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A Network for Standardized Ocean Color Validation Measurements

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The Aerosol Robotic Network (AERONET), originally developed to evaluate aerosol optical properties and validate satellite retrievals of those properties at various scales with measurements from worldwide-distributed autonomous Sun photometers [*Holben et al.,* 1998], since January 2006 has been extended to support marine remote sensing and monitoring applications. This new network component, called AERONET–Ocean Color (AERONET-OC), provides the additional capability of measuring the radiance emerging from the sea—the 'water-leaving radiance'—with modified Sun photometers installed on offshore platforms such as lighthouses, oceanographic towers, and derricks.

AERONET-OC is proving to be instrumental in supporting satellite ocean color validation activities through standardized measurements performed at different sites with identical measuring systems and protocols, calibrated using a single reference source and method, and processed with the same code. Recent investigations [*Zibordi et al.,* 2006] suggest that in order to generate accurate climate data records from remote sensing data, time series of in situ measurements from a cadre of AERONET-OC sites could play a major role in the assessment and merging of radiometric products from different ocean color missions.

Ocean Color Validation Requirements

The Coastal Zone Color Scanner satellite mission of the early 1980s demonstrated the capability to remotely map the concentration of surface chlorophyll-*a*, a proxy for marine phytoplankton biomass. Following this major achievement, since the mid-1990s several Earth observing systems have been put into space to support studies of marine biogeochemistry and climate. Systems providing continuous global coverage include the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Medium Resolution Imaging Spectrometer (MERIS), and starting in 2009 the Visible Infrared Imager Radiometer Suite (VIIRS). A common cross-system requirement is the need for highly accurate, frequent, and globally distributed in situ observations to validate derived products. These observations are essential to support the creation of consistent data records from different Earth observing systems.

Satellite-derived normalized water-leaving radiance (L_{WN}), at various center wavelengths is determined from top-of-atmosphere radiance measurements corrected for the perturbing effects of the atmosphere, and is the primary product generated from marine optical (i.e., ocean color) remote sensors. Higher-level products, such as chlorophyll-*a* concentration or seawater inherent optical properties (i.e., absorption, back-scattering), are derived from L_{WN} data. The validation of this primary radiometric product usually relies on its direct comparisons with in situ point observations.

Considering the difficulty of producing large individual data sets of in situ measurements representative of the various marine trophic regimes, present validation programs combine field observations from many different and fully independent sources into a single data set [*Werdell et al.,* 2003]. This combination impairs the quantification of measurement uncertainties that depend on factors such as the performance of different field instruments, the use of diverse sampling methods, the adoption of a variety of calibration sources and protocols, and the application of assorted processing schemes. Round-robin experiments [*McClain et al.,* 2004] have shown that the former factors may increase the total uncertainty budget above the maximum 5% value established for L_{WN}, thus reducing the effectiveness of validation processes. Therefore, standardized networks of instruments continuously operating at different sites representative of distinct water types could reduce many sources of uncertainty and consequently improve operational validation activities.

AERONET-OC Test Sites

Advances in autonomous above-water radiometry [*Zibordi et al.,* 2004] recently have demonstrated the feasibility of continuous deployments at fixed sites, including in the usually eutrophic coastal regions where in-water observations may be affected by bio-fouling perturbations. Relevant in this context is the extended capability of the CE-318 automated Sun photometer manufactured by CIMEL Electronique (Paris, France) and operated at the AERONET sites, to perform marine radiometric measurements for determining L_{WN} in addition to the regular

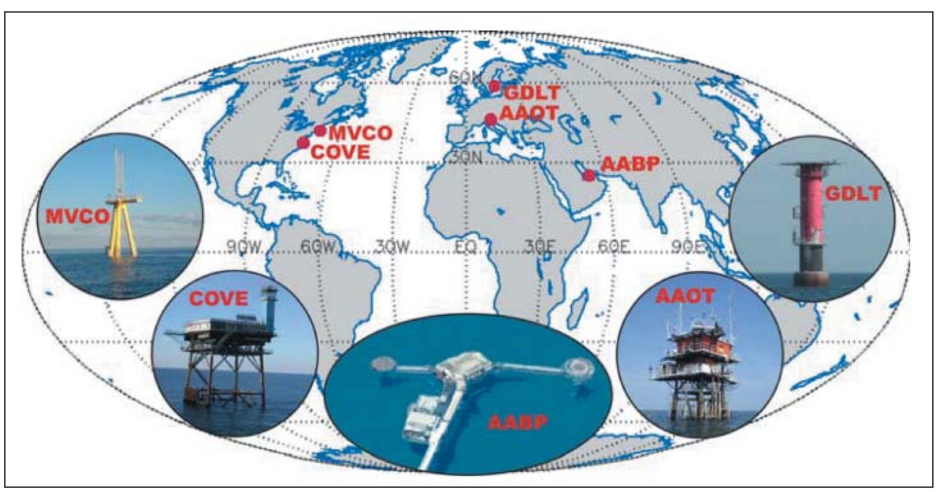

Fig. 1. AERONET-OC sites during the network testing phase (2002–2005).

BY G. ZIBORDI, B. HOLBEN, S. B. HOOKER, F. MÉLIN, J.-F. BERTHON, I. SLUTSKER, D. GILES, D. VANDEMARK, H. FENG, K. RUTLEDGE, G. SCHUSTER, AND A. AL MANDOOS

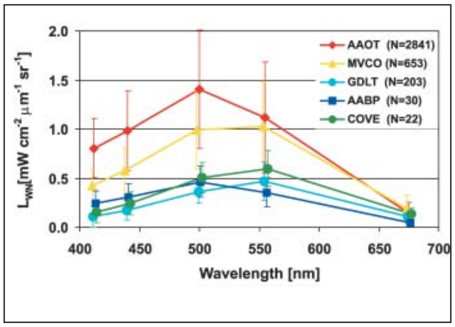

Fig. 2. Average spectra of normalized water-leaving radiance, L_{WN}*, from the AERONET-OC test sites. Error bars indicate ±1 standard deviation, and N is the number of quality-assured spectra. Center wavelengths are slightly shifted for visualization purposes.*

atmospheric data for retrieving aerosol optical properties. This instrument, called the SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM), autonomously performs multiple sky- and sea-radiance observations at programmable viewing and azimuth angles at eight (nine in the 2006 instrument release) center wavelengths in the 412–1020 nanometer spectral range. The data transmission is made through the data collection systems of geostationary meteorological satellites and allows for near-real-time data processing.

SeaPRISM performance has been evaluated over a four-year period using various deployment platforms located in the five different coastal locations that constituted the AERONET-OC test sites. Continuous or occasional deployment platforms (see Figure 1) have been the Acqua Alta Oceanographic Tower (AAOT) of the Italian National Research Council in the northern Adriatic Sea, since spring 2002; the Martha's Vineyard Coastal Observatory (MVCO) tower of the Woods Hole Oceanographic Institution off the Massachusetts coast in the Atlantic, for different periods since spring 2004; the TOTAL Abu-al-Bukhoosh oil platform (AABP, shown through an artistic rendition in Figure 1) in the Persian (Arabian) Gulf, in fall 2004; the Gustaf Dalén Lighthouse Tower (GDLT) of the Swedish Maritime Administration in the Baltic Sea, in summer 2005; and the platform at the Clouds and the Earth's Radiant Energy System (CERES) Ocean Validation Experiment (COVE) site off the Virginia coast in the Atlantic, since fall 2005.

Data Handling and Application

Within the framework of AERONET-OC, SeaPRISM data are now collected, processed following the scheme outlined by *Zibordi et al.* [2004], and archived at NASA Goddard Space Flight Center (Greenbelt, Md.). Derived products are accessible through a Web interface (http://aeronet.gsfc.nasa.gov) under a specified data policy.

Analogous to regular AERONET atmospheric products, the SeaPRISM ocean color products are available at three different levels. Data at level 1.0 include all L_{WN} determined from sequences of sea measurements taken with viewing geometries minimizing the platform perturbations. Level 1.5 data include screened L_{WN} from level 1.0 products not affected by cloud perturbations as determined from direct Sun irradiance measurements, high variability in sea observations indicating elevated wave perturbations, or high L_{WN} values in the near-infrared suggesting the presence of obstacles along the optical path between the instrument and the water surface. Level 2.0 data refer to fully quality-assured L_{WN}, corresponding to level 1.5 products originated from SeaPRISM instruments exhibiting differences smaller than 5% between the calibration coefficients determined before and after typical one-year deployment periods.

Figure 2 shows averages of L_{WN} quality-assured spectra from the AERONET-OC test-sites. Notable are the differences in L_{WN} shapes and intensity across the various deployment locations, which highlight a variety of bio-optical regimes. The scatterplots in Figure 3 present matchups of MODIS and SeaPRISM L_{WN} (i.e., coincident satellite and in situ data) at three center wavelengths. While the number of AAOT matchups included in this analysis was restricted to the first 50 of the 215 identified during the testing phase [*Zibordi et al.,* 2006], the small number of matchups produced for the other sites is explained by the brief deployment periods and the screening of cases affected by high seawater variability or contamination by the reflectance of the nearby land surface.

Results from the AERONET-OC testing phase fully confirm that SeaPRISM data can be a major complement to ship and mooring measurements for the validation of ocean color radiometric products applied to biogeochemistry and climate studies. Additionally, in agreement with accuracy requirements for the multinational Global Earth Observation System of Systems, AERONET-OC strengthens the capability of tracing uncertainties in products from different remote sensing systems through time series of highly consistent in situ data. This capability now calls for an expansion of AERONET-OC with the addition of new globally distributed measurement sites.

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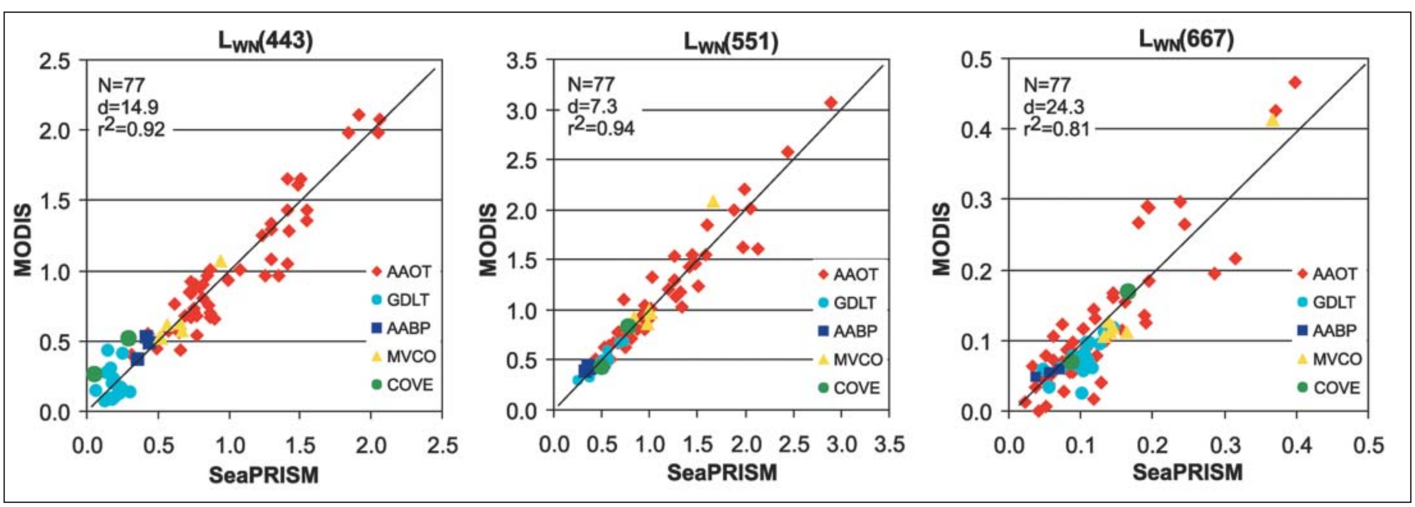

Fig. 3. Scatterplots of satellite-derived (MODIS-AQUA) versus in situ L_{WN} *in units of mW cm*$^{-2}$ μ*m*$^{-1}$ *sr*$^{-1}$ *at the 443-, 551-, and 667-nanometer MODIS center wavelengths, for the AERONET-OC test sites (N is the number of matchups, d is the median of the absolute percent differences, and* r^2 *is the determination coefficient). MODIS data were processed using the SeaWiFS Data Analysis System (SeaDAS), release 4.8. The matchups are 50 for AAOT, 16 for GDLT, three for AABP, six for MVCO, and two for COVE.*

Water Resources Studies (Abu Dhabi, United Arab Emirates), for facilitating and maintaining the AABP site; Niklas Strömbeck from Uppsala University, Sweden, for support in managing the GDLT site; the Woods Hole Oceanographic Institution for access to the MVCO tower; the Italian National Research Council for use of the AAOT; and the U.S. Coast Guard for allowing operation of the COVE site on its Chesapeake Lighthouse platform.

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Author Information

Giuseppe Zibordi, European Commission, Joint Research Centre, Ispra, Italy, E-mail: giuseppe.zibordi@jrc.it; Brent Holben and Stanford B. Hooker, NASA Goddard Space Flight Center, Greenbelt, Md.; Frédéric Mélin and Jean-François Berthon, European Commission, Joint Research Centre; Ilya Slutsker and David Giles, Science Systems and Applications Inc., Lanham, Md.; Doug Vandemark and Hui Feng, University of New Hampshire, Durham; Ken Rutledge and Gregory Schuster, NASA Langley Research Center, Hampton, Va.; and Abdulla Al Mandoos, Department of Atmospheric Studies, Abu Dhabi, United Arab Emirates.

Ripple Effect: Unforeseen Applications of Sand Studies

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Sand ripples and their deposits are playing a crucial role in unraveling the history of flowing water on Mars, conducting experimental floods to restore beaches in the Grand Canyon, and improving the ability to detect explosive mines buried beneath the seafloor. Even the visionary geologists who discovered the origins of ripples and ripple stratification could never have imagined these future applications of their work.

Sand ripples formed by blowing wind and flowing water have been studied for almost 150 years. This article briefly reviews some key discoveries in understanding ripples, reviews three studies that are currently utilizing ripples, and illustrates how simple fundamental discoveries have unexpected practical applications.

Anyone who has walked across a sandy creek or windy beach has stepped on ripples. The curious might have wondered what kind of layering or sedimentary structures the ripples leave behind.

Understanding ripple stratification is more complicated than it might seem, because ripples on a riverbed or seafloor include some regions where sand accumulates and other regions where sand erodes. To predict the stratification of a deposit, a geologist must visualize how an evolving three-dimensional bedform moves through space (ignoring all areas undergoing erosion) and then imagine what the structure will look like when the strata are viewed in an irregular outcrop that might be oblique to the original bedding. Many geologists have difficulty visualizing these complex spatial patterns even when guided by three-dimensional computer models [*Rubin,* 1987].

The first study of ripple stratification was conducted by visionary British geologist Henry Clifton Sorby [*Sorby,* 1859], who examined active ripples to learn how flowing water deposited sand 300 million years ago (now preserved as sandstones). More than a century later, Ralph Hunter (U.S. Geological Survey, retired) [*Hunter,* 1977] discovered that lamination of wind ripples differs from that of subaqueous ripples and that distinguishing the two kinds of stratification is one of the best ways to determine whether sand was deposited by wind or water (Figure 1).

Ripples in the Headlines

Today, researchers examining images collected by NASA's Mars Exploration Rovers are using ripple structures to interpret the geologic history of Mars [*Grotzinger et al.,* 2005]. Some of the Martian structures resemble the windblown ripple structures Hunter described, while others resemble Sorby's waterlain ripples. Although the discovery

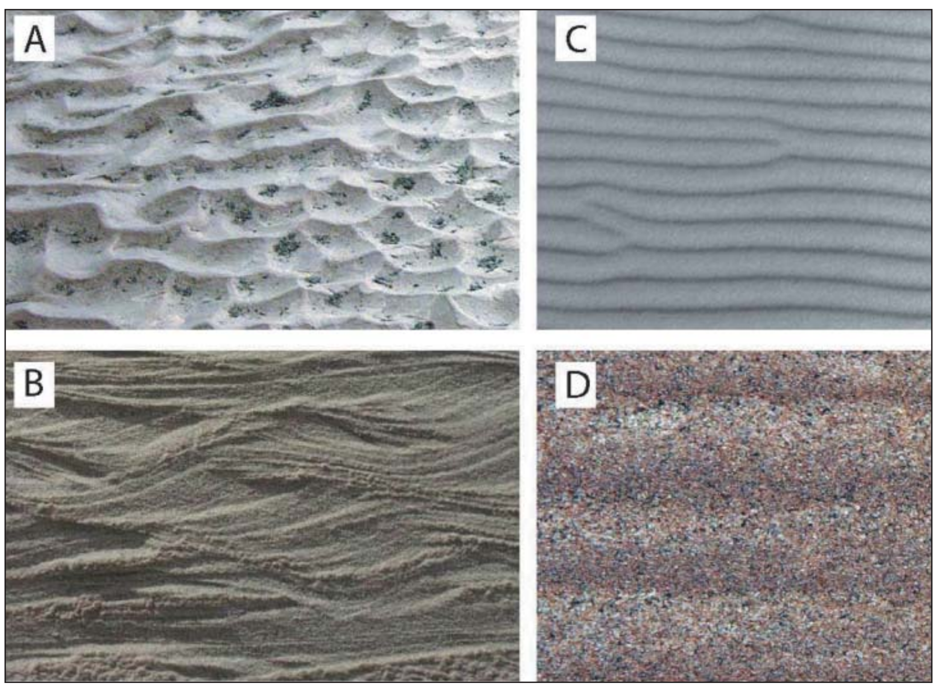

Fig. 1. Ripples and ripple stratification. (a) Ripples formed by flowing water have complicated shapes that change through time. Colorado River, oblique photograph; ripple wavelength is approximately 10 centimeters. (b) Vertical cross section through structures deposited by ripples in the Colorado River; stratification includes curved laminae that preserve the shape of the depositional sites of the original ripples. Thickness of deposit is 10 centimeters. (c) Ripples formed by wind tend to be more regular in space and time than ripples in water. Vertical view from Dillon Beach, Calif.; wavelength is approximately 10 centimeters. (d) Oblique cut through four layers deposited by wind ripples. The four layers were deposited by four ripples that migrated across the bed; each layer gradually coarsens from base to top, reflecting the grading of grain sizes on the lee surface of the original ripple. No evidence of the original ripple shape is preserved. Layers are several millimeters thick; Grand Canyon, Ariz.

BY D. M. RUBIN