SVENSKA
HYDROGRAFISK-BIOLOGISKA KOMMISSIONENS
SKRIFTER

Ny serie: Hydrografi XIV.

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NILS G. JOHNSON AND *GÖSTA LILJEQUIST*

Received from *Svenska Hydrografisk-Biologiska Kommissionen, Hydrografiska avdelningen,* Göteborg 3

Skrifter, Ny serie, Hydrografi N:o 12, 13

Fyrskeppsundersökning år 1933

Date

Signature

Svenska Hydrografisk-Biologiska Kommissionen

BORNÖ STATION
GÅSEBERG
SWEDEN

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LUND
PRINTED BY HÅKAN OHLSSON
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DURING the last years the use of selenium rectifying photo-elements has made it possible to develop a novel and simple technique for measuring submarine daylight. Such measurements are of fundamental importance for the study of various problems met with in oceanography and marine biology. In May 1936 the International Council for the Exploration of the Sea set up a subcommittee for submarine measurements, i. e. for discussing methods and units of light- and transparency-measurements. A draft report based on the committee's deliberations was published by HANS PETTERSSON and HORACE H. POOLE »Measurements of Submarine Daylight»[1] (Compare also W. R. G. ATKINS and H. H. POOLE[6]), in which details of the routine work are treated. In all daylight measurements it is recommended to mount the cell behind an opalflashed glass, at first introduced by POOLE and ATKINS.[2] The cell when facing upwards in the manner here described will react on the vertical component of the light flux only, since effect of oblique rays are reduced according to the cosine law, assumed to hold accurately. However, for many purposes it is important to know the total light flux rather than its vertical component. For instance, when studying the production of organic matter in the sea by the photosynthesis of phytoplankton we want to know the total flux of radiant energy incident from *all* directions on a plankton cell suspended in the water. Therefore, it is necessary to know the distribution of the radiant energy over the unit sphere, i. e. the angular distribution of the submarine light.

In connection with the studies of submarine illumination, of the transparency of sea-water and of their interrelationship with biological phenomena in the sea which have been carried out by Svenska Hydrografisk-Biologiska Kommissionen since 1933,[3] we have undertaken to investigate the angular distribution of subsurface light, a subject which has so far been very little studied. In the spring of 1936 a photometer for measuring the relative light intensities from various directions in the water was constructed at Bornö Station. At first the apparatus was submerged from the point of the observation pier at Bornö but the rocks, cutting off a great deal of the diffuse light from the sky, were found to affect the measurements. Later experiments, therefore, have been carried out from the research ship »Skagerak». — Another photometer with a shadowing screen for studying the zonal distribution of subsurface light has been in use since the summer of 1936.

A preliminary account of the investigations was given by HANS PETTERSSON[8] at the meeting of the Council in May 1938.

Purpose of the investigations.

From a practical point of view the most important question to settle was the following: Is it possible to find a factor with which the readings of a horizontal cell (+ opalflashed glass) in the water are to be multiplied in order to get the total illumination? How does this factor depend on

1) the character of the radiation, especially on the sun's altitude and on the amount of diffuse daylight,
2) the depth,
3) the opacity of the water,
4) the wind?

Further, how will these factors affect the different light components (different colours).

Also, from a theoretical point of view, it is of interest to study how the angular distribution of both the diffuse and the directed components of submarine light vary with increasing depth under different conditions.

Earlier measurements.

Several scientists have carried out experiments for measuring the upward component of the submarine illumination with an inverted photometer. CLARKE[4] found in the deep basin in the Gulf of Maine a ratio between the upward and the downward components of 2,5 % which remained constant down to a depth of 20 m. From experiments made in the waters of the San Juan Archipelago UTTERBACK[5] has for three narrow spectral bands found the above mentioned ratio to vary with the depth.

Some measurements of the horizontal components of submarine light incident on a vertical cell should also be mentioned. POOLE and ATKINS[2] state that the ratio between the horizontal and the vertical light in the English Channel amounts to about 50 % and is almost independent of depth down to 25 m. — CLARKE[4] used a rotating vertical photocell, and found in every depth investigated a maximum and a minimum of intensity, maximum values of the ratio varying between 6 and 20 % and minimum values between 3 and 7 %. In conclusion CLARKE states that the illumination becomes more diffuse with increasing depth, but that the directional character of the light is only slowly lost.

In 1935 POOLE and ATKINS[6] suggested the use of an integrating globe, a sphere of opal glass with additional internal diffusing surfaces mounted over a photocell, in order to measure atmospheric radiations incident on the spherical surface, irrespective of the altitude and of the azimuth of the sun. They have used this globe integrating photometer for daylight measurements in air assuming that it gives a measure of the total light, received by spherical surface.

Measurements with a screened photometer.

At first we studied the angular distribution of submarine light with an ordinary submarine photometer arranged with a shadowing screen, which can be mounted at different vertical distances above the cell. Fig. 1 shows this arrangement. The circular screen has a diameter of 60 cm. The distance A between screen and upper surface of the photometer can be varied through a range of 75 cm.

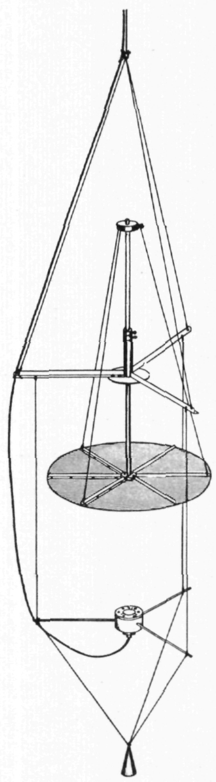


Fig. 1. The screened photometer.

In using this photometer the usual precautions recommended with the ordinary submarine photometer were observed. The cell was provided with a colour filter below an opal-flashed glass. In small depths it was necessary to shield the Lange cell with a reducing screen, made from a Schott grey-glass NG 5, 3 mm thick. This filter was cemented to an opal-flashed glass and the combination placed above the colour filter, the opal-flashed surface uppermost. In greater depths this combination was replaced by another, clear glass + opal. Comparative readings were taken before and after the change. The variations in the incident daylight above the watersurface were observed by means of a deck photometer with colour filter and reducing screen.

The measurements were carried out in rapid succession in different depths with a given value of the distance A. After changing A to a new value the measurements were repeated.

Calling U_n and U_{n+1} the readings found with two slightly different values of the distance, A_n and A_{n+1} respectively, the difference $U_n - U_{n+1}$ represents the light energy reaching the cell through the zone between the zenith distances Θ_n and Θ_{n+1}. The differences $U_n - U_{n+1}$ $(n = 0, 1, 2 \ldots)$ are reduced to the same solid angle by division by $\cos \Theta_{n+1} - \cos \Theta_n$, whereas the correction due to the cosine law is realized by a further division through

$$\cos \frac{\Theta_n + \Theta_{n+1}}{2} = \cos \Theta_m .$$

These expressions

$$\frac{U_n - U_{n+1}}{(\cos \Theta_{n+1} - \cos \Theta_n) \cos \Theta_m}$$

are then compared *inter se*. They represent the light flow received by a spherical cell through narrow, zonical apertures reduced to the same solid angle. For practical reasons we have generally worked with 6 different values of A and have in addition also used the cell without any shadowing screen, i. e. $A = \infty$.

We have set out our results in polar coordinates in the graphs of Figures 2 and 3. It should be emphasized that the »lightvector» represents by its length the average light flux (per steradian) entering through the zone indicated by the angle of the vector. Fig. 2 and 3 show two measurements with the green filter VG 9 (2 mm thick) from Schott und Genossen, Jena, one carried out in the autumn 1937 in a deep basin of the Baltic, the Bornholm Deep (55° 21′ N; 15° 39′ E) the other in Febr. 1938 in the Gullmar-fjord, Bohuslän, near Finsbo Tuva (58° 18′ N; 11° 30′ E). The following distances screen- opal were used $A = 80, 55, 40, 30, 21, 15$ cm. The two systems of curves * show clearly that the average obliquity of the light decreases with increasing depth. Fig. 4 where the angles of obliquity are plotted against the depth, indicates that the approach towards the vertical is greater in the opaque water of Finsbo Tuva than in the clearer water of the Bornholm Deep. But it should be added that in the former case the solar altitude was much smaller than in the latter.

These results confirm a statement by H. H. POOLE[7]: »It is evident that true absorption, by reducing the oblique rays more rapidly, reduces the average obliquity, and that

* The curves for the greater depths are here — as in following figures — drawn on a larger scale indicated in the graph.

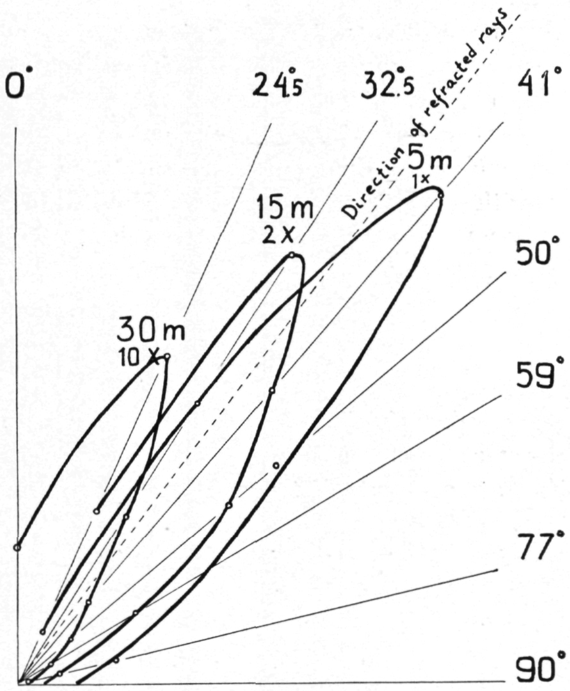


Fig. 2.

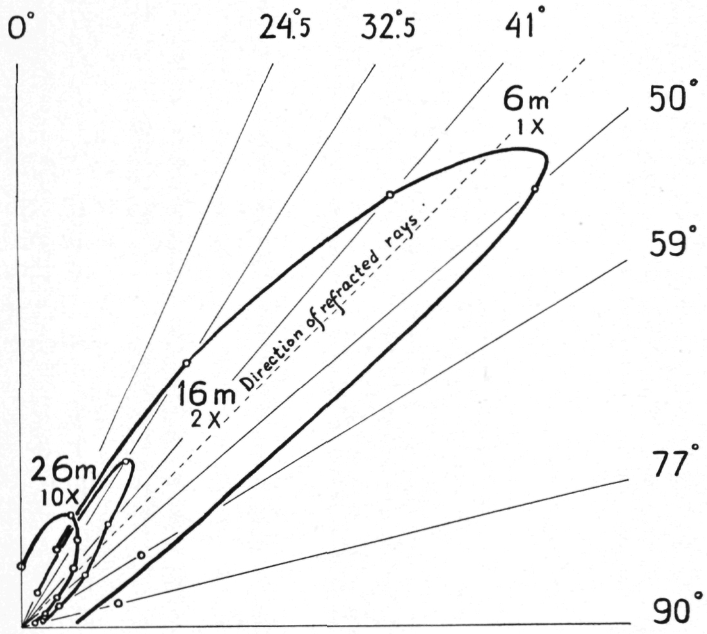


Fig. 3.

at a great depth, in the absence of all scattering the light would be almost vertical». Anyhow our experiments indicate a fairly continuous decrease of the average obliquity down to 26 m. at Finsbo Tuva, down to 30 m. at Bornholm. In these depths the inclinations to the vertical of the maximum light-vector amount to 25°.

The directional photometer.

This photometer is constructed so that the cell can be turned in any direction in the water. The cell receives a narrow cone of light (aperture 15°) limited by three diaphragms of a cylindrical screen. The diaphragm close to the cell is provided with a circle of holes screened from light round the photometer case, in order to admit water into the screen when the photometer is submerged.

The photometer case is attached to one end of a short

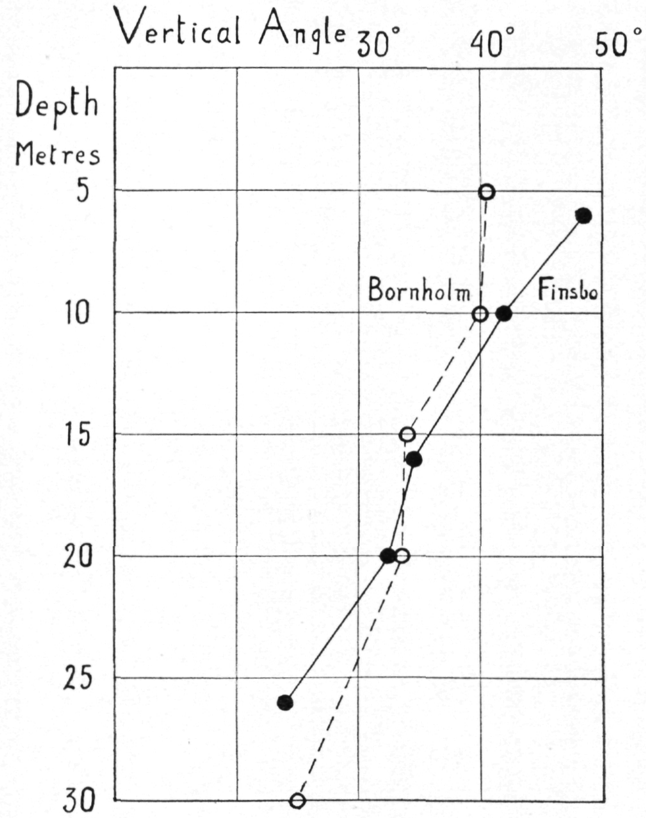


Fig. 4. The decrease of the average obliquity with depth.

bar and is balanced by a counterprise at the opposite end. The apparatus can be turned round a horizontal axis, the desired vertical angle being read off a scale after clamping the movable part by means of a screw. At both ends the horizontal axis is supplied with a guide through which runs a wire. The wires kept taught with heavy weights define the azimuthal angle of the photometer and also serve to keep the vertical angle constant. The photometer suspension is movable upwards and downwards, in addition to which the whole bifilar arrangement can be turned and oriented to any azimuthal angle, as will appear from Fig. 5.

In the directional photometer first constructed a small Lange cell was used (active surface 19 mm diam.). The corresponding cylindrical screen was 12 cm. in diam. and 18 cm. in length. As measurements at greater depths demanding a more sensitive photo-electric equipment were found to be desirable, a photometer was later designed for a cell of normal size (active surface 38 mm diam.). The screen was increased to 18 cm. in diam. and 27 cm. in length. At the same time — after practice with the former apparatus had given suitable vertical angles — a simple device was fitted for the automatic adjustment of the vertical angle, consisting of a hatchet wheel fastened to the horizontal axle and a pawl attached to the movable photometer. The pawl was lifted from above by a cord and the photometer was turned by means of a weight until the pawl engaged the next tooth. The toothed wheel was spaced for successive adjustment to the following vertical angles: 0°, 10°, 20°, 30°, 45°, 60°, 90°, 180°.

The whole outfit was mounted at the end of the light 7 m. crane of the »Skagerak». Generally the ship was double-anchored with the sun athwart (Fig. 6). Measurements

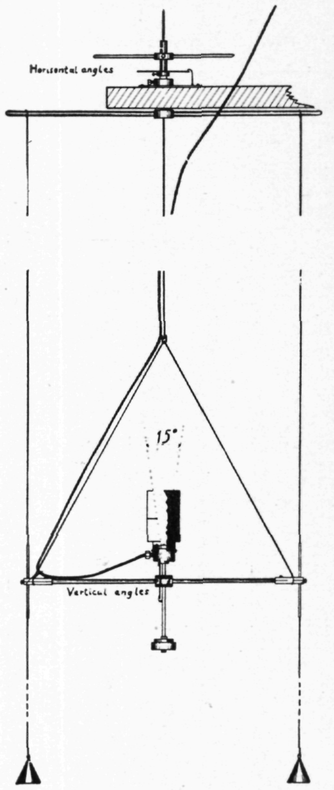


Fig. 5. The directional photometer.

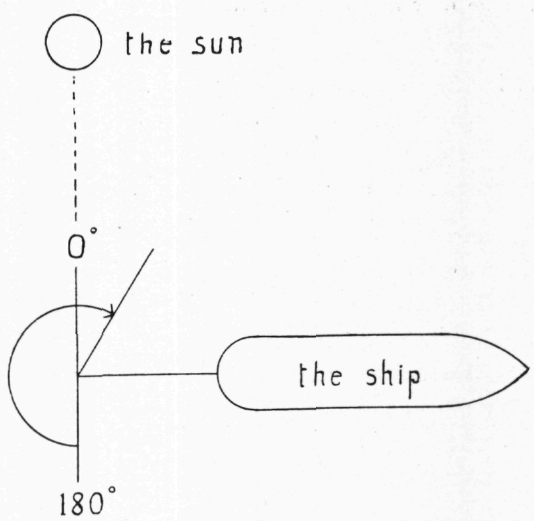


Fig. 6.

with the photometer directed towards the ship were avoided, as they were influenced by the shadow of the ship. For this reason measurements were only taken over a range of about 210° on the horizontal scale. However, plotting the light vectors in a central vector diagram the enveloping curves should be symmetrical to the direction through the sun and it is therefore permissible to extrapolate for the missing angles.

The observations were carried out under good light conditions: the daylight illumination registered by the deck photometer should not vary too much; for instance, on account of clouds passing the sun's disc. However, there is progressive change in the sun's altitude during an experiment (lasting for about one hour), and this causes a progressive change in the reading of the deck photometer. Preferably the observations were made at noon when this effect is small.

When measurements were being taken, the vertical angle of the photometer was kept constant and the readings of the galvanometer were observed at each depth for different horizontal angles by turning the bifilar suspension. For practical reasons the index was set to point to 0° on the horizontal scale when the vertical plane of the photometer coincided with that through the sun. Measurements were then usually made at the following azimuthal angles: 180°, 90°, 45°, 30°, 20°, 10°, 0°, — 10°, — 20°, — 30°.

Theoretical.

We assume that the light from the sky, including direct sunlight, comes from the surface of a hemisphere circumscribed at a great distance R round our point of observation.

Let E be the light flux per steradian emitted in a approximately radial direction by a square centimeter of the spherical surface having angular zenith distance Θ and azimuth φ. E will in general be a function of Θ and of φ.

The surface of a horizontal cell AB (F cm^2) receives from an element dS of the hemisphere (Fig. 7) a light flux:

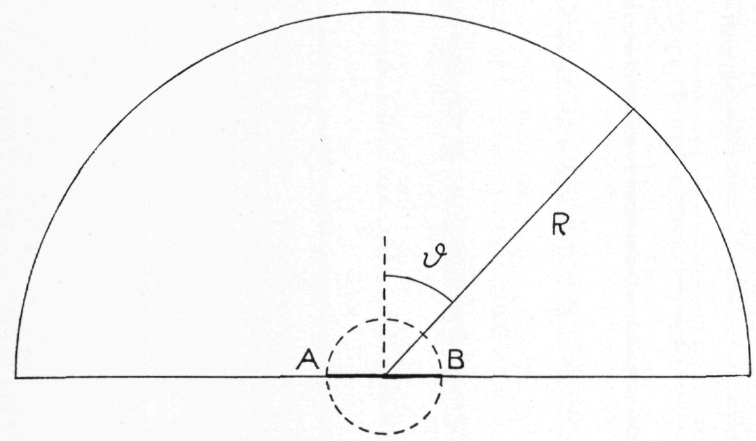


Fig. 7.

$$\frac{E\,dS\,F\cos\Theta}{R^2}$$

Integrating over the hemisphere and putting the total light flux proportional to the reading of the galvanometer U_h, the factor of proportionality being C, we get

$$U_h = CF\int E\cos\Theta\,\frac{dS}{R^2}.$$

But

$$\frac{dS}{R^2} = \sin\Theta\,d\Theta\,d\varphi$$

and hence

$$\underline{U_h = CF\int\int E\sin\Theta\cos\Theta\,d\Theta\,d\varphi.}$$

Similarly the reading for a spherical cell U_t, of the same diameter as the horizontal one (Fig. 7) should be:

$$\underline{U_t = CF\int\int E\sin\Theta\,d\Theta\,d\varphi.}$$

Our directional photometer receives through the screen within the solid angle ω (Fig. 8) a light flux:

$$\frac{E\omega R^2 F}{R^2} = E\omega F:$$

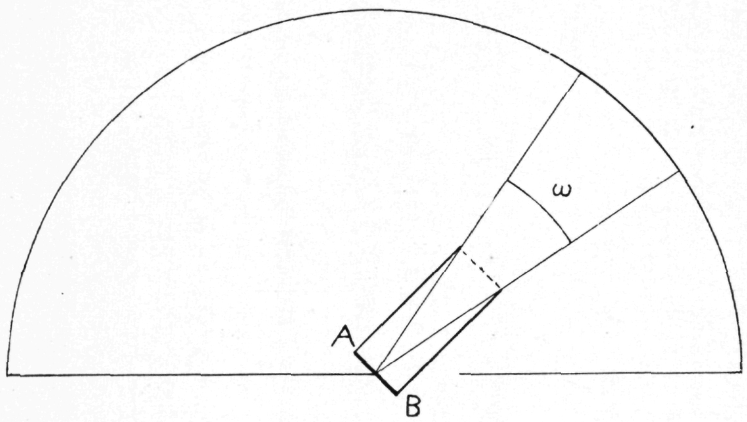


Fig. 8.

and, if the corresponding galvanometer reading is U, evidently

$$U = CE\omega F$$

Thus

$$E = \frac{U}{C\omega F},$$

U like E being a function of Θ and φ.

Hence

$$U_h = \frac{1}{\omega}\int\int U \sin\Theta \cos\Theta \, d\Theta \, d\varphi$$

and

$$U_t = \frac{1}{\omega}\int\int U \sin\Theta \, d\Theta \, d\varphi.$$

In order to get the total illumination U_t we have to multiply the reading of the horizontal cell U_h by a theoretical factor R_t given by the ratio:

$$\underline{R_t = \frac{U_t}{U_h} = \frac{\int\int U \sin\Theta \, d\Theta \, d\varphi}{\int\int U \sin\Theta \cos\Theta \, d\Theta \, d\varphi}}$$

The two integrals are simply calculated from the experimental results. From the azimuthal curves we get by integration values of $\int_0^{2\pi} U d\varphi$ for the different vertical angles Θ. These values are multiplied by $\sin\Theta$ and $\sin\Theta \cos\Theta$ respectively and then we integrate once more over Θ from 0 to $\pi/2$.

The results.

The results of the experiments 1—4 were obtained with the smaller apparatus in calm weather in fjords in Bohuslän. The cell was provided with only a colour filter. Other diagrams refer to measurements in off-shore water with some wind. In these later experiments, 5—10, an opal-flashed glass * was inserted above the colour filter in order to make possible the following comparison. In connection with the directional measurements the reading of the cell was observed when the photometer functioned as an ordinary horizontal submarine photometer, the cylindrical screen being removed and the photometer put to vertical angle 0°. Thus we can compare the reading of the horizontal cell obtained by direct experiment and that obtained by calculation from the directional measurements.

TABLE 1.

Comparison between the reading U_h of a horizontal submarine photometer obtained by experiment and obtained by calculation from directional measurements with a narrow-angle photometer. Colour filters from Schott und Genossen, Jena.

Experiment	Colour filter	Depth m	U_h Exper.	U_h Calcul.
5	VG 9	5	28000	30500
		15	2900	2880
10	VG 9	2	6960	7160
6	—	20	6430	6160
		30	1040	970
		40	178	164
7	RG 1	5	15500	14300
		15	314	314
8	BG 12	5	11200	11800
		15	505	532

Table 1 gives the results of the comparison. The discrepancies are well within the experimental errors. Really the experimental value should be a little smaller than the calculated one owing to reflexion losses at the upper surface of the opal-flashed glass. We have neglected this correction — which will be taken into consideration later —, doing so with less hesitation because our theoretical treatment is not free from objections: we have assumed that the solid angle ω is very small but we had to work with a rather large aperture of the cylindrical screen in order to get good intensity, as well as to smooth out — especially in smaller depths — the influence of waves on the submarine light.

Angular distribution of green light (VG 9).

Green light has the smallest extinction coefficient and is predominant in the submarine daylight; and most of our experiments deal with the angular distribution of green light (VG 9) in the water.

As illustration we give in Table 2 a record of measurements with the directional photometer. This experiment (10) and further Experiment 9 are not shown elsewhere in the diagrams. The column *Water* contains the readings of the submarine photometer, the column *Air* those of the deck photometer (R = Reading, Sh = Shunt). The experiment was made on an occasion when the daylight was quite diffuse

* The opal-flashed glass is flush with the metal rim surrounding the photometer window.

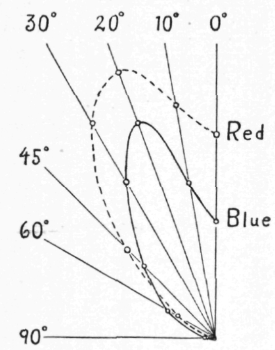
TABLE 2.

Experiment 10.

Measurement with the directional photometer at the Bornholm Deep 27. Aug. 1938. Colour filter: VG 9 (2 mm). Depth: 2 m. Sky: Quite overcast. Water: Medium transparency. Wind: 1 m/s.

Time	10^h47^m			10^h50^m			10^h55^m			10^h57^m			11^h00^m			11^h03^m			11^h05^m			11^h07^m		
Vertical angle	0°			10°			20°			30°			45°			60°			90°			180°		
	Water		Air	Water		Air	Water		Air	Water		Air	Water		Air	Water		Air	Water		Air	Water		Air
Azimuth	R	Sh	R	R	Sh	R	R	Sh	R	R	Sh	R	R	Sh	R	R	Sh	R	R	Sh	R	R	Sh	R
180°	56	10	75,4	45	10	74,9	122	3	69,7	100	3	70,9	66	3	70,8	35	1	72,9	9	1	74,3	2	1	73,2
90°				54	10	71,7	51	10	70,0	138	3	70,9	78	3	71,0	42	1	75,8	10	1	74,2			
45°				61	10	71,8	67	10	70,2	60	10	70,9	113	3	71,3	63	1	80,2	13	1	74,2			
0°				62	10	70,2	86	10	70,6	97	10	70,9	56	10	71,8	115	1	75,6	16	1	74,1			
	The screen removed																							
	61	100	68,5																					

Shunt 3 = 3,11 × Shunt 1
» 10 = 10,2 »
» 100 = 111 »



Vertical Section
90° - 270°

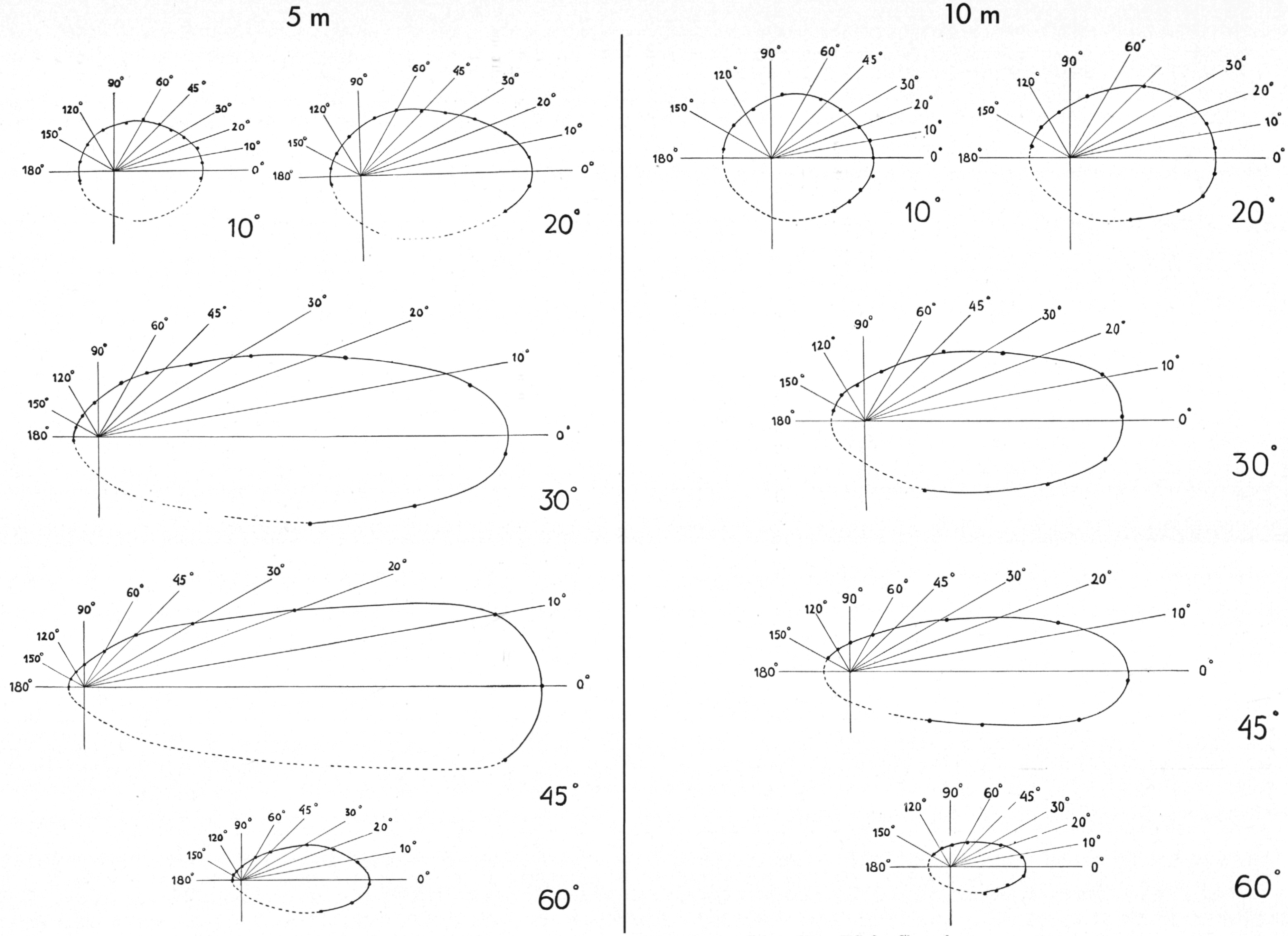
Experiment 1. Colour filter: RG 1 and BG 12. Clear sky.

and yet fairly constant. In this case observations at only four azimuthal angles were necessary to investigate the distribution of the submarine daylight.

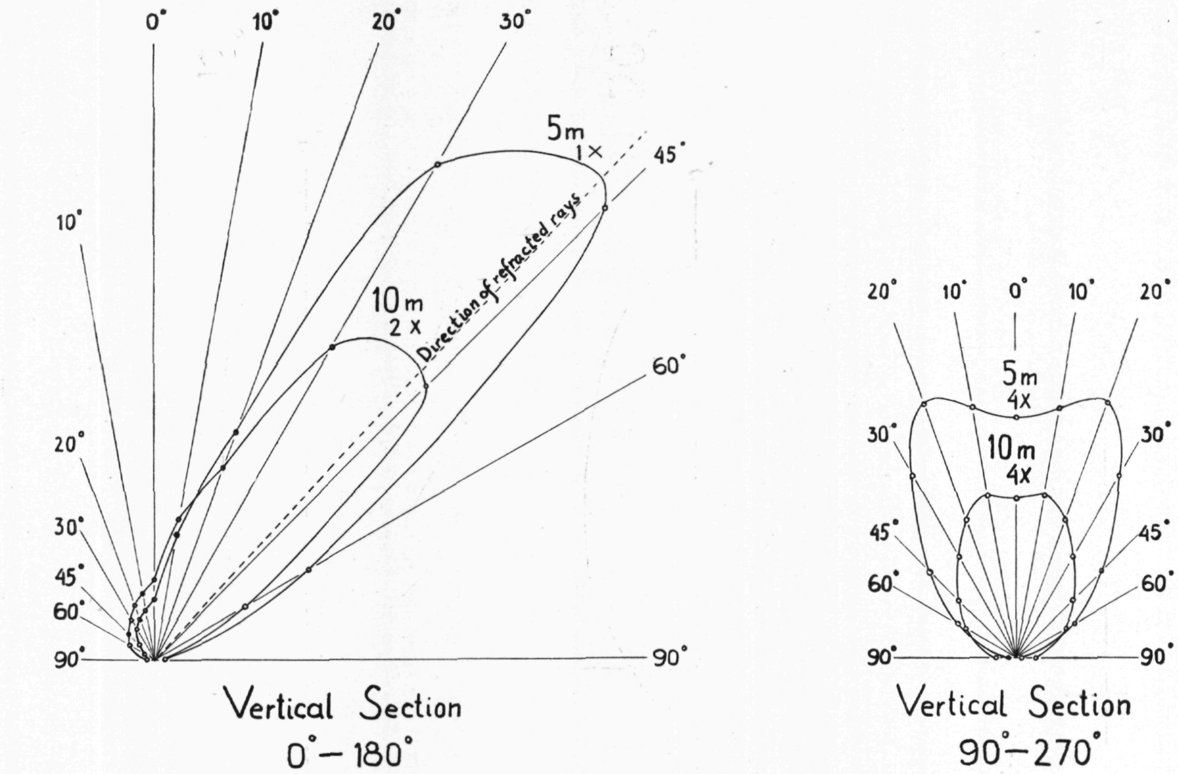
The results of other experiments are represented by two graphs for each experiment, showing the light vectors at different vertical angles in vertical planes respectively through and incident to the vertical plane of the sun. In one instance, Experiment 2, the azimuthal curves for 5 and 10 m are given, i. e. the light vectors plotted against the horizontal angles for each vertical angle. The direction of the refracted rays in the water was about 43°, this rendering the 45°-curve the most lengthened one. It is to be seen from curves made with the same vertical angle that, comparatively speaking, these curves grow on the side turned from the sun (180°) with increasing depth: through scattering the light gets more diffuse. This effect, most obvious at greater vertical angles, is conspicuous, although the difference in depth between the two system of curves is only 5 m.

We can assume the submarine daylight just below the water surface to consist of two parts: directed light mainly concentrated in and near the direction of the refracted rays from the sun, and diffuse light from the sky mainly incident within twice the angle for total reflexion $2 \times 48°,5 = 97°$. These two components, the directed part of which predominates in clear weather, are fused together in the subsurface light. It is also seen from all vertical sections 0°—180° representing measurements with VG 9 at 5 m that the direction of maximum light coincides fairly well with that of the refracted sunrays and that there is a rapid decrease of the light vectors at about 48°.

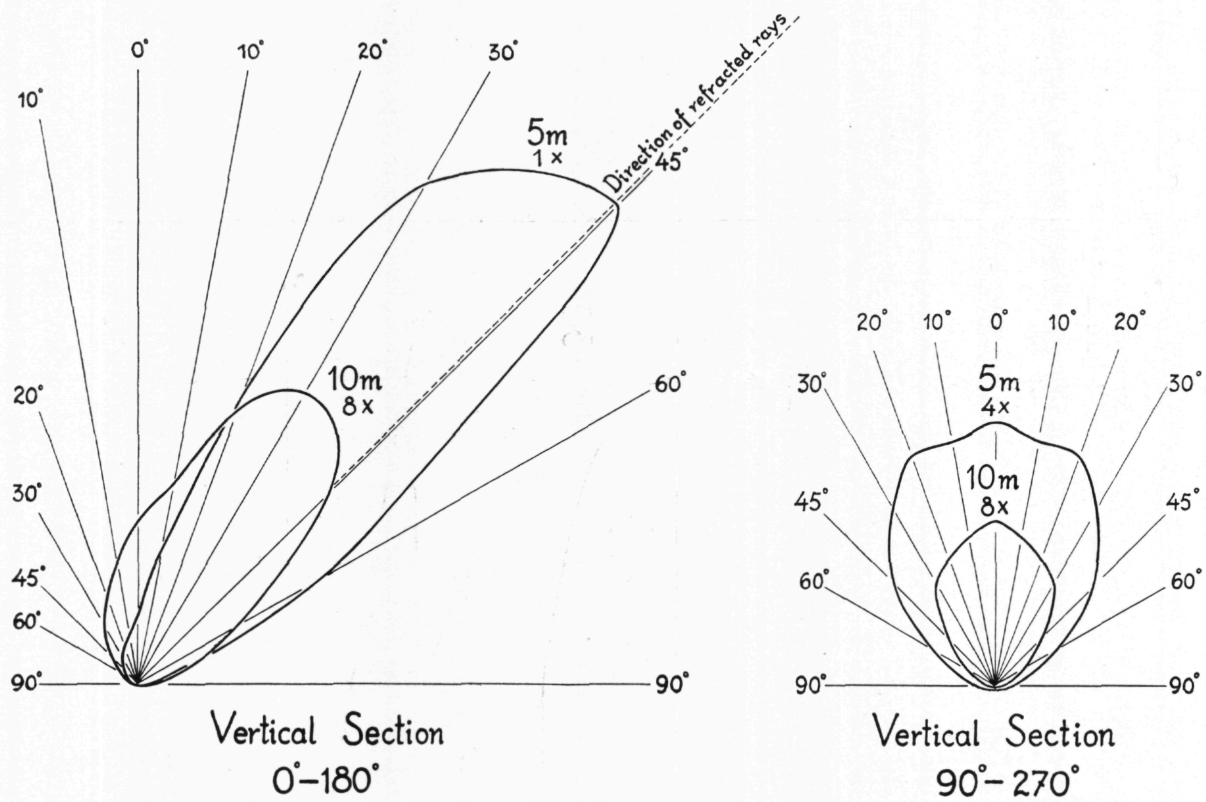
When the green light has penetrated thicker layers at 10 or 15 m depth, the shape of the curve is a little altered. There is, however, a distinct approach of the direction of the maximum light towards the vertical. The light as a whole becomes more vertical and more diffuse, but yet at 40 m (Experiment 6) made on a clear day, the light had not lost its directed character. The relative increase of the light vectors is greatest for the vertical angle 0°, but is present even up to 60° on the side »from the sun». Such an decrease in the average obliquity is to be expected, and was also verified by our measurements with the screened photometer. ATKINS and POOLE [6] concluded as a result of their above-



Experiment 2. Azimuthal curves for 5 and 10 m depth. Colour filter: VG 9. Clear sky.



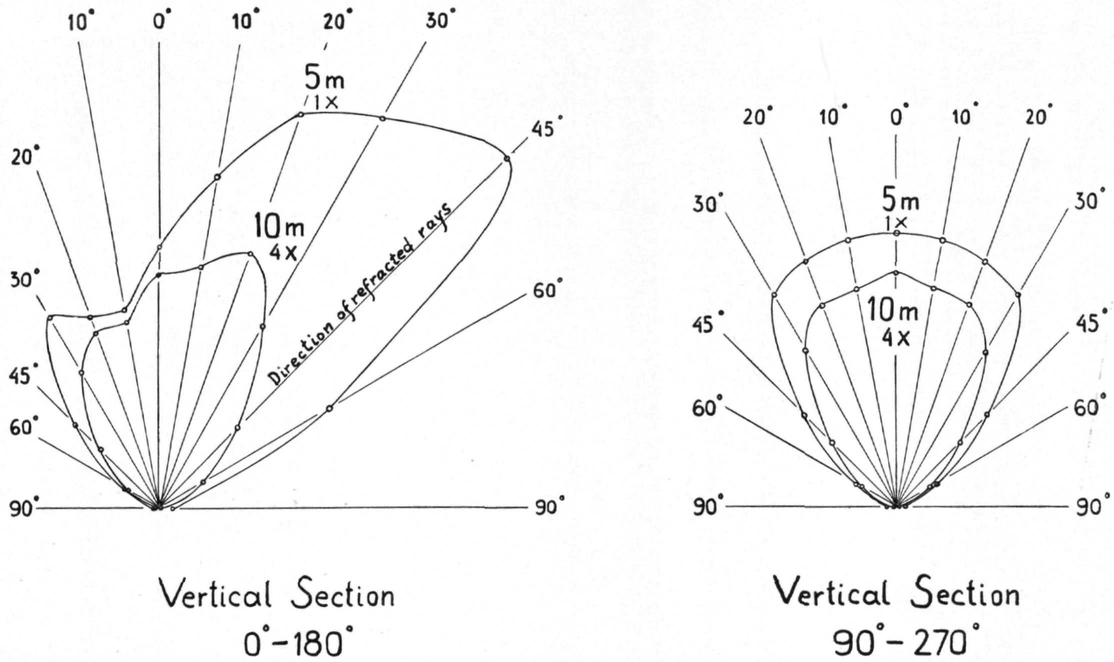
Experiment 2. Colour filter: VG 9. Clear sky.



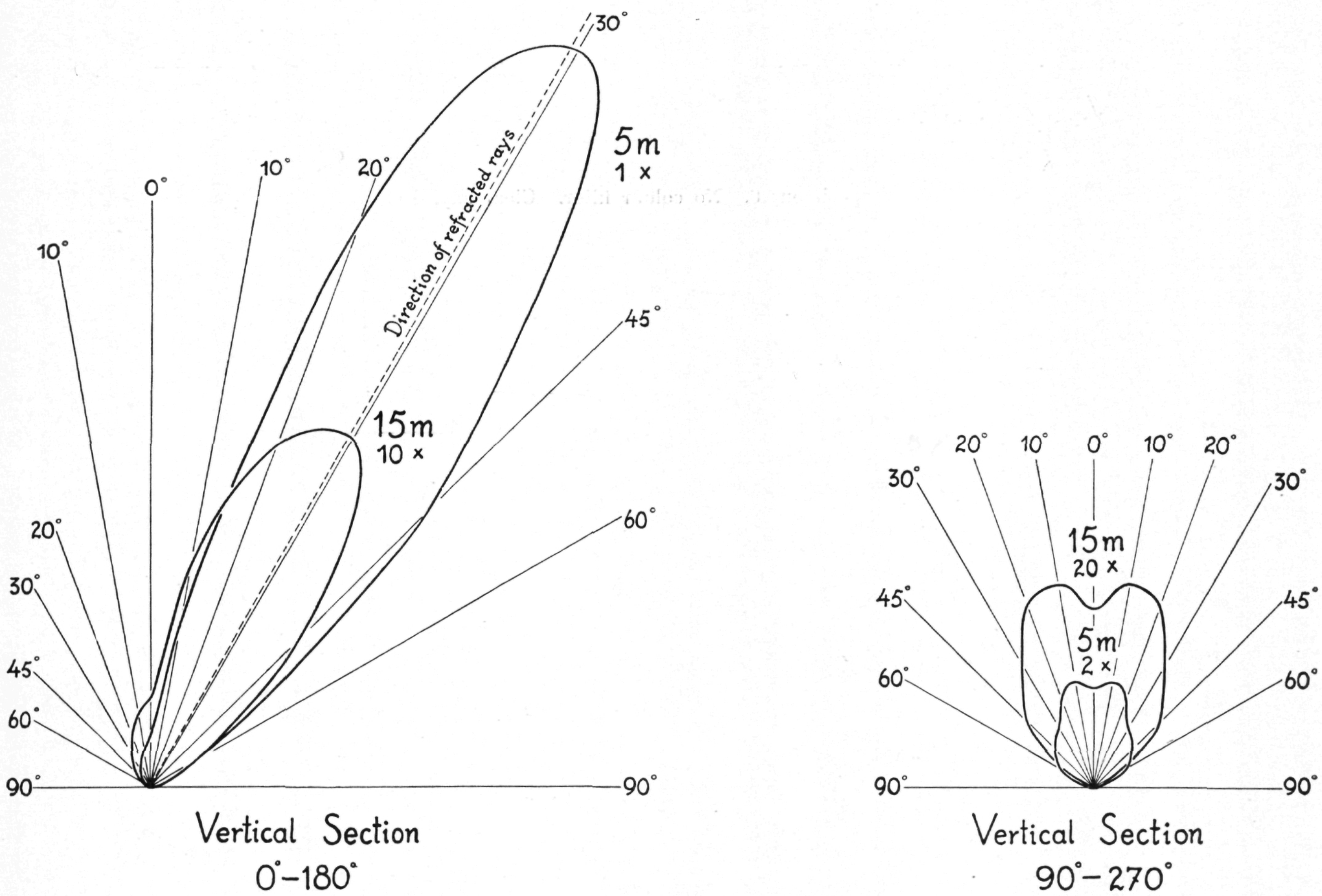
Experiment 3. Colour filter: VG 9. Clear sky.

mentioned work that »the average obliquity at the deeper levels is chiefly governed by a balance between the effects of absorption, which by filtering out the more oblique rays reduces the average obliquity, and scattering, which increases it.»

When studying the decrease of the average obliquity we must take into consideration both the vertical sections 0°—180° and 90°—270°. It is evident that the decrease in the average obliquity is proportional to the obliquity itself; so that the decrease is great at low solar altitude and vice versa, which is evident from a comparison of the experiments 3 and 5. This conclusion, supported by the measurements with the screened photometer refers to observations on clear days. When diffuse light predominates (Experiment 4) the direction of maximum light is not very definite and is fairly independant of the solar altitude, but, naturally, there is also in this case a decrease of the average obliquity with the depth.

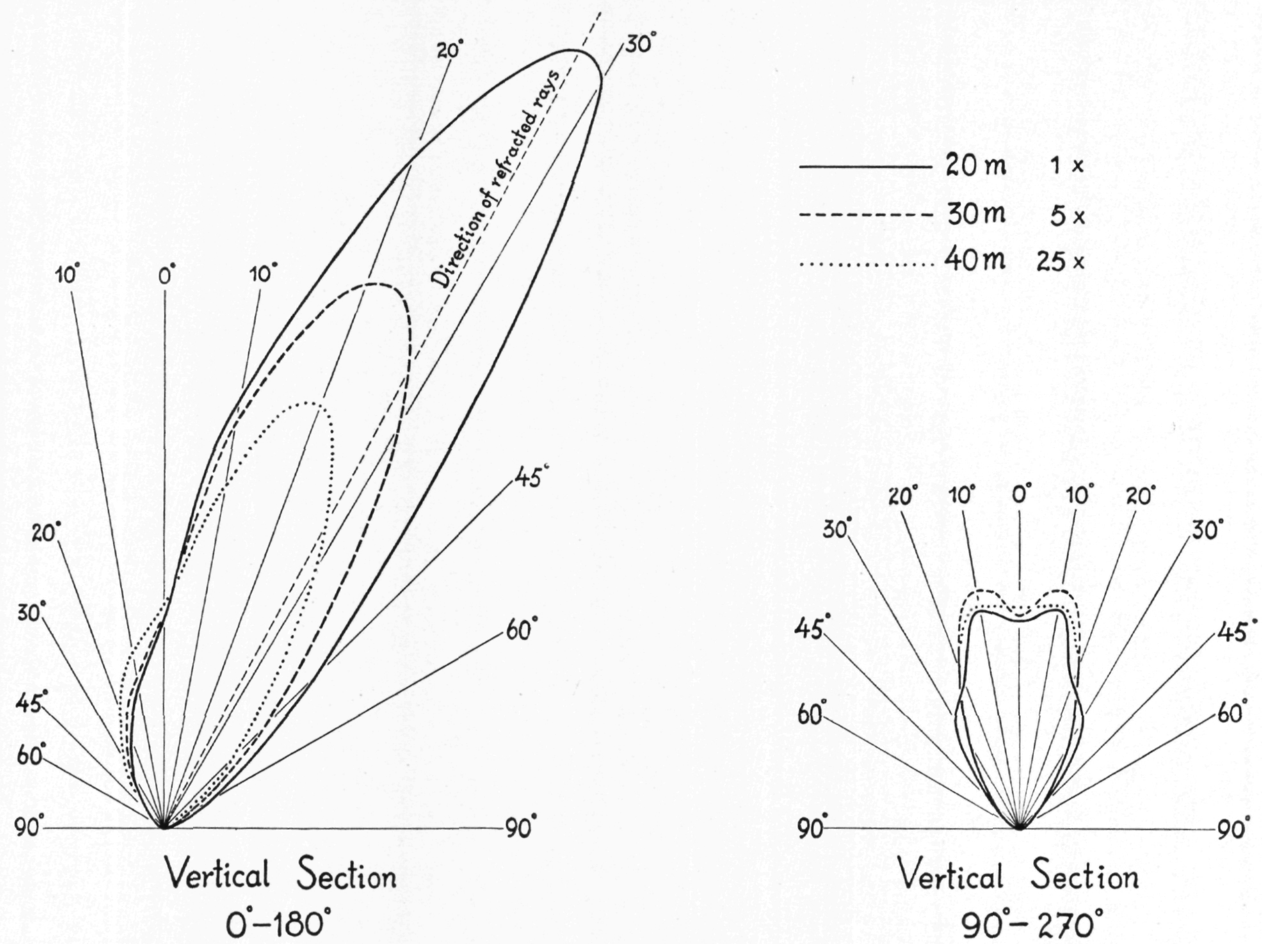


Experiment 4. Colour filter: VG 9. Clouded sky.

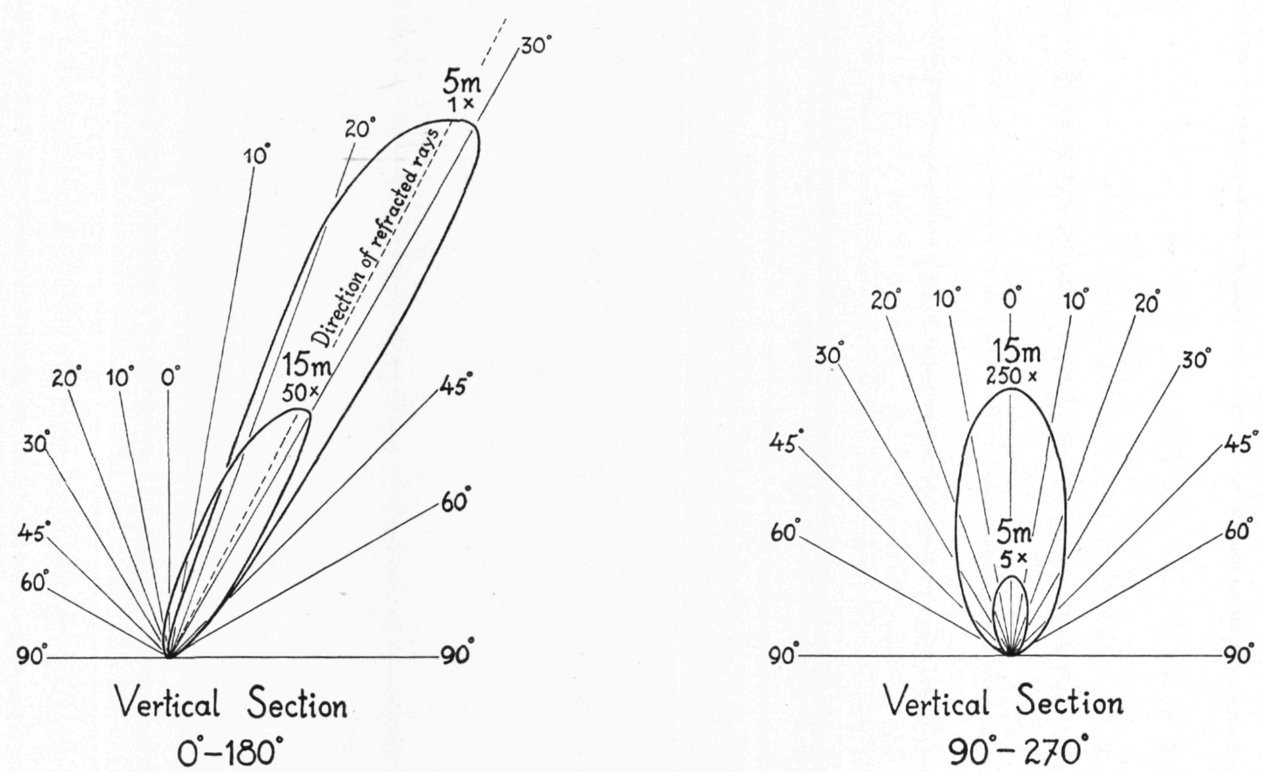


Experiment 5. Colour filter: VG 9. Clear sky.

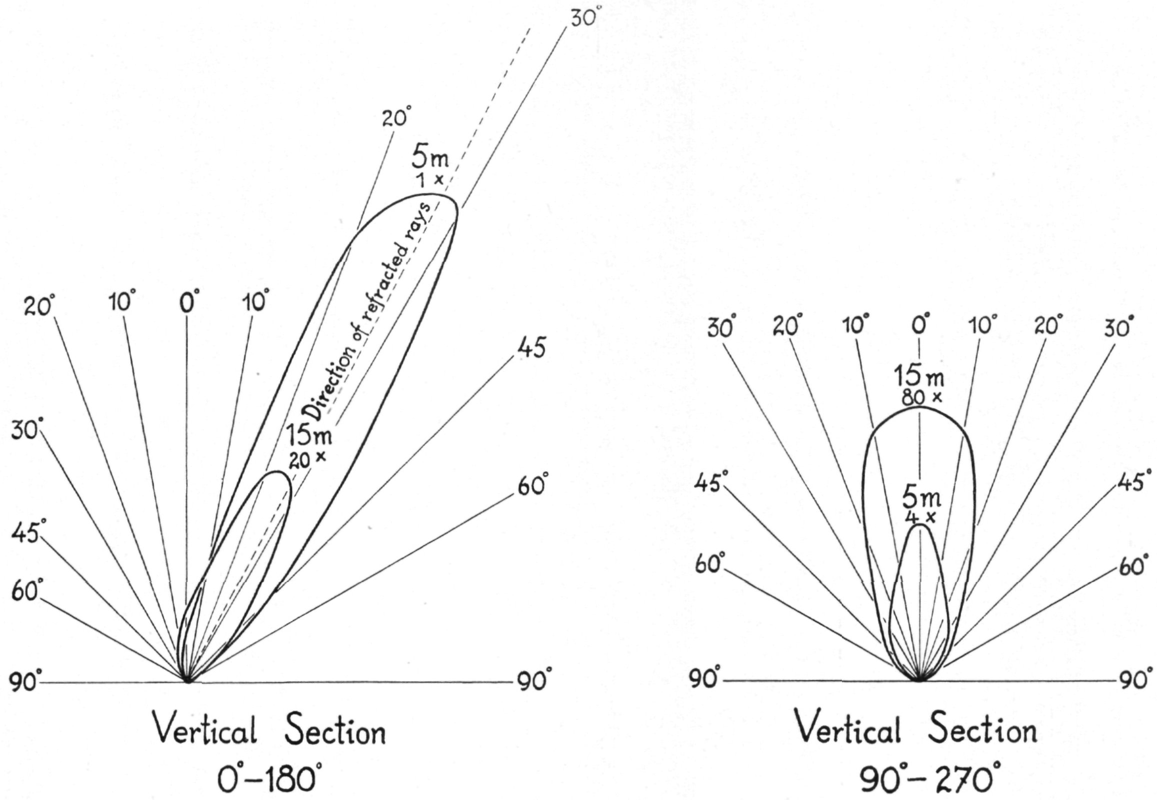
It is seen that most curves representing the vertical sections are not quite smooth, showing a slight concavity in the upper part. From investigations on the distribution of sky brightness it is well known (Fig. 9) that there is a darkest point in the sky nearly 90° from the sun on the same vertical circle. As the skylight below the surface becomes mainly concentrated within an aperture of $2 \times 48°,5$, this minimum must be more marked in subsurface illumination — leaving out reflexion losses at the water surface — and is probably the cause of these anomalies in our curves. On the other hand, the structure and distribution of clouds can lead to an anomalous distribution of subsurface light as apparent in the curves. However, such effects have been avoided in our experiments.



Experiment 6. No colour filter. Clear sky.



Experiment 7. Colour filter: RG 1. Clear sky.



Experiment 8. Colour filter: BG 12. Clear sky.

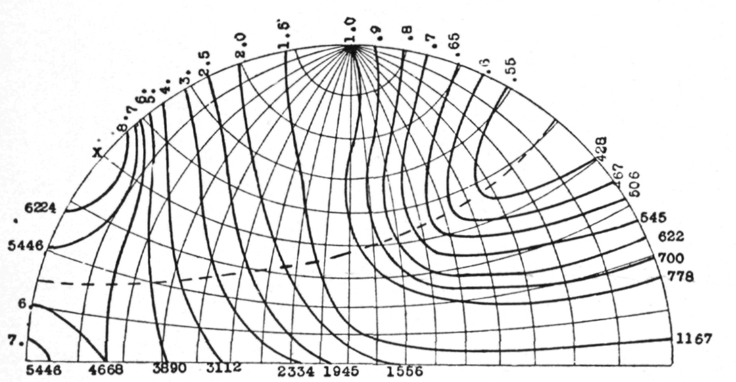


Fig. 9. Distribution of sky brightness with a cloudless sky and the sun 40° above the horizon. (The position of the sun is indicated by x.) A stereographic projection of the half of the sky on one side of the sun's vertical. The figures at the top give the brightness relative to zenith brightness; the figures at the opposite ends of the lines of equal brightness give the brightness in millilamberts. (After Physics of the Earth — 3, Meteorology, p. 56.)

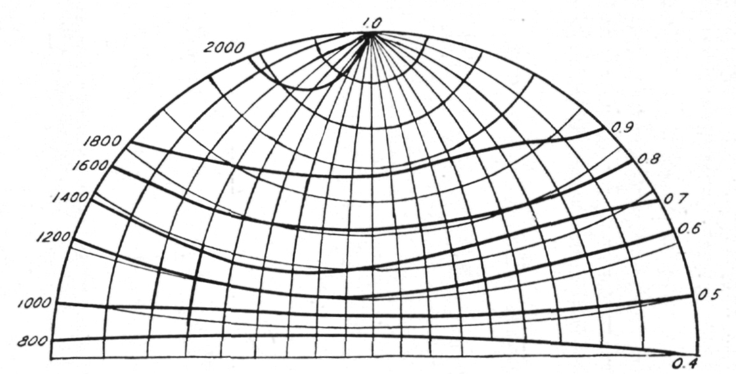


Fig. 10. Distribution of sky brightness with the sky covered with dense clouds, and the sun 40° above the horizon. (See further Fig. 9.) (After Physics of the Earth — 3, Meteorology, p. 57.)

The factor R_t for green light (VG 9).

In table 3 the values of the factor R_t are set out, being the results from all experiments hitherto carried out. The factors R_t are calculated according to the described theoretical procedure, but it should be emphasized that they include the amount of light energy from the lower hemisphere also: so R_t means the ratio between the total light flux from both hemispheres and its vertical component from the upper hemisphere. The factor K shows in percentages the ratio between the amounts of light from the lower and from the upper hemisphere. The table also shows the experimental conditions which could be expected to affect the factor R_t, viz. the colour filter used, the solar altitude, the cloudiness, the transparency of the water and the wind. As a measure of the transparency rough values of the vertical extinction-coefficients are given.

In clear weather R_t is in the first instance dependent on the solar altitude, decreasing when the altitude increases. However, the dependence proves to be rather small: when the altitude varies from 22° (Experiment 3) to 49° (Experiment 5) R_t decreases only from 1,51 to 1,40.

When the sky is covered with clouds, especially when the disc of the sun is screened, the diffuse light predominates over the direct light and the factor R_t is smaller than with a clear sky (Experiments 4, 9 and 10) owing to the distribution of the diffuse daylight from an overcast sky (Fig. 10), which is brightest near the zenith. In our experiments the sky was covered not with dense but with light clouds, and hence our R_t values for diffuse light are still to some extent dependent on the solar altitude.

TABLE 3. The factors R_t calculated (over the whole sphere) from the experiments. K = the ratio between the light energy from the lower and from the upper hemisphere.

Experiment	Station	Time	Solar altitude	Direction of refracted sunrays	Sky	Vertical extinction-coeff.	Wind m/s	Colour filter	Depth	K %	R_t
2	Bornö, Gullmar Fjord 58°23'N; 11°35'E	1937 October 1	25°	43°	clear	0,10	0	VG 9	5 10	3 3	1,49 1,46
3	Koster Fjord 58°59'N; 11°05'E	1938 February 21	22°	44°	clear	0,35	0	VG 9	5 10	5 6	1,51 1,50
4	Mouth of Gullmar Fjord 58°18'N; 11°30'E	February 24	20°	45°	light clouds before the sun	0,35	0	VG 9	5 10	3 3	1,37 1,34
5	The Baltic 58°39'N; 18°10'E	May 15	49°	29°	clear	0,20	6	VG 9	5 15	3 4	1,40 1,36
6	The Baltic 56°43'N; 17°29'E	May 16	52°	27°,5	clear	0,20	4	—	20 30 40	2 2 3	1,31 1,23 1,22
7	The Baltic 56°43'N; 17°29'E	May 23	52°	27°,5	clear	0,45 0,40	1	RG 1	5 15	1 1	1,23 1,23
8	The Baltic 56°43'N; 17°29'E	May 23	52°	27°,5	clear	0,45 0,40	1	BG 12	5 15	1 1	1,25 1,25
9	Kalmar Sound 56°30'N; 16°17'E	August 15	48°	30°	clouded, the sun unscreened	0,10	1	VG 9	2 5	4 4	1,32 1,32
10	The Baltic 55°21'N; 15°39'E	August 27	43°	33°	quite overcast	0,20	1	VG 9	2	4	1,33

The decrease in the average obliquity with the depth discussed above causes a corresponding decrease in the values of R_t. In all cases investigated by us this seems, however, to be small in the uppermost 15 m. The relation between R_t and the depth must be considered with due regard to the opacity of the water, as the opacity generally varies with the depth. In Fig. 11 a diagram is shown giving the decrease of R_t with the depth. The values of R_t are calculated from the results of experiments 5 and 6, the former carried out at 5 and 15 m depth with VG 9, the latter at 20, 30 and 40 m without colour filter. In view of the fact that at 20 m the light rather resembles the VG 9 light we venture to group together the results of the two experiments in spite of the fact that they were not carried out exactly at the same place though under the same conditions of solar radiation and water transparency. In the diagram the transparency-curve, got from measurements with the transparency-meter and identical in both experiments is also drawn. In the upper layers down to 15 m, where the water is comparatively opaque and the light is highly scattered, the value of R_t decreases only slowly. At greater depths increased transparency is accompanied by a more rapid decrease of R_t. Thus we have an opaque upper layer acting as a milk glass on the submarine light, rendering it more diffuse in the more transparent lower layers and filtering out more oblique rays, so that the value of R_t rapidly decreases. Then, between 30 and 40 m the curve bends again and approaches a constant value of $R_t = 1{,}22$. Thus these and other experiments (Experiment 3) seem to support Poole's contention that the decrease in the average obliquity and, therefore, in R_t is impeded in opaque water. However, the influence of the transparency on the value of R_t seems not to be considerable (Compare Experiments 2 and 3, 9 and 10).

So far as we can infer from our measurements the effect of wind and waves is to produce more diffuse light in the water, but this will only in a small degree influence the value of R_t.

Angular distribution of red and blue light.

In the foregoing we have only treated measurements with green light (VG 9). The angular distribution of the red and blue submarine daylight is of less interest. Owing to the high absorption coefficients of the red (RG 1) and the blue (BG 12) light, the scattered light, which passes through a greater thickness of water than the direct light, will soon be lost, and the submarine light will be mainly made up of light of the direction of the refracted sunrays. Even at 5 m (Experiments 7 and 8) R_t attains a value which holds at greater depths and which is a little greater than cosine for the vertical angle of the refracted sunrays.

The first directional measurement (Experiment 1) we carried out (at the extreme end of the Bornö pier) aimed at a comparison between red (RG 1) and blue (BG 12) light in a vertical plane at 90° to that of the sun. It is seen that when the light vectors from greater angeles with the vertical, the blue light increases relative to the red light, this being

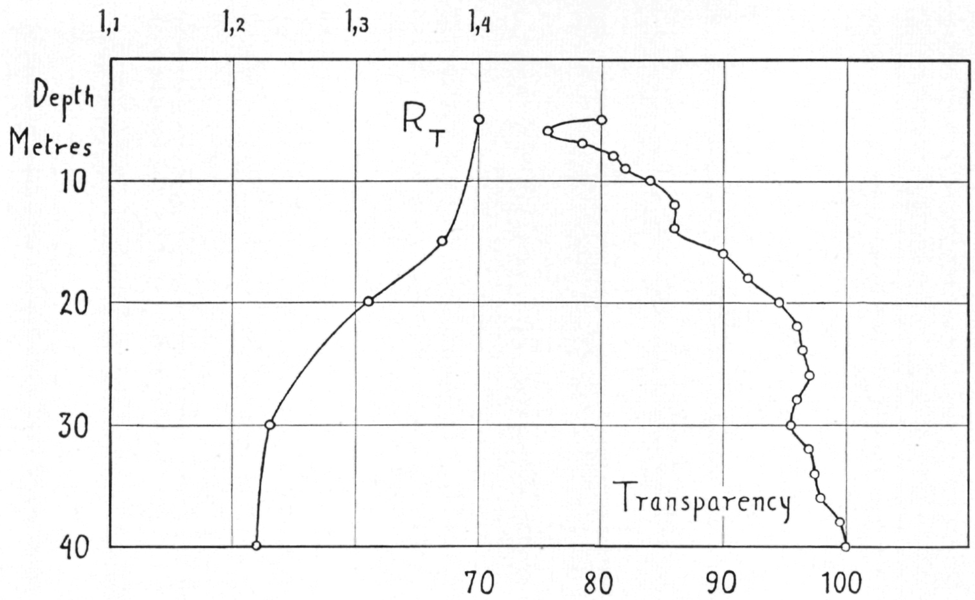


Fig. 11. The factor R_t as function of the depth and the transparency of the water. (Experiments 5 and 6.)

due to the fact that the blue light is more scattered but less absorbed than red.

The strong absorption of red and blue light appears to call for an extension of our directional measurements by a special investigation with colour filters just below the water surface, which we hope to attack in the near future.

The practical factor R_p.

We have seen that for a certain colour the angular distribution of the subsurface light is determined by several factors, among which, however, the depth, the solar altitude and the character of the prevailing daylight in the main determine the value of R_t. It should be emphasized that in the theoretical values of R_t enter no corrections for reflexion losses. Experiments by POOLE and ATKINS [7] have shown that, in order to correct for the corresponding loss of sensitivity, the readings of a photometer standardised in diffuse light, in air, have to be multiplied by 1.09 when the photometer is submerged. This factor may be employed without serious error for any photometer of ordinary type fitted with a diffusing glass above the window. In Table 4 the factors $R_p = 1.09\ R_t$ are set out and with these the readings of a horizontal submarine photometer standardized in diffuse light, in air, are to be multiplied in order to get the total illumination. Here R_p can be taken as accurate to within say $\pm$ 3 % which is sufficient for most purposes. Thus Table 4 summarizes for practical use the results from our measurements.

TABLE 4.

The factor R_p with which the readings of a horizontal submarine photometer fitted with an opal-flashed glass above the colour filter and standardised in diffuse light, in air, are to be multiplied in order to get the total illumination.

Colour filter	Depth *m*	Solar altitude	Direction of refracted sunrays	R_p Clear sky	R_p Clouded sky
VG 9	5	20°	45°	1,65	1,50
		50°	29°	1,55	1,45
	10	20°	45°	1,60	1,45
		50°	29°	1,50	
—	20	50°	45°	1,45	
	30	50°	29°	1,35	
	40	50°	29°	1,35	
RG 1	5	50°	29°	1,35	
	15	50°	29°	1,35	
BG 12	5	50°	29°	1,35	
	15	50°	29°	1,35	

Fil. Mag. S. Landberg, late Assistant to our Kommission, has kindly helped us in several of the earlier attempts. The mechanic in Bornö Station, Mr A. Fries, has very ably carried out the construction of the instruments designed for these investigations. We have also great pleasure in acknowledging our indebtedness to the officers and crew of the research ship »Skagerak», who with their usual energy and ability have assisted us in the measurements.

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