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Field test of a system for predicting visibility of swimmers from measurements of the clarity of natural waters

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FIELD TEST OF A SYSTEM FOR PREDICTING VISIBILITY BY SWIMMERS FROM MEASUREMENTS OF THE CLARITY OF NATURAL WATERS

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I. INTRODUCTION AND SUMMARY

1. Introduction

A continuing program concerned with the visibility of submerged objects has been in progress within the Visibility Laboratory for more than a decade. Early experimental and theoretical work[1,2] provided a basis for predicting visibility by swimmers from instrumental measurements of water clarity. Further investigations, theoretical and experimental, and instrumental developments of many kinds verified and extended the original work and enabled this Laboratory to provide the U. S. Navy Hydrographic Office with an accurate water clarity meter[3] and nomographic charts[4] for the interpretation of its readings in terms of the limiting range at which swimmers can sight any flat, horizontal object lying on the bottom of the sea.

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[1] Duntley, S. Q., "Interim Report on Exploratory Studies of the Physical Factors which Influence the Visibility of Submerged Objects," Minutes and Proceedings Armed Forces-NRC Vision Committee, 23d meeting, March 1949 (p. 123).

[2] Duntley, S. Q., "The Visibility of Submerged Objects;" Final Report under Contract NSori-07831, NSori-07864, and NObs-50378; August 1952.

[3] Austin, R. W., "Water Clarity Meter Operating and Maintenance Instructions," SIO Ref. No. 59-9, Visibility Laboratory, Univ. of Calif., La Jolla, Contract NObs-72092, February 1959.

[4] Duntley, S. Q., "Nomographs for Calculating Visibility by Swimmers," Report No. 3-1, May 1958, Contract NObs-72039.

In providing the Navy with water clarity measuring equipment and the associated nomographic charts, the Laboratory has a responsibility for providing evidence of the over-all validity of the system. A careful review of all experimental evidence relative to the components of the system disclosed that (1) no sufficiently critical test of an underwater sighting range prediction had ever been made and (2) that experiments with earlier instruments showed a disturbing lack of close agreement between the apparent contrast of underwater objects calculated by means of the contrast reduction equation and corresponding values of apparent contrast measured directly with photographic or photoelectric telephotometers. There is, however, considerable evidence that the equation is valid when supplied with water clarity constants derived from direct contrast reduction measurements.

1.2 The New Water Clarity Meter

The lack of close agreement between the two methods for obtaining the water clarity constants was believed to be attributable to perturbations of the underwater light-field due to the presence of the target, if large, and to the presence of the measuring apparatus. Both water clarity meter readings and telephotometer observations are affected, but ordinarily to different extents. There is, moreover, a perturbation of the underwater light-field by the presence of the swimmer in the case of visual target sightings. Agreement between the different methods for measuring water clarity constants and their applicability to sighting range predictions requires that the effective perturbation of the light-field match in all three instances.

During the design of the new water clarity meter for the Navy, Dr. R. W. Preisendorfer of the Visibility Laboratory was asked to make a theoretical exploration of underwater light-field perturbations. His results[5], which relate to effects due to the presence of the target only, were used to establish design criteria for the new instrument. Great care was exercised to reduce the perturbations far below those of any previous hydrophotometer and to endeavor to match the residual effects with those which are always produced by the presence of a human observer.

1.3 The Field Test

It was necessary, obviously, to conduct a field test to ascertain whether the intent of the instrumental design had been successfully realized, i.e., to see if the water clarity constants obtained by means of the instrument provide a valid measure of contrast reduction as seen by swimmers or as observed with a telephotometer. A field test for this purpose was conducted at the Diamond Island Field Station of the Visibility Laboratory during the summer of 1958 and is described in this report. The successful result constitutes evidence that the clarity meter and nomograph method for predicting underwater sighting range works as a system.

The α-measuring equipment used for the field test embodied the same basic optical design as the water clarity meter constructed for the Navy. In the field test the K-measuring portion of the water clarity

[5] Preisendorfer, R. W., "A General Theory of Perturbed Light Fields with Application to Forward Scattering Effects in Beam Transmittance Measurements," SIO Ref. 58-37, Visibility Laboratory, Univ. of Calif., La Jolla, Contract NObs-72092, 1 May 1958.

meter was a physically separate unit. The coefficient K was determined by measuring the vertical gradient of downwelling irradiance; this was accomplished by means of an upward facing photovoltaic cell covered by a matte-surfaced diffusing plate which, by test, evaluated flux in proportion to the cosine of the angle of incidence, thus measuring the irradiance on the surface of the plate. Absorption filters were used to correct the photocells to photopic response.

1.4 Experimental Procedure

Contrast reduction was measured by means of an underwater photoelectric telephotometer in a carefully prepared perturbation-minimized mounting and compared with values predicted by theory on the basis of data from the water clarity meter. Concurrently, underwater sighting ranges were determined under identical viewing conditions by an experienced observer and compared with ranges predicted from the water clarity meter readings.

1.5 Conclusions

All of the data are in excellent agreement; they constitute experimental evidence that:

(1) the new water clarity meter provides values of the water clarity constants, α and K, which are valid for predicting the apparent contrast of underwater objects by means of equation (1), and

(2) the sighting ranges predicted by the nomographic charts are valid when based upon values of α and K from the new water clarity meter.

2. MEASUREMENTS OF APPARENT CONTRAST

2.1 Introduction

It was discovered experimentally during Visibility Laboratory underwater experiments in 1948[1] and subsequently derived analytically[2,6] that the apparent contrast of any submerged object observed against a deep-water background is reduced exponentially as the object-to-observer distance (r) is increased along any path of sight having uniform (homogeneous and isotropic) optical properties, as follows:

$$C_r = C_o \, e^{-(\alpha - K \cos \theta) r} \tag{1}$$

Here C_r and C_o are apparent contrast and inherent contrast respectively. The contrast attenuation coefficient is $(\alpha - K \cos \theta)$, where θ is the zenith angle of the path of sight and the water clarity constants α and K are, respectively, the volume attenuation coefficient* and the diffuse attenuation coefficient.

The water clarity meter is designed to measure α and K, and these coefficients can also be obtained by measuring the contrast attenuation coefficient $(\alpha - K \cos \theta)$ for two or more paths of sight having different zenith angles θ. Conversely, the apparent contrast of any object seen against a deep-water background can be measured

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* The constant α is also sometimes referred to as the beam attenuation coefficient, since it specifies the attenuation of a beam of photons.

6 Preisendorfer, R. W., "Model for Radiance Distribution in Natural Hydrosols," SIO Ref. 58-42, Visibility Laboratory, Univ. of Calif., La Jolla, Contract NObs-72092, 1 August 1959.

at any given object-to-observer distance or it can be calculated from values of α and K from the water clarity meter. The field test data will be presented in the latter form in this report since apparent contrast (or, alternatively, the contrast reduction factor) is regarded as the datum of primary significance.

The measurements of apparent contrast, as well as the visual sighting-range measurements described in section 3 of this report, were made from a specially constructed barge having an underwater room with windows 30 inches below the surface of the water. This research barge, constructed in 1948 and depicted in references (1) and (2), was equipped in 1949 with an underwater track extending 28 feet in front of the window and supported at its outer end by a float. The track carries a small car on which targets of any kind can be mounted. This unique research facility has been used throughout the years for many contrast reduction studies and other researches in hydrologic optics.

The Diamond Island Field Station is a uniquely favorable site for experiments of this type owing to the optical uniformity of the water (i.e., the lack of vertical stratification), to the constancy of K and α, to the convenient degree of water clarity, the lack of bottom influence on the light-field, and to several other favorable factors. The tests described in this report were performed at this location for a small fraction of the cost of carrying out the same work at sea.

Theory[6,7] and experiment[9] have demonstrated that the magnitude of the diffuse attenuation coefficient K depends upon the distribution of light within the water. During sunny weather the variation of K with depth near the surface may not be negligible. In order to minimize any variation of K with depth and to enable more perfect minimization of the effect of the presence of the barge on the underwater light field, all of the 1958 field tests were conducted under overcast skies or prior to sunrise. This choice of lighting condition was realistic inasmuch as the nomographic charts are for objects lying on the bottom where the lighting distribution often differs but little between sunny and cloudy conditions.

2.2 Experimental Details

The experimental equipment shown in Figure 1, consisted of an underwater room with windows 30 inches below the water surface. An optical bench track 28 feet long was mounted outside one of the windows.

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6 Preisendorfer, R. W., "Directly Observable Quantities for Light Fields in Natural Hydrosols," SIO Ref. 58-46, Visibility Laboratory, Univ. of Calif., La Jolla, Contract NObs-72092, July, 1958.

7 Preisendorfer, R. W., "Some Practical Consequences of the Asymptotic Radiance Hypothesis," SIO Ref. 58-60, Visibility Laboratory, Univ. of Calif., La Jolla, Contract NObs-72092, September, 1958.

8 Tyler, J. E., Richardson, W. H., and Holmes, R. W., "The Optical Properties of Lake Pend Oreille," SIO Ref. 58-80, Visibility Laboratory, Univ. of Calif., La Jolla, 3 December 1958, Contract NObs-72092.

The outboard end of the track could be adjusted in depth to obtain angles up to 45° from the horizontal. A small cart on the track carried the target and could be manually adjusted to any desired path length by means of rope A and the counterweight. The target itself was over-weighted on the outboard side of its hinge pin and could be raised by rope B or allowed to fall back in a matter of seconds. In order to reduce the perturbation of the light field, created by the presence of the underwater room and floats, the side C of the room facing the optical bench was camouflaged with canvas painted to reflect a luminance equal to equilibrium luminance in the horizontal direction. In addition to this, a six-foot air path was provided by the air tube to insure that the target-to-barge distance would be large for small path lengths r. The water between the air tube and the window was shielded from light by means of a black cloth. The target was a metal disc covered with black Norzon cloth which had previously been soaked to remove any excess water-soluble dye. When this target was in contact with the air tube window, the telephotometer reading was less than 10^{-4} of the maximum reading of background luminance.

For inclined paths of sight an auxiliary window was mounted inside the room. Its angle corresponded to the angle of observation. This auxiliary window provided an air-glass-water interface that was perpendicular to the line of sight.

Measurements of apparent target luminance B_r and background luminance B were made with a reflex telephotometer employing a 931A multiplier phototube corrected for photopic response, a log-chassis and a Brown recording potentiometer. Calibration of the telephotometer system was done on a special photometer bench using the inverse square law to achieve a 10^5 range in light level. Three complete calibrations were run for the measurements reported here, one just before the telephotometer measurements began, one on completion of the horizontal path data and one on completion of the inclined path data. The known instrument error revealed by these calibrations has been converted to variability in $1 - B_r/B$ and is shown graphically in Figures 2 and 3 (dotted lines). As B_r/B approaches 1 the precision of the "black-target" experiment becomes increasingly poor.

The angular field of view of the telephotometer was 1.05° (full cone angle). The target slightly more than filled this field at the maximum path lengths.

A flat-plate irradiance collector (shown in Figure 1) was used to obtain experimental values of the diffuse absorption coefficient K and an hydrophotometer (not shown) was used to measure the volume attenuation coefficient α in the vicinity of the target. All the measurements were made using a bandwidth corresponding to that of the C.I.E. luminosity curve.

Data were taken during periods of relative calm and also when the sun was obscured by clouds or horizon. Since the ratio of apparent luminance to background luminance is independent of the level of illumination, data could be taken under variable lighting conditions by operating the target rapidly.

2.3 Horizontal Paths of Sight.

For horizontal paths of sight, $(\theta = 90^\circ)$ and black targets $(B_o = 0)$ Equation 1 predicts that the apparent contrast C_r, will be exponentially attenuated at a rate determined by α alone, see Equation 2 :

$$1 - \frac{B_r}{B} = e^{-\alpha r} = - C_r \qquad (2)$$

It can be seen from Equation 2 that when $r = 0$, $(1 - B_r/B)$ must equal 1 and that the slope of the plot of $(1 - B_r/B)$ vs r on semi-log paper (Figure 2) should be $-\alpha$, the volume attenuation coefficient.

The points in the semi-log graph of Figure 2 are values of $(1 - B_r/B)$ computed from telephotometer data. The slight but systematic departure of the points from linearity is introduced by perturbation of the light field, that is, shadowing of the path near the air tube which results in values of B_r that are disproportionately low compared with B. The straight line of Figure 2 is not drawn through the points but has a slope equal to the numerical value of α = .490/meter as measured with the hydrophotometer.

It can be seen from Figure 2 that, except for residual perturbation, the contrast reduction is valid for submerged horizontal paths and the value of α obtained with our hydrophotometer can be used to predict apparent contrast along such paths.

2.4 Inclined Paths of Sight

For inclined paths of sight Equation 1 may be written

$$1 - \frac{B_r}{B} = e^{-(\alpha - K \cos\theta) r} \qquad (3)$$

Equation 3 predicts that for black targets seen along inclined paths of sight the apparent contrast will be exponentially attenuated at a rate determined by the expression $(\alpha - K \cos\theta)$. As before, when r = 0, $(1 - B_r/B)$ must be 1.

The points of Figure 3 are computed from telephotometer data taken before sunrise and during a day of sometimes broken overcast, with the track angle θ set at 121.2°. Evidence of perturbation of the light field is now missing owing partly to deeper operation and partly to the angle of the track. As before, the straight line is not drawn through the points but has the numerical value of $(\alpha - K \cos\theta)$ computed from hydrophotometer determinations of α and flat-plate determinations of K. In this case the average value of α from 14 determinations was .585/m, the average value of K from 14 determinations was .350/m.

It can be seen from Figure 3 that the apparent contrast of the target was predicted correctly by means of the contrast reduction equation (1) and values of the water clarity constants α and K obtained from independent instrumental measurements.

3. MEASUREMENTS OF SIGHTING RANGE

3.1 Introduction

Sighting ranges for a small black target were determined by a young, well-trained observer concurrently with the measurements of apparent contrast and the water clarity constants. The observer removed the telephotometer at the underwater window of the research barge (see Figure 1) and viewed the target through the air-tube. In this way the perturbation of the light-field was precisely the same low value attained in the case of the apparent contrast measurements. The target was a small, black, conical cavity 0.311 inches in diameter at the open end, facing the observer; it was mounted to the movable cart by means of a transparent Lucite bracket. The observer was unable to see the cart at any time because of the limited field of view afforded by the air-tube so that, near threshold, the target appeared as a small black disc in an otherwise unstructured field.

3.2 Experimental Procedure

The luminance of the underwater light field was measured at frequent intervals throughout the experiment by means of a carefully calibrated Macbeth illuminometer equipped with a telescopic attachment which limited its field of view to a small portion of the air-tube window. A Wratten No. 40 filter was found to provide an excellent color match of the 2360° K Macbeth comparison field with the greenish light coming from the water; the transmission of this filter for light of 2360° K color temperature was calculated from spectrophotometric data in the usual manner. Additional monitoring of the luminance level was provided by placing the photoelectric telephotometer at another underwater window in order to produce a strip-chart record of the underwater luminance it observed throughout the period of observations. Analysis of these records showed that the coefficient of variance (s/m) of the underwater luminance did not exceed 0.17 during either of the series of observations reported. This was, of course, a measure of the stability of the overcast under which the experiments were performed.

The observer (male, age 21) had more than a year of experience in laboratory visual threshold measurements. His thresholds were well stabilized and closely duplicated those of the Tiffany data within the range of adaptation levels and angular target subtenses involved in the field test. Before departing for the field station the observer underwent extensive practice on a simulation of the planned experiment, and at the field station he practiced freely with the actual underwater viewing task until it was familiar to him. Because of this practice there is reason to believe that learning effects had vanished before the sighting range data were taken, and that the observer's responses were stable in the field environment.

The observations were made by the method of adjustment, the observer moving the target along the track by means of a pull cord. At the outset of the experiment the car was at the outer end of the track, far beyond the point at which the target disappeared. The observer was careful to use no fixed over-run, so that he had no mechanical or kinesthetic position cues. He then moved the target toward himself until he detected its presence and an assistant recorded the target position as indicated by a steel tape attached to the car.

The observer then moved the target close to the air-tube window and permitted it to recede slowly by allowing the pull cord to slip through his fingers. When the target disappeared he stopped the cart and an "out" distance was measured. This process was repeated ten or more times, depending upon the stability of the overcast. Great care was taken to accept data only when the water was so completely calm that there was no relative motion of the target with respect to the barge. This additional stringent requirement reduced the number of occasions when data could be taken to two. In both cases the path of sight was 30.8° downward from horizontal, i.e., zenith angle $\theta = 120.8°$.

3.3 Sighting Range Data

Sighting range data were obtained on 13 August and 17 August; these were the only two occasions during the expedition when observing conditions fulfilled all requirements and contrast reduction data were available.

Figures 4 and 5 display these data graphically in combination with apparent contrast values calculated from water clarity constants measured by means of the water clarity meter. In each figure the plotted points show the average "out" distance, the average "in" distance, and the mean of both "out" and "in" distances. The curve connecting these points shows apparent contrast as a function of target distance expressed in terms of visual angle.

3.4 Calibration of the Observer

After the observer had returned to the laboratory his contrast thresholds were measured for the same type of visual task which he had encountered in the field. An accurate simulator was constructed in which a circular target was presented by projection on an unstructured, uniformly bright screen which could be moved throughout the same range of distances encountered in the field experiment, due allowance having been made for refractive effects at the underwater windows. The field-of-view restriction imposed by the six-foot air-tube was duplicated. The luminance levels in the simulator duplicated those which prevailed during the field experiment, and thresholds were measured by varying the target distance in a realistic manner. The method of adjustment was used, as in the field experiment, and the means of "in" and "out" distances are given in Table 1. These data differ from classical (e.g., Tiffany) thresholds primarily because of adaptive and accommodative effects due to the presence of the air-tube. These visual effects and their implications are to be discussed in more detail in a separate report.

Table I

Laboratory Visual Thresholds

Adaptation Luminance (ft-L)	Target Contrast	Threshold Target Size (min)
4.09	.0206	6.22
4.09	.0295	4.99
8.05	.0198	5.60
8.05	.0291	4.85
8.05	.0360	4.53

3.5 Comparison of Observed and Predicted Sighting Ranges

The dotted curves on Figures 4 and 5 have been drawn through the threshold points listed in Table 1 and indicated by crosses.

At the intersection of the solid and dotted curves the apparent contrast of the target equals the contrast threshold for the observer, and the target would, therefore, be predicted to be just visible at this visual angle (target distance.) It will be noted from Figure 4 that the predicted sighting range is 15.2 feet whereas the mean of the observed sighting ranges was 15.6 feet. In Figure 5 the predicted and observed sighting ranges are in precise agreement.

3.6 Conclusions

The agreement between the predicted and observed sighting ranges exhibited by the data in figures 4 and 5 constitutes evidence of the validity of the basic method for predicting underwater sighting ranges from water clarity meter data, the contrast reduction equation, and visual contrast thresholds. Since the nomographic charts for predicting visibility by swimmers are an embodiment of this method, the results of the field test provide a careful spot-check of the validity of the clarity meter-and-nomograph system.

The field test provides experimental evidence that:

(1) the new water clarity meter provides values of the water clarity constants, α and K, which are valid for predicting the apparent contrast of underwater objects by means of equation (1), and

(2) the sighting ranges predicted by the nomographic charts are valid when based upon values of α and K from the new water clarity meter.

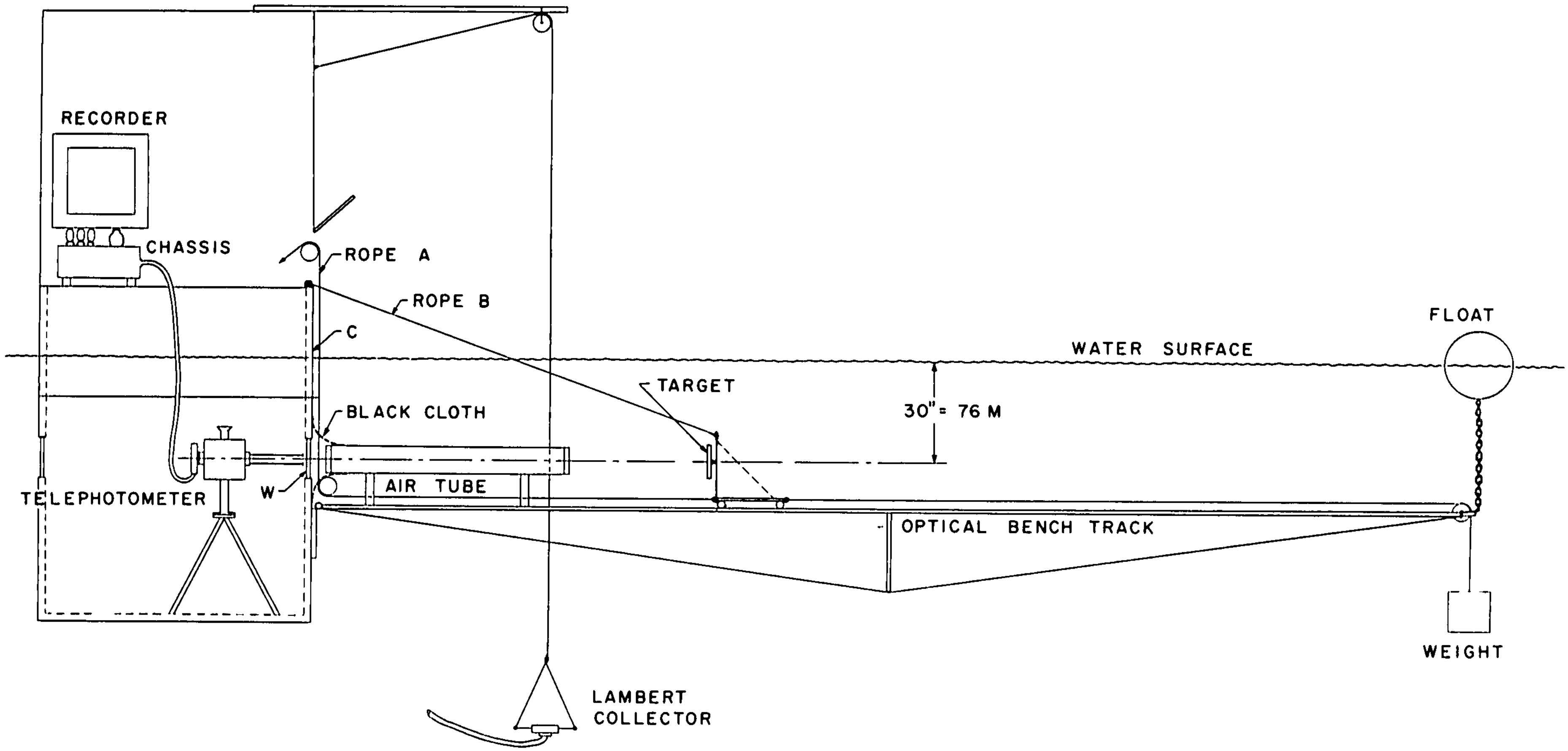
RECORDER
CHASSIS
ROPE A
ROPE B
C
FLOAT
WATER SURFACE
TARGET
30" = 76 M
BLACK CLOTH
AIR TUBE
W
TELEPHOTOMETER
OPTICAL BENCH TRACK
WEIGHT
LAMBERT
COLLECTOR

FIG. 1

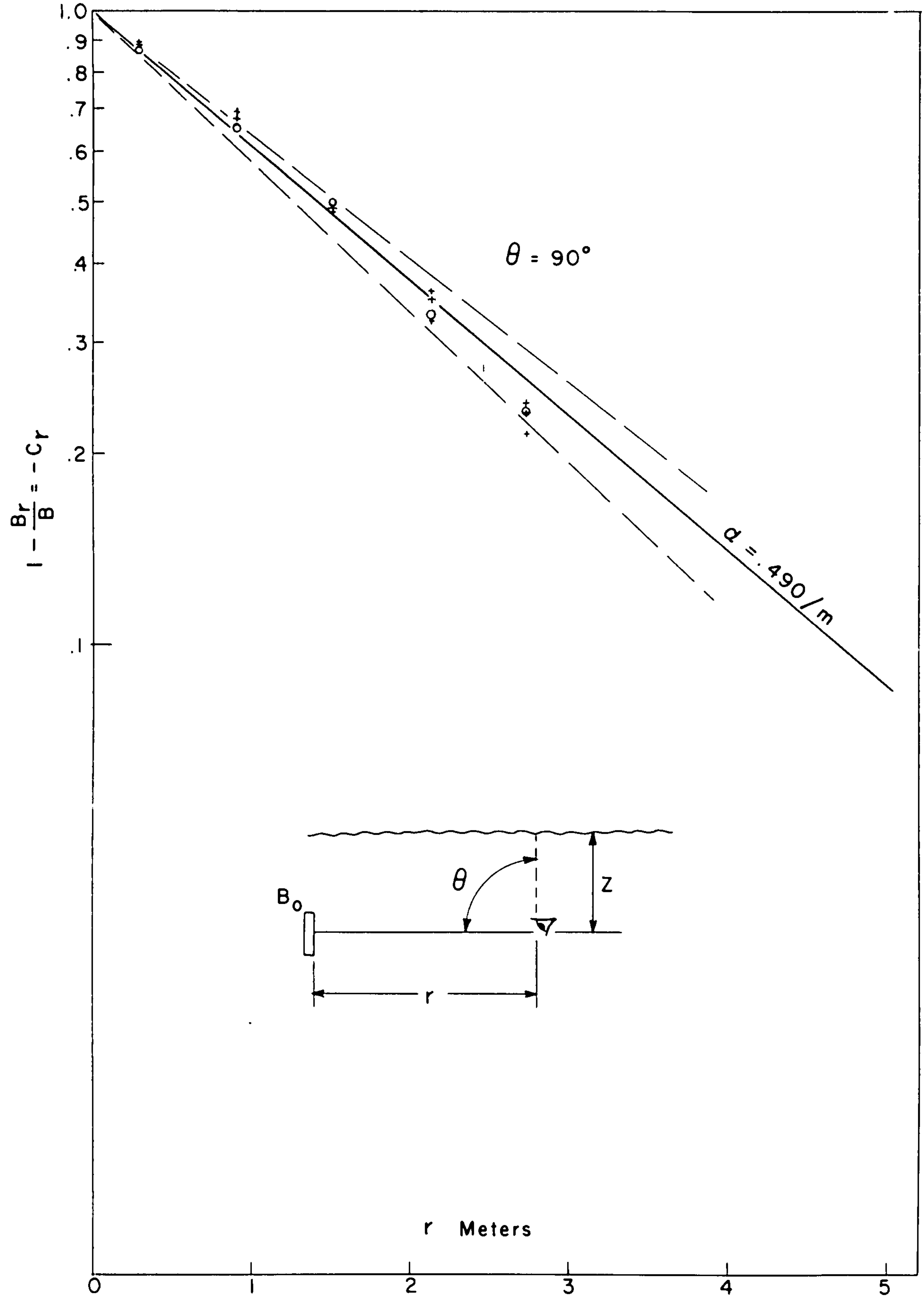

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FIG. 2

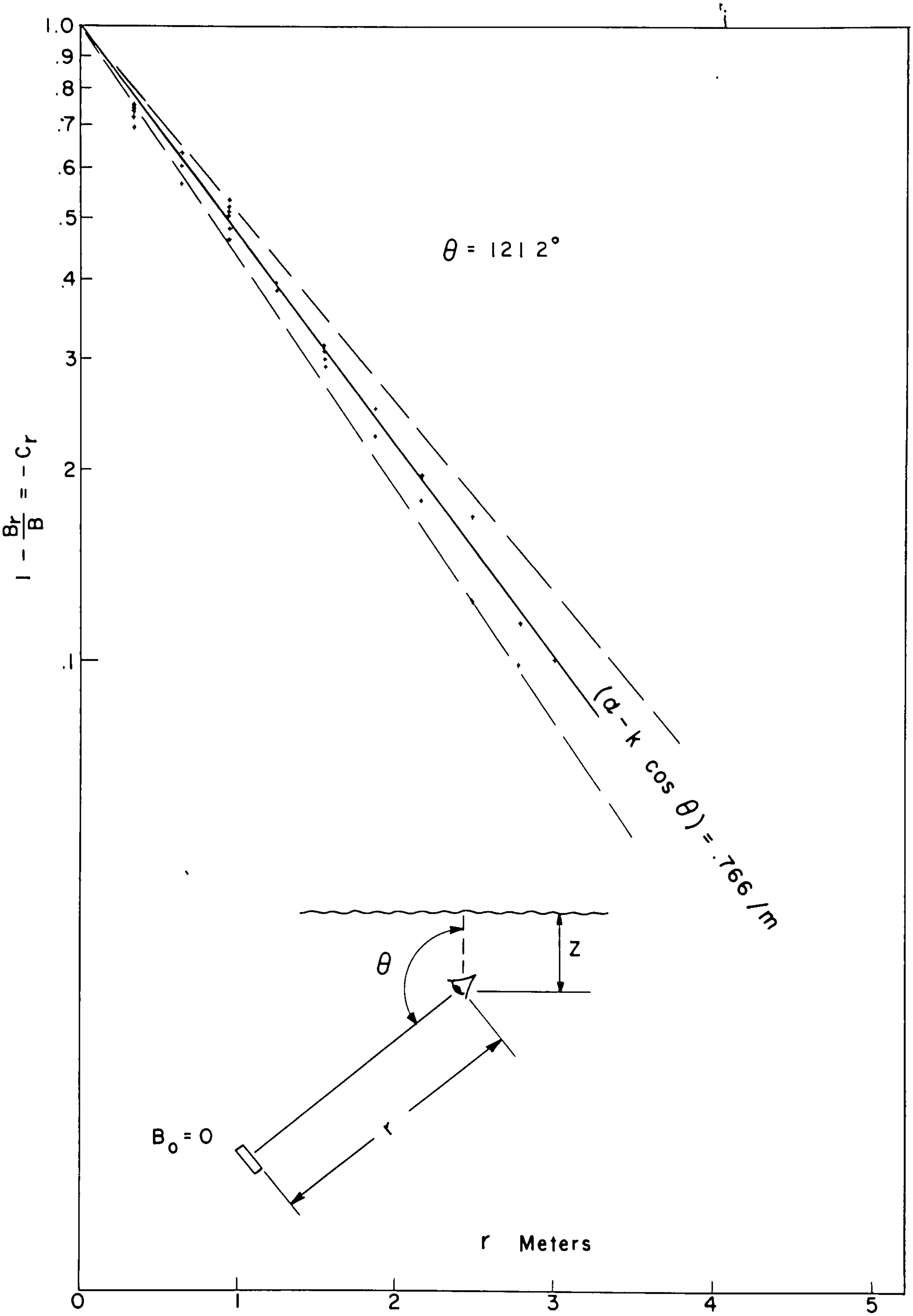

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FIG. 3

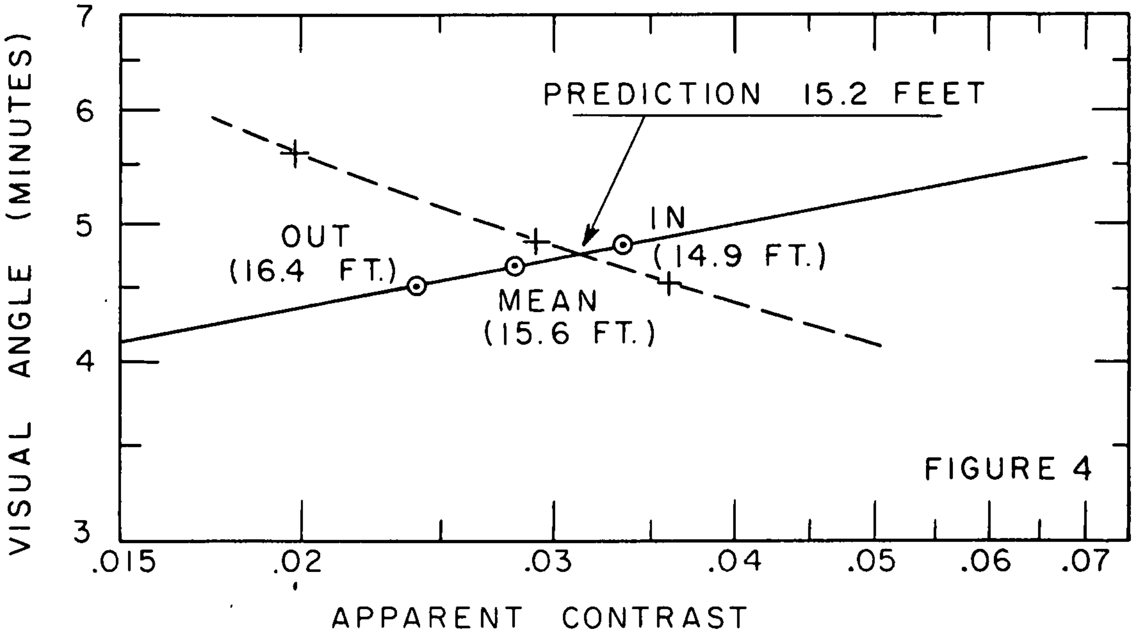
13 AUGUST 1958

BACKGROUND LUMINANCE

8 FOOT LAMBERTS

TARGET DIAMETER 0.311 IN.

PATH DEPRESSION 30.8°



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17 AUGUST 1958

BACKGROUND LUMINANCE

4 FOOT LAMBERTS

TARGET DIAMETER 0.311 IN.

PATH DEPRESSION 30.8°