Uncertainty budget for Sea-Bird Scientific radiometers following cross-site calibration

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Abstract

In-situ and above water radiometers are a critical for validating Ocean Color Satellite measurements, used to monitor in-water constituents of the global ocean. The calibration process, instrument response characterization, and environmental measurement all contribute to the overall uncertainty budget of the radiometric measurement. An integral part of this uncertainty traceability chain is accurate laboratory calibration of radiometric sensors. Over its lifetime, the Sea-Bird Scientific Halifax site (formerly Satlantic, LP) participated in inter-laboratory comparisons to ensure the quality of its calibrations. These include: NASA's Seventh SeaWIFS Intercalibration Round-Robin Experiment (SIRREX-7, Hooker et al. 2002), conducted in 1999, compared Halifax to the Center for Hydro-Optics and Remote Sensing (CHORS, San Diego State University, California, USA) and the Joint Research Centre (JRC, Ispra, Italy). More recently, Sea-Bird Scientific participated in the European Space Agency (ESA) sponsored Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) program. 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 (formerly WET Labs, Inc.). As part of this transition, the radiometer calibration facility was reproduced at the Philomath site and Sea-Bird Scientific conducted an extensive cross facility set of experiments 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.

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Introduction:

In-situ and above water radiometers are a critical for validating Ocean Color Satellite measurements, used to monitor in-water constituents of the global ocean. The calibration process, instrument response characterization, and environmental measurement all contribute to the overall uncertainty budget of the radiometric measurement. An integral part of this uncertainty traceability chain is accurate laboratory calibration of radiometric sensors.

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Approach:

A specialized laboratory was designed and built in PHI to replicate the calibration environment established in HAL. Both laboratories monitor temperature and humidity and conditions are controlled to maintain consistent environmental conditions. To minimize dust entering the rooms, both laboratories are kept under positive pressure. Sticky mats and booties are used to further maintain a clean working environment and to reduce dust that would scatter light. To minimize stray light, curtains enclose the entire setup and surround the aperture, separating the part of the room with the FEL lamp from the sensor area. The walls are painted with special matte black paint that is designed to have very low reflectance. All in-room equipment is black, including: curtains, table tops and rails. Additional black fabric is used to cover the rails, power supply, and other equipment on the optical tables.

To perform radiometric calibrations, both laboratories have replicate equipment including: FEL irradiance standards and power supplies from Gooch and Housego, a precision 0.01 ohm shunt used in series with the lamp, and a multimeter to monitor lamp and shunt voltage (providing a measure of current). For radiance calibrations, an 18-inch square Spectralon plaque manufactured by Labsphere is used to provide Lambertian reflectance. Each site maintained a complete set of equipment, with a 6 month recalibration frequency.

Calibration procedures follow standard procedures as outlined in the FRM4SOC 3a and 3b reports (Banks *et al.* 2017). At both sites, the calibration procedure involves mounting and aligning a sensor, installing the lamp, allowing the lamp to warmup up for 20 minutes, and then collecting data for 3-5 minutes depending on the sensor. To detect any changes to the lamp, voltage and current are recorded before and after calibration. Sea-Bird Scientific standard work uses lamps for up to 50 hours to limit effects due to lamp aging. Calibration software monitors the sensor for changes such as: integration time, temperature swings, excessive noise, and poor dark readings. Sensors are mounted in V-blocks pre-set to the height required for sensor model. Alignment is achieved using a laser, located well behind the lamp, and a lamp alignment jig with crosshairs on a glass surface. Front surface mirrors placed on the front of sensors and plaque reflect the laser back onto itself. Sensor position is measured from the front surface using a square and a ruler that is part of the rail assembly. Offsets between lamp electrodes and the carrier base, and between the plaque surface and its carrier base, are performed by averaging multiple measurements made with calibrated calipers. Irradiance calibrations are performed at the standard 50 cm distance, at which the FEL lamps are calibrated. Radiance calibrations are performed with a lamp-to-plaque distance of 130 cm. Distances for radiance calibrations were chosen as a tradeoff between the level and uniformity of radiance that could be achieved, with the balance being the sensor view of the plaque and the spatial reflectance of the plaque, where the edges of the plaque have different reflectance.

To quantify repeatability uncertainties for calibrations within and between laboratories, replicate calibrations were performed on a set of reference radiometers at each site. The reference radiometers are used during the standard calibration process to periodically verify that no changes to the equipment have occurred. The sensors are a critical part of the Sea-Bird Scientific chain of calibration and are also used to verify the calibration result of newly fabricated sensors under naturally occurring ambient light conditions. Calibrations were performed over the period of one year, between 2017 and 2018. Reference sensors included in this experiment were: 7-channel Multispectral 500 series Ocean Color Radiometers (OCR-507) and Hyperspectral Ocean Color Radiometers (HOCR). Table 1 lists the radiometer model, parameter, description, channels and serial numbers evaluated.

For all radiometers included in the uncertainty study, four replicate calibrations were performed at each site on the same sensor. The average of the four repeated calibrations reduces the effects of random effects at each site for the comparison. To determine within laboratory uncertainty, data were normalized to the mean calibration from each site, reported as expanded uncertainty, $k = 2$. Repeated calibrations for OCR-507 sensors were collected using different equipment over the period of 8 months. For reference, over the period of time that replicate calibrations were performed, each site used at least three different FEL lamps. To ensure that uncertainty due to operator and equipment alignment was included, equipment was reset between calibrations. Data for HOCR reference sensors was collected differently between sites. In this experiment, the same power supply, shunt, lamp, and plaque was used at both sites for sensor calibrations. The time between calibrations performed in HAL and those performed in PHI was approximately 3 months. Replicate calibrations were collected over 1-2 days at the PHI site and over 1-3 days at the HAL site. To ensure lamp, plaque, and sensor mount repositioning uncertainty was included in the measurements, calibrations alternated between radiance and irradiance.

Several components contribute to absolute calibration uncertainties. Uncertainties due to power supply, lamp ageing, lamp alignment, and thermal effects are described in the literature (Berhard and Seckmeyer (1999), Kuusk *et al.* (2017), Yoon and Gibson (2011), Yoon *et al.* (2012), Zibordi *et al.* (2017). Calibration uncertainties observed at PHI and HAL are compared to a budget of expected uncertainties (Table 2). For HOCR radiometers, site uncertainties are compared to expected uncertainties for the same equipment (Table 2, Top) and OCR-507 radiometers are compared to expected uncertainties calculated for different equipment (Table 2, Bottom).

To identify and correct any differences between laboratories during the initial phase of laboratory replication, a series of new sensors were built and calibrated at the PHI site and then calibrated at the HAL site. These sensors included three HOCR irradiance sensors and four HOCR radiance sensors. For each sensor, a single calibration was performed at each site. The mean was computed for the calibrations performed at each site by sensor model and type (i.e. $n = 3$ HOCR irradiance sensors; $n = 4$ HOCR radiance sensors).

To evaluate possible systematic bias, the difference of PHI site was computed and compared relative to established standards of the HAL site for all observations made during this study.

Results:

Repeatability uncertainty for two calibration laboratories: Repeated calibrations of multichannel OCR-507 irradiance sensors show uncertainties, $k = 2$, for HAL site are 2.3% or less (Figure 1A). Similar results were found for PHI site with the expected uncertainties of 2.2% or less. For comparison, repeatability uncertainty from PHI and HAL were compared to a budget of combined uncertainty components for use of different equipment during calibration (Table 2). PHI is below the expected uncertainty values from 400-500 nm and 650-750 nm. Between 500-600 nm and above 800 nm, values for PHI are slightly higher than expected. HAL shows a similar trend, where uncertainties between 450-650 nm and above 700 nm are greater than expected. During the experiment, calibrations for S/N 353 were repeated over a short period of time (1 day) at the PHI site and repeatability uncertainty reduced to 1.2%.

A comparison between laboratories shows calibration uncertainties observed for OCR-507 radiance sensors are 2.0% for HAL and 2.1% for PHI (Figure 1B). Across all wavelengths, uncertainties at both HAL and PHI sites, were below theoretical uncertainties for use of the different equipment (Table 2, Bottom). To investigate any improvement in repeatability, calibrations for S/N 150 were repeated in PHI over a short period of time (3 days). Uncertainty due to calibration repeatability decreased to 0.6% and approaches the theoretical uncertainty for use of the same equipment, 0.5% (Table 2, Top).

Calibrations for the same HOCR sensors were repeated using the same equipment at each site. Repeatability uncertainty for HOCR irradiance sensors shows uncertainty of 0.3 % from 350 to 600 nm for HAL (Figure 2A). For longer wavelengths, uncertainty increased to 0.8% in IR. Overall, uncertainty observations for the PHI site are < 0.5% with a flat spectral shape indicating no spectral trends. However, uncertainties observed in PHI are higher than HAL from 350 to 600 nm. Comparison of these results to the expected uncertainty budget for the same equipment (Table 2, Top), show PHI site is below the uncertainty values of 0.5% across the spectrum (350-800 nm). Whereas HAL uncertainties are below expected values between 350 to 600 nm, but are slightly higher than expected for longer wavelengths.

Comparison of uncertainty values for repeated calibrations of HOCR radiance sensors at HAL are below 0.4% between 390 to 800 nm, with the exception of 415 nm (Figure 2B). These values are also below the 0.5% budget of uncertainty values for use of the same calibration equipment (Table 2, Top). Calibration uncertainty values for PHI are about 0.5% for wavelengths between 450 to 700 nm, which are at uncertainties expected for the same equipment. Both labs show a slight spectral trend with higher uncertainties in ultraviolet (UV) and near infrared (IR).

For observations made during the early phase of the laboratory replication, uncertainties for the three HOCR irradiance sensors are about 0% in the blue, increasing to about 1.2% at shorter and longer wavelengths (Figure 3A). Observed uncertainties are close to values expected for use of different equipment (Table 2, Bottom). Of the four HOCR radiometers evaluated, uncertainties are 2.7% in the UV and below 2.5% from 365 nm on, with some higher peaks in the red and infrared reached up to 3.3% (Figure 3B). Yet, the uncertainty for both HAL and PHI are still below uncertainties expected for use of different equipment (Table 2, Bottom).

Differences between laboratories: For repeated calibrations of OCR-507 irradiance reference sensors, the difference between PHI and HAL was -0.1% (Figure 1A). The difference between laboratories for HOCR irradiance sensors was found to be -0.3% to 0.3%, with a spectral trend increasing from 350 to near IR (Figure 2A). Observations from single calibrations of HOCR irradiance sensors made during the early phase of laboratory replication show difference of less than 0.2% between laboratories over the range of 380-740 nm (Figure 3A). However, observations from single calibrations of HOCR radiance sensors made early during the transition showed a -1.0% difference between laboratories with a decreasing spectral trend from 350 to 800 nm (Figure 3B). This trend was also observed during initial observations of repeated calibrations for OCR-507 S/N 150 and 151 radiance reference sensors (data not shown). Following this discovery, the distance of the sensor to the plaque was adjusted to optimize the radiance sensor field of view. Subsequent repeated calibrations for OCR-507 reference sensors used this new geometry. Differences between PHI and HAL laboratories reduced to -0.1% for radiance sensors (Figure 1B). For repeated calibrations of HOCR radiance reference sensors, the overall difference between PHI and HAL laboratories was found to be -0.2%, with a slight spectral trend from 350 to 800 nm (Figure 2B).

Discussion and Conclusions:

This study shows little difference between the calibration laboratories and processes between PHI and HAL. This work also demonstrated that when large differences between laboratories were found, actions were taken to correct and verify implemented changes. When compared to the budget for repeatability uncertainty for the same or different equipment, both laboratories perform well with uncertainty values below or close to expected.

Early during the replication of the laboratory in PHI, single calibrations of four HOCR radiance sensors showed a -1% difference relative to HAL. Upon further investigation, sensors calibrated at the PHI site were seeing less light than those calibrated at the HAL site. This would lead to an increase in the calibration coefficient over the HAL site and a negative difference between the labs. Knowing that radiance drops off near the edges of the plaque (because the edges are farther from the lamp than the center of the plaque), the geometry was modified so the sensor viewed a smaller area on the plaque. HOCR radiance sensors used for the original experiment were no longer available, however calibrations performed with OCR-507 radiance sensors (S/N 150 and 151) demonstrate the improvement. Observations were made prior to changing the radiometer field of view and showed a -1.2% difference relative to HAL (data not shown). Following the change in geometry, the difference between PHI calibration coefficients relative to HAL decreased to -0.1% (Figure 1B). Further investigation to reduce the observed difference between laboratories may include implementing a system to map radiance spatially over the surface of the plaque. Mapping the radiance distribution for different lamps could help identify when the peak radiance is not well-centered on the plaque.

Differences between laboratories are small, even when different equipment is used and replicate calibrations are performed over a long period of time (up to 8 months). PHI showed a positive difference (0.1%) relative to HAL for OCR-507 irradiance sensors and a negative difference (-0.1%) for OCR-507 radiance sensors. Therefore, it is likely there is no systematic bias between the labs and the small difference found may be less than our ability to resolve it.

Compared to expected uncertainties described in Table 2, repeatability uncertainties observed for OCR-507 radiance sensors are below expected values for both HAL and PHI sites. However, we are currently unsure as to why uncertainties for OCR-507 irradiance sensors at both sites were somewhat higher than expected. What is promising, is that when the same equipment was used (lamp, shunt, power supply and plaque) and repeated calibrations are performed on the same sensor over a short period of time, as was for HOCR radiance and irradiance sensors, uncertainty is significantly reduced. Uncertainties observed at both sites, were at or below those expected for the same equipment across most of the spectral range. Differences from expected uncertainties were observed between laboratories that may best be explained by changes in temperature.

The spectral trend observed in HAL for uncertainty values of the HOCR irradiance sensors is likely due to the thermal response of the spectrometer. Zibordi *et al.* (2017), found similar temperature response for radiometric sensors from 400-800 nm. Although one would expect the uncertainties observed with the same sensor at PHI site to show a similar trend, temperature effects due to the spectrometer were likely masked by control of laboratory temperatures during this experiment.

Calibrations for HOCR irradiance and radiance sensors at the PHI site were performed over a single day, where the lamp remained on for an extended period of time (up to 4 hours) while the calibrations were performed. Although, room temperature and humidity in the vicinity of the lamp were not recorded during this experiment we think that the laboratory temperature increased beyond that for standard calibrations. Operation of the lamp is typically 1-1.5 hours for standard calibrations. Therefore, we would expect that under standard operating conditions any temperature effects would be much smaller. Several process changes were implemented following this study, which include acclimation of sensors to the laboratory temperature prior to calibration, installation of several fans and opening curtains between calibrations to improve airflow. To test implemented changes, calibrations were repeated with lamp turned off and curtains opened to improve air circulation between subsequent calibrations. Overall repeatability uncertainty decreased by 0.2% (data not shown). Even with improvement in temperature control, overall uncertainty was greater for PHI than for HAL. Therefore, investigation is ongoing to improve temperature control at the PHI site.

This work demonstrates that the new calibration laboratory at PHI is in excellent agreement with the established HAL site. There were no significant biases between the two sites, the repeatability of calibrations is similar at each site, and uncertainties generally agree well with prepared uncertainty budgets.

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Tables & Figures:

Table 1: Reference sensors used for determination of HAL and PHI laboratory calibration uncertainties.

Model	Type	Description	Model	S/N	Channels						
OCR-507	ICSA	Irradiance Cosine in Air	OCR-507	350	412	443	490	510	555	665	683
OCR-507	ICSA	Irradiance Cosine in Air	OCR-507	351	456	532	560	590	620	705	865
OCR-507	ICSW	Irradiance Cosine in Water	OCR-507	352	456	532	560	590	620	705	865
OCR-507	ICSW	Irradiance Cosine in Water	OCR-507	353	412	443	490	510	555	665	683
OCR-507	R08A	Radiance 08 deg Half-Angle Air	OCR-507	150	412	443	490	510	555	665	683
OCR-507	R08A	Radiance 08 deg Half-Angle Air	OCR-507	151	456	532	560	590	620	705	865
HOCR-HPE	ICSW	Irradiance Cosine in Water	HOCR-HPE	306	350-800 nm with 3.3 nm/pixlel resolution or similar						
HOCR-HSE	ICSA	Irradiance Cosine in Air	HOCR-HSE	451	350-800 nm with 3.3 nm/pixlel resolution or similar						
HOCR-HPL	R08W	Radiance 08 deg Half-Angle Water	HOCR-HPL	611	350-800 nm with 3.3 nm/pixlel resolution or similar						
HOCR-HSL	R03A	Radiance 03 deg Half-Angle Air	HOCR-HSL	446	350-800 nm with 3.3 nm/pixlel resolution or similar						

Table 2: Expected uncertainties for same equipment (Top) and different equipment (Bottom).

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**
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 (Radiance only)	1.00%	0.80%	0.80%	1.50%	Calibration certficate, Avian Technologies
	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**

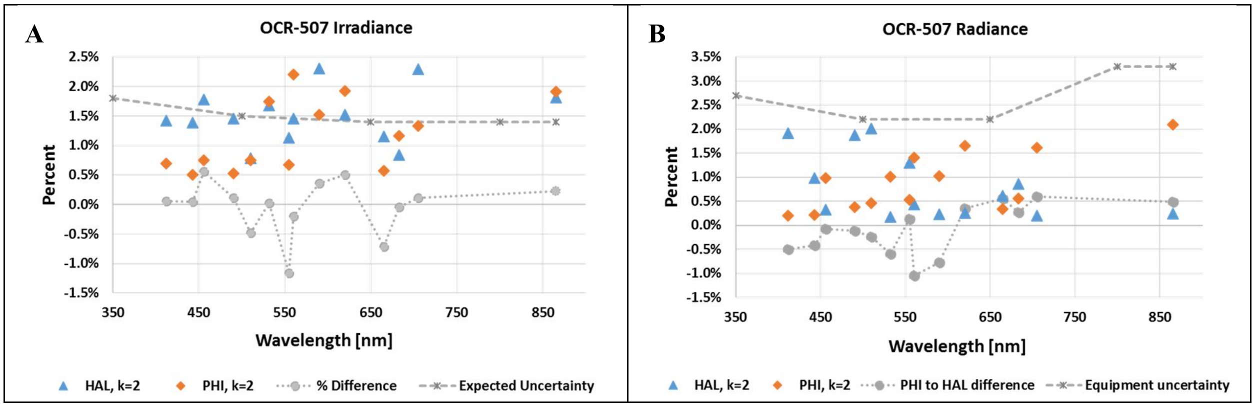

Figure 1: A. Uncertainties for repeated calibrations of OCR-507 irradiance sensors ($k = 2$) for HAL (blue triangle) and PHI (orange diamond) sites. B. Uncertainties for repeated calibrations of OCR-507 radiance sensors ($k = 2$) for HAL (blue triangle) and PHI (orange diamond) sites. The percent difference of PHI relative to HAL site (gray dots) and expected uncertainties for use of the same equipment (gray asterisks) are also shown.

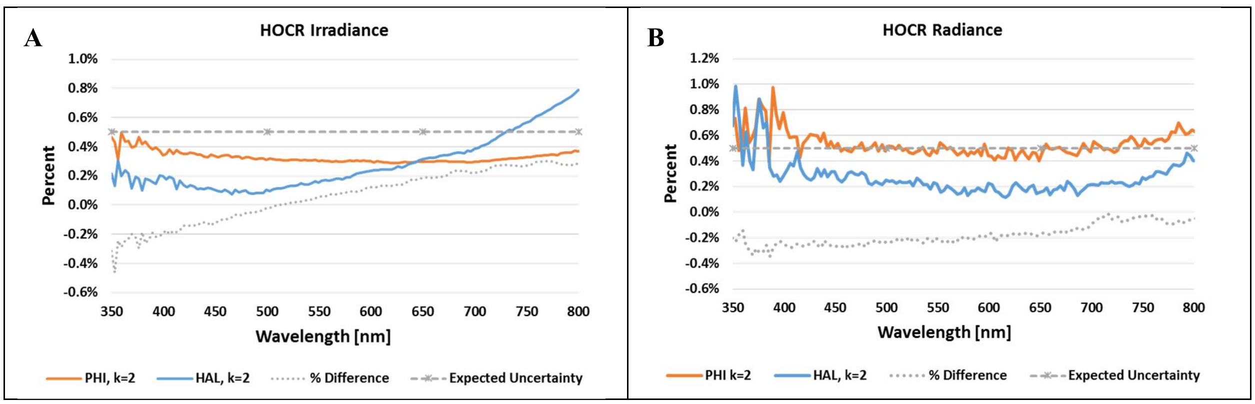

Figure 2: A. Uncertainties for repeated calibrations of HOCR irradiance sensors ($k = 2$) for HAL (blue line) and PHI (orange line) sites. B. Uncertainties for repeated calibrations of HOCR radiance sensors ($k = 2$) for HAL (blue line) and PHI (orange line) sites. The percent difference of PHI relative to HAL site (gray dots) and expected uncertainties for use of the same equipment (gray asterisks, dashed line) are also shown.

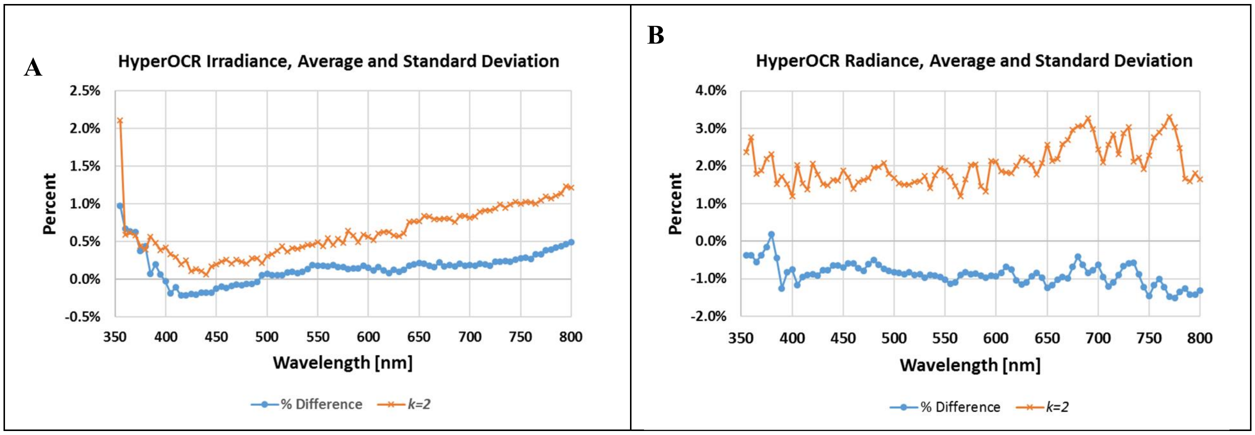

Figure 3: A. Uncertainties for single calibrations of three HOCR irradiance sensors ($k = 2$) for HAL (blue line) and PHI (orange line) sites. B. Uncertainties for single calibrations of four HOCR radiance sensors ($k = 2$) for HAL (blue line) and PHI (orange line) sites.