

Secchi Depth Analysis Using Bio-Optical Parameters Measured In The Arabian Sea

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ABSTRACT

Secchi depth provides the oceanographer with the first hand information about transparency and penetration of light in the water. Here we present results of the Secchi depth and the optical properties measured in the Arabian Sea. Our analyses show spatial and temporal variability of Secchi depth and their dependence on the optical properties beam attenuation and diffuse attenuation the biological parameter of Chlorophyll. The in-situ measured inherent and apparent optical properties have been used to understand the underwater light properties and their relations to the Secchi depth in various water types. The Secchi depth model is validated using the measured optical properties. We also present an empirical method to determine Secchi depth from the satellite ocean color sensor, and the application of the same to the IRS-P4 OCM is found to provide comparable results to the measured values.

Keywords : Secchi depth, Arabian Sea, optical properties, transparency, water clarity, Kd, water quality, SeaWiFS, OCM, Secchi disk, euphotic depth.

1. INTRODUCTION

The Secchi disk is well known device used by the marine scientists and oceanographers to measure transparency of water due to its simplicity and the utility value. Here we examine the Secchi depths measured in the Arabian Sea and the relationships with the bio-optical properties. We subscribe to the views of Preisendorfer¹, who had suggested that deriving optical properties using Secchi depth would be futile and incorrect exercise. These relationships have been developed to compare with the results obtained by others regions and also validate the theories with the in-situ measured values of the inherent and apparent optical properties and provide an understanding of the light properties. The Secchi disk measurements have been carried-out to determine the rough estimate of the euphotic depth and thus decide on the depths for collecting water samples at discrete depths.

The Secchi disk originated with Fr. Pietro Angelo Secchi, an Italian astrophysicist, who used a white disk to measure the clarity of the water in the Mediterranean Sea in April 1865. Since then, the Secchi disk has been used to measure transparency of the water. It is the simplest method for estimating the transparency of water. The depth at which the Secchi disk disappears, known as the Secchi depth (Z_{sd}), is a measure of the transparency or the clarity of water. Clarity indicates how deep light can penetrate into the water. The higher the Secchi depth, the deeper the light penetrates into the water. Standard size of Secchi disk for oceanographic application is 20 cm, though its size may vary from 20 to 30 cm. Secchi disk with alternating black and white quadrants to improve contrast originated in 1899 by G.C. Whipple is known as "Whipple's" disk². Davies-Colley³ measured transparency using a black disk.

The bio-optical properties analyzed here were measured in the Arabian Sea from seven cruises during 1996 and 2000, for different seasons and in varying water types from shallow coastal regions to the deep ocean. The data include the in-situ measured inherent optical properties of absorption and beam attenuation at nine wavelengths (412, 440, 488, 510, 532, 555, 650, 676, 715 nm) using the instrument AC-9 (<http://www.wetlabs.com/>), the apparent optical properties derived from Satlantic make radiometer (<http://www.satlantic.com/>) and the biological parameter chlorophyll a obtained from analysis of water samples collected by CTD at discrete depths.

The data of Secchi depth collected in the Arabia Sea vary from shallow depth of 1 m in the coast waters, to a maximum depth of 30 m in the clear open ocean. There is a distinct seasonal variation in the Secchi depth in the Arabian Sea, with relatively higher transparency being observed during summer compared to the winter. The regions with the lowest transparency were found off the Gulf of Khambat coastal waters. It is also interesting to observe that the deep Secchi depths were also recorded just outside this shelf region. (Fig. 1).

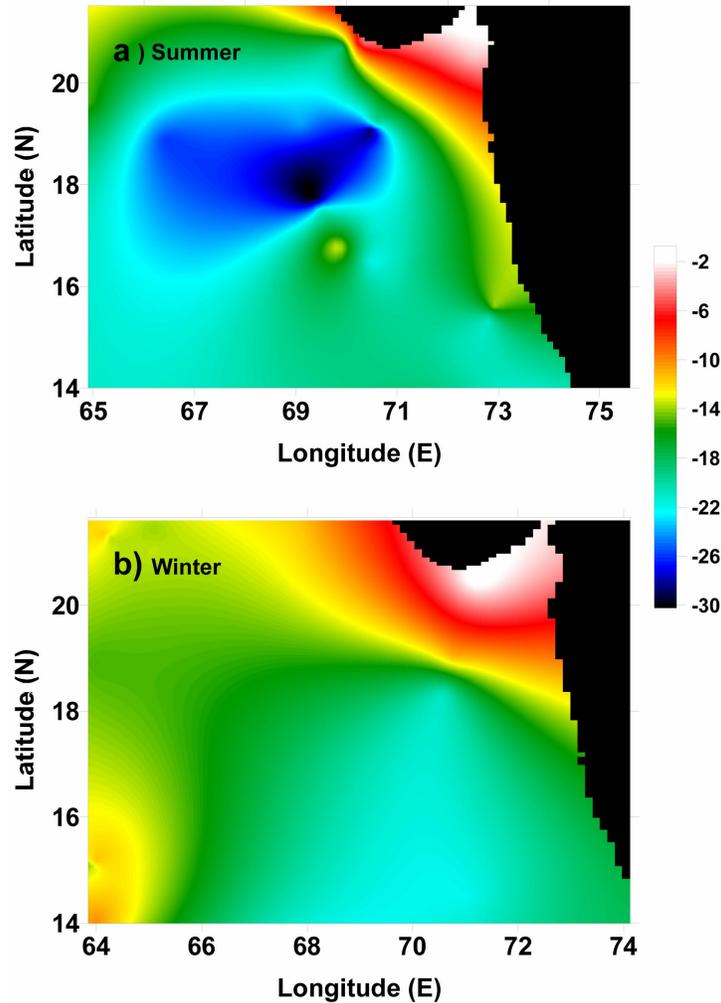


Fig. 1. Variations of Secchi depth during (a) Summer (b) Winter.

2. SECCHI MODEL

The Secchi depth depends on four parameters, a radiation source (sunlight), a medium that the radiation travels through (water), an object (the Secchi disk), and a sensor (our eye). The Secchi models are based on the visibility theory. Here we determine the luminous flux or the brightness of light as observed by the human eye, which is given in lumens per cross-sectional area per solid angle centered in the direction of viewing. (Lumens/m²/sr). The theory is based on determining the brightness contrast of the Secchi disk with respect to the background. The contrast C is defined as

$$C = \frac{B_T - B_B}{B_B} \quad 1$$

where B_B is the luminance of the background and B_T is the luminance of the target. Luminance is analogous to brightness and is the photometric equivalent of radiance. Contrast that leads to 50% probability of detection is called the threshold contrast and is identified as C_t . Using the similar concept of vision, we can call the $B_T - B_B$ as Just-Noticeable-Difference (JND). The threshold contrast depends on the lighting of the background and the angular size of the target^{4,5}. According to Levin⁶ the realistic value C_t is 0.02. For the targets with angular size $d/z \geq 0.006$ and for the high background luminance, the smallest value is, $C_t = 0.01$. Rose⁵ and with our disk size of 0.3 m and maximum depth of 31 m qualifies the limit. The C_t does not make any significant difference in Z_{sd} , which implies that Z_{sd} values will not differ with different observers⁷. The contrast varies due to the variations of light on the surface of water. The surface waves reduce the contrast C_t by about 40%¹. Since the water background luminance is higher on the sunny than under the shade, therefore, from the definition of contrast, it follows that the contrast will be greater on the shady side at any given water depth. This is in accordance with Preisendorfer's Law 10¹. The use of a viewer box removes the interfering effects of water surface glare and glitter enhances the contrast and thus increases the Secchi depth measurement^{1,8}.

Though sunlight is required to determine the Z_{sd} , Gordon⁷ has found the variations of Z_{sd} with solar elevation to be of less significance and the study of Verschuur⁹ finds the variations to be within 15% for the changes in solar zenith angle. The relative ability of radiant energy to produce varying sensations of brightness in the human observer is described by the photopic luminosity function $y(\lambda)$ ¹⁰. The photopic region where the eye is spectrally sensitive is from 390 nm to 760 nm and it is not spectrally uniform, but nearly symmetric around a peak at 550 nm. In view of this, the optical properties are not spectral, but spectrally averaged values weighted by the photopic luminosity function $y(\lambda)$. For our analysis we have used the spectral values of the inherent optical properties at 510 nm and the diffuse attenuation coefficient at 490 nm.

The Secchi models have been developed using the radiative transfer and the visibility model with some valid assumptions and empirical approximations^{7,1,6}. The general form of the Secchi model is given as

$$Z_{SD} = \frac{1}{(c + K_d)} \ln[\beta] \quad 2$$

where c is the beam attenuation coefficient (an inherent optical property), K_d is the diffuse attenuation coefficient (an apparent optical property) and β is a function of contrast and reflectance.

2.1 Secchi Model

Levin^{6,11} refined the model taking into account the limitations indicated by Preisendorfer¹ and considering the factor due to sunlight and shadow over the water and provided the following model

$$Z_{SD}(\lambda) = \frac{1}{(c + K_d)} \ln \left[\frac{C_t (kA_s + A_2 r)}{A_1 R_d} \right] \quad 3$$

where

- c - beam attenuation coefficient
- C_t - human eye contrast threshold
- K_d - diffuse attenuation coefficient
- $k = E_{dif} / E_0$. E_{dif} is diffuse solar irradiance and E_0 is total solar irradiance
- $A_s = r_s n^2 (1 - R_s)^{-1} t_s^{-1}$
- r_s - radiance reflectance of flat sea surface for sky radiation
- n - refractive index of water
- R_s - Fresnel reflectance of sea surface for total irradiance

t_s - surface transmittance for radiance in zenith direction

$r = \pi L / E_d$ is radius reflectance of water layer, where L is upwelling radiance and E_d is downward radiance just below the surface of water. $r = \pi R_{rs}$, where R_{rs} is the remote sensing reflectance. In Russian literature referred as "Sea Radiance Coefficient" and differing from Remote Sensed Reflectance, Lu / E_d by π

R_d - disk reflectance.

A_1 and A_2 are constants that depend on the observations (sunny side or shadow).

We have used this model of Levin with $C_t = 0.02$, $A_s = 0.038$, $A_1 = 1$, $A_2 = 1$, $R_d = 0.08$, $n = 1.34$, $t_s = 0.98$, $r_s = 0.02$ and the measured values of c , K_d and R_{rs} . The values of k were derived using the solar radiation model, Bird¹² with the measured aerosol parameters. The agreement between the measured Z_{sd} and those derived using the measured values of optical properties in the model are found to closely agree. (See Fig. 2). The RMSE for the Z_{sd} derived from the model of Levin¹¹ is 9.6. After discarding results with very large errors, most of the values were found to be within an error of 22.6%. The probable sources of error are due to error in the measurement of Secchi depth, ambiguity in the position of the observer and the sun during the measurement, reflectance value of the Secchi disk, error in the measured optical properties and eye contrast threshold and other approximations of parameters.

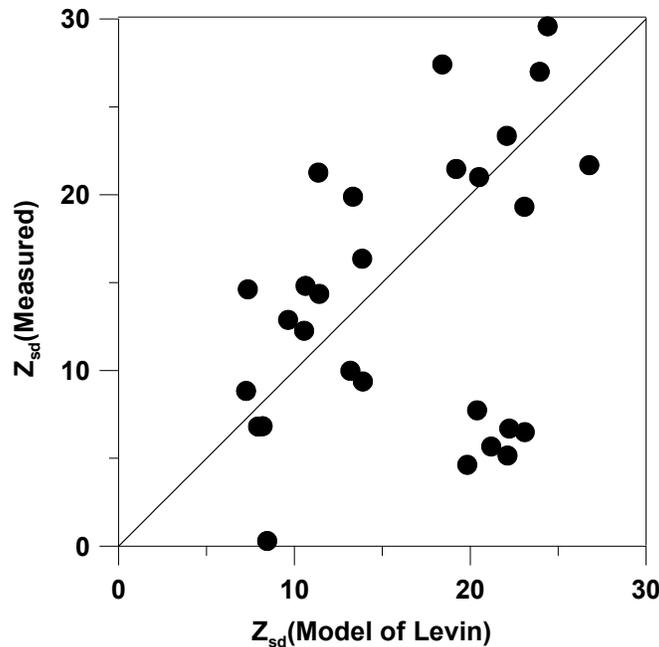


Fig. 2 Comparison of the measured Secchi depth with model of Levin.

3. RELATIONSHIPS WITH BIO-OPTICAL PROPERTIES

Here now we present results of the relationships of the bio-optical parameters measured in the Arabian Sea and the Secchi depth.

3.1 Beam attenuation coefficient, c

Here we obtain an empirical relationship of the beam attenuation coefficient. The value of cZ_{sd} is found to be within a range of 6 and 7.7^{13, 14, 15} and is assumed to be a constant. For our data we observed the following relationship (Fig. 3)

$$c = \frac{6.24}{Z_{SD}} \quad 4$$

Secchi depth showed a very weak dependence on the single scattering albedo⁷. The particulate beam attenuation coefficients show spectral relationships i.e $c(\lambda) \sim \lambda^{-\alpha}$. The α provides information about the particulate size distribution and it varies between 0 to 1.3. The variations of Z_{sd} with α is found to be independent which indicates that Z_{sd} variations are attributed to the total transmission factors or the amount of particulate matter rather than the sizes of the particulate matter in water.

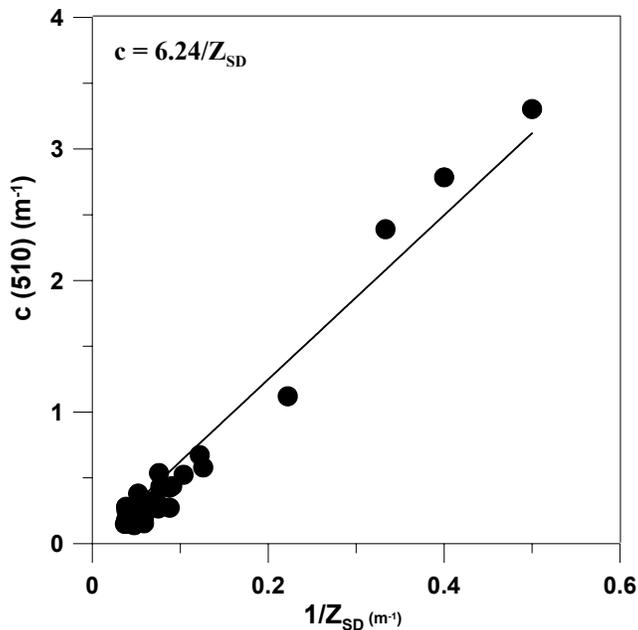


Fig. 3. Variations of beam attenuation coefficient $c(510)$ with Secchi depth

3.2 Diffuse attenuation coefficient, K_d

Values of $K_d Z_{sd}$ are found to vary between 0.4 and 1.7^{7, 13, 16}. For the data analyzed we have (Fig. 4)

$$K_d = \frac{1.448}{Z_{SD}}$$

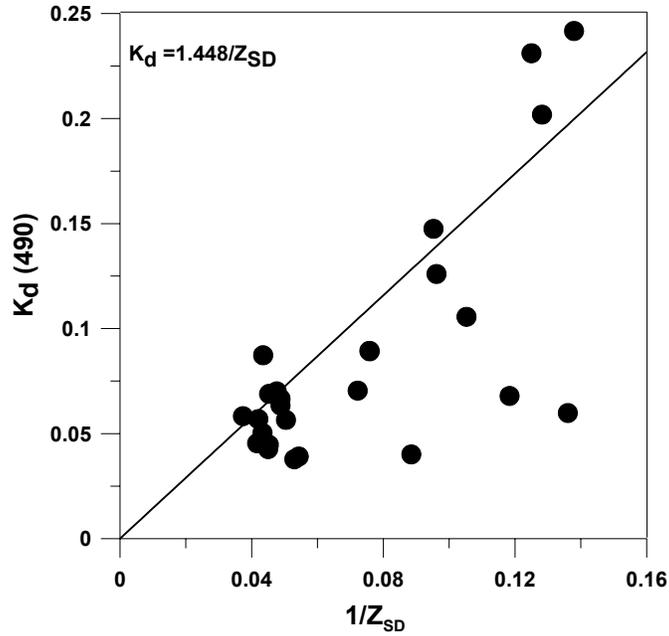


Fig. 4. Variations of diffuse attenuation coefficient, $K_d(490)$ with Secchi depth

3.3 $c + K_d$

The relationship between $c+K_d$ and Z_{sd} are found to be linear and the values of $Z_{sd}(c+K_d)$ are usually reported within a range of 8 to 9, with values being reported by some as 8.69 by Tyler¹⁵, 9.42 by Holmes¹³ and 9 by Preisendorfer¹. This value is found to be comparatively lower from our analysis. (Fig.5).

$$Z_{SD}(c + K_d) = 5.66$$

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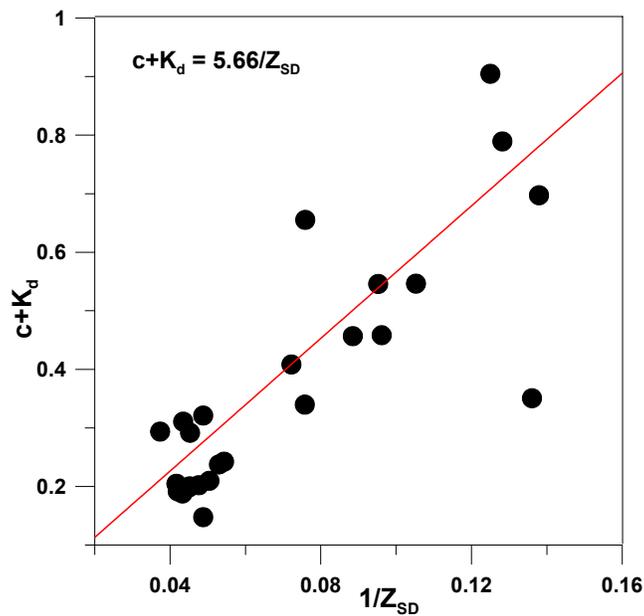


Fig. 5. Variations of $c+K_d$ with Secchi depth.

3.4 Chlorophyll

Chlorophyll concentrations is found to hold a linear relationship with $1/Z_{sd}$. Renk¹⁷, Lewis¹⁸, indicating that transparency is relatively lower in productive waters, which is the reason for the lower Secchi depths observed in the Northern Arabian Sea during winter as compared during the summer. Enhanced Chlorophyll concentrations are observed in these regions during winter, Madhupratap¹⁹.

$$Chl = aZ_{SD}^b \quad 7$$

where $a = 0.5$ and $b = -0.321$. (See Fig. 6).

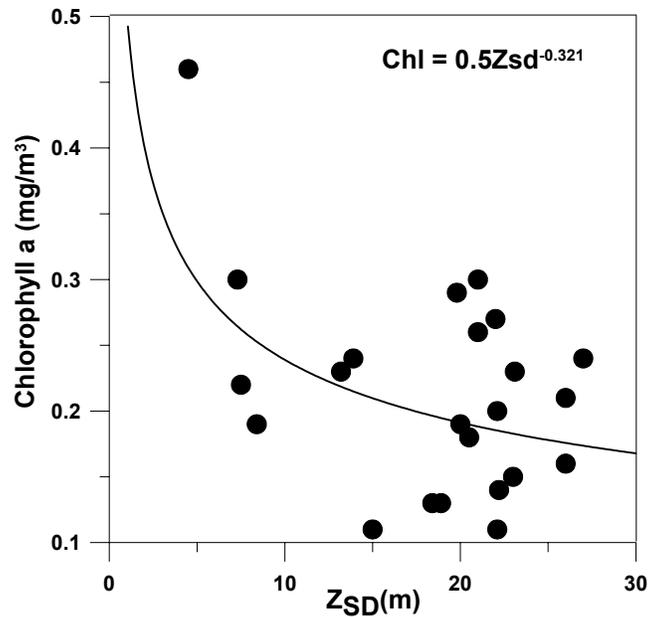


Fig. 6. Variations of Chlorophyll with Secchi depth.

3.5 Algorithm to derive from satellite data

There have been attempts at providing transparency maps using the measured values²⁰ and from the satellite data^{21, 22}. Ocean color satellite sensor is found to be suitable for these applications. We have derived an empirical relation using the radiometric data for the Arabian Sea s given below.

$$Zsd = A + B \left(\frac{Rrs(490)}{Rrs(555)} \right) \quad 8$$

where $A = 2.27212$, $B = 7.239$.

The image of Secchi depth derived from the satellite data for the Arabian Sea for winter is comparable to the measured data (Fig.7).

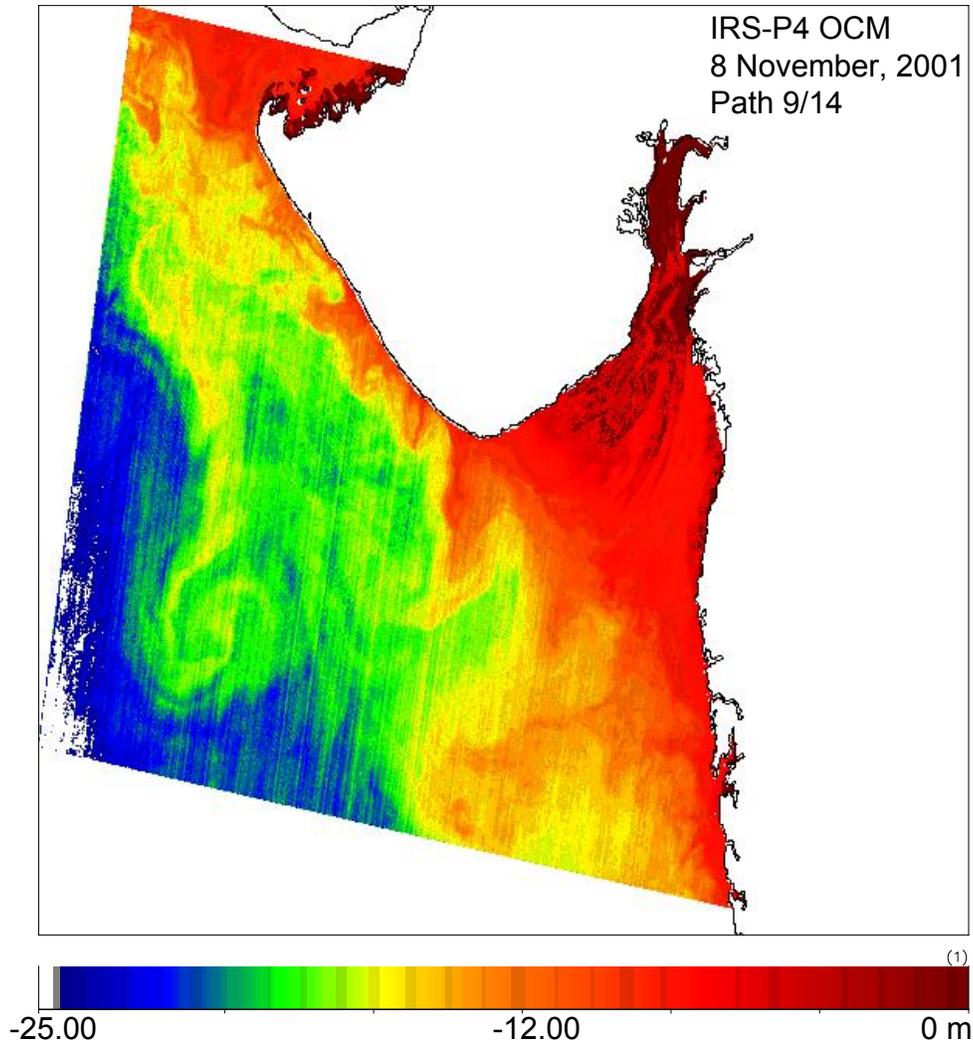


Fig. 7. Secchi depth map derived from IRS-P4 OCM during winter (8 November, 2001) for a region of Arabian Sea off Gujarat and west coast of India.

3.6 Euophotic depth

Euophic depth, Z_{eu} is the depth at which the light is 1% of the light available at the surface of water. It is used in various models to determine the primary productivity and other similar oceanographic studies. The Secchi depth measurements are often used to provide a rough estimate of the Z_{eu} , using simple thumb rule scaling factor. Here we determine the availability of underwater solar irradiance at Z_{sd} and then using this provide a factor to determine the Z_{eu} for the Arabian Sea. This should not be taken as an accurate universal factor or for the region, but as a rule of thumb to provide approximate estimate in absence of optical measurements. The percentage of light available at Z_{sd} given as the percentage of $E_d(Z_{sd})/E_d(0)$ varies from 20 to 40%^{23, 24}, where $E_d(0)$ and $E_d(Z_{sd})$ are lights at the surface and at the Z_{sd} respectively. In the waters of the Arabian Sea, the percentage of light available observed is about 31%, which provides us an approximate simple relationship for Z_{eu} as

$$Z_{eu} \approx m \times Z_{sd} \quad 11$$

where $m = 1.97$. This agrees with the rule of thumb followed by the oceanographers, that the euophotic depth is twice the Secchi depth in the Arabian Sea. The value of m is comparable to those reported by others¹⁴.

4. CONCLUSION

The validation of the Secchi depth model is found to yield results close to the measured values. The Secchi depth is found to vary inversely with the diffuse attenuation coefficient, K_d and beam attenuation coefficient, c and the optical state of the sea surface and chlorophyll. Though empirical relations have been derived to determine the optical parameters, it however discouraged to use them as they can only be used to provide a rough estimate and first hand information. Euphotic depth is found to be approximately twice the Secchi depth and thus for the Arabian Sea the multiplication factor for the rule of thumb to determine the euphotic depth using the Secchi depth is 2. The empirical method derived to determine the Secchi depth using the ocean color satellite SeaWiFS and IRS-P4 OCM is found to provide the transparency maps that are comparable with the measured values.

Though the measurement of Secchi is considered to be a trivial exercise during oceanographic expeditions, systematic recording of the data over years have provided information about the variations in the water clarity and its health^{25, 20, 26}. Secchi depth measurements though a very rudimentary method of determining the transparency of water and thus deriving rough estimate of the penetration of the light in water, it is essential to record the same for determining the health of the water body and the changes. It is suggested to carryout this measurement on a routine basis and following standard protocol along with all other measurements during ocean color campaigns²³.

Acknowledgement

Authors are grateful to the Director, National Institute of Oceanography for the kind support. We also would like to thank Dr. Ehrlich Desa, Ex-Director for the encouragement and support. This work was carried-out under project funded by Space Application Centre (ISRO), Ahmedabad for the development of bio-optical algorithms for the IRS-P4 OCM applications. We also appreciate the help rendered by our colleagues Ms. Ancy Rodrigues and Miss. Madhubala Talaulikar for the preparation of the manuscript and processing of the data.

REFERENCES

1. R. W. Preisendorfer, "Secchi disk science: Visual optics of natural waters", *Limnology & Oceanography*, **31**, 909-926, 1986.
2. G. C. Whipple, *The Microscopy of Drinking Water*, John Wiley and Sons, New York-London.
3. R. J. Davies-Colley, "Measuring water clarity with a black disk", *Limnol. and Oceanogr.*, **33**, 616-623, 1988.
4. H. R. Blackwell, "Contrast Thresholds of the Human Eye", *J. Opt. Soc. Amer.*, **36**, 624-643, 1946.
5. A. Rose, *Vision, Human and Electronic*, Plenum Press, New York - London, 1973.
6. I. Levin, Eh. Desa, El. Desa, T. Suresh, Radomyslskaia T., "Can the Secchi depth measurements be used for determination of water inherent optical properties?", *Current Problems in Optics of Natural Waters (ONW' 2001)*, I. Levin and G. Gilbert, Proceed. of the Int.Conf., 360-366, St. Petersburg, 2001.
7. H. R. Gordon, Wouters A.W., "Some relations between secchi depth and inherent optical properties of natural waters", *Applied Optics*, **17**, 3341-3343, 1978.
8. D. G. Smith, M. Hoover, "Standardization of Secchi disk measurement, including use of viewer box", *Journal of American Water Research Association*, **35**, 1183-1189, 1999.
9. G. L. Verschuur, "Transparency measurements in Garner lake, Tennessee; the relationship between Secchi depth and solar altitude and a suggestion for normalization of Secchi depth data", *J. Lake and Reserv. Manage.*, **13**(2), 142-153, 1997.
10. C. D. Mobley, *Light and Water. Radiative transfer in natural waters*, Academic Press, San Diego, USA, 1994.
11. I. M Levin, "Back to Secchi depth theory: when, how and why can it be used?", *Proceedings of D.S Rozhdestvensky Optical Society: The II International Conference Current problems in Optics of Natural waters (ONW' 2003)*, Iosif Levin, Gary gilberst, St Petersburg, Russia, 2003.
12. R. E. Bird, C. Riordan, "Simple solar model for direct and diffuse irradiance on horizontal and tilted planes at Earth's surface for cloudless atmospheres", *J. Clim. And Applied meteorology*, **25**, 87-97, 1986.
13. Holmes, "The Secchi disk in turbid coastal water", *Limnology & Oceanography*, **15**(5), 688-694, 1970.

14. N. K. Hojerslev, "Visibility of the sea with special reference to the Secchi disc", *Ocean Optics*, M. Blizard, Editor, VII, V. 637, 294 – 305, SPIE, 1986.
15. F. E. Tyler, "The Secchi disc", *Limnol. Oceanogr.*, **13**, 1-6, 1968.
16. H. H. Poole, W. R. Atkins, Photoelectric measurements of submarine illumination throughout the year, *J. Mar. Biol. Assoc. U.K.*, **16**, 297-324, 1929.
17. H. Renk, J. Nakoneczny, S. Ochocki, Z. Lorenz, R. Majchrowski, D. Ficek, "Secchi depth-chlorophyll relationship in the Baltic", *Acta Ichthyol. Piscat.*, **21**, 203–211, 1991.
18. M. R. Lewis, N. Kuring, C. Yentsch, "Global patterns of ocean transparency: Implications for the new production of the open ocean", *J. Geophys. Res.*, **93**, 6847-6856, 1988.
19. M. Madhupratap, S. Prasanna Kumar, P. M. A Bhattathiri, M. Dileep Kumar, S. Raghukumar, K. K. C. Nair, Ramaiah N., "Mechanism of the biological response to winter cooling in the northeastern Arabian Sea", *Nature*, **384**, 549– 552, 1986.
20. T. Aarup, "Transparency of the North Sea and Baltic Sea – a Secchi depth data mining study", *Oceanologia*, **44 (3)**, 323–337, 2002.
21. K. S. Prasad, R. L. Bernstein, M. Kahru, B. G. Mitchell, "Ocean color algorithms for estimating water clarity (Secchi depth) from SeaWiFS", *J. Adv. Mar. Sci. Tech. Soci.*, **4(2)**, 301-306.
22. S. Kratzer, B. Håkansson, C. Sahlin, "Assessing Secchi and Photic Zone Depth in the Baltic Sea from Satellite Data", *AMBIO*, **32(8)**, 577–585, 2003.
23. J. L. Mueller, "Field Measurements, Sampling Strategies, Ancillary Data, Metadata, and Data Archival", General Protocols, in *Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4, I*, NASA/TM-2003-21621/Rev-Vol I, 2003
24. R. O. Megard, T. Berman, "Effects of algae on the Secchi transparency of the southeastern Mediterranean", *Limnology and Oceanography*, **34**, 424-432, 1989.
25. P. Sandén, B. Håkansson, "Long-term trends in Secchi depth in the Baltic Sea", *Limnol. Oceanogr.*, **41**, 346-351, 1996.
26. D. G. Borkman, T.J. Smayda, "Long-term trends in water clarity revealed by Secchi-disk measurements in lower Narragansett Bay", *ICES Journal of Marine Science*, **55 (4)**, 668-679, 1998.