Submerged reflectance measurements as a function of visible wavelength

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ABSTRACT

Submerged spectral reflectance measurements made on paint samples using two different techniques are compared. With the first technique spectral measurements are made with a simple thin water film measurement technique originally used for photopic viewing. A comparison of these measurements with a second technique in which the measured sample is immersed in water in a cylindrical container and the submerged reflectance is measured with a goniophotometer shows good agreement for wavelengths from 420 to 700 nm.

1. INTRODUCTION

Knowledge of the submerged reflectance of an object is necessary for determining its underwater visibility. The reflectance of an object's surface, when submerged, can be significantly different from its dry reflectance. In the early 1950's, S. Q. Duntley[1] developed a simple technique for measuring the submerged reflectance of a surface. This technique involved the measurement of the reflectance of a surface wetted with a thin film of water and the calculation of the submerged reflectance from the wetted surface reflectance. This technique is applicable for a sample irradiated at 45° and viewed at normal (0°) incidence. Duntley's work resulted in a semiempirical equation for converting the value of measured reflectance (the "wetted" reflectance) to submerged reflectance (for the water-object interface). This work was performed using a photopic optical filter to simulate the human eye response which has its peak sensitivity at 555 nm. It would be very useful to validate the use of Duntley's equation at other wavelengths in the visible region of the spectrum. This work compares the submerged reflectances of several painted samples at 20 nm intervals between 420-700 nm measured by the thin film technique with the direct technique involving an immersed sample. The reflectance used here is the "radiance factor" which is defined as the ratio of the reflected radiance of the sample in a specific direction to the radiance of a perfectly reflecting Lambertian diffuser identically irradiated.

2. SUBMERGED REFLECTANCE MEASUREMENT TECHNIQUES

2.1 Duntley's thin film technique

This section describes the thin film technique for measuring submerged reflectance both with a photopic filter and multispectrally.

2.1.1 Thin film technique with photopic filter

In Duntley's technique the sample is wetted with a thin film of water; the measurement is not sensitive to the thin film thickness. The wetted sample is irradiated at 45° and viewed at normal incidence (0°) as shown in Fig. 1. Because of refraction of the light at the air-water interface, the angle of incidence at the water-object interface becomes 32°. This work resulted in a semiempirical equation for converting the value of measured reflectance (the "wetted" reflectance) to submerged reflectance (for the water-object interface),

$$R_s(32,0)=\frac{R_w}{0.420R_w+0.564} \tag{1}$$

0-8194-0665-1/91/$4.00

where $R_s(32,0)$ is the submerged reflectance for an incidence angle of 32° and 0° viewing,
and R_w is the measured (wetted) reflectance in decimal form, i.e., 10% is written as 0.10.

Detailed work measuring submerged reflectance directly in a tank has been done by Petzold and Austin[2] to substantiate this equation and no need was found to change either its form or the values of the constants. The above works of Duntley and Petzold and Austin were performed using a photopic optical filter to simulate the human eye response which has its peak sensitivity at 555 nm.

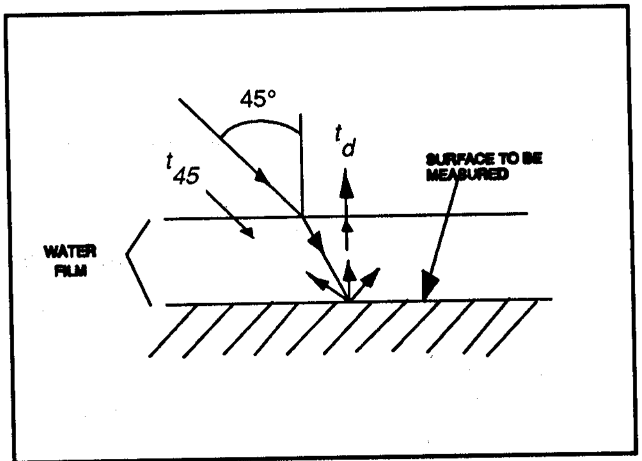

Fig. 1. Geometry of reflectance measurement

2.1.2 Multispectral thin film measurement considerations

As shown in reference 2, prior to obtaining equation 1, one derives

$$R_s(32,0) = \frac{R_w}{r_d R_w + t_{45} t_d} \tag{2}$$

where $R_s(32,0)$ and R_w are as defined in equation (1) and t_d and r_d are the effective emergent transmission (as shown in Fig. 1) and effective emergent reflectance respectively for which $t_d + r_d = 1$. Equation (1) is semiempirical because it depends on the experimental measurement of the effective emergent transmittance of light which has been reflected from the measured surface through the water film-air interface. (For a discussion of effective emergent transmission and reflectance, see reference 3.) Duntley's measured value of t_d was 0.580. The quantity t_{45} for the transmission of incident light at the air-water interface (as shown in Fig. 1) was computed using Fresnel's equation with a water index of 1.333. The quantities t_d, r_d and t_{45} are dependent on the water index. However the index of fresh water varies only from 1.343 for 400 nm to 1.330 for 700 nm[4] and it is estimated that the maximum error in the submerged reflectance value introduced by using equation (1) at wavelengths other than 555 nm is less than two percent. Because of this small estimated error, it was considered acceptable to use equation (1) to determine submerged reflectance from wetted reflectances measured at all wavelengths in the visible spectrum.

2.1.3 Multispectral thin film measurement instrument

The multispectral wetted reflectances, R_w were measured with a Macbeth *2025+* spectrophotometer. A schematic for this instrument is shown in Figure 2. This 45°/0° instrument operates as follows. The irradiance on the sample is provided from an annular ring that illuminates the sample at 45° with a spot diameter of 20 mm. The reflected light is collected normal to the sample. The light received from the sample is focused onto a fiber optics bundle that carries it to the entrance slit of a spectral analyzer. The collimating lens directs light from the entrance slit onto a diffraction grating, which diffracts the light in the direction of the integrating lens. This lens images the visible spectrum (400 to 700 nm) onto a linear array of 16 silicon photodiodes. These photodiodes simultaneously measure 16 channels spaced at 20-nm intervals, each with a FWHM of 16 nm. The signals derived from the detectors are processed in parallel; each channel is amplified and digitized. Once in digital form, the data are transferred to the microprocessor, processed, and sent to an IBM-compatible computer. The absolute accuracy of the submerged reflectance measurements is estimated to be a few percent of the measured value.

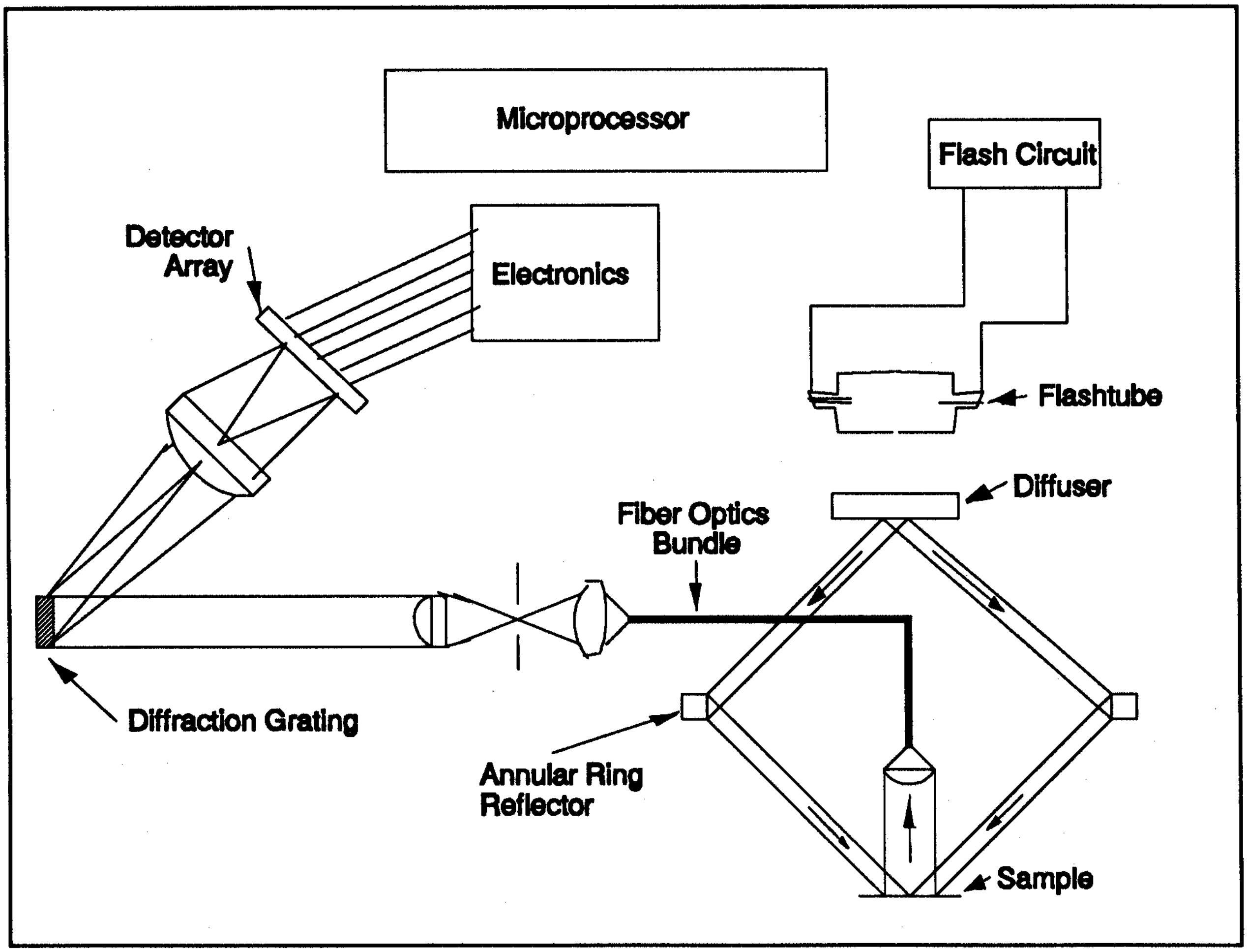

Figure 2. Macbeth 45°/0° Spectrophotometer.

2.2 Direct Submerged Reflectance Measurements

Direct submerged reflectance measurements were also made for the (32,0) geometry with the sample plaques using a goniophotometer manufactured by Gardner Laboratory, Inc.

2.2.1 Description of Goniometer

The Gardner goniometer shown in Figure 3 was modified in several ways. The samples were mounted in the center of a glass cylinder filled with distilled water. The original detector was replaced with a radiometer manufactured by Research Support Instruments, Inc. (RSI) which has a grating monochromator and a photomultiplier detector allowing narrow band spectral measurements of the reflectance to be made. The size of the illuminating spot on the sample was approximately 5 mm in diameter.

2.2.2 Calibration of instrument and corrections to data

The goniometer was calibrated with a dry, pressed white $BaSO_4$ plaque, the reflectance of which was measured with a portable reflectometer in three wavelength regions over the visible spectrum. The submerged

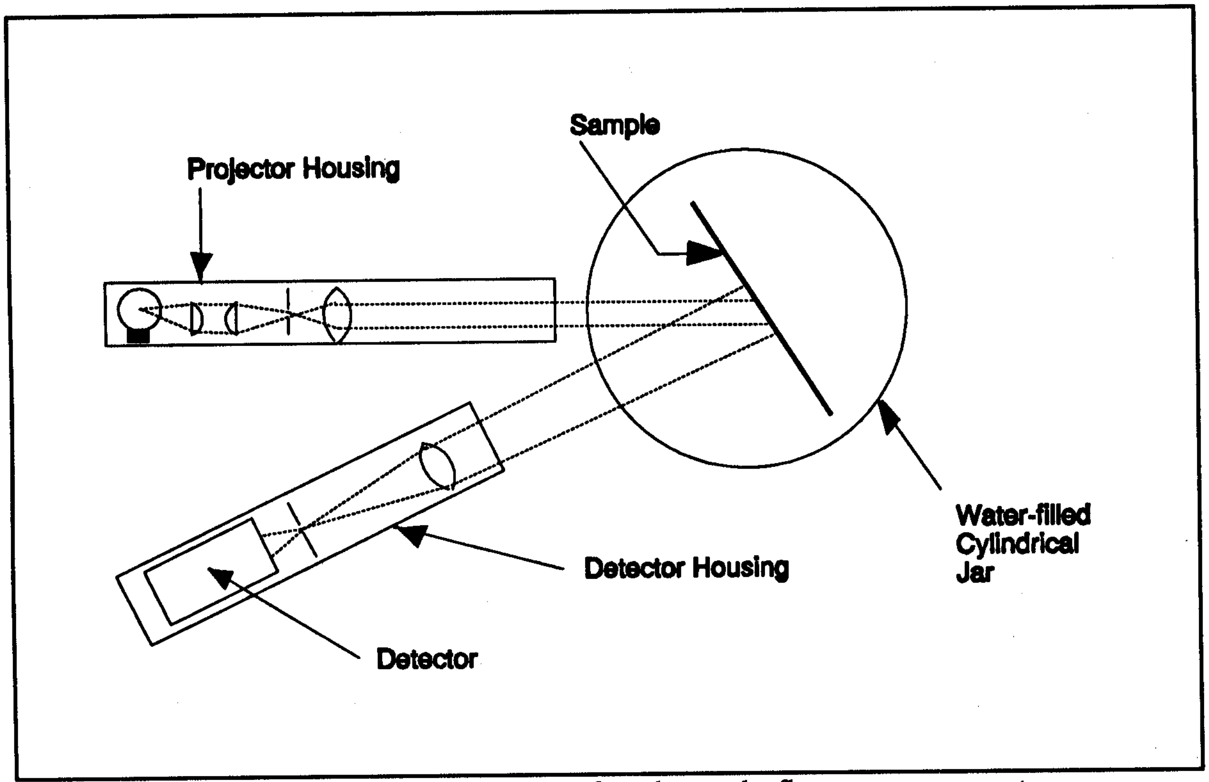

Figure 3. Gardner goniophotometer for submerged reflectance measurements

measurements were corrected for the differences introduced by the measurement of the paint samples in water as compared with the $BaSO_4$ plaque in air. These corrections consisted of three parts as discussed below.

a) *Correction to solid angle*: For the standard, there is no modification of the solid angle of the radiance at the glass cylinder interface, since both the sample and the photometer are in air. For the paint samples, the solid angle is modified due to refraction at the glass-water interface reducing the solid angle of reflected radiance from the sample which is viewed by the photometer. With a cylindrical geometry, the reduction in solid angle is proportional to the index of refraction of water.

b) *Correction due to air-glass and water-glass interface*: The air-glass and water-glass interfaces have different Fresnel transmission coefficients resulting in a transmission factor of $(T_{w\text{-}gl}/T_{a\text{-}gl})^2$ = 1.07 for n_w=1.33, n_{gl}=1.48, and n_a=1.00.

c) *Correction due to water transmission*: The samples were submerged in distilled water with transmission losses due primarily to absorption. The upper limit for the transmission factor for our path length of about 20 cm can be estimated using the absorption coefficients for clearest ocean water of Smith and Baker[5]. These coefficients are shown in Table 1 which is shown and discussed below.

Corrections b and c above are shown in Table 1. The first column shows the wavelengths. The second column shows the absorption coefficients taken from ref. 5. The third column labeled "Ta" is the transmission through the water after considering the effect of the water absorption coefficient. Factors b and c above can be included together into a "transmission" factor. The calculated values for this factor are shown in column 4. An experimentally determined "transmission" factor was also measured by looking straight through the sample chamber with and without water. This factor is shown in column 5 under the heading of "Texp" and agrees with the theoretically determined "transmission" factor within several percent. The experimentally determined "transmission" factors were used for correcting the data.

TABLE 1. Transmission factors for direct measurement of submerged reflectance.

Wavelength (nm)	a (m^{-1})	Ta	$(Tw\text{-}gl/Ta\text{-}gl)^{2}*Ta$	Texp
450	0.0145	1.00	1.07	1.05
500	0.0257	0.99	1.06	1.06
550	0.0638	0.99	1.06	1.06
600	0.244	0.95	1.02	1.03
650	0.349	0.93	1.00	1.01
700	0.650	0.88	0.94	0.93
750	2.47	0.61	0.65	0.61

3. SUBMERGED REFLECTANCE MEASUREMENT RESULTS

Reflectance measurements using the two techniques were made on 14 painted plaques which varied in submerged reflectance values from less than one percent to about six percent. The agreement in the reflectance values was generally very good for wavelengths of 420 to 700 nm for all the plaques. The greatest discrepancy was about 10 percent of the measured value (for a reflectance value of about 2%) which occurred at some wavelengths for one sample. The other thirteen samples had a discrepancy of about 4 percent or less of the measured values at a particular wavelength for reflectance values which varied from about 0.9 percent reflectance to about 6 percent. Comparisons are shown for three of the samples in Figures 4, 5, and 6. Goniometer measurements and thin film measurements made on two separate days show the good repeatability of the measurements; these plots also show the good agreement of the 4 measurements. For all 14 of the samples, the goniometer reflectance value at 400 nm was significantly less than the thin film value. However the source flux at 400 nm in the goniometer measurement was weak and the measurement at that wavelength not considered reliable; therefore a comparison of the two methods at 400 nm is not shown in the plots.

Thus the validity of using the much simpler thin film technique for the measuring the spectral submerged reflectance from 420 to 700 nm for an angular configuration of (32,0) in the low reflectance region of these 14 samples is verified.

4. ACKNOWLEDGEMENTS

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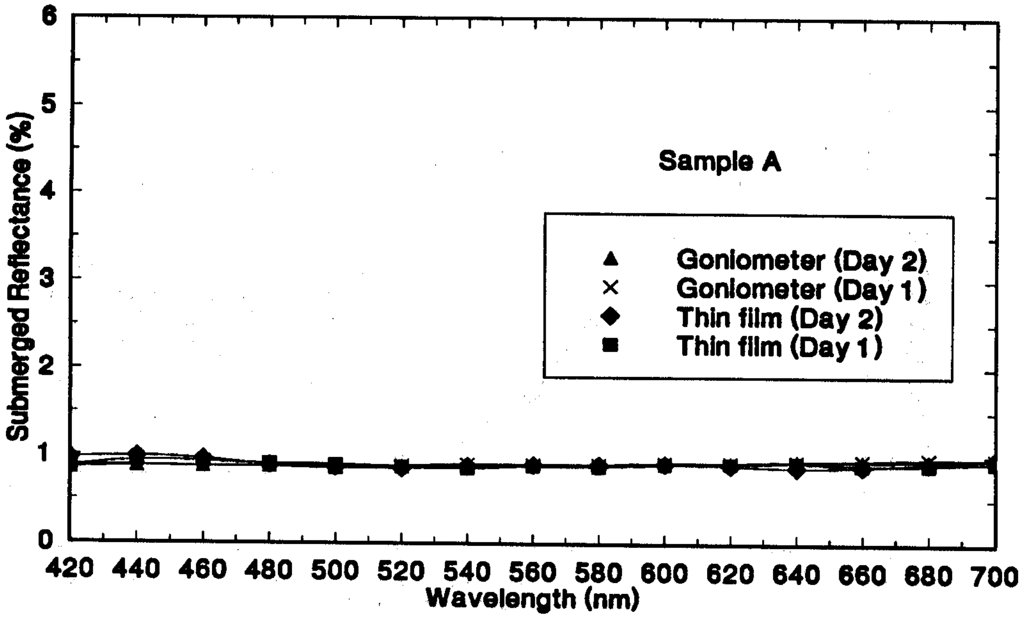

Fig. 4. Submerged reflectance values of sample A

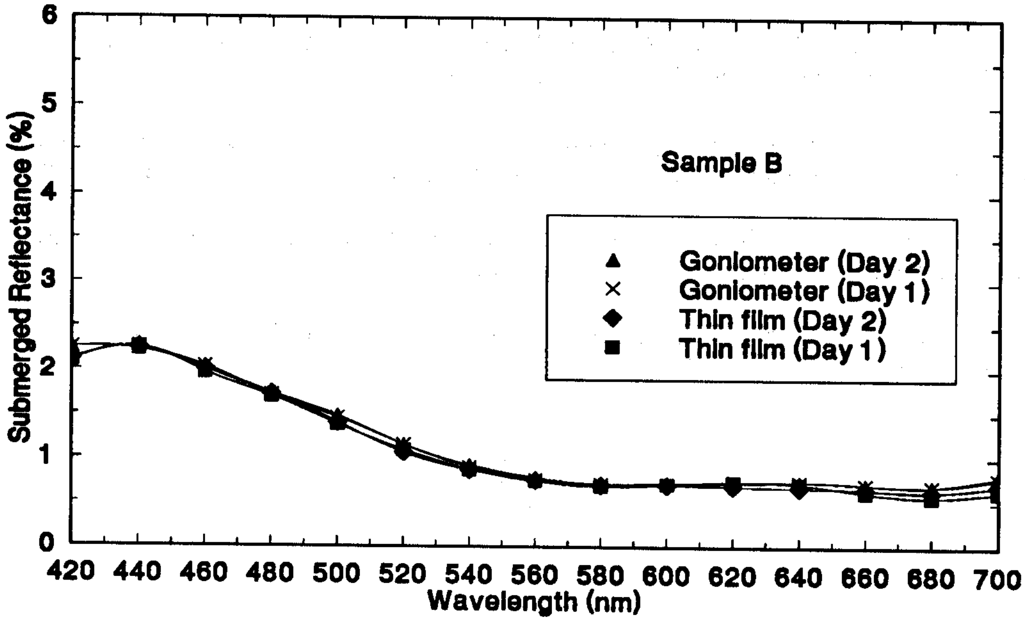

Fig. 5. Submerged reflectance values of sample B.

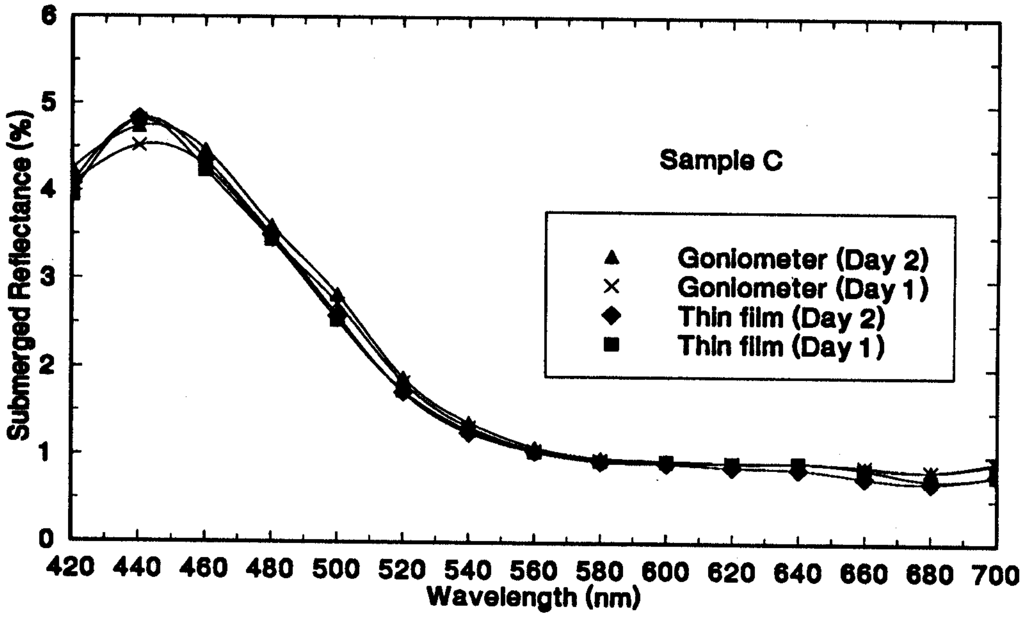

Fig. 6. Submerged reflectance value for sample C

5. REFERENCES

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