Spectral Dependence of the Seawater–Air Radiance Transmission Coefficient

KENNETH J. VOSS

Physics Department, University of Miami, Coral Gables, Florida

STEPHANIE FLORA

Moss Landing Marine Laboratory, San Jose State University, San Jose, California

(Manuscript received 6 March 2017, in final form 2 May 2017)

ABSTRACT

The transmission coefficient T_L commonly used to propagate the upwelling nadir radiance from just below the ocean surface to above the surface has been assumed to be a constant value of 0.543 in seawater. Because the index of refraction of seawater varies with wavelength, salinity, and temperature, the variation of T_L with these parameters should be taken into account, especially if low uncertainty is required for the quantities derived using T_L. In particular, the wavelength dependence of this factor is important. For example, at a salinity of 35 g kg^{-1} and a temperature of 26°C, T_L will be 1.3% lower at 380 nm and 1.1% higher at 700 nm than the constant value (0.543) and should be taken into account when calculating the water-leaving radiance and the normalized water-leaving radiance from in-water measurements.

1. Introduction

In ocean color satellite measurements, system vicarious calibration (SVC) is used to improve the total system performance and retrieval of the satellite-derived water-leaving radiance $L_w(\lambda)$ and the normalized water-leaving radiance $L_{wn}(\lambda)$. The surface ground truth values for $L_w(\lambda)$ and $L_{wn}(\lambda)$ used in the SVC process must necessarily be of the highest possible quality, and the uncertainties involved in producing these quantities must be understood. For in-water systems, which provide an estimate of the upwelling nadir water-leaving radiance just below the surface $L_u(0^-, \lambda)$, a factor must be introduced to propagate $L_u(0^-, \lambda)$ through the surface to form $L_w(\lambda)$ and $L_{wn}(\lambda)$. The equation relating $L_u(0^-, \lambda)$ to $L_w(\lambda)$ is usually written as (Austin 1974; Mueller 2003)

$$L_w(\lambda) = \frac{1-\rho}{n^2} L_u(0^-, \lambda) = T_L L_u(0^-, \lambda), \qquad (1)$$

where n is the index of refraction of water, ρ is the Fresnel reflectance at the air–ocean surface, and T_L combines these factors for simplification. The index of refraction of air is taken to be 1. The coefficient T_L is described in the current literature (Austin 1974; Mueller 2003) as a constant value of 0.543.

The goal of SVC data is to have the total uncertainty in $L_w(\lambda)$, or $L_{wn}(\lambda)$, be less than 5% (Zibordi and Voss 2014). The Marine Optical Buoy (MOBY; Clark et al. 1997) dataset has been used for vicarious calibration of many of the international ocean color satellites (Franz et al. 2007; Wang et al. 2016; Melin et al. 2011). At this time the MOBY dataset is following the current protocol (Mueller 2003) and has used a constant value for T_L (0.543). In developing an uncertainty estimate for the MOBY dataset, we have been investigating the uncertainties in each factor that goes into deriving $L_w(\lambda)$ and $L_{wn}(\lambda)$. Examples of these sources of uncertainties include calibration errors (Brown et al. 2007), instrument self-shadowing errors (Mueller 2004), errors in the calculation of the upwelling radiance attenuation coefficient (Voss et al. 2017), and errors in the cosine response of the downwelling surface irradiance collector (Zibordi and Bulgarelli 2007). The value of $T_L = 0.543$ has been experimentally verified (Wei et al. 2015) but with an uncertainty of 10%, which is much larger than we can use in the MOBY uncertainty budget. To reduce uncertainty in T_L, we need to look closely at the factors that go into this parameter.

2. Discussion

Morel et al. (2002) defined R, a term that combines all of the effects due to reflection and refraction at a

Corresponding author: Kenneth Voss, voss@physics.miami.edu

DOI: 10.1175/JTECH-D-17-0040.1

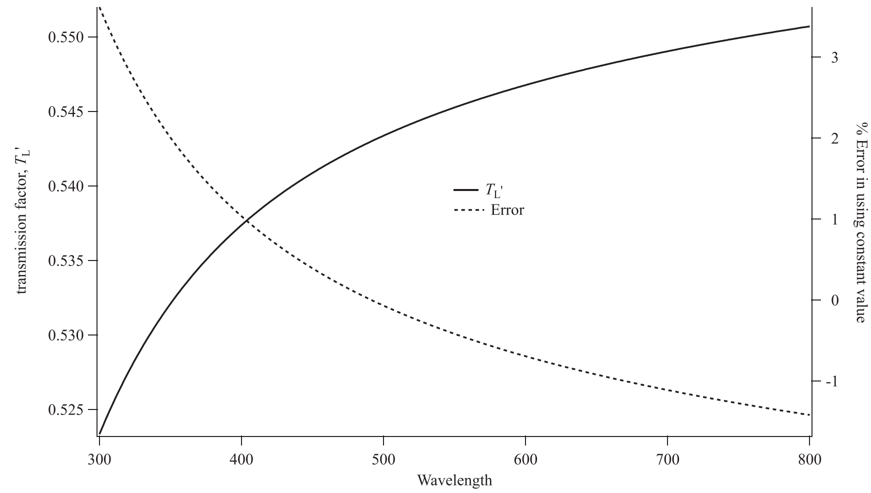

FIG. 1. Graph showing the spectral dependence of the transmission factor T_L' and the error in $L_w(\lambda)$ caused by assuming T_L' is a constant value of 0.543. This calculation was done for a salinity of $35\,\mathrm{g\,kg^{-1}}$ and a temperature of 25°C.

wind-disturbed, wavy air–sea interface. This term includes the effects on downwelling irradiance, when propagating from air into the water, and the effects on the upwelling radiance as it propagates upward through the interface. While investigating R, Gordon (2005) stated that the transmittance of upwelling radiance through the air–sea interface was within 1% of the flat surface Fresnel transmittance, for solar zenith angles less than 60° and for wind speeds less than $16\,\mathrm{m\,s^{-1}}$. But this 1% constraint is still larger than it needs to be because Gordon (2005) showed that because of reciprocity, several constraints could be made on the relationship between reflectance and transmittance of the air–water interface. In particular, the sum of the reflectance in a given direction $\hat{\xi}$ of uniform radiance incident from above, defined as $r_+(-\hat{\xi})$, and the transmittance of uniform radiance in the same direction, incident from below, defined as $t_-(-\hat{\xi})$, is equal to unity

$$r_+(-\hat{\xi}) + t_-(-\hat{\xi}) = 1. \tag{2}$$

Although the actual upwelling radiance distribution in the water is not uniform, the departure from uniformity is not large enough to seriously affect the use of this observation. In addition, $r_+(-\hat{\xi})$ is equal to the irradiance reflectance (spectral albedo) of the surface from a parallel beam incident from the $-\hat{\xi}$ direction. Figure 18 in Preisendorfer and Mobley (1986) shows the result of a calculation of the spectral albedo and provides a more stringent constraint. This result shows that for incident angles less than 10° and for wind speeds up to $20\,\mathrm{m\,s^{-1}}$ (neglecting whitecaps and breaking waves), there is no difference in $r_+(-\hat{\xi})$ between a wind-roughened surface and a flat surface. Therefore, $t_-(-\hat{\xi})$ is also the same for a wind-roughened surface and a flat surface, through the reciprocity condition of Gordon (2005), and we can calculate this transmittance exactly using the Fresnel equation for transmittance at normal incidence through an air–sea interface.

The full parameter, including the index of refraction of air, T_L', is given by the Fresnel transmittance [the first part of the term on the right side of Eq. (3)] and the invariance of L/n^2 [the second part of the term on the right side of Eq. (3)],

$$T_L' = \frac{4n_a n_w}{(n_a + n_w)^2}\left(\frac{n_a}{n_w}\right)^2, \tag{3}$$

where n_a is the index of refraction of air and n_w is the index of refraction of water.

When one calculates T_L' using a nominal value of the index of refraction of seawater at 500 nm, $35\,\mathrm{g\,kg^{-1}}$ salinity, and 25°C (Austin and Halikas 1976), this gives the nominal value of $T_L' = 0.543$. However, if one uses the wavelength dependence of the index of refraction of seawater, as parameterized by Quan and Fry (1995) and shown to be valid over the range 300–800 nm by Huibers (1997), it can be seen that for MOBY data (380–700 nm) this factor can vary from 0.536 to 0.549 for a salinity of $35\,\mathrm{g\,kg^{-1}}$ and a temperature of 25°C. Thus, a constant value of 0.543 is biased high by 1.3% at 380 nm and low by 1.1% at 700 nm. Figure 1 shows T_L' and the error resulting from using the constant value over the 300–800-nm spectral range. To be used in SVC, the uncertainty goal for $L_w(\lambda)$ and $L_{wn}(\lambda)$ is 5%. There are many factors that go into this total uncertainty, including radiometric response uncertainty (2%–4%), instrument self-shadowing (1%–12%), and others (Brown et al. 2007). In addition, a bias such as this is not reduced through averaging multiple datasets, as opposed to other factors that randomly vary. Thus, if the goal is data suitable for SVC, over a large wavelength range, it is important that a spectrally varying factor is used for T_L'. If Eq. (3) is used to derive T_L', using the true values of the index of refraction of seawater for each wavelength, then the uncertainty in T_L' is reduced to the uncertainty in the knowledge of the salinity and temperature of the specific measurement of $L_w(\lambda)$. In the case of the MOBY site, off of the island of Lanai, Hawaiian Islands, our salinity record indicates a range of salinities from 33 to 36 g kg^{-1} (mean salinity is 34.85 $\pm$ 0.18 g kg^{-1}) and surface water temperatures of 23°–30°C (mean temperature is 25.9° $\pm$ 1.0°C). Using a 7-yr record (2001–09) of salinities and temperatures at the MOBY site, we calculated T_L' for each individual data point. For this 7-yr period, the uncertainty in using the spectrally varying average value for T_L' is reduced to 0.1%.

The final conclusion is that ignoring the wavelength dependence of T_L' introduces an unnecessary spectrally varying bias in the calculation of $L_w(\lambda)$ and $L_{wn}(\lambda)$. For sites with more salinity and temperature variations, or for measurements in many locations, it would be best to have contemporaneous salinity and temperature values with which to calculate a specific and spectrally varying T_L' for that dataset.

Acknowledgments. This work was supported by NOAA under Grant NA15OAR4320064 and by NASA under Grant NNX14AP63G.

REFERENCES

Austin, R. W., 1974: The remote sensing of spectral radiance from below the ocean surface. *Optical Aspects of Oceanography*, N. G. Jerlov and E. S. Nielson, Eds., Academic Press, 317–344.

——, and G. Halikas, 1976: The index of refraction of seawater. Scripps Institution of Oceanography Tech. Rep. SIO Reference 76-1, 121 pp.

Brown, S. W., and Coauthors, 2007: The marine optical buoy (MOBY) radiometric calibration and uncertainty budget for ocean color satellite sensor vicarious calibration. *Sensors, Systems, and Next-Generation Satellites XI*, S. Habib et al., Eds., International Society for Optical Engineering (SPIE Proceedings, Vol. 6744), 67441M, doi:10.1117/12.737400.

Clark, D. K., H. R. Gordon, K. J. Voss, Y. Ge, W. Broenkow, and C. Trees, 1997: Validation of atmospheric correction over the oceans. *J. Geophys. Res.*, **102**, 17 209–17 217, doi:10.1029/96JD03345.

Franz, B. A., S. W. Bailey, P. J. Werdell, and C. R. McClain, 2007: Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry. *Appl. Opt.*, **46**, 5068–5082, doi:10.1364/AO.46.005068.

Gordon, H. R., 2005: Normalized water-leaving radiance: Revisiting the influence of surface roughness. *Appl. Opt.*, **44**, 241–248, doi:10.1364/AO.44.000241.

Huibers, P. D. T., 1997: Models for the wavelength dependence of the index of refraction of water. *Appl. Opt.*, **36**, 3785–3787, doi:10.1364/AO.36.003785.

Melin, F., G. Zibordi, J.-F. Berthon, S. Bailey, B. Franz, K. Voss, S. Flora, and M. Grant, 2011: Assessment of MERIS reflectance data as processed with SeaDAS over the European seas. *Opt. Express*, **19**, 25 657–25 671, doi:10.1364/OE.19.025657.

Morel, A., D. Antoine, and B. Gentili, 2002: Bidirectional reflectance of oceanic waters: Accounting for Raman emission and varying particle scattering phase function. *Appl. Opt.*, **41**, 6289–6306, doi:10.1364/AO.41.006289.

Mueller, J. L., 2003: In-water radiometric profile measurements and data analysis protocols. Radiometric measurements and data analysis protocols, J. L. Mueller, G. S. Fargion, and C. R. McClain, Eds., Vol. III, Ocean optics protocols for satellite ocean color sensor validation, NASA Tech. Memo. NASA/TM-2003-21621/Rev-Vol III, Revision 4, 7–20. [Available online at https://oceancolor.gsfc.nasa.gov/docs/technical/protocols_ver4_voliii.pdf.]

——, 2004: Shadow corrections to in-water upwelled radiance measurements: A status review. Special topics in ocean optics protocols, J. L. Mueller G. S. Fargion, and C. R. McClain, Eds., Ocean optics protocols for satellite ocean color sensor validation, NASA Tech. Memo. NASA/TM-2004, Revision 5, Vol. VI, Part 2, 1–7. [Available online at https://oceancolor.gsfc.nasa.gov/docs/technical/protocols_ver5_volvi_pt2.pdf.]

Preisendorfer, R. W., and C. D. Mobley, 1986: Albedos and glitter patterns of a wind-roughened sea surface. *J. Phys. Oceanogr.*, **16**, 1293–1316, doi:10.1175/1520-0485(1986)016<1293:AAGPOA>2.0.CO;2.

Quan, X., and E. S. Fry, 1995: Empirical equation for the index of refraction of seawater. *Appl. Opt.*, **34**, 3477–3480, doi:10.1364/AO.34.003477.

Voss, K. J., H. R. Gordon, S. Flora, B. C. Johnson, M. Yarbrough, M. Feinholz, and T. Houlihan, 2017: A method to extrapolate the diffuse upwelling radiance attenuation coefficient to the surface as applied to the Marine Optical Buoy (MOBY). *J. Atmos. Oceanic Technol.*, doi:10.1175/JTECH-D-16-0235.1, in press.

Wang, M., W. Shi, L. Jiang, and K. J. Voss, 2016: NIR- and SWIR-based on-orbit vicarious calibrations for satellite ocean color sensors. *Opt. Express*, **24**, 20 437–20 453, doi:10.1364/OE.24.020437.

Wei, J., Z. Lee, M. Lewis, N. Pahlevan, M. Ondrusek, and R. Armstrong, 2015: Radiance transmittance measured at the ocean surface. *Opt. Express*, **23**, 11 826–11 837, doi:10.1364/OE.23.011826.

Zibordi, G., and B. Bulgarelli, 2007: Effects of cosine error in irradiance measurements from field ocean color radiometers. *Appl. Opt.*, **46**, 5529–5538, doi:10.1364/AO.46.005529.

——, and K. J. Voss, 2014: Requirements and strategies for in situ radiometry in support of satellite ocean color. *Optical Radiometry for Ocean Climate Measurements*, G. Zibordi, C. J. Donlon, and A. C. Parr, Eds., Experimental Methods in the Physical Sciences, Vol. 47, Academic Press, 531–556.