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Secchi disk observation with spectral-selective glasses in blue and green waters

ZHONGPING LEE,[1] SHAOLING SHANG,[2] GONG LIN,[2] TONGTONG LIU,[2] YANGYANG LIU,[2] KEPING DU,[3] AND KELLY LUIS[1]

[1]*Department of Environmental, Earth and Ocean Sciences, University of Massachusetts, Boston, MA 02125, USA*
[2]*State Key Lab of Marine Environmental Science, Xiamen University, Xiamen 361005, China*
[3]*State Key Laboratory of Remote Sensing Science, School of Geography, Faculty of Geographical Science, Beijing Normal University, Beijing, 100875, China*
zhongping.lee@umb.edu, slshang@xmu.edu.cn

Abstract: Radiative transfer modeling of Secchi disk observations has historically been based on conjugated signals of eye response and radiance, where water's attenuation in the entire visible band is included in the attenuation when deciding the Secchi disk depth in water. Aas et al. [Ocean Sci. **10**(2), 177 (2014)] and Lee et al. [Remote Sens. Environ. **169**, 139 (2015)] hypothesized that it is actually the attenuation in water's transparent window that matters to the observation of a Secchi disk in water. To test this hypothesis, observations of Secchi disks in blue and green waters were conducted via naked eyes, blue-pass glasses, and green-pass glasses. Measurement results indicate that for blue waters, the observed Secchi depths via naked eyes match the depths obtained with blue-pass glasses and much deeper than the depths with green-pass glasses, although the green-pass glasses match the highest response of human eyes. These observations experimentally support the hypothesis that our eye-brain system uses the contrast information in the transparent window to make a judgement decision regarding sighting a Secchi disk in water.

OCIS codes: (010.4450) Oceanic optics; (010.7295) Visibility and imaging; (330.0330) Vision, color, and visual optics.

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1. Background

Visibility is one of the oldest, and most intuitive, parameters used to represent air and water quality. For visibility in air, a common definition is the distance when a "suitable size" black target in the background of sky is no longer viewable by human eyes [3, 4]. For visibility in water, also known as water clarity, it is commonly represented by the Secchi disk depth (Z_{SD}, m) [5]. Developed by Angelo Secchi in 1866, the Secchi disk is one of the oldest "optical instruments" to measure water quality parameters [6]. This white or black-white disk with a diameter of ~30 cm is tied to a rope and lowered in water to determine water clarity; the depth at which the disk is no longer viewable by our eyes from surface is called the Secchi disk depth or Secchi depth [6]. Since its invention, nearly a million measurements worldwide have been made due to its simple and low-cost nature [7] with Z_{SD} values generally ranging from a few centimeters in coastal or inland waters to ~75 m in the south Pacific gyre.

In parallel to field measurements of visibility, a visual optics science to interpret visibility in both air and water was also developed [3, 5, 8]. One of the highly cited articles regarding Z_{SD} is Preisendorfer [8], where the contrast between the disk and background water is evaluated using photometric quantities. The derivation of a Secchi disk depth (Z_{SD}) in these studies followed the derivation of visibility in air [3, 4] and the upwelling spectral radiance above the disk measured at a depth z ($L_T(z,\lambda)$) is converted to photometric luminance ($N_T(z)$, Lumens) as

$$N_T(z) = \int_{400}^{700} L_T(z,\lambda) Y(\lambda) d\lambda \tag{1}$$

with $Y(\lambda)$ the spectral response function of human eyes. Note that $L_T(z,\lambda)$ includes upward photons originated from the disk (by reflecting downwelling light) and photons scattered by the layer of water between z and Z_{SD}.

Similarly the radiance of the background water at this depth ($L_W(z,\lambda)$) is also converted to luminance

$$N_W(z) = \int_{400}^{700} L_W(z,\lambda) Y(\lambda) d\lambda, \tag{2}$$

Then the contrast in luminance between the disk side and the background side observed at depth z ($C_N(z)$) is

$$C_N(z) = \int_{400}^{700} \left(L_T(z,\lambda) - L_W(z,\lambda)\right) Y(\lambda) d\lambda. \tag{3}$$

The contrast without attenuation by water (i.e., the inherent contrast) is the value of $C_N(Z_{SD})$, and the relation between $C_N(z)$ and $C_N(Z_{SD})$ is considered following the law of contrast reduction [5, 8]

$$C_N(z) = C_N(Z_{SD}) e^{-\alpha(Z_{SD}-z)}. \tag{4}$$

The measured Z_{SD} is thus the depth value when $C_N(0)$ matches the threshold of a human eye [5, 8, 9]. Equation (4) rewritten as the attenuation coefficient of the contrast is then

$$\alpha = \frac{1}{Z_{SD}} \ln\left(\frac{\int_{400}^{700} \left(L_T(Z_{SD},\lambda) - L_W(Z_{SD},\lambda)\right) Y(\lambda) d\lambda}{\int_{400}^{700} \left(L_T(0,\lambda) - L_W(0,\lambda)\right) Y(\lambda) d\lambda} \right). \tag{5}$$

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Therefore, in the classical underwater visibility theory, the attenuation of the contrast is interpreted as conjugate information between the spectral attenuation of radiance through the water layer and the spectral response of a human eye ($Y(\lambda)$), where $Y(\lambda)$ is peaked around 550 nm [10]. However, it is necessary to keep in mind that when observing a Secchi disk in water, human eyes are never positioned at the depth of Z_{SD} as implied by Eq. (5). Rather, our eye-brain system uses contrast information observed just at (or under) the sea surface.

For the observation of a Secchi disk in water, Aas et al. [1] and Lee et al. [2] hypothesized that our eye-brain system simply uses the light information in the transparent window of the water to detect an object in water, instead of the spectrally conjugated signal. The contrast in radiance at this transparent window can be written as

$$C_L(z) = L_T(z, \lambda_{tw}) - L_W(z, \lambda_{tw}), \tag{6}$$

with λ_{tw} for the transparent window of a water body. Further, the propagation of C_L follows

$$C_L(0, \lambda_{tw}) = C_L(Z_{SD}, \lambda_{tw})\, e^{-K(\lambda_{tw})\, Z_{SD}}. \tag{7}$$

Here $K(\lambda_{tw})$ is the diffuse attenuation coefficient of a water body in the transparent window.

Since both $K(\lambda)$ and $Y(\lambda)$ are highly spectrally dependent and have different spectral variations, the above two models (Eq. (4) vs. Equation (7)) represent different understandings of visual detection in aquatic environment; and, thus, the two models will predict different Z_{SD} values and different potentials in remote sensing applications. Although the Z_{SD} values estimated based on Eq. (7) matched very well with measurements for a wide range of water bodies [2], this hypothesis of the spectrally selective feature for detection has not been directly tested.

Aas et al. [1] presented observations of Secchi disk with blue-, green- and red-pass glasses in Oslofjord–Skagerrak area and found that for those waters (Z_{SD} is ~3-11 m), it is the measurements with green-pass glasses better match (~70%) that of naked eyes, but the measurements with blue- and red-pass glasses are just ~50% of Z_{SD} by naked eyes. Because the waters of Oslofjord–Skagerrak area are mostly green transparent (Fig. 2 of Aas et al. [1]) which matches the highest response of human eyes, these observations cannot for sure support the hypothesis of Aas et al. [1] and Lee et al. [2]. In this study, observations of Secchi disks via naked eyes, blue-, and green-pass glasses, respectively, were carried out in wide range of waters, especially in blue oceanic waters where waters' transparent window does not match the highest response of human eyes. The obtained Secchi disk depths of these waters and comparisons with water's spectral attenuation coefficients are reported. These results provide an experimental effort to understand the decision making of our eye-brain system in aquatic environments.

2. Data and methods

Field measurements at two distinctly different water bodies (see Fig. 1 for locations) were carried out in October and November 2016. Six stations were surveyed at the West Pacific Ocean's blue waters and seven stations (six locations with one location surveyed at two different times) were surveyed at the Jiulong River mouth's green waters. Measured properties include Z_{SD} and radiances, which were used for the derivation of remote sensing reflectance (R_{rs}, sr^{-1}) [11].

Z_{SD} of these stations was measured with a white disk of 30 cm diameter. For each station, three sets of Z_{SD} were obtained. The first Z_{SD} set was conducted via the standard approach (i.e. observing the disk by naked eyes) and the results are represented as Z_{SD}^{n}. The second Z_{SD} set was obtained by wearing a pair of blue-pass glasses and the results are represented as Z_{SD}^{b}. The third Z_{SD} set was obtained by wearing a pair of green-pass glasses and the results are represented as Z_{SD}^{g}. Figure 2 shows the band pass information of the two types of glasses.

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Generally it has been found that operator-related uncertainties in field Z_{SD} measurements are ~10%, which provide a confidence in using such data for this analysis.

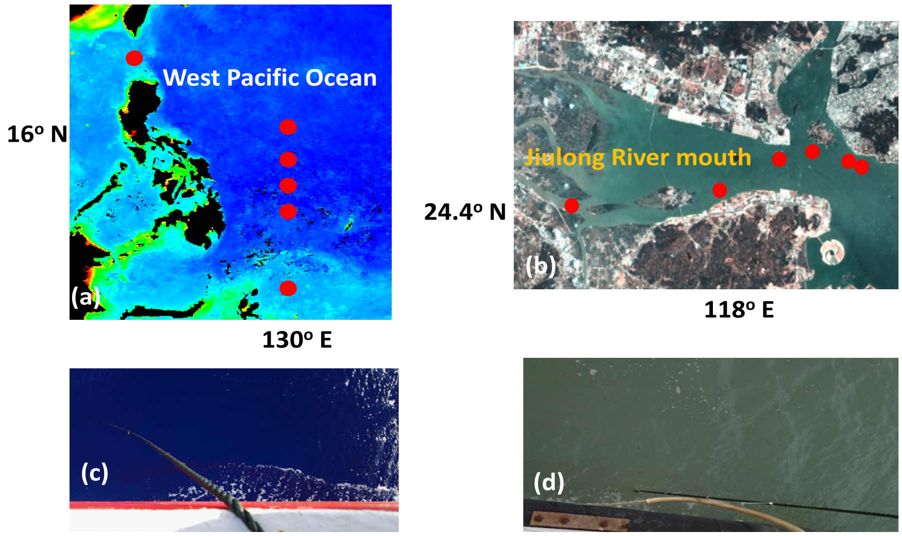

Fig. 1. Measurement locations (the red dots) and water colors. (a): West Pacific Ocean, Sept. 26 - Oct. 25, 2016. The background map is climatology chlorophyll-a concentration in September, obtained from NASA OBPG. Black for land or no data. (b): Jiulong River mouth, China, Nov. 16, 2016. Note that one location was sampled twice. Background is a Landsat image of the sampling area. (c) and (d): General color of waters in the west Pacific Ocean and Jiulong River mouth, respectively.

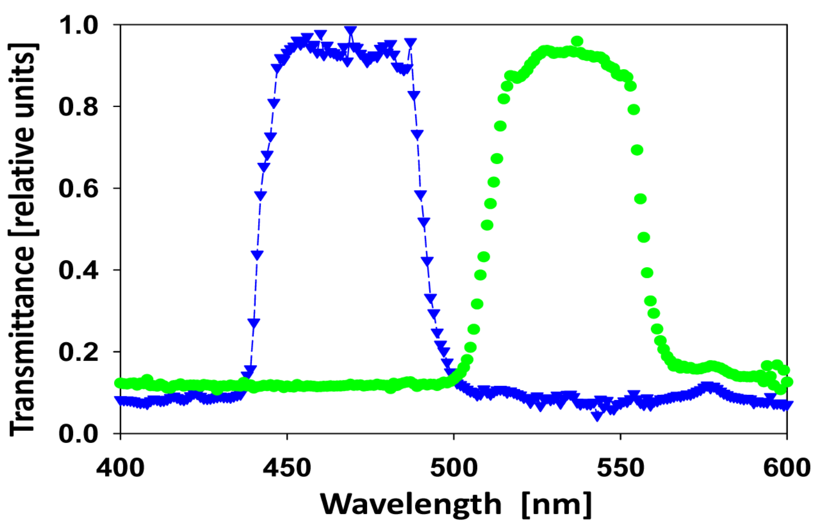

Fig. 2. Band pass information of the blue-pass and green-pass glasses used during the field experiments.

The above-water approach [11] was employed to obtain spectral R_{rs} of the sampled waters. Specifically, a GER 1500 spectrometer was used to measure total radiance (L_t) that includes water-leaving radiance and surface-reflected light, and radiance from the sky (L_{sky}). For both measurements, the angular position was ~90° from the solar plane, and ~30° zenith (nadir) angle for L_t (L_{sky}). Radiance (L_G) from a standard reflectance panel was also measured with the same instrument, and R_{rs} was calculated from these measurements following [12, 13]

$$R_{rs}(\lambda)=\frac{\rho(\lambda)}{\pi}\frac{L_t(\lambda)-F\,L_{sky}(\lambda)}{L_G(\lambda)}-\Delta. \tag{8}$$

ρ is the reflectance of the standard reflectance panel with a reflectance value of 50%. F is the Fresnel reflectance of a flat sea surface and a value of 0.023 was used. Δ (sr^{-1}) represents the residual surface contribution to L_t and was determined using a spectral optimization model [13, 14]. R_{rs} spectra of both locations are presented in Fig. 3. A clear contrast of the green vs. blue waters of the two locations are revealed by these R_{rs} spectra, where R_{rs} of Jiulong River mouth peaks around 575 nm, while R_{rs} of the West Pacific Ocean peaks around 400 nm.

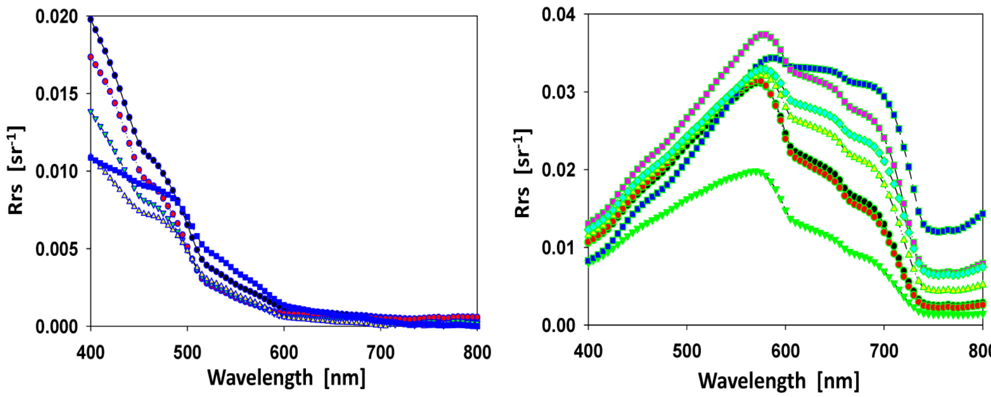

Fig. 3. Spectra of remote sensing reflectance (R_{rs}) obtained during the two field experiments. Left: R_{rs} spectra of west Pacific Ocean; Right: R_{rs} spectra of Jiulong River mouth.

3. Results and discussion

For the waters surveyed, the range of Z_{SD}^{n} is ~0.4 - 1.0 m for the green waters, while it is ~21 - 28 m for the blue waters (see Fig. 4). Also included in Fig. 4 are the values of Z_{SD}^{b} and Z_{SD}^{g}. These results clearly show the distinct contrast between the two types of aquatic environments. As in Aas et al. [1], we calculated the ratio of Z_{SD}^{b} to Z_{SD}^{n} (represented as BNR) and the ratio of Z_{SD}^{g} to Z_{SD}^{n} (represented as GNR) for each station with the range, average and standard deviation of the two water types, respectively, presented in Table 1. For green waters (N = 7), the BNR has a range of 0.63 – 0.90 with the average and standard deviation as 0.79 ± 0.09, while the GNR has a range of 0.88 – 1.08 with the average and standard deviation as 1.01 ± 0.07, which clearly shows Z_{SD}^{n} is similar to Z_{SD}^{g} for such waters. On the other hand, for blue waters (N = 6), the BNR has a range of 0.81 – 1.08 with the average and standard deviation as 0.95 ± 0.09, while the GNR has a range as 0.67 – 0.88 with the average and standard deviation as 0.79 ± 0.08, which is opposite of the pattern observed in green waters and indicates that Z_{SD}^{n} is similar to Z_{SD}^{b}. Further, we calculated the ratio of Z_{SD}^{b} to Z_{SD}^{g} for the two water bodies, respectively, with ranges and averages also presented in Table 1. Clearly, for blue waters, Z_{SD}^{b} is systematically deeper (~20% on average) than Z_{SD}^{g}. Note that the green-pass glasses match very well with the highest response of human eyes (see Fig. 5), thus it is expected that Z_{SD}^{n} should better match Z_{SD}^{g} following the classical underwater visibility theory. These results and those in Aas et al. [1] show a clear spectral preference in observing a Secchi disk in aquatic environments by human eyes.

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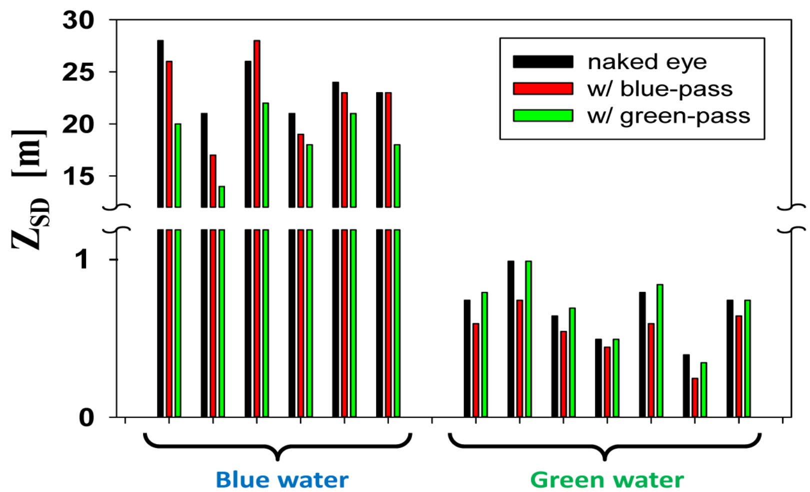

Fig. 4. Ranges and values of Secchi disk depth observed via naked eye, with blue-pass glasses, and green-pass glasses, of the two water bodies, respectively.

Table 1. Ratio of Z_{SD} with color filters (Z_{SD}^{b} , Z_{SD}^{g}) to Z_{SD} by naked eye (Z_{SD}^{n}), and ratio of Z_{SD}^{b} to Z_{SD}^{g} . Values in parentheses are the ranges.

	Blue water (N = 6)	Green water (N = 7)
Blue-pass glasses	0.95 ± 0.09 (0.81-1.08)	0.79 ± 0.09 (0.63-0.90)
Green-pass glasses	0.79 ± 0.08 (0.67-0.88)	1.01 ± 0.07 (0.88-1.08)
Blue-pass to green-pass	1.20 ± 0.10 (1.06-1.30)	0.78 ± 0.07 (0.71-0.90)

This finding is consistent with the spectral characteristics of the diffuse attenuation coefficient ($K_d(\lambda)$, m^{-1}) of the two water bodies (see Fig. 5), which were calculated following the IOPs model [15] with absorption and backscattering coefficients derived using the latest version of the Quasi-Analytical Algorithm [16]. For green waters (Jiulong River mouth), $K_d(\lambda)$ is lowest in the ~550 - 600 nm range and this spectra range represents the transparent window of these waters, which matches well the highest response of $Y(\lambda)$ and overlaps with the green-pass glasses. On the other hand, for the blue waters (West Pacific Ocean), the $K_d(\lambda)$ is lowest (~0.03 m^{-1}) in the ~450 - 490 nm range, which overlaps with the blue-pass glasses, but does not match the highest response of human eyes. These results provide further evidence that although our eyes are more sensitive to green light (as we commonly experience when a green laser pointer is used in presentations), but it is the information of the disk in the blue wavelengths for waters in the West Pacific Ocean determines its detection by our eye-brain system. Further, although there were no measurements made in the West Pacific Ocean with red-pass (600-650 nm) glasses, a spectral band that human eyes have higher sensitivity than the blue-pass band, it is reasonable to speculate that for such blue waters, the Secchi depth observed with red-pass glasses would be much shallower than that with the blue-pass glasses. This is supported from measurements in the Oslofjord–Skagerrak area [1] where the observed Z_{SD} by red-pass glasses is just about half of that by naked eyes, although the waters encountered there were more of greenish (Z_{SD} ~8 m), rather blue waters we tested (Z_{SD} ~25 m).

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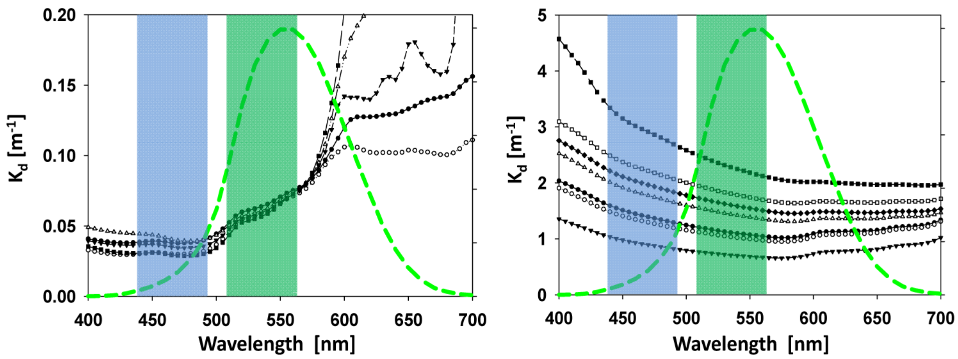

Fig. 5. Spectra of diffuse attenuation coefficient (K_d) of the two water bodies, and annotated with the band-pass information (vertical bars) of the two types of glasses, and spectral response function of human eyes (green dash line). Left: West Pacific Ocean; Right: Jiulong River mouth. Note that the wide range of K_d of West Pacific Ocean for wavelengths > ~600 nm is a result of the extremely low R_{rs} values of these waters for such longer wavelengths, where the measured R_{rs} has high uncertainties due to surface reflectance.

For an aquatic environment, when the disk is lowered in water, because of the spectrally-dependent extinction of light by water, only photons in the transparent window penetrated to deeper depths, hit the disk, propagate upward, and then enter our eyes. In these processes, note that the photons go through this spectrally selective path twice; consequently, the information about when a Secchi disk is approaching disappearance only exists in the spectrally transparent window. Specifically, for such blue waters, although our eyes are still very sensitive to photons in the 600-650 nm spectral window, few photons in this band carry information of a Secchi disk. Therefore, if N_T - the $Y(\lambda)$ conjugated signal - is used to interpret Z_{SD}, a much shallower depth would be resulted because $K_d(\lambda)$ in the longer wavelengths (> 520 nm), which are much greater than $K_d(\lambda)$ in in the transparent window (see Fig. 5), will contribute significantly to the attenuation of N_T due to the strong weighting of $Y(\lambda)$ in the longer wavelengths. For instance, for such blue waters, for a white disk at a depth of 25 m, the diffuse attenuation coefficient of N_T propagating from 25 m to subsurface is ~0.06 m^{-1}, but K_d in the transparent window is ~0.03 m^{-1}. This contrast in attenuation coefficient further supports why Z_{SD}^{n} matches Z_{SD}^{b} for such blue waters, and that photons in red wavelengths have negligible involvement for the detection of a target in such waters (although important for the diffuse attenuation coefficient of N_T).

This visual perception is different from visual observations in air, where the spectral dependence of air extinction coefficient is weak; thus, it is necessary to account for the contrast of all wavelengths to enhance the detection of a target in air. Further, $Y(\lambda)$ matters for two separated locations (but within the field-of-view of our eyes) with different colors. For instance, imagine there are a green light and a blue light of the same intensity on a distant wall. We will notice the green light much easier than the blue light due to the spectrally selective response of human eyes. But this is not the case when we determine Z_{SD} in aquatic environments. When a Secchi disk is lowered in water and approaches a depth no longer viewable, the colors within the field view of human eyes (which include a point over the disk and an adjacent background point) are very similar [2]. Therefore, the spectral responses of our eyes to these two contrasting points are nearly the same, so the spectral selective response of our eyes is no longer important for observing a Secchi disk in water. This is evidenced from results obtained in the blue waters, where our eyes have much lower sensitivity to blue photons compared to green photons (see Fig. 5), but the observed Secchi depths by naked eyes match that with blue-pass glasses, rather that with green-path glasses. This understanding further supports the hypothesis that detection of a target in water is not necessarily a function of $Y(\lambda)$-weighted signal as presented in the classical visibility theory

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[5,8], instead the detection of a target in water is a function of the signal in the spectrally transparent window [2].

4. Conclusions

Historically the detection of a Secchi disk in water was explained follow the understanding of visibility in air, where it uses the eye-response function weighted signal to quantify the change of contrast for varying distance. It was recently hypothesized [1, 2] that for a target in water human eyes simply use information in the transparent window for this detection. Secchi disk observations with blue-pass and green-pass (matching the highest response of human eyes) glasses were then carried out, in particular in blue waters, to test this hypothesis experimentally. The results obtained indicate that Secchi disk depth observed with naked eyes is nearly identical with the Secchi disk depth observed at the spectrally transparent window of the blue and green waters, respectively. These results support the notion that human eyes indeed rely on information in the transparent window of water for the detection of an object in water, not the spectrally conjugated signal as in the classical under-water visibility theory. This is consistent with the nature of aquatic environments where the extinction of light signal is highly spectrally selective.

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