Advanced Methods for Characterizing the Immersion Factor of Irradiance Sensors

STANFORD B. HOOKER

Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, Maryland

GIUSEPPE ZIBORDI

Institute for Environment Sustainability, Joint Research Centre, Ispra, Italy

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ABSTRACT

Two new immersion factor methods are evaluated by comparing them with the so-called traditional (or incremental) method. For the first method, the optical measurements taken at discrete water depths are substituted by continuous profiles created by removing the water from the tank used in the experimental procedure at a constant flow rate with a pump. In the second method, the commonly used large tank is replaced by a small water vessel with sidewall baffles, which permits the use of a quality-assured volume of water. The summary of the validation results produced for the different methods shows a significant convergence of the two new methods with the traditional method with differences generally well below 1%. The average repeatabilities for single-sensor characterizations (across seven wavelengths) of the three methods are very similar and approximately 0.5%. The evaluation of the continuous method demonstrates its full applicability in the determination of immersion factors with a significant time savings. The results obtained with the small water vessel demonstrate the possibility of significantly reducing the size of the tank (along with decreasing the execution time) and permitting a completely reproducible methodology (based on the use of pure water). The small tank approach readily permits the isolation and quantification of individual sources of uncertainty, the results of which confirm the following aspects of the general experimental methodology: (a) pure water is preferred over tap water, (b) the water should not be recycled (so it does not age), (c) bubbles should be removed from all wetted surfaces, (d) the water surface should be kept as clean as possible, (e) sidewall reflections can be properly minimized with internal baffles, and (f) a pure water characterization can be easily corrected to produce an appropriate seawater characterization. Within the context of experimental efficiency and reproducibility, this study suggests that the combination of a properly baffled small tank with a constant-flow pump would be an optimal system.

1. Introduction

The immersion factor $I_f(\lambda)$ is a necessary part of the spectral characterization of an in-water irradiance sensor (λ denotes wavelength), because when a cosine collector is immersed in water, its light transmissivity is less than it is in air. Irradiance sensors are calibrated in air, however, so a correction for this change must be applied when the in-water raw data are converted to physical units. The immersion factor must be determined experimentally, using a laboratory protocol, for each collector. When in situ measurements are used to create ground-truth databases for remote sensing calibration and validation activities, like those established for the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) project (Hooker and Esaias 1993), the uncertainties in the former ultimately influence the quality of the data products. The SeaWiFS ground-truth uncertainty budget can only be satisfied if each contributing uncertainty is on the order of 1%–2% (Hooker and McClain 2000). As a generalized description, this constitutes so-called 1% radiometry; in other words, uncertainty sources in the calibrated use of a sensor—like the immersion factor—must be kept at approximately the 1% level.

Studies of immersion effects date back to the work of Atkins and Poole (1933), who attempted to experimentally estimate the internal and external reflections for an opal glass diffuser. Additional investigations by

Corresponding author address: Stanford B. Hooker, Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
E-mail: stan@ardbeg.gsfc.nasa.gov

Berger (1958, 1961) refined the laboratory procedures, and Westlake (1965) gave detailed explanations for the internal and external reflection contributions. Although there were aspects of the protocols used in these early investigations that are no longer considered appropriate, many of the primary elements were properly recognized.

- A source of constant light flux is needed to vertically illuminate a diffuser at the bottom of a water vessel that has been blackened (and perhaps roughened) with waterproof *dull* black paint to minimize reflections.
- The measurements must be made in a dark room, with baffles and screens used to (a) eliminate diffuse light originating from the light source and (b) to illuminate an area only slightly larger than the diffuser.
- In-air and in-water measurements are required, and the latter should be made using optically clear water (frequently interpreted to mean tap water) or pure (distilled) water.
- A variety of water depths above the diffuser are measured, but they must exceed a so-called critical depth, $z_c = 0.9\ R_d$, where R_d is the radius of the diffuser.
- Air bubbles must be minimized, because they can create *conspicuous* bright patches, and contamination from soluble *coloring matter*, perhaps derived from the components placed in the water vessel, can influence the properties of the water being used and cannot be removed by filtering the water.

A comprehensive description of a protocol for a more modern Plexiglas diffuser was given by Smith (1969) and recommended the use of a collimated beam as a light source to avoid changes in the flux reaching the collector when the water depth changed. The study presented here is concerned with more recent diffuser designs and laboratory protocols. For the latter this means the incremental, or what is now referred to as the traditional, method. The traditional method has been in use for the past 25 yr, and originated with the protocol revisions suggested by Aas (1969) and communicated more widely by Petzold and Austin (1988). They all advocated using a lamp as a light source and including a geometric correction factor as a function of the lamp-collector distance, incremental changes in the water depth, and the water refractive index.

Mueller (1995) used the traditional method to analyze Plexiglas and Teflon diffusers for several radiometers from the same manufacturer. At any given wavelength, the immersion factors had a standard deviation (σ) between collectors that typically ranged from 3% to 5%, with total variations at some wavelengths as large as 10%. More recently, Zibordi et al. (2004) investigated the immersion factors for nine OCI-200 sensors, manufactured over a 7-yr time period by Satlantic, Inc. (Halifax, Nova Scotia, Canada), as part of the eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8). The sensors, which had identical (nominal) center wavelengths, were characterized at three different facilities (including the manufacturer's) using virtually the same traditional method. One of the radiometers was selected as a so-called reference sensor and was measured more frequently than the others.

The SIRREX-8 data showed intralaboratory repeatabilities, based on multiple characterizations of the reference radiometer, that ranged from about 0.3% to 0.6%. Interlaboratory uncertainties, evaluated with data from the nine common radiometers, showed average values lower than 0.6%. Typical $I_f(\lambda)$ values, constructed from quality-assured averages of the sensors, were less than the values supplied by the manufacturer (except one red wavelength), but were approximately within the range of variability established by Mueller (1995): more than 10% in the blue domain, and approximately 2%–6% in the green and red regions. The SIRREX-8 activity also demonstrated the inefficiencies of the traditional method: (a) sensor trial times were very long, requiring 100–330 min; and (b) the water tanks were large with water volumes measured in hundreds or thousands of liters. The lengthy experimental time limited the number of sensors characterized per day to two to five, while the large tanks required spacious work rooms, a significant capability to deal with the large amounts of water, and irreproducible volumes of water (between laboratories).

As a separate inquiry, alternatives to the traditional method (section 2) were proposed and tested with specific experiments interspersed with those designed to meet the SIRREX-8 intercomparison objectives. The new methods centered around decreasing the amount of time to execute an instrument trial and reducing the size of the experimental apparatus (specifically, the water vessel). The latter was achieved by refining the capabilities of the Compact Portable Advanced Characterization Tank (ComPACT), which had already been built for working with immersed sensors (section 3). The time efficiency was achieved primarily by making a small change to the traditional method (section 4a), and then refining the generalized protocol for the ComPACT apparatus (section 4b). The data processing requirements for the new methods share many elements with the traditional method, and the results from the use of these new capabilities (section 5) suggest they are sufficiently accurate to replace the traditional method (section 6).