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Stanford B. Hooker and Elaine R. Firestone, Editors

Volume 26, New Laboratory Methods for Characterizing the Immersion Factors of Irradiance Sensors

Giuseppe Zibordi, Davide D'Alimonte, Dirk van der Linde, Stanford B. Hooker, and James W. Brown

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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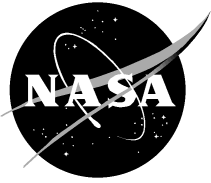
SeaWiFS Postlaunch Technical Report Series

Stanford B. Hooker, Editor
NASA Goddard Space Flight Center, Greenbelt, Maryland

Elaine R. Firestone, Senior Scientific Technical Editor
Science Applications International Corporation, Beltsville, Maryland

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Giuseppe Zibordi, Davide D'Alimonte, and Dirk van der Linde
JRC/Institute for Environment Sustainability, Ispra, Italy

Stanford B. Hooker
NASA Goddard Space Flight Center, Greenbelt, Maryland

James W. Brown
RSMAS University of Miami, Miami, Florida

July 2003

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

PREFACE

One of the primary objectives of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Calibration and Validation Program has been to improve *in situ* measurement accuracies. This has been pursued through calibration and data analysis round robins; measurement protocol development and evaluation; and instrument design, development, and performance analysis. These activities have made a substantial improvement in our satellite products and our ability to validate those products. In the present case, the authors revisit the measurement of the immersion factors for submersible irradiance instruments. The immersion factor corrects the instrument calibration, which is performed in air, to account for changes in the cosine collector transmissivity when in water.

Historically, immersion factors were assumed to be constant for a particular material and design with little regard for how the values might change over time or for different lots of the same material. This practice was largely because of the rather cumbersome and time consuming method of measurement, which required a large tank, and the assumption that other measurement errors were much larger. In Volume 21 of the *SeaWiFS Postlaunch Technical Report Series*, results from an immersion factor intercomparison experiment showed that errors greater that 10% in the blue portion of the spectrum have been present in our existing data sets from some instruments. The results also showed a need for characterizing each single irradiance sensor to appreciably increase the accuracy of in-water measurements, and demonstrated the difficulty of standardizing immersion factor measurements at different laboratories despite the adoption of the same basic protocol.

In this volume, the authors go into greater detail on the measurement methodology and data analysis. They also describe a much simpler, yet highly accurate, measurement apparatus and methodology they developed, which will allow more routine characterizations of irradiance immersion factors. This work underscores the importance of continued scrutiny of instrument calibration methods, and the need for ongoing measurement technology development support.

Greenbelt, Maryland — C. R. McClain
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Table of Contents

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

ABSTRACT

The experimental determination of the immersion factor, $I_f(\lambda)$, of irradiance collectors is a requirement of any in-water radiometer. The eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8) showed different implementations, at different laboratories, of the same $I_f(\lambda)$ measurement protocol. The different implementations make use of different setups, volumes, and water types. Consequently, they exhibit different accuracies and require different execution times for characterizing an irradiance sensor. In view of standardizing the characterization of $I_f(\lambda)$ values for in-water radiometers, together with an increase in the accuracy of methods and a decrease in the execution time, alternative methods are presented, and assessed versus the traditional method. The proposed new laboratory methods include: a) the continuous method, in which optical measurements taken with discrete water depths are substituted by continuous profiles created by removing the water from the water vessel at a constant flow rate (which significantly reduces the time required for the characterization of a single radiometer); and b) the Compact Portable Advanced Characterization Tank (ComPACT) method, in which the commonly used large tanks are replaced by a small water vessel, thereby allowing the determination of $I_f(\lambda)$ values with a small water volume, and more importantly, permitting $I_f(\lambda)$ characterizations with pure water. Intercomparisons between the continuous and the traditional method showed results within the variance of $I_f(\lambda)$ determinations. The use of the continuous method, however, showed a much shorter realization time. Intercomparisons between the ComPACT and the traditional method showed generally higher $I_f(\lambda)$ values for the former. This is in agreement with the generalized expectations of a reduction in scattering effects, because of the use of pure water with the ComPACT method versus the use of tap water with the traditional method.

Prologue

When an irradiance sensor is illuminated, the raw optical data at each wavelength, λ, are recorded as digitized voltages, $V(\lambda)$, in counts. Each sample is recorded at a specific time, t_i, which also sets the water depth, z. Raw irradiance data are typically converted to physical units using a calibration equation of the following form:

$$E_{\text{cal}}(\lambda, t_i) \;=\; C_c(\lambda)\, I_f(\lambda)\, E(\lambda, t_i), \qquad (1)$$

where $E_{\text{cal}}(\lambda, t_i)$ is the calibrated irradiance, $C_c(\lambda)$ is the calibration coefficient (determined during the radiometric calibration of the sensor), $I_f(\lambda)$ is the so-called *immersion factor*†, and $E(\lambda, t_i)$ is the net signal detected by the radiometer while exposed to light.

In most cases,

$$E(\lambda, t_i) \;=\; V(\lambda, t_i) \;-\; \bar{D}(\lambda), \qquad (2)$$

where $\bar{D}(\lambda)$ is the average bias or dark voltage measured during a special *dark cast* with the caps on the radiometer. In some cases, dark voltages are replaced by so-called *background* or *ambient* measurements, so illumination biases can be removed along with the dark correction. The latter is particularly important if the room where the experimental procedures are being conducted cannot be completely darkened.

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† For the purposes of the calibration equation, the immersion factor for an above-water irradiance sensor is always equal to unity.

The immersion factor is a necessary part of the characterization of an in-water irradiance sensor, because when a cosine collector is immersed in water, its light transmissivity is less than it was in air. Irradiance sensors are calibrated in air, however, so a correction for this change in collector transmissivity must be applied when the in-water raw data are converted to physical units. The immersion must be determined experimentally, using a laboratory protocol, for each collector.

Studies of immersion effects date back to the work of Atkins and Poole (1933) who attempted to describe the internal and external reflection factors for an opal glass diffuser. To experimentally estimate these reflection contributions, they used a gas-filled lamp as a light source to vertically illuminate a diffuser at the bottom of a water vessel filled with varying depths of *distilled* water. Measurements were taken in air and in water, with distinctions (and corrections) made for *dry* and *wet* in-air measurements (the latter is distinguished from the former by a few millimeters of water on the diffuser). The in-water measurements were made in a *blackened* water vessel at a variety of depths using a protocol that recognized the importance of a water depth exceeding 0.9 times the radius of the diffuser. Based on many trials, a constant value of $I_f = 1.09$ was proposed for opal glass diffusers (the most popular diffuser material of the time).

Berger (1958) presented a discussion of immersion effects in the presence of a thin layer of water producing direct reflections between the external surface of the diffuser

and the water subsurface (a limiting element in the characterization of the immersion factor), as well as a method to experimentally determine the immersion factor for disk-shaped diffusers. The method was based on a wooden tub, with its inner surface roughened and coated with *dull* black paint to prevent the generation of upwelled light. The tub was dimensioned to hold a depth of clear *tap* water above the diffuser that exceeded a so-called *critical* depth, $z_c = 0.9\,R_d$, where R_d is the radius of the diffuser. For the diffuser designs of the time, the water depth was usually less than 5 cm.

Berger (1958) also included experimental observations and theoretical data on the immersion effects for different disk-shaped diffusers made of plastic and silicate glass showing a wide range of variations for the immersion factor. The culmination of these analyses was a proposed method using a wide, blackened funnel and *optically clear, pure* water. The flare of the funnel was to be approximately 120° to ensure the funnel did not generate any upwelling light that might reflect onto the diffuser. The water depth was to be determined using the $z \geq 0.9\,R_d$ restriction.

Data from Berger (1961) were later used by Westlake (1965) to extensively describe the reflection-refraction processes occurring at the air–diffuser and water–diffuser interfaces in the presence of thin or deep layers of water. Westlake (1965) presented estimates of the different internal and external reflection contributions and suggested a constant immersion factor of $I_f = 1.19$ for opal glass diffusers, significantly higher than that proposed by Atkins and Poole (1933).

A comprehensive description of a protocol for the experimental characterization of the immersion factor of underwater irradiance collectors, was given by Smith (1969). The protocol, which included vertical measurements in air and in water with different depths of water above the diffuser, suggested the use of a collimated beam as a light source to avoid changes in the light flux reaching the collector when different water depths were used. Smith (1969) presented a spectral characterization of the immersion factor of a cosine collector made of clear Plexiglas™† bonded together with translucent Plexiglas (with the latter in contact with water). The immersion factors ranged from 1.34–1.22, almost linearly varying in the spectral range 400–750 nm (as summarized in Tyler and Smith 1970) and qualitatively explained the spectral values with a dependence on the absorbance of the collector.

For the purposes of this study, the so-called *traditional* method for characterizing the immersion factor of in-water irradiance collectors has been in use for the past 15 years, and originated with the protocol revisions suggested by Petzold and Austin (1988). They proposed using a lamp

as a light source by introducing a geometric correction factor that, as a function of the lamp–collector distance, water depth, and water refractive index. The advantage of the geometric correction factor is it minimizes the effects caused by changes in the flux reaching the collector as a function the change in water depth.

Mueller (1995) used the Petzold and Austin (1988) method and analyzed diffusers manufactured with Plexiglas and Teflon™‡ for several radiometers from the same manufacturer. The $I_f(\lambda)$ values had a very nearly linear dependence with wavelength, and ranged, on the average, from 1.38–1.32 in the spectral region 406–670 nm.

More recently, Zibordi et al. (2002) investigated the immersion factors supplied by an individual commercial manufacturer of in-water irradiance sensors as part of the eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8). The SIRREX-8 activity involved nine irradiance sensors, with identical (nominal) center wavelengths, manufactured over a seven-year time period. The sensors were all characterized at three different facilities, one of which was the manufacturer's, using similar laboratory protocols. One of the radiometers was selected as a so-called *reference* sensor and was measured more frequently than the other eight.

The analysis of the SIRREX-8 data showed intralaboratory measurement repeatabilities, evaluated through multiple characterizations of the reference radiometer and defined by two standard deviations, ranging from approximately 0.3–0.6%. Interlaboratory uncertainties, evaluated with data from the nine common radiometers, showed average values lower than ±0.6%. Typical $I_f(\lambda)$ values from SIRREX-8, constructed from quality-assured averages of the various sensors, differed from the values originally supplied by the manufacturer by more than 10% in the blue part of the spectrum, and approximately 2–6% in the green and red regions. In all cases, except one red wavelength, the new immersion factors were less than those supplied by the manufacturer.

The SIRREX-8 activity also demonstrated the inefficiencies of the traditional method: a) sensor trial times were long; and b) the water tanks were large or very large, so the volumes of water involved were measured in hundreds (even thousands) of liters. The lengthy experimental time limited the number of sensors characterized per day to 2–5, while the large tanks required commensurately large work spaces and a significant capability to deal with the large amounts of water.

As a separate part of the SIRREX-8 activity, a smaller team of scientists discussed alternatives to the traditional method, and tested the agreed upon ideas with specific experiments. The new methods centered around decreasing the amount of time to execute an instrument trial, and reducing the size of the experimental apparatus (i.e.,

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† "Plexiglas" is a registered trademark of Röhm GmbH and Co. KG (Darmstadt, Germany).

‡ "Teflon" is a registered trademark of E.I. du Pont de Nemours and Co. (Wilmington, Delaware).

the water vessel). The former was addressed primarily by making a relatively small change to the traditional method (Chapt. 2); whereas, the latter was achieved by refining the capabilities of the Compact Portable Advanced Characterization Tank (ComPACT), which had already been built for experimenting with immersed sensors (Chapt. 3), and then defining a protocol for using this new piece of equipment (Chapt. 4). The data processing requirements for the new methods share a great deal with the traditional method (Chapt. 5), and the preliminary results from the use of these new capabilities suggests they are both sufficiently accurate to be used as alternatives to the traditional method (Chapt. 6).

The international science team assembled to investigate new laboratory methods for characterizing in-water irradiance sensors was composed of groups already capable of executing an experimental protocol or groups working on an alternative protocol (Appendix A). The primary participating organizations were the Joint Research Centre (JRC) and the Goddard Space Flight Center (GSFC). A summary of the material presented in each chapter is given below.

1. The Traditional Method

Whether for a single aperture or multi-aperture sensor, the traditional method for characterizing the immersion factor of an in-water irradiance sensor involves a relatively simple procedure and can be recounted as a small number of steps: a) a tungsten-halogen lamp, with a small filament and powered by a stable power supply, is placed at some distance above the diffuser(s); b) the instrument is placed in a tank of water with the irradiance diffuser(s) level and facing upward; c) the depth of the water is lowered in (5 cm) increments and readings are recorded for all wavelengths from each carefully measured depth; d) a final reading is taken with the water level below the collector(s) with the diffuser(s) dry. Computing the immersion factor from the recordings requires a correction to the irradiance values at each depth interval to account for the change in solid angle of the light leaving the source and arriving at the diffuser(s), which is caused by the light rays geometrically changing direction at the air–water interface.

2. The Continuous Method for Determining Immersion Factors

The continuous method was implemented as a modification to the traditional method. In the latter, a series of incremental water depths are created by emptying (or filling) the water vessel in discrete intervals, whereas for the former, the tank is emptied (or filled) using a constant flow-rate pump. The tank emptying (or filling) is carried out in conjunction with the data logging, which leads to the creation of an optical profile, where the depth variable is the varying thickness of the water layer above the sensor. When compared to the traditional method, the continuous method provides a much faster execution of the ensemble

of measurements required for $I_f(\lambda)$ determination. In the specific case of the traditional method implemented at the Center for Hydro-Optics and Remote Sensing (CHORS), the execution time can be reduced from 120 min to 35 min.

3. The ComPACT Mechanical Design

The ComPACT unit was designed for the execution of quality tests and for the characterization of the immersion coefficient of in-water irradiance sensors. The unit is composed of a water vessel for the radiometer under test, baffling elements to minimize internal reflections, and two light source adapters. One adapter is used with a point source (i.e., a lamp), and the other with the SeaWiFS Quality Monitor (SQM). The former includes the capability of attaching an adjustable aperture, so the light from the lamp is restricted to the area of the sensor faceplate containing the diffusers. The bottom of the tank includes a built-in capability of kinematically mounting a sensor with a 3.5 in (8.9 cm) diameter, or a smaller sensor fitted inside an adapter with an equivalent diameter. In contrast to traditional tanks used in immersion factor characterizations, the ComPACT unit is relatively small. Consequently, only a small amount of water (about 3 L) is needed, which means it is economically feasible to repeatedly fill the water vessel with pure water.

4. The ComPACT Method for Determining Immersion Factors

The determination of the immersion factor using the traditional method implemented in different laboratories has highlighted the importance of water purity to minimize uncertainties. The reduction in the size of the water vessel used in the experimental setup, reduces the volume of water required to fill the tank, thereby making it practical to use pure water in the characterization of immersion factors. The ComPACT method uses a small water vessel (containing approximately 3 L of water) which makes it practical to use pure water during $I_f(\lambda)$ determinations. This leads to the possibility of better standardizing the method for $I_f(\lambda)$ characterization and thus reducing the differences in its determinations at different sites.

5. Data Processing of Alternative Methods

Two processors were developed by the JRC and GSFC to support the determination of $I_f(\lambda)$ data with the alternative continuous and ComPACT methods. The JRC processor was written in the Interactive Data Language (IDL) programming environment, while the GSFC processor was written in the C CodeWarrior programming environment for the Macintosh operating system. The JRC data processor has a graphical user interface (GUI) that assists the user in the selection of data input and output options, as well as the selection of measurement parameters and processing features. Program control with the GSFC processor is carried out through a traditional command line interface, wherein the user selects the processing options

by setting switches, which are used to pass needed numerical, string, or logical values to the main program. Both processors produce quality assurance data supporting the identification of degraded results.

6.   *Preliminary Results*

The continuous and ComPACT methods are intercompared with the traditional incremental method using $I_f(\lambda)$ determinations from various radiometers. The analysis of a series of experiments shows that the continuous method has uncertainties and variability comparable to that of the traditional method. The analysis of the results from the ComPACT and traditional methods shows generally higher $I_f(\lambda)$ values for the former. This is in agreement with the generalized expectations of a reduction in scattering effects, because of the use of pure water with the ComPACT method versus the use of demineralized tap water with the traditional method. The comparison of methods is also extended to the comparison of the JRC and GSFC processors for $I_f(\lambda)$ computations. The results, presented for data taken with the continuous method, show differences to within 0.2%, which are comparable to the repeatability of traditional $I_f(\lambda)$ determinations. Correction values for immersion coefficients determined with pure water, and applied to marine measurements, are also presented and discussed.

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

Chapter 1

Overview and the Traditional Method

STANFORD B. HOOKER
NASA/Goddard Space Flight Center
Greenbelt, Maryland

GIUSEPPE ZIBORDI
JRC/IES/Inland and Marine Waters Unit
Ispra, Italy

ABSTRACT

Whether for a single aperture or multi-aperture sensor, the traditional method for characterizing the immersion factor of an in-water irradiance sensor involves a relatively simple procedure and can be recounted as a small number of steps: a) a tungsten-halogen lamp, with a small filament and powered by a stable power supply, is placed at some distance above the diffuser(s); b) the instrument is placed in a tank of water with the irradiance diffuser(s) level and facing upward; c) the depth of the water is lowered in (5 cm) increments and readings are recorded for all wavelengths from each carefully measured depth; d) a final reading is taken with the water level below the collector(s) with the diffuser(s) dry. Computing the immersion factor from the recordings requires a correction to the irradiance values at each depth interval to account for the change in solid angle of the light leaving the source and arriving at the diffuser(s), which is caused by the light rays geometrically changing direction at the air–water interface.

1.1 INTRODUCTION

SIRREX-8 was conducted using Satlantic, Inc. (Halifax, Canada) ocean color irradiance series-200 (OCI-200) sensors. To eliminate any chance of bias associated with one group's implementation of the immersion factor measurement protocol, three different facilities participated in the SIRREX-8 activity, and a common set of nine sensors were characterized at each facility. The three groups that participated were CHORS, JRC, and Satlantic, Inc. Although there were differences between the methods used at each facility, the basic protocol was the same and in keeping with the traditional method (Petzold and Austin 1988).

The primary objective of SIRREX-8 was a detailed investigation of the immersion factor: a) quantify the uncertainties associated with measuring the immersion factor with a standard protocol, b) establish if instrument-to-instrument variability prevents the assignment of a set of immersion factors for an entire series of sensors, and c) compare average immersion factors obtained from sample OCI-200 radiometers with those provided by the manufacturer for the same series of instruments. A secondary objective was to measure the cosine response of one sensor at two of the facilities, and a tertiary objective was to explore new laboratory methods and equipment for characterizing in-water irradiance sensors. These latter inquiries took place at CHORS and the JRC.

Both downward and upward irradiance sensors, $E_d(\lambda)$ and $E_u(\lambda)$, respectively, were measured during SIRREX-8. The reason for selecting both sensor types was an $E_u(\lambda)$ sensor is more sensitive, so its signal-to-noise ratio (SNR) is higher. The distinction was considered important, because some of the lamps frequently used in optical experiments have a low flux in the blue part of the spectrum. The greater sensitivity of E_u sensors means lower wattage lamps and greater lamp-to-sensor distances can be used without degrading the data. The use of lower wattage lamps is an experimental advantage, because they have smaller filaments, so the approximation that the lamp is a point source is better satisfied. The use of greater lamp-to-sensor distances (keeping the same sized filament) significantly improves the point-source approximation and permits different experimental distances at satisfactory flux (or SNR) levels.

Satlantic OCI-200 sensors were selected for SIRREX-8, because they are compact (so they can be accommodated in relatively small water vessels) and are widely used by the broader ocean color community (so any conclusions derived from their use would have a larger applicability). All

the irradiance sensors had D-shaped collars fitted to them at a set distance, usually 3.81 cm (1.5 in), from the face-plate (front) of the sensor. The use of the D-shaped collar ensures the sensor can be mounted at a reproducible location and orientation (Hooker and Aiken 1998 and Hooker et al. 2002).

A summary of the sensors used during SIRREX-8 is presented in Table 1. The Eu130 sensor was selected as the so-called *reference* sensor and was measured much more frequently than the other eight. One of the unique sensors used during SIRREX-8 was Eu047. This sensor was modified to have low saturation levels, with respect to the standard in-water configuration, so it could be used with sources emitting low light levels. It was also only used in laboratory experiments, so it did not have any of the inevitable diffuser degradation associated with field instruments. To further determine whether or not field use resulted in any unusual aging properties, two new sensors, Ed161 and Eu162, were also measured during SIRREX-8.

Table 1. The radiometers used during SIRREX-8. The sensor codes are formed from the measurement type, Ed for $E_d(\lambda)$ or Eu for $E_u(\lambda)$, plus a three-digit serial number (S/N). The manufacturing dates are based on the first time the instruments were calibrated at Satlantic in the configuration they were used for SIRREX-8.

Sensor Code	Manufacturing Date	Instrument Owner (Notes)
Ed015	September 1994	JRC (oldest)
Ed040	March 1996	GSFC
Eu047†	June 1996	GSFC (low sat.)
Eu048	June 1996	GSFC
Ed050	June 1996	GSFC
Ed071	April 1997	JRC
Ed097	June 1998	JRC
Eu098	May 1998	JRC
Eu109	July 1998	GSFC
Eu130	July 1999	JRC (reference)
Ed161†	September 2001	JRC (newest)
Eu162†	September 2001	JRC (newest)

† Only measured at the JRC.

The mixture of the new sensors with the old field sensors produced a seven-year span of instrument production. Although the field sensors were subjected to a diverse set of field campaigns and shipping circumstances, they were all cared for diligently. This included the use of double-packed (box within a box) professionally designed shipping containers, regular calibrations (either at a recurring frequency or before and after field deployments), custom-made instrument stands to minimize the likelihood of instrument damage in the field, etc. A visual inspection of the diffusers for the field instruments showed they were all in very good condition.

Before presenting the alternatives to the methods used at CHORS and the JRC, the traditional method, including the laboratory apparatus and data processing typically associated with the traditional method, is reviewed in more detail.

1.2 BACKGROUND

There are many aspects of the historical investigations of immersion effects that are worth recounting as part of a review of the traditional method. One reason such a summary is worthwhile is it makes clear a) how much of the problem set associated with any laboratory effort at accurately determining $I_f(\lambda)$ has already been noted in the literature, and b) which aspects have been retained over time. In many cases, the requirements date back to time periods when it must have been very difficult to quantify seemingly small influences on the methods being used (Atkins and Poole 1933, Berger 1958 and 1961, and Westlake 1965):

- The measurements must be made in a dark room, with baffles and screens used to eliminate diffuse light originating from the light source.
- The illumination source must provide a constant flux of light onto the diffuser.
- Apertures placed in the path of the direct beam from the light source must be used to illuminate an area only slightly greater than the diffuser, thereby preventing any illumination of the side walls and bottom of the water vessel (which minimizes light reflections within the water vessel).
- The water vessel must be blackened (and perhaps roughened) with waterproof *dead* black enamel or *dull* black paint.
- Optically clear or pure (distilled) water (the former was frequently interpreted to mean tap water) must be used in the experimental process.
- Air bubbles must be minimized, because they can create *conspicuous* bright patches.
- 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.

It is important to note the list of items includes every major aspect of the experimental process: the lamp, the tank, and the water.

The traditional method for characterizing the immersion factor for an in-water irradiance sensor was incorporated into the SeaWiFS Ocean Optics Protocols (SOOP) for calibration and validation of the remote sensing data (Mueller and Austin 1992), and the subsequent revisions to the protocols (Mueller and Austin 1995, and Mueller

2000 and 2002) have not materially changed the methodology except to point out that the original class characterizations are not suitable for calibration and validation activities (Mueller 2002). Although the latter point was first noted by Mueller (1995), the change to the protocol did not occur until after SIRREX-8.

The traditional method involves a relatively simple procedure and can be recounted as a small number of steps (Mueller and Austin 1995):

A. A tungsten-halogen lamp, with a small filament and powered by a stable power supply, is placed at some distance above the diffuser(s).

B. The instrument is placed in a tank of water with the irradiance diffuser(s) level and facing upward.

C. The depth of the water is lowered in increments and readings are recorded for all wavelengths from each carefully measured depth.

D. A final reading is taken with the water level below the collector, i.e., with the collector in the air.

The refinements that were published in the revisions to the SOOP included a) making it clear that the in-air measurement is only done when the diffusers are dry; b) using a minimum water depth of 5 cm, a maximum water depth of 40–50 cm, and a water depth increment of 5 cm; and c) repeating the measurement procedure with a different lamp-to-diffuser(s) distance to verify an appreciable uncertainty does not affect the results.

It is important to note the traditional method does not include any detailed specification about the water surface (should it be kept free of floating particles) or the actual water to be used (many laboratories use tap water which has been filtered to remove suspended particulates), and it assumes the water vessel is properly blackened (or baffled, if necessary) and of the appropriate dimensions. The objective in choosing the size and internal characteristics of the tank should be to produce an interior with minimal and diffuse reflections. In most cases, this requires the use of one or more apertures, with an adjustable aperture on top of the tank to make sure the light reaching the sensor is restricted to a narrow cone that does not directly illuminate the sides of the tank. The point is to produce as *black* an interior as possible.

1.3 LABORATORY EQUIPMENT

In its simplest form, the laboratory apparatus needed to execute the traditional method involves just a few components:

1. A lamp of suitable wattage to provide a flux of light at all sensor wavelengths well above dark values, typically at least 100 digital counts, with the appropriate baffling and apertures to minimize diffuse light contributions into the tank (in general, a lamp with a small filament is preferred, because it better approximates a point source);

2. A water vessel or tank with a removable lid and aperture, with the latter sized (or adjusted) to ensure the direct beam of light from the lamp has an area that is only slightly larger than the area of the diffuser(s);

3. The interior of the tank must be *flat* black, and contain a sensor support system that permits an accurate horizontal leveling of the diffuser(s) and an accurate alignment of the sensor with respect to the centerline of the lamp filament;

4. An accurate system for determining the depth of water above the diffuser(s);

5. A regulated lamp power supply to ensure the emitted flux from the lamp is stable (to within less than 0.1%) over the time period of each characterization trial; and

6. A sensor power supply and a data acquisition system to record readings from the sensor diffuser(s).

For most experimental systems, the water depth above the diffuser(s) is determined using a *sight* tube mounted on the exterior of the tank. The tube is usually a clear plastic pipe with a long (adhesive) metric ruler attached to it. The water level that just begins to cover the diffusers is noted as the *zero depth point*, and all subsequent readings are differenced with respect to the first reading to yield the depth of water above the diffuser(s).

A variety of additional components (here considered *optional* for categorization purposes) have proved useful by various investigators:

7. A water filter to trap any particles when the tank is filled;

8. A lamp screen to make it easier to work around the apparatus while the lamp is on (in many cases, 1,000 W lamps are used and the amount of radiation is harmful, so a lamp screen or protective eye wear is mandatory);

9. Intermediate apertures to ensure the light flux reaching the diffuser(s) is as direct a beam as possible;

10. A sensor to monitor the lamp and confirm the absence of any anomalies in the emitted flux, which can be accomplished with another radiometer, or with a digital voltmeter (DVM) that monitors the voltage across a precision lamp shunt;

11. A fan to cool the lamp screen and divert the heat rising from the lamp (the latter is mandatory if a monitoring radiometer is used, otherwise the heat buildup on the monitoring sensor diffuser(s) can cause damage);

12. A pump to decrease the amount of time needed to empty the tank (particularly useful if repeated trials are being executed);
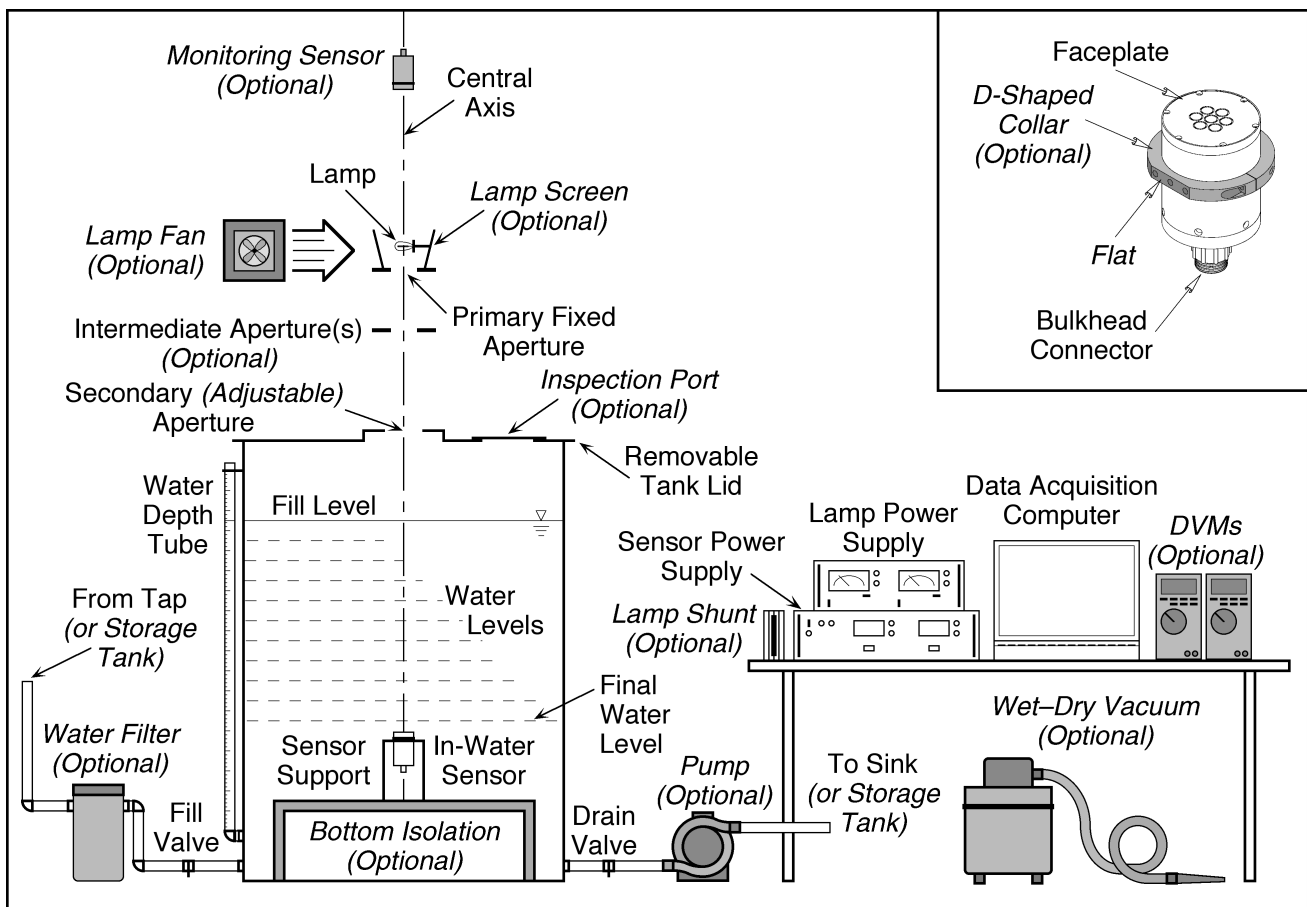
Fig. 1. The traditional laboratory setup used for characterizing the immersion factor. Optional equipment is labeled with the slanted typeface. In some cases, the water from the tank is drained into a sink, while for others it is pumped into a second tank (not shown) and reused in subsequent experimental trials. The inset panel shows a Satlantic OCI-200 sensor fitted with a D-shaped collar.

13. A wet–dry vacuum for keeping the water surface as clean as possible;

14. An inspection port in the tank lid that permits a visual inspection of the tank interior with a minimum amount of disturbance to the tank interior (this can also be used for maintaining the quality of water surface with the wet–dry vacuum); and

15. An internal tank structure that isolates the sensor and its support system from the bottom of the tank (i.e., increases the height of the sensor above the turbulence around the fill and drain ports, and any reflections associated with the bottom of the tank).

The latter can be particularly effective if it is covered with a fine (black) mesh, i.e., a material with a large surface area to rapidly dampen any turbulent water motions.

Figure 1 presents all of the equipment discussed above to execute the traditional method. During SIRREX-8, the monitoring sensor was a required component at each facility to ensure the only data used corresponded to a constant light flux from the lamp. In addition, at CHORS and the JRC, a shunt resistor in series with the lamp, was used as an additional means to monitor the light source stability, which was accomplished by measuring the voltages across the shunt and the lamp with DVMs. Other differences between the methods at each facility were as follows:

- The lamp was screened at CHORS and the JRC, and both facilities used a fan to keep the lamp and monitoring sensor cooled.
- Alignment of the components along the central axis was done using a laser at the JRC and Satlantic, but was done visually (using projected shadows) at CHORS.
- The angular orientation of the sensor, based on the position of the flat part of the D-shaped collar, was maintained at the JRC and CHORS.
- All three facilities used a pump to drain the tank; Satlantic and the JRC stored the water in a second tank, so it could be used again during subsequent trials.

Other procedural and systematic differences between the methods are summarized in Table 2.

8

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

Table 2. A comparison of the principal methodological parameters used by the different laboratories participating in SIRREX-8. The number in parentheses below the tank radius is the tank radius divided by the instrument radius, and the values given next to the number of depth intervals is the depth increment in centimeters.

Parameter	CHORS	JRC	Satlantic
Tank Volume [L]	780	350	3,527
Tank Radius [cm] (Radii Ratio)	40.5 (9.1)	40.0 (9.0)	45.0 [1] (10.1)
Water Type	Tap	Tap [2]	Sea [3]
Depth Intervals	15 (2.5)	13 (2.5)	10 (5.0)
Interior Tank Obstructions	None	Small	Large
Surface Cleaning	Vacuum	Vacuum	Soap & Dip Net
Lamp Power [W]	400	1,000	1,000
Lamp Filament	Small	Large [4]	Large
Lamp-to-Diffuser Distance [cm]	86.0 [5]	105.0	100.0
Trial Time [min]	120	100	330 [6]

[1] The smaller dimension of the $90 \times 123 \, \text{cm}^2$ tank.
[2] Demineralized, with a typical resistance of 5–8 MΩ, partially or completely replaced every 2–3 days.
[3] Aged for about one year, occassionally chlorinated, and a single, coarse filtration each time the tank is drained during the experimental process.
[4] The filament is U-shaped which allows the outer glass envelope to be relatively small.
[5] A second distance of 100.0 cm is an option.
[6] Includes 300 min for tank filling and settling.

The Table 2 parameters make it clear that even with a common protocol, choices as to how facilities implement the protocol will naturally lead to differences. Some of these differences will probably not account for any significant changes in the uncertainty budget (e.g., the small differences in the lamp-to-diffuser distance) or their importance has not been quantified (e.g., clearing the water surface of any particles that might have accumulated by touching the water surface above the sensor with a very small amount of liquid detergent).

1.4 PROCESSING SCHEME

The light flux arriving at the diffuser(s) varies with the water depth and is a function of a) the attenuation at the air–water interface (which varies with wavelength), b) the attenuation over the water path length (which is a function of depth and wavelength), and c) the change in solid angle of the light leaving the source and arriving at the diffuser(s). The latter is caused by the light rays geometrically changing direction at the air–water interface, which varies with wavelength and water depth, and must be properly accounted for in the processing scheme to determine the immersion factor(s) of the diffuser(s).

Deriving the computational methodology for computing the immersion factor begins with a simple relationship: the calibrated irradiance measured in air (indicated by $z = 0^+$), and transmitted through the air–water interface, must equal the calibrated irradiance measured at null depth (indicated by $z = 0^-$). Using the nomenclature established with (1), but replacing the time variable with depth, this equality is expressed as

$$E_{\text{cal}}(0^-, \lambda) = E_{\text{cal}}(0^+, \lambda) \, T_s(\lambda), \qquad (3)$$

where $T_s(\lambda)$ is the transmittance of the air–water interface to downward irradiance. Substitution of (1) into (3), while remembering $I_f(\lambda) = 1$ for an in-air measurement, yields:

$$C_c(\lambda) \, I_f(\lambda) \, E(0^-, \lambda) = C_c(\lambda) \, E(0^+, \lambda) \, T_s(\lambda). \qquad (4)$$

Rearranging (4) and removing common terms (the calibration coefficient) yields:

$$I_f(\lambda) = \frac{E(0^+, \lambda)}{E(0^-, \lambda)} T_s(\lambda). \qquad (5)$$

From the point of view of using a small lamp (approximating a point source) as part of the immersion factor method, the formulation in (5) assumes the $E(0^-, \lambda)$ values are exact (within experimental uncertainties), that is, a geometric correction factor, $G(z, \lambda)$, has been applied to account for the change in solid angle as a function of the water depth and the distance between the lamp and the diffuser(s):

$$G(z, \lambda) = \left[1 - \frac{z}{d} \left(1 - \frac{1}{n_w(\lambda, S, T)} \right) \right]^{-2}, \qquad (6)$$

where d is the distance of the lamp source from the diffuser(s) surface and $n_w(\lambda, S, T)$ is the index of refraction of the water, which depends on the salinity, S, and temperature, T, of the water (D'Alimonte and Zibordi 2002):

$$n_w(\lambda, 0, 20) = 1.31891 + \frac{6.31446}{\lambda - 139.596} \qquad (7)$$

and

$$n_w(\lambda, 35, 20) = 1.32483 + \frac{6.53318}{\lambda - 139.589}, \qquad (8)$$

where λ is in units of nanometers.

The $G(z, \lambda)$ terms are computed at each depth and are used in the least-squares fit of the logarithms of the in-water irradiance data, that is, the linear regression is computed using the $\ln \left[E(z, \lambda)/G(z, \lambda) \right]$ values. The only remaining unknown is the transmittance of the air–water interface to downward irradiance, which is computed using the Fresnel reflectance equation

$$T_s(\lambda) = \frac{4 \, n_w(\lambda, S, T)}{\left[1 + n_w(\lambda, S, T) \right]^2}. \qquad (9)$$

A processing capability based on (5)–(9) was used during SIRREX-8 (D'Alimonte and Zibordi 2002).

9

1.5 SUMMARY

Several of the differences between the methods used during SIRREX-8 (Table 2) pose practical problems when it comes to reproducing the methods. Two of the most notable differences are the amount of time needed to complete an experimental trial, and the size of the tank. The former range from 100–330 min, and the latter from 350–3,527 L.

Given a standard work day is split into 4 h morning and 4 h afternoon sessions, the typical number of trials that could be executed is 1–4 per day. By comparison, approximately 12 sensors could be radiometrically calibrated in the same time period, so a significant reduction in the time needed to complete an immersion factor trial is required if a commensurate level of temporal and cost effectiveness is to be attained.

Large volumes of water necessarily require large laboratory spaces capable of dealing with the commensurate water source and waste requirements. Although the cost involved is always an infrastructure issue, the biggest problem is any method relying on a large volume of water is at some level irreproducible, because the exact properties of a large volume of water being used at one facility are not easily reproduced at another. A solution to both these problems was to investigate the capabilities of a smaller tank, specifically the ComPACT apparatus.

The ComPACT unit was originally designed with the objective of producing a small tank that could be used with a) moderately-sized laboratory rooms, b) minimal source and waste water requirements, and c) a portable, stable light source for monitoring the radiometric stability of a radiometer. The light source was imagined to be the SQM, because it had a proven capability in the field and in harsh environments (Hooker and Aiken 1998).

In addition to being able to use the tank for immersion factor characterizations, there was also a desire to have a capability of quantifying the response of a sensor while it was immersed in water. The reason for the latter was the recognized need of trying to accurately quantify the effects of bio-fouling on in-water radiometers. The envisioned methodology was to measure a sensor immersed, before it was fouled, and then to measure it again after bio-fouling had occurred.

Chapter 2

The Continuous Method for Determining Immersion Factors

Stanford B. Hooker
NASA/Goddard Space Flight Center
Greenbelt, Maryland

Giuseppe Zibordi
JRC/IES/Inland and Marine Waters Unit
Ispra, Italy

Abstract

The continuous method was implemented as a modification to the traditional method. In the latter, a series of incremental water depths are created by emptying (or filling) the water vessel in discrete intervals, whereas for the former, the tank is emptied (or filled) using a constant flow-rate pump. The tank emptying (or filling) is carried out in conjunction with the data logging, which leads to the creation of an optical profile, where the depth variable is the varying thickness of the water layer above the sensor. When compared to the traditional method, the continuous method provides a much faster execution of the ensemble of measurements required for $I_f(\lambda)$ determination. In the specific case of the traditional method implemented at CHORS, the execution time can be reduced from 120 min to 35 min.

2.1 INTRODUCTION

An alternative method for producing the data required for determining the immersion factor takes advantage of having a pump to drain the tank. In the case of CHORS, the pump was capable of an almost constant discharge rate. For a cylindrical tank, like the CHORS tank, this means the water depth can be approximated as a linear function of time when the tank is being emptied.

The principal advantage of the so-called *continuous method*, in terms of the actual execution of the method, is the time needed to complete an experimental trial is significantly reduced. As shown in Table 2, the typical time for a trial using the CHORS (traditional) method was 120 min, whereas it was about 35 min using the continuous method. In general, these trials included dark and background measurements, so the continuous method could be executed in about 30 min if only one of these measurements was made.

2.2 THE CHORS METHOD

The CHORS laboratory procedure for characterizing immersion factors for an irradiance sensor is an implementation of the traditional method (Petzold and Austin 1988). The apparatus used (Fig. 2) was designed to accept a large variety of sensor types, both large and small, from different manufacturers. Although measurement accuracy

was an important objective of the method, another priority was to be able to execute the measurement process in a time-efficient manner.

The basic elements of the measurement protocol were the alignment of the mechanical and optical components, and the collection of in-air and in-water data for computing $I_f(\lambda)$. The alignment procedures were as follows:

- The tank lid with attached baffles, lamp holder, and rigid duct was leveled and aligned vertically.

- The lamp was powered on and the monitoring sensor was aligned by centering it in the projected light cone from the top of the rigid duct.

- The in-water sensor was iteratively aligned by centering it in the projected light cone from the light baffles and leveling it using a bullet level.

- The adjustable baffle was set to ensure the outer diameter of the projected light cone matched the outer diameter of the D-shaped collar fitted to the in-water sensor.

Although every effort was made to minimize any perturbation to the alignment when sensors were changed within the tank, some disturbance was inevitable. To ensure alignment integrity over time, occasional realignment checks were made over the course of the measurements.
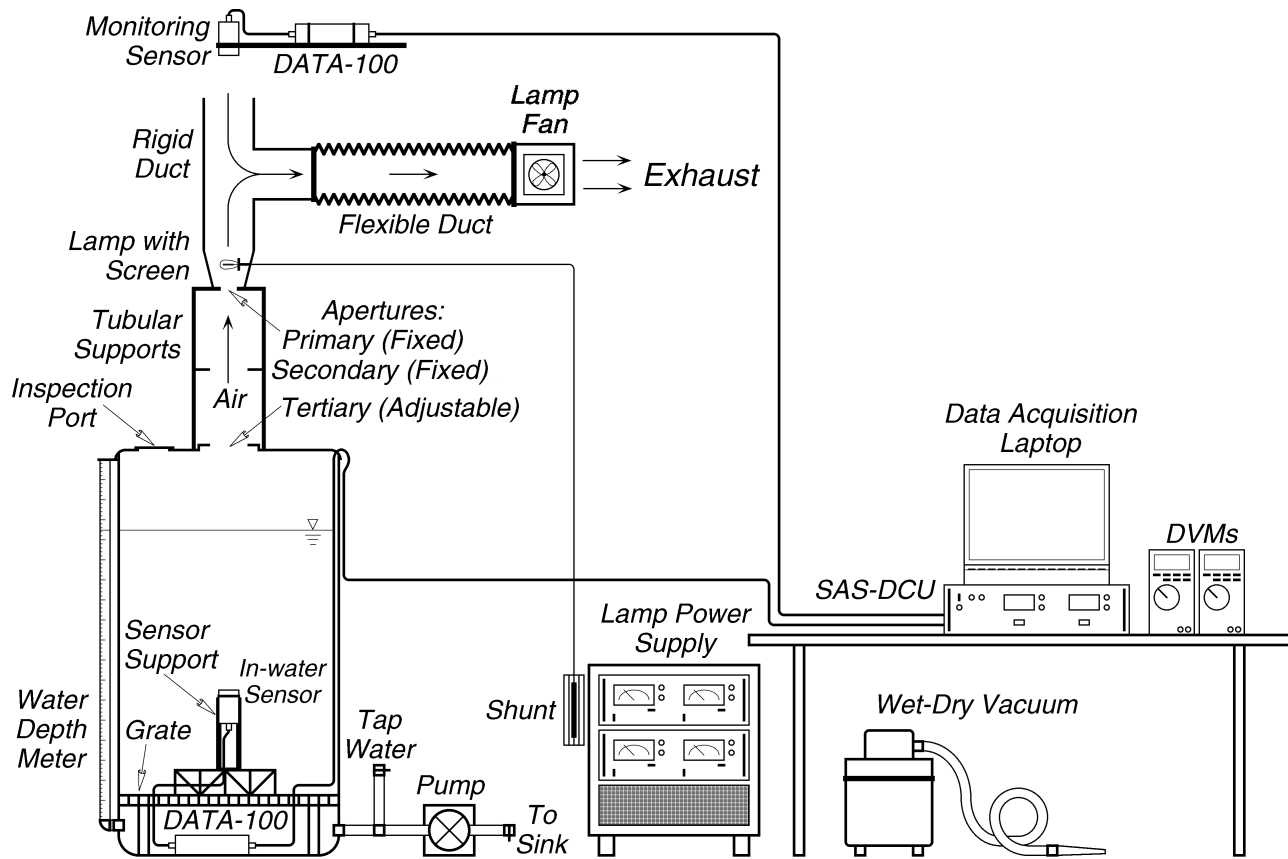
Fig. 2. The laboratory setup used at CHORS for characterizing the immersion factor. The monitoring and in-water sensors are aligned by centering the equipment with respect to the illumination circles associated with the rigid duct and adjustable aperture, respectively.

The computation of $I_f(\lambda)$ primarily requires one in-air and a multitude of in-water irradiance measurements. The latter must be taken at different water depths, so an accurate determination of the subsurface irradiance value can be made. In addition, dark or ambient data are needed to remove any bias voltages (in a properly baffled setup, these two measurements are almost identical). After setting up the monitoring sensor, the collection of all these data at the CHORS facility required the following successive steps:

1. The lamp was powered on by slowly increasing the current until the operational rating was reached; the lamp was allowed to warm up for at least 30 min.

2. The in-water sensor was installed in the tank support frame (the D-shaped collar permitted an accurate sensor repositioning during subsequent trials).

3. In-air data from the two light sensors were recorded for 3 min, and the DVM voltages were logged.

4. The tank was filled until the water depth above the in-water sensor was 5 cm.

5. While the tank was being filled, any air bubbles that formed on, or near, the diffusers were removed.

6. When the tank was filled, the water surface was skimmed with a wet–dry vacuum.

7. Data from the in-water and monitoring sensors were collected for 3 min, and the voltages across the lamp and shunt were measured by the DVMs and logged.

8. Water was added to the tank in 5 cm increments, and data were collected at each interval until the water depth above the diffuser(s) was at least 40 cm.

9. The pump was used to lower the water depth by 2.5 cm and all data were recorded.

10. Successive pump and measurement sequences were repeated at 5 cm intervals until the water depth above the diffusers was 7.5 cm, at which point, a final set of data was recorded.

11. The pump was used to lower the water depth below the D-shaped collar; the diffusers were dried using compressed air and lint-free tissue, and data from all the sensors were collected.

12. Dark data (caps on the sensors) were collected.

In many cases, ambient data were also collected with the source off, so only illumination from other light-emitting devices in the room reached the sensor aperture.

The final in-air measurement was made so it could be used as a quality control procedure by comparing it to the

first in-air measurement. The ambient measurement was also intended to be a quality assurance opportunity, because this measurement included any secondary sources of light in the room. The use of ambient data is preferred over dark data, but (as has already been noted) in a properly baffled measurement system the two should be nearly identical.

Another quality assurance procedure was to use two different lamp-to-sensor distances with the same radiometer (in the alternative lamp position, the lamp is 14.0 cm farther from the sensor). Although this was an established part of the CHORS method, it was only executed once during SIRREX-8, because the time available did not permit recurrent use of this procedure.

2.3 THE CONTINUOUS METHOD

The continuous method was implemented as a modification to the standard CHORS method, and was usually executed after a standard CHORS trial to ensure all continuous method trials took place in temporal proximity to a standard trial:

1. In-air data from the two light sensors were recorded for 3 min, and the DVM voltages were logged.

2. The tank was filled until water just began to wash over the diffusers (the reading on the water depth meter was noted as the null depth point).

3. While the tank was being filled, any air bubbles that formed on, or near, the diffusers were removed.

4. The tank was filled until the water depth above the diffusers was 40–55 cm; the water surface was skimmed with a wet–dry vacuum, and the voltages across the lamp and shunt were measured by the DVMs and logged.

5. The pump was turned on, the time recorded, and data from the in-water and monitoring sensors were collected continuously as the tank emptied.

6. The time when the water level reached the null depth point was recorded, and data acquisition from the in-water and monitoring sensors was halted; the voltages across the lamp and shunt were measured by the DVMs and logged.

7. The pump was used to lower the water depth below the D-shaped collar; the diffusers were dried using compressed air and lint-free tissue, and data from all the sensors were collected.

8. Dark data, then background data were collected.

Chapter 3

The ComPACT Mechanical Design

DIRK VAN DER LINDE
JRC/IES/Inland and Marine Waters Unit
Ispra, Italy

ABSTRACT

The ComPACT unit was designed for the execution of quality tests and for the characterization of the immersion coefficient of in-water irradiance sensors. The unit is composed of a water vessel for the radiometer under test, baffling elements to minimize internal reflections, and two light source adapters. One adapter is used with a point source (i.e., a lamp), and the other with the SQM. The former includes the capability of attaching an adjustable aperture, so the light from the lamp is restricted to the area of the sensor faceplate containing the diffusers. The bottom of the tank includes a built-in capability of kinematically mounting a sensor with a 3.5 in (8.9 cm) diameter, or a smaller sensor fitted inside an adapter with an equivalent diameter. In contrast to traditional tanks used in immersion factor characterizations, the ComPACT unit is relatively small. Consequently, only a small amount of water (about 3 L) is needed, which means it is economically feasible to repeatedly fill the water vessel with pure water.

3.1 INTRODUCTION

SIRREX-8 focused on the determination of immersion factors for a single class of in-water radiometers. The approach involved the intercomparison of results achieved at three different laboratories all using the same basic (traditional) method. Each laboratory, however, used different tank sizes and water types. The average tank was very large, using hundreds of liters of water (Table 2), and required a work space that was both significant in size and capable of dealing with large volumes of water. The ComPACT unit was originally designed with the objective of minimizing the size of the water vessel used in immersed-sensor experiments. The small size of the apparatus provides the possibility of using it to characterize immersion factors with pure water. The SIRREX-8 activity showed that water purity is an important factor in ensuring repeatability and comparability of immersion factors.

3.2 THE COMPONENTS

The ComPACT apparatus (Fig. 3) was designed and built for quality tests on immersed radiometers, e.g., the characterization of immersion factors of an in-water irradiance sensor. The unit is composed of a small water vessel, baffling elements to minimize the light reflections inside the tank, and two adapters permitting the use of a lamp or an SQM, as a light source. All components of the ComPACT unit are anodized dull black to minimize reflections.

3.2.1 The Water Vessel

The water vessel is a cylinder (40 cm high) with an internal diameter of 10.2 cm. The bottom side is shaped to accommodate either an OCI-200 or an ocean color radiance series-200 (OCR-200) radiometer. The radiometer is installed with the diffusers (or apertures) facing the internal side of the water vessel, and is kinematically mounted with small wing nuts. The wing nuts tighten a small plate against a D-shaped clamp (Fig. 1 inset panel), which affixes the radiometer against the bottom of the water vessel. In addition to permitting an easy and safe installation of the radiometer, the D-shaped clamp also allows an accurate repositioning of the sensor during successive trials. An o-ring at the radiometer–tank interface prevents any water leakage.

Two different adapters can be attached to the upper side of the water vessel. The first is designed to be used with an adjustable aperture and a point light source (i.e., a lamp). The second allows the coupling of the water vessel with an SQM mounted vertically (the normal operational configuration is horizontal). A series of tapped holes, equally spaced at 5 cm intervals along the long (vertical) side of the water vessel, provide an accurate control of the water level within the tank. Stainless steel screws, with o-rings placed over the threads and under the caps, are used to open and close the holes.

After completely filling the tank, the sequential removal of the screws from the top to the bottom, produces a series
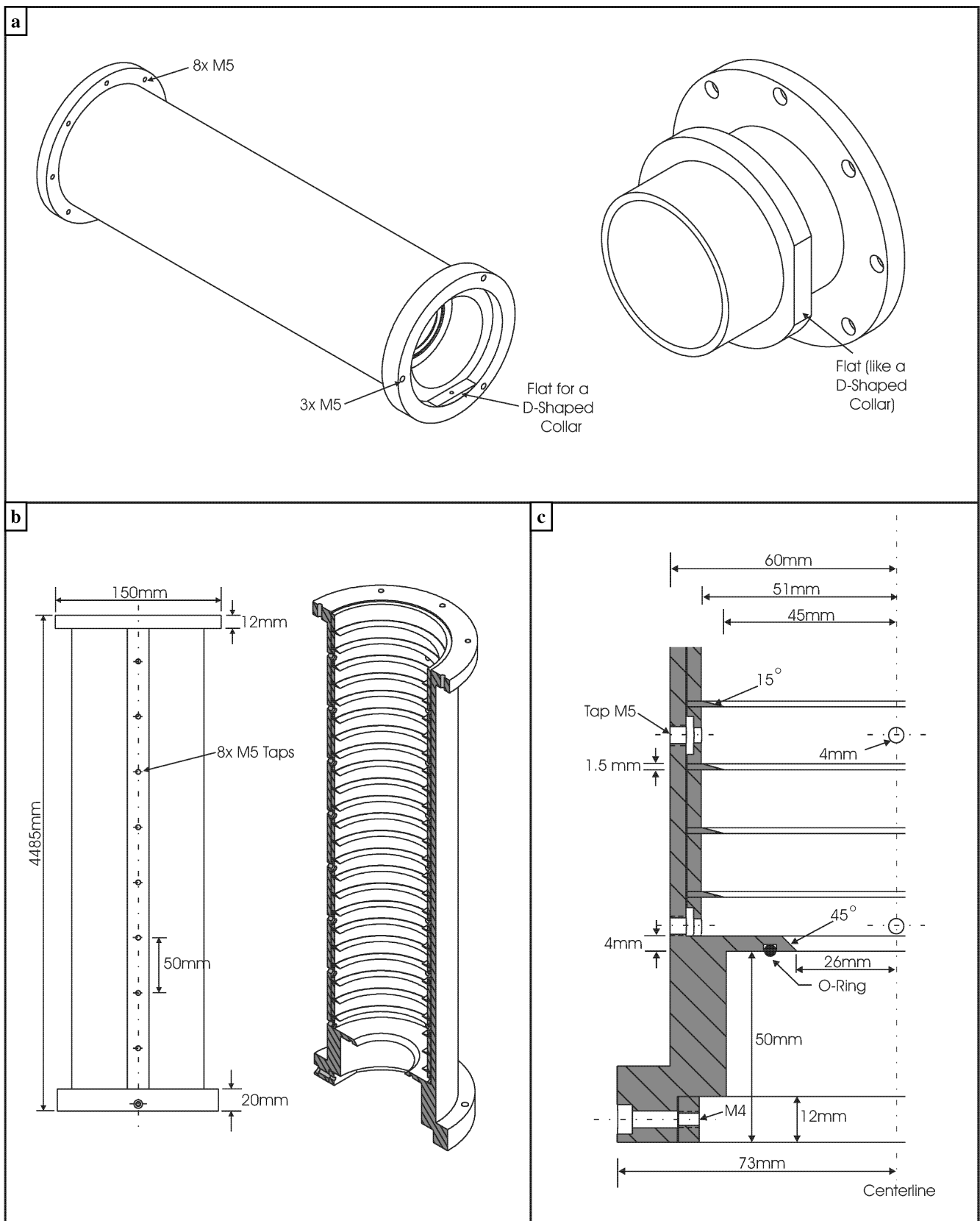
Fig. 3. The ComPACT apparatus showing **a)** the overall water vessel and the SQM adapter, **b)** a side view with a cut-away view revealing the series of internal baffles, and **c)** a detailed cut-away view showing the lower part where the sensor is inserted.

of decreasing water depths above the radiometer. Specifically, it provides seven measurements, with water depths ranging from 37.5 cm down to 7.5 cm, in 5 cm decrements.

3.2.2 Internal Baffles

The internal baffling was designed to minimize any light reflection from the side walls of the water vessel. The baffles are spaced 1.5 cm apart, which is accomplished through the use of two types of spacer rings. One set of rings are simple collars, while the other are shaped to facilitate the outflow of the water in the vicinity of the M5 taps. Each baffle is beveled, with the bevel face (or knife edge) facing the incident flux to minimize any reflections onto the radiometer. The inner diameter of the baffles was dimensioned such that, after setting the minimum opening of the adjustable aperture to illuminate all the diffusers with the tank completely filled, the light cone did not illuminate the edge of any baffle with the tank completely empty.

3.2.3 Light Source Adapters

Two different adapters were designed to use the water vessel with two different light sources: a lamp or an SQM. A lamp is the required source for the characterization of

immersion factors, whereas an SQM (i.e., a diffuse light source) is a suitable source for quality tests on in-water radiometers covered with water. The lamp adapter has an adjustable aperture that allows a careful dimensioning of the light cone illuminating the diffusers. The SQM adapter is sized to fit onto the entrance aperture of the SQM and it has an internal aperture equal to the internal diameter of the baffles within the water vessel.

3.3 SUMMARY

The ComPACT unit was designed for the execution of quality tests with any 200-series sensor (including the OCR-200 radiometer) and the characterization of the immersion factors of OCI-200 radiometers (or radiometers fitted into an adapter with an equivalent outer dimension). Adapters permit measurements with two different types of sources: a lamp or an SQM. Screws fitted to the side of the water vessel allow the accurate setting of seven water depths above the radiometer (i.e., from 37.5 cm down to 7.5 cm, in 5 cm decrements). The small size of the water vessel (10.2 cm diameter and 40 cm high with about a 3 L volume) makes it economically feasible to use pure water for instrument quality tests or characterizations.

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

Chapter 4

The ComPACT Method for Determining Immersion Factors

GIUSEPPE ZIBORDI
JRC/IES/Inland and Marine Waters Unit
Ispra, Italy

STANFORD B. HOOKER
NASA/Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

The determination of the immersion factor using the traditional method implemented in different laboratories has highlighted the importance of water purity to minimize uncertainties. The reduction in the size of the water vessel used in the experimental setup, reduces the volume of water required to fill the tank, thereby making it practical to use pure water in the characterization of immersion factors. The ComPACT method uses a small water vessel (containing approximately $3\,\mathrm{L}$ of water) which makes it practical to use pure water during $I_f(\lambda)$ determinations. This leads to the possibility of better standardizing the method for $I_f(\lambda)$ characterization and thus reducing the differences in its determinations at different sites.

4.1 INTRODUCTION

The SIRREX-8 activity showed a variety of laboratory measurement setups for the determination of $I_f(\lambda)$, which relied on the same protocol (Mueller and Austin 1995). A major element differentiating the implementation of the protocol was the use of different types and volumes of water. This showed the difficulty in standardizing measurements. In fact, water purity may significantly affect the accuracy of the computed $I_f(\lambda)$ values. The reduction in size of the water tank used for making the measurements with the instrument immersed is a viable solution to ensure a better control of the water quality. The ComPACT method makes use of a small tank (containing approximately $3\,\mathrm{L}$ of water) which permits the use of pure water (e.g., Milli-Q™†) for the determination of the $I_f(\lambda)$ values. This solution creates the possibility of standardizing immersion factor measurements.

4.2 LABORATORY SETUP

A schematic of the ComPACT method, as implemented at the JRC, is illustrated in Fig. 4. The general apparatus for the ComPACT method is the same one used during the SIRREX-8 activity, except the large water tanks

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† "Milli-Q" is a registered trademark of Millipore Corporation (Bedford, Massachusetts).

(primary measurement tank and companion storage tank) have been replaced with the ComPACT water vessel and a small waste water tank. The radiometer to be characterized is shown attached to the bottom of the ComPACT water vessel, and this entire system is attached to an optical bench. The light source (a $1,000\,\mathrm{W}$ tungsten-halogen lamp), a lamp screen with primary baffle, and a monitoring radiometer for the light source are also installed on the optical bench, and all of these optical components can be independently positioned.

The alignment of the optical components is accomplished using a laser that is temporarily inserted in the clamp support of the monitoring sensor. A shunt resistor, in series with the lamp, is used as an additional means to monitor the light source stability. This is accomplished by measuring the voltages across the shunt and the lamp with two DVMs. Two independent data loggers (so-called *DATA-100s*) are used for powering the in-water and the monitoring sensors, and converting the analog voltages to a serial telemetry that is recorded with a laptop computer.

To protect the lamp in the event of a power failure, the lamp power supply and the lamp fan are connected to an uninterruptible power supply (UPS). The purpose of the lamp fan is to prevent an excessive heat buildup on the lamp screen and the monitoring sensor. The movement of air away from the central axis of the instrumentation, also minimizes the flux of particles into the water vessel.
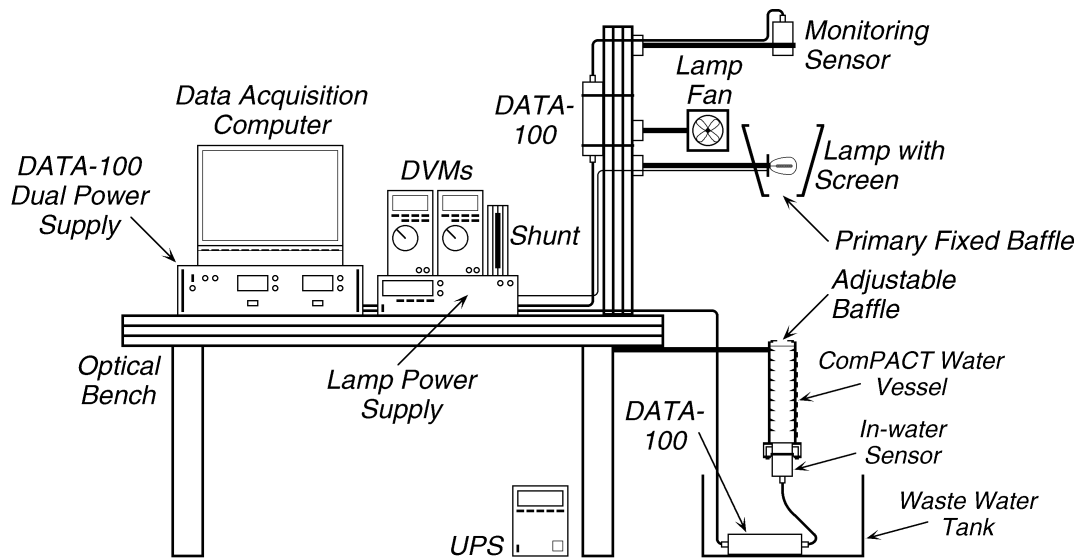
Fig. 4. A schematic of the laboratory setup used at the JRC for characterizing the immersion factor with the ComPACT method. Some elements are shown in an exaggerated perspective to make the presentation of the component parts clearer. The entire experimental setup is operated in a dark room with the walls painted flat black.

4.3 MEASUREMENT PROTOCOL

The basic elements of the ComPACT measurement protocol are concerned with the alignment of the primary components and the collection of in-air and in-water data for $I_f(\lambda)$ computation. The alignment of the components involves three adjustments:

- Horizontally leveling each component connected to the optical bench (i.e., the monitoring radiometer support, the lamp holder, the primary baffle and the ComPACT water vessel).

- Vertically aligning these same components using a 3 mW laser, mechanically centered (with the aid of an adapter) in the clamp support used for the monitoring radiometer.

- Adjusting the aperture at the entrance of the ComPACT water vessel, such that the light flux is restricted to the area defined by the cosine collectors on the in-water sensor faceplate (Fig. 1), which minimizes the diffuse light contributions within the tank.

The overall alignment is performed once and it is only occasionally checked, because none of the mechanical parts constituting the measurement system are moved during the installation or removal of the radiometers.

The computation of $I_f(\lambda)$ values requires an in-air irradiance measurement and several in-water irradiance measurements recorded at different water depths. Additional measurements include the so-called *dark, background,* and *ambient* data. Dark data are acquired by capping the monitoring sensor and covering the adjustable aperture with a sensor cap, so no lamp flux reaches the sensors. Background data are acquired by occulting the direct illumination of the sensor by the source with an intervening *on-axis baffle*, so only indirect light (from the source and any other light emissions from equipment in the room) reaches the sensor aperture. Ambient data are collected with the source off, so only illumination from other light-emitting devices in the room reaches the sensor aperture. For a laboratory setup properly baffled and with no other light-emitting devices other than the lamp source, ambient data are not required.

The collection of all these data, after setting up the monitoring radiometer, requires the following successive steps:

1. Power on the lamp by slowly increasing the operating current to the lamp, and allow it to warm up for at least 30 min.

2. Install the in-water radiometer at the bottom of the ComPACT water vessel (with the collectors facing the internal part of the tank). The use of a D-shaped collar (Fig. 1), ensures accurate repositioning of the device with respect to the system in successive measurement sequences.

3. Collect dark data for both the monitoring and in-water sensors.

4. Collect background data for the in-water radiometer (by blocking the direct light from the source using an on-axis circular baffle sized for the area occupied by the collectors and placed at the entrance of the ComPACT water vessel). The latter measurement is intended to include the contribution of internal

reflections from the tank walls and baffles. The use of background data in the processing, is preferred to the use of the dark data, even though differences between dark and background data have not shown any appreciable difference in the computed $I_f(\lambda)$ data.

5. Collect the in-air measurement with the collectors completely dry. (When the water vessel is used repetitively, water drops can fall from the tank walls, so regular inspections are needed to verify the sensor faceplate and diffusers are dry. Clean, compressed air is a convenient mechanism from removing excess water clinging to the tank sidewalls and baffles before a new sensor is attached.)

6. Fill the tank with pure (Milli-Q) water, and then overfill it to remove dust particles that inevitably fall into the tank.

7. Remove any air bubbles, which may have formed at or near the sensor diffusers, as well as on the edges of the interior tank baffles. The use of a plastic pipette has proved to be an efficient tool for dislodging bubbles. In addition, a vigorous filling of the tank, which creates a lot of turbulence, has proved to produce fewer bubbles than a gentle, slow filling of the tank.

8. Decrease the water depth in the tank using the drain hole below the current water level (this operation ensures accurate water depths above the radiometer faceplate within the 37.5 to 7.5 cm interval, in 5.0 cm decrements).

9. Record the voltages across the lamp and the shunt to detect conditions affected by significant changes in the light source.

10. Collect data from the in-water and monitoring sensors until an appropriate number of samples, which respects the SNR of the instrument being characterized, has been acquired. For the sensors used here, more than 500 data records were acquired (the radiometers had a 6 Hz data rate, so 1.5 min of data were collected).

11. Repeat steps 8–10 until data have been collected with the lower allowed water depth above the radiometer faceplate.

A complete measurement sequence, from sensor setup, tank filling, and then to blowing out the water vessel with compressed air, typically lasted about 40 min.

The most relevant parameters and quantities defining the $I_f(\lambda)$ determination through the ComPACT protocol (as implemented at JRC), are given in Table 3. A comparison of these values with the equivalent values for the traditional approaches given in Table 2 reveals the most significant aspects of the ComPACT method are: a) the small size of the tank) and, thus, the small volume of water involved (3 L versus as much as 3,527 L); b) the rapid

execution time (less than 1 h rather than as much 2–6 h); and the use of a reproducible type of water (Milli-Q rather than local tap water or aged seawater).

Table 3. The quantities and parameters defining immersion factor measurements using the Com-PACT method at the JRC.

Parameter	Value	Notes
Tank Volume [L]	3.0	
Tank Radius [cm]	5.1	Height is 45 cm
(Radii Ratio)	(1.1)	
Water Type	Pure	Milli-Q water
Depth Intervals	7†	5 cm intervals
Interior Tank Obstructions	None	Sidewall baffles
Surface Cleaning	Overfill	
Lamp Power [W]	1,000‡	
Lamp Filament	Large	U-shaped
Lamp-to-Diffuser Distance [cm]	125	
Trial Time [min]	40§	

† The maximum and minimum water depths are 37.5 and 7.5 cm, respectively.

‡ The lamp current was set to 4.0 and 4.2 A for E_d and E_u measurements, respectively.

§ Based on 1.5 min data records, and including 10 min for set-up time, plus one dark, one background, and one in-air measurement.

4.4 DATA PROCESSING

The computation of immersion factors using data produced with the ComPACT method can be carried out using processing tools developed for the traditional (incremental) method. Specifically, I_f at a given wavelength λ, is computed using (5)–(9). Such a scheme was implemented by D'Alimonte and Zibordi (2002) for the SIRREX-8 activity. In their approach, a GUI supports the user in the selection of the relevant parameters for data processing (i.e., the refractive index of the water, the source–collector distance, the application of dark or background data, and enabling of the normalization of the in-water radiometer data with respect to the monitoring radiometer data). A more complete description of the data processing capability developed at the JRC for the ComPACT method is presented in Chapt. 5.

4.5 SUMMARY AND DISCUSSION

The basic ComPACT measurement system has the major advantage of using a relatively small quantity of pure water (about 3 L of Milli-Q water), and this provides the possibility of standardizing the $I_f(\lambda)$ measurement protocol. Investigations with the ComPACT method implemented at the JRC, which uses an optical bench to mount all the parts to be accurately aligned (lamp, primary baffle,

and monitoring radiometer), showed that elements which may become a source of uncertainties in the determination of $I_f(\lambda)$ are mostly related to the small size of the tank. Specifically, the following was observed:

1. A poor anodization of the internal surfaces of the tank and baffles contributed to an increase of the diffuse light in the water, and

2. A poor alignment of the ComPACT tank can produce reflections of the illumination light cone at the edge of the internal baffles and, thus, create secondary sources of illumination within the tank.

The ComPACT method is a recent alternative to the traditional approach, however, so additional refinements are expected as more experience is gained with this apparatus.

Chapter 5

Data Processing of Alternative Methods

Davide D'Alimonte
JRC/IES/Inland and Marine Waters Unit
Ispra, Italy

James W. Brown
RSMAS/University of Miami
Miami, Florida

Abstract

Two processors were developed by the JRC and GSFC to support the determination of $I_f(\lambda)$ data with the alternative continuous and ComPACT methods. The JRC processor was written in the IDL programming environment, while the GSFC processor was written in the C CodeWarrior programming environment for the Macintosh operating system. The JRC data processor has a GUI that assists the user in the selection of data input and output options, as well as the selection of measurement parameters and processing features. Program control with the GSFC processor is carried out through a traditional command line interface, wherein the user selects the processing options by setting switches, which are used to pass needed numerical, string, or logical values to the main program. Both processors produce quality assurance data supporting the identification of degraded results.

5.1 INTRODUCTION

The implementation of the continuous and ComPACT alternative laboratory methods for the determination of $I_f(\lambda)$ required the implementation of computer codes for the handling and processing of the related data. Two codes were independently implemented by the JRC and GSFC. In addition to providing a separate capability of supporting JRC and GSFC in $I_f(\lambda)$ data analyses, the two data processors provide the unique opportunity of verifying the convergence of results independently produced at the two research facilities.

5.2 THE JRC PROCESSOR

The JRC data processing software was developed to support the analysis of field and laboratory measurements collected to sustain ocean color calibration and validation activities. Among the functions included within the package is a calibration tool supporting the absolute radiometric calibration of optical instruments. This includes a specific module for the computation of $I_f(\lambda)$ values through the traditional (incremental) method as implemented at the JRC (Zibordi et al. 2002). The module was written in the IDL programming environment from Research Systems, Inc. (Boulder, Colorado) to take advantage of its graphical capabilities for data visualization and presentation.

The IDL graphical functions are mostly used to display data at different stages in the processing in order to identify measurements (for instance at single depths) affected by artifacts (i.e., light focusing due to bubbles in the proximity of the collectors, noise caused by a perturbed water surface). The data processing is supported by a GUI that assists the user in the selection of data input and output options (e.g., file names and directory pathways), the selection of measurement parameters (e.g., the source–collector distance and the index of refraction for the water), and of processing features (i.e., the use of dark or background data or enabling the normalization of measurements using data from a radiometer monitoring the light source).

The $I_f(\lambda)$ processing module presented in D'Alimonte and Zibordi (2002), and specifically developed for the traditional method, was upgraded to provide a processing capability for the data taken with the continuous method. A comprehensive description of the upgraded JRC $I_f(\lambda)$ processing module is presented in the following subsections.

5.2.1 Processing Steps

The input file names of the processing module are used to identify the radiometer type (i.e., E_u or E_d), the radiometer serial number, the type of data (i.e., dark, background, and radiometric measurements taken in air or water), the water depth (for the in-water measurements), the

measurement method (i.e., traditional or continuous), and the sequence index (in case of multiple measurement sequences for the same radiometer). Specifically, the files used for computing immersion factors may contain the following data types:

1. Dark data (taken with the cap on the radiometer);

2. Background data (taken with the direct light from the source blocked by an on-axis baffle) or, alternatively, ambient data (taken with the source off and keeping the same illumination conditions existing during the measurement sequence);

3. In-air data (taken with the collectors dry); and

4. In-water data (taken with the collectors submerged).

Measurements from types 2–4 are taken keeping constant the distance d between the source and the collectors of the radiometer.

During SIRREX-8, dark, background (or ambient), and in-air data files were identified by coded file names. The names were composed of a prefix followed by a three-letter suffix or file name extension. The data files from the in-water radiometer, and those from the monitoring sensor, are taken at the same time and have the same file name prefix, but are distinguished by different extension suffixes.

The file name encoding scheme uses a simple algorithm represented by `iinnncm.ext`, wherein

`ii` Indicates the instrument type (i.e., `Eu` or `Ed`);

`nnn` Encodes the three-digit serial number (i.e., `130`);

`c` Is a one-letter code for the data type and is set to `d` for dark data, `b` for background (or ambient data), and `a` for in-air data;

`m` Serializes the measurement sequence for the specific instrument using a one-letter alphabetic ordering (i.e., `a` for the first, `b` for the second, etc.); and

`.ext` Is the file extension (`ocp` for the in-water sensor and `mvd` for the monitoring sensor).

The files for the submerged measurements were identified by a slightly different coded file name `iinnna_dddm.ext`, where `c` was replaced by `a_ddd`:

`a` Establishes the methodological approach, `s` for data taken with the traditional method at fixed depths `ddd` (i.e., data were taken with the collectors at fixed depths `ddd` below the water surface), or `f` for data taken with the continuous method using a water layer of depth `ddd` (i.e., data were taken with water depth decreasing or increasing above the sensor, up to or from a maximum depth `ddd`).

For the latter, `ddd` is encoded in millimeters (as a three-digit sequence).

The average values of dark and background (or ambient) data records in each specific file, are used for the analysis of the in-air, $E(0^+, \lambda)$, and in-water, $E(z, \lambda)$, irradiance data. The data required for the $I_f(\lambda)$ determination

at wavelength λ with the traditional method, are the averages of all records in each specific data file computed after subtracting the average dark (or background) values.

In the case of the continuous method, the depth-specific $E(z, \lambda)$ data are produced by binning the continuous profile data as a function of depth with a user-defined binning size, after subtracting the average dark value. The absolute depth, z, of each element in the data file is determined by assuming a constant flow rate for emptying the tank:

$$z(t) \; = \; \left(1 - \frac{\delta t}{\Delta t}\right)\Delta z, \qquad (10)$$

where, Δz is the maximum water depth in the tank, Δt is the time required for emptying the tank, and δt is the time decrement with respect to Δt associated with the depth at time t, $z(t)$.

When the normalization option is chosen, the in-air and the in-water dark (or background) corrected data are divided by the time correspondent data from the monitoring sensor and are then multiplied by the monitoring radiometer data taken at time t_0 (where t_0 is the time in the first record of the in-air measurement data file). This normalization reduces uncertainties due to changes in the flux of the light source during the measurement sequence.

The $I_f(\lambda)$ values, for both the traditional and continuous method, are then computed using (5)–(9).

5.2.2 Output and Quality Assurance

The $I_f(\lambda)$ processing module produces graphic output for each wavelength of the radiometer, and ensures identification of depth-specific or wavelength-specific data affected by measurement artifacts. In addition to the graphic output, a file log is also created to store intermediate results from the different processing steps. Relevant stored data are the average values computed for each depth at each wavelength, and the related standard deviations, σ. A high σ value suggests changes in the measurement conditions during data collection (i.e., due to an instability of the water surface or the presence of large suspended particles slowly moving over the collectors).

Other relevant quantities stored in the file log, aside from the specific values used for $I_f(\lambda)$ computation, are the $K(\lambda)$ values (i.e., the slopes of the linear regression as a function of water depth of in-water data corrected with the $G(z, \lambda)$ factor). Significant changes in $K(\lambda)$ among successive measurement sequences, suggest changes in the water quality or in the optical–mechanical setup of the system.

5.3 THE GSFC PROCESSOR

The GSFC data processing software for computing immersion factors was developed to support the analysis of experimental data collected using the continuous, ComPACT, and traditional methods. The program was written in the C CodeWarrior programming environment for

the Macintosh operating system from Metroworks, Corp. (Austin, Texas).

Program control is through a traditional command line interface, wherein the user selects the processing options by setting switches, which are used to pass needed numerical, string, or logical values to the main program. A command line can be entered at run time, or a variety of command lines can be stored in a file and accessed by a unique reference number. The program interface is accessible for one-of-a-kind, exploratory processing, or for the reprocessing of complete or partitioned data sets in a batch mode.

The basic philosophy of the program architecture is the so-called *default-loaded, exception-executed programming* (Hooker and Brown 1985, and Brown and Hooker 1985), that is, all program variables are initialized with a set of default values, and the user provides a set of exceptions (using the command line switches) to ensure the program executes in a manner consistent with the user's objectives. In most cases, the primary exception is to direct the program to ingest the user's data, but a full exploration of the data usually involves turning various options on or off to investigate how the data products are influenced.

5.3.1 Processing Steps

Data processing begins with the input data. The program architecture supports the decoding of needed variables from three sources: a) the file names themselves, b) a file header block, and c) the command line. The former are derived from the naming conventions described in Sect. 5.2.1, and the latter two are identified by a unique keyword. The program architecture allows the user to customize the *syntax* of the processing variables by editing the file defining the keywords and their default values.

Once the data source(s) and pathways are identified, the primary processing variables that must be set are as follows:

1. The lamp-to-sensor distance (the default value is 1 m);

2. Whether or not reference sensor data will be used to normalize the in-water data (the default is to apply a normalization);

3. What type of dark, ambient, or background data will be removed from the in-water sensor data (the default is to use just the dark data); and

4. The type of statistical filtering to be used with any ensemble data for outlier rejection.

The default for the latter is to apply a two standard deviation (2σ) noise reduction filter to all data averages and curve fits.

Processing proceeds based on whether or not the original data acquisition was for a continuous or incremental method. For the continuous data, the initial water depth above the sensor must be known, either from the command line or from the file name. In addition, the processor option for whether or not the tank is being emptied or filled must be set, and the shape option for the water vessel must be set if the tank was not a constant area cylinder (the JRC tank used during SIRREX-8, for example, had tapered sides).

All of the data must be time stamped to permit the proper normalization of the in-water data using the reference sensor data, and to allow for the proper calculation of the water depth above the in-water sensor during the continuous method. For the water depth calculation, a constant pumping rate is assumed, and the start and stop times are taken from the data file (it is assumed the data were started and stopped in synchronization with the pump).

The depth of water above the in-water sensor (z) at any given time, t, is computed from the total change in water depth (Δz), and the total change in time (Δt) from when the pump was started and stopped. The formulation for the water depth is based on computing a percentage, $\alpha(t)$, of the total change in depth,

$$z(t) \;=\; \alpha(t)\,\Delta z, \tag{11}$$

and $\alpha(t)$ is set based on whether or not the tank is being emptied or filled:

$$\alpha(t) \;=\; \begin{cases} 1 - \dfrac{\delta t}{\Delta t}, & \text{if emptying the tank,} \\[2ex] \dfrac{\delta t}{\Delta t}, & \text{if filling the tank,} \end{cases} \tag{12}$$

where, δt is the elapsed time for the sample at $z(t)$ with respect to the start of the experimental trial.

Once the depth of each data sample is known, the $G(z, \lambda)$ terms are computed at each depth (6) and are used to correct the in-water data. The in-air measurement and the Fresnel reflectance (7)–(9) are combined (5), log transformed, and fitted as a function of z. The $K(\lambda)$ value is retrieved from the slope of the fit, and the $I_f(\lambda)$ values are retrieved from the anti-log of the y-intercept.

5.3.2 Output and Quality Assurance

The value of any switch that is set during program execution is recorded in a log file, which also contains any warnings or program termination notices. The values of a more complete set of settings, plus more verbose diagnostic information, can be retrieved by enabling the diagnostic printing flag.

5.4 SUMMARY

The JRC and GSFC processors supporting the analysis of data collected from alternative methods for $I_f(\lambda)$ characterizations were developed using different programming

environments. The final data products and much of the mathematical formulations, however, are very similar.

The JRC processor was written in the IDL programming environment to take advantage of its graphical capabilities for data visualization and presentation. The IDL graphical functions are mostly used to display data at different stages in the processing to identify measurements (for instance at single depths) affected by artifacts (i.e., light focusing caused by bubbles in the proximity of the collectors, or noise caused by a perturbed water surface). The data processing is supported by a GUI that assists the user in the selection of data input and output options (e.g., file names and directory pathways), the selection of measurement parameters (e.g., the source-to-collector distance and the index of refraction for the water), and of processing features (i.e., the use of dark or background data or enabling the normalization of measurements using data from a radiometer monitoring the light source).

The GSFC data processing software for computing immersion factors was written in the C CodeWarrior programming environment for the Macintosh operating system. Program control is carried out through a traditional command line interface, wherein the user selects the processing options by setting switches, which are used to pass the needed parameters to the main program. A command line can be entered at run time, or a variety of command lines can be stored in a file and accessed by a unique reference number. The program interface is accessible for one-of-a-kind, exploratory processing, or for the reprocessing of complete or partitioned data sets in a batch mode. The basic philosophy of the program architecture is the so-called default-loaded, exception-executed programming, that is, all program variables are initialized with a set of default values, and the user provides a set of exceptions (using the command line switches) to ensure the program executes in a manner consistent with the user's objectives.

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

Chapter 6

Preliminary Results

Giuseppe Zibordi
JRC/IES/Inland and Marine Waters Unit
Ispra, Italy

Stanford B. Hooker
NASA/Goddard Space Flight Center
Greenbelt, Maryland

Abstract

The continuous and ComPACT methods are intercompared with the traditional incremental method using $I_f(\lambda)$ determinations from various radiometers. The analysis of a series of experiments shows that the continuous method has uncertainties and variability comparable to that of the traditional method. The analysis of the results from the ComPACT and traditional methods shows generally higher $I_f(\lambda)$ values for the former. This is in agreement with the generalized expectations of a reduction in scattering effects, because of the use of pure water with the ComPACT method versus the use of demineralized tap water with the traditional method. The comparison of methods is also extended to the comparison of the JRC and GSFC processors for $I_f(\lambda)$ computations. The results, presented for data taken with the continuous method, show differences to within 0.2%, which are comparable to the repeatability of traditional $I_f(\lambda)$ determinations. Correction values for immersion coefficients determined with pure water, and applied to marine measurements, are also presented and discussed.

6.1 INTRODUCTION

The analysis of the traditional method for $I_f(\lambda)$ determinations, as implemented at the laboratories participating in SIRREX-8, highlighted two significant drawbacks: a) the need for a long execution time, and b) the requirement of large volumes of water. The former diminishes the operational use of the method, because it reduces the number of instruments that can be characterized in a given amount of time, and the latter decreases the reproducibility and accuracy of the measurements, because of the intrinsic difficulty in taking data in water whose properties are not quality assured. Overcoming these two major limitations was the motivation for producing two alternative methods for $I_f(\lambda)$ determination: the continuous method, to save time, and the ComPACT method, to implement a quality assurance capability for water properties. The principal water properties of concern here are those associated with surface particles and scatterers in the water column.

The continuous method makes use of a pump to empty (or fill) the tank, under the assumption of a constant flow rate. The tank emptying (or filling) is carried out in conjunction with the data logging. This leads to the creation of an optical profile, where the depth variable is the varying thickness of the water layer above the sensor. When compared to the traditional method, the continuous method provides a much faster execution of the ensemble of measurements required for $I_f(\lambda)$ determination. In the specific case of the traditional method implemented at CHORS, the execution time can be reduced from 120 min to 35 min. This result immediately demonstrates the operational use of the continuous method for routine instrument characterizations.

The ComPACT method makes use of a very small water vessel for executing the in-water measurements. This makes possible the use of pure water, for instance Milli-Q water, which is easily produced in a laboratory setting. When compared to the traditional method, the ComPACT method can ensure a better reproducibility and accuracy of $I_f(\lambda)$ determinations. These elements suggest that the ComPACT method could be suitable for a standardization of $I_f(\lambda)$ measurements.

The objective of the analyses presented here, aside from a general introduction of the common perturbation elements in $I_f(\lambda)$ characterizations, is to evaluate the differences in results obtained with the continuous and ComPACT methods versus the traditional method. For completeness, the sources of uncertainty associated with data

processing are investigated by intercomparing the JRC and GSFC processors for $I_f(\lambda)$ determination.

The comparisons are presented by computing a relative percent difference (RPD), ψ, defined as:

$$\psi = 100 \frac{Y - X}{X}, \qquad (13)$$

where X is a reference measurement and Y is the measurement to be investigated.

6.2 QUALITY ASSURANCE

Surfactants and in-water scatterers increase the uncertainties in determining immersion factors, but by opposite influences. Surfactants tend to decrease the amount of light reaching the sensor, because of an increase in the amount of reflection at the surface, which leads to an overestimation of $I_f(\lambda)$. In-water scatterers, usually caused by a decrease in water purity, tend to increase the amount of light reaching the sensor, which produces an underestimation of $I_f(\lambda)$. The first of these effects is considered in Fig. 5, which shows the RPD values in determining $I_f(\lambda)$ for four sets of Eu130 trials (solid symbols), wherein the RPD values are calculated with respect to the average $I_f(\lambda)$ values from a fifth set of trials representing unequivocally clean surface conditions (open circles).
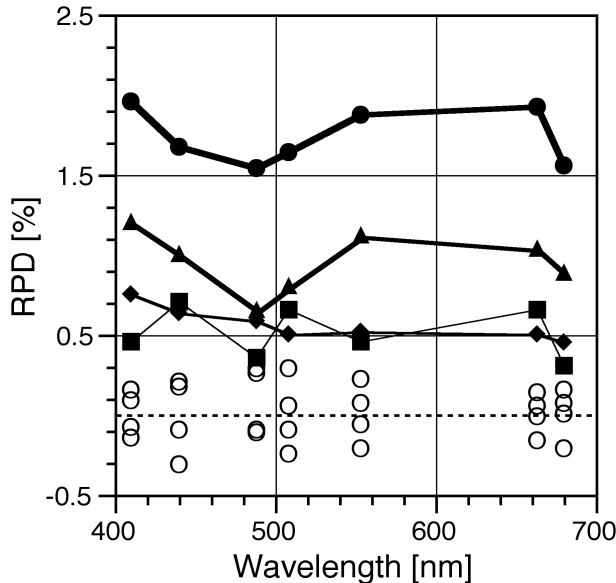

Fig. 5. The effects of surface cleaning on the determination of $I_f(\lambda)$ for Eu130. The cleanest surface conditions (from extensive wet–dry vacuuming) are given by the open circles, and the effect of cleaning a dirty surface is given by the sequence of solid symbols. The latter starts with no surface cleaning for an unrealistic water surface covered by high concentrations of particles (solid circles and solid triangles) and concludes with extensive manual removal (solid diamonds) and light wet–dry vacuuming (solid squares).

The progression from uncleaned to increasingly cleaned surface conditions in Fig. 5 shows a commensurate and steady decrease in RPD values. Neglecting the two extreme cases, presented by the solid triangles and solid circles and associated with a high density of surface particles, the results show that dust particles can easily produce an average spectral overestimation in the computed $I_f(\lambda)$ on the order of 0.5%. The latter is appreciably greater than the 0.2% average variability associated with determining $I_f(\lambda)$ with clean surface conditions.

An important aspect of the surface cleaning results (Fig. 5) is there is no significant spectral component to the results. Although there are spectral features in the results (recurring dips at 490 and 665 nm), there is no clear indication that a particular portion of the spectrum is more influenced than another. In general, the presence of particles on the surface of the water leads to a broadband decrease in the amount of light transmitted through the surface, so all sensor channels are influenced rather equally.

Figure 6 shows the comparison between a set of $I_f(\lambda)$ values determined for the Eu130 sensor using tap water with respect to average $I_f(\lambda)$ values determined with demineralized tap water. The latter was accompanied by filtering the former to remove as many particles as possible. The resulting resistivity, which is a commonly used indicator of water purity, was approximately 5–8 MΩ for the demineralized water. The $I_f(\lambda)$ values determined with tap water are persistently the smallest values, which confirms the presence of scatterers in the water reduces the immersion factors.
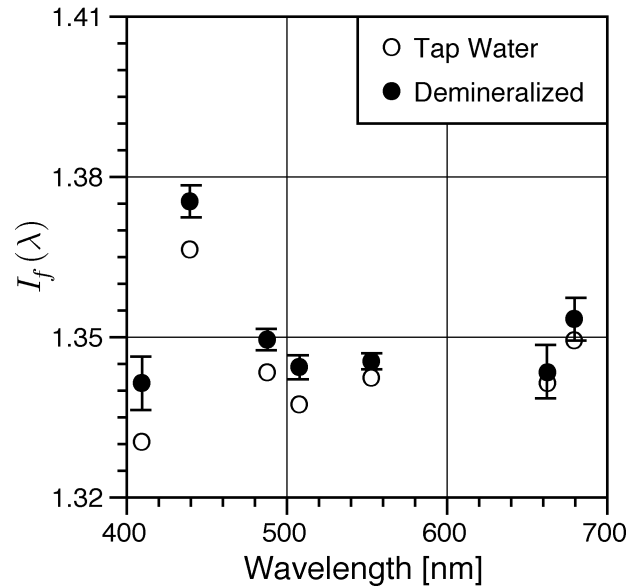

Fig. 6. The effects of scattering on $I_f(\lambda)$ as determined by comparing the results using tap water (open circles) versus demineralized water (solid circles). The error bars correspond to two standard deviations ($\pm 2\sigma$) of variation in the demineralized measurements.

There are also spectral properties in the differences between the two sets of $I_f(\lambda)$ values in Fig. 6. The differences are maximal in the blue domain, and tend to decrease with increasing wavelength. In fact, in the red part of the spectrum, the differences are within the variance (as indicated by the error bars) of the $I_f(\lambda)$ values for demineralized water. Particles scatter more in the blue domain, thus, larger uncertainties are expected at smaller wavelengths.

6.3 METHOD VALIDATION

The validation of the new methods proceeds by comparing them to the traditional (incremental) method. Specifically, the immersion factors derived from the new and traditional methods are intercompared, with the latter used as the so-called *reference* in (13). This approach maximizes the estimated uncertainty, because it is not shared equally between the methods—all of the uncertainty is attributed to the new method.

6.3.1 The Continuous Method

One of the unique experiments conducted for evaluating the continuous method was to collect a series of continuous trials for `Eu048` interspersed with three traditional trials. These data provide the opportunity to reliably estimate the uncertainty in repeatability for the continuous method, as well as to validate the basic methodology. Comparisons between average $I_f(\lambda)$ values determined with the traditional method and multiple realizations made with the continuous method are shown in Fig. 7.
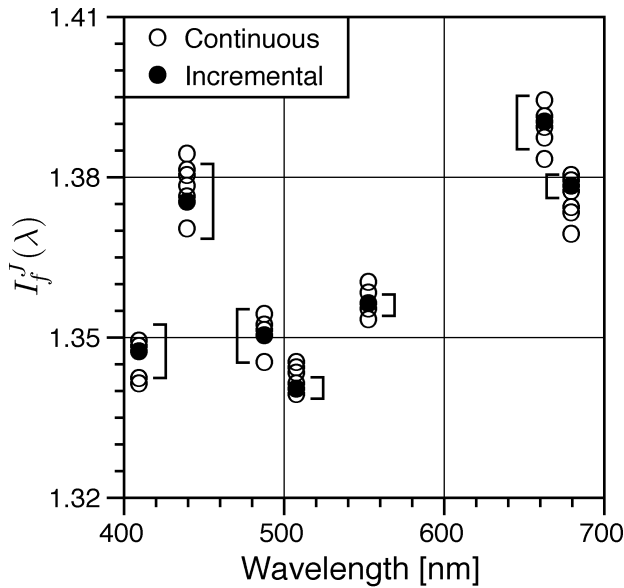
Fig. 7. A comparison of multiple applications of the continuous and traditional (incremental) methods for `Eu048` using the JRC processor to determine the immersion factors, $I_f^J(\lambda)$. The incremental values are an average derived from three trials, and the offset bars indicate plus or minus one standard deviation for the three trials.

The Fig. 7 results show the immersion factors computed with the continuous method overlay the range of variability (defined by $\pm 1\sigma$) determined with the traditional method, but these data are only for one sensor. A scatter plot of $I_f(\lambda)$ values for different sensors determined with the continuous method versus the incremental method is presented in Fig. 8. The plot and RPD histogram shows the continuous method overestimates immersion factors with respect to the traditional method by approximately 0.1%. This discrepancy falls within the repeatability variance of $I_f(\lambda)$ determinations for a single sensor, as presented here in Figs. 6–7, and in terms of the results presented for SIRREX-8 (Zibordi et al. 2002). These data show the continuous method is an acceptable alternative to the traditional method.
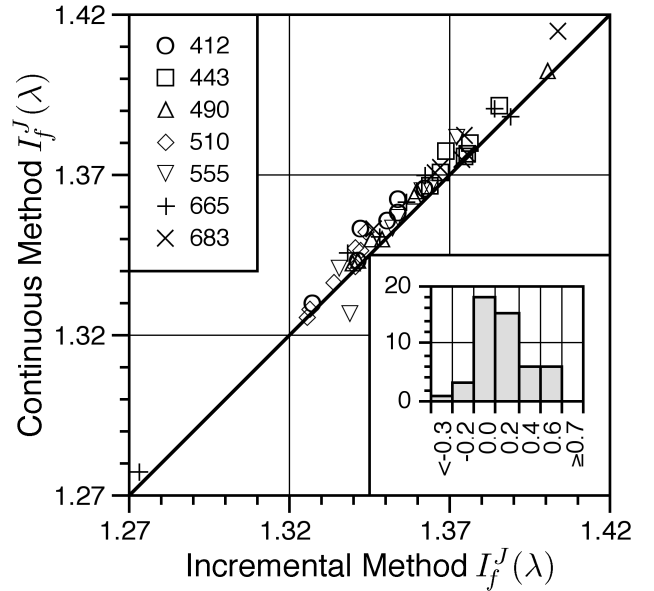
Fig. 8. A comparison of the continuous and traditional incremental methods for determining $I_f(\lambda)$, all processed with the JRC processor. A histogram of the RPD values between the two methods, using the incremental method results as the computational references, is shown in the inset panel.

6.3.2 The ComPACT Method

Although the ComPACT method uses the traditional incremental method, it is considered a new method, because the apparatus involved is completely new. The differences between the $I_f(\lambda)$ values determined with the traditional method and those determined with the ComPACT method for the `Eu130` sensor are presented in Fig. 9. The ComPACT method used pure water, whereas the traditional method results were determined at the JRC using demineralized tap water. Based on the earlier experiments with tap and demineralized water (Fig. 6), increased water purity leads to an increase in $I_f(\lambda)$ values, so the general expectation is that the immersion factors derived from the

ComPACT method will exceed the traditional method values. This is precisely what is seen in Fig. 9.
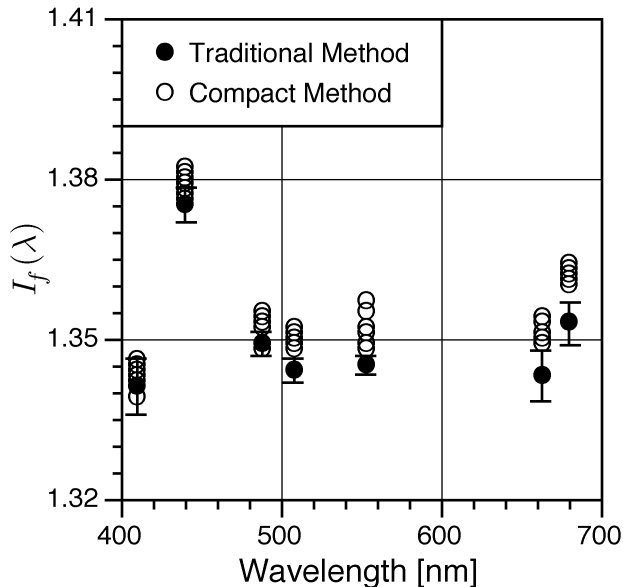

Fig. 9. The determination of $I_f(\lambda)$ values for the ComPACT method and compared to the traditional method using the JRC apparatus. The error bars indicate $\pm 1\sigma$ for the latter.

The results in Fig. 9 deserve additional consideration. In general, the inaccuracy between the two methods varies as a function of wavelength, which suggests the presence of spectral perturbations affecting the ComPACT measurements. Given all the different components of the ComPACT method, this is most likely caused by reflections within the water vessel, perhaps from the anodized surfaces being insufficiently *black* and not completely *flat* (i.e., selectively reflective at some wavelengths). Although incomplete or *patchy* anodization is a recurring quality control problem, suitable levels of anodization are achievable, and this should not be considered a limitation of the ComPACT method.

6.4 PROCESSOR COMPARISON

Quantification of the uncertainties induced by the application of different processing schemes is addressed by comparing the $I_f(\lambda)$ values determined with the continuous method using the JRC and GSFC processors. This comparison is shown in Fig. 10 for a variety of radiometers. The average RPD between the processors is approximately 0.2%. Both processors make use of the same relationships for determining $n_w(\lambda)$, $G(z, \lambda)$, and $T_s(\lambda)$, in (6)–(9), so the differences are mostly explained by the implementation of a noise reduction filter in the GSFC processor, and by the binning of data as a function of depth in the JRC processor. Because the differences between the two processors are within the repeatability of $I_f(\lambda)$ determinations,

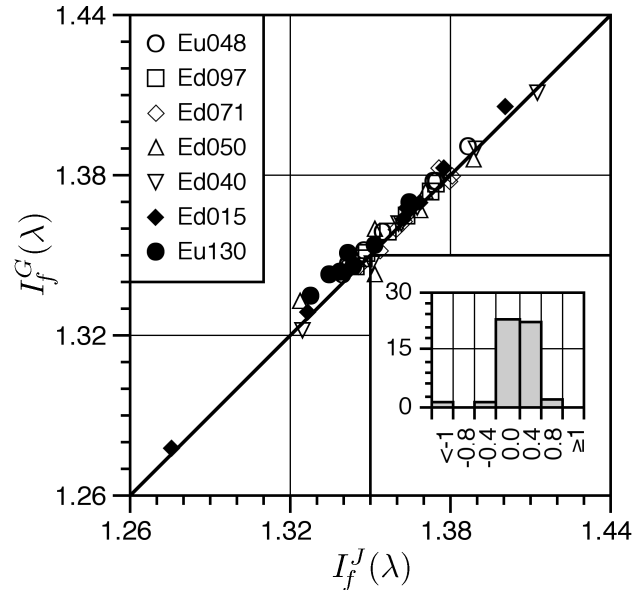no additional effort has been made in producing a better convergence of the results.

Fig. 10. A comparison of the JRC and GSFC processors for determining $I_f(\lambda)$ using the continuous method [the GSFC results are denoted $I_f^G(\lambda)$]. A histogram of the RPD values between the processors, using the JRC processor as the reference, is shown in the inset panel.

6.5 SUMMARY AND DISCUSSION

SIRREX-8 showed different implementations, at different laboratories, of the same basic $I_f(\lambda)$ measurement protocol presented in Mueller and Austin (1995). The different implementations made use of different setups, tank volumes, and water types; consequently, they required a different execution time to characterize a radiometer and exhibited different accuracies. The need for standardizing the characterization of $I_f(\lambda)$ values, while increasing the accuracy of candidate methods and decreasing the execution time, was the primary motivation for proposing and exploring the capabilities of alternative methods. These investigations led to the proposal of two new methods:

1. The continuous method, in which optical measurements taken with discrete water depths are substituted by continuous profiles created by removing the water from the tank at a constant flow rate with a pump; and

2. The ComPACT method, in which the commonly used large tank is replaced by a small water vessel thereby permitting the determination of $I_f(\lambda)$ values with a quality-assured and reproducible water volume.

The primary advantage of the continuous method is a significant reduction in the time required for the characterization of a single radiometer, whereas, the primary advantage of the ComPACT method is the possibility of using

pure water that can be economically produced (because of the small water vessel volume).

It is important to remember there are also secondary benefits with both methods, with respect to the traditional method executed with a large tank:

- Once the water surface is cleaned, the continuous method is executed sufficiently fast that additional surface cleanings are not needed.

- The ComPACT method also saves time, because the water surface can be very easily and rapidly cleaned (it has a very small surface area), plus the amount of time used for draining and filling the tank is reduced.

- The ComPACT method requires a modest amount of space and significantly simpler waste water requirements.

- The ComPACT method easily accommodates specialized experiments with contaminated water, because the water vessel can be quickly cleaned and restored (similarly, the small size of the tank allows for considerably easier maintenance over time).

Examples of the latter include the addition of scattering or absorption materials, or other substances associated with a unique measurement environment.

Within the discussions of uncertainties and the ultimate selection of an immersion factor method, it is important to remember the analytical approach adopted here can be considered conservative, because the uncertainties are not shared equally—all the differences in a new-versus-traditional comparison were ascribed to the new method. This is a consequence of there being no absolute truth associated with the entire process, so the traditional method was selected as the reference for evaluation purposes. Consequently, if a new method satisfies the general protocol, and produces results within the variance of the accepted method, there is no reason to ignore it, particularly if it provides demonstrable advantages (like the ones listed above).

The concept that there is no absolute truth in characterizing the immersion factor is an important one. There is nothing that can be purchased from a standards laboratory that will allow the investigator to compare the experimental results with a set of known values. The *answer* is achieved experimentally by following an accepted protocol as accurately as possible.

Figure 11 shows a summary of the validation results produced for the different methods and processors presented in this study. The $I_f(\lambda)$ values are for the Eu130 sensor, and the values determined with the traditional incremental method are the results by which the others are evaluated. There is a significant convergence of the continuous and traditional methods regardless of the selected processor.
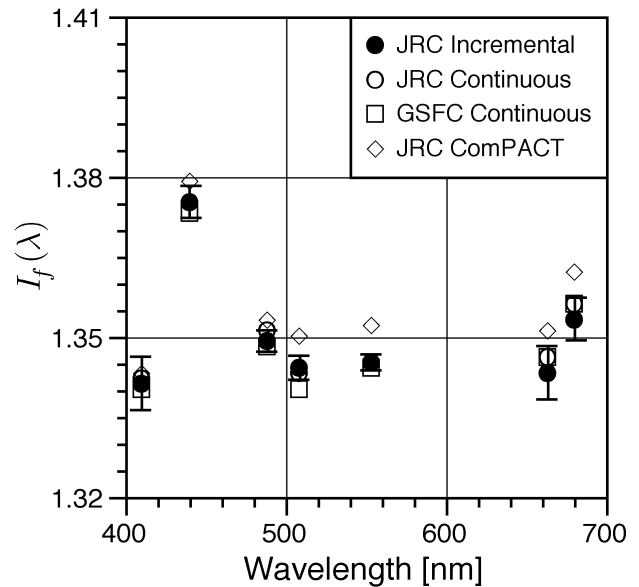

Fig. 11. A comparison of the different methods and processors for the determination of $I_f(\lambda)$ for Eu130 (the so-called reference sensor). The error bars denote $\pm 1\sigma$ for the incremental method using the traditional apparatus.

Although the Fig. 11 data show an overall convergence between the different methods, the $I_f(\lambda)$ values determined with the ComPACT method are usually higher than those obtained with the other methods. This result is most likely explained by a) the use of Milli-Q water with the ComPACT method, which is purer than the demineralized tap water used with the other methods and, thus, yields more accurate and slightly higher $I_f(\lambda)$ values; and b) the presence of internal reflections not properly baffled or minimized by the anodized surfaces, which produces spectral perturbations.

As mentioned above, a relevant advantage provided by the ComPACT method, because of the small volume of water needed to fill the water vessel (approximately 3 L), is the possibility of designing specific experiments to quantify the uncertainties of perturbing factors, e.g., absorption or scattering material, surfactants, etc. This capability was exploited through a specific experiment designed to evaluate the consequences of using pure water rather than salt water when characterizing $I_f(\lambda)$ values. The basic objective was to determine whether or not the pure water approach could be satisfactorily corrected for marine measurements. The experiment was conducted with a combination of real and synthetic seawater: a) two samples were produced by filtering seawater from the northern Adriatic Sea with 0.22 μm pore size filters, and b) two more samples were synthetically produced by adding 3.5% pure sea salt and aquarium sea salt to volumes of Milli-Q water, and then successively filtering the two solutions with 0.22 μm pore size filters.

Figure 12 shows the comparison between average Eu130 $I_f(\lambda)$ values determined with the ComPACT method using

Milli-Q water and different determinations obtained with the ComPACT method and salt water. The $I_f(\lambda)$ data for salt water, exhibit higher values with respect to those determined with pure water. This result is in agreement with the higher refractive index of seawater with respect to that of pure water.
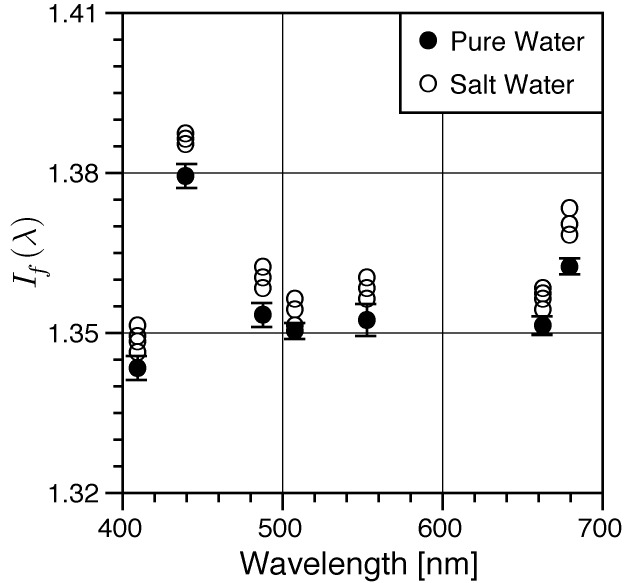

Fig. 12. A comparison of the determination of $I_f(\lambda)$ using pure water (solid circles) versus salt water (open circles) and the ComPACT method. The error bars denote $\pm 1\sigma$ for the pure water results.

Average pure water and salt water $I_f(\lambda)$ values determined with the ComPACT method for the `Eu130` sensor are given in Table 4, together with RPDs of pure versus salt water $I_f(\lambda)$ values. The correction coefficients for $I_f(\lambda)$ values determined using pure water, but applied to seawater measurements, are quantified through the RPD which range from 0.3–0.6%, with a spectrally averaged value of 0.5%. The latter confirms the empirical estimate of approximately 0.5% proposed by Zibordi et al. (2002).

Table 4. Pure and salt water $I_f(\lambda)$ values determined with the ComPACT method for the `Eu130` sensor (the $\pm$ values indicate 1σ). The RPD is the relative percent difference of pure water with respect to salt water $I_f(\lambda)$ values. The number of trials is given by N.

λ [nm]	Pure Water ($N = 4$)	Salt Water ($N = 4$)	RPD [%]
412	1.343 ± 0.002	1.349 ± 0.002	-0.43
443	1.379 ± 0.002	1.386 ± 0.001	-0.55
490	1.353 ± 0.002	1.361 ± 0.002	-0.56
510	1.350 ± 0.002	1.354 ± 0.002	-0.28
555	1.352 ± 0.003	1.358 ± 0.002	-0.41
665	1.351 ± 0.002	1.356 ± 0.002	-0.39
683	1.362 ± 0.001	1.370 ± 0.002	-0.58

G. Zibordi, D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown

APPENDICES

A. The Alternative Methods Science Team

Appendix A

The Alternative Methods Science Team

The alternative methods science team members are presented alphabetically.

James Brown
MPO/RSMAS/U. of Miami
4600 Rickenbacker Cswy.
Miami, Florida 33149
Voice: 305–361–4770
Fax: 301–361–4622
Net: jim.brown@miami.edu

Davide D'Alimonte
JRC/IES/IMW T.P. 272
I–21020 Ispra (VA)
ITALY
Voice: 39–0–332–785–727
Fax: 39–0–332–789–034
Net: davide.d'alimonte@jrc.it

Stanford Hooker
NASA/GSFC/Code 970.2
Bldg. 28, Room W126
Greenbelt, Maryland 20771
Voice: 301–286–9503
Fax: 301–286–0268
Net: stan@ardbeg.gsfc.nasa.gov

Dirk van der Linde
JRC/IES/IMW T.P. 272
I–21020 Ispra (VA)
ITALY
Voice: 39–0–332–785–362
Fax: 39–0–332–789–034
Net: dirk.vanderlinde@jrc.it

Giuseppe Zibordi
JRC/IES/IMW T.P. 272
I–21020 Ispra (VA)
ITALY
Voice: 39–0–332–785–902
Fax: 39–0–332–789–034
Net: giuseppe.zibordi@jrc.it

GLOSSARY

CHORS Center for Hydro-Optics and Remote Sensing
ComPACT Compact Portable Advanced Characterization Tank
DATA-100 Not an acronym, but a designator for the Satlantic, Inc., series of power and telemetry units.
DVM Digital Voltmeter
GSFC Goddard Space Flight Center
GUI Graphical User Interface
IDL Interactive Data Language
JRC Joint Research Centre
NASA National Aeronautics and Space Administration
OCI Ocean Color Irradiance
OCI-200 OCI series-200 (sensor)
OCR Ocean Color Radiance
OCR-200 OCR series-200 (sensor)
RPD Relative Percent Difference
RSMAS Rosenstiel School of Marine and Atmospheric Science
S/N Serial Number
SeaWiFS Sea-viewing Wide Field-of-view Sensor
SIRREX SeaWiFS Intercalibration Round-Robin Experiment
SIRREX-8 The Eighth SIRREX (September–December 2001)
SNR Signal-to-Noise Ratio
SOOP SeaWiFS Ocean Optics Protocols
SQM SeaWiFS Quality Monitor
UPS Uninterruptible Power System

SYMBOLS

$C_c(\lambda)$ The spectral calibration coefficient.
d The distance between the lamp and the diffuser faceplate.
$\bar{D}(\lambda)$ The average bias or dark voltage.
$E(\lambda)$ Spectral irradiance.
$E(z,\lambda)$ Spectral irradiance at a given depth.
$E(\lambda, t_i)$ Net signal detected by the radiometer while exposed to light.
$E_{\text{cal}}(\lambda, t_i)$ Spectral calibrated irradiance.
$E(0^+,\lambda)$ In-air spectral irradiance.
$E(0^-,\lambda)$ In-water spectral irradiance.
$E_d(\lambda)$ In-water spectral downward irradiance.
$E_u(\lambda)$ In-water spectral upward irradiance.
G The code used for indicating GSFC data processing.
$G(z,\lambda)$ In-water spectral correction for geometric effects.
$I_f(\lambda)$ The spectral immersion factor.
J The code used for indicating JRC data processing.
$K(\lambda)$ The spectral diffuse attenuation coefficient.
N The number of trials.
$n_w(\lambda, S, T)$ The refractive index of water.
R_d Radius of the diffuser.
S Salinity.
t Time.
T Water temperature.
t_0 A reference time (generally chosen to coincide with the start of a measurement sequence).
t_i A specific time.
$T_s(\lambda)$ The spectral transmittance of the water surface to downward irradiance.

$V(\lambda, t_i)$ Spectral digitized voltages (in counts).

X An arbitrary reference measurement.

Y An arbitrary measurement to be investigated.

z The vertical (depth) coordinate, where the depth is the height of water above the cosine collectors.

z_c The critical depth.

δt Time variation.

Δt The amount of time to empty the tank.

Δz The total water depth with the tank filled.

$\alpha(t)$ The function relating time to water depth.

λ Wavelength.

σ Standard deviation.

ψ The RPD value.

References

Atkins, W.R.G., and H.H. Poole, 1933: The photo-electric measurement of the penetration of light of various wave lengths into the sea and the physiological bearing of results. *Phil. Trans. Roy. Soc. London,* **222,** 129–164.

Berger, F., 1958: *Über die ursache des "oberflächeneffekts" bei lichtmessungen unter wasser. Wetter u. Leben,* **10,** 164–170.

——, 1961: *Über den "Taucheffekt" bei der lichtmessung über and unter wasser. Arch. Meteorol. Wien.,* **11,** 224–240.

Brown, J.W., and S.B. Hooker, 1985: FIXSRC: A FORTRAN preprocessor. *Comp. Phys. Comm.,* **38,** 435–440.

D'Alimonte, D., and G. Zibordi, 2002: "Computing the immersion factor." In: Zibordi, G., D. D'Alimonte, D. van der Linde, J-F. Berthon, S.B. Hooker, J.L. Mueller, G. Lazin, and S. McLean, The Eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8), September–December 2001. *NASA Tech. Memo. 2002–206892, Vol. 20,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 21–24.

Hooker, S.B., and J.W. Brown, 1985: CENTER: A software package for center estimation. *Comp. Phys. Comm.,* **38,** 421–433.

——, and J. Aiken, 1998: Calibration evaluation and radiometric testing of field radiometers with the SeaWiFS Quality Monitor (SQM). *J. Atmos. Oceanic Tech.,* 995–1,007.

——, S. McLean, J. Sherman, M. Small, G. Lazin, G. Zibordi, and J.W. Brown, 2002: The Seventh SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-7), March 1999. *NASA Tech. Memo. 2002–206892, Vol. 17,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 69 pp.

Mueller, J.L., 1995: "Comparison of irradiance immersion coefficients for several marine environmental radiometers (MERs)." In: Mueller, J.L., R.S. Fraser, S.F. Biggar, K.J. Thome, P.N. Slater, A.W. Holmes, R.A. Barnes, C.T. Weir, D.A. Siegel, D.W. Menzies, A.F. Michaels, and G. Podesta: Case Studies for SeaWiFS Calibration and Validation, Part 3. *NASA Tech. Memo. 104566, Vol. 27,* S.B. Hooker, E.R. Firestone, and J.G. Acker, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 3–15.

Mueller, J.L., 2000: "Overview of measurement and data analysis protocols." In: Fargion, G.S., and J.L. Mueller, Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 2. *NASA Tech. Memo. 2000–209966,* NASA Goddard Space Flight Center, Greenbelt, Maryland, 87–97.

——, 2002: "Overview of measurement and data analysis protocols." In: Mueller, J.L., and G.S. Fargion, Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 3, Volume 1. *NASA Tech. Memo. 2002–210004/ Rev3–Vol1,* NASA Goddard Space Flight Center, Greenbelt, Maryland, 123–137.

——, and R.W. Austin, 1992: Ocean Optics Protocols for SeaWiFS Validation. *NASA Tech. Memo. 104566, Vol. 5,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 43 pp.

——, and R.W. Austin, 1995: Ocean Optics Protocols for SeaWiFS Validation, Revision 1. *NASA Tech. Memo. 104566, Vol. 25,* S.B. Hooker, E.R. Firestone, and J.G. Acker, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 67 pp.

Petzold, T.J., and R.W. Austin, 1988: Characterization of MER 1032. *Tech. Memo. EN–001–88t,* Vis. Lab., Scripps Institution of Oceanography, La Jolla, California, 56 pp. plus appendices.

Smith, R.C., 1969: An underwater spectral irradiance collector. *J. Mar. Res.,* **27,** 341–351.

Tyler, J.E., and R.C. Smith, 1970: *Measurements of Spectral Irradiance Underwater.* Gordon and Breach, New York, 103 pp.

Westlake, D.F., 1965: Some problems in the measurement of radiation under water: A review. *Photochem. Photobiol.,* **4,** 849–868.

Zibordi, G., D. D'Alimonte, D. van der Linde, J-F. Berthon, S.B. Hooker, J.L. Mueller, G. Lazin, and S. McLean, 2002: The Eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8), September–December 2001. *NASA Tech. Memo. 2002–206892, Vol. 20,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 39 pp.

The SeaWiFS Postlaunch Technical Report Series

Vol. 1

Johnson, B.C., J.B. Fowler, and C.L. Cromer, 1998: The SeaWiFS Transfer Radiometer (SXR). *NASA Tech. Memo. 1998–206892, Vol. 1,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 58 pp.

Vol. 2

Aiken, J., D.G. Cummings, S.W. Gibb, N.W. Rees, R. Woodd-Walker, E.M.S. Woodward, J. Woolfenden, S.B. Hooker, J-F. Berthon, C.D. Dempsey, D.J. Suggett, P. Wood, C. Donlon, N. González-Benítez, I. Huskin, M. Quevedo, R. Barciela-Fernandez, C. de Vargas, and C. McKee, 1998: AMT-5 Cruise Report. *NASA Tech. Memo. 1998–206892, Vol. 2,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 113 pp.

Vol. 3

Hooker, S.B., G. Zibordi, G. Lazin, and S. McLean, 1999: The SeaBOARR-98 Field Campaign. *NASA Tech. Memo. 1999–206892, Vol. 3,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 40 pp.

Vol. 4

Johnson, B.C., E.A. Early, R.E. Eplee, Jr., R.A. Barnes, and R.T. Caffrey, 1999: The 1997 Prelaunch Radiometric Calibration of SeaWiFS. *NASA Tech. Memo. 1999–206892, Vol. 4,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 51 pp.

Vol. 5

Barnes, R.A., R.E. Eplee, Jr., S.F. Biggar, K.J. Thome, E.F. Zalewski, P.N. Slater, and A.W. Holmes 1999: The SeaWiFS Solar Radiation-Based Calibration and the Transfer-to-Orbit Experiment. *NASA Tech. Memo. 1999–206892, Vol. 5,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, 28 pp.

Vol. 6

Firestone, E.R., and S.B. Hooker, 2000: SeaWiFS Postlaunch Technical Report Series Cumulative Index: Volumes 1–5. *NASA Tech. Memo. 2000–206892, Vol. 6,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 14 pp.

Vol. 7

Johnson, B.C., H.W. Yoon, S.S. Bruce, P-S. Shaw, A. Thompson, S.B. Hooker, R.E. Eplee, Jr., R.A. Barnes, S. Maritorena, and J.L. Mueller, 1999: The Fifth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-5), July 1996. *NASA Tech. Memo. 1999–206892, Vol. 7,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, 75 pp.

Vol. 8

Hooker, S.B., and G. Lazin, 2000: The SeaBOARR-99 Field Campaign. *NASA Tech. Memo. 2000–206892, Vol. 8,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, 46 pp.

Vol. 9

McClain, C.R., E.J. Ainsworth, R.A. Barnes, R.E. Eplee, Jr., F.S. Patt, W.D. Robinson, M. Wang, and S.W. Bailey, 2000: SeaWiFS Postlaunch Calibration and Validation Analyses, Part 1. *NASA Tech. Memo. 2000–206892, Vol. 9,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, 82 pp.

Vol. 10

McClain, C.R., R.A. Barnes, R.E. Eplee, Jr., B.A. Franz, N.C. Hsu, F.S. Patt, C.M. Pietras, W.D. Robinson, B.D. Schieber, G.M. Schmidt, M. Wang, S.W. Bailey, and P.J. Werdell, 2000: SeaWiFS Postlaunch Calibration and Validation Analyses, Part 2. *NASA Tech. Memo. 2000–206892, Vol. 10,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, 57 pp.

Vol. 11

O'Reilly, J.E., S. Maritorena, M.C. O'Brien, D.A. Siegel, D. Toole, D. Menzies, R.C. Smith, J.L. Mueller, B.G. Mitchell, M. Kahru, F.P. Chavez, P. Strutton, G.F. Cota, S.B. Hooker, C.R. McClain, K.L. Carder, F. Müller-Karger, L. Harding, A. Magnuson, D. Phinney, G.F. Moore, J. Aiken, K.R. Arrigo, R. Letelier, and M. Culver 2000: SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3. *NASA Tech. Memo. 2000–206892, Vol. 11,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, 49 pp.

Vol. 12

Firestone, E.R., and S.B. Hooker, 2000: SeaWiFS Postlaunch Technical Report Series Cumulative Index: Volumes 1–11. *NASA Tech. Memo. 2000–206892, Vol. 12,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 24 pp.

Vol. 13

Hooker, S.B., G. Zibordi, J-F. Berthon, S.W. Bailey, and C.M. Pietras, 2000: The SeaWiFS Photometer Revision for Incident Surface Measurement (SeaPRISM) Field Commissioning. *NASA Tech. Memo. 2000–206892, Vol. 13,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 24 pp.

Vol. 14

Hooker, S.B., H. Claustre, J. Ras, L. Van Heukelem, J-F. Berthon, C. Targa, D. van der Linde, R. Barlow, and H. Sessions, 2000: The First SeaWiFS HPLC Analysis Round-Robin Experiment (SeaHARRE-1). *NASA Tech. Memo. 2000–206892, Vol. 14,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 42 pp.

Vol. 15

Hooker, S.B., G. Zibordi, J-F. Berthon, D. D'Alimonte, S. Maritorena, S. McLean, and J. Sildam, 2001: Results of the Second SeaWiFS Data Analysis Round Robin, March 2000 (DARR-00). *NASA Tech. Memo. 2001–206892, Vol. 15,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 71 pp.

Vol. 16

Patt, F.S., 2002: Navigation Algorithms for the SeaWiFS Mission. *NASA Tech. Memo. 2002–206892, Vol. 16,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 17 pp.

Vol. 17

Hooker, S.B., S. McLean, J. Sherman, M. Small, G. Lazin, G. Zibordi, and J.W. Brown, 2002: The Seventh SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-7), March 1999. *NASA Tech. Memo. 2002–206892, Vol. 17,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 69 pp.

Vol. 18

Firestone, E.R., and S.B. Hooker, 2002: SeaWiFS Postlaunch Technical Report Series Cumulative Index: Volumes 1–17. *NASA Tech. Memo. 2002–206892, Vol. 18,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 28 pp.

Vol. 19

Zibordi, G., J-F. Berthon, J.P. Doyle, S. Grossi, D. van der Linde, C. Targa, and L. Alberotanza 2002: Coastal Atmosphere and Sea Time Series (CoASTS), Part 1: A Tower-Based Long-Term Measurement Program. *NASA Tech. Memo. 2002–206892, Vol. 19,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 29 pp.

Vol. 20

Berthon, J-F., G. Zibordi, J.P. Doyle, S. Grossi, D. van der Linde, and C. Targa, 2002: Coastal Atmosphere and Sea Time Series (CoASTS), Part 2: Data Analysis. *NASA Tech. Memo. 2002–206892, Vol. 20,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 25 pp.

Vol. 21

Zibordi, G., D. D'Alimonte, D. van der Linde, J-F. Berthon, S.B. Hooker, J.L. Mueller, G. Lazin, and S. McLean, 2002: The Eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8), September–December 2001. *NASA Tech. Memo. 2002–206892, Vol. 21,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 39 pp.

Vol. 22

Patt, F.S., R.A. Barnes, R.E. Eplee, Jr., B.A. Franz, W.D. Robinson, G.C. Feldman, S.W. Bailey J. Gales, P.J. Werdell, M. Wang, R. Frouin, R.P. Stumpf, R.A. Arnone, R.W. Gould, Jr., P.M. Martinolich, V. Ransibrahmanakul, J.E. O'Reilly, and J.A. Yoder, 2003: Algorithm Updates for the Fourth SeaWiFS Data Reprocessing, *NASA Tech. Memo. 2003–206892, Vol. 22,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 74 pp.

Vol. 23

Hooker, S.B., G. Zibordi, J-F. Berthon, D. D'Alimonte, D. van der Linde, and J.W. Brown, 2003: Tower-Perturbation Measurements in Above-Water Radiometry. *NASA Tech. Memo. 2003–206892, Vol. 23,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 35 pp.

Vol. 24

Firestone, E.R., and S.B. Hooker, 2003: SeaWiFS Postlaunch Technical Report Series Cumulative Index: Volumes 1–23. *NASA Tech. Memo. 2003–206892, Vol. 24,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, (in prep.).

Vol. 25

Doyle, J.P., S.B. Hooker, G. Zibordi, and D. van der Linde, 2003: Validation of an In-Water, Tower-Shading Correction Scheme. *NASA Tech. Memo. 2003–206892, Vol. 25,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 32 pp.

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Zibordi, G., D. D'Alimonte, D. van der Linde, S.B. Hooker, and J.W. Brown, 2003: New Laboratory Methods for Characterizing the Immersion Factors of Irradiance Sensors. *NASA Tech. Memo. 2003–206892, Vol. 26,* S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 34 pp.

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Giuseppe Zibordi, Davide D'Alimonte, Dirk van der Linde, Stanford B. Hooker,
and James W. Brown
    Series Editors: Stanford B. Hooker and Elaine R. Firestone

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Laboratory for Hydrospheric Processes
Goddard Space Flight Center
Greenbelt, Maryland 20771

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E.R. Firestone: Science Applications International Corporation, Beltsville, Maryland; G. Zibordi, D. D'Alimonte, and D. van der Linde: JRC/Institute for Environment Sustainability, Ispra, Italy; and J.W. Brown: RSMAS/University of Miami, Miami, Florida

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The experimental determination of the immersion factor, $I_f(\lambda)$, of irradiance collectors is a requirement of any in-water radiometer. The eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8) showed different implementations, at different laboratories, of the same $I_f(\lambda)$ measurement protocol. The different implementations make use of different setups, volumes, and water types. Consequently, they exhibit different accuracies and require different execution times for characterizing an irradiance sensor. In view of standardizing the characterization of $I_f(\lambda)$ values for in-water radiometers, together with an increase in the accuracy of methods and a decrease in the execution time, alternative methods are presented, and assessed versus the traditional method. The proposed new laboratory methods include: a) the continuous method, in which optical measurements taken with discrete water depths are substituted by continuous profiles created by removing the water from the water vessel at a constant flow rate (which significantly reduces the time required for the characterization of a single radiometer); and b) the Compact Portable Advanced Characterization Tank (ComPACT) method, in which the commonly used large tanks are replaced by a small water vessel, thereby allowing the determination of $I_f(\lambda)$ values with a small water volume, and more importantly, permitting $I_f(\lambda)$ characterizations with pure water. Intercomparisons between the continuous and the traditional method showed results within the variance of $I_f(\lambda)$ determinations. The use of the continuous method, however, showed a much shorter realization time. Intercomparisons between the ComPACT and the traditional method showed generally higher $I_f(\lambda)$ values for the former. This is in agreement with the generalized expectations of a reduction in scattering effects, because of the use of pure water with the ComPACT method versus the use of tap water with the traditional method.

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