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SUBMERGED REFLECTANCE

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Techniques for the determination of the submerged reflectance of painted surfaces are described. Absolute reflectance values were obtained of sample surfaces immersed in a large tank. The values were then transferred to laboratory instruments as calibration standards. The several measurement procedures and equipments are described. The technique for determining submerged reflectance from the measurement of a wetted surface is presented and experimental validation given.

1.0 Introduction

The study of submerged reflectance which is described below was undertaken as a part of a program supported by the Naval Ships System Command under Contract N00024-68-C-1100. The statement of work of this contract provided that the Visibility Laboratory of the Scripps Institution of Oceanography undertake special optical tasks "in the fields of visibility, concealment, detection and electro-optical devices."

The visibility of a submerged object is determined by the contrast between the luminance produced by the object and the luminance of the surrounding background. Contrast in this context is defined as

$$C = \frac{B_t - B_o}{B_o}$$

where B_t = the luminance of the target or object under observation

and B_o = the luminance of the background.

The luminance of an object may be exactly determined from a knowledge of the angular distribution of the luminance incident on the surface of the object and the complete specification of the bi-directional reflectance properties of the surface. To use such a procedure to determine the object luminance would be ponderous and, in most cases, unnecessarily cumbersome even if one could acquire the requisite angular distribution of luminance and reflectance. Underwater, the angular distribution of the light field is fairly well behaved and can be determined from a knowledge of the solar zenith angle, the depth of the object, and the scattering and absorption properties of the water. The collimated component of the light field due to sunlight is effectively converted to diffuse light by scattering in the water within a few tens of meters of the surface in the clearest ocean water and in a few meters in the more turbid coastal waters. The angular distribution of the diffuse light field is sharply peaked in the direction of the sun and is a minimum at the nadir. The ratio of the maximum to the minimum luminances may be 4000 to one at a depth of 10 meters in moderately turbid water. Thus the luminance of the background against which an object is observed, as well as the manner in which the object is illuminated, is affected in a major way by the direction of observation.

In the design of painting schemes to minimize the detectability or contrast of a submerged object, the reflectance of the paint would, ideally, vary with the orientation of the surface with respect to the sun and the vertical. Unless a paint with an adaptive reflectance ("chameleon" paint) could be devised, it is necessary to compromise the reflectance specification such that reflectance varies with the orientation of the surface with respect to the vertical and accept the change in contrast encountered as the sun changes its position with respect to the surfaces involved. Nature has also made such a compromise in some fishes which have a very low reflectance when viewed from above and are essentially white when viewed from below with intermediate reflectances between. Such a reflectance distribution does not assure optimum concealment under all conditions but does minimize, on the average, the contrast of the fish as viewed by predators approaching from a variety of directions.

It is not currently possible to devise paints which have either adaptive reflectances or the bi-directional reflectance properties required to match the background luminance for all paths of sight, thereby providing a universal zero contrast object. If the problem is made less general and a particular viewing situation is considered, the requirements for minimizing the contrast of an object may be met satisfactorily for a useful range of lighting and water conditions.

One such viewing situation which embraces a large class of important problems consists of viewing a submerged object from above the ocean surface. Because of the refraction and reflection of light at the ocean surface, we are concerned only with light approaching the surface with angles less than about 45° from the vertical. Additionally, the reflectance of the surface as seen from above also increases rapidly as the angle of view exceeds 70° from the nadir (i.e., for paths of sight from 20° below the horizon to the horizontal), and the reflected skylight further reduces the observer's ability to detect objects below the surface. As 70° in air becomes 45° (approximately) after refraction at the water surface, we find we are concerned only with the appearance, i.e. contrast, of the object in the upper 45° cone underwater. Similarly, most of the illumination on the object comes from this same 45° cone. We have, therefore, circumscribed the range of bi-directional reflectances which will be of concern. A further consideration is that the observer can never effectively see below the surface by looking into the solar glitter pattern since the reflected luminance of the sun by the wind-roughened surface completely masks the signal from below. This consideration means, for example, that the gloss characteristics of horizontal surfaces are essentially unimportant since a specular return from a truly horizontal surface that has the proper reflectance for other illumination and viewing situations would be lost in the sun glitter. The gloss characteristics of non-horizontal surfaces, however, is a matter of major concern. Further discussion of these considerations is given in Section 4.2.

We have implied above that the reflectance of a surface is a function of the angles of illumination and view and cannot, therefore, be completely described by a single value. There are a number of types of reflectances which are commonly used which, although less general than the complete bi-directional reflectance of function, do provide useful single values. One example is the reflectance obtained when the object is illuminated at 45° and viewed at 0° (i.e., viewed normal to the surface). Instruments for performing this particular bi-directional reflectance measurement are available commercially, and the procedures for their use are well documented. This reflectance, denoted R(0°, 45°) is generally useful for determining the appearance of surfaces, and it is particularly pertinent to the problem of determining the contrast of submerged horizontal surfaces against the surrounding water background.

The bi-directional reflectance used in this report is more precisely a bi-directional luminance factor, i.e., the value is the

the ratio of luminance of the surface to the luminance of a perfect diffuser when identically illuminated. The concept is important since it explains the otherwise difficult notion that reflectances may be greater than unity. This usually occurs in the vicinity of the direction of specular reflection (i.e., when the angle of reflection is equal and opposite the angle of illumination), particularly as the angles become large. For surfaces having moderate gloss, the reflectances can easily exceed that of a perfect diffuse reflector by factors of four or five in the region of specularity and yet have an $R(0°, 45°)$ of only a few percent.

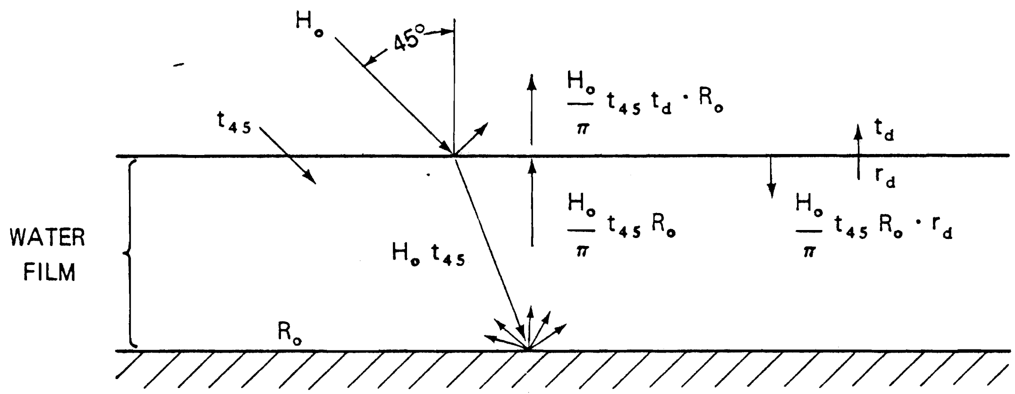
The reflectance of a surface when submerged can be significantly different from its reflectance in air. Moreover, there is no unique relationship between these two reflectances. Some low reflectance surfaces will have a higher dry than submerged reflectance, while others will be the reverse. Major factors in the nature of this change are the index of refraction of the vehicle or resin used in the paint, the type of pigment, and the degree of surface gloss. Since the submerged reflectance of a surface is central to the determination of the contrast a submerged object will have against its background, the validity of the method of measuring submerged reflectances is of paramount importance. Duntley (1952) described a method whereby the surface in question could be wetted with a thin film of water and a measurement of the wet reflectance, $R_W(0°, 45°)$, performed with standard reflectance measuring instruments. A simple relationship was then used to compute submerged reflectance, $R_O(0°, 32°)$, using the value of R_W. As new paints and new measuring instruments were to be used in the study reported here, there was strong motivation to perform basic reflectance determinations underwater and validate the earlier procedure for present circumstances. Further, the Duntley method provides only the one reflectance value and does not provide the required angular reflectance values. The equipment devised for the absolute submerged reflectance measurements was designed to allow the measurements to be made over a large range of angles of incidence and view so that the complete angular characteristics of the reflectance function could be obtained. These measurements were performed in an outdoor tank. A commercial laboratory instrument built for performing such measurements in air was modified to allow paint samples to be immersed in water, and angular submerged reflectance measurements were than possible in the laboratory using standards calibrated in the outdoor tank.

The units used in the remainder of the report are radiometric rather than photometric, but this results in no loss of generality. Thus the use of irradiance (symbol H) can be equated conceptually to illuminance, E, and radiance, N, is equivalent for this development to luminance, B. The reflectance values were all obtained using physical photometers having a quasi-photopic response.

2. THE DETERMINATION OF THE SUBMERGED REFLECTANCE FROM THE MEASURED REFLECTANCE OF A WETTED SURFACE

A technique for determining submerged reflectance, R_0 using any conventional reflectometer which irradiates the sample at 45° and views it normally was developed by Duntley and described in the report "The Visibility of Submerged Objects," Visibility Laboratory, Massachusetts Institute of Technology, August 1952. The analysis which follows has been slightly modified to use the nomenclature of this report and will review the development for those not familiar with the earlier work. The technique involves wetting the sample and measuring it while the surface is covered by a thin film of water.

Consider a wet surface being irradiated with an irradiance H_0 at an angle of 45°.



The irradiance arriving at the reflecting surface will be $H_0 t_{45}$ where t_{45} is the transmittance of the air-water interface at 45°, and the transmittance of the thin film of water is considered to be 1.0. If R_0 is the submerged reflectance, a radiance, $H_0 t_{45} R_0/\pi$, will be reflected back toward the air-water interface, equal in all directions assuming that the submerged surface is a lambertian or completely diffuse reflector. Now a radiance

$$\frac{H_0}{\pi} \cdot t_{45} \cdot t_d \cdot R_0$$

will exit from the surface where t_d is the transmittance of the water film.

A portion, $\frac{H_0}{\pi} t_{45} R_0 r_d$, will be reflected back from the interface where r_d is is the emergent reflectance and $r_d + t_d = 1$. This portion returns to the painted surface and a part of it is in turn reflected back toward the air-water interface. Thus an infinite series of inter-reflections occurs and the emergent radiance may be shown to be

$$N = \frac{H_o}{\pi} t_{45} \frac{t_d R_o}{(1-r_d R_o)} .$$

The apparent reflectance, R_w, of the wet surface as measured by the reflectometer will be

$$R_w = \frac{t_{45} t_d R_o}{1-r_d R_o}$$

Solving for R_o gives

$$R_o = \frac{R_w}{r_d R_w + t_{45} t_d} \qquad (2\text{-}1)$$

The value $t_{45} = 0.9719$ is computed by means of Fresnel's equation for reflectance with a water of index 1.333. The values $t_d = 0.580$ and thus $r_d = 0.420$ were determined experimentally by Duntley by making direct measurements of R_o and R_w and computing these values with the aid of (2-1).

The flux being reflected from the surface during the inter-reflections is not all arriving at 45° and leaving at 0° and using R_o in the terms of the series used to derive (2-1) is an approximation. The terms t_d and r_d are the effective emergent transmittance and emergent reflectance respectively which apply to the geometry of this measurement. However, the relationship between R_o and R_w would appear to be of the form of (2-1) and empirical determination of r_d and t_d give the working relationship

$$R_o = \frac{R_w}{0.420\ R_w + 0.564} . \qquad (2\text{-}2)$$

Recent work at the Laboratory (See Section 3) has substantiated equation (2-2) and has shown no need to change either its form or value of the constants.

3. ABSOLUTE MEASUREMENT OF SUBMERGED REFLECTANCE

The determination or the knowledge of the submerged reflectance characteristics of painted surfaces is critical to the engineering calculation of the visibility of many man-made submerged objects. Because of this importance a method was developed which could be used to make a series of absolute submerged reflectance measurements. The goal was to obtain a set of reference standards of submerged reflectance and to verify, using paints and equipment currently available, the method conceived by Duntley of making reflectance measurements in air on wetted surfaces from which the submerged reflectance could be computed. This work was performed in an outdoor test tank at the Visibility Laboratory. The techniques used and the results are described below.

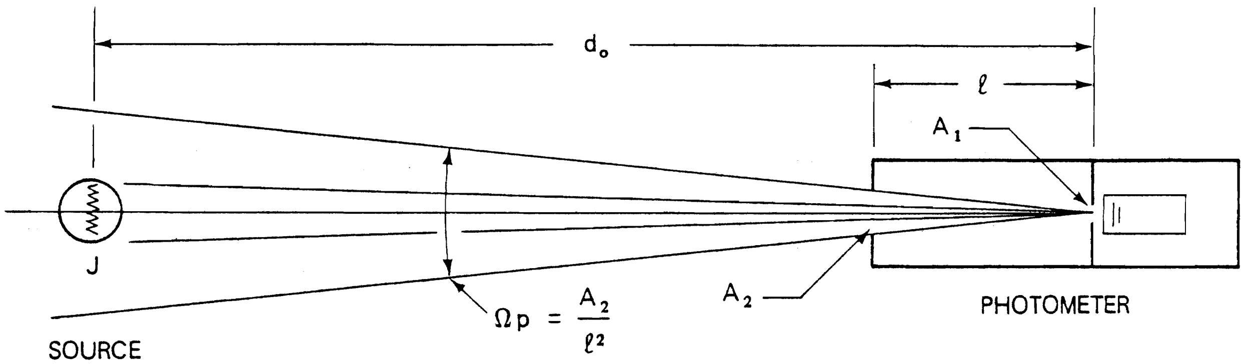
3.1 THEORY OF ABSOLUTE SUBMERGED REFLECTANCE MEASUREMENT

An absolute measurement of the reflectance of a surface can be obtained by making two relative measurements. One measurement is of the relative irradiance received from a light source at a known distance and the second measurement is of the relative radiance received from the reflecting surface when it is illuminated by the same source placed at a known distance. If this procedure is used, it is not necessary to have a photometer with an absolute calibration. It is only necessary to know the relative response of the photometer and to know that the photometer and the light source remain stable over the period of the two measurements.

In some circumstances it is possible to adjust the distance between the surface and the lamp to obtain identical photometer response for both measurements, in which case no calibration is required for the photometer and it need only be stable.

A photometer with an entrance aperture of area A, and field of view of solid angle Ω_p is used for both measurements.

For the first measurement the lamp is placed in front of the photometer on axis within the field of view at distance d_0. See Figure 1.



RELATIVE LAMP OUTPUT MEASUREMENT
Figure 1

The relative response, F_1, of the photometer to a lamp of radiant intensity J, assuming a linear response for the photometer, will be

$$F_1 = CP_1 = CJ \frac{A_1}{d_0^{\ 2}} \quad . \qquad (3\text{-}1)$$

P_1 is the power arriving over Area A_1 and the constant, C, is determined by the efficiency of the optical system of the photometer, the gain of the photometer electronics, the units used, the spectral response of the photometer, and the spectral output (color temperature) of the source.

The geometry used for the relative reflectance measurement is shown in Figure 2.

The irradiance across the target will vary within the field of view of the photometer because of the angle Θ_i. This effect can be kept small by keeping the distance d_1 large relative to the area on the target seen by the photometer. The photometer responds to the integrated average over the total area and this average is nearly identical to the irradiance at the midpoint, well within the precision of the measurement. With this in mind, the mean irradiance arriving at the target is

$$H = \frac{J \cos \Theta_i}{d_1^{\ 2}} \quad .$$

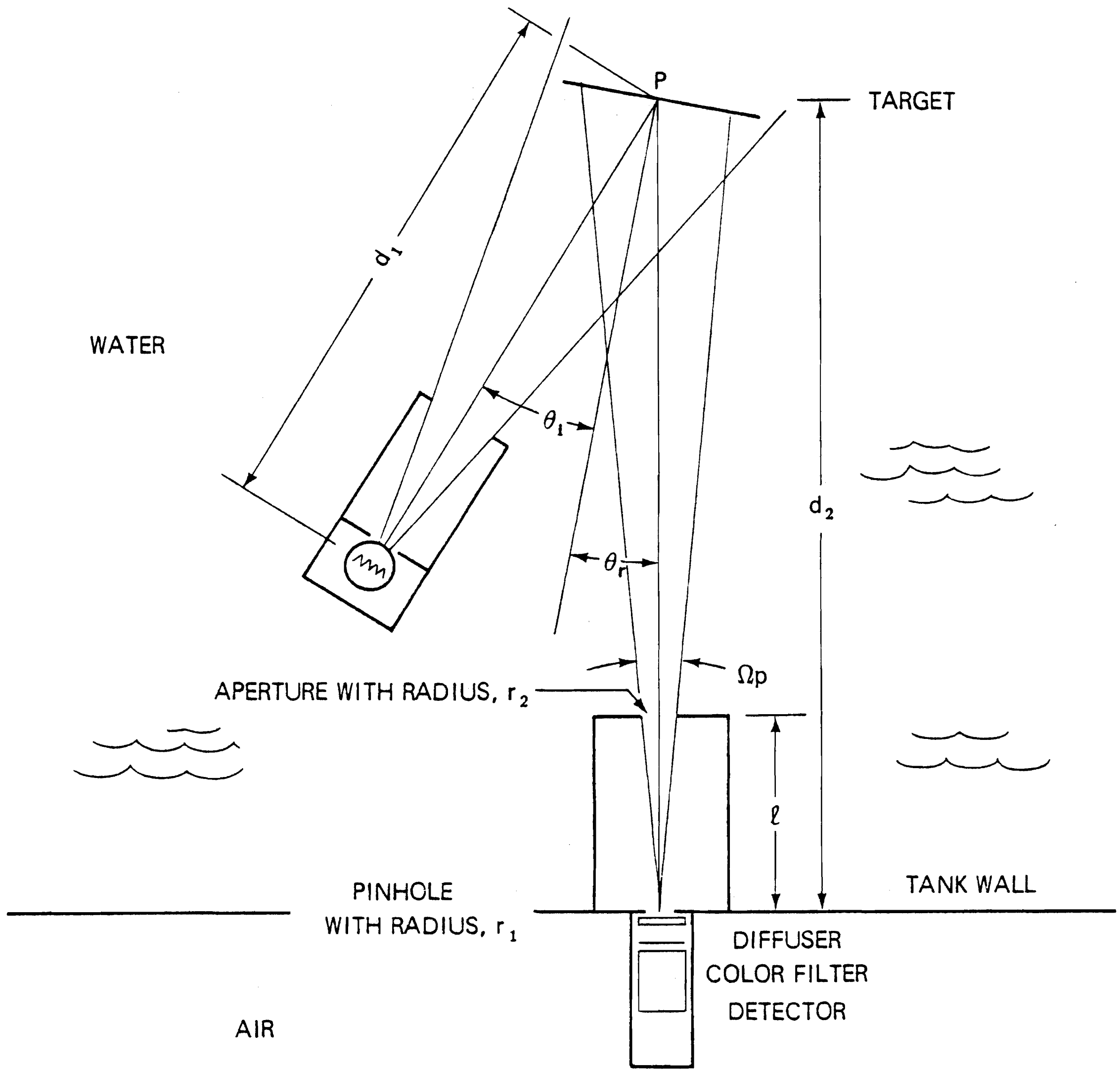
The radiance of the target in the direction of the photometer will be

$$N = R(\Theta_i,\Theta_r)\ \frac{H}{\pi}\ ,$$

where $R(\Theta_i,\Theta_r)$ is the directional reflectance at angle, Θ_r, with incident illumination at angle, Θ_i. (See Section 3.4 for further discussion.)

The field of view of the photometer used was limited by the use of two stops. One stop determines the field of view and has area A_2 and radius r_2 and a pinhole with Area A_1 and radius r_1 separated by a distance ℓ. The solid angle of acceptance for every point on the pinhole is then

$$\Omega_p = \frac{A_2}{\ell^2}\ \text{steradians.}$$



GEOMETRY USED FOR REFLECTANCE MEASUREMENT
Figure 2

The relative response of the photometer, F , will then be

$$F_2 = CP_2$$
$$= C \cdot N \cdot \Omega_p \cdot A_1 \quad ,$$

Where P_2 is the power arriving over the area of the pinhole A_1, and C is a constant of proportionality and is the same constant that appears in (3-1).

It follows that

$$F_2 = C \cdot R(\Theta_i,\Theta_r) \cdot \frac{H}{\pi} \cdot \Omega_p \cdot A_1$$

$$F_2 = C \cdot R(\Theta_i,\Theta_r) \frac{J \cdot \Omega_p \cdot A_1 \cdot \cos \Theta_i}{\pi d_1{}^2} \quad . \qquad (3\text{-}2)$$

From (3-1) we can write

$$J = \frac{F_1 \, d_0{}^2}{C \, A_1}$$

and since $\Omega = A_2/\ell^2 = \pi r_2{}^2/\ell^2$.

$$F_2 = R(\Theta_i,\Theta_r) \cdot F_1 \cdot \left(\frac{d_0}{d_1}\right)^2 \cdot \left(\frac{r_2}{\ell}\right)^2 \cdot \cos \Theta_i \ .$$

Solving for $R(\Theta_i,\Theta_r)$ gives

$$R(\Theta_i,\Theta_r) = \frac{F_2}{F_1} \cdot \left(\frac{d_1}{d_0}\right)^2 \cdot \left(\frac{\ell}{r_2}\right)^2 \cdot \frac{1}{\cos \Theta_i} \quad . \qquad (3\text{-}3)$$

3.2 TECHNIQUES USED

The development given in Section 3.1 is the basis used for the submerged reflectance measurements. The measurements were made with the equipment in water.

It can be seen by examining (3-3) that the dimensions ℓ and r_2 and the distances d_0 and d_1 can be selected so that $F_2=F_1$ for any reflectance value. That is if ℓ and r_2 are fixed and a reading for the reflectance measurement of the photometer F_2 is taken at a distance d_1 then a distance d_0 can be found for the lamp power measurement where $F_1=F_2$. If this is done, the photometer is used only as a "memory" device and does not need to be linear or have a relative calibration but only be stable. For example, if $\ell=20r_2$ and with the target normal to the projector axis, i.e., $\cos \Theta_i=1$, then

$$\frac{d_0}{d_1} = \left(\frac{1}{R_{\Theta_r}} \cdot \frac{F_2}{F_1}\right)^{1/2} \cdot \frac{\ell}{r_2}$$

and for F_1 equal to F_2, $\frac{d_0}{d_1} = \frac{20}{(R_{\Theta_r})^{1/2}}$. For $R_{\Theta_r} = 1.0$, $d_0= 20\ d_1$ and for $R_\Theta = 0.01$, $d_0 = 200\ d_1$. This is a desirable way to make the reflectance measurement since it eliminates one source of error, the linearity or calibration of the photometer. This method was applied, using a photometric bar, to obtain "wet" reflectance values to compare with measured submerged reflectance values but could not be used to make the submerged reflectance measurements because of the limitations imposed by the tank dimensions.

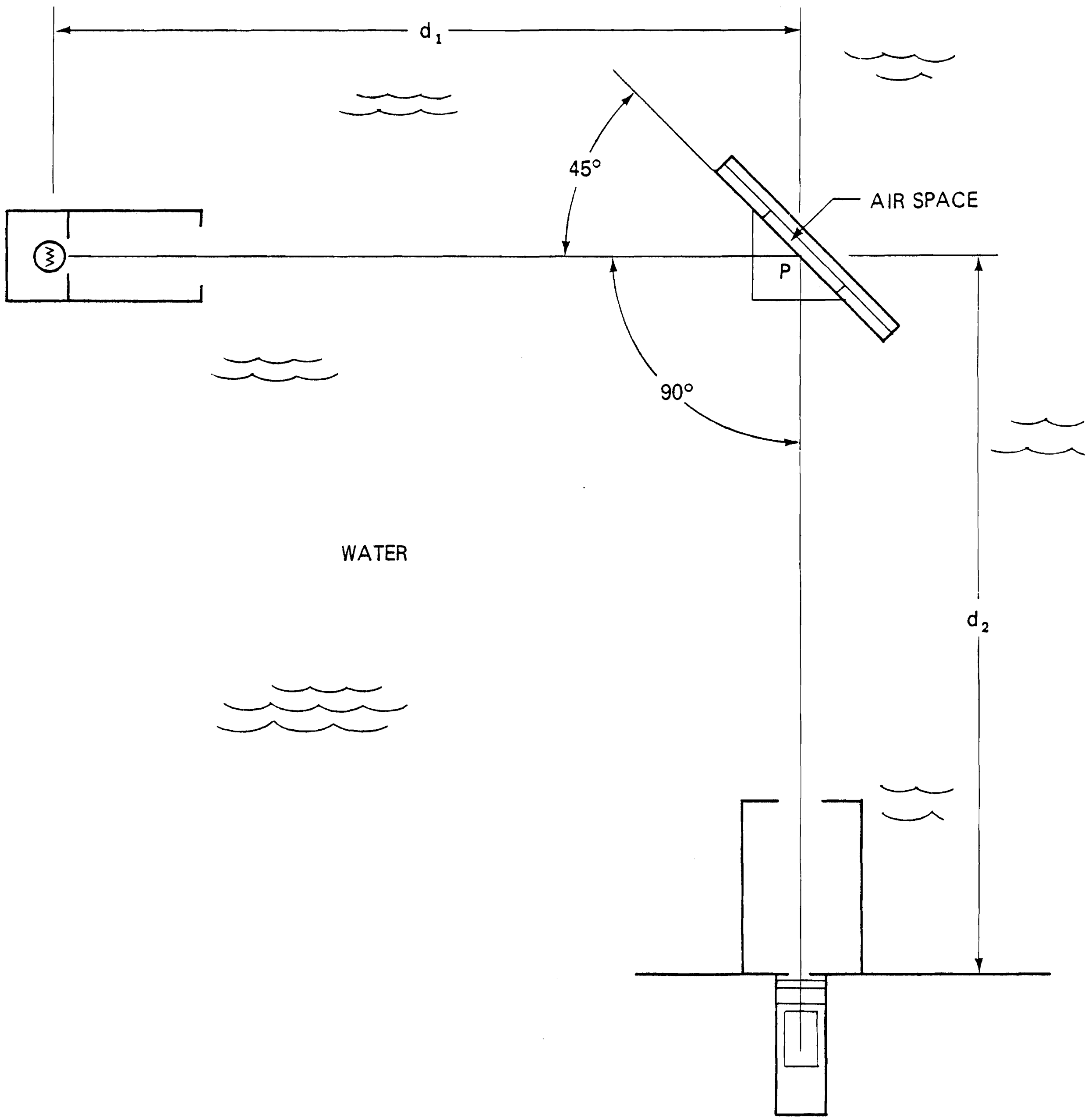
Because of the dimensions of the tank, $\frac{F_2}{F_1} \approx \frac{R_\Theta}{90}$. This required that the photometer have a dynamic range of 10^4 with a resolution of one in 10^5 if meaningful measurements of low reflectance paints were to be obtained.

The source used was a 500 watt projection lamp enclosed in a metal housing behind a baffle system. When submerged, water filled the baffle system and lamp enclosure. The baffles restricted the illumination to the target area which reduced the amount of illuminated water volume to keep light scattered from the water and reaching the photometer to a minimum. The projector was mounted on a swinging arm which pivoted about point "P", see Figure 2, and had an azimuth angle readout dial above a light-tight cover over the tank. The targets were mounted so they could be rotated about a vertical axis through their front surface and point "P", and an angular position dial above the cover indicated target position. A regulator was used to power the lamp and the voltage and current were monitored during all tests. The photometer was installed in a porthole available in the side of the tank. Water filled the aperture system and a diffuser behind the pinhole served as a barrier between the water and the phototube with its electronics. A photomultiplier tube with spectral filtering to obtain photopic response was used. The photometer was calibrated for linearity on a photometric bar. The output of the photometer was read with a precision differential voltmeter.

The tank was covered and sealed so that the photometer saw no ambient light with the light source turned off. The angle of illumination, Θ_i, and the viewing angle, Θ_r, could be readily changed by use of the azimuth dials without opening the tank. The dials were set accurately by using a mirror and a right angle prism at the target position to set the o° or 90° point on a machine engraved dial.

3.2.1 MEASUREMENT OF RELATIVE SOURCE OUTPUT

The relative measurement of the source output was obtained by placing the lamp on axis some distance d_0 in front of the photometer. The dynamic range the photometer must cover was lessened by making d_0 large. Since the measurement was made in water, the path length obtainable was limited by the tank dimensions. To increase the path length and also to facilitate change-over from the lamp-power-measurement to the reflectance-measurement mode, the path was folded at point "P" in the target plane. This was accomplished by placing a large right angle prism with its hypotenuse at 45° in the target plane and placing the projector at 90° to the photometer axis as shown in Figure 3. A fixture was made which could mount in place of the targets and properly position the prism. The surfaces of the prism were uncoated and the hypotenuse was sealed over an air space. Using an uncoated surface and an air space insured 100% internal reflection at the 45° hypotenuse. A small loss occurs due to reflection at the water to glass and glass to water interfaces and a small change in path length occurs due to the different index of refraction in the glass. These factors were accounted for and are discussed in detail in Section 3.2.2.



CONFIGURATION FOR RELATIVE MEASUREMENT OF SOURCE OUTPUT
Figure 3

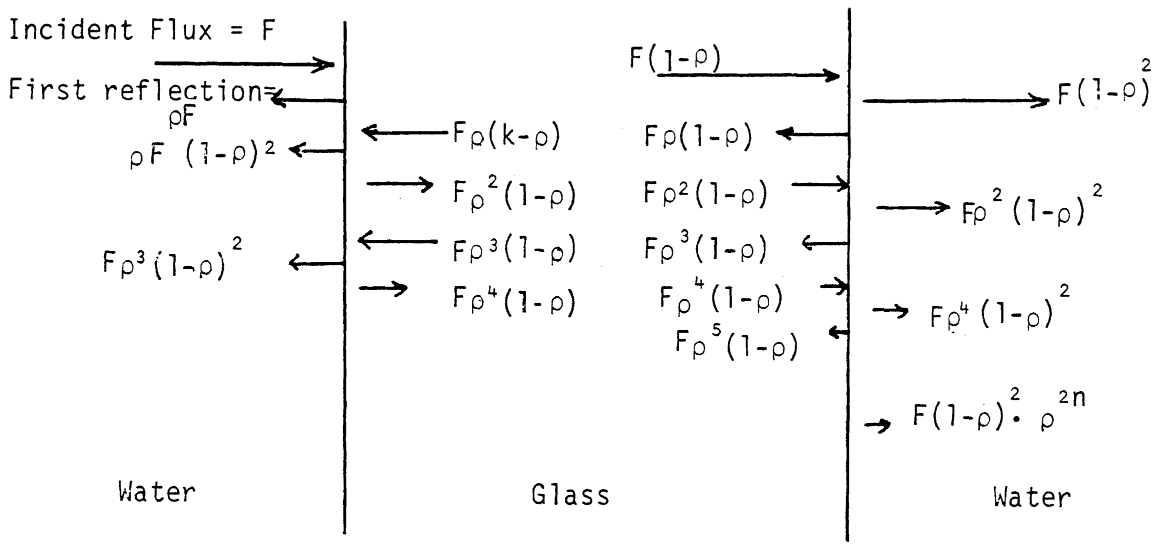
3.3.2 CORRECTION FACTORS AND FINAL REFLECTANCE EQUATION

(a) Transmission Loss through Prism

When light travels through an interface between two media with different indices of refraction, part of the energy is reflected. For light traveling normal to the interface, the amount reflected is given by

$$\rho = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

Where n_2 and n_1 are the two indices. For the prism, two interfaces are involved as sketched below without showing the internal 100% reflection.



Internal refluxing increases the transmission over that which would be obtained by simply considering two interface losses. The transmission can be written, including the internal reflexing, as

$$T_p = (1-\rho)^2 \sum_0^\infty \rho^{2n}$$

$$= (1-\rho)^2 \cdot \frac{1}{(1-\rho^2)}$$

$$T_p = \frac{1-\rho}{1+\rho}$$

The index of the glass used was n_g=1.5245 and if n_w=1.3333 for the water, then

$$\rho = 4.4762 \times 10^{-3}$$

and

$$T_p = .9911$$

The water during the test was well filtered and clear; it was assumed that the transmission difference through the prism glass and the same short length (1.93 inches) of water is insignificant.

(b) Path Length Correction

The prism has a higher index than the water and when inserted into the line of sight makes the lamp appear slightly closer and the photometer will read slightly high as a result. If Δd is the apparent path length change, the correction factor will be

$$K_r = \left(\frac{d_0}{d_0 - \Delta d}\right)^2$$

Where $d_0 = d_1 = d_2$, see Figures 1 and 3.

The change in path length is given by

$$\Delta d = t_g \left(\frac{n_g - n_w}{n_g}\right)$$

Where t_g is the glass path length. Substituting t_g=1.93 inches, n_g = 1.5245 and n_w = 1.333 we get

$$\Delta d = 0.2420 \text{ inches}$$

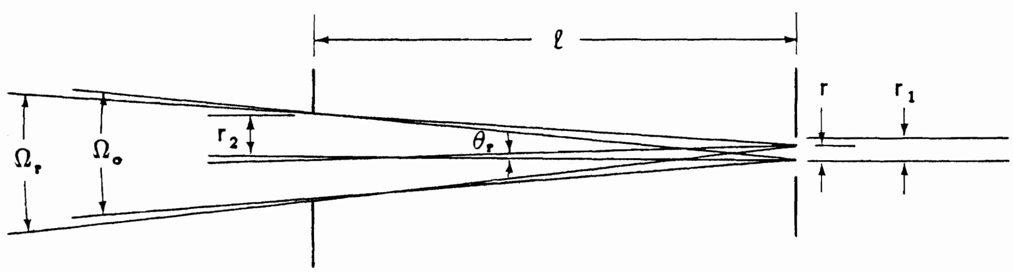
and then

$$K_r = \left(\frac{d_0}{d_0 - .242}\right)^2 \quad ; \ d_0 \text{ in inches.}$$

For the measurements made d_0 = 102.929 inches and K_r = 1.0047

(c) Receiver Field of View Correction

The receiver field of view is determined by two stops. The forward and larger stop has a radius r_2 and the rear stop has a radius r_1. These stops are separated by distance ℓ. Each point on the rear stop receives light through the solid angle determined by the apparent area of the forward stop and its distance.



In the development of (3-3) in Section 3.1, the solid angle of acceptance for the photometer was taken to be

$$\Omega_p = \frac{A_2}{\ell^2} = \pi\left(\frac{r_2}{\ell}\right)^2$$

which is an approximation.

An exact expression for a point on axis, i.e., at $r_1 = o$, is

$$\Omega_0 = 2\pi\left[1 - \cos\left(\arctan\frac{r_2}{\ell}\right)\right]$$
$$= 2\pi\left[1 - \frac{\ell}{(\ell^2+r_2^2)^{1/2}}\right]$$

This applies exactly only to the solid angle subtended by the midpoint of the rear stop with radius r_1. For points off axis, the apparent area of the forward stop would be reduced by very nearly the cosine of the off axis angle and the distance ℓ would be increased by the reciprocal of the cosine of the same angle. If the off axis angle is called Θ_r, then the solid angle subtended by a point distance r from the axis in the plane of the rear stop is

$$\Omega_r = \Omega_0 \cdot \cos^3\Theta_r$$
$$= \Omega_0 \cdot \cos^3\left(\arctan\frac{r}{\ell}\right)$$
$$= \Omega_0 \cdot \frac{\ell^3}{(\ell^2 + r^2)^{3/2}}$$

The solid angle on axis, r=0, is effective at one point. The solid angle at radius r, Ω_r, is effective over a distance $2\pi r$ and the effective or mean solid angle, Ω_e, over the entire area is

$$\Omega_e = \frac{2\pi\int_0^{r_1} \Omega_r \cdot r \cdot dr}{\pi r_1^2}$$

$$= \Omega_0 \frac{2\ell^3}{r_1^2} \int_0^{r_1} \frac{r}{(\ell^2\ r^2)^{3/2}} \cdot dr$$

$$= \Omega_0 \frac{2\ell^3}{r_1^2} \left[\frac{-1}{(\ell^2+r^2)^{\frac{1}{2}}} \right]_0^{r_1}$$

$$= \Omega_0 \frac{2\ell^3}{r_1^2} \left[\frac{1}{\ell} - \frac{1}{(\ell^2+r_1^2)^{\frac{1}{2}}} \right]$$

$$= 4\pi \frac{\ell^3}{r_1^2} \left[1 - \frac{\ell}{(\ell^2+r_2^2)^{\frac{1}{2}}} \right] \cdot \left[\frac{1}{\ell} \quad \frac{1}{(\ell^2+r.^2)^{\frac{1}{2}}} \right]$$

Since $\Omega_p = \frac{A_2}{\ell^2} = \frac{\pi r_2^2}{\ell^2}$ effectively appears in the denominator of (3-3) the correction factor is

$$K_\Omega = \frac{\Omega_p}{\Omega_e} = \frac{r_1^2 r_2^2}{4\ell^4[1-\ell/(\ell^2+r_2^2)^{\frac{1}{2}}] \quad [1-\ell/(\ell^2+r_1^2)^{\frac{1}{2}}]}$$

For the values used: $\ell = 10$, $r_1 = 0.122$ and $r_2 = 0.500$ inches

$$K_\Omega = 1.00199$$

(d) Final Reflectance Equation

Adding the three correction factors for; (a) transmission loss through prism used for relative lamp output measurement, T_p; (b) change in path length due to insertion of prism, K_r; and (c) receiver field of view, K_Ω; we get

$$R(\Theta_i,\Theta_r) = \frac{F_2}{F_1} \cdot \left(\frac{d_1}{d_0}\right)^2 \cdot \left(\frac{\ell}{r_2}\right)^2 \cdot \frac{1}{\cos\Theta_i} \cdot T_p \cdot K_r \cdot K_\Omega \quad (3\text{-}4)$$

Referring to figures 1, 2, and 5, we see that $d_0 = d_1 + d_2$. The following is a list of the dimensions used:

d_1	48.152 inches
d_2	54.777
$d_0=d_1+d_2$	102.929
r_2	0.500
ℓ	10.000

The absolute reflectance measurements were made with Θ_i=0°, i.e., with the target normal to the source. Substituting these values and the three correction factors into (3-4) gives

$$R(\Theta_i,\Theta_r) = 87.34 \frac{F_2}{F_1} \tag{3-5}$$

3.3 RESULTS

Measurements were made in the tank using the method described previously to determine the absolute submerged reflectance, $R_0(0,45)$ of six paint samples covering a wide range of reflectances. The submerged reflectance of these same samples had previously been determined by calculation from reflectance measurements with their surfaces wet.

An ANSCO Reflectometer was used to obtain the wet reflectance, R_W. The wet reflectance of three of these samples was also measured using a photometric bar. Four samples were added to the original six and all ten were measured on the ANSCO repeating the measurements on the original six. Additionally, five of the samples were measured using a modified Gardner Portable Reflectometer. Subsequently all ten sample paints were measured in the tank repeating the measurments of the original six. All of the submerged reflectance values obtained are tabulated in Table I. A plot of the results of the measurements made with the ANSCO Reflectometer on 26 July and the three measurements made on the photometric bar vs the direct measurements made in the tank is shown in Figure 4.

All of the measurements reported on in this section are for Θ_i=45° and Θ_r= 0°.

TABLE I

COMPARISON OF METHODS OF OBTAINING SUBMERGED REFLECTANCE

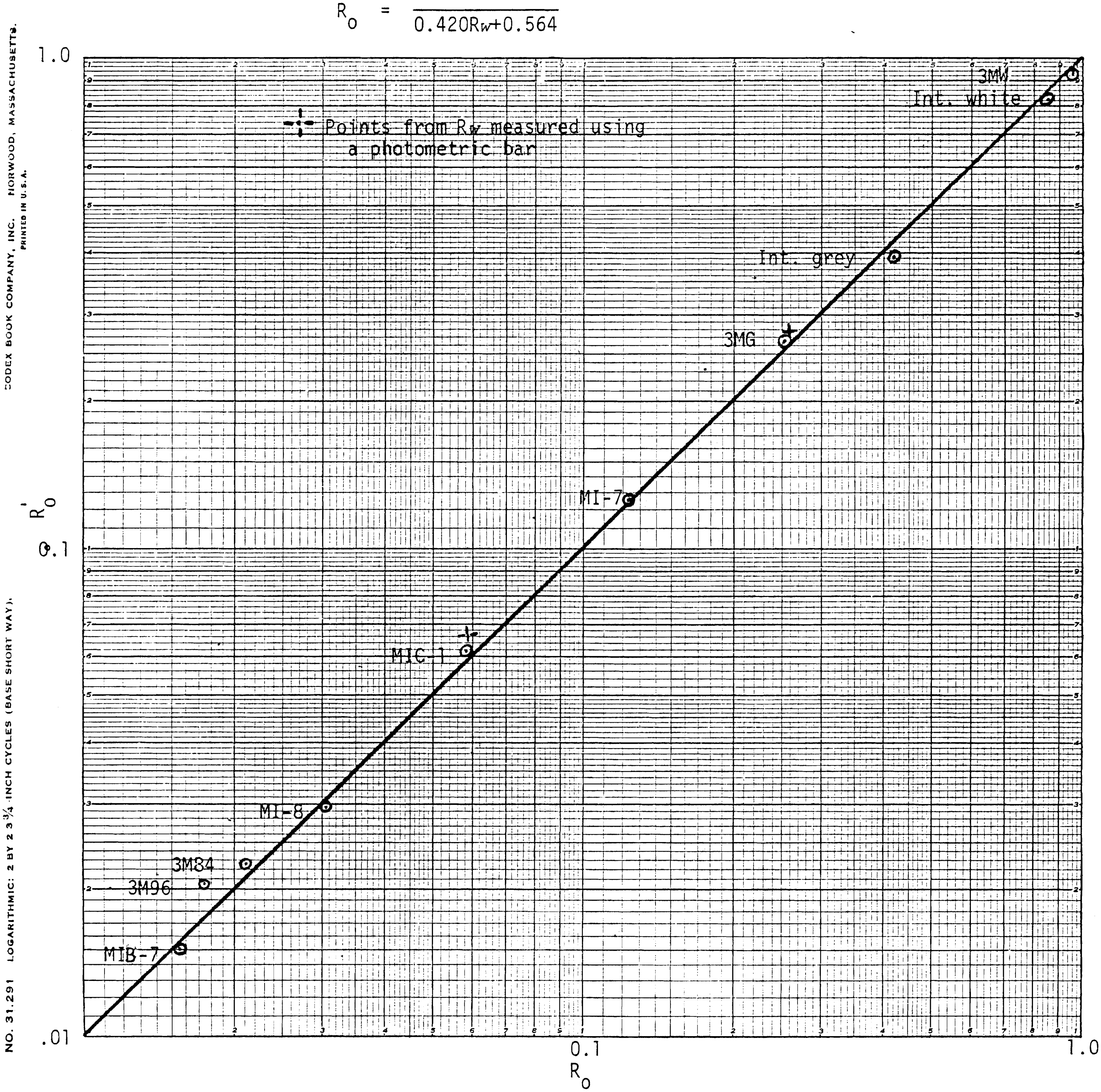
SAMPLE	Direct Meas. Underwater		R_o From R_w Meas. with ANSCO		R_o From R_w Meas. on Bar	R_o From R_w Gardiner Port. Ref.
	First Measurement	Second Measurement	First Measurement	Second Measurement		
3MW	.950	.954	.924	.936	.959	-
Int. White	-	.839	.810	-	-	-
Int. Grey	-	.406	.375	-	-	-
3MG	.251	.249	.246	.246	.251	.253
MI-7	.120	.121	.117	.127	-	.129
MIC-1	.0585	.0577	.0585	.0585	.0623	.0622
MI-8	.0306	.0306	.0293	.0304	-	.0314
3M84	-	.0210	.0220	-	-	-
3M96	-	.0175	.0202	-	-	-
MIB-7	.0182	.0157	.0150	.0155	-	.0176

Direct Measurements (cols. 2&3) represent the underwater measurements of absolute reflectance. Values in columns 4-7 are calculated from measurements of the wet reflectance, R_w, performed using the wet film technique.

R_o - Direct underwater absolute reflectance measurement

R_o' - Submerged reflectance calculated from a wet (R_w) reflectance measured with an Ansco reflectometer

$$R_o = \frac{R_w}{0.420R_w+0.564}$$



COMPARISON OF TWO METHODS OF OBTAINING SUBMERGED REFLECTANCE
Figure 4

3.4 DISCUSSION

The reflectance considered in this report is a directional type of reflectance where the incident flux arrives at a nominal angle, Θ_i, with the normal to the surface distributed over a solid angle, Ω_i, and a portion of the reflected flux is collected over a small solid angle, Ω_r, about a nominal angle, Θ_r, with the normal. In the development in Section 3.1, it is stated "The radiance of the target in the direction of the photometer will be,

$$N = R(\Theta_i,\Theta_r) \cdot \frac{H}{\pi} ,$$

where $R(\Theta_i,\Theta_r)$ is the directional reflectance at angle, Θ_r, with incident illumination at angle, Θ_i." If the target were a perfect diffuse reflector the radiance would be,

$$N_D = \frac{H}{\pi}$$

therefore

$$R(\Theta_i,\Theta_r) = \frac{N}{N_D} .$$

Thus, the reflectance we are using is the ratio of the radiance in a specific direction of the sample to the radiance a perfect reflecting diffuser would have in the same direction identically irradiated. This type of reflectance is called "radiance factor" and is discussed in detail by Judd*.

Widely used standard conditions for reflectance measurements are to illuminate the surface at 45° (Θ_i=45°) and view it perpendicular to the surface (Θ_r=0°). Identical results are obtained if these two angles are interchanged since a reciprocity relation applies to this type of measurement, i.e., R(0,45°)= R(45°,0). One purpose of the underwater measurements

*Judd, D. B., "Terms, Definitions, and Symbols in Reflectometry"; Journal of the Optical Society of America; Vol. 57, No. 4, April 1967.

was to verify the computation of submerged reflectance from reflectance measurements made on a wetted surface using standard commercial reflectometers. Light arriving at 45° at the wetted surface will, due to refraction at the air-water interface, arrive at the sample surface at 32° to the normal. Therefore, the submerged reflectance determined this way is for $\Theta_i=32°$; $\Theta_r=0$. For most surfaces of interest R(32°, 0°) is indistinguishable from R(45°,0°). The absolute submerged measurements made in the tank were all made at both 0°, 45° and 0°, 32°. In most cases both measurements were identical. It is the 0°, 32° results which are presented.

It was necessary to take care in selecting the dimensions of r_1 and r_2 (see Figure 2). The following requirements had to be met:

1) The field of view must include all of the light source when directly viewing the lamp to measure the signal, F_1. (Also the aperture of the prism used to fold the path must not occlude any of the direct light during this measurement).

2) The field of view must fall within the uniformly illuminated area of the target samples when measuring the signal, F_2.

Within these restrictions, r_2 is maximized to obtain a minimum dynamic range between F_1 and F_2 and r_1 is adjusted to place the readings within the span of the photometer.

Light scattered by the water and into the acceptance field of the photometer would be a source of error. The water used was highly filtered and low in scattering. To test for scattered light a piece of flat, polished, black, light absorbing glass was placed in the target plane and set at an angle such that any specular reflection component would not enter the photometer. With this light absorbing glass in place and the tank covered the light source was turned on and off. No change in the dark reading of the photometer was indicated.

Stray ambient light was also below the photometer threshold as determined by comparing the dark signal with the photometer capped and with it looking into the covered tank with the light source turned off.

At the beginning of each set of measurements, the lamp output was adjusted to set F_1 to a full scale value. The lamp was operated on a well regulated supply and the voltage and current monitored during the run. F_1 was also remeasured at the end of the run to determine any drift. For the first set of direct underwater measurements (See Table I), F_1 had changed from 10.00 volts to 9.45 volts over a period of 2 hours, 12 minutes. For the second set of direct underwater measurements, things were apparently more stable and F_1 was 10.00 ± .01 volts at the finish, 1 hour, 50 minutes later. The photometer output was measured with a differential voltmeter having a resolution of $\pm 10^{-5}$ volts. The lowest reading for F_2 was 0.00110 volts which is in the non-linear region of the photometer, and it was necessary to use the calibration curve to correct the readings for the low reflectance paints.

The sources of error with an estimate of the probable error are listed:

	High Reflectances % Error	Low Reflectances % Error
Calibration (relative)	±0.1	± 1
Stability (1st set V/W meas.)	± 1	± 1
Measurement of F_1	±0.1	±0.1
Measurement of F_2	±0.1	± 1
d_1	±0.1	±0.1
d_0	±0.2	±0.2
ℓ	±0.1	±0.1
r_2	±0.1	±0.1

In the computation indicated by (3-3) d_0, d_1, ℓ and r_2 are squared so the error in the measurement of these distances is effectively doubled. Taking this into account the root-mean-square error is

	High Level	Low Level
σ =	±1.1%	±1.8%
and the total sum is,		
Sum of errors =	±2.3%	±4.1%

4.0 TANK GONIO-REFLECTANCE MEASUREMENTS

The directional reflectance of a surface is a function of the angle of incidence, Θ_i, and the angle of viewing, Θ_r. The particular directional reflectance R(45,0), where $\Theta_i = 45^o$ and $\Theta_r = 0^o$, is useful as a readily obtained characteristic with which surfaces can be quickly compared. But this one point value gives no indication of the specular or gloss characteristics of the surface and, in fact, can be quite misleading if it is used indiscriminately in computations involving other angles of viewing and irradiance. The computation of the radiance of an object under various conditions of illumination and viewing, for instance, can involve a whole array of directional reflectance values. The solution of the problem of the detectability of a submerged object, when viewed from above the surface under natural lighting conditions, requires the knowledge of a limited set of directional reflectance values. A method of presenting the three-dimensional array of directional reflectance for a surface and the limits of the angles of viewing and illumination involved in this problem are discussed in Part 4.2 of this Section.

4.1 Technique

Section 3 describes in detail the apparatus and techniques used to make underwater measurements of absolute directional submerged reflectance. The same apparatus was used to make a series of underwater gonio reflectance measurements. The absolute reflectance measurements included a measurement of the output of the light source. For the directional reflectance measurements; the samples measured in an absolute manner were used as standards of submerged reflectance, and the measurements were made relative to these standards. Absolute measurements could have been made, but it was more expeditious to use the carefully measured standards.

In Section 3 (3-4), the following expression was derived:

$$R(\Theta_i,\Theta_r) = \frac{F}{F_1^2} \left(\frac{d}{d_0}\right)^2 \left(\frac{\ell}{r_2}\right)^2 \frac{1}{\cos\Theta_i} \cdot T_p \cdot K_r \cdot K_\Omega \quad .$$

where:

$R(\Theta_i,\Theta_r)$ = Directional Reflectance

Θ_i = Direction of Incident Illumination

Θ_r = Direction of Viewing

F_2 = Relative Flux from Sample (Photometer Reading)

F_1 = Relative Flux from Lamp (Photometer Reading).

The other symbols represent constants of the system and are described in Section 3. If we let C represent these constants, then

$$R(\Theta_i,\Theta_r) = C \cdot \frac{1}{\cos\Theta_i} \cdot \frac{F_2}{F_1} \qquad (4\text{-}1)$$

If $R'(\Theta_i',\Theta_r')$ is the known reflectance of the standard used and $R(\Theta_i,\Theta_r)$ is the reflectance of the unknown sample, then from (4-1) we can derive that

$$R(\Theta_i,\Theta_r) = \frac{\cos\Theta_i'}{\cos\Theta_i} \quad \frac{F_2}{F_2'} \quad R'(\Theta_i,\Theta_r) \qquad (4\text{-}2)$$

if the lamp output is constant during the two measurements of F_2' and F_2.

During the directional measurements, the lamp was run on a well-regulated power supply and allowed to warm up and stabilize before starting the measurements. A standard with a known submerged reflectance close to that of the sample to be measured was selected, placed in the configuration at which it was calibrated ($\Theta_i=0^o$; $\Theta_r=32^o$), and the photometer reading F_2' was obtained. The sample to be measured was then positioned at a selected angle Θ_r, and the light source positioned at various selected angles of Θ_i, and values of F_2 were recorded for each position. This was repeated at other angles of interest for Θ_r. At the end of the series of measurements for each sample, the reference standard was again used to recheck F_2' and confirm that the system was stable during the run.

4.2 Data Presentation

The presentation of the values of the bi-directional reflectance of a surface is complicated by the multidimensional nature of the function. One can visualize, for example, a three-dimensional surface representing the magnitude of the reflectance as the radial distance from a point of origin. In this type of diagram, a perfect diffuse reflector would be a hemisphere of unit radius. For real surfaces the radius vector representing the reflectance will increase in the specular direction, and the surface will have a bump or protrusion in this direction. If we now change the angle of incidence of the light used in the measurement, we will obtain a new surface with the specular bump at a different location. Thus to depict the complete reflectance function would require a series of these surfaces for each set of incidence angles of concern. Since most of the change in the bi-directional reflectance occurs in the plane containing the incident ray and the surface normal, we may compromise by presenting only the reflectance values in this plane. We now require only a family of curves -- say, for example, polar diagrams -- to convey this information. Such diagrams are in common use and are the usual manner of presenting such data.

It became obvious from the start that the quantity of data required in the study would be such that a better technique of presentation would be most desirable. The technique arrived at not only has the advantage of showing all the data contained in a series of polar diagrams in a single compact diagram but, additionally, allows the interpolation between measuring conditions to be readily performed and permits the investigator to discern measurement difficulties by invoking certain laws of reciprocity.

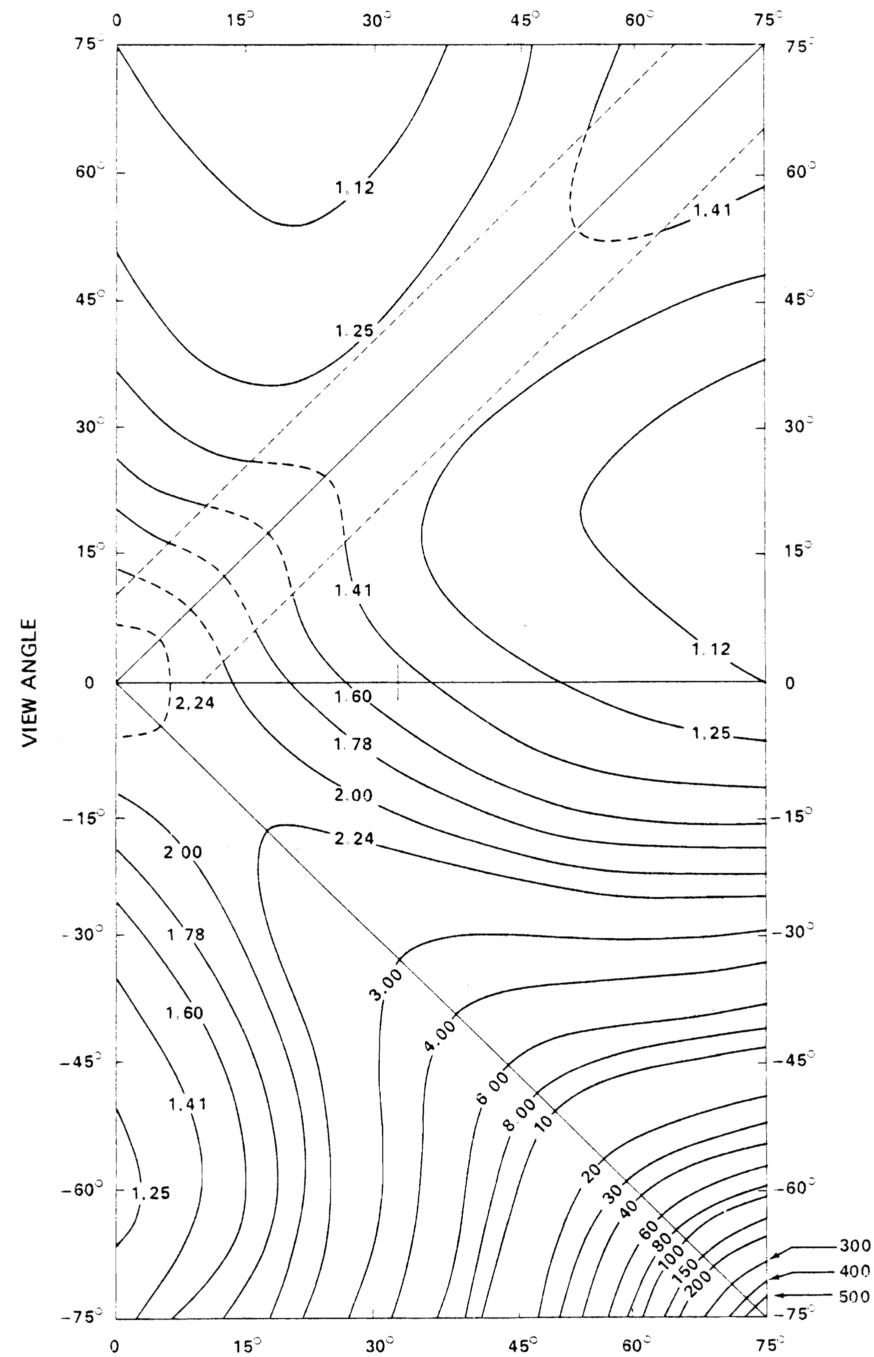
The new presentation shows contours of constant reflectance on a two-dimensional plot, with the angle of illumination (source angle) displayed horizontally and the angle of view shown vertically. Figure 5 contains such an iso-reflectance contour chart showing the reflectance properties of a dark matte paint (having a submerged reflectance $R_0(0°,32°)$ of 1.5%) over a range of source angles from 0° to 75° and view angles from +75° to 0° to -75°. The convention used for the sign of the view angles is that positive indicates the surface is illuminated and viewed from the same side. Conversely, negative view angles indicate that the viewing and illuminating are from opposite sides of the surface normal. The line at 45° in the lower half of the diagram represents the condition where the angle of view is equal and opposite to the angle of illumination, i.e., the condition for specular reflectance. It is for angular conditions along this line that gloss measurements are made.

The line at 45° in the upper half of the diagram represents the condition when the illumination and view angles are the same and represents a situation termed back-gloss. The phenomena of back-gloss are significant for surfaces with some degree of texture and result from the complete lack of surface shadowing that occurs under these conditions. The lack of shadow results in an increase in reflectance for these conditions, which is similar to the specular gloss condition but of a considerably smaller magnitude.

The contour presentation can be thought of as a plan view of a three-dimensional plot of reflectance, much the same as a topographic map shows the elevation of the terrain. All contours must be continuous and the closeness of the spacing indicates the rate of change of reflectance with angle. Various portions of the diagram are significant for different orientations of the surface with respect to the vertical. For example; for a horizontal submerged surface, the region from 0° to 45° source angle and +45° to 0° to -45° view angle would be of concern. For a surface tipped 45° from the horizontal, the entire upper half of the diagram would have significance.

A fundamental reciprocity law applies in reflectance measurement, i.e., that the angles of view and illumination may be exchanged without changing the value of the reflectance. A consequence of this law is that symmetry exists about the two 45° lines on the upper and lower half of the diagram. On Fig. 5, measurements were actually performed over all angles (except for the region within 10 of the back-gloss line), and the results showed excellent symmetry except at large angles in the lower half of the diagram.

ISOREFLECTANCE CONTOUR CHART



Low reflectance, matte paint. Submerged bi-directional reflectances measured in a laboratory goniophotometer. $R_o(0°, 32°) = 15\%$

Figure 5

5.0 LABORATORY GONIO-REFLECTANCE MEASUREMENTS

The submerged reflectance work accomplished using the tank and special apparatus described in Sections 3 and 4 provided the Laboratory with standards of submerged reflectance, demonstrated the validity of the application of the theoretical basis for these measurements and provided much needed gonio-reflectance data. To be able to obtain submerged gonio-reflectance measurements more routinely, as new paints required study, the Laboratory purchased and modified a commercial gonio-reflectometer. The instrument purchased was a Gardner Precision Goniophotometer Sensing Unit, Catalog No. GG-9204, Model UX-9 and Automatic Measurement Unit Catalog No. PG-5000.

The instrument was modified to enable its use for the measurement of submerged reflectance. A glass cylinder sealed to a base was installed in the center surrounding the target area. This provided a means of submerging the sample in water while leaving the projector and receiver optics in air. The optics were modified to correct for the change in path length due to the water path. The housings of the moveable projector and the stationary receiver were also modified to allow measurements to be made with the angle of view and angle of illumination separated by only ten degrees. It was found that the astigmatism caused by the curved cylinder was not detrimental to the measurement, and no astigmatic correction was made to the optical system. Also the instrument, as modified, can still be used to make dry gonio-reflectance measurements.

The instrument is calibrated by using a standard of known submerged reflectance. The glass cylinder is nearly filled with distilled water and the standard is placed in position submerged in the water. The view angle Θ_r and incident angle Θ_i are set to the values at which the standard was calibrated, and the response of the instrument is adjusted to obtain the reflectance value on the readout of the Automatic Measurement Unit. The calibrated standard is removed and the sample to be measured is positioned in place. The angle of view is set and the response noted as the projector arm is positioned for various angles of incidence. If the angle of view is different from the angle of view used with the calibration standard, it is neccessary to make a cosine correction. In this instrument the field of view of the receiver is always larger than the illuminated area on the sample, and the apparent size of this area as seen by the receiver varies as the cosine of the viewing angle, Θ_r, and the following correction must be applied to compensate for this:

$$R(\Theta_r,\Theta_i) = \frac{\cos\Theta_r'}{\cos\Theta_r} \; R'(\Theta_r',\Theta_i') \times \frac{S_{sample}}{S_{std}}$$

where

$R(\Theta_r,\Theta_i)$ is the directional reflectance of the sample at viewing angle Θ_r and incident angle Θ_i.

$R'(\Theta_r',\Theta_i')$ is the known reflectance of the standard at view angle Θ_r', and incident angle Θ_i'.

S_{std} is the output response obtained with the standard. Usually S_{std} is set to equal $R'(\Theta_r',\Theta_i')$.

S_{sample} is the output response obtained from the sample.

If S_{std} is set equal to $R'(\Theta'_r,\Theta'_i)$ then

$$R(\Theta_r,\Theta_i) = \frac{\cos\ _r'}{\cos\ _r} \times S_{sample} \quad .$$

This is the essence of the procedure used to make laboratory gonio measurements. The proper use of the instrument is described in more detail in the manual provided with the instrument.

Figure 6 shows two views of the Gardner UX-9 Goniophotometer as modified by the Visibility Laboratory to perform laboratory measurements of the submerged bi-directional reflectance of paint samples.

6.0 LABORATORY 0°, 45° REFLECTANCE MEASUREMENTS

Laboratory measurements of submerged reflectance at 0°, 45° were made by the following methods: 1) direct measurement using instrumentation in the Laboratory's testing tank, 2) photometric bar, 3) Ansco Reflectometer, 4) Gardner, UX-2 Reflectometer and 5) modified Gardner Portable Reflectometer. The Gardner Reflectometer, Catalog No. RG-4838, Model UX-2 and the Gardner Portable Reflectometer, Catalog No. RG-4806, Model 45-PR-4 were purchased along with the Gardner Goniophotometer and Automatic Measurement Unit mentioned in Section 5. The Automatic Measurement Unit is used with both the UX-2, Reflectometer and the UX-9, Goniophotometer. The portable reflectometer was modified to increase its sensitivity and to improve the precision of measurement for the low reflectance values that were of interest. This was accomplished by adding an operational amplifier with adjustable gain between the output of the sensing photocell and the microammeter readout. The full scale sensitivity may be adjusted to represent 10% to 25% reflectance.

The method used to make direct 0°, 45° submerged reflectance measurements in the testing tank, and a comparison of the results with other laboratory 0°, 45° measurements are given in detail in Section 3. The designation 0°, 45° is used to signify that the reflectance number is a directional type reflectance which the material exhibits when illuminated at 45° to the normal to the surfaced and viewed at 0°, i.e., normal to the surface. This is a particular directional reflectance, just as total diffuse reflectance or specular (gloss) reflectance values. Directional reflectance is described briefly in Section 3.4. The 0°, 45° measurement is frequently used as a "standard" reflectance measurement and is used by this Laboratory to be consistent with common practice; as a reflectance designator or "tag"; and for quick, although very incomplete, intercomparison of surfaces and surface finishes. This one-point directional measurement does not indicate the specularity or "gloss" characteristics of the surface (or lack of glossiness, i.e., flatness). A more complete description of the directional reflection properties of a surface is given by a series of gonio measurements as described in Section 5.

6.1 TECHNIQUE OF 0^o, 45^o MEASUREMENT - DRY

Commercial equipment is available which is designed to make 0^o, 45^o reflectance measurements. The procedure used for this measurement is essentially the same for all these units. It is usually neccessary to have standards of known 0^o, 45^o reflectance which are used to adjust or calibrate the span of the instrument. This Laboratory, for example, has used calibrated tiles obtained from Gardner Laboratory, Inc.

The procedure for using the Gardner UX-2 Unit follows:

1) Set Zero

With the unit on, warmed up and set to the sensitivity range to be used, a polished black glass plaque is placed over the port in the sample platform and the zero control adjusted to obtain an indication of zero reflectance. The polished black glass has a specular (mirror-like) surface and is also highly absorbing of any light which passes through the surface,so that the light which strikes the surface at 45^o is very nearly all absorbed or reflected (about 5%) in a direction away from the detector.

2) Set Span

A calibrated tile with a reflectance value in the range of the specimen to be measured is selected and placed over the port. The sensitivity is adjusted to obtain a reflectance indication corresponding to the reflectance of the calibrated tile or some convenient multiple of this value.

3) Recheck Zero

4) Recheck Span

5) Measure Unknown Specimen

Place specimen over port and read reflectance directly, or obtain reflectance from this reading by applying the calibration factor determined in Step 2).

The portable reflectometer is used to make a reflectance measurement on surfaces which cannot be brought to the UX-2. It has been used extensively, by this Laboratory, to directly measure the reflectance of paints applied to submarine decks and hull surfaces and to monitor the stability of these paints over a period of time during operational use. In use; the instrument is held with the port, which is in the bottom, against the surface of interest. The following procedure is used:

1) Place instrument with port against a black surface and with lamp off, adjust zero.

2) Place instrument with port against calibrated tile; and with lamp on, adjust to read correct reflectance on meter by adjusting the lamp current or the gain of the amplifier or both.

3) Place port against surface to be measured and read reflectance on the meter.

6.2 TECHNIQUE FOR OBTAINING 0^o, 32^o SUBMERGED REFLECTANCE USING A STANDARD REFLECTOMETER.

The procedure followed to indirectly get the submerged 0^o, 32^o reflectance of a surface is identical to that used to get a "dry" 0^o, 45^o reflectance, except that the surface of the unknown specimen is wet during measurement, and the submerged reflectance is calculated from the wet measurement using the equation

$$R_o = \frac{R_w}{0.420\ R_w + 0.564}$$

where,

$$R_o = \text{Submerged } 0^o, 32^o \text{ reflectance}$$

and,

$$R_w = \text{Measured wet } 0^o, 45^o \text{ reflectance.}$$

The rationale leading to this equation is given in Section 2.0, and experimental verification is presented in Table I and Fig. 4, Section 3.3.

The specimen can be wetted by soaking in clean water, draining momentarily, and placing immediately over the sample port of the reflectometer and taking a reading while the surface is covered with a uniform thin film of water. Large surfaces to be measured, when using the portable reflectometer, can be wetted by sponging with clear water. Some surfaces do not wet easily and the water draws together into beads, leaving dry areas. Adding a small amount of wetting agent or clear detergent to the water helps in maintaining a uniform film of water.

The 45^o incident illumination upon the wetted specimen is refracted at the air-water interface and arrives at the specimen surface at 32^o to the normal. The submerged reflectance obtained from measurement of a wetted specimen is therefore a 0^o, 32^o reflectance. Gonio measurements show that reflectance values measured at 0^o, 32^o and 0^o, 45^o are usually not greatly different, and the results of measurements on a wetted surface are frequently designated as 0^o, 45^o values rather than the more correct 0^o, 32^o.