
Communication Box Weight	6.4 kg (14 lb.)
Tether Cable Length	42 m
Rope Attachment Points	3
ELECTRICAL	
Power	120 VAC, 60 Hz
Communications	Ethernet

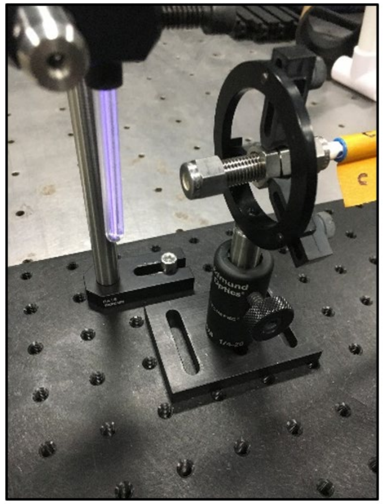
SOFTWARE	
AquaFloat Control GUI	Control of the sensors and real time data display for all sensors
Data Format	Data is saved as binary format
Data Extraction Software	Exports data from binary into CSV format

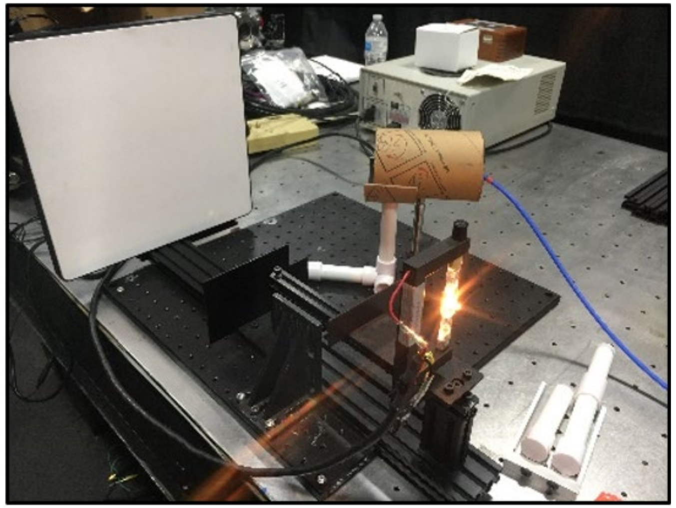
SPECTROMETERS	
Spectral Range	~ 300 - 1100 nm
Spectral Resolution, Optical	~ 1 nm
Spectral Resolution, Sampling	~ 0.7 nm
Number of Pixels	1024
D/A	18-bit
Max DN	200,000
Shutter in each Spectrometer	Yes
Temperature Stabilization	TEC
Spectrometer Set Temperature	0°C typical
Integration Time Range	8 msec - 60 min
Radiometric Calibration	Yes

DOWNWELLING SENSOR	
OPTICAL	
Downwelling Irradiance Sensors	1
Collection Optics	Cosine Collector
Auxiliary Sensors	GPS, IMU
MECHANICAL	
Sensor Size	79 cm × 26 cm × 13 cm
Sensor Weight	3.6 kg (8 lb.)
Power Supply Dimensions	20 cm × 18 cm × 13 cm
Power Supply Weight	6.1 kg (13.5 lb.)
ELECTRICAL	
Power	120 VAC, 60 Hz
Communications	3 × USB2

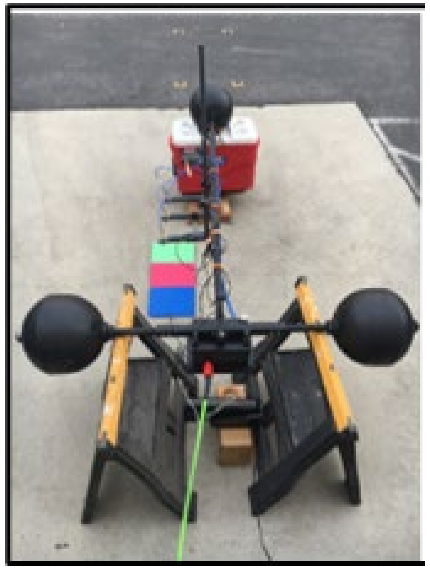
Laboratory characterization

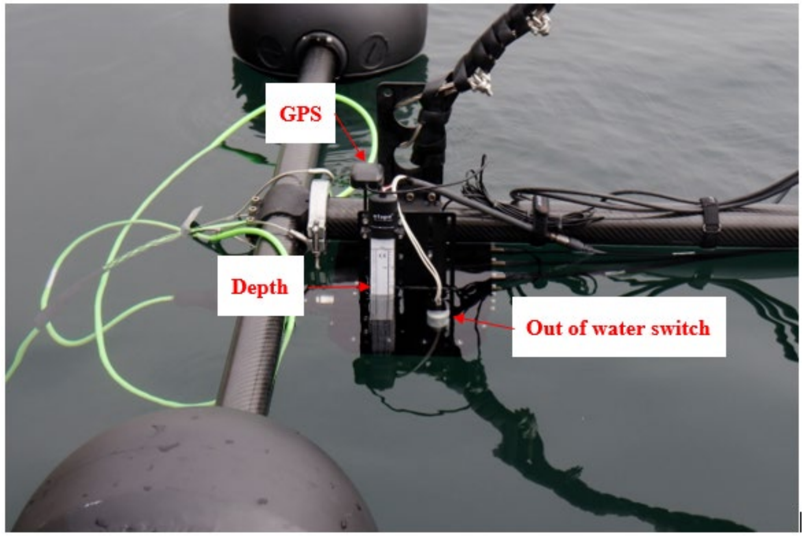
- ❑ Spectral
- ❑ Radiometric
- ❑ Straylight
- ❑ Noise
- ❑ Polarization sensitivity



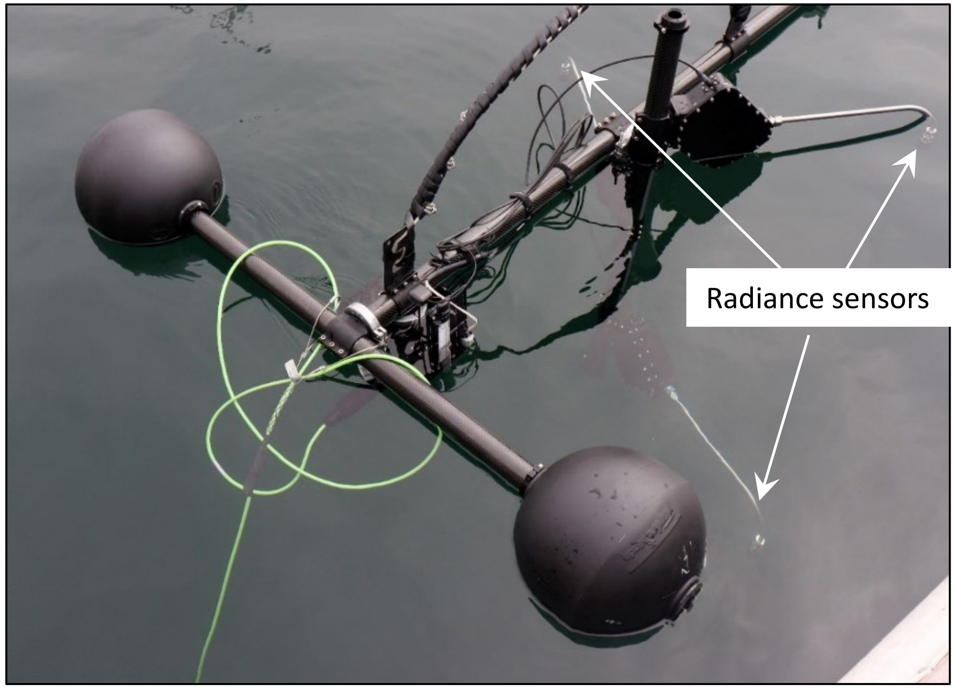


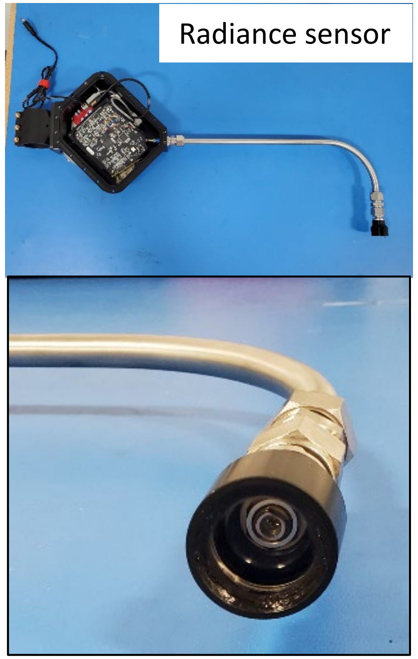
Outdoor testing





Underwater electronics
Ancillary sensors

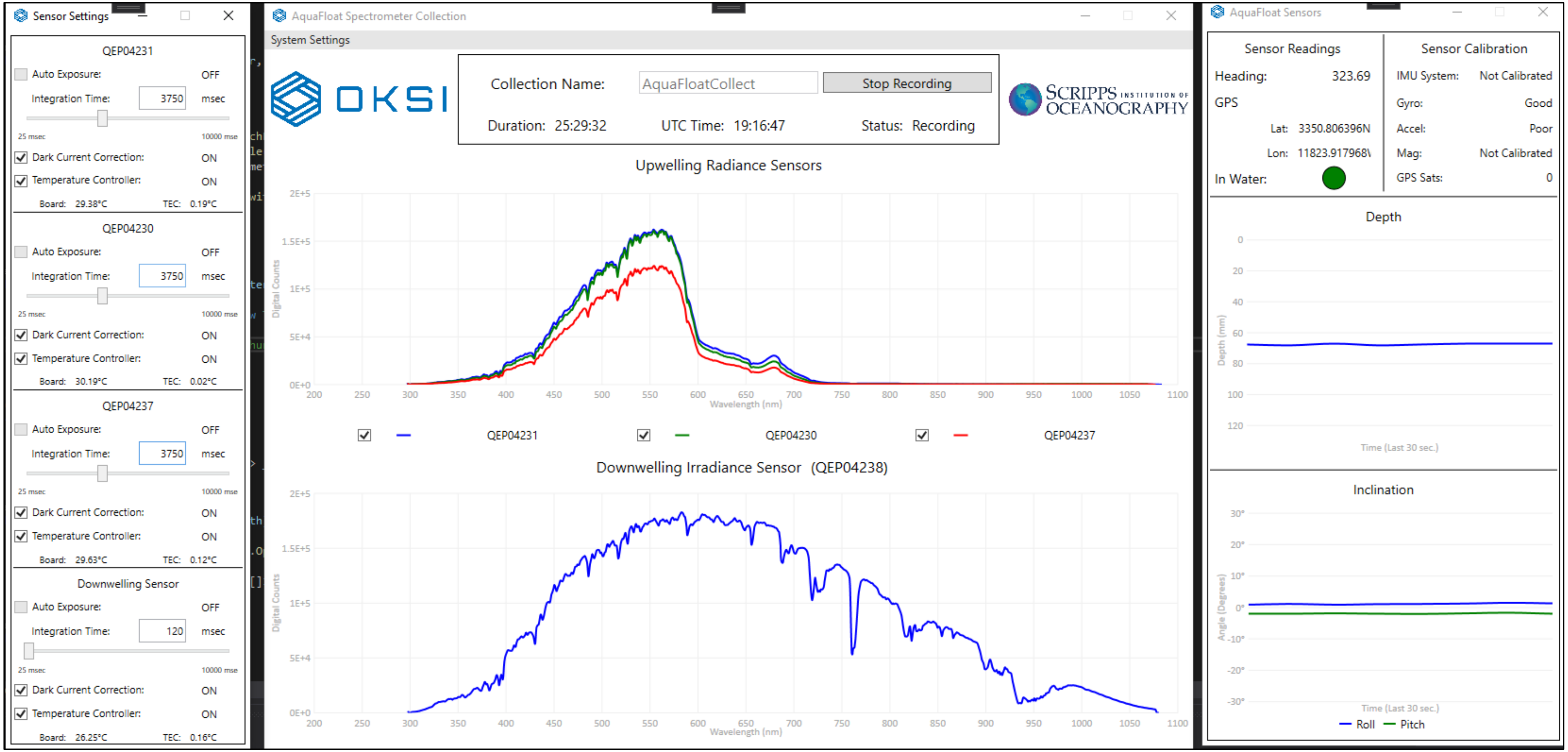




Power & communication unit

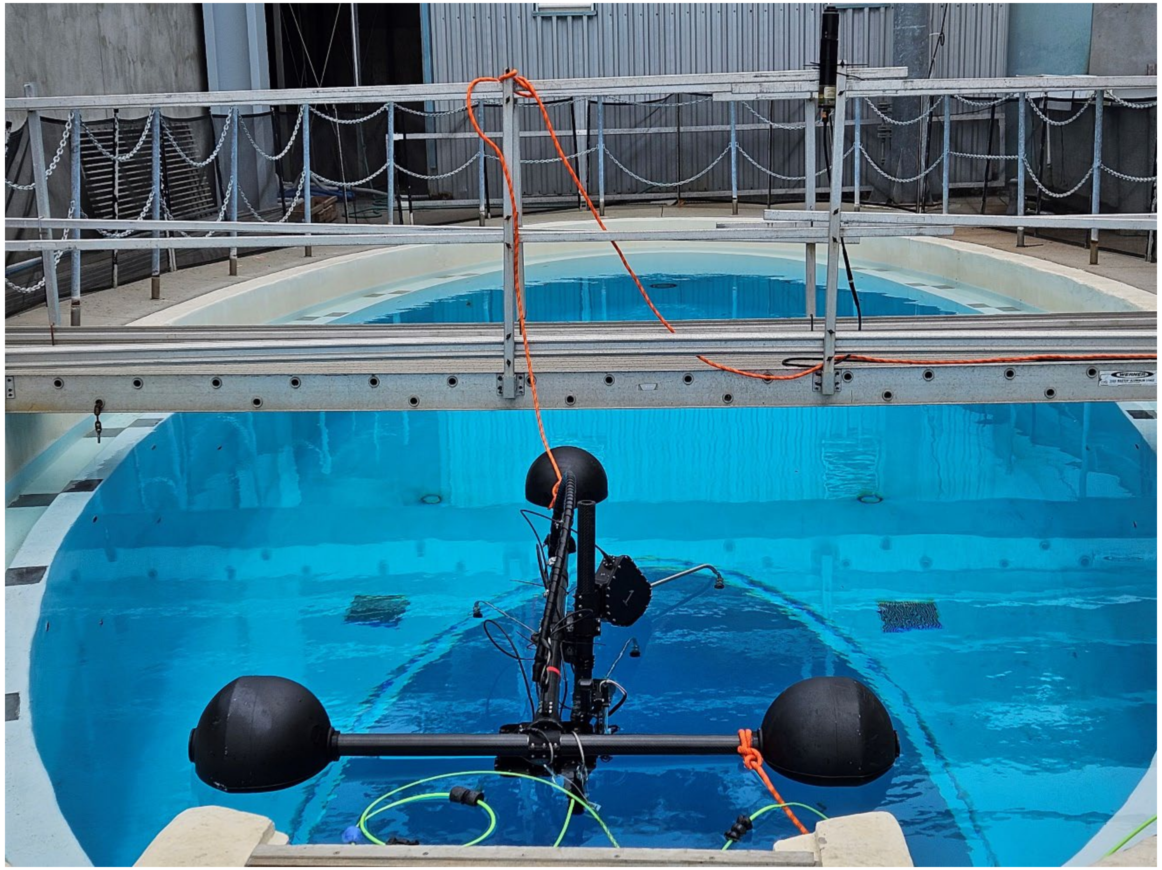
Above-water downwelling
irradiance sensor

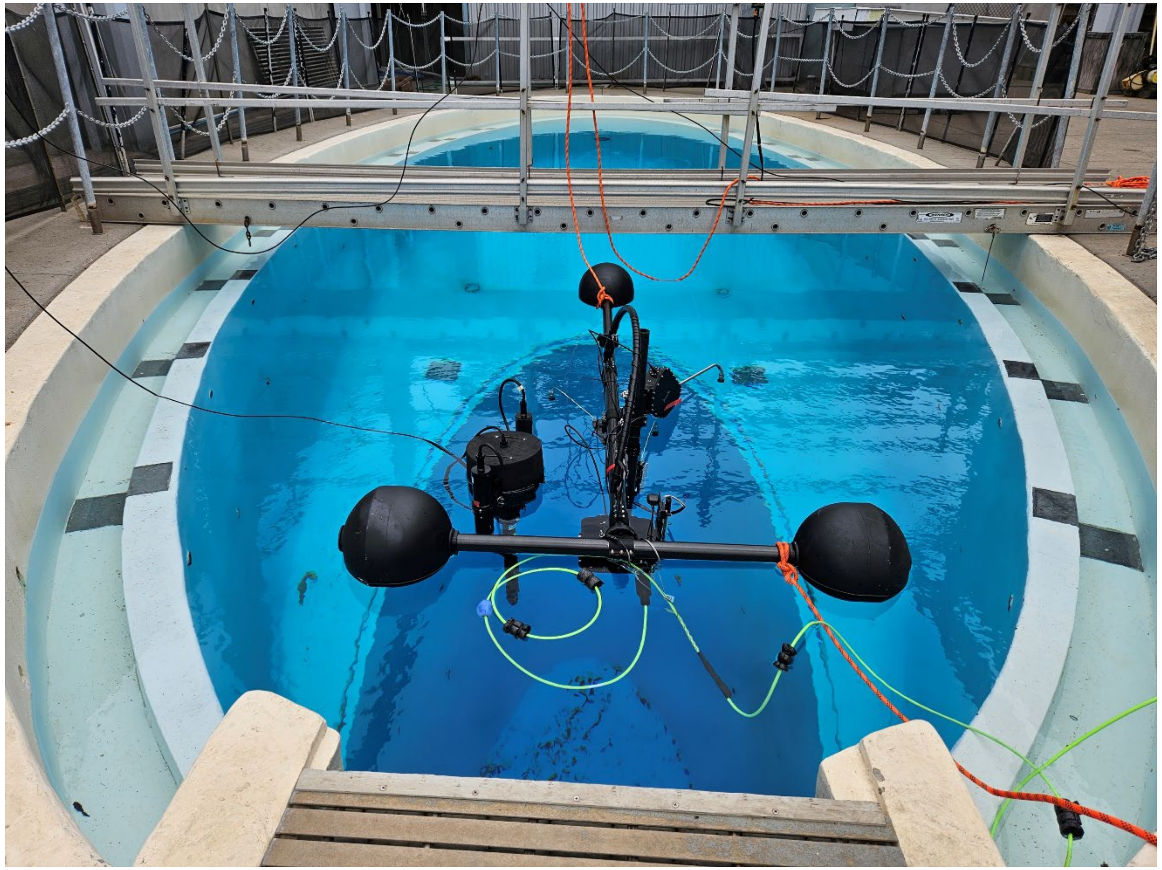
AquaFloat software and user interface

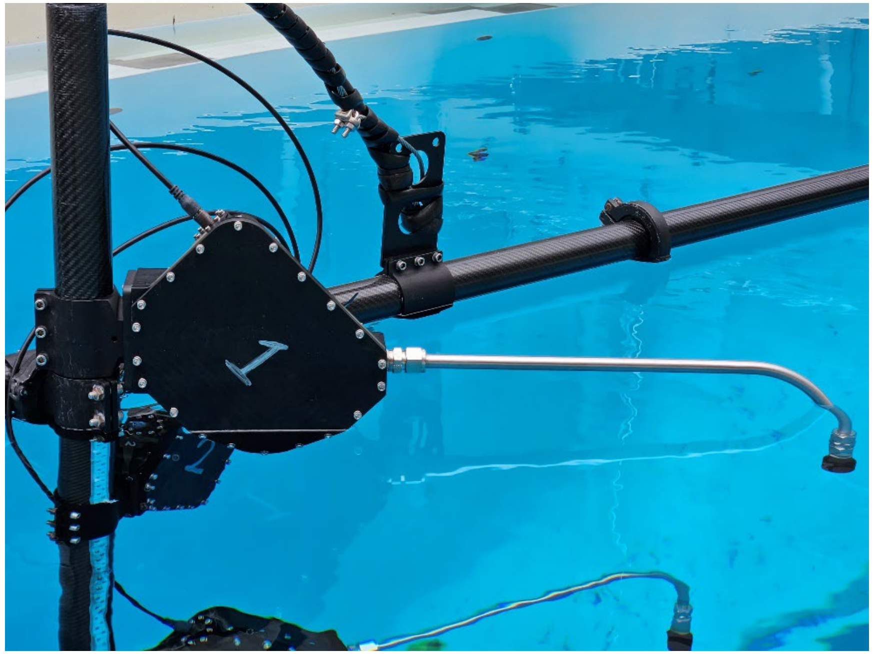


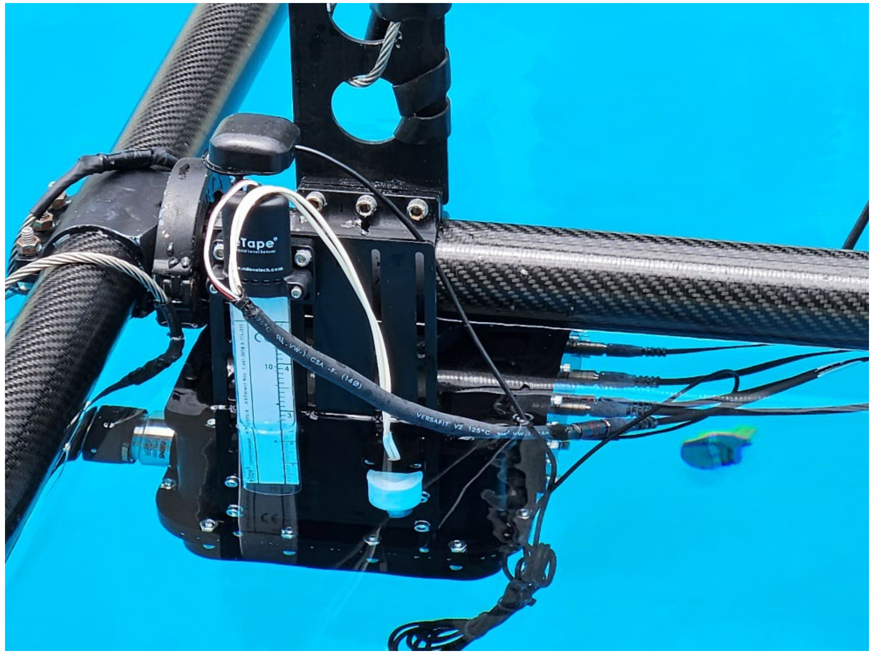
Tests of AquaFloat in the SIO Keck Deep Pool (August 10, 2023)

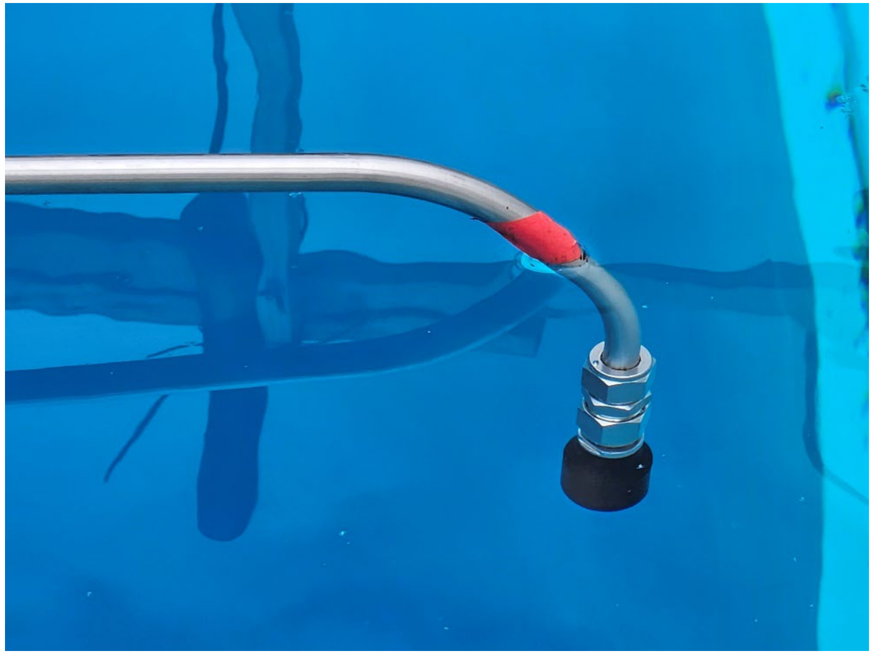
Oval shape, interior dimensions are 5.5 m width and 12.5 m length, shallow depth is 4 m with a deep section at 9.1 m.
Fresh or salt water is available.

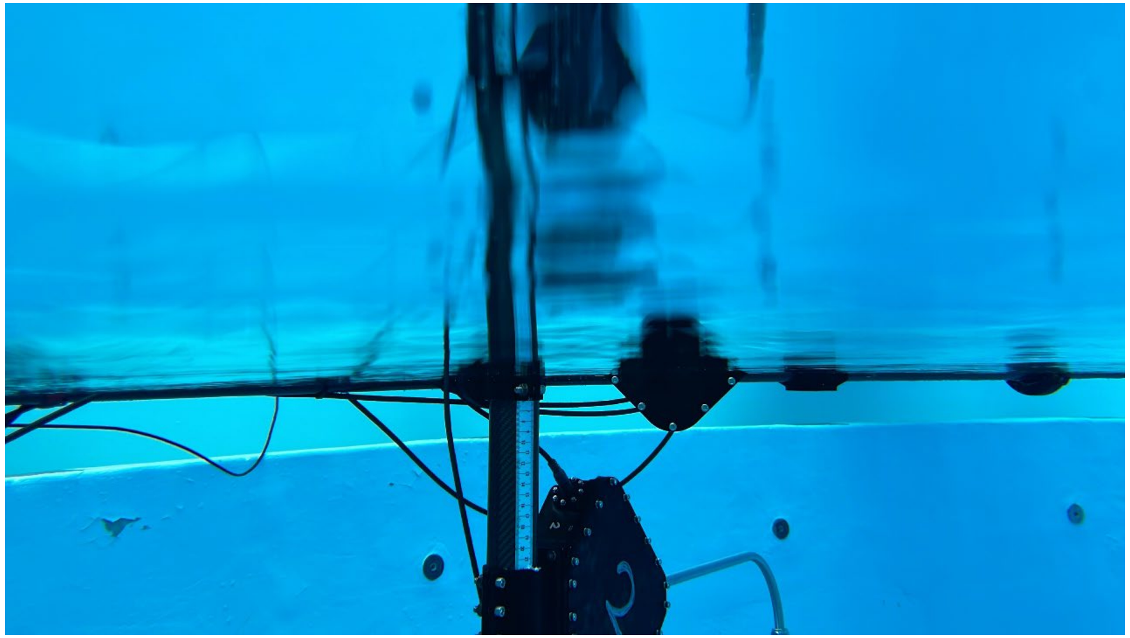




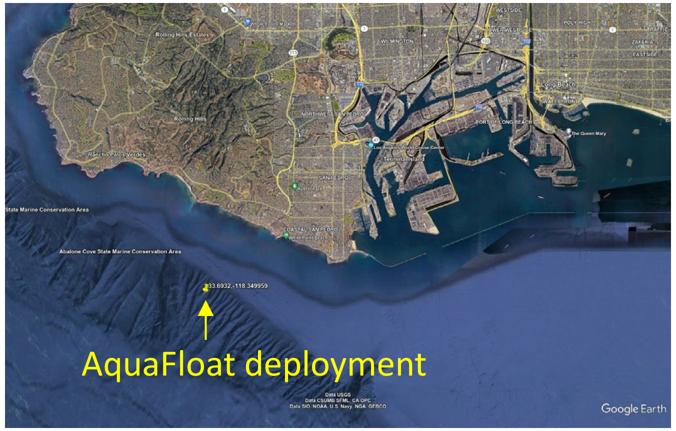


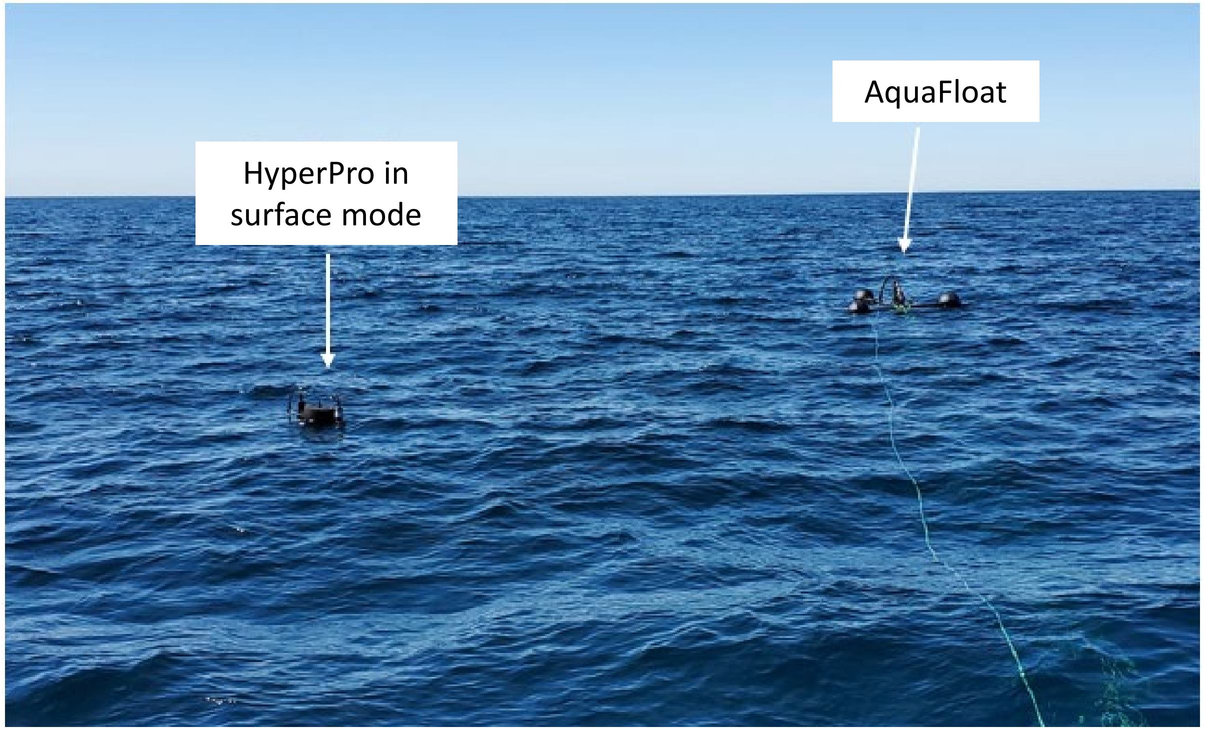

eTape

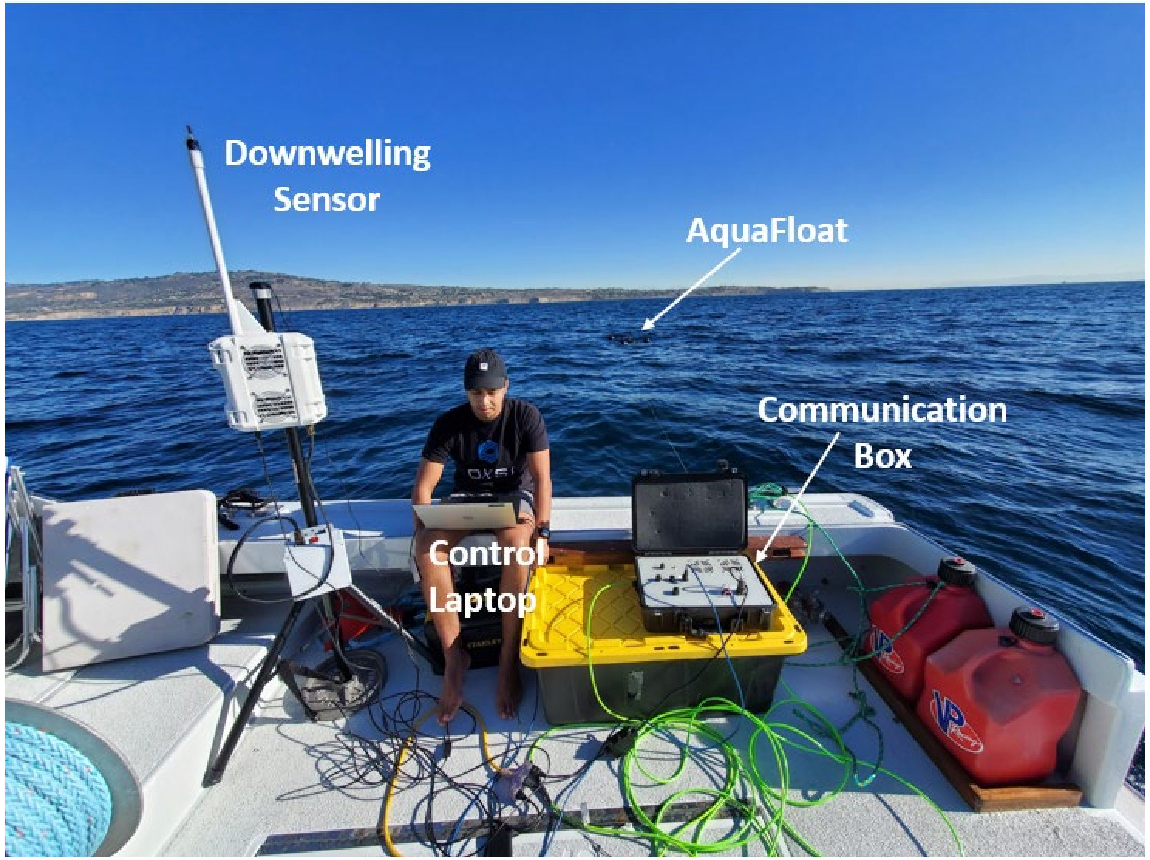




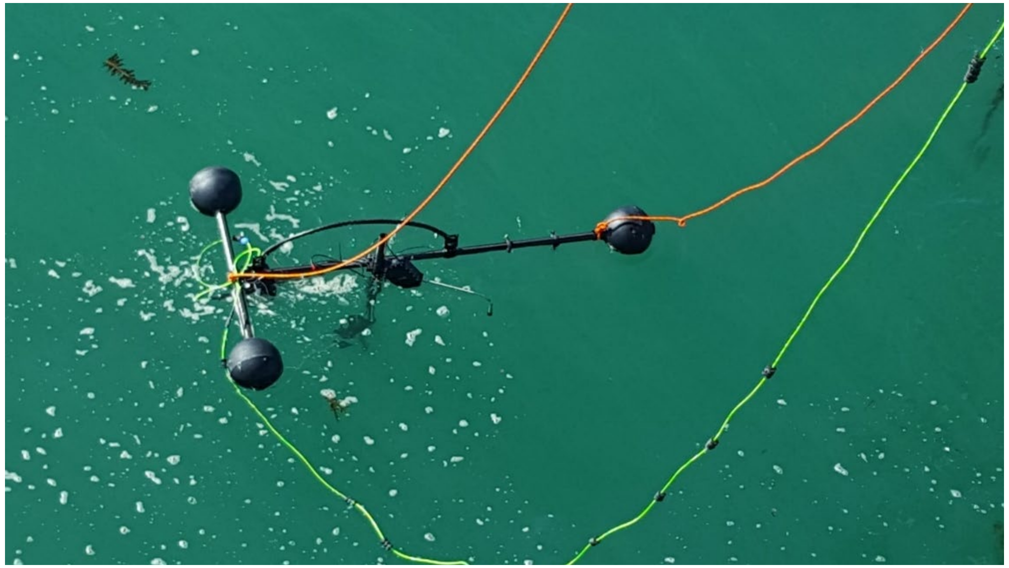
AquaFloat deployment off San Pedro Harbor (October 24, 2022)







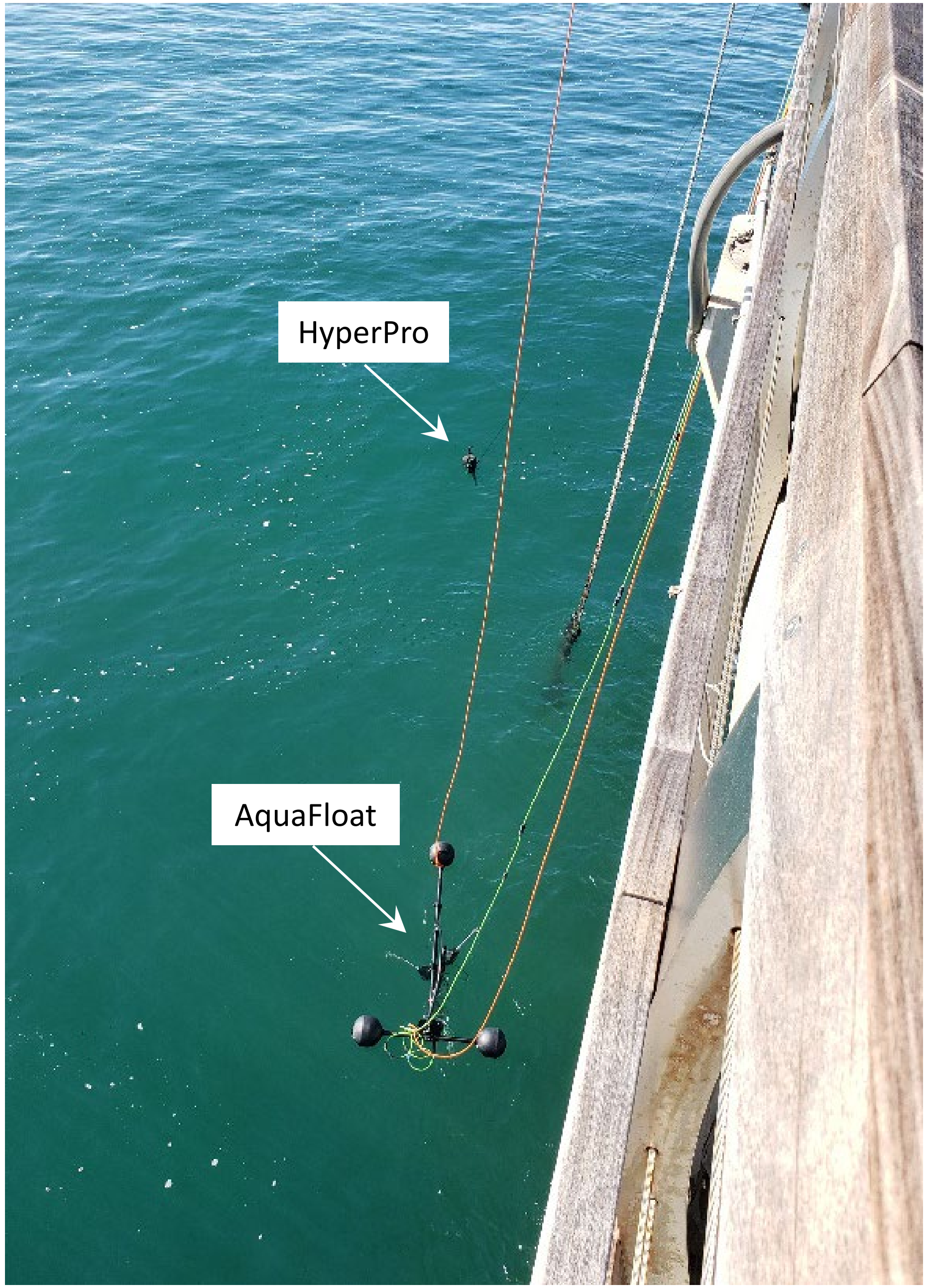
AquaFloat deployment – Scripps Pier (January 20, 2023)



AquaFloat and HyperPRO II deployment – Scripps Pier

(December 6, 2023)

- A 1.5-hr time series was recorded that encompassed local noon (11:50 to 13:25 PST, UTC −08:00).
- Clear skies with a solar zenith angle of ~55° (approaching winter solstice).
- Winds were negligible (< 1 m s^{-1}) but significant wave heights on the order of 1 m (14 s period) with times of much larger wave activity were observed throughout the time series.
- Chlorophyll-a concentration was moderate, ~ 0.6 mg m^{-3}, and dinoflagellates dominated the microphytoplankton assemblage (data from the SIO Coastal Ocean Observing Laboratory).



Time series of AquaFloat sensor measurements from the SIO Pier

- **_Top:_** Out-of-water switch with value of 1 indicating sensor is in air.

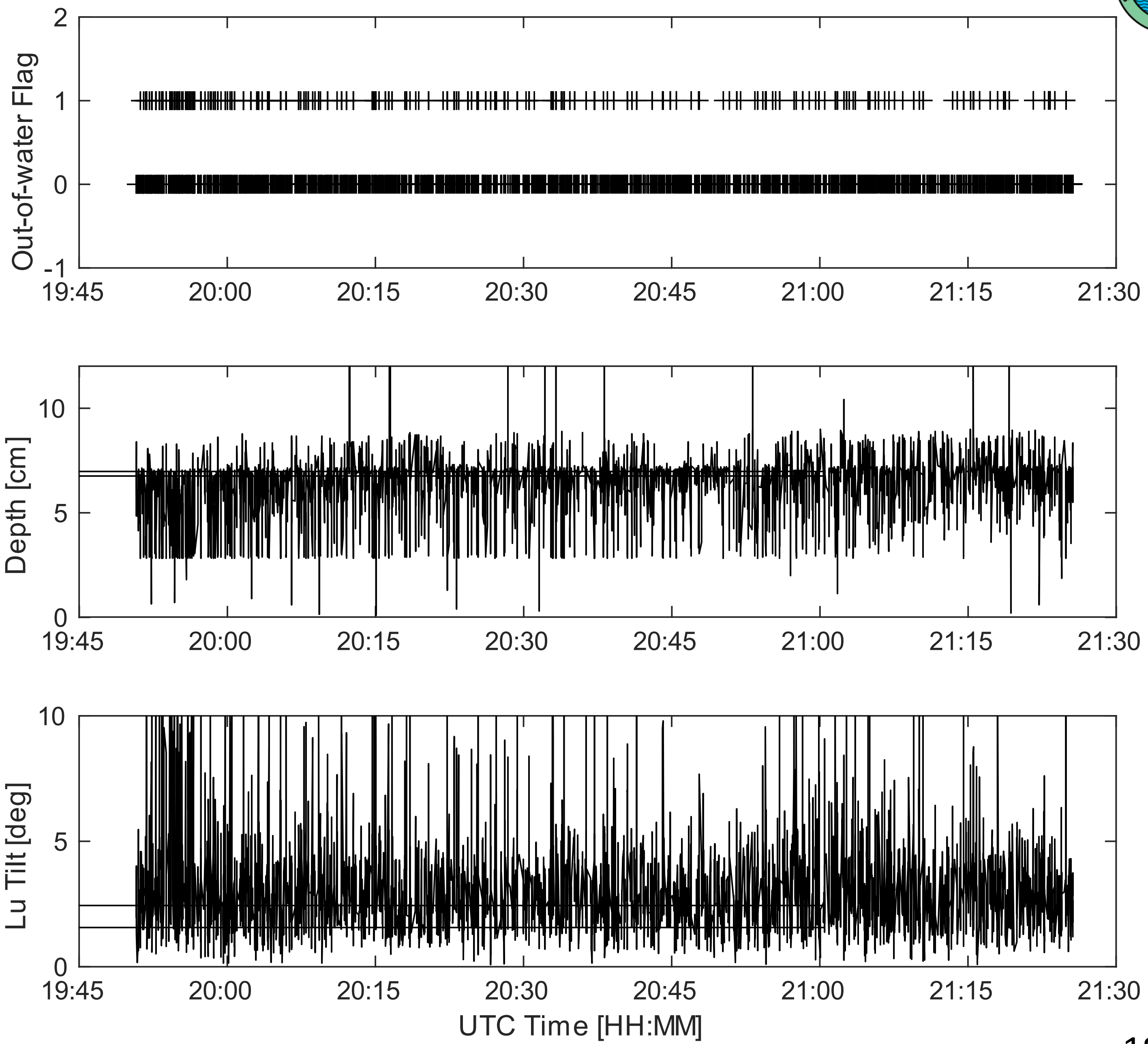
  The sensor recorded 307 out-of-water occurrences (~7% of the time series) during the 1.5-hr time series.

- **_Middle:_** Depth of shallowest L_u sensor.

  The shallowest radiance sensor indicates a mean depth of 6.5 ± 2.6 cm beneath the sea surface.

- **_Bottom:_** Vertical inclination angle of L_u sensor relative to the zenith direction.

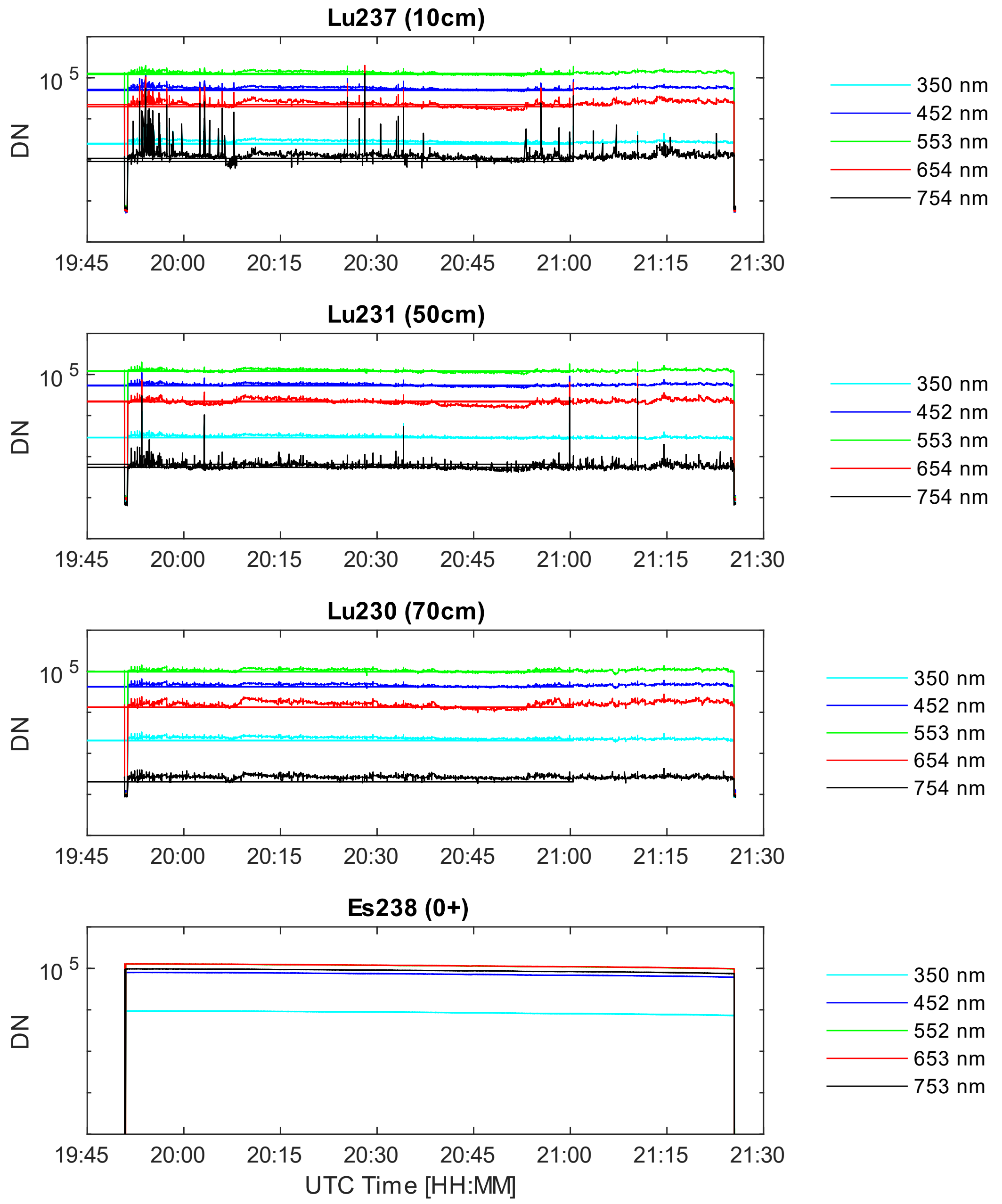
  The inclination angle was, on average, 3.1 ± 2.2^{o} with ~12% of the observations exceeding a value of 5^{o} .



Time series of AquaFloat radiometric measurements

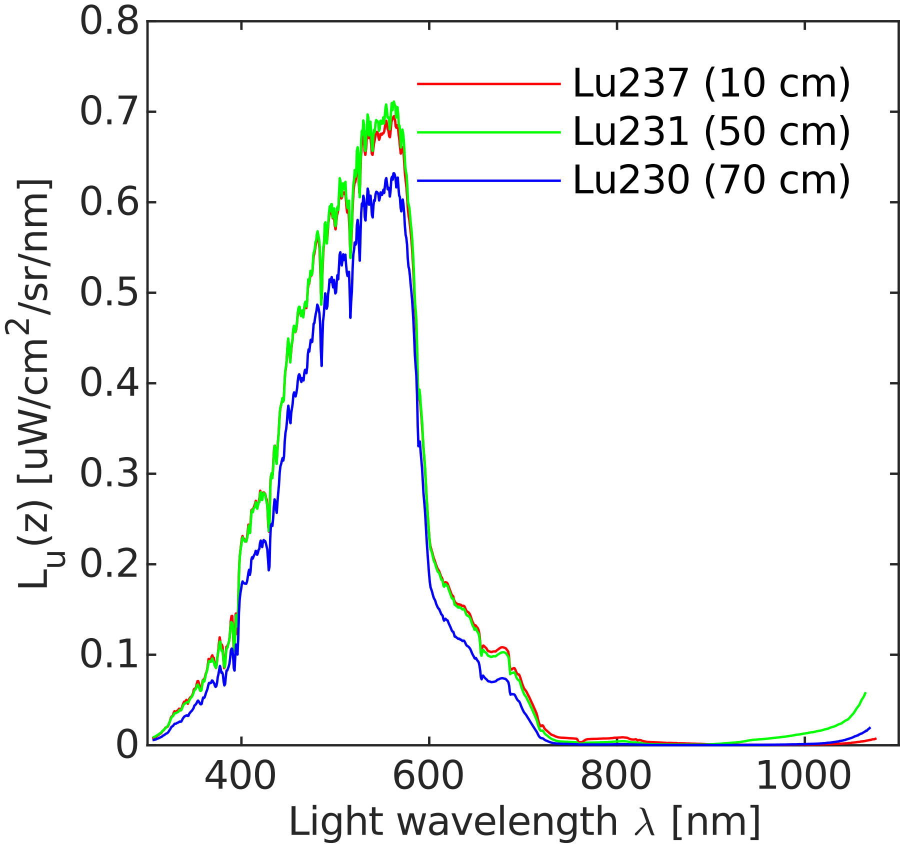
- ❑ ***Top 3 panels:*** Time series of raw $L_u(\lambda)$ measurements recorded at three nominal depths as indicated.
- ❑ ***Bottom:*** The corresponding time series of $E_s(\lambda)$ measurements are shown in the bottom panel.

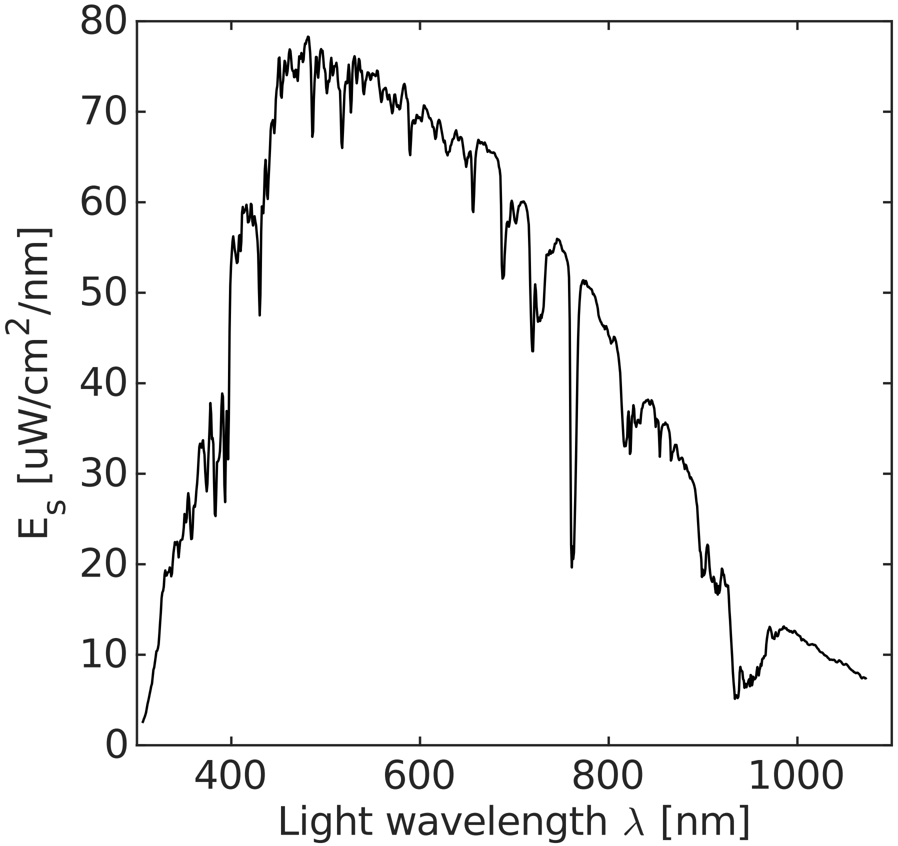
For each sensor, data in digital number (DN) counts prior to any processing are depicted for 5 selected wavelengths. The first and last 20 measurements of the time series represent dark current measurement for which a shutter was placed before the spectrometer. The S/N ratio was generally on the order of 100 in the peak region of spectrum near 550 nm and decreased to <10 only in the UV and NIR regions of the spectrum.



Mean spectra of $L_u(\lambda)$ at three depths and above-surface $E_s(\lambda)$ obtained by averaging AquaFloat radiometric measurements over selected 5-min period (20:13 to 20:18 UTC)

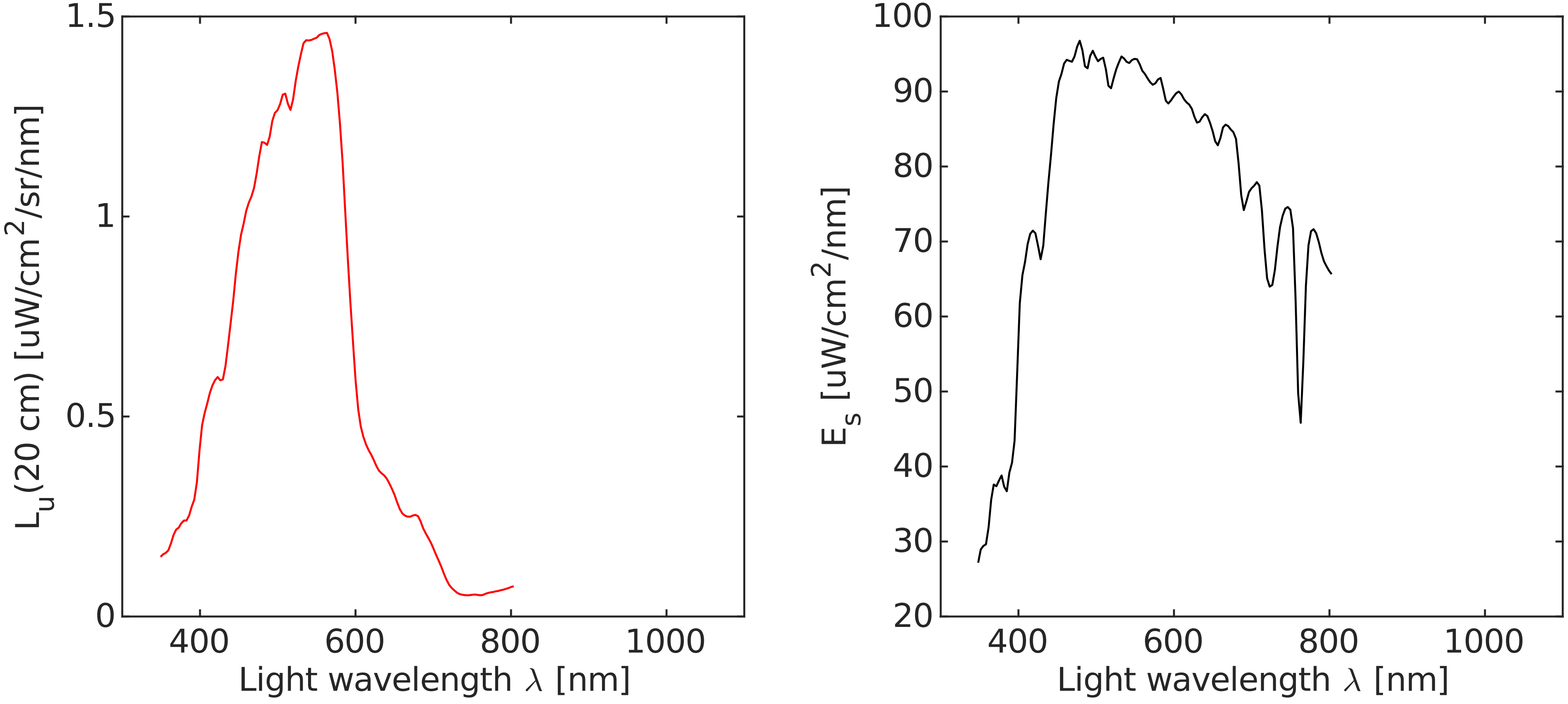
Data are displayed at the original spectral sampling interval of ~0.7 nm and are in calibrated units following correction for dark current and application of a **preliminary calibration** (e.g., no correction for immersion factor for L_u sensors).





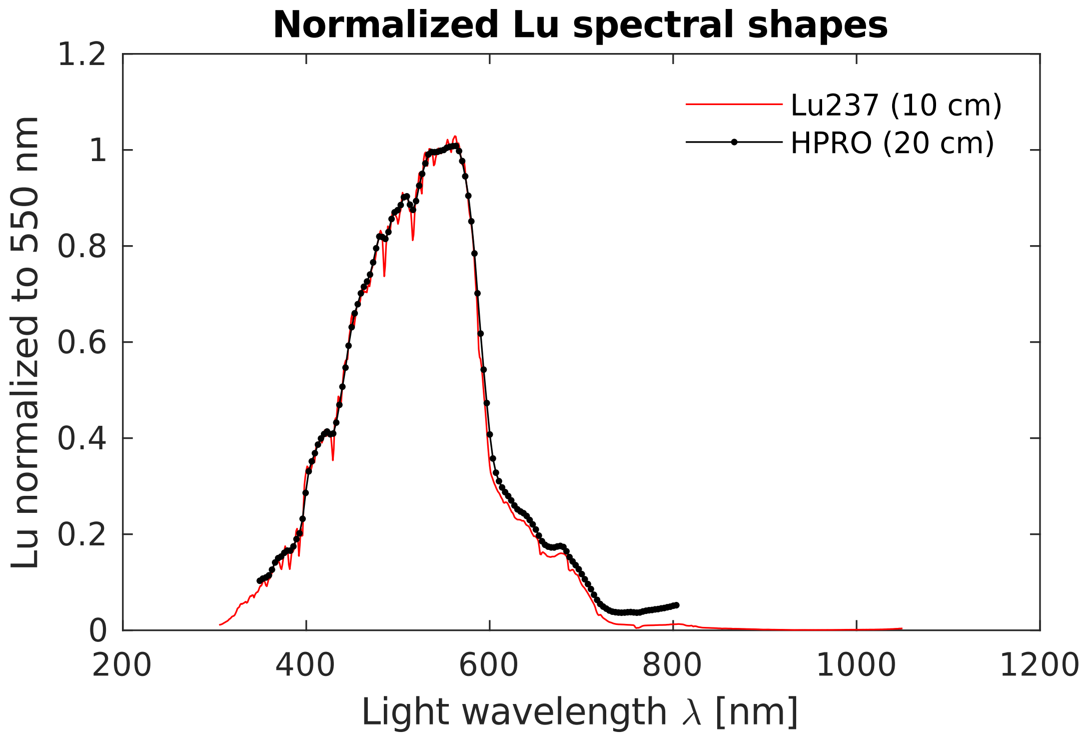
Mean spectra (5-min period) of $L_u(\lambda)$ and above-surface $E_s(\lambda)$ obtained from measurements with HyperPRO II

The HyperPRO instrument was configured as a surface buoy for L_u measurements at a nominal depth of 20 cm

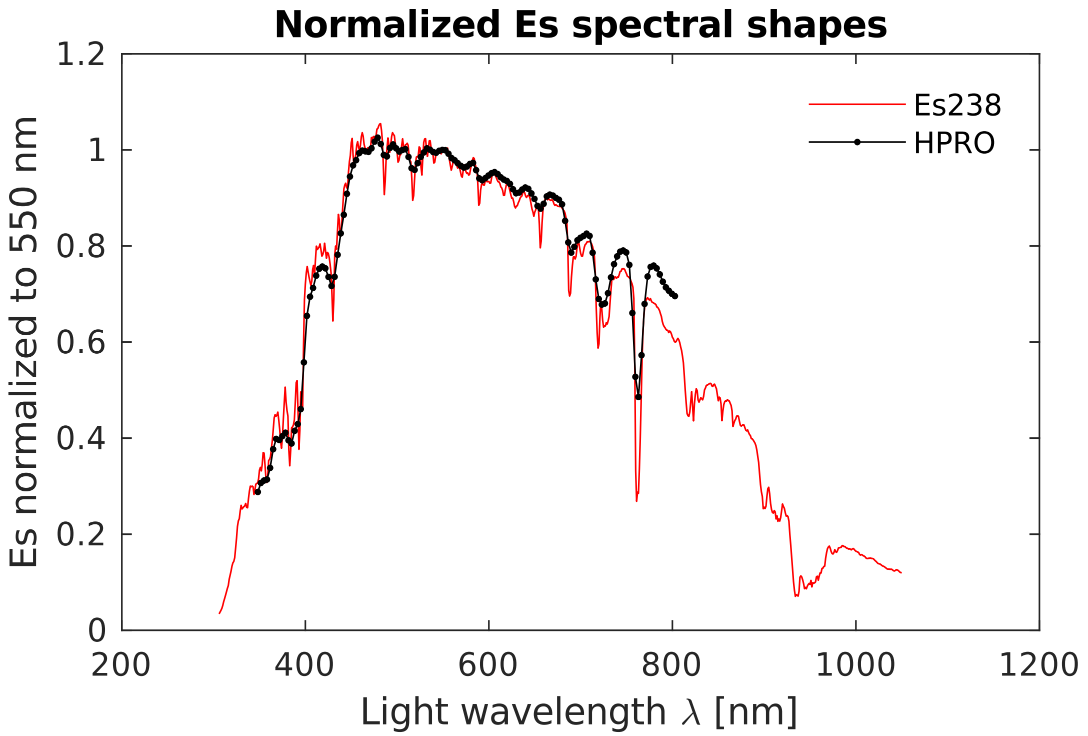


Comparison of spectral shapes of AquaFloat and HyperPRO II measurements
The spectral data are normalized to the value measured at 550 nm

Spectra of L_u measured at a nominal depth of 10 cm with AquaFloat (red) and 20 cm with HyperPRO II (black)



Spectra of above-surface E_s measured with AquaFloat (red) and HyperPRO II (black)



The AquaFloat data are plotted at ~0.7 nm sampling intervals and the HyperPRO data are plotted at ~3.3 nm intervals.

Summary of key novel features and advantages of AquaFloat

- Simultaneous multi-depth measurements at shallow near-surface depths from about 5-10 cm to 1-1.5 m address the vertical gradients in light attenuation within the near-surface extrapolation interval (Raman scattering, vertical heterogeneity of inherent optical properties).
- Simultaneous multi-depth time-series measurements within the near-surface layer address the temporal variability in underwater light due to surface wave effects, intermittent bubble clouds, and sky/cloud conditions.
- Hyperspectral capabilities in the broad spectral range from about 300 nm to 1000 nm addresses the need for routine acquisition of accurate data from the UV through visible to near-infrared with high spectral resolution (~ 1 nm).
- A T-structure float provides optimal movement control on waves and minimizes self-shading effects.
- Customizable specifications, portable, and easy to deploy from ships or other platforms in deep ocean, littoral regions, estuaries, and inland water bodies.
- The AquaFloat offers novel features which are critical for improving in situ measurements of L_w in support of cal/val activities and vicarious calibration activities of current and future ocean color missions.
- Commercial availability of AquaFloat will support and improve the application of satellite ocean color data by government, academic, and commercial users around the world.

Further plans

The AquaFloat is a new instrument that has not had time yet to undergo rigorous testing under variety of conditions. We need to:

- Conduct additional series of instrument calibrations including spectral, radiometric, stray light, and immersion factor to assess instrument stability.
- Perform additional field tests from the SIO Pier and research vessel to test deployment and recovery under various sea state conditions.
- Consider development of multiple options of the AquaFloat system, such as simplified version (with reduced cost) for most routine applications and an enhanced system (e.g., including polarization measurements).
- Conduct collaborative field work to demonstrate the AquaFloat operation and obtain independent tests of performance and comparisons with other instruments
  - Participate in cruises of opportunity, especially the dedicated NOAA ocean color cal/val cruises to collaborate with NOAA/NESDIS, NASA Field Support Group and academic investigators, and also leverage potential international cruise opportunities.
  - Collaborate on joint conference presentations and peer-reviewed publications.
- OKSI/SIO team will require funding for these tasks (e.g., pre-cruise preparation, instrument calibrations, travel and instrument shipment, data processing).

AquaFloat funding history

- Initial funding under NASA SBIR P-I and P-II (started in August 2020 and ended in December 2023)
- Subsequent funding under NASA SBIR P-II/E and P-III (contribution of NASA OBB Program) each at $25K (ends in December 2024)

Potential future funding opportunities to cross the "Valley of Death":

- The NASA SBIR under the CCRPP (Civilian Commercialization Readiness Pilot Program) program will match 1:1 outside funding sources between $500K (minimum) to $2.5M for further development and commercialization. The $500K can be split among multiple investments / agencies.
- Other sources? Ocean color cal/val programs?