Radiance Distribution in the Upper Layers of the Sea

By N. G. JERLOV, Oceanographic Institute, Göteborg,

and

M. FUKUDA, Faculty of Fishery, Hokkaido University, Hakodate

(Manuscript received March 2, 1960)

Abstract

The angular distribution of underwater radiance for green light has been studied in the upper turbid layers of the Gullmar fjord by means of a radiance meter which is lowered in the sea along a guide wire with a fixed orientation. A theoretical discussion considers the different components entering into the light field, *viz.* direct sunlight, skylight, and scattered light. On the basis of available measurements of the volume scattering function the scattered light is evaluated by integrating light scattered from the predominant sun beam alone. The experimental angular distributions of radiance compare well with the theoretical distributions. In particular it is demonstrated that the radiance in the angle interval $\pm 45°$ from the sun attains a maximum below the surface.

Our present knowledge of the angular distribution of underwater radiant energy from sun and sky and its change with depth has been attained through a number of investigations employing specific instrumentation (JERLOV and LILJEQUIST, 1938; TAKENOUTI, 1940; WHITNEY, 1941; DUNTLEY *et al.*, 1955; SASAKI *et al.*, 1955; TYLER, 1958). It is manifest that in the upper layers the radiance distribution is much predominated by direct sunlight whereas with increasing depth the light takes a more diffuse character. At great depths an equilibrium state of distribution is approached which is symmetrical round a vertical axis. We do not know with certainty where this asymptotic radiance distribution is reached. Measurements in clear ocean water suggest a depth of about 400 m (JERLOV, 1951).

The theoretical conceptions of underwater radiance are to be based on some assumption about the volume scattering function (POOLE, 1945; LENOBLE, 1957; PREISENDORFER, 1959). Considering the great variety of particles suspended in the sea it is realized that this critical factor should preferably be determined by experiments. ATKINS and POOLE (1952) have initiated such experimental work through a laboratory study of the angular scattering of light by sea water. Recently TYLER and RICHARDSON (1958) and JERLOV (unpublished) have built and used *in situ* instruments to record the significant volume scattering function.

A great deal of interest is connected with the passage of radiant energy through the interface air-water. In his above-mentioned investigation TYLER has studied this problem in the near-surface layer of homogeneous lake water and with an overcast sky and has demonstrated some principal optical effects. The present work is also directed to the surface stratum of the sea and aims at computing for a clear sky the radiance as the resultant of different components by employing radiance quantities observed above the sea together with a simple model for integrating the scattered energy. The predicted distributions are compared to data collected by field work, especially in the near-surface layer.

Apparatus

The setting of the radiance meter at different angles requires in the first place a fixed reference direction. It is wellknown that the vertical position of a wire even if weighted is not easily established in the sea. For these experiments conducted in the Gullmar fjord at Bornö Station an accurate orientation of the radiance meter was obtained in the following way. A heavy weight was anchored at 50 m depth off the station. A wire was tightened between the weight and the station bridge in the direction west-east and with an angle of 60° from the vertical. At the observations the meter, which was provided with two wheels, was lowered along this guide wire (Fig. 1). The meter was stabilized with a weight so that its measuring head could be set at different vertical angles in a meridional plane. Land was far away from the observation point in this plane, and the disturbing effect of land contours was judged to be inconsiderable.

The meter was devised so as to present equally large surfaces above and below the guide wire so that the vertical angle would be little affected by the drag of prevailing currents. The depth change of the measuring head when rotating it was negligible.

Sufficient sensitivity was obtained by using a photovoltaic cell as detector in connexion with an Ising galvanometer (sensitivity $4 \cdot 10^{-10}$ ampères per scale-unit). By means of a lens-pinhole system the apex angle of the cone of acceptance was limited to 7.0° in water which is equivalent to 9.3° in air. A high resolving power is desirable but there is not much to gain by choosing a smaller angle because of the wave-induced fluctuations in radiance which especially tend to disturb observations close to the sun.

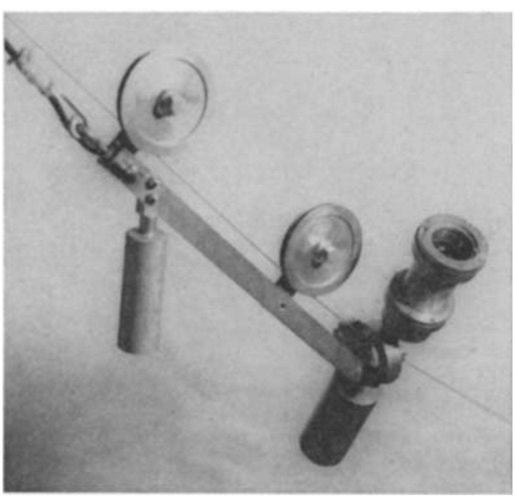

Fig. 1. The radiance meter mounted on the guide wire.

Measurements

The radiance was measured solely in a meridional plane. Usually the following settings of vertical angle at both sides of the vertical line were employed: 0°, 20°, 30°, 40°, 45°, 60°, 90°, 135° and 180°. Observations with settings close to the sun were obviously critical and must be made when the sun passed the meridian. The radiance at other angles being less dependent on the azimuth was recorded as near noon as possible. In the deep layers no attention was paid to radiance from below which is probably affected by the bottom.

Experiments were conducted in June 1958 and completed in June 1959. Weather conditions were clear sky and low wind. The sun's altitude was 48—50° which corresponds to a refraction angle in the water of about 30°.

As the chief object was to study the radiance distribution for wavelengths having maximum transmittance in the fjord water the meter was provided with a green Schott filter (4 mm VG 9, centre 535 mμ).

At the measurements the water of the Gullmar fjord showed a typical stratification with a top layer of less salinity and lower transparency than underlying layers. This water structure was studied by collecting water samples from different depths and determining their attenuation coefficient by means of an ELKO meter. The characteristic result was a homogeneous top layer with a thickness of 2 m having an attenuation coefficient of 0.5 m^{-1}. Towards greater depth the attenuation decreased rapidly. Through comparative tests on these water samples in a scattering meter (Jerlov, 1958) the total scattering coefficient in the top layer was estimated at 0.3 m^{-1}.

It would be too voluminous to present the whole supply of observations. The material lends itself to a combined representation as the data were obtained very much under the same conditions. Radiance in a logarithmic scale as a typical function of depth for different angles is given in Fig. 2. It is noted that the

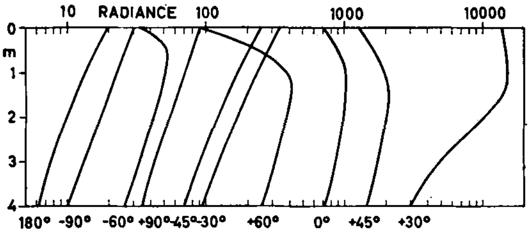

Fig. 2. Observed radiance for green light (535 mμ) as a function of depth for different vertical angles. The sun at +30°.

radiance for angles between 0° and +60° attains a maximum below the surface. This maximum is most conspicuous for +60°.

The representation of the angular distribution is restricted to 0 m and 1.86 m depth, *i.e.* to the homogeneous top layer (Fig. 3). These curves will later be compared to those theoretically derived.

An instance of radiance distribution followed to great depth is adduced in Fig. 4. It is evident that the approach to a pattern symmetrical round the vertical is for green light not fully accomplished at 30 m depth.

Theory

The different components will be considered separately, *viz.* direct sunlight, skylight and scattered light, which enter into the total flux

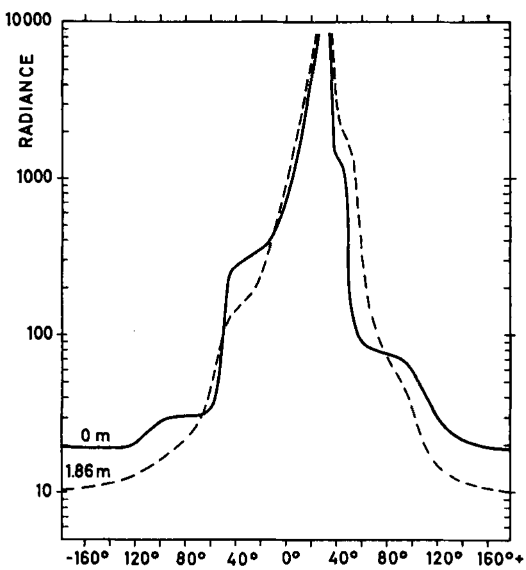

Fig. 3. Angular distribution of observed radiance (535 mμ) at surface and at 1.86 m depth.

available to the radiance meter. The discussion is confined to the vertical plane through the sun.

Most of the energy passing the surface layers

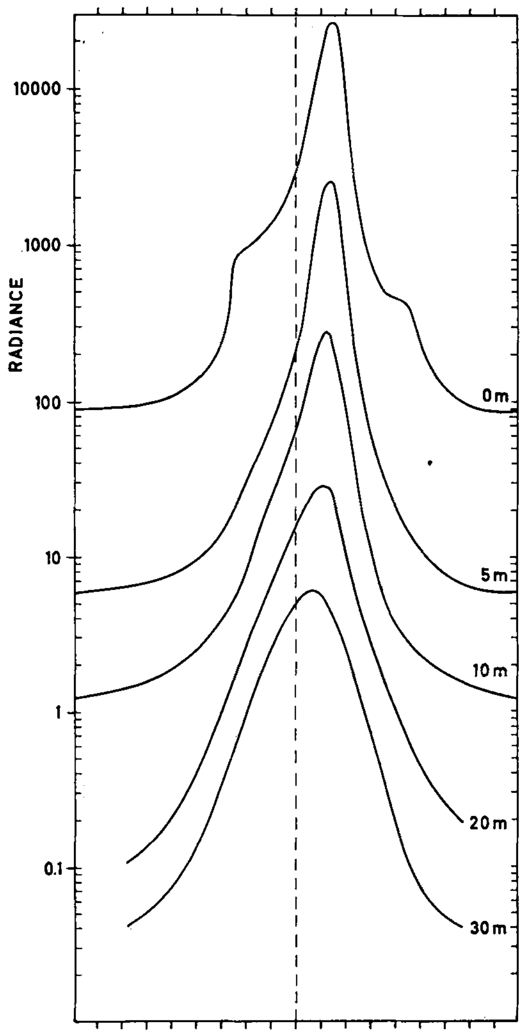

Fig. 4. Angular distribution of observed radiance (535 mμ) followed down to 30 m depth in order to illustrate the approach to a distribution symmetrical round the vertical.

is direct sunlight. Accordingly, the radiance distribution solid is in the surface layer much elongated in the sun's direction. This is fluctuating in a degree dependent on the formation of surface waves.

The penetration into the sea of the diffuse skylight exhibits some wellknown features.

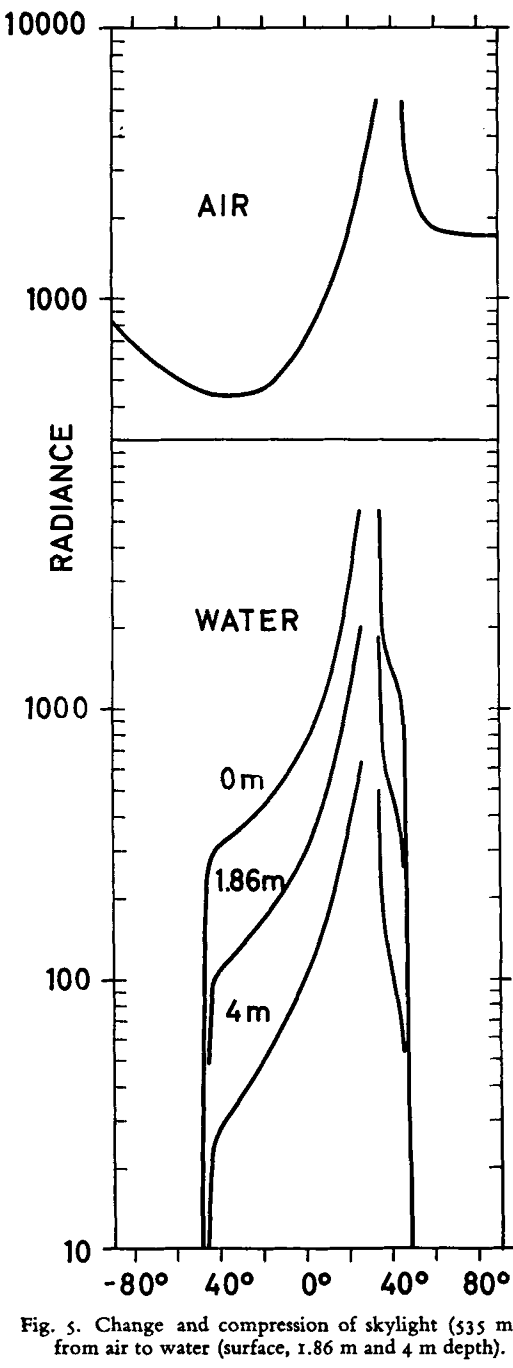

Fig. 5. Change and compression of skylight (535 mμ) from air to water (surface, 1.86 m and 4 m depth).

With a flat surface the light field is by refraction compressed within a cone of an apex angle 2 × 48.6°. It is evident from Snell's law that the edge of this cone corresponding to high angles of incidence is fairly stable and not much affected by waves.

Leaving, for the present, reflexion losses out of account a beam of radiant energy is considered which passes from air to water through a flat water surface, the angles of incidence and refraction being i and j respectively. The geometry of the light beam is characterized by the solid angle $\Delta\omega_a$ in air and $\Delta\omega_w$ in water. The relation between these solid angles is

$$\frac{\Delta\omega_a}{\Delta\omega_w} = \frac{2\pi \sin i \,\Delta i}{2\pi \sin j \,\Delta j}$$

With the aid of Snell's law, $\sin i/\sin j = n$, it follows

$$\frac{\Delta\omega_a}{\Delta\omega_w} = n^2 \frac{\cos j}{\cos i} \qquad (1)$$

As mentioned this type of radiance meter collects flux within a solid angle which in air is n^2 times as large as in water. Consequently, readings taken in air in the direction i should be multiplied with $\cos i/\cos j$ in order to convert them to readings in water in the direction j. It remains to pay regard to reflexion losses at the water surface. The magnitude of this reflexion is evaluated according to Fresnel's formula for unpolarized light. Furthermore it is observed that the window of the measuring head in air reflects a percentage of 4 % which almost disappears in water.

The typical change and compression of the skylight field from air to water is illustrated in Fig. 5. These underwater values depicted for 0, 1.86 and 4 m have been computed on the basis of observed atmospheric values by applying the above conversion.

An interpretation of the scattered light must proceed from a determination of the volume scattering coefficient $\beta(\varphi)$. JERLOV has measured for green light the factor $\beta(\varphi)/b$, where b is the total volume scattering coefficient. By definition

$$b = \int_{4\pi} \beta(\varphi)\, d\omega = 2\pi \int_0^{\pi} \beta(\varphi) \sin\varphi \, d\varphi \qquad (2)$$

These results shown in Fig. 6 are well representative for the Gullmar fjord in the early summer. They give evidence of a pronounced forward scattering and of minimum scattering at about 120°.

It is reasonable to presume that in the near-surface layer the sun is the primary source of scattered light. The radiance from the upper hemisphere may accordingly be derived by a simple integration if multiple scattering is neglected.

Let E_0 be the irradiance at the surface. The small volume element, dv, at P is irradiated by (see Fig. 7)

$$E_0 e^{-cx \sec j}$$

The irradiance at Q will be

$$dE = E_0 e^{-cx \sec j} \beta(\theta - j)\, dv \frac{1}{r^2} e^{-cr}$$

where $dv = r^2\, d\omega\, dr$.

By integrating with respect to r and introducing the radiance $L = dE/d\omega$ it is found

$$L(\pm) = E_0 \frac{\beta(\pm\theta \mp j)}{c} \frac{\sec\theta}{\sec j - \sec\theta} \cdot$$
$$\cdot \left(e^{-cz \sec j} - e^{-cz \sec\theta}\right) \qquad (3)$$

$L(+)$ referring to positive and $L(-)$ to negative θ.

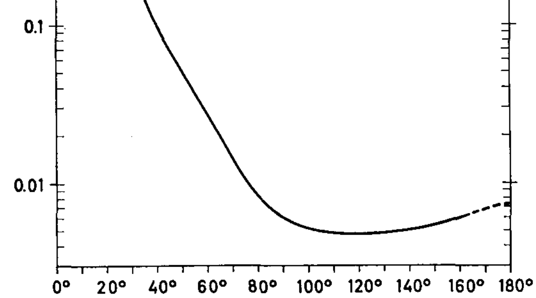

Fig. 6. The ratio between the volume scattering function $\beta(\varphi)$ and the total scattering coefficient b for green light (JERLOV).

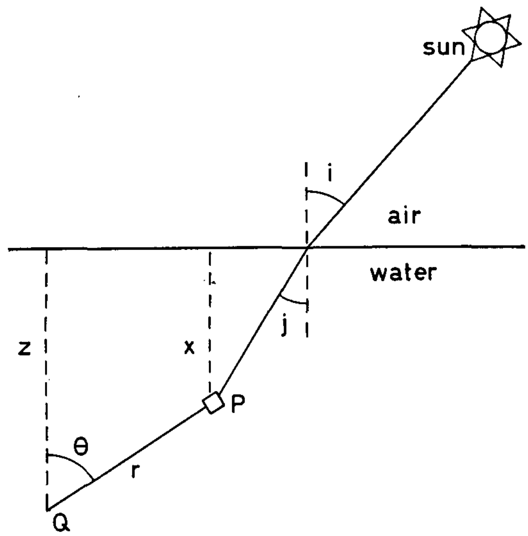

Fig. 7. Sketch of primary scattering of sunlight.

In the special case of $|\theta| = |j|$, which has a significance only for negative θ-values, equation (3) reduces to the simple form

$$L(-) = E_0 z \frac{\beta(2j)}{\cos\theta} e^{-cz \sec j} \qquad (4)$$

Similar integrations have been performed by LE GRAND (1939) assuming isotropic scattering, by LAUSCHER (1947) and by TAKENOUTI (1949) both dealing with pure Raleigh scattering.

Equation (3) has some important applications. Maximum in radiance is attained at a depth z_m

$$z_m = \frac{1}{c} \frac{\ln\sec\theta - \ln\sec j}{\sec\theta - \sec j} \qquad (5)$$

This formula is identical with that found by LAUSCHER who also points out that for $\theta = j$

$$z_m = \frac{1}{c} \cos\theta \qquad (6)$$

In this case

$$L(-)_{\max} = E_0 \frac{\beta(2j)}{c} e^{-1} \qquad (7)$$

It is gathered that the field of scattered light is built up in magnitude unto a certain depth which is independent of the scattering function.

An application of equations (3)—(7) will give a concrete illustration of the radiance of scattered light as a function of depth. With reference to the measurements, the j-value is chosen at 30°, the c-value at 0.5 m^{-1} and the b-value at 0.3 m^{-1}. The estimating of E_0 is beset with some difficulty. We have adopted the atmospheric value converted to underwater irradiance according to the same arguments as given for skylight. Thus we take it for granted that the glitter pattern of the sun has the same angular subtense as the radiance meter. Though

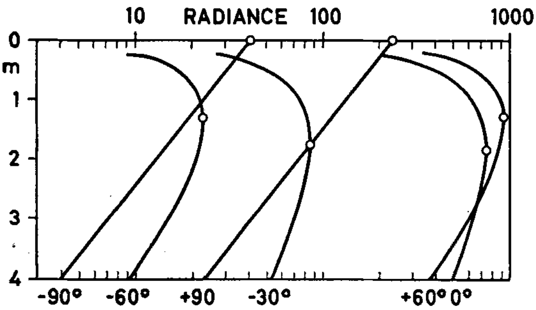

Fig. 8. Computed radiance of downward scattered light (535 m μ) as a function of depth for some vertical angles. Positions of radiance maximum are indicated by small circles.

this is supported by the observations it is nothwithstanding subject to uncertainty.

The set of computed curves are shown in Fig. 8. They demonstrate that the radiance maximum is encountered at the greatest depth, 1.86 m, for $\theta = 0°$ and that it moves to the surface when θ grows to 90°.

The radiance of light scattered from the lower hemisphere is deduced in a similar way. It will come out by integrating from the depth z to infinite depths as follows

$$L(\pm) = E_0 \frac{\beta(\pm\theta \mp j)}{c} \frac{\sec\theta}{\sec j + \sec\theta} e^{-cz\sec j} \quad (8)$$

In this case the light field continuously reduces in magnitude when the depth increases.

It must not be disregarded that upward scattered light is reflected against the water surface and enters into the light field of the upper hemisphere. Particularly in the angle interval 48.6°—90° (with a flat surface), where total reflection takes place, this light contribution is appreciable.

The light scattered upwards from an infinite

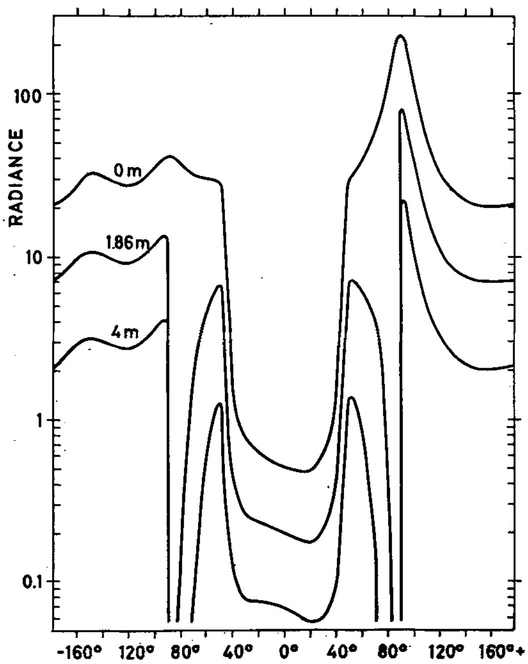

Fig. 9. Angular distribution of upward scattered light (535 mμ) at surface, 1.86 m and 4 m depth. Reflexion takes place at the sea surface in the interval +90° to −90°, and total reflexion between +48.6° and +90° as well as between −48.6° and −90°.

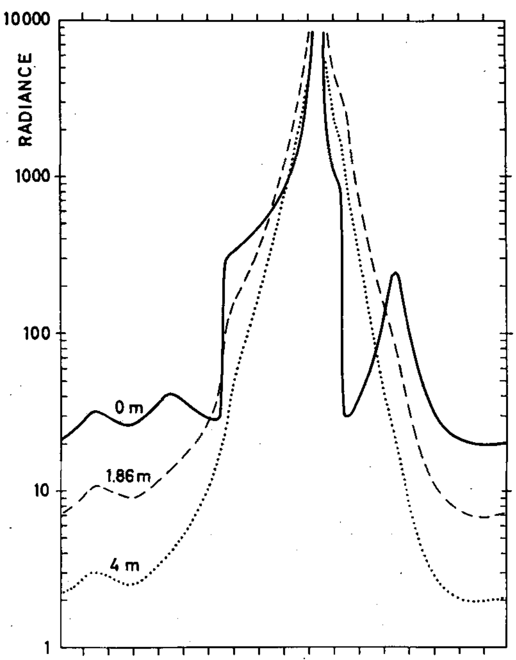

Fig. 10. Angular distribution of computed radiance (535 mμ) at surface, 1.86 m and 4 m depth.

path is thus distributed over all angles. The radiance is evaluated from equation (8) with the mentioned numerical values and with reflexion values obtained from Fresnel's formula. The resulting surface distribution (Fig. 9) exhibits a profound minimum between $+48.6°$ and $-48.6°$, where reflexion is low, as well as two maxima at $+90°$ and $-90°$. The former, being against the sun, is much more conspicuous than the latter. Another slight maximum at $-150°$ is attributed to pure backscattering (at 180° from the sun). The change of radiance with depth is very drastic for the totally reflected light close to 90° on account of the depth function $e^{-cz \sec \theta}$.

Finally the total light field is yielded by adding the different components examined under the assumption of clear sky and flat water surface. The three curves in Fig. 10 representing distributions at 0, 1.86 and 4 m give evidence of the strong predominance of radiance near the sun. The sudden fall of surface radiance at the critical angle of 48.6° becomes less conspicuous towards greater depth. The two outstanding peaks at 90° in the surface distribution are almost extinguished at depth.

Discussion

The conclusions centre on a comparison between radiance distributions obtained experimentally (Fig. 3) and those obtained theoretically (Fig. 10). On the whole the characteristic features in the two sets of curves are consistent. The 1.86 m curve is in both pictures well above the surface curve between $-10°$ and $+80°$, or about in the interval $\pm 45°$ from the sun, and also in a small angle interval at $-55°$. Existing discrepancies may be explained as the effect of wave motion at the measurements which is apt to smooth out fine details in the theoretical pattern derived for at flat surface. Thus the minimum at $+50°$ combined with the maximum at $+90°$ in the theoretical surface distribution is almost completely levelled off in the experimental distribution, chiefly on account of fluctuations of the scattered light from below totally reflected at the surface. The computed slight maximum at $-150°$ does not show up in Fig. 3 because of lack of sufficiently dense observations in this region.

The radiance distribution in the sea has been sketched in its general outline twenty years ago. Improved technique has later made possible the finding of significant details. An investigation by SASAKI *et al.* has given clear evidence of the peak of radiance which occurs at 90° though they did not interpret this as a maximum. The mentioned distributions with an overcast sky obtained by TYLER are in comparable features consistent with the present results.

It may be inferred that the observed radiance in the upper layers of the sea conforms with a theoretical conception based on a simple integration of light scattered from the sun beam alone. This assumption does not hold true at greater depths where the direct sunlight has lost its predominating character.

REFERENCES

ATKINS, W. R. G., and POOLE, H. H., 1952. An experimental study of the scattering of light by natural waters. *Proc. Roy. Soc. B*, **140**, p. 321.

DUNTLEY, S. Q., UHL, R. J., AUSTIN, R. W., BOILEAU, A. R., and TYLER, J. E. An underwater photometer. *Journ. Optical Soc. America*, **45**, p. 904 (A).

JERLOV, N. G., and LILJEQUIST, G., 1938. On the angular distribution of submarine daylight and on the total submarine illumination. *Svenska hydrogr.-biol. Komm. Skr., Hydrogr.*, **14**, p. 3.

JERLOV, N. G., 1951. Optical studies of ocean waters. *Rep. Swedish Deep-Sea Exp.*, 1947—48, **3**, No. 3.

JERLOV, N. G., 1958. Distribution of suspended material in the Adriatic Sea. *Estratto dall'Archivio di Oceanografia e Limnologia*, **11**, p. 227.

LAUSCHER, F., 1947. Zur Strahlungstheorie der Hydrosphäre. *Sitzungsberichte Akademie der Wissenschaften in Wien, Abt. II A*, **155**, p. 281.

LE GRAND, Y., 1939. La pénétration de la lumière dans la mer. *Ann. de l'Inst. Océanographique*, **19**, p. 393.

LENOBLE, JACQUELINE, 1957. Étude de la pénétration du rayonnement ultraviolet naturel dans la mer. *Bull. d'Information du Comité Central d'Océanographie et d'Étude des Côtes*, **9**, p. 8.

POOLE, H. H., 1945. The angular distribution of submarine daylight in deep water. *Scient. Proc. Roy. Dublin Soc.*, **24**, p. 29.

PREISENDORFER, R. W., 1959. *Journ. Marine Res.*, **18**, p. 1.

SASAKI, T., OKAMI, N., WATANABE, S., and OSHIBA, G., 1955. Measurements of the angular distribution of submarine daylight. *Journ. Scient. Res. Inst.*, **49**, p. 103.

— 1957. *Measurements of the angular distribution of daylight in the sea.* Records Oceanogr. Works Japan (spec. number), p. 42.

TAKENOUTI, Y., 1940. Angular distribution of submarine solar radiation and the effect of altitude of the sun upon the vertical extinctions coefficient. *Bull. Jap. Soc. Sci. Fish.*, **8**, p. 213.

TAKENOUTI, Y., 1949. On the diffusion-ratio of underwater illumination. *The Oceanogr. Mag.*, **1**, p. 43.

TYLER, J. E., 1958. Comparison of light distribution above and below water. *Journ. Marine Res.*, **16**, p. 96.

TYLER, J. E., and RICHARDSON, W. H., 1958. Nephelometer for the measurement of volume scattering coefficient *in situ. Journ. Opt. Soc. America*, **48**, p. 354.

WHITNEY, L. V., 1941. The angular distribution of characteristic diffuse light in natural waters. *Journ. Marine Res.*, **4**, p. 122.