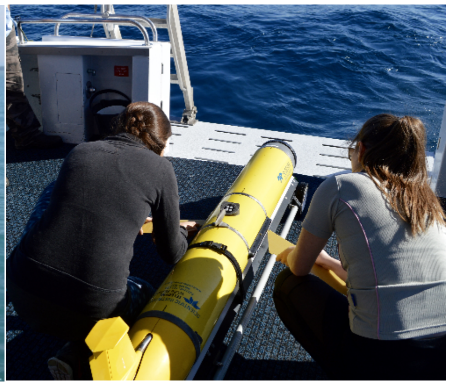
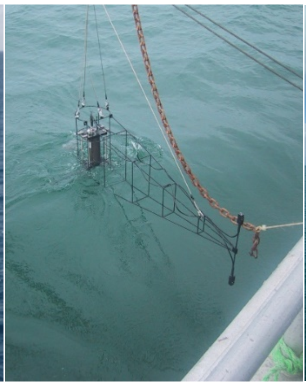
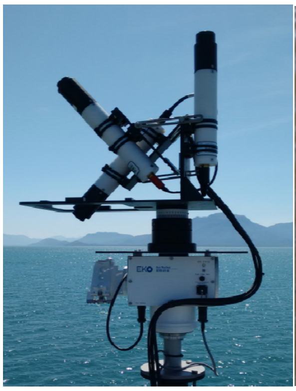
IMOS radiometry community-of-practice document

RAMSES | OCR500 on a glider


DALEC | HYDRORAD | SeaPRISM



HyperOCR (Lucinda) | HyperOCR (Freefall) | HyperOCR (Thetis)

Photo credits: K. Oubelkheir (Ramses, Hydrorad, HyperOCRs freefall and on the Thetis moored profiler), P. Thomson (OCR500 on Glider) and T. Schroeder (DALEC, SeaPRISM and HyperOCR at the Lucinda Jetty Coastal Observatory).

This is a 'living document' that will be updated as new information becomes available. Therefore, contributions and suggestions from the wider Australian radiometric community are welcome!

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1 Background.

In 2010, the Australian Integrated Marine Observing System (IMOS) formed a "Bio-optics working group" with the aim of working towards building a national bio-optical Community of Practice. This working group, initially led by Martina Doblin (UTS) and Christine Hanson (UWA), developed protocols on the measurements of phytoplankton fluorescence and particle backscattering (in line with the requirements for the sensors routinely deployed at the IMOS National Reference Stations). In 2016, this WG was followed by the "IMOS Radiometry Task Team", led by David Antoine (Curtin University) and Thomas Schroeder (CSIRO), with a final report published in June 2017. This task team, as stated in its name, focused on the measurements of radiometric quantities, namely above or below water radiances and irradiances. These measurements are used to derive "apparent optical properties" (AOPs), which are dependent on the in-water constituents and the illumination conditions at the surface. AOPs include the remote sensing reflectance (R_{rs}) and diffuse attenuation coefficient for downward irradiance (K_d), both used for instance in validation of satellite ocean colour products. The task team issued 26 recommendations, including recommendation 6 *'to pool together documentation on protocols for easy access by the Australian bio-optics community'*. This document addresses this recommendation, now also among the IMOS satellite ocean colour sub-facility deliverables.

2 Goal of this document

This IMOS radiometry community-of-practice document summarises important elements of community-agreed, internationally used, protocols for measurement of radiometric quantities in open ocean, coastal and inland waters (from instrument deployment to data handling protocols). The aim is to raise awareness about important aspects of field protocols for measurements of radiometric quantities in the wider community, potentially carrying out such measurements in the field. This document does not pretend to supersede the need for thorough reading of existing detailed protocol documents that are the result of years of experience by the global research community in these domains (see Appendix 1 and 2). Its goal is to highlight the most salient features of these protocols, by pointing users to both what must be done and what must be avoided to ensure that the desired data quality is met. This document is aimed at the wider oceanographic community, from long-term users to 'prima' users of in situ radiometry for environmental studies in aquatic systems (including students, technical staff and scientists not familiar with the caveats of radiometric data acquisition and processing).

The long-term 'aspirations' for this community-of-practice group are also to:

- Establish standard formats for log-sheets and metadata files with key metadata information (per measurement type, e.g., in-water or above-water, ship-based, mooring or glider). This will facilitate metadata entry (excel or access databases), and is particularly critical during the data processing stages with the possibility to streamline the information from log sheets records to database archiving, in national databases such as AODN and international databases such as SeaBASS and NOMAD (NASA), MERMAID (ESA) or the Copernicus Ocean Colour Database (EUMETSAT).

- Establish working groups on specific topics (calibrations, specific applications for phytoplankton groups studies, coral reefs or seagrass, or turbid waters).
- Tackle issues relevant to Australian users. Australia is the 'land of the extremes', with some of the clearest (e.g., Great Barrier Reef lagoon) and muddiest waters (tropical rivers outflows) in the world, and thus present some specific challenges.
- Possibly coordinate field campaigns (to save time and money in organisation and to bring possible synergies of interests and expertise).
- Exchange information (including on activities of international working groups and ocean colour validation teams).

3 Essentials of field radiometry protocols

This chapter first recalls some basics about radiometry measurements, and then summarizes the 'Essentials, Recommended and To Avoid' for radiometric measurements in the field, to provide an overview of requirements for quality radiometric measurements. The logic is not to repeat existing information, which would anyway be impracticable because of their extensive nature, but to provide as specific as possible directions to the relevant documentation.

3.1 Why radiometric measurements are particularly difficult to carry out properly?

Before entering into the practical information about protocols, we try to highlight what is making radiometry measurements so particular. Each geophysical parameter that we try to quantify by measuring it at sea comes with a measurement protocol. What is common to all field measurements is the need for well calibrated and characterised instruments and for detailed and accurate metadata, and radiometry measurements are no exception.

Radiometry strongly differs from other measurements, however, because:

1- The value of a radiometric quantity at a given point in the water column (e.g., the downward irradiance at a depth of 10 m) instantaneously results from the interaction of the light field (photons) with the atmosphere and water over a large spatial domain around the measurement point (**Figure 1A**). For instance, a cloud passing by a few kilometres away in the sky has an immediate impact on above and below water irradiance measurements (**Figure 1B**).

2- These measurements can therefore be compromised by many external factors, such as an operator inadvertently coming too close to a sensor, the ship's shadow or the reflection of sunlight and skylight on the ship's superstructure, or a ship's propeller generating a cloud of bubbles (more on that topic in Appendix 2 on 'Considerations on sources of uncertainties in radiometric measurements'). One can compare this example with, for instance, measurements of water temperature: the water temperature that a sensor records at a given depth does not depend on what the temperature is a few meters away from it (or, if it depends on it, it is on a longer time scale, for instance because of currents or mixing, which is not relevant here).

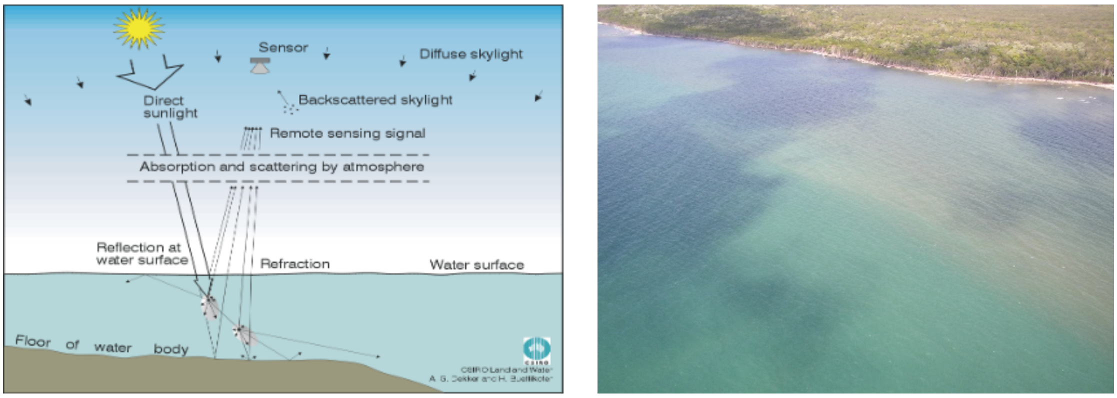

Figure 1. A. Schematic of light propagation in the atmosphere and underwater (Courtesy of A. Dekker and H. Buettikofer, CSIRO). **B.** Aerial photo of the Daintree coastal region showing the change of water colour as a function of in-water constituents (e.g., highest sediment content closest to shore) and the illumination conditions (e.g., impact of clouds) (*Photo credit: K. Oubelkheir*).

3- As a consequence of (1), the measurement platform can significantly perturb the measurement. Let us use a simple analogy, again with seawater temperature measurements. Would anyone do this by dropping a sensor under the ship's engine water cooling pipe? The answer is no, of course, because the perturbation is obvious. But radiometers are still quite often deployed on a frame that is lowered along the hull of large research vessels. In such a configuration, the perturbation of the light field by the ship is of the same "order of magnitude" as the temperature perturbation in the above naive example. It might just not be so obvious for an operator who does not necessarily understand how radiative transfer in the atmosphere and ocean works.

In summary: the water AOP's (Apparent Optical Properties) depend on the optically significant constituents therein, such as phytoplankton, non-algal particles and dissolved materials (which determine the so-called water Inherent Optical Properties: absorption and scattering) and on the illumination conditions at the surface (**Figure 2**). These conditions are always perturbed by the measurement platform and keeping this perturbation minimal or avoiding it completely when possible is therefore essential.

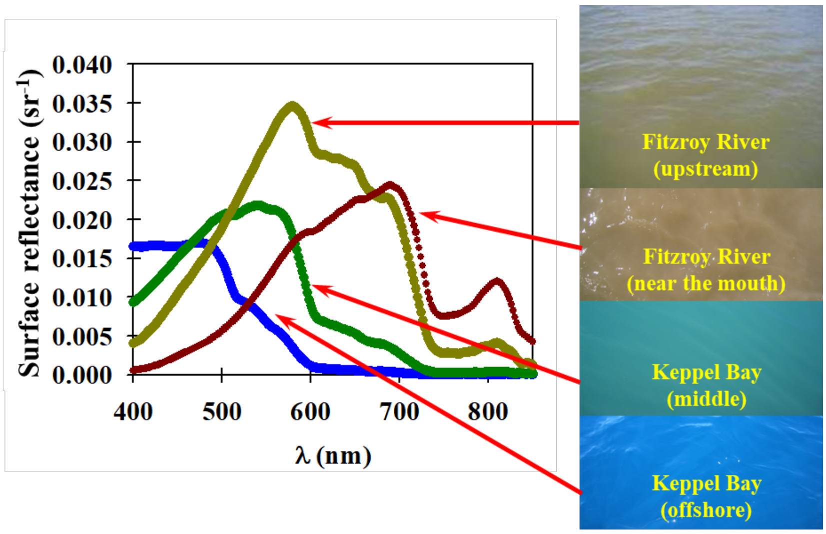

Figure 2. Left: Examples of surface reflectance spectra in contrasted situations (from the highly turbid waters of the Fitzroy Estuary to the clear blue waters offshore in nearby Keppel Bay). Right: Corresponding water surface photos (*Photo credit: K. Oubelkheir*).

These fundamental characteristics of radiometry explain why particular precautions must be taken for the collected data to be of any useful quality, the most important ones being tentatively summarised in the following sections.

For a more detailed introduction on marine optics and radiometry, see Vol. I of the NASA Ocean Optics protocols, and Chapters 1 and 2 of the IOCCG In Situ Optical Radiometry protocols.

3.2 Essentials

Briefly, the commercially available radiometric instruments can be deployed:

- In profiling mode in the water column, using either a winch-deployable frame or freefall profiling systems. They can also be accommodated on ocean gliders, ROVs or on an autonomous moored profiler as the Thetis,

- On a mooring at several fixed depths (e.g., BOUSSOLE or MOBY optical buoys),

- Above the surface, either fixed on a ship's bow for underway measurements or on a fixed platform as done at the Lucinda Jetty Coastal Observatory.

They can be multi-spectral (set of spectral channels with given central wavelengths and spectral response functions), hyperspectral (high spectral resolution, generally from around 350 to 800 nm at an about 3nm resolution), or be quanta-type instruments measuring PAR (Photosynthetically Active Radiation). The commercially available multi-spectral and hyperspectral radiometric instruments commonly used in the Australian community are succinctly presented in Appendix 3.

Some considerations below are valid for all radiometric measurements, while others are specific to the type of measurements (e.g., in-water and above-water, deployment from either a ship, a mooring or a glider), and the water types (clear open ocean, coastal waters or highly turbid waters).

3.2.1 Sensor's absolute calibrations and characterisation

It is essential to perform regular laboratory calibrations for traceability to SI units (abbreviated from the French 'Le Système International d'Unités'), to monitor possible sensor drift/degradation and therefore to keep track of any change in the stability of sensor's responsivity over time[1-3]. The sensor's responsivity is defined as the output signal of the sensor produced in response to a given incident irradiance or radiance (i.e., input signal). Note that the sensors degradation is not only linked to how often the instrument is used. Properties of some of the sensors' components can also change over time. Absolute calibrations are thus recommended at least once a year, and laboratory and field calibration protocols should be fully recorded. Due to time constraints, logistics (intense field work schedule and long turnover time for manufacturer calibrations) and/or capability in each laboratory (having the right set-up to do in-house calibrations), this is not always possible. However, regular calibrations mean quality radiometric measurements.
In addition to sensors absolute calibrations, sensors detailed characterisation through specific laboratory procedures allows a full characterisation of the responsivity for an individual radiometer or for a class of radiometers.

When possible, inter-calibration and inter-comparison of sensors are also recommended (using Lambertian reference panels such as Spectralon panels for single field of view sensors). For inter-comparison of sensors, see for example the NASA SeaWiFS Inter-calibration Round-Robin Experiments (SIRREX) and the ESA Fiducial Reference Measurement inter-comparison in the Adriatic Sea (FRM4SOC project, see section 4.5 for more information).

For more information on instrument calibration and characterisation, see Vol. II of the NASA Ocean Optics protocols and Chapter 3 of the IOCCG In Situ Optical Radiometry protocols.

3.2.2 Ancillary data and Metadata

It is essential to record key metadata information for processing and quality control of radiometric measurements, and to identify the possible sources of error (see Appendix 2).
Having a 'ready list' of key metadata (e.g., using standard log sheets) is a good safety guard when working at sea (with sometimes non-optimal working conditions). Here, we provide an overview of the key information required.

- Type of instrument, serial number for each sensor (critical over the long-term when we have several sensors or if a sensor needs replacement) and corresponding calibrations prior to the field survey.
- Date and time, latitude and longitude. Generally use UTC, and indicate if otherwise. This information is also needed to calculate the sun zenith angle, which is an important quality criterion for radiometry measurements (e.g., environmental perturbations and resulting uncertainties increase as the sun zenith angle increases[2,3]).
- Cloud cover conditions (% cover, clouds types) and horizontal visibility. Digital photos are recommended: into sun, away from sun and sky view.
- Wind speed and direction, barometric pressure.
- Sea State (digital photos of in water conditions next and away from the profiler are recommended).
- Air and water temperature.
- Bottom depth.

For the full list of ancillary measurements, see Vol. III of the NASA Ocean Optics protocols (section 2.3) and Chapters 2 and 4 of the IOCCG In Situ Optical Radiometry protocols.

3.2.3 Set-up and deployment considerations

Set-up:

- If radiometers are deployed on a frame, record the position of the detector surfaces relative to the pressure sensor of the deployment package (if this is not already part of the default information provided by the manufacturer), and verify their proper alignment. On nominal position, irradiance sensors should have their cosine collector horizontal and radiance sensors have the glass window horizontal as well, so that the sensor points at zenith or nadir respectively (when deployed underwater). It is generally accepted that a tilt < 5 degrees is acceptable, although tilt values < 2 degrees can be maintained with proper care in setting up and deploying instruments.

- Install an above-water reference irradiance sensor when possible (not the case for ocean gliders or moored profilers). Deck sensors should be ideally above any superstructures[3]. When not possible, move them as far as you can from the main ship superstructure. When possible, they are advantageously gimbaled to avoid large errors due to the pitch, roll and yaw of the ship. If the orientation of the ship is going to be often the same, then try to have the deck sensor on the sunny side (e.g., on port for a ship heading east in the southern hemisphere).
- During sensors deployment, avoid shading by the deployment package (cage), platform or perturbation by a superstructure[4-9], even when the instrument is deployed on the illuminated ('sunny') side. Use a freefall profiling system for in-water deployments if possible, otherwise use a boom to deploy as far away from the ship as possible.
- Use the sensor in the configuration it was designed for, in-water or above-water, due to different designs for the collecting surfaces, and as a result different immersion factors to correct for the sensor's cosine collector responses underwater or in the atmosphere[10-13].
- Photos of the instruments set-up, which can be checked later including during the data processing stages.
- For hyperspectral sensors using spectrometers, an internal temperature sensor should be included. This is essential in areas where the field temperature can be quite different from normal room temperatures at which sensors are calibrated (e.g., tropics or polar seas) and thus impact the measurements[14,15].

Deployments:

- Leave instrument to equilibrate with ambient water temperature at the beginning of each cast to avoid sensors temperature biais[14,15], in particular when temperature differences between deck and in water conditions are large. Keep instruments in the shade when not deployed to avoid overheating.
- Dark readings before and after deployments, as they are a function of the instruments internal temperature. When possible, a full cast with the caps ON is useful. Otherwise, measurements with caps ON are performed on deck.
- Do not perform radiometry measurements when the above-surface irradiance is fluctuating too much (e.g., broken clouds). This is going to make data processing extremely difficult, and results will have large uncertainties[3]. If the sky is anyway instable and you still want to collect data, be patient and try to be ready to immediately deploy when a sufficiently "long" time window becomes available (e.g., a good in-water profile can be obtained within < 3 minutes)
- Near-surface measurements profiles should be done through at least the top three optical depths to enable reliable extrapolation to $z=0^-$ (just below the surface), or at least the first optical depth[11].
- Depth resolution: at least 2 and preferably 6 to 8 samples per meter[16].
- Repeat vertical profiles at a given site ('multicasting') to minimize environmental and deployment effects such as wave focussing/defocussing[16-19]. The recommended number of profiles is three per site. Note however that a good cast is better than 3 bad ones. Therefore, when feasible, wait for the optimal sky conditions to perform casts.

- Regularly clean the sensors' collecting surfaces (glass windows for radiance sensors and cosine collectors for irradiance sensors). When not possible on moorings, moored profilers or gliders, minimize biofouling using bio-wipers and/or copper tape around the sensors.

For more information on set-up deployment considerations to take into account for each type of deployment, see Vol. III of the NASA Ocean Optics protocols (Chapter 2 for in-water measurements and Chapter 3 for above-water measurements) and the IOCCG In Situ Optical Radiometry protocols (Chapter 4 for in-water measurements and Chapter 5 for above-water measurements).

3.3 Recommended

- Record additional metadata such as Secchi depth and water colour (e.g., digital photos).
- Sun photometer measurements of aerosol optical depth (together with wind and cloud conditions, they are critical for removing reflected sky radiance from the measured surface radiance[20,21]).
- Standard format log-sheets and metadata digital files for easier merging with data acquired by other team members elsewhere and by teams from other organizations. This will also be particularly valuable further down the line to streamline data processing and exchange information between different teams.
- If such other measurements have been carried out, record filenames of concurrent CTD (temperature and salinity) and Inherent Optical Properties (IOPs) profiles, and sample names of other discrete biogeochemical measurements.

3.4 Avoid

We recall here some common mistakes to avoid (in addition to 'what not to do' from above):

- Install the deck reference where it is going to be inevitably shaded.
- Deploy a sensor designed to be used in-water above the water (and vice versa) due to different collector designs and immersion factors[10-13].
- Leave the instruments on deck exposed to elevated temperature for long periods of time as this leads to a strong increase in the internal temperature of the sensors and impacts the measurements[14,15]. Cover the instruments when required.
- Deploy the sensors too close to the deployment platform (even if on the illuminated side due to the perturbation of the light field associated with the platform[4-9]).
- Forget to take the protective cap off the reference above water sensor (cover the cap with black tape if transparent to realize straightaway when looking at the spectra).

4 Appendix 1: Sources of information on radiometry

4.1 International Ocean Colour Coordinating Group

The IOCCG is an international committee of experts which promotes the application of remotely-sensed ocean-colour/inland water radiometry data across all aquatic environments, through coordination, training, liaison between providers (space agencies) and users (scientists), advocacy and provision of expert advice. Below are some links to specific resources from the IOCCG Publications list, from reference documents and recommendations to training material:

- IOCCG Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry (v3.0)
- INSITU-OCR White Paper (see section 3.0 on In Situ Data)
- IOCCG educational resources

4.2 NASA Ocean Biology Processing Group

The NASA's Ocean Biology Processing Group (OBPG) supports the collection, processing, calibration, validation, archive and distribution of ocean-related products from NASA supported missions. The 'Ocean Color Web' site gives access to a large array of resources, from technical documents to software and processing tools, and data archives.

1. Technical documents (some relevant examples are given below):
   - Ocean Optics protocols: Instrument Specifications, Characterization and Calibration (Volume II) and Radiometric Measurements and Data Analysis Protocols (Volume III).
   - Series of White Papers on specific topics, from data archiving to advances in radiometric measurements in coastal waters.
2. Various processors: Processors from different teams are described in a series of presentations. Practical considerations for case 2 waters radiometric measurements and processing are discussed for example in S. Hooker's presentation.

4.3 Paper Books

The well-known 'reference' paper-back books are listed below:

- 'Light and Water: Radiative Transfer in Natural Waters' by C. Mobley (1994). A PDF copy is available here.
- 'Optical Radiometry for Ocean Climate Measurements' edited by G. Zibordi , C. Donlon, and A. Parr (2014). A preview of the content is available here (IOCCG website).
- 'Light and Photosynthesis in Aquatic Ecosystems' by J. Kirk (2010). A PDF copy can be requested here.
- 'Advances in Ocean Optics: Issues of Closure', Journal of Geophysical Research Special issue (1995), Vol. 100, C7.
- 'Physical Principles of Ocean Color Remote Sensing' by Howard Gordon. For quite advanced users, but useful to understand radiative transfer and ocean colour in general. Available online here.

4.4 Web Book

The Ocean Optics web book by C. Mobley, E. Boss and C. Roesler provides great resources and references in optical oceanography and ocean colour remote sensing both for education purposes and for the broader optical oceanography and ocean colour remote sensing communities.

4.5 Fiducial Reference Measurements for Satellite Ocean Colour

A Remote Sensing journal special issue on fiducial reference measurements was published in 2020 following the FRM4SOC project (funded by ESA). This working group on uncertainties in ocean colour remote sensing and the ocean colour satellite sensor calibration task force conducted a series of comparisons of ground-based measurements of ocean colour parameters to evaluate and improve the state-of-the-art in ocean colour validation.
See also the FRM4SOC technical report 'A review of commonly used fiducial reference measurement (FRM) ocean colour radiometers (OCR) used for satellite OCR validation'.

4.6 Australian-specific resources/information

IMOS Radiometry task team (2016-2017)

The IMOS Radiometry Task Team objectives were to perform activities that can ultimately improve usability of IMOS radiometric data sets for research purposes and for validation of satellite ocean colour products. This includes an inter-comparison exercise of various in situ radiometers at the Lucinda Jetty Coastal Observatory (North Queensland) and, as mentioned earlier, the establishment of a series of recommendations provided in the Final Report.

IMOS Bio-optical working group (2008-2012)

The IMOS National Working Group on Bio-optical Instrumentation and Observing aim was to tackle issues of national relevance related to bio-optical measurements and interpretation (in particular for the IMOS facilities). This working group issued a series of recommendations on in situ fluorescence[22], scattering and turbidity measurements.

5 Appendix 2: Considerations on sources of uncertainties in radiometric measurements

The FRM4SOC working group (see FRM4SOC and Remote Sensing journal special issue) presents the most recent synthesis on fiducial reference measurements of water-leaving irradiance and radiance, from a review of measurements protocols[2,3] to inter-comparisons of radiometric measurements in the laboratory[23] and in the field[8]. Below, we provide an overview of the different sources of uncertainty in radiometric measurements and the corresponding references for more details on the topic. Some considerations are valid for all radiometric measurements while others are specific to the type of measurement (e.g., in-water or above-water measurements) or deployment (e.g., oceanographic cruise, fixed platform, mooring, gliders, underway measurements).

For more information on sources of uncertainties, see Vol. III of the NASA Ocean Optics protocols (Chapter 2 for in-water measurements and Chapter 3 for above-water measurements) and the Data analysis sections in Chapter 4 and Chapter 5 of the IOCCG In Situ Optical Radiometry protocols.

5.1 Instrument itself (instrument characteristics/performance, calibration), deployment conditions and operation

The first level of uncertainties is inherent to the instrument itself, due to factors such as straylight[24,25], out-of-band response, non-linear and non-cosine response for irradiance sensors[8,12], and immersion factors[10-13]. The second level of uncertainty is the instrument deployment conditions and operation, such as instrument tilt, self-shading by the instrument housing and deployment platform[4-9], the sensor's internal temperature[14,15], inelastic processes[26] and waves perturbations[17-19,27]. Some issues are specific to deployment type, such as perturbations from a superstructure (ship or fixed platform[11,28-30]), profiling floats[31], long term deployments (e.g., biofouling), or above-water measurements (e.g., sunglint[32] and sky-light polarization[19,27,33]).

5.2 Data reduction/processing

During the data reduction/processing steps, we aim to correct for the errors introduced by the instrument itself and the environmental variability and perturbations. The resulting sources of uncertainty include:

- Instruments corrections (calibration and characterization, depth offset and dark offsets, and self-shading perturbations, as described in section 3.2.1).
- Extrapolation methods applied to in-water measurements to derive sub-surface values: the extrapolation method and layer selected, the method used to minimize measurements artefacts such as outliers or elevated tilt, and the correction for bidirectional effects and inelastic processes[16-19,26,34-40]. Sub-surface extrapolations are particularly impacted by environmental factors such as changes in illumination conditions and water optical properties during a given profile, and by wave perturbations on the measurements.
- Estimation of above-water irradiance: it is not recommended to estimate the above-water irradiance from in-water determinations except when above-water irradiance cannot be measured during a deployment (e.g., glider or moored profiler).
- Estimation of the remote sensing reflectance, by normalization of in-water measurements by surface irradiance from above-water sensors with different sampling rates and tilts. A recent study[8] showed that downwelling irradiance measurements accounted for most of the variance in the remote sensing reflectance, underlying the need to minimize errors in irradiance measurements.
- Biases from incorrect reflectance convolution[41].
- For above-water radiometric measurements: corrections for the non-nadir viewing geometry and accuracy of the surface reflectance factors[42,43].
- Bottom effects in shallow waters.

5.3 Uncertainty budgets

Uncertainty budgets can be estimated for field measurements from different platforms/set-up[2,3,11] (oceanographic campaigns[34], buoys[44-46], fixed observing systems[47-49], autonomous profiling systems[31] and unattended above-water radiometers[50,51]). Uncertainties should be provided in both % and physical units, and are range and measurement conditions specific. To improve these estimates, additional characterization of radiometers and environmental ancillary measurements are recommended[2,3,11].

Note: This section on uncertainties is a work in progress, relevant additional information will be added as we progress. Comments Welcome.

6 Appendix 3: Commercially Available Radiometers.

Below is a table with the commercially available multi-spectral and hyperspectral radiometers, manufacturers and corresponding websites.

Radiometer name	Deployment Platform(s)	Spectral range and resolution (nm)	Manufacturer	Above- or in-water
C-OPS	C-OPS Free-fall profiler	19 bands	Biospherical Instruments	In-water
OCR-500 series	Gliders, Moorings, Profiling system	4 bands	Sea-bird (Satlantic)	In-water
SEAPRISM CE318-TV12-OC	SEAPRISM system, fixed platforms	12 bands	Cimel	Above water
HyperOCR	HyperPRO free-fall profiler, Thetis moored profiler	350-900 nm, 3nm step	Sea-bird (Satlantic)	In-water
	HyperSAS system			Above-water
DALEC	Underway from ship or fixed platform (e.g., LJCO)	350-900 nm, 3nm step	In-Situ Marine Optics	Above water
RAMSES	Profiling system	350-900 nm, 3nm step	TriOS	In- and above-water
ASD FieldSpec	Portable, hand-held	350 – 2500 nm	Malvern Panalytical	In and above-water
SR-3500	Portable, hand-held	350-2500 nm	Spectral Evolution	Above-water
WISP-3	Portable, hand-held	350-800 nm	Water Insight	Above-water

7 References List

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