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Radiance distribution as a function of depth in the submarine environment

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RADIANCE DISTRIBUTION AS A FUNCTION OF DEPTH IN THE SUBMARINE ENVIRONMENT

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INTRODUCTION

During the decade from 1935 to 1945 there seems to have been considerable interest in the angular distribution of natural light underwater.[1/2/4/5/10/11] Ingenious although somewhat crude instruments were devised including the "shadowing-screen" photometer (described by Pettersson[1/] and also by Johnson ans Liljequist[2/]), and the Gershun[3/] tube photometer which directly limited the solid angle of acceptance. The objective of the work at this time seems to have been largely exploratory, although a theoretical treatment based on isotropic scattering was published by Poole[4/]. Observations were made on clear, sunny days and compared with observations on overcast days. Observations were also made at various depths and through various color filters. The light field was explored in a vertical plane in the sun's direction and in the vertical plane at right angles to the sun's direction. In addition, both Johnson and Liljequist[2/] and Whitney[5/] explored the light field with azimuth sweeps taken at various zenith angles.

As a result of this research it was observed that the angular distribution pattern of the natural light field changed in shape with depth, and it was surmised that at some unknown depth an equilibrium shape might be reached. It was also noted that the direction of the "bright" spot in the submarine light field tended to approach the zenith as depth was increased.

Although the data obtained during this period was adequate for the purpose for which it was intended, it does not now lend itself to detailed investigations of the submarine light field or to the computation of water constants. The resolving power of the instruments used was never better than 15°; (this refers to the apex angle of the circular cone of collection). Large angles of collection such as this average too much information, especially in the direction of the sun, and tend to broaden the shape of the distribution diagram in that direction and at the same time to lower the apparent value of the peak radiance.

The data from the various publications cannot be combined because of differences in geographical location and instrumentation details (for example, in the selection of filters and photo cells). The papers individually have insufficient information on the homogeneity of the water sample which was being measured, and for computational purposes have insufficient data points covering the radiance of the submarine light field.

The importance of the radiance distribution of the natural submarine light field as a primary means for documenting the optical properties of large bodies of water was first recognized by Dr. S. Q. Duntley in 1949 while he was conducting research on visibility problems in scattering-absorbing media. ~~At that time~~ Dr. Duntley then initiated a program of instrument development and study which has been continued to the present time.

Some of the theoretical work accomplished by this program has been published in the Journal of the Optical Society of America,[5] and in reports[6] from the Visibility Laboratory, and some is being brought to the attention of the Optical Society by Dr. R. W. Preisendorfer.[12/13]

The development of instrumentation for the measurement of radiance distribution was first described to the Optical Society by Dr. Duntley in a paper presented at the October 1955 meeting in Pittsburgh and the program of work in progress at that time was discussed by Mr. Tyler.[8] Following the summer of 1956, major design changes were made in the instrumentation, and in the spring of 1957 field operations were conducted in deep water at the United States Navy Electronics Laboratory Calibration Station on lake Pend Oreille in Northern Idaho.

The objective of the 1957 field work was to obtain detailed data on radiance distribution as a function of depth in homogeneous water under "clear sunny sky" and "overcast sky" lighting conditions. Since the data was to provide new input to the theory of radiative transfer through an hydrosol, measurements were confined within a narrow wavelength band.

Pertinent Description of Lake Pend Oreille

Lake Pend Oreille is in many ways ideally situated for submarine optical investigations. The field station is a barge moored at the south end of the lake about two miles from the village of Bayview and about one-half mile from the nearest shoreline. Cape Horn Peak to the north, rises 16.5° above the horizon, and peaks of the western edge of the Bitterroot mountains block out, at most, 12.5° of the sky to the south. To the east and west the sky line is much lower than this. Although the effect of the sky line on the submarine light field is not yet known, it is presumed to be small due to Fresnel reflection at these high angles of incidence, and also due to the fact that refraction reduces the angular subtense of the sky line so that the 16.5° between sky line and horizontal becomes only 2.7° in the underwater scene.

The major inlet to Lake Pend Oreille is Clark Fork some twenty miles to the north of the station and practically in line with the Pend Oreille River, which is the major outlet. Thus the largest source of particulate matter has little effect on the water near the station. The eleven streams and creeks along the south and east shore line that were examined at the time of the experiment were all carrying clear water from melting snow over streambeds of clean boulders.

The lack of currents in the lake, the somewhat stagnant location of the station, and the absence of silt-laden drainage into the southern end of the lake all helped to minimize the possibility of stratification or inhomogenity in the water.

DESCRIPTION OF EXPERIMENTAL SET-UP

The Pend Oreille Calibration Station is a two-story, 40 by 40 foot barge floated on T6 pontoons and held in place by mooring cables which are designed to minimize yaw. The siding, at the time of the experiment, was painted light green and as a result the barge, at noon, exhibited high positive contrast as seen from the instrument. The new underwater photometer was suspended from a single supporting cable at the end of a 30 foot boom on the south side of the building. The inboard end of the boom was fastened to the barge near the water line and the outboard end was about six to eight feet above the water. The instrument was thus 30 feet or more from the barge at all times. The maximum horizontal angles subtended by the barge at the point of immersion were 45.5° to the east, 8.5° to the west and about 33.7° in the vertical direction*. The image of the barge and the submarine shadow created by the barge have a noticeable effect on the natural light field near the surface and a detectable effect even at the deeper stations. The depth of the water at the station is 750 feet which assured the absence of bottom reflection effects in the measurements.

INSTRUMENTATION

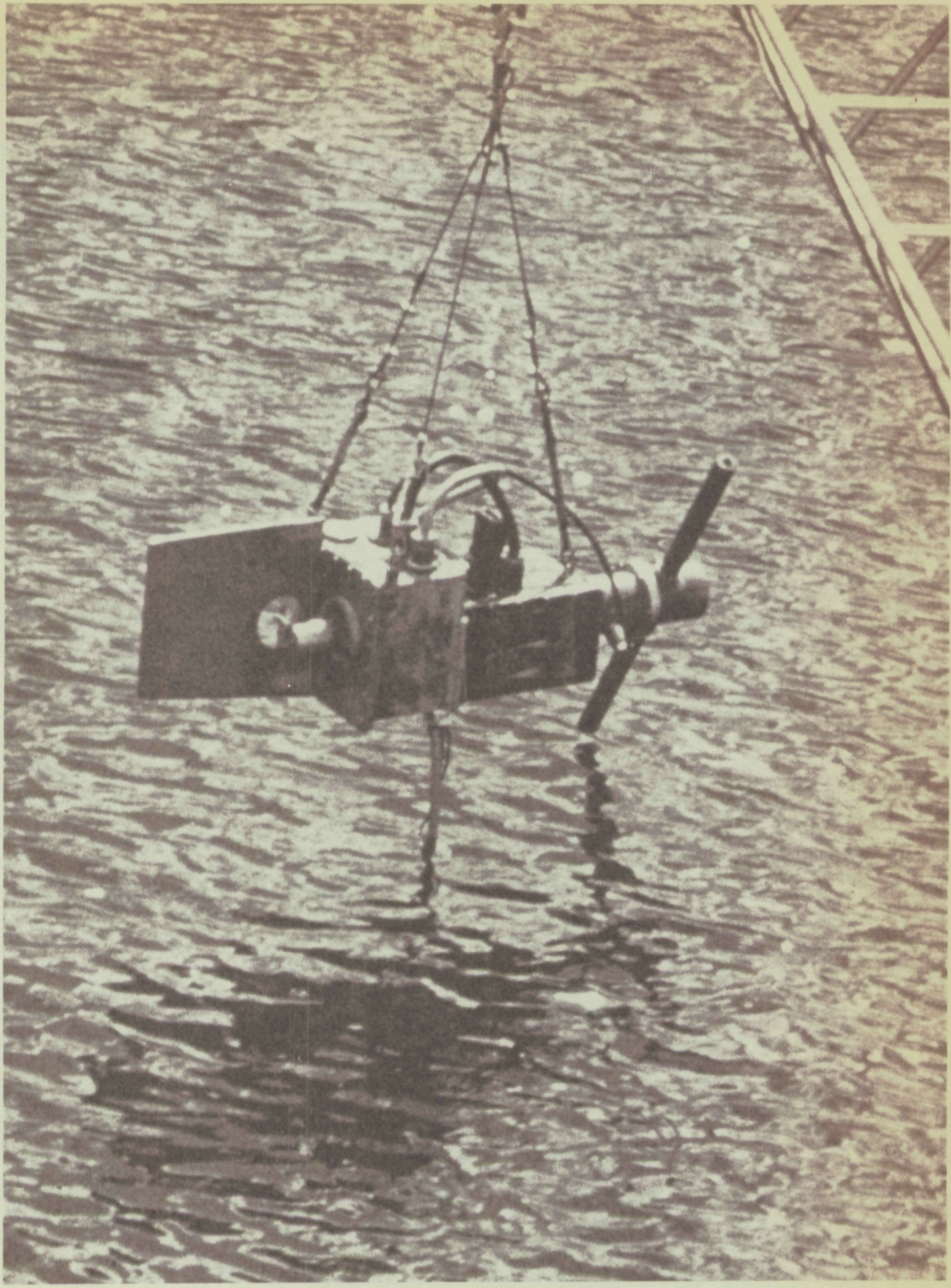
All of the radiance distribution data presented herein were taken with the underwater photometer shown in Fig. 1**. This instrument was suspended on a single cable and powered by a 31-conductor electric cable looped into the underside at the vertical axis of rotation. The instrument was thus free to rotate around this vertical axis. Rotation about this axis was controlled by means of a gyrosyn compass assembly in the instrument with control transformer and indicator on the main control panel. The error signal resulting from an azimuth mismatch between the control transformer and the gyro heading was used to drive a propeller which rotated so as to minimize the error signal. With this mechanism it was possible to maintain an azimuth setting to plus or minus 1° or better.

* From a point below the surface the barge subtended a vertical angle of about 10° at the instrument, and appears between tilt angles of 38° and 48°.

** This instrument will be described in detail in a later publication.

Figure 1

The Visibility Laboratory's Photometer mounted and ready for lowering into Lake Pend Oreille, Idaho. The measuring head with its Gershun tubes is on the right and the propeller and damping fin on the left.



For all the data presented here the azimuth error is less than plus or minus 1°.

The optical system of the underwater photometer measuring head, shown in Fig. 2, is a dual detecting system, each channel consisting of a 931A multiplier phototube wrapped with black tape except for a window covered with a Wratten No. 45 blue-green gelatine filter.*

The measured transmittance characteristics of this filter are shown in Table I. Since the readings obtained are proportional to

$$\int_{\lambda_1}^{\lambda_2} E S T_F T_W \, d\lambda$$

E = Energy distribution of the light just below the surface

S = Spectral sensitivity of phototube

T_F = Transmittance of No. 45 filter

T_W = Transmittance of water path

and since the combination ST_W limits the value of λ_2 to 700 millimicrons or less, it can be seen that this data is tagged with an energy distribution having half band width of 64 millimicrons and extreme limits between 430 millimicrons and 546 millimicrons.

In order to extend the range of measurement, each tube is surrounded by a cylinder containing openings covered by filters having neutral densities of about 0, 1, 2, 3, 4, and infinity. The window in the pressure housing is frosted on the inside to assure a constant coupling factor between the collection system

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* Deep water measurements in this region of the spectrum would not necessarily require an auxiliary filter since the combination of water and phototube sensitivity would provide all the "filtering" action required. In this work the Wratten No. 45 filter was used simply to make the shallow water measurement consistent in bandwidth with the deep water measurements.

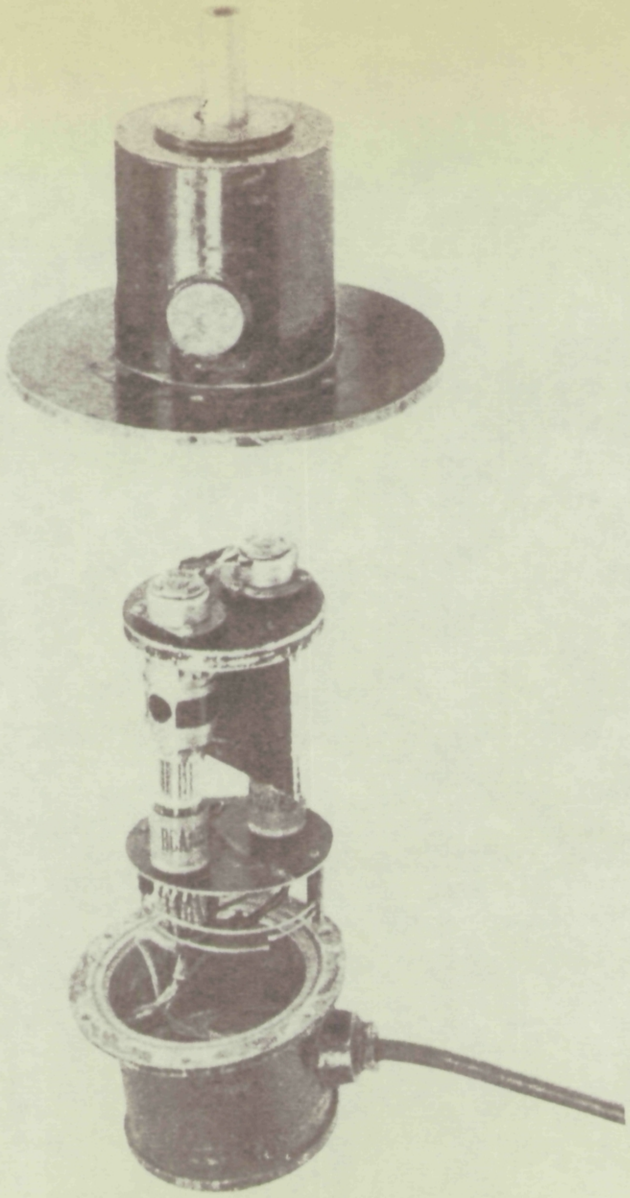
TABLE I

MEASURED TRANSMITTANCE OF WRATTEN NO.45 GELATINE FILTER

	%T		%T		%T		%T
203	0	490	16.9	770	84.0	1500	56.5
10	0	500	14.4	80	86.0	1600	44.5
20	0	10	10.0	90	87.0	1700	35.0
40	0	20	5.3	800	87.5	1800	27.0
50	0	30	2.0	10	87.8	1900	22.0
		536	1.0				
60	0	40	0.32	20	88.5	2000	20.5
		546	0.10				
70	0	50	0	30	88.8		
80	0	60	0	40	89.0		
90	0	70	0	50	89.5		
300	0	80	0	60	89.6		
10	0	90	0	70	89.8		
20	0	600	0	80	89.5		
30	0	10	0	90	89.8		
40	0	20	0	900	89.8		
50	0	30	0	10	89.8		
60	0	40	0	20	89.8		
70	0	50	0	30	89.8		
80	0	60	0	40	89.8		
90	0	70	0	50	89.8		
400	0	80	0	60	89.5		
10	0	90	0	70	89.8		
20	0	700	0.25	80	89.8		
30	0.1	10	3.3	90	90.0		
433	1.0						
40	3.4	20	19.0	1000	90.2		
50	10.0	30	42.5	1100	90.8		
60	15.0	40	62.0	1200	90.5		
70	17.0	50	74.5	1300	86.5		
80	17.6	60	80.8	1400	76.5		

Figure 2

Exploded view of the measuring head of the Visibility Laboratory's Underwater Photometer. The two multiplier phototubes with the cylinders containing neutral density steps can be seen in the central assembly. The Gershun tubes (not shown) are mounted over the windows, one of which is shown in the housing on the right.



and the multiplier phototube. The internally baffled radiance tubes limit the angle of acceptance to 6.6°. The whole head can be tilted through a range of somewhat more than 180° by means of a synchronous motor. Event marks are automatically recorded at a specific angle at the beginning of each tilt sweep.

HOMOGENEITY OF THE WATER

Considering the intended application of this data, to examine the ability of current theory to describe and predict the passage of natural light through a homogeneous hydrosol, it was of the utmost importance for the water sample to be homogeneous. The favorable location of the barge and the absence of conditions likely to produce inhomogeneity in the water have already been mentioned. The water itself was also examined for evidence of inhomogeneity. This examination consisted of:

A. Bathythermograph measurements. It is well known that certain lakes, including lake Pend Oreille, undergo seasonal changes in their temperature profile, that warm weather will develop a layer of warm water at the surface and that various forms of microorganisms will "bloom" in or near this warm layer. Stratification of this type means discontinuous changes in the structure of the light field as a function of depth, a condition which would not yield suitable data. The absence of a thermocline implies that the bloom has not occurred and that this source of inhomogeneity is absent.

Bathythermograph measurements were made at frequent intervals during the entire operation, and consistently showed no thermocline. The record for March 16, for example, shows a surface temperature of 2.35° C rising at a constant rate to 3.20°C at 122 M depth. The record for 29 April shows a constant temperature of 3.6°C from the surface to 137 M. More critical examination (on 29 April 1957) of the top two meters, with a bucket thermometer, showed 4.5°C at the surface, 4.0°C at 1.25m and 4.0°C below 1.25 m indicating a calibration error in the bathythermograph that is not significant to these light measurements, and possibly a slight surface heating due to full sunshine on the 28th of April. All other bathythermograph records were, happily, monotonously the same.

B. Beam Transmittance. Beam transmittance and its variability with depth were measured with a beam transmissometer. Total transmittance for a collimated beam of light was 67.3% per meter at the surface and increased at a steady rate to about 68.6% per meter at 61m. (Measurements of 29 April 1957) Other determinations taken during the period of field operations showed no significant variation from this condition.

C. Particulate Matter. One and two liter samples were taken with a Nansen bottle at descrete depths from 6m to 60m and filtered through Millipore H A filters having a pore size of 0.45 microns plus or minus 0.02 microns. Results are shown in Table II.

TABLE II

Depth	Particulate Matter
6.1m	0.32 mg per liter ± .07 mg/liter
12.2m	0.37 " " " "
24.4m	0.40 " " " "
30.5m	0.41 " " " "
48.8m	0.51 " " " "
54.9m	0.41 " " " "
61.m	0.55 " " " "

Although each of the above tests seems to exhibit a trend with increasing depth, the trends are conflicting, and the variation of the parameter in each case is close to the expected error. Definitive evidence of stratification or inhomogeneity was considered to be absent during the period of the experiment.

Further evidence of the homogeneity of the lake water is provided by the results of calculations from radiance distribution measurements.

Constancy of the Surface Lighting

The natural lighting on the surface of the water can undergo changes in ambient level and also in structure, that is, in the position of bright spots, such as the sun or single white clouds, or in the relative proportions of specular to diffuse light. The effect of very slow changes in ambient level can be successfully corrected, but no method is known at present which will properly correct for the effect of rapid changes in ambient level or for the effect of changes in the structure of the light field. One must wait for desirable lighting conditions and even then may be forced to reject some data because of these uncontrollable variables.

For several years ~~now~~ it has been the practice of this laboratory to monitor the natural lighting at the surface with an instrument* sensitive to both the light level and to its structure and on the basis of this record to sort and reject data. For the data taken on 28 April no rejection was indicated.

PLAN OF OPERATION

The plan of operation was dictated to a large extent by azimuth and elevation changes in the sun's position, by the proposed computations from the data, and by the operating characteristics of the instrument. For computational purposes,

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* A description of this instrument will be the subject of a separate paper.

data at equally spaced azimuth intervals was needed. A 20° interval would give 18 continuous tilt sweeps with each measuring channel, or two complete radiance distributions at a fixed depth station in 25 minutes. In the progress of such a run a sweep by one radiance tube would be repeated 12 and 1/2 minutes later by the sweep of the opposite radiance tube.

The most favorable period for making the measurements would be two hours each side of noon (sun time) since this is the period of minimum change in sun elevation and consequently of minimum change in ambient light level and structure. Allowing 30 minutes at each station would provide for eight stations between 10 AM and 2 PM. Since there would be some ambient light level change during this four hour period a monitoring run was planned for noon. For this run the radiance tubes were set in a vertical position and measurements were made at descrete depths, including all station depths in about 10 minutes. Thus in the final data reduction all radiance distributions for the day could be adjusted to a single sun altitude.

DISCUSSION AND TREATMENT OF DATA

Data recording on April 28 was begun at 0850 at a depth of 66.1m and continued until 1441. The order of depth stations is given in Table III.

The original data clearly shows the features of the environment. The image of the sunlit barge wall is obvious at the shallow stations and the shadow of the barge can be seen at all stations although it is not obvious at the deeper ones (See Fig. 3.) The position of the "bright spot" is always recognizable and at the shallow stations the edge of the "man hole" can be seen, as can the shadow of the instrument itself. In addition, changes in the sun's azimuth position and in its elevation can be detected in the data.

TABLE III

Depth Station (Meters)	Time* Start	Time* Stop	Elapsed Time	Sun Altitude		Sun Azimuth	
66.1	0852	0924	32 min	41.0	45.5	119	127.5
53.7	0927	0947	20	46.0	48.5	128	134
41.3	0949	1009	20	48.5	51.0	135	142
29.0	1012	1033	21	51.0	53.0	143	150.5
16.65	1039	1103	24	53.5	55.0	153	162.5
10.43	1105	1126	21	55.0	55.5	163.5	172.5
4.24	1128	1152	24	55.5	55.5	173.5	183.5
Vertical Run	1158	1210	12	.2° change		186.	191.5
66.1	1211	1249	38	55.5	53.5	192.0	207.5
53.7	1252	1313	21	53.0	51.5	208.5	216.
41.3	1316	1338	22	51.0	48.5	217	224.5
29.0	1341	1402	21	48.5	45.5	225.5	232
16.65	1405	1425	20	45.0	42.5	233	338.5
Vertical Run	1432	1441	9	1.2° change		241.0	243.0

In order to remove as much of this distortion from the data as possible the following proceedure was adopted:

1. <u>Calibration Correction</u>

The original data, which is very nearly linearly proportional to the log of the radiance, was read at ten degree intervals of tilt with a special "rule" which converted the data to radiance units and at the same time removed any small departures from linearity that might be present. Each information channel, consisting of the multiplier phototube plus the chassis plus the recorder, has its own calibration "rule." The data for these rules was obtained at the site of the experiment just before and just after the measurements.

2. <u>Changes in Ambient Light Level</u>

Inspection of the data for the nadir direction indicated the extent of the ambient light level change due to altitude changes of the sun. When necessary this has been removed by normalizing all tilt sweeps for the station to the average nadir reading.

3. <u>Azimuth Motion of the Sun</u>

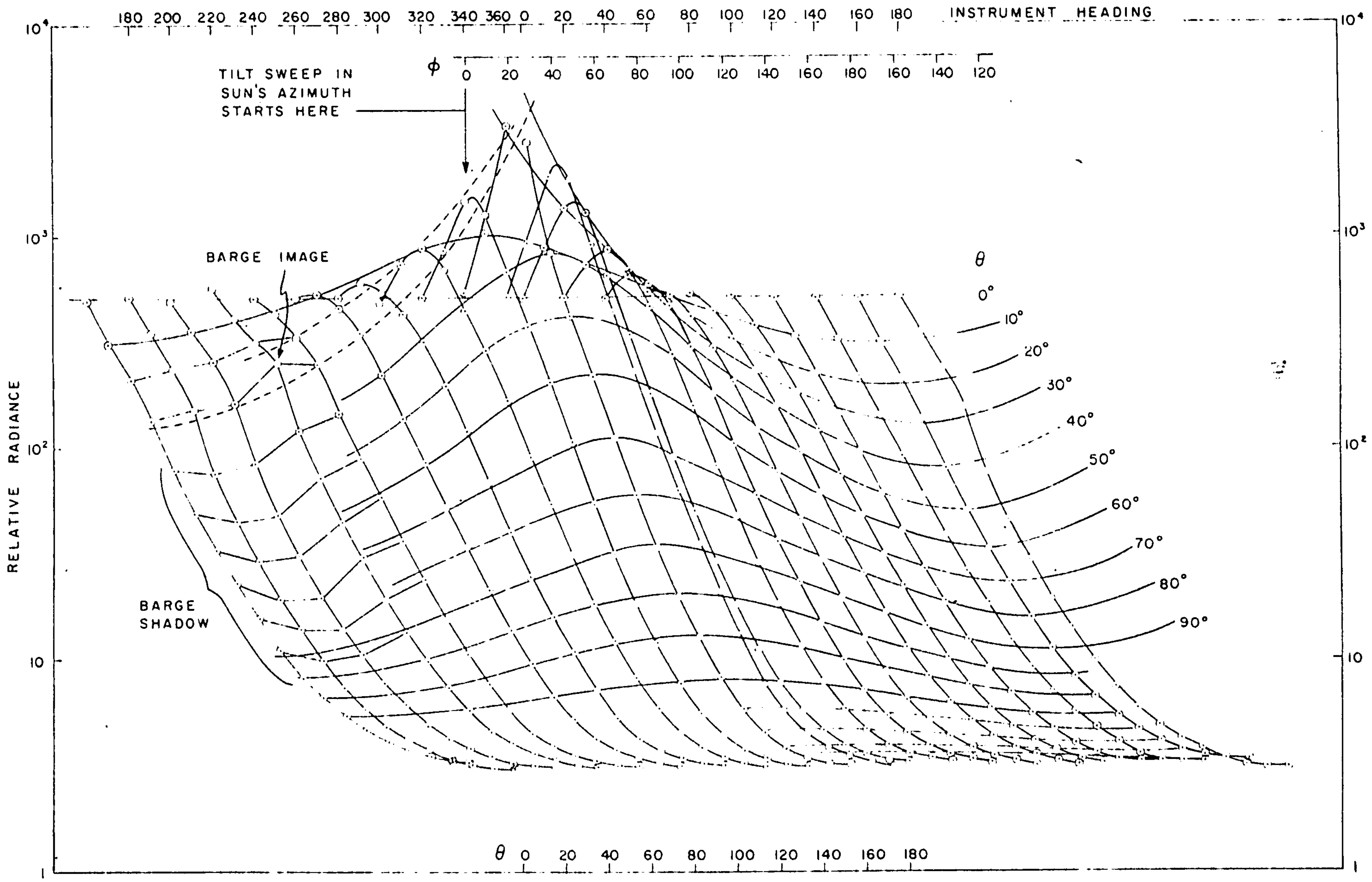
The data thus obtained was replotted on semi-log paper, as shown in Fig. 3. In this plot tilt angle and azimuth angle are both plotted along the abscissa. The known azimuth angle between the sun and the instrument heading was used to locate each tilt sweep on the plot. Thus the azimuth motion of the sun relative to the instrument is not superimposed on the data.

4. <u>Barge Image and Shadows</u>

The data points resulting from step three were joined by smooth curves to give azimuth sweeps at constant tilt as well as tilt sweeps at constant azimuth (See Fig. 3.) The image of the barge, its shadow etc., can be positively

Figure 3

Typical working plot of the data, showing the image of the barge as seen through 16.6 m of water, and ~~also~~ the shadow of the barge. In this plot the angles at the top marked "instrument heading" are relative to a fixed compass point. They are plotted progressively short of the azimuth scale of the graph in order to remove motion of the sun relative to the instrument heading. The ϕ scale at the top applies to the azimuth sweep at $\theta = 0^\circ$ and must be moved 10° to the right for each succeeding azimuth sweep. Azimuth sweeps in the upper hemisphere are marked with their appropriate tilt angles (θ) at the right. The θ scale at the bottom applies to each individual tilt sweep by relocating it to the right or left in 20° steps. It is shown lined up with the $\phi = 0^\circ$ curve.



INSTRUMENT HEADING
180 200 220 240 260 280 300 320 340 360 0 20 40 60 80 100 120 140 160 180
φ 0 20 40 60 80 100 120 140 160 180 160 140 120
TILT SWEEP IN SUN'S AZIMUTH STARTS HERE
BARGE IMAGE
BARGE SHADOW
RELATIVE RADIANCE
10⁴
10³
10²
10
1
θ
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
θ 0 20 40 60 80 100 120 140 160 180

identified in these plots. Sections of the data which were distorted by these spurious signals were not used in the data reduction. The physical location of the instrument was such that only about 54° of the horizontal sweep was distorted by the presence of the barge. The position of the sun was located by the maximums of the azimuth sweeps and checked with the known position of the sun in each case.

5. Read Out

The resulting azimuth curves were read out to give the appropriate data with the sun located at 0° azimuth.

6. Duplicate Runs

Both information channels functioned perfectly during the entire operation and consequently duplicate runs were available at all depth stations. These were treated independently through step five above and the read outs were then averaged. A double run was made at the 66.1m station giving a total of four complete determinations at this depth. All determinations are averaged together in the final read out.

7. Depth-Difference Correction

The ends of the brightness tubes are about a half a meter from the center of rotation of the measuring head. As a result the depth does not remain constant, but changes continuously with tilt angle according to the equation:

$$Z_t = Z \pm r \cos \theta$$

Where Z_t is the true depth, Z is the reported station depth to the center of rotation of the instrument and r is the distance from the center of rotation to the end of the radiance tube.

The averaged data ~~was~~ were corrected to give the radiance distribution at a point by determining the slope of the curve of path radiance vs depth for every pair of values of tilt angle and azimuth angle and making the proper correction along this slope.

8. Sun Altitude Changes

In addition to changes in ambient light level on the surface, large changes in the altitude of the sun result in a change in the ratio of the zenith to nadir path radiance and a reorientation of the whole radiance distribution solid in the direction of the sun. The depth stations were taken in the order shown in Table III, in order that the shallow stations would be at noon and the others would be clustered around noon in such a way that a complete set of stations could be selected from those nearest noon. Changes in the shape of the distribution solid ~~due~~ to changes in the sun's altitude would in this way be minimized.

9. Normalization to the Vertical Run

Before the seven morning runs could be normalized to the single vertical run at noon it was necessary to demonstrate that the radiance distribution solid for the 66.1m station was substantially the same in shape at 0908 as it would have been at 1200, that the radiance distribution solid for the 53.7m station was substantially the same in shape at 0937 as it would have been at 1200, etc. To do this the ratio of the average zenith to average nadir reading for each depth station was compared with the ratio of the zenith to nadir reading found from the noon vertical run. For all depth stations duplicate ratios were found indicating that no significant error is introduced by adjusting these runs to a single sun altitude. It was also found that the complete data for the 66.1m and 53.7m morning stations duplicated the data for the 66.1m and 53.7m afternoon stations. For the remaining morning stations the change in sun altitude between station time and 1200 is very small indeed. After refraction the change in sun angle from 1000 to 1200 is only four tenths of the resolving power of the radiance tube. During this period the greatest incremental change in sun angle takes place at the depth where it has the smallest effect on the shape of the distribution solid. It is, in fact, progressively true throughout the morning data that the large incremental changes in the sun's altitude occur at the depths where they have the least effect and the near zero changes in sun's altitude occurs near the surface where large changes would have had a very large effect.

On the strength of the above evidence, the data for the seven stations given in Tables IV, V, VI, VII, VIII, IX, and X is presented as data for one sun altitude.

DATA FOR THE CLEAR SUNNY CASE

Data representing the clear sunny case was obtained on 28 April 1957. The voice recorded notes for the day read as follows:

> "28 April 1957. It would not be possible to have a more perfect day for the sunny-sky case than today.
> Between seven in the morning and three-thirty in the afternoon there were no overhead clouds what so ever. The few small clouds that did appear just over the mountain peaks rapidly evaporated. At no time was it possible to see evidence of a high altitude cirrus layer. In addition to this the lake was practically flat calm all day."

Later computations place the clouds mentioned at an altitude of 13° in the southern sky. They appeared one at a time and evaporated within 10 minutes. Their angular subtense was never more than 1.5°. The optical state of the lake surface is shown in the photograph (Fig. 4) which was taken on April 28 at about 1500.

The radiance distribution data for the clear sunny case is given for seven depth stations in Tables IV through X inclusive.

DISCUSSION OF DATA AND EVALUATION OF SOURCES OF ERROR.

In the body of the tables, the overall variation in the value of radiance at any one setting is ± 5% of the radiance at that setting. This includes

RADIANCE DISTRIBUTION
CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 4.24 Meters θ = Tilt Angle Φ = Azimuth Angle

θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	204,000	204,000	204,000	204,000	204,000	204,000	204,000	204,000	204,000	204,000
10	541,000	481,000	374,000	286,000	220,000	174,000	139,000	119,000	108,000	104,000
20	4,300,000	1,320,000	545,000	277,000	168,000	118,000	93,000	79,600	72,100	69,100
30	7,980,000	1,100,000	401,000	198,000	123,000	87,200	69,400	59,700	54,500	52,400
40	573,000	427,000	234,000	135,000	90,500	68,300	56,300	48,700	44,100	42,300
50	207,000	164,000	106,000	69,500	49,300	37,700	31,000	26,500	23,800	23,200
60	114,000	91,800	66,400	47,700	35,300	27,300	22,300	19,000	17,100	16,600
70	61,300	55,800	45,100	34,300	26,700	21,200	17,500	14,800	13,200	12,400
80	41,500	38,200	31,500	25,100	20,100	16,100	12,900	11,300	10,000	9,460
90	26,900	25,300	21,500	17,600	14,200	11,700	9,840	8,560	7,820	7,480
100	17,000	16,000	13,900	11,700	9,940	8,590	7,620	6,860	6,390	6,140
110	11,200	10,700	9,280	8,060	7,180	6,490	5,990	5,600	5,340	5,220
120	7,430	7,170	6,630	6,020	5,590	5,250	5,000	4,800	4,670	4,590
130	5,360	5,220	4,950	4,710	4,520	4,320	4,180	4,040	4,010	3,990
140	4,230	4,170	4,040	3,960	3,850	3,780	3,710	3,650	3,620	3,600
150	3,570	3,560	3,520	3,480	3,440	3,380	3,340	3,300	3,280	3,260
160	3,250	3,250	3,250	3,250	3,250	3,240	3,240	3,240	3,230	3,230
170	3,110	3,110	3,110	3,110	3,110	3,110	3,110	3,110	3,110	3,110
180	3,050	3,050	3,050	3,050	3,050	3,050	3,050	3,050	3,050	3,050

RADIANCE DISTRIBUTION

CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 10.4 Meters Θ = Tilt Angle Φ = Azimuth Angle

Θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	127,000	127,000	127,000	127,000	127,000	127,000	127,000	127,000	127,000	127,000
10	274,000	258,000	215,000	166,000	129,000	103,000	86,800	78,300	73,300	71,400
20	1,970,000	610,000	284,000	158,000	101,000	72,000	57,300	49,600	46,500	45,400
30	2,540,000	472,000	208,000	110,000	68,500	49,200	39,000	33,400	30,900	30,300
40	298,000	207,000	118,000	71,000	46,900	34,400	27,200	22,900	20,300	19,200
50	118,000	104,000	69,900	45,900	31,300	23,000	17,700	14,800	13,500	13,000
60	55,900	51,400	41,000	29,400	20,400	14,700	11,600	9,670	8,700	8,360
70	32,500	30,100	24,000	17,900	13,200	10,100	8,150	6,800	6,100	5,860
80	18,100	17,200	14,700	11,400	8,740	6,900	5,660	4,800	4,320	4,150
90	10,600	10,100	8,700	7,020	5,630	4,640	3,960	3,530	3,320	3,270
100	6,500	6,160	5,540	4,800	4,000	3,380	3,000	2,730	2,590	2,540
110	4,320	4,120	3,750	3,320	2,880	2,500	2,260	2,110	2,030	2,010
120	2,940	2,830	2,640	2,440	2,220	1,970	1,840	1,750	1,700	1,690
130	2,020	1,980	1,930	1,860	1,770	1,720	1,630	1,570	1,540	1,530
140	1,630	1,620	1,610	1,570	1,540	1,500	1,450	1,420	1,390	1,390
150	1,410	1,410	1,400	1,370	1,350	1,330	1,310	1,280	1,260	1,260
160	1,240	1,240	1,240	1,240	1,240	1,240	1,240	1,240	1,230	1,230
170	1,180	1,180	1,180	1,180	1,180	1,180	1,180	1,180	1,180	1,180
180	1,180	1,180	1,180	1,180	1,180	1,180	1,180	1,180	1,180	1,180

RADIANCE DISTRIBUTION
CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 16.6 Meters θ = Tilt Angle Φ = Azimuth Angle

θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	59,100	59,100	59,100	59,100	59,100	59,100	59,100	59,100	59,100	59,100
10	121,000	111,000	93,100	74,100	59,900	48,700	41,000	36,500	34,000	33,200
20	350,000	183,000	109,000	71,500	49,400	36,900	29,100	24,400	21,900	21,200
30	385,000	169,000	86,200	53,000	36,300	26,700	20,400	16,700	14,600	13,800
40	88,200	75,900	53,500	35,700	24,500	17,900	13,600	10,300	9,380	8,780
50	45,300	41,000	31,700	21,700	14,900	11,100	8,550	6,860	5,880	5,490
60	24,400	22,500	17,400	12,500	9,030	6,950	5,500	4,590	3,960	3,670
70	12,400	11,200	9,100	7,230	5,670	4,520	3,460	3,040	2,670	2,530
80	6,750	6,360	5,490	4,510	3,640	2,990	2,500	2,130	1,870	1,750
90	4,050	3,770	3,280	2,790	2,340	1,970	1,660	1,440	1,310	1,250
100	2,360	2,280	2,070	1,800	1,540	1,330	1,180	1,070	990	964
110	1,520	1,470	1,350	1,210	1,090	982	891	832	796	778
120	1,010	995	946	884	816	758	711	684	666	656
130	740	732	717	685	658	633	606	584	572	564
140	595	587	581	566	550	536	522	512	510	510
150	502	499	497	495	486	480	472	465	462	462
160	451	451	451	450	447	443	439	434	433	433
170	422	422	422	422	422	422	422	422	422	422
180	418	418	418	418	418	418	418	418	418	418

RADIANCE DISTRIBUTION
CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 29.0 Meters θ = Tilt Angle Φ = Azimuth Angle

θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	9,630	9,630	9,630	9,630	9,630	9,630	9,630	9,630	9,630	9,630
10	14,300	13,300	12,000	10,600	9,460	8,410	7,540	6,850	6,330	6,080
20	22,100	16,300	12,100	9,530	7,730	6,440	5,490	4,750	4,220	3,980
30	20,000	13,500	9,280	6,990	5,560	4,620	3,900	3,320	2,880	2,680
40	9,970	8,090	6,080	4,740	3,820	3,110	2,590	2,180	1,820	1,660
50	5,110	4,610	3,750	3,040	2,490	2,030	1,650	1,350	1,100	993
60	2,780	2,490	2,070	1,730	1,440	1,210	1,010	842	708	651
70	1,440	1,330	1,140	986	839	719	618	530	455	425
80	799	739	657	579	505	444	389	343	303	281
90	470	447	412	365	323	287	254	225	202	191
100	293	278	256	231	210	192	175	159	148	143
110	191	185	172	159	150	138	129	121	113	111
120	135	130	123	116	110	105	98.9	94.2	90.0	88.6
130	99.2	97.0	93.6	90.1	87.3	84.1	80.5	78.3	76.4	75.5
140	79.6	78.4	76.4	74.6	73.4	72.1	70.5	69.1	67.8	66.5
150	68.3	67.6	66.3	65.8	64.7	63.7	62.8	61.8	61.3	60.6
160	60.4	59.9	59.6	59.1	58.9	58.5	58.1	58.0	57.4	57.3
170	56.2	56.2	56.2	56.2	56.2	56.2	56.2	56.2	56.2	56.2
180	55.2	55.2	55.2	55.2	55.2	55.2	55.2	55.2	55.2	55.2

RADIANCE DISTRIBUTION
CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 41.3 Meters θ = Tilt Angle Φ = Azimuth Angle

θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	1,380	1,380	1,380	1,380	1,380	1,380	1,380	1,380	1,380	1,380
10	1,650	1,600	1,510	1,410	1,320	1,250	1,180	1,120	1,070	1,050
20	1,680	1,580	1,420	1,270	1,120	1,010	910	822	750	721
30	1,260	1,180	1,049	921	811	716	631	557	496	474
40	859	800	700	614	533	465	408	361	322	306
50	510	478	426	376	333	294	259	229	202	191
60	300	285	254	222	194	170	149	132	117	111
70	165	156	143	126	113	101	90.2	80.6	73.2	70.8
80	88.9	84.5	79.1	72.5	66.6	60.8	55.7	50.9	47.3	45.2
90	51.3	50.4	47.7	44.9	41.7	38.6	36.0	33.4	31.4	30.4
100	33.5	32.5	30.7	28.9	27.2	25.6	24.1	22.8	21.7	20.9
110	21.8	21.5	20.9	19.9	19.0	18.1	17.4	16.7	16.0	15.7
120	15.8	15.8	15.4	14.9	14.3	13.8	13.3	12.9	12.5	12.3
130	12.3	12.2	12.0	11.7	11.5	11.2	11.0	10.8	10.6	10.5
140	10.2	10.1	10.0	9.90	9.78	9.65	9.57	9.45	9.33	9.02
150	8.75	8.73	8.66	8.63	8.57	8.53	8.46	8.40	8.35	8.34
160	7.88	7.88	7.88	7.88	7.87	7.87	7.87	7.87	7.86	7.86
170	7.53	7.53	7.53	7.53	7.53	7.53	7.53	7.53	7.53	7.53
180	7.43	7.43	7.43	7.43	7.43	7.43	7.43	7.43	7.43	7.43

RADIANCE DISTRIBUTION
CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 53.7 Meters θ = Tilt Angle Φ = Azimuth Angle

θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	202	202	202	202	202	202	202	202	202	202
10	219	218	212	205	194	184	173	163	157	155
20	194	192	180	168	156	143	132	123	116	113
30	139	137	130	120	110	98.8	89.8	82.7	77.6	75.5
40	88.7	87.2	82.9	77.0	70.7	63.9	58.2	53.3	49.9	48.6
50	52.7	52.3	50.1	47.1	43.7	39.6	36.2	33.4	31.2	30.0
60	32.0	31.2	29.6	27.4	25.1	23.1	21.3	19.9	18.8	18.4
70	17.8	17.6	16.9	16.0	14.9	13.8	12.8	12.0	11.4	11.2
80	10.3	10.2	9.87	9.32	8.80	8.28	7.82	7.48	7.14	7.02
90	6.27	6.17	5.98	5.70	5.50	5.27	5.06	4.87	4.67	4.58
100	4.00	3.98	3.91	3.78	3.63	3.49	3.37	3.26	3.18	3.17
110	2.67	2.65	2.63	2.60	2.54	2.46	2.41	2.34	2.31	2.30
120	1.99	1.98	1.97	1.94	1.91	1.86	1.82	1.79	1.76	1.75
130	1.54	1.53	1.53	1.52	1.51	1.48	1.47	1.46	1.45	1.44
140	1.30	1.30	1.30	1.29	1.28	1.28	1.28	1.27	1.27	1.27
150	1.16	1.16	1.16	1.15	1.15	1.15	1.15	1.15	1.15	1.15
160	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
170	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
180	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990

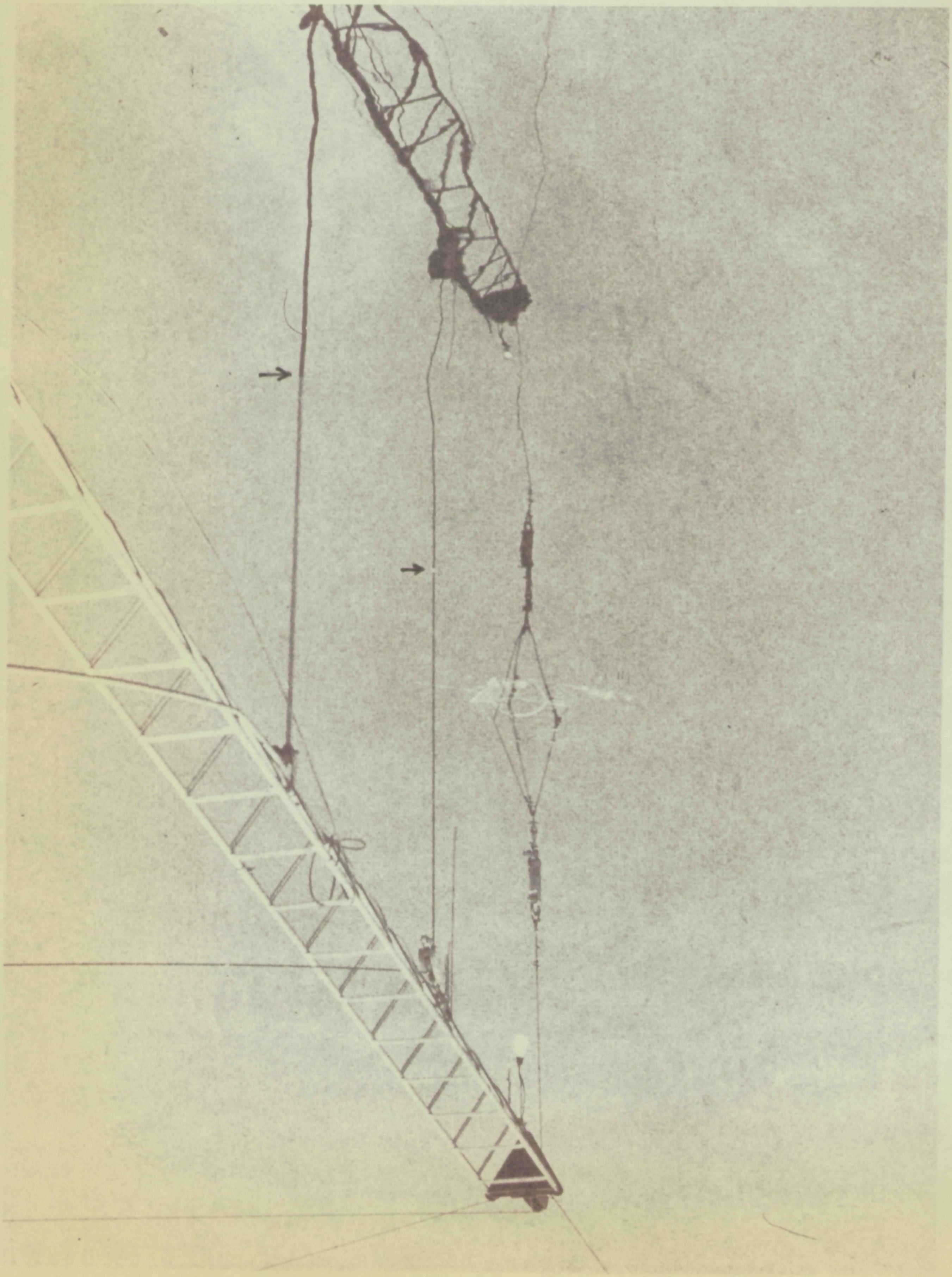
RADIANCE DISTRIBUTION
CLEAR SUNNY SKY

Sun Altitude 56.6° Depth = 66.1 Meters θ = Tilt Angle Φ = Azimuth Angle

θ \ Φ	0	20	40	60	80	100	120	140	160	180
0	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
10	29.8	29.6	29.2	28.4	27.7	26.9	26.1	25.3	24.5	24.1
20	26.1	25.7	24.7	23.8	22.8	21.6	20.6	19.6	18.9	18.5
30	19.7	19.3	18.5	17.5	16.5	15.6	14.6	13.8	13.1	12.8
40	12.7	12.4	11.9	11.3	10.6	10.1	9.44	8.87	8.41	8.19
50	7.64	7.54	7.20	6.83	6.46	6.09	5.70	5.40	5.14	5.01
60	4.43	4.34	4.18	3.98	3.78	3.58	3.38	3.20	3.08	2.98
70	2.46	2.44	2.37	2.29	2.20	2.11	2.01	1.92	1.86	1.81
80	1.43	1.42	1.39	1.35	1.29	1.25	1.19	1.14	1.11	1.09
90	0.858	0.855	0.839	0.817	0.788	0.757	0.727	0.700	0.677	0.661
100	0.531	0.525	0.518	0.506	0.496	0.482	0.468	0.453	0.445	0.439
110	0.357	0.355	0.349	0.342	0.334	0.325	0.317	0.311	0.305	0.301
120	0.252	0.250	0.247	0.244	0.241	0.239	0.235	0.233	0.231	0.226
130	0.186	0.184	0.184	0.181	0.180	0.179	0.177	0.175	0.173	0.172
140	0.146	0.145	0.145	0.144	0.144	0.143	0.142	0.141	0.141	0.139
150	0.124	0.124	0.124	0.122	0.122	0.121	0.121	0.120	0.120	0.120
160	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108
170	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
180	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975	0.0975

Figure 4

Optical state of the lake surface on 28 April. Arrows indicate points where wires pass thru interface.



instrument errors, reading and plotting errors, errors made in setting and and holding azimuth positions, and in fact all errors that have entered the measurements before their presentation in the tables.

In the direction of the sun, azimuth steps of 20° move the acceptance cone by a distance which is almost equal to its base diameter. If the air-water boundary were flat the sun's image would therefore be within the cone only once during this group of azimuth settings. However, the direction of the sun is a glitter pattern whose size depends on the optical state of the surface (which in turn depends on the wind velocity). During the measurements of 28 April the wind velocity was less than 1 $\frac{m}{sec}$, which would indicate a glitter pattern considerably smaller than 10° in angular subtense* but larger than a single sun image. ~~Due~~ owing to the optical state of the surface on 28 April this glitter pattern probably consisted of widely separated points of light. Because of the geometry discussed above, it is possible that the solid angle of acceptance never covered more than half of the glitter pattern. This would mean that the reading obtained in the sun's direction could be low by a factor of 2 in the worst case.

In certain directions, and especially at the shallow stations, the presence of the glitter generates a noise signal which varies in both frequency and amplitude as a function of depth. Typical high and low values of this noise together with its frequency are given in Table XI. In Tables IV thru X average experimental values for radiance are reported in these directions.

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* Cox and Munk, (9) have found that the glitter pattern subtends an angle of 10° when the wind velocity is 7.m/sec.

Table XI

Depth	Maximum Variation from Mean Radiance	Frequency
4.24 Meters	+ 93.6%	128/min (about)
10.43	± 75.0	74
16.65	± 47.4	60
28.95	± 10.5	50

Amplitude and frequency of the noise signal in the direction of the sun.

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Radiance distribution data taken at the Lake Winnepesaukee Field Station at a fixed depth (in 1956) established the need for an instrument with remote azimuth control which could be hung from a single supporting cable. Concepts like this come with ease, but the reduction to practice can be quite another matter. The difficult job of engineering, building, and testing this new underwater photometer was done by Mr. Roswell W. Austin, Research Engineer at the Visibility Laboratory, and a group of co-workers, including Theodore Petzold, Mechanical Engineer and Robert Howarth, Electronic Engineer. Their excellent workmanship is amply demonstrated by the success of this experiment, and is gratefully acknowledged. Procurement of a Sperry Gyrosyn Compass system was a special problem ably solved by Commander Carrol Walsh whose help in this and other respects is gratefully acknowledged.

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