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THE SECCHI DISC

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ABSTRACT

The theory and practice of the Secchi disc experiment are discussed. It is shown, in theory, that the Secchi disc reading can be used to calculate the sum of the total and diffuse attenuation coefficients, α and K. To obtain independent values of α and K it is necessary to make some other measurement.

Some recent measurements of the per cent of surface light reaching various depths, obtained in conjunction with Secchi disc readings, are discussed with respect to their usefulness in determining α and K independently.

It is suggested that the Secchi disc could be calibrated against modern instrumental measurements of α and K and a practical value for apparent contrast thus determined for the Secchi disc experiment. However if modern instruments are available for measuring α and K, it would probably be better not to undertake such a calibration.

The idea for determining the transparency of seawater by making visual observations on a submerged white disc seems to have originated with a casual observation by a certain Captain Bérard who, during a passage from Wallis Island to the Mulgraves observed a dish contained in a net at a depth of 40 m. This observation might have gone unnoticed but for Arago (1786–1853) who made mention of it in his writings. Even so, the Secchi disc would not have achieved the fame it now enjoys except for the diligence and foresight of Commander Cialdi, who, in 1865, was head of the Papal Navy.

Commander Cialdi was interested in the transparency of the sea, the visibility of the bottom, and the theory of wave movements in the sea. No doubt he had practical navy problems in mind, but his actions were those of a scholar. He read Arago's works and finding the reference to the dish, he immediately prepared several discs of different diameters and colors with which to repeat and study Captain Bérard's observation. He then obtained the services of Prof. P. A. Secchi, to organize and conduct a scientific program of observations on board the SS *L'Immacolata Concezione* (Cialdi 1866). After a little over a month of experimental work at sea, Cialdi published the results of the expedition's work under the title *sul Moto Ondoso del Mare e su le correnti de esso specialmente auquelle littorali.*

The published report includes a memorandum written by Secchi in which he meticulously examines the effect of many variables on the visibility of the disc. Secchi's experiments showed that the depth of visibility increased with the size and whiteness of the disc and with the altitude of the sun. He noted that image dissection by surface refraction caused the visibility of the disc to decrease and that the ship's shadow underwater also influenced its visibility. He demonstrated the detrimental effect of surface reflections on the measurement and recommended a wide shadow over the place where the observations were being made. He also made observations on the effect of the clearness of the sky, the color of the water and of the disc, and the height of the observer above the water.

His work established the experimental procedure for obtaining transparency with a Secchi disc, as it is now called. In the years following Secchi's work, the Secchi disc became a standard piece of equipment, but it was never really standardized. That is to say, it was used widely because of its simplicity but its physical properties were never fully specified nor was the method for its use. It is typical that the U.S. Hydrographic Office (1955) simply states that the Secchi disc "is covered with a flat white paint," but does not specify its reflectance.

Duntley (1952) published theoretical work that can be directly applied to the Secchi disc experiment. He gives the equation,

$$C_R = C_0 e^{-(\alpha + K\cos\theta)R}, \tag{1}$$

which describes the attenuation of the contrast of a submerged object along an inclined path of sight.

In this equation, C_0 is the inherent contrast of the object against its background, C_R is its apparent contrast as seen by an observer at some distance, R is the length of the path of sight and α and K are the attenuation coefficients for collimated and diffuse light.

Observation downward along a vertical path reduces equation (1) to

$$C_R = C_0 e^{-(\alpha + K)R}, \tag{2}$$

which is specific for Secchi disc observation.

A Secchi disc "reading" should therefore be simply a record of the object distance for the condition of liminal visual detection. It should be, in fact, the value of R in equation (2) for a value of C_R equal to liminal visual contrast. Liminal visual contrast for circular targets in air has been thoroughly investigated by Blackwell (1946) and data for a wide variety of lighting conditions are available in the literature. From a single Secchi disc reading, values for two of the unknowns in equation (2) can be obtained.

If, as suggested by Tyler (1960), the irradiance, H, is measured at two depths in the same water as the Secchi disc reading, then the value of K in equation (2) can be independently determined by means of the relationship

$$H_{Z_2} = H_{Z_1} e^{-K\Delta Z}, \tag{3}$$

and the value of C_0 in equation (2) can be estimated. For example, an irradiance H_0 falls on the water surface. Neglecting surface reflectance, the irradiance on the Secchi disc at depth Z will be

$$H_Z(-) = H_0 e^{-KZ}. \tag{4}$$

The radiant emittance of the Secchi disc will be $H_Z(-)\, r$ where r is its measured reflectance. The radiant emittance of the water background at the depth of the Secchi disc will be $H_Z(+)$ which can be obtained from the reflectance factor, $H_Z(+)/H_Z(-)$, for water, which for photopic band width usually has the value 0.02. Thus the radiant emittance of both the Secchi disc and its background (at depth Z) can be determined.

An observer does not, of course, see the full radiant emittance of an object since he can collect only that radiant flux that enters the solid angle defined by the pupil of his eye. If the same directional reflectance characteristic is assumed for both the target and the water background, then the inherent contrast of an object having reflectance r can be expressed as follows:

$$C_0 = \frac{H_Z(-)r/\pi - 0.02 H_Z(-)/\pi}{0.02 H_Z(-)/\pi} = \frac{r - 0.02}{0.02}, \tag{5}$$

where π simply indicates that both target and background are assumed to be Lambert emitters.

Callaway (1957), Callaway and McGary (1959), and Graham and Craig (1961) have published Secchi disc readings together with "photometer" data obtained simultaneously. It should be possible therefore to calculate independent values of the diffuse and total attenuation coefficients for the stations listed. For example, at each station of *Manning* Cruise 36 (Callaway and McGary 1959), a Secchi disc reading (R) in meters was obtained. From the estimated angular subtense of the submerged disc and the reported ambient light level, it can be found from the National Defense Research Committee (1946) smoothed tables based on Blackwell's (1946) data that C_R for these Secchi disc experiments would be 0.0066 after making a normal ($\times 2$) conversion from liminal detection to the threshold of conscious sighting.

To determine C_0 it is necessary to assume a reflectance for the Secchi disc because none is given. For convenience, a reflectance of 82% is assumed. C_0 is therefore,

$$C_0 = \frac{0.82 - 0.02}{0.02} = 40.$$

With these numbers, equation (2) can be reduced to

$$(\alpha + K) = \frac{8.69}{Z_{SD}}. \qquad (6)$$

The α and K coefficients in equation (6) will of course be average values for the water column through which the Secchi disc is observed. A comparable K coefficient from the photometer data should therefore be an average value of K for this same depth. In the *Manning* Cruise 36 (Callaway and McGary 1959), data depths at which 10% of the surface light was measured have about the same magnitude as the Secchi disc depths. Therefore, equation (3) can be reasonably rewritten as

$$K = \frac{2.3}{Z_{10\%}}. \qquad (7)$$

Equations (6) and (7) can be combined to give

$$\frac{3.78\,K}{(\alpha + K)} = \frac{Z_{SD}}{Z_{10\%}}. \qquad (8)$$

It will be remembered that α increases with the absorption coefficient and the

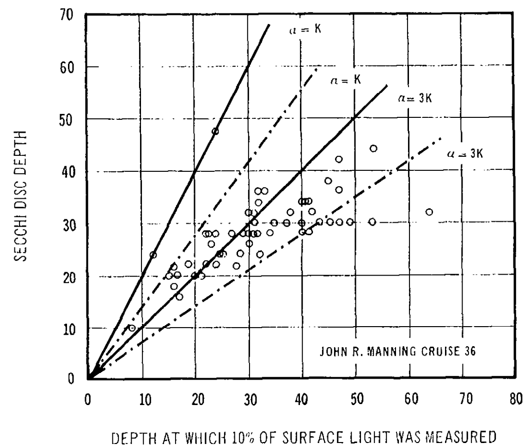

FIG. 1. Data from *Manning* Cruise 36. Solid straight lines represent plots of equation (8) for $C_R = 0.0066$ and values of $m = 1$ and $m = 3$ in the equation $\alpha = mK$. Dashed straight lines represent equation (8) for $C_R = 0.066$ and the same two values for m.

total scattering coefficient and that in a stable light field, K increases with the absorption coefficient and the back-scattering coefficient. For real ocean data at depths of 20 m or more, and for an α value that is always a fixed multiple of K, a plot of Z_{SD} vs. $Z_{10\%}$ would be a straight line through the origin.

In Fig. 1, I have plotted Secchi disc depth vs. the depth at which 10% of the surface light was measured. All data are from *Manning* Cruise 36. Superimposed on the graph are solid straight lines representing equation (8) for $\alpha = K$ and $\alpha = 3K$. The line for $\alpha = K$ is a real boundary, because K cannot be greater than α, whereas the line $\alpha = 3K$ is a presumed boundary for ocean water. It can be seen that these limits do not satisfactorily encompass the data.

Equation (8) is based on certain important assumptions, among them, that the observer's eyes were below the water surface. For an observer above the surface, the image of the Secchi disc is ordinarily fragmented by refraction effects caused by motion of the water surface. In addition there is always some reflected light from the water surface. Both of these effects will tend to reduce the visibility of the

Secchi disc when observation is from above the surface. Fig. 1 seems to be illustrating this fact.

The dashed straight lines in Fig. 1 have been computed in the same way as the solid lines, but it has been assumed that the apparent contrast of the Secchi disc at the recorded depth must have been 10 times larger (that is, $C_R = 0.066$) to compensate for the aforementioned reduction in visibility.

A factor of this size can be interpreted to mean that field conditions are exerting an undue influence on the Secchi disc experiment. This interpretation is supported by other features of the data. For example, *Manning* Cruise 32 (Callaway 1957) requires a significantly different value for C_R than does *Manning* Cruise 36 (Callaway and McGary 1959), and *Smith* Cruise 52 (Graham and Craig 1961) requires a value of C_R that is different from that for either of the *Manning* cruises. Also, although α will, to some extent, vary independently of K, it is highly unlikely that a constant Secchi disc reading of 30 m would be obtained over a range of K values from 0.074/m to 0.0435/m, as reported for *Manning* Cruise 36. Furthermore, it seems that the Secchi disc experiment must be suffering from uncontrolled variables when the scattering of the data points increases in spite of the precision with which the Secchi disc observations were made.

Graham (1966) has made a statistical analysis of selected data from these same three cruises. He plots "Secchi disc reciprocal" vs. "extinction coefficient," apparently in the belief that there is only one attenuation coefficient involved. The relationship between his chosen variables can be derived from equation (8) by simply rewriting it in the form

$$\frac{K}{Z_{SD}} = \frac{(\alpha + K)}{Z_{10\%}} \times \text{constant.} \qquad (9)$$

In real life α is not necessarily a fixed multiple of K, so there is no reason to expect a perfect correlation in either Graham's plots or in mine. If the data points were accurate, they would represent real variations in the optical properties of the ocean from point to point and it would be possible to determine the range of the ratio α/K.

TABLE 1. *Average photopic values of α and K for the total depth from the surface to the depth indicated*

Depth (m)	α/meter	K/meter
0		
5	0.1055	0.0991
10	0.0931	0.0875
15	0.0861	0.0800
20	0.0815	0.0748
25	0.0783	0.0708
30	0.0758	0.0679
35	0.0740	0.0653
40	0.0724	0.0633
45	0.0714	0.0616
50	0.0702	0.0598

A useful way of examining the data from the *Manning* and *Smith* cruises might be to determine the most probable value of C_R, which should be used in equation (2), and its range of variability. This could be done by experimentally establishing real limits for the factor m in the equation $\alpha = mK$. This range of m could then be plotted on the data in the form of two straight lines, as has been done in Fig. 1, but for a greater range of values for C_R. A plot of C_R vs. the number of data points encompassed by the range of m should then lead to a curve suitable for statistical analysis.

It might be of interest to examine here some aspects of the Secchi disc experiment that have not been given much attention in print. For example, under midday, sunny lighting conditions what would be the greatest depth at which one could expect to see a Secchi disc having 22 min angular subtense? To answer this question α and K values for the cleanest water available are necessary. Furthermore, the coefficients must be calculated for photopic band width since the Secchi disc is so observed. Table 1 gives photopic values of α and K. Each entry represents the coefficient for the whole water depth from the surface to the tabulated depth. The photopic K values were obtained from the data of Smith and Tyler (1967) by computing the spectral irradiance at the various depths, Z, from measured values of the spectral irradiance at the surface (H_0) and spectral values of K for Crater Lake (Smith and Tyler 1967). This was done by means of equation (10).

$$H_Z = H_0 e^{-KZ}. \qquad (10)$$

The relative total illuminance at each depth, E_Z, was then determined by the method shown in equation (11)

$$E_Z = \Sigma H_Z \bar{y} \Delta \lambda, \qquad (11)$$

where $\bar{y}$ is the visibility function of the human eye.

Average values of the photopic attenuation coefficient $K(\bar{y})$ were then computed by means of equation (12):

$$E_Z = E_0 e^{-K(\bar{y})Z}. \qquad (12)$$

The photopic α values were obtained similarly from Hulburt's (1945) spectral α values for distilled water after adjusting the latter to ensure that at every wavelength, K in Smith and Tyler (1967) was not larger than the appropriate α found by Hulburt (1945).

If the values of α and K for 50 m are used in equation (2) together with $C_0 = 40$, and $C_R = 0.0066$, the Secchi disc reading is $R = 67$ m.

It is well known from the measurements of Gilbert and Rue (1967) that the transmittance (and hence the α coefficient) of the upper 100 m of ocean water may differ greatly from that of the deeper water. Ordinarily the upper 100 m exhibits much lower transmission. The Secchi disc must therefore be accepted as an instrument that can give, at best, no more than average values of α and K and these only in the upper 70 m or less of the ocean, where the highest concentration of contamination will generally be found.

Secchi disc readings are usually obtained on the shadow side of the ship to avoid, insofar as possible, the undesirable effects of surface reflection. This objective is commendable, but the shadow side is also the side where the underwater shadow of the ship exists. A Secchi disc lowered from the shadow side will therefore be lowered right through the ship's underwater shadow. This can result in very large errors in the Secchi disc reading, making them quite useless for the determination of α or K. Furthermore, when Secchi disc readings are influenced in this way they cannot be accurately compared with one another.

There are many other problems associated with the Secchi disc experiment that must be solved or avoided if the Secchi disc is to yield useful information at sea. It is essential that the disc should remain horizontal, otherwise the lighting on its surface will not be correct. The supporting cord should remain vertical. If the disc is observed at some angle, rather than vertically, the angle of observation must be accurately known and equation (1) must be applied to the result. The white painted surface of the disc must be maintained at a known reflectance.

Perhaps most important of all, the practical value for C_R should be experimentally determined and the parameters affecting its value should be specified. This might best be done by a skin diver who would cast the smallest possible shadow on the water and who would be able to make his observations with the aid of a face mask while others on the ship made measurements of α and K with appropriate instrumentation. Of course, since the value of C_R is critically dependent on the condition of observation, all future Secchi disc readings, to be meaningful, would then have to be made by a skin diver.

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