Effect of 3-D instrument casing shape on the self-shading of in-water upwelling irradiance

Jacek Piskozub

Institute of Oceanology PAS, ul. Powstancow Warszawy 55, 81-712 Sopot, Poland
piskozub@iopan.gda.pl

Abstract: The self-shading measurement error of the upwelling irradiance caused by the presence of a typical cylindrical housing of an optical instrument was calculated with the 3-D Monte-Carlo code as a function of the housing dimensions and of the optical parameters of seawater. The resulting values were compared to the self-shading error for a flat disk of the same diameter, originally used to establish self-shading error estimations universally used in marine optics. The results show that the self-shading of upwelling irradiance is underestimated by up to 25% producing a significant underestimation of the measured upwelling irradiance, and therefore reflectance, especially in turbid waters.

OCIS codes: (010.4450) Ocean Optics; (290.4210) Multiple Scattering.

References and links

1. H.R. Gordon and K. Ding, "Self-shading of in-water optical instruments," Limnol. Oceanogr. **37**, 491-500 (1992).
2. G. Zibordi and G. M. Ferrari, "Instrument self-shading in underwater optical measurements:experimental data," Appl. Opt. **34**, 2750–2754 (1995).
3. E. Aas and B. Korsbo, "Self-shading effect by radiance meters on upward radiance observed in coastal waters," Limnol. Oceanogr. **42**, 968–974 (1997).
4. J. Piskozub, A.R. Weeks, J.N. Schwarz, and I.S. Robinson, "Self-shading of upwelling irradiance for an instrument with sensors on a sidearm," Appl. Opt. **39**, 1872-1878 (2000).
5. R.A. Leathers, T.V. Downes and C.D Mobley, "Self-shading correction for upwelling sea-surface radiance measurements made with buoyed instruments," Opt. Express **8**, 561-570 (2001), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-8-10-561
6. J. Piskozub, "Effects of surface waves and sea-bottom on self-shading of in-water optical instruments," in *Ocean Optics XII*, Proc. SPIE **2258**, 300-308 (1994).
7. J. Piskozub, "Influence of instrument casing shape on self-shading of in-water radiation," paper presented at Ocean Optics XIV Conference, Kailua-Kona, Hawaii, USA, Nov 10-13 1998.
8. J. Piskozub, P.J. Flatau and J.R.V. Zaneveld, "Monte Carlo study of the scattering error of a quartz reflective absorption tube," J. Atmos. Ocean. Technol. **18**, 438-445 (2001).
9. D. Stramski and J. Piskozub, "Estimation of scattering error in spectrophotometric measurements of light absorption by aquatic particles from 3-D radiative transfer simulations," Appl. Opt. **42**, 3634-3646 (2003).
10. J. Piskozub, "Effect of ship shadow on in-water irradiance measurements," Oceanologia **46**, 103-112 (2004).
11. T.J. Petzold, "Volume scattering functions for selected ocean waters," SIO Ref. 72-78, Scripps Institute of Oceanography, U. California, San Diego (1972).
12. C. Cox and W. H. Munk, "Slopes of the sea surface deduced from photographs of sun glitter," Scripps. Inst. Oceanogr. Bul. **6**, 401-488 (1956).

1. Introduction

The self-shading error for upwelling radiance and irradiance is an inherent phenomenon as the sensor must not be transparent to avoid registering the downwelling light. However, all upwelling photons at a given sea depth must have been downwelling photons at the same depth at an earlier moment of time, a fraction of which could have had been absorbed by the sensor housing on its way down. The effect is well known and was first described by Gordon

#4440 - $15.00 US
Received 25 May 2004; revised 30 June 2004; accepted 1 July 2004

and Ding [1] in 1992, and later studied by Zibordi and Ferrari [2], Aas and Korsbo [3], Piskozub, Weeks, Schwarz, and Robinson [4] and Leathers, Downes and Mobley [5]. Therefore, in modern ocean optics experiments, the measured upwelling (ir)radiance is usually corrected for self-shading. However, many users of the well-known Gordon-Ding estimates of self-shading error (depending on shading radius and seawater absorption) are probably unaware that the results were calculated for the flat, circular shading of an upwelling radiation meter and thus should not be used for an instrument casing which has a third dimension (height). Adding volume results to self-shading error simulation must lead to higher error value as some additional photons are blocked by the top and sides of the housing so the housing blocks more light on its way to the upwelling sensor than the Gordon-Ding flat disk shading of the same radius. This 3-D effect was discussed by Leathers *et al.* [5] for upwelling radiance. The current paper studies it for upwelling plane irradiance.

This author used the Monte-Carlo code that allowed tracing the photon history to calculate the self-shading error of upwelling plane irradiance for both flat disk shading and a cylindrical housing of the same radius. This method permits calculating the effect for an instrument casing of any shape without using any more mathematically complicated reverse direction Monte-Carlo methods. The purpose of the calculations was to estimate the additional self-shading error as a function of seawater optical parameters as well as the instrument housing dimensions.

2. Materials and methods

Photons in the Monte-Carlo algorithm used in the calculations are traced in the "natural" forward direction. An absorption event ends the photon's history, i.e., no "partial" photons are traced. The history of every photon that reached the assumed depth of the instrument's sensor on its way upwards is then traced back to see if it passed through the instrument casing shape on its way down. The instrument is represented by a black cylinder with height h and radius r (no photons are reflected from the surface). The ratio of the number of such "blocked" photons to all photons upwelling through the instrument depth is the sought ratio of self-shading for the upwelling plane irradiance. The self-shading ratio for the upwelling scalar irradiance is calculated using the sums of the inverted cosines of zenith angles of the photons instead of the sums of photons.

An earlier version of the Monte-Carlo code was used to determine the effects of sea-surface roughness on the self-shading on an in-water upwelling irradiance meter [6] and for an early version of this study presented [7] at a conference (the early results had 40-fold fewer photons, and an error in result processing led to some overestimation of the self-shading error values). The code was later used in several projects including studying the self-shading of upwelling irradiance for an instrument with sensors at the end of a side-arm [4], scattering error of absorption measurement [8,9], and the effect of ship shadow [10]. For the sake of simplicity, the sea is modeled as a homogeneous water column of absorption a and total scattering b. The sea depth was assumed infinite to avoid bottom effects that would make the studied problem more complicated. Similarly, the atmosphere used was a thin 10m layer with negligible scattering to allow calculations of self-shading for a partly submerged instrument casing. The zenith angle of the sun was usually 30 and the fraction of sky-glow radiance at sea level (which is not directly from the sun) was 40% as a realistic representation of conditions in a sunny but hazy day in the middle latitudes. The standard Petzold scattering phase function for open turbid waters was used [11].

The code used is able to represent the roughness of the sea surface by the Cox-Munk probability distribution of wave slopes [12]. Because the surface roughness does not affect self-shading significantly, at least in sea conditions possible to simulate with the Cox-Munk surface [6], a flat sea surface was assumed in all calculations.

Unless described differently, the calculation parameters were as follows: the number of photons in the calculations $n=4*10^7$; attenuation $c=0.5\ \mathrm{m}^{-1}$; photon survival probability $\omega_0 \equiv b/(a+b) = 0.8$; sun zenith angle $\theta_0 = 30°$; instrument height $h = 1.0$ m; instrument radius $r = 0.15$ m. Most of the calculations were done with the sensor placed 2 m below the water

#4440 - $15.00 US
Received 25 May 2004; revised 30 June 2004; accepted 1 July 2004

surface (z=2 m). Some calculations were done with another “fatter” configuration (r=0.25 m, h=0.5 m).

The error bars shown on all figures in this paper are standard deviations of the values calculated with the Monte Carlo code. This statistical error is an inherent feature of the Monte-Carlo method. It is proportional to the square root of the number of photons used. Therefore the computation time increases by a factor of four for a reduction in error of 50%.

The calculations presented were carried out on a Pentium4 2.8 GHz PC running Fedora Core 1 Linux in the Institute of Oceanology, Sopot, Poland. The ASSI C Monte Carlo code was compiled using gcc. The results for the rough sea-surface model presented here were calculated using 40 million photons. Calculations for each million photons took 30-60 seconds on the machine depending on the solar zenith angle and the degree of sea roughness.

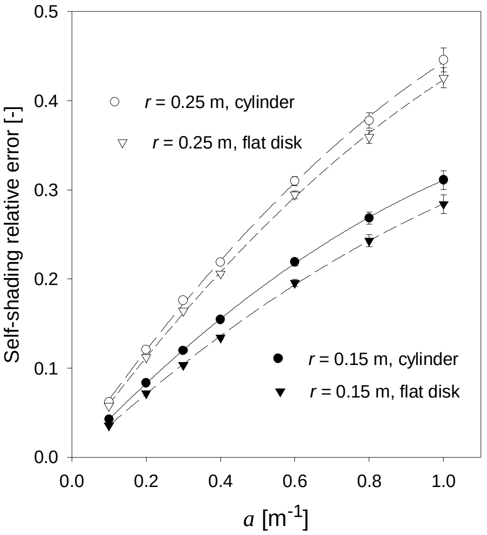

Fig. 1 The self-shading error dependance on absorption a for instruments with two radii, a flat disk and cylindrical shape (b=0.3 m^{-1} see text for other input data details)

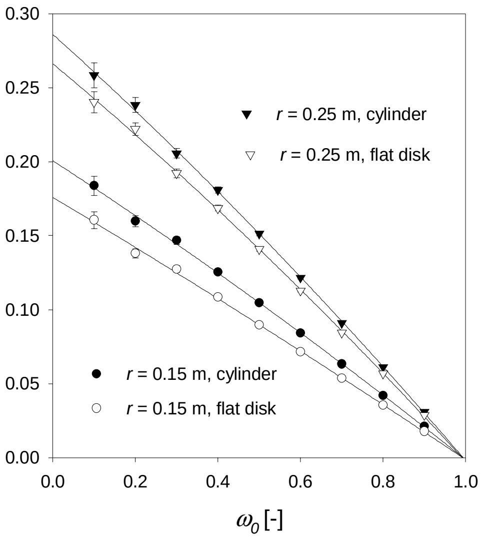

Fig 2. The self shading error dependance on photon survival ratio ω_0 for instrument with a flat disk and cylindrical shape (c=0.5 m^{-1} see text for other input data details)

3. Results and discussion

The ratio of the self-shading of upwelling irradiance for a sensor at the center of the bottom of a cylindrically shaped housing, is usually represented by a Gordon-Ding type formula [1] which for ra < 0.05 can be simplified to

$$\delta(E_u)/E_u = A\,r\,a \tag{1}$$

where $\delta(E_u)/E_u$ is the self-shading ratio, r - the instrument radius, a - absorption of the seawater and A is a constant. The Gordon-Ding formula was calculated (with Monte-Carlo simulations) for a flat disk (not a cylindrical shape) and therefore is an understatement of the real error for a cylindrical instrument with the upwelling irradiance sensor at the center of the bottom. The value of the constant A depends on the shape and size of the sensor itself, on the type of upwelling irradiance measured (plane or scalar), and to a lesser degree on light conditions at the sea surface and the depth of the sensor. This leads to values of this “constant” in the range $A \approx 2.2$ -2.6, depending on the receiver setup.

Received 25 May 2004; revised 30 June 2004; accepted 1 July 2004

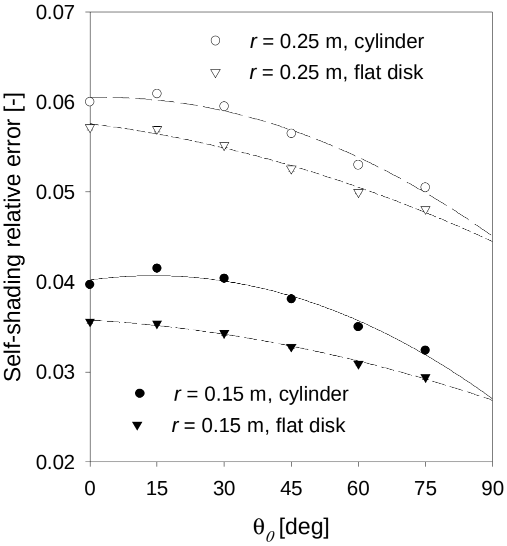

Fig. 3 The self-shading error of upwelling vector irradiance as a function of the sun zenith angle for flat disk shading and cylindrical housing of two radii (c=0.6 m^{-1}, ω_0=0.8).

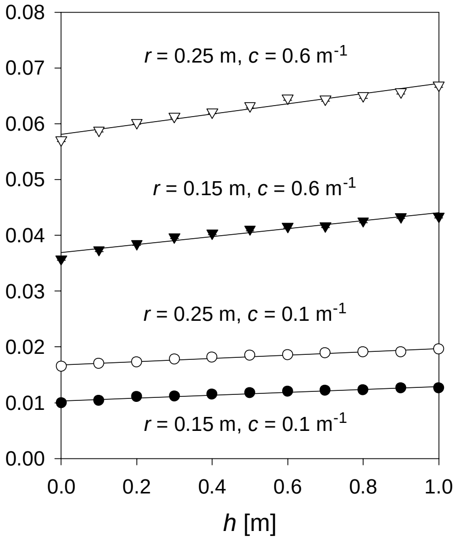

Fig. 4 The self-shading error of upwelling vector irradiance as a function of the cylindrical housing height h, for two instrument radii and two values of attenuation c (ω_0=0.8).

The Gordon-Ding self-shading error for a sensor placed centrally in the instrument bottom is roughly proportional to absorption. Figure 1 shows the self-shading relative error for two radii of the instrument both for a flat disk shading and a cylindrical casing for two cases: r=0.15 m, h=1 m and r=0.25 m h=0.5 m (input data for all figures if not shown are identical to those listed above). Taking into account the third dimension of the casing causes a consistent increase in the values of the self-shading relative error by about 5-20% (the percentage increases slightly with absorption and decreases with the instrument radius). Figure 2 presents the dependence of the self-shading error on the photon survival ratio ω_0 for the same two instrument setups. The results show that the cylinder/disk error ratio is virtually constant with the changing ω_0 value, while the value of the surplus self-shading error increases with decreasing ω_0 (which also follows from the results in Fig. 1 - for a constant c value a smaller ω_0 means more absorption). The self-shading error value also depends on the solar zenith angle, though not as strongly as on absorption and instrument sizes. Figure 3 researches this relationship. The self-shading error increases as the sun gets closer to the zenith. More importantly, the cylinder/disk surplus error also increases relatively and absolutely.

Figure 4 shows the self-shading error as a function of the height of the cylindrical housing h (all other factors are constant). The results are calculated for two attenuation values: c=0.1 m^{-1} and c=0.6 m^{-1} (ω_0=0.8) and two instrument radii r=0.15 m and r=0.25 m. The self-shading error for h=0 represents the flat disk case. Even as the increase of the self-shading error is more pronounced with greater attenuation and grows almost linearly with h, the percentage increase of the error is greatest for the smaller instrument (up to 26% for c=0.1 m^{-1} r=0.15 m and h=1 m). The relative error value is also almost linearly dependent on instrument radius r, both for a flat shading and for a 3-D instrument housing (Fig. 5). The relative difference between the curves for instruments of different height is greatest for the smallest instrument radii, although the absolute value of the error is then usually negligible. It is obvious that the smaller the instrument the better. However, a minimum casing volume is needed for the irradiance meter to work. Therefore, self-shading as a function of instrument

Received 25 May 2004; revised 30 June 2004; accepted 1 July 2004

radius and height with a constant instrument volume was studied. The effects of varying both *r* and *h*, while keeping the instrument volume $V=\pi r2h$ constant, are shown in Fig. 6. The results show that the optimal shape of a cylindrical housing to minimize the self-shading error is as long and narrow as possible. However, this is exactly the shape that leads to the highest differences of self-shading correction between a flat disk and a real cylindrical instrument housing.

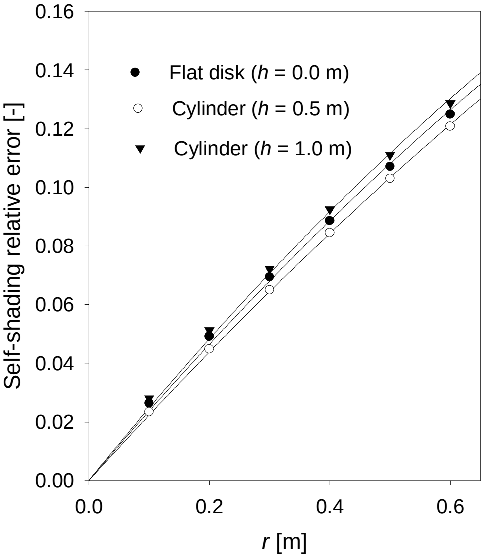

Fig. 5 The self-shading error of upwelling vector irradiance as a function of the instrument radius *r*, for a flat disk shading and a cylindrical housing where height h=1 m (c=0.6 m^{-1}, ω_0=0.8).

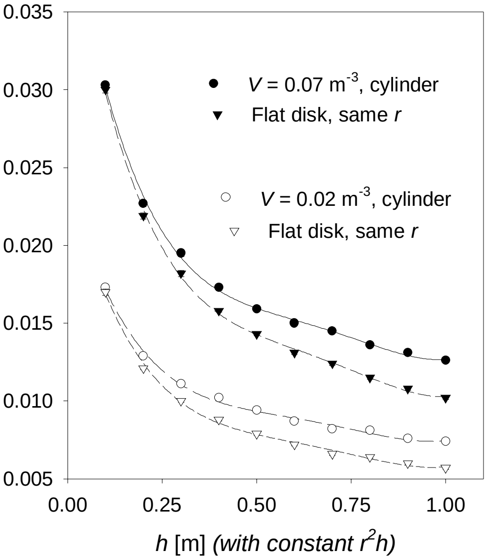

Fig. 6 The self shading error of upwelling vector irradiance as a function of instrument height for cylindrical housing of a constant volume $V=\pi r^2 h$ (c=0.6 m^{-1}, ω_0=0.8)

4. Conclusions

The results show that in most real situations adding a third dimension to the instrument housing increases the self-shading error of upwelling irradiation in optically deep waters by up to 25%. When the absolute value of the error is small (small instrument in low absorption water), flat disk shading constitutes a good approximation of the self-shading phenomenon for real 3-D instrument housings. However, with large instruments (or instruments used in clusters) and especially in turbid (“Case 2”) waters, this can lead to the notable underestimation of upwelling irradiance, which also leads to underrating reflectance. As the relative surplus self-shading error is greatest with small instrument radii, the construction of long, narrow housings aimed at minimizing self-shading error may, paradoxically, lead to especially high underestimations of upwelling irradiance in the measurement results, after self-shading has been accounted for.

It is quite feasible to create new semi-empirical formulae for the estimation of the self-shading ratio in order to correct the experimental upwelling irradiance results. However, this author strongly believes that a better solution (at least for a profiling instrument measuring both *c* and *a*) is to calculate the error with a Monte-Carlo code in “quasi real-time” (a delay of only a few minutes), which can provide better data correction for every measuring station.

Received 25 May 2004; revised 30 June 2004; accepted 1 July 2004