Above- and in-water radiometry: Methods and Calibration

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Satellite and *In Situ* Observations

The Global Climate Observing System (GCOS) requires calibration and validation actions to ensure a confident application of remote sensing products to long-term monitoring of the Earth’s surface.

Most of the actions satisfying the former requirement for satellite ocean color products, need accurate and globally distributed *in situ* radiometric measurements.

Such a need, motivated by the production of highly accurate Ocean Color Essential Climate Variables for the creation of Climate Data Records, has become the rationale for advanced research in marine radiometry during the last two decades.
Fully recognizing the effort that since early 1920s generated know-how in marine optical radiometry, quantitative optical radiometry started only in the mid 1960’s thanks to development of spectral radiometers (Jerlov 1965, Tyler et al 1970) and highly accurate secondary standards of spectral irradiance (Slater 1980).

Major advances in the assessment and implementation of *in situ* optical radiometry methods were driven by satellite missions aiming at mapping the phytoplankton biomass at global scale.

The SeaWiFS program played a major role in such a development and assessment for more than a decade by supporting SIRREXs (e.g., Mueller 1992, Johnson et al. 1995, Johnson et al. 1999, Hooker et al. 2002, Zibordi et al. 2002) and finalizing the ocean optics protocols (e.g., Mueller and Austin 1992, Mueller et al. 2003).
In Situ Data and Satellite Ocean Color

Data Reception and Processing

Atmosphere

Sea Surface

Remote Sensor Pre-Launch Calibration

Remote Sensor Vicarious Calibration

In Situ Instrument Calibration

Traceable Reference

Products Development

Products Validation
Requirements for field data supporting cal/val programs

1. **Traceable** (measurements should have well defined uncertainties quantified, when possible and appropriate, through standards);

2. **Globally distributed** (measurements should represent the wide range of geophysical conditions that remote sensing systems are expected to observe);

3. **Continuous** (time-series of quality assured data are fundamental for assessing remote sensing products from individual and mostly successive space missions);

4. **Cross-site consistent** (measurement uncertainties should be likely the same for all measurement sites and measurement conditions);

5. **Accessible** (measurement availability, through suitable data policy, is a key element for any actual cal/val program).
Radiometric Definitions

National Physical Laboratory. Units and Standards of Measurements employed at the National Physical Laboratory: II Light. 5, 1-8, 1952.

Radiometry is the measurement of physical quantities like radiance and irradiance, performed through light-measuring instruments called radiometers.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant Energy</td>
<td>( Q )</td>
<td>Joule</td>
</tr>
<tr>
<td>Radiant Flux</td>
<td>( \Phi )</td>
<td>Watts (Joule/sec)</td>
</tr>
<tr>
<td>Irradiance</td>
<td>( E )</td>
<td>Watts/m(^2)</td>
</tr>
<tr>
<td>Radiance</td>
<td>( L )</td>
<td>Watts/(m(^2) sr)</td>
</tr>
<tr>
<td>Irradiance Reflectance</td>
<td>( E_u/E_d )</td>
<td>-</td>
</tr>
<tr>
<td>Remote Sensing Reflect.</td>
<td>( L_u/E_d )</td>
<td>sr(^{-1})</td>
</tr>
<tr>
<td>Q-factor</td>
<td>( E_u/L_u )</td>
<td>sr</td>
</tr>
</tbody>
</table>
Radiometers

A radiometer is composed of at least three basic components:
1. the optics which collect the input radiant flux through an aperture, decompose it through spectral filters (or alternatively disperse it through prisms or gratings), and focus it on a field stop;
2. the detector which transduces the input radiant flux received through the field stop into an electrical signal;
3. the analog to digital converter which translates the analog output of the detector (typically a voltage or a current) into a digital number.
Of all the techniques used in remote sensing, the observation of the Earth from optical sensors is perhaps the most easily understood in concept, because it is the most similar to our own personal remote sensing device – the human eye.

Ian Robinson (2004)
In-Water Radiometry

**Historical dates**
- 1920s: First successful measurements
- 1960s: Accurate absolute calibrations
- 1990s: Methods assessment
- 2000s: Accurate uncertainty analysis
In-Water Radiometry

Normalization to account for fluctuations in illumination

Extrapolation just below the surface

Propagation through the surface

Transformation to exact normalized water-leaving radiance

\[ L_{u}(z, \lambda, t) = \frac{L_{u}(0^+, \lambda, t)}{L_{u}(0^+, \lambda, i)} E_{d}(0^+, \lambda, t) \]

\[ L_{u}(0^+, \lambda, t) = L_{u}(z_0, \lambda, t_0) - K_{t}(\lambda, z_1, z_2)z_0 \]

\[ L_{wn}(\lambda) = L_{w}(\lambda) \frac{E_{0}(\lambda)}{E_{d}(0^+, \lambda)} C_{\text{wn}}(\lambda, \theta, \tau_a, IOP) \]


Assigning vertical profiles of the downward irradiance $E_d$ and its diffuse attenuation coefficient $K_d$ on the basis of the data measured during vertical movement of the probe in the most upper layer of the sea is improper, or at least extremely inaccurate.

The use of two integrating detectors working simultaneously at different depth appears to be much more accurate to calculate optical profiles in the most upper layer.

An (almost) Anonymous Reviewer, 2003
Comparisons have generally been made using independent measuring systems, without explicitly quantifying the uncertainties related to:

a. the measuring systems (e.g., absolute calibration, immersion factor, self-shading), and

b. the measurement methods (i.e., fixed-depth and continuous profiling).

A specific comparison was performed utilizing identical:

i. instrumentation;

ii. deployment structure and

iii. processing code.

Fixed-depth and Continuous Profile Data

As long as discrete deployment depths are properly selected, fixed-depth and continuous profile data products are equivalent (i.e., inter-comparisons will exhibit statistical differences lower than the composition of the uncertainties from individual methods).

Depth resolution

$E_d$ from profiles produced with different depth resolutions

Uncertainty in sub-surface values as function of depth resolution

$K_d(490)=0.2 \text{ m}^{-1}$
$W_h=0.1 \text{ m}$

$K_d(490)=0.2 \text{ m}^{-1}$
$W_h=0.1 \text{ m}$

$K_d(490)=0.1 \text{ m}^{-1}$
$W_h=0.4 \text{ m}$

$K_d(490)=0.1 \text{ m}^{-1}$
$W_h=0.4 \text{ m}$

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BiOMaP (Bio-Optical Marine Properties): a European Ocean Color Development Program

BiOMaP measurements are produced applying cross-site identical and consolidated: technology, measurement and calibration protocols, processing codes and quality assurance criteria.

BiOMaP (Bio-Optical Marine Properties): \( L_{WN} \) spectra from the various European Seas

Radiance distribution (now)

NURADS
(Voss & Chapin 2005)

Upwelling radiance distribution
(MOBY site)


Above-Water Radiometry

Above-Water Radiometry

**Historical dates**
- 1920s: First observations
- 1980s: First documented methods
- 1990s: Methods assessment
- 2000s: Accurate uncertainty analysis
The viewing geometry: a key element for above-water radiometry.

Sea-surface reflectance

Above-Water Radiometry

Removal of sky-glint contribution
Correction for off-nadir view
Transformation to exact normalized water-leaving radiance


\[
L_W (\varphi, \theta, \lambda) = L_T (\varphi, \theta, \lambda) - \rho (\varphi, \theta, \theta_0, W) L_i (\varphi, \theta', \lambda)
\]

\[
L_W (\lambda) = L_T (\lambda) C_{\text{OP}} (\lambda, \theta, \varphi, \theta_0, \tau_a, \text{IOP}, W)
\]

\[
L_{\text{wn}} (\lambda) = L_W (\lambda) \left( D^2 t_d (\lambda) \cos \theta \right)^{-1} C_{\text{OP}} (\lambda, \theta_0, \tau_a, \text{IOP})
\]
Wave-Perturbations


Dynamic Filtering

Threshold Filtering

Threshold Filtering

Data Rejection =10%, d=17%

Data Rejection =50%, d=12%

Data Rejection =95%, d=6%

Average before data rejection

Average after data rejection
Viewing-angle dependence

\[ \theta = 30^\circ \]
\[ \phi = 90^\circ \]
\[ \rho = 0.030 \]

\[ \theta = 40^\circ \]
\[ \phi = 90^\circ \]
\[ \rho = 0.028 \]

Current management and responsibilities

- **NASA** manages the network infrastructure (i.e., handles the instruments calibration and, data collection, processing and distribution within AERONET).
- **JRC** has the scientific responsibility of the processing algorithms and performs the quality assurance of data products.
- **PIs** establish and maintain individual AERONET-OC sites.
Examples of AERONET-OC Sites

Site: AAOT
Location: Northern Adriatic Sea
Water type: Case-1/Case-2
Period: 2002–present

Site: GDLT
Location: Northern Baltic Proper
Water type: Case-2
Period: 2005–present (summer)

Site: AABT
Location: Persian Gulf
Water type: Case-1 (?)
Above- v.s. In-Water

Above-Water

Advantages
1. Long-term deployments are insensitive to bio-fouling
2. Insensitive to coastal water optical stratifications
3. Relatively fast deployment time during short-term activities

Drawbacks
1. Cannot produce profiles of radiometric quantities
2. Restricted to a few radiometric quantities (i.e., $L_w$)
3. Highly sensitive to wave perturbations

In-Water

Advantages
1. Produces comprehensive (fixed depths or continuous) profiles of radiometric quantities
2. Open to several radiometric quantities (i.e., $L_w$, $E_d$, $E_u$)
3. Upward radiometric quantities are almost not affected by wave perturbations

Drawbacks
1. Long-term deployments can be very sensitive to bio-fouling
2. Relatively slow deployment time during short-term activities
3. Sensitive to coastal water optical stratifications
Radiometric Calibration: Absolute

The process of quantitatively defining the system response to known and controlled signal inputs (in the specific case of radiometry this is achieved with a "(working) reference standard" that provides a direct realization of a radiometric SI quantity).
Calibration Equation for a Field Radiometer

\[ R(\lambda) = C_{R}(\lambda)I_{f}(\lambda)[D_{N}(\lambda) - D_{0}(\lambda)] \]

- \( R(\lambda) \): Radiometric Quantity, \( E \) or \( L \)
- \( D_{N}(\lambda) - D_{0}(\lambda) \): Measurement in Relative Units
- \( C_{R}(\lambda) \): In-Air Calibration Factor
- \( I_{f}(\lambda) \): Immersion Factor \((I_{f} \neq 1 \text{ for in-water meas.})\)
In-Air Absolute Irradiance Calibration

\[ C_E(\lambda) = \frac{E_0(\lambda) \left(\frac{d_0}{d}\right)^2}{D_N(\lambda) - D_0(\lambda)} \]

- **\( C_E \)**: Calibration coefficient
- **\( E_0 \)**: Lamp Irradiance at distance \( d_0 \)
- **\( D_N \)**: Sensor output with the source at distance \( d \)
- **\( D_0 \)**: Sensor output without any source (dark signal)
In-Air Absolute Radiance Calibration

\[ C_L(\lambda) = E_0(\lambda) \left( \frac{d_0}{d} \right)^2 \left( \frac{\rho(\lambda)}{\pi} \right) c_p(\theta) / (D_N(\lambda) - D_0(\lambda)) \]

**C\(_L\)**: Calibration coefficient

**E\(_0\)**: Lamp Irradiance at distance \( d_0 \)

**D\(_N\)**: Sensor output with the source at distance \( d \) from the Standard Plaque

**D\(_0\)**: Sensor output without any source (dark signal)

**\( \rho \)**: Reflectance of the Standard Plaque

**\( c_p \)**: Correction factor for the non-Lambertian response of the Plaque at angle \( \theta \)

For a Lambertian source \( L = E/\pi \)