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Irradiance fluctuations
Focusing of sunlight
Sea surface waves

On the mechanism for producing flashing light under a wind-disturbed water surface

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Abstract

By means of a simple numerical analysis the focusing effect is reexamined in the context of the recent experimental data on near-surface strong flashes of irradiance. For relating these unusual optical effects to surface wave dimensions, the variations in light intensity as a result of the focusing produced by the realistic profile of short-fetch wind-generated water waves are calculated. The theoretical predictions compare well with the experimental data. These results, together with additional approximate calculations, are sufficient to deduce that small, smooth waves with the steepness of the order of 10^{-2} and the length of several centimetres, that is in the gravity-capillary transition region, and may be of direct importance in the problem of underwater flashing light. Recalling the earlier theory of Schenck (1957) the importance of short, steep gravity waves of up to 1 m or so in length is also suggested. The validity of theoretical predictions is demonstrated by measurements of flashing light in a short-fetch water tank with steadily generated surface waves exposed to the sunlight.

1. Introduction

The refraction of sunlight at a wind-disturbed sea surface produces fluctuations in the underwater downward irradiance on time scales from a fraction of a second to tenths of seconds. Sun-rays which pass through the sea surface continually change directions and may be bunched and spread out. It has been known long that the main refractive effect, which causes large variations in underwater light intensity, is the focusing and defocusing of light beams caused by fluctuations of surface curvature (Schenck, 1957; Snyder and Dera, 1970).

The experimental studies of maximum effects of sunlight focusing occurring in the top few metres of the sea were reported earlier by Dera and Olszewski (1978), Dera and Stremski (1987), Stramski (1986). Important findings of the cited studies show that these effects have the form of successive pulses (called flashes) in time signal of downward irradiance $E_{\downarrow}(t)$. For brevity, the subscript '$\downarrow$' is later omitted. The flashes are characterized by short durations, lying typically between a few milliseconds and tenths of milliseconds, and by high intensities of up to almost six times the average irradiance at a given underwater point.

In earlier research Schenck (1957) theoretically predicted that intensity peaks few times greater than the average light intensity are possible due to the focusing effect. Considering the focusing produced by a trochoidal and sinusoidal wave he concluded that, in view of light attenuation in natural waters, '... only short, steep waves are of practical interest in the focusing problem'. To describe the general features of the focusing effect simple models using sinusoidal surface waves were further developed (Nikolaev and Khulapov, 1976; Khulapov and Nikolaev, 1977). As far as the wave profile is concerned, one can notice that the true geometric structure of the wind-generated waves has no simple mathematical form. Recall, however, that the linearized hydrodynamic theory predicts the sinusoidal form for gravity waves with infinitesimal heights (Lamb, 1932). With the increase of the wave height the profile differs more and more from the simple harmonic, so that for gravity waves of finite height the shapes are approximately trochoidal (see Defant, 1961). On the other hand, it is known that the small waves and capillary ripples, whose shape is very rounded in section (Crapper, 1957; Schooley, 1958), play a major role in the reflection and refraction of light incident on the sea surface.

In this paper the theoretical work of Schenck is extended to show the role played in the focusing problem by the waves in the gravity-capillary transition region. An extremely simplified model of focusing effect, based partly on our experimental data, is considered in an attempt to relate the flashes to surface wave dimensions. The photographs of short-fetch wind-generated water waves of Schooley (1958) are used as the source of wave data, and then the effect of a realistic wave profile on incident sunlight is shown and analysed numerically. A brief discussion on the source mechanisms of, irradiance fluctuations in the context of the observed flashes is included. Furthermore, the measurements in a short-fetch water tank have been performed to determine the typical statistical properties of flashing light in the absence of larger waves. A comparison between the results from the wave tank and the field is used to verify the importance of short waves in the strongest fluctuations of irradiance under a wavy sea surface.

2. Source mechanisms for sunlight fluctuations

It is perhaps useful at this stage to give a brief outline of the mechanisms producing short-term fluctuations of underwater irradiance. The mechanisms have been described in detail by Snyder and Dera (1970) who developed a first-order ray theory of wave-induced light fluctuations in the sea. This theory is based on two simplifying assumptions. First, the underwater irradiance field in the uppermost few metres of the sea is taken to be entirely the result of direct sun-rays. Second, the sun is modeled as a point source of light. Despite the limited range of agreement with observations, this theory successfully identifies several refractive effects being sources of irradiance fluctuations. These are as follows:

(i) fluctuations of path length caused by fluctuations of surface elevation,

(ii) fluctuations of path length caused by fluctuations in the orientation of the refracted ray as a result of fluctuations of surface slope,

(iii) fluctuations of the transmittance of radiant energy through the water surface associated with fluctuations of surface slope,

(iv) fluctuations of the projection of the water surface patch onto the incoming beam caused by fluctuations of surface slope, and fluctuations of the same projection caused by fluctuations of the orientation of the refracted rays associated with fluctuations of surface slope,

(v) fluctuation of the projection of the water surface patch onto the incoming beam caused by fluctuations of surface curvature, *ie* the focusing effect.

An evaluation of the relative roles played by these mechanisms in the context of the physical explanation of the most intense fluctuations of underwater irradiance is a matter of some importance. A simple means of doing this is particular mechanism extraction and specification of its geometric setting, allowing the simplified numerical analysis to be done. Before this, on the basis of empirical facts (Dera and Stramski, 1987) we specify a fairly narrow range of conditions which favours the strongest fluctuations of irradiance. Accordingly, the case of special interest is characterized by the high sun in the clear sky (solar altitude greater than 40°) and light winds (wind velocity less than 5 m/sec) that correspond to slight sea surface disturbances with a significant wave height extending to approximately 0.5 m and a standard deviation angle of inclination of the surface normal of up to about 10° from the vertical. We take no account of oceanic conditions under which swell is usually present. Furthermore, there is an interest in small depths – to a few metres in waters, that cover the range from clear oceanic water types to moderately turbid coastal waters of type 5, according to the optical classification of Jerlov (1976). Principally all the considerations are with the deepest penetrating light wavebands, unless otherwise specified. Direct measurements in these circumstances indicated that the downward irradiance E – colected on a small area (a circular diffusing disk of 2,5 mm in diameter) within the green spectral band (525 nm with a 10 nm passband) – often exceeds its time-averaged value $\bar{E}$ by a factor 1.5, 2, and extremely 5. This is shown in Figure 1*a* where the average number of irradiance pulses *per* 1 minute is plotted *versus* the irradiance expressed as some multiple of

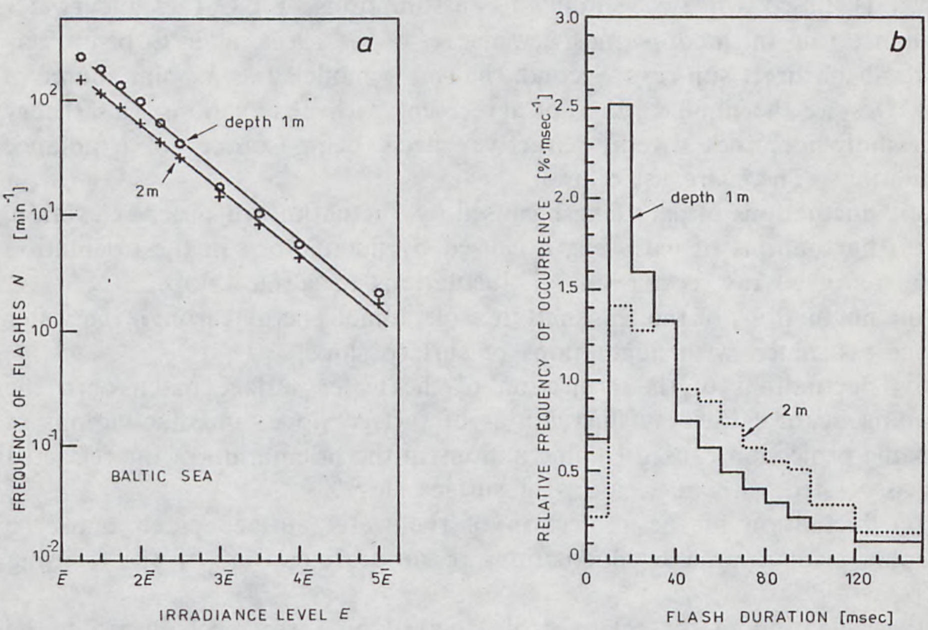

Fig. 1. Typical experimental data on near-surface flashing light in the open Baltic waters under conditions which favour strong focusing effect.
a – the frequency of flashes (N) *vs* flash intensity E. The solid lines are the least squares fit to the data by the exponential function $N = N_0 \exp(-AE)$. The estimated regression parameters are as follows: $A = 1.33\bar{E}^{-1}$, $N_0 = 1225.3\,\text{min}^{-1}$ for a depth of 1 m, and $A = 1.29\bar{E}^{-1}$, $N_0 = 782.0\,\text{min}^{-1}$ for a depth of 2 m, b – the histograms of flash durations on the irradiance level $1.5\bar{E}$

the mean value. The histogram of flash durations for a 1.5 $\bar{E}$ level, is shown in part *b* of the figure mentioned. A depth of 1 m was assumed to be a standard in the measurements of the flashes. The presented field data may be regarded as representative of the defined most favourable conditions. Recall that in order, to study such intense fluctuations the term "flash" was introduced and defined to be the momentary pulse of underwater downward irradiance E exceeding its mean value $\bar{E}$ by more than 50 per cent (Dera and Stramski, 1987). The defining criterion has not only an experimental base but is motivated for physical reasons as will be shown in the following discussion.

We shall now be concerned with the mechanisms mentioned in items from (i) to (iv), and our goal is to say whether these mechanisms may account for the observed strong flashes of irradiance. As will be shown, this is answered in the negative. To avoid unnecessary complications in all that follows we neglect the diffuse light.

The single-ray geometry of the mechanisms designated by items (i) and (ii) associated with fluctuating path length is depicted schematically in Figure 2.

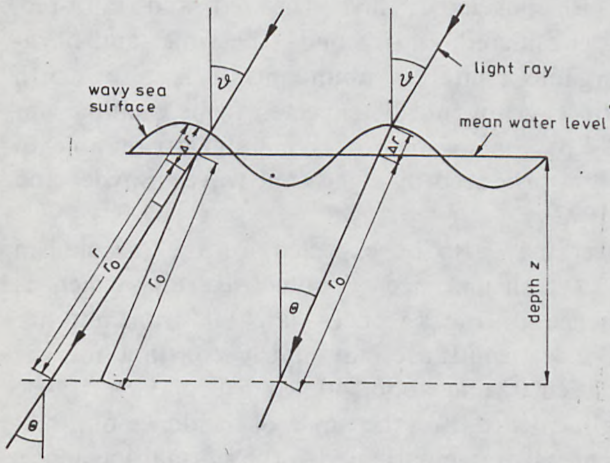

Fig. 2. Geometry of the source mechanism for irradiance fluctuations associated with fluctuations in path length

The wave profile is in the vertical plane containing the sun. The incoming radiance of the sun $L(\vartheta)$ and the light-beam attenuation coefficient in the water c can be reasonably assumed to be constant in time. Let r_0 be the fixed geometric length of the refracted ray in the case of undisturbed water surface, and let Δr be the variable element of the path length due to surface elevation and surface slope. Thus, the total geometric length r of a ray in the water along the direction Θ is the sum of r_0 and Δr. We are interested in variation of the irradiance $\mathrm{d}E$ induced by the radiance L of the sun in the direction Θ at a given depth. The exponential factor $\exp(-c\Delta r)$ represents here the effect of variable path length on the irradiance $\mathrm{d}E$. Provided we deal with blue-green light in the circumstances of interest, the typical values of the exponent $-c\Delta r$ work out to be $\pm 10^{-3}$ or $\pm 10^{-2}$, so that the exponential factor is not significantly different from unity. Thus, it is easy to see that, due to the path length variations, the irradiance $\mathrm{d}E$ can vary on the order of a few percent from the mean value $\mathrm{d}E$ (which is understood as that corresponding to the undisturbed sea surface) for clear oceanic water. Of course, this estimate increases with water turbidity (the increase of c) but extends only to 10-20 per cent for coastal water of type 5. From this we see that the mechanism under question is negligible in the context of the observed flashes. Furthermore, one can note that the assumed idealized geometry leads to loss of essential reality. In fact, the downward irradiance is the sum of the scattered and direct irradiances. The resultant fluctuation intensity would thus be reduced in comparison with above estimates which lends support to the apparent neglect of the considered mechanism. However, apart from stormy sea or highly turbid water, there is one noteworthy exception in which the fluctuating path length may contribute largely to the total fluctuation intensity under clear sky conditions. This is the case when the spectral region of high absorption of light is considered; first – the red and infra-red, regardless of water type being considered, and second – the violet and ultra-violet, when the dissolved organic matter is abundant. It is also worth remarking that fluctuating path length would be expected to be dominant at low frequencies of 0,1 to 0,2 c.p.s. or so since it is mainly attributable to variations of water column height produced by significant waves (Snyder and Dera, 1970; Nikolaev *et al*, 1972).

Generally, a negligible effect may also be expected for the mechanism associated with fluctuations of transmittance – denoted as (iii) – which is principally a simple consequence of the Fresnel's law for transmittance through the water surface. The transmittance stays fairly constant for the angle of incidence varying between 0° and about 40°, and displays a drastic decrease only for near grazing incidence. For the angle of incidence of 70° it is decreased by about 20 percent when comparing with the normal incidence, which still involves a relatively slight fluctuation in the context of the present discussion.

In accordance with the main line of discussion we now consider the

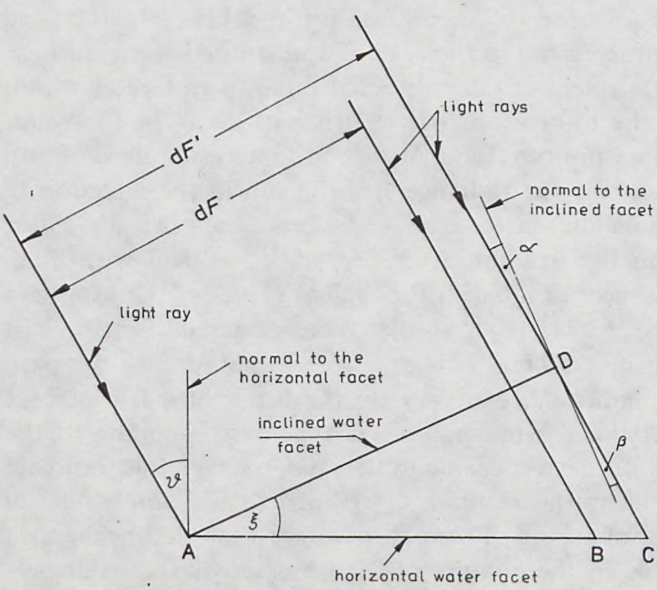

Fig. 3. Geometry of the source mechanism for irradiance fluctuations associated with fluctuations in slope of a water facet

mechanism designated by item (iv). A simple graphical interpretation of this mechanism is given in Figure 3 illustrating a thin collimated beam of steady radiant flux incident on the air-water interface (an anologous geometrical setting was considered by Ivanov, 1975). The beam is tipped ϑ degrees from the vertical. Suppose the flux $\mathrm{d}F$ is incident on the flat, horizontal facet AB at time t. An instant Δt later the same facet will be tipped away ξ degrees from the horizontal as denoted by AD, and now the flux $\mathrm{d}F'$ will flow into it. The ratio between $\mathrm{d}F'$ and $\mathrm{d}F$ represents the first part of the mechanism (see item iv). After refraction the horizontal surfaces AB and AC are irradiated at time t and $t+\Delta t$ respectively by the respective radiant fluxes transmitted through respective facets of water surface. The ratio between the two irradiated areas represents in turn the second part of the mechanism. By means of simple mathematical operations the irradiance just below a water surface at an arbitrary time $t+\Delta t$ can be expressed as:

$$E = E_s \cdot T \frac{\cos\alpha \cos(\beta+\xi)}{\cos(\alpha+\xi)\cos\beta}, \tag{1}$$

where:
E_s — the irradiance on a horizontal water surface at time t,
T — the transmittance through the inclined facet,
α, β — the angles of incidence and of refraction for the inclined facet, respectively.

The sign in parentheses depends on the assumed azimuth of the ascent of the facet. If we write the ratio $T/\bar{T}$ (where $\bar{T}$ denotes the Fresnel's transmittance for the angle of incidence of 0°) instead of T, the irradiance E_s is replaced by the underwater irradiance $\bar{E}$ corresponding to the case of horizontal water surface. Because the sea surface has a negligible mean tilt, the quantity $\bar{E}$ may be, for our purposes, regarded as mean irradiance. The trigonometric factors describe the considered mechanism associated with fluctuations of surface slope. Under circumstances of interest the irradiance E expressed by equation (1) can vary on the order of 10-20 per cent of the mean value. Thus, the magnitude of this effect is far too small to account for the observed light flashes and in practical situations it may play a role only immediately below the water surface.

Summarizing this section: we have shown that the mechanisms associated with fluctuations in surface elevation and surface slope contribute a small percentage to the total fluctuation intensity of underwater irradiance under a wind-disturbed sea surface. The fact that our resulting estimates are approximate rather than exactones does not seem to alter the main point at all, so it may be suggested that the focusing effect is the main source mechanism of the most intense fluctuations in underwater irradiance that we call light flashes.

3. Focusing effect

We shall now consider the focusing effect in terms of geometrical optics. We direct attention to the downward irradiance E of direct sunlight at a shallow depth of the order of 1 m on a horizontal collecting surface of fixed size S'. This quantity can be written:

$$E = E_s \cdot T_{eff} \frac{S}{S'}, \tag{2}$$

where:

E_s – the downward irradiance of the sun at the air-water surface assumed to be constant,

S – the area of a projection in horizontal plane of a wave crest from which the radiant flux comes and falls onto the collecting surface S' at a given depth,

T_{eff} – the effective transmittance of the considered radiant flux through the water surface and the water column.

Under circumstances of interest mentioned earlier, the transmittance T_{eff} varies slightly over considered time scales, but for our present purposes can be reasonably assumed to be constant. On these assumptions the fluctuations

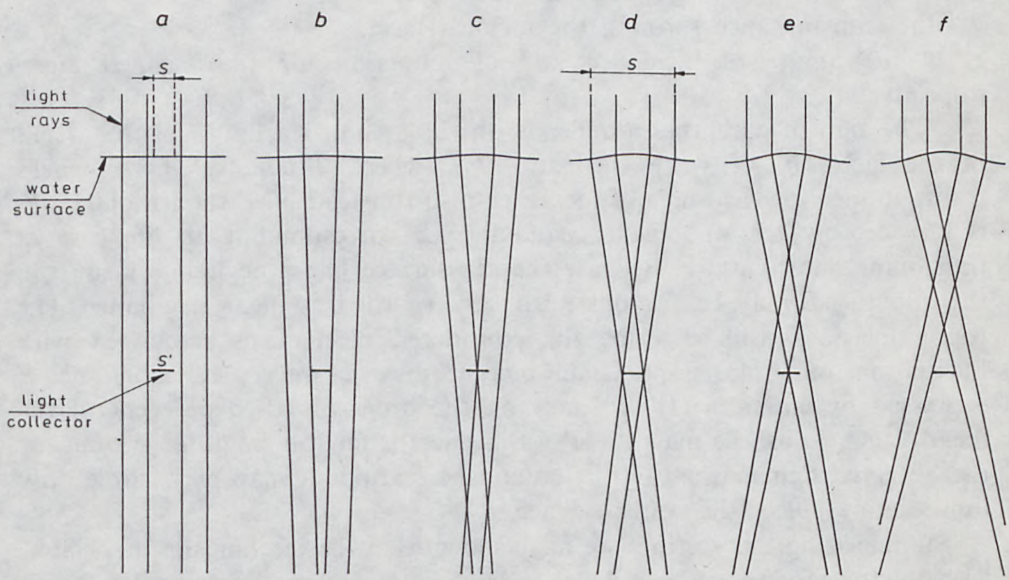

Fig. 4. Schematic details of sunlight focusing by wave crest for a light collector of fixed size placed at a fixed depth.
Part *d* shows the sharpest focusing effect. The sinusoidal wave shape is taken as the water surface, the value of 1.33 is taken as the index of refraction for water surface, the horizontal and for a wave profile scale is four times greater than vertical one. S' denotes the collecting surface, and S denotes the area of a projection of a wave crest from which the radiant flux comes and falls onto the collecting surface

of underwater irradiance E given in equation (2) are induced solely by fluctuations in the area S caused by fluctuations of surface curvature. This is what, in essence, we can see as a result of the focusing effect produced by the refracted sun-rays.

We turn next to the illustration of lens action of individual waves (Fig. 4). One can expect that the waves have the focus more or less diffuse, and the departures from the ideal point focus manifest themselves like 'aberrations'. From amongst various permissible geometrical patterns the one shown in Figure 4*d* gives the sharpest focusing effect. In this case the diffuse focus coincides entirely with the collecting surface S'. To gain a rough idea of the wave dimensions being of direct importance in the focusing problem, we recall the experimental fact that the intensity of flashes measured with a collector 2.5 mm in diameter can attain the level almost six times higher than the average irradiance at a given point under a wavy sea surface (Dera and Stramski, 1987). Let us further assume that the time-averaged underwater irradiance is:

$$\bar{E} = E_s \cdot T_{eff}, \tag{3}$$

which formally corresponds to $S = S'$, as would be the case with a flat, horizontal water surface (Fig. 4*a*). From equations (2) and (3) we see that the flash intensity is peaked x-times over the average irradiance when the radiant flux falling onto a collecting surface S' comes, or is focused, from a surface having the area $S = xS'$. On setting $S' = \frac{\pi}{4} \cdot 2.5^2$ and $x = 6$, we have $S \simeq 0.3\,\mathrm{cm}^2$ which may be regarded either as the area of the crest of a small wave having a length of centimetres or the crest of a small wave having a length of centimetres of as the area near the crest of larger, irregularly shaped wave. In a physical situation the small scale roughness is superimposed on a wave crest which, in consequence, cannot act as an 'ideal' lens; therefore, somewhat larger wave than predicted in this simple way should be expected to produce the same optical effect.

It is worth-wile at present to provide more realistic simulation of focusing effect along with the numerical analysis. This may be done in the way based on a concept of Schenck (1957). However, instead of trochoidal or sinusoidal form the water waves in our simulation have physically realistic profiles in the gravity-capillary transition region. We use the experimental profiles of wind-generated waves that were photographed with a high-speed motion camera in a small transparent water-wind channel (Schooley, 1958). A selected frame from the motion picture film with the view subtended about 4.5 cm in width is used. Thus, the effect of adjacent wavelets is not to be studied. As a base for our numerical procedure the geometrical arrangement is made so that a series of seventy nine equally spaced sun-rays are distributed over the wave profile along the y-axis. No other irradiation falls on the water surface. The data consisting of 80 points describing the wave profile were read off accurately from the enlarged photograph so that each ray passing through the water surface has an associated flat wave facet with a fixed slope. After that, knowing the sun altitude, the angle of incidence of each ray on a water surface is readily determinable. Since the wave profile is very smooth, the Fresnel's transmittances for the radiant fluxes associated with different sun-rays passing the water surface are approximately the same, and therefore, they are assumed not to affect the following numerical calculations. Further we assume that the index of refraction of the air-water interface is 1.33, and then that the water is a source-free optical medium in which the index of refraction is constant and the light does not undergo scattering or absorption. With these preliminaries established it is easy to find the direction of any ray after its passage through the interface and to locate the position of any ray at the arbitrary depth level. What is shown above is the geometric essence of the calculations. Now, by specifying the measure of light intensity, the distribution of downward irradiance produced by the refracted sun-rays converging and diverging beneath the wave profile can be evaluated. Since an irradiance meter must respond equally to all photons that impinge upon its collector regardless of the angle of incidence, we find it convenient to assign an intensity of unity to each particular ray which is incident on a collecting surface. In our simulation an increment 2.5 mm in length is taken to represent the collecting surface of the meter (see also Dera and Stramski, 1987). With all the above essentials in mind, as a final step of the numerical investigation, the light intensity curves $E\ (y, z)$ are computed by shifting the 'collector' in sufficiently small steps at a given depth z in parallel to the undisturbed surface. The limiting condition of a flat water surface results in the uniform light intensity in the water and – to the present task – this intensity may be used as the average irradiance $\bar{E}$. The results of calculations for a wavy surface are compared to this base level of light intensity.

We select for illustration the situation when perpendicular light rays are incident on the water surface which under circumstances of Schooley's experiment corresponds to the initation of wave formation. The wave profile was generated under low air turbulence by a ten-knot wind (1 knot = 0.515 m/sec) blowing over a fetch of about 35 cm (the threshold wind velocity at which waves start to form on open bodies of water is considerably smaller). The considered waves have a length of 1 to 2 cm and a height of a fraction of a millimetre, so the height-to-length ratio, that is the wave steepness, lies somewhere between 0.03 and 0.05. The intricate pattern of light rays produced by these waves in a two-meter surface layer is shown in Figure 5. Several marked foci can be found under the wave profile, in general the sharper ones nearer the surface. It is also apparent that more than one wave can contribute to a single focus. However, the essential fact to observe here is that a smooth, gently sloped wave in the capillary-gravity transition region can give a crucial contribution to the focus; such a wave may thus be responsible for the observed flashes of irradiance. It is quantitatively confirmed in Figure 6 showing the light intensity curves for selected depths. In fact, the results represent the instantaneously 'frozen' wave and light patterns but we can imagine that the surface is in motion and interpret this figure as

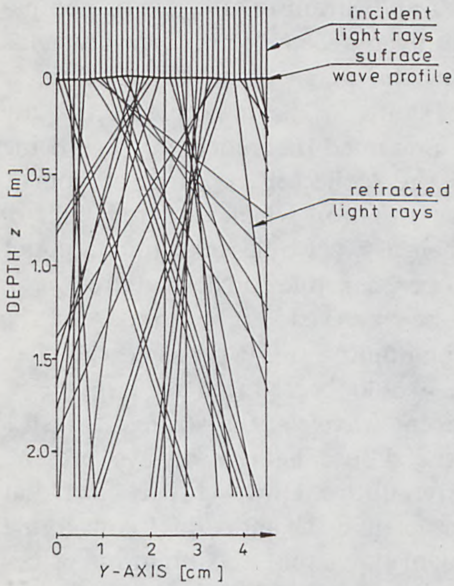

Fig. 5. A complex pattern of light rays under realistic profile of wind-generated water waves in the gravity-capillary transition region

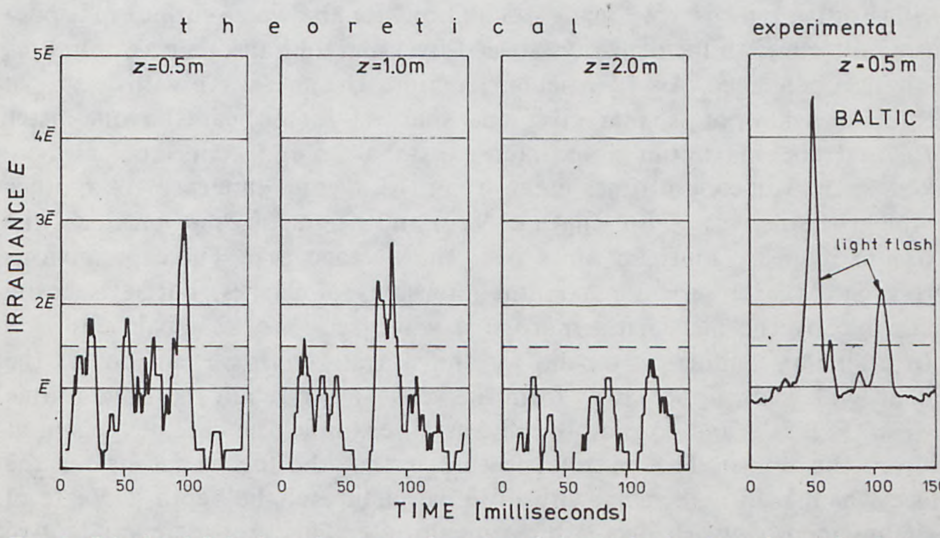

Fig. 6. Calculated light intensity curves for selected depths having intensity peaks due to the focusing produced by a wave profile shown in Figure 5. For comparison, a typical sample of *in situ* record of downward irradiance fluctuations is also shown

a temporary rather than a spatial characteristic. The time axis is set up assuming that the wave phase velocity is 30 cm/sec – as measured by Schooley. As is shown, the intensity peaks exceed the average light intensity $\bar{E}$ by a factor of 1.5, 2, and almost 3. The 'width' of the peaks on the $1.5\bar{E}$ level is ranging on the order of a few milliseconds to 20 msec. This is generally consistent with empirical facts about flash intensities and flash durations (Fig. 1) discussed in detail elsewhere (Dera and Stramski, 1987). For comparative purposes, a typical sample of *in situ* irradiance (525 nm) measurements under sunny conditions, reproduced from the magnetic tape recording, is plotted to scale in the rightmost part of Figure 5. The resemblance is quite evident. The zero-valued intensities in the presented theoretical curves – being obtained with no ray passing through the 'collector' – are, of course, artificial. Thus, imagine the more realistic situation when scattered light of constant intensity exists in the water. Then, if we would take into account the average irradiance increased by 20-30 per cent due to the scattered light, the abnormal intensity peaks would still be observed. For example: for the ratio of scattered to total light intensity amounting to 30 per cent, the peak of maximum intensity at a depth of 1 m would be reduced to $1.9\bar{E}$.

Apart from the possible effect of adjacent wavelets, the strongest flashes ($E > 5\bar{E}$), observable in the sea where the diffuse light is always present, cannot be explained by the waves considered above. However, it is clear that somewhat longer waves may analogously act like the individual converging 'lenses', and they would be needed to explain the actual maximum intensities of flashes. No doubt Figures 5 and 6 would look quite similarly, though most likely with higher intensity peaks penetrating more deeply, if it were possible to take pictures with smooth waves being several centimetres long. For illustrative purposes we made calculations for the water surface in a pure sinusoidal form with incident rays spaced by 1 mm and all other assumptions remaining unchanged. As a particular example, the sine wave with length of 4.5 cm and height of 0.5 mm gives the sharpest focus near the one-meter depth, and the maximum light intensity on a 2.5 mm "collector" is here peaked to the value eight times higher than the average intensity. As another example, the sine wave with length of 9 cm and height of 2 mm produces the maximum intensity fourteen times over the average one. These predictions overestimate the empirical maximum intensities of flashes, but it is easily explainable by the fact that a pure sine wave acts like an ideal 'lens'.

In a similar manner as we did for the sun at zenith we can do for the incident light beam tipped away from the vertical. We retain the wave profile shown in Figure 5 and consider briefly, as an example, the case of the sun at 60° from the zenith. The essential feature is that the foci occur nearer the surface which is in agreement with intuitive picture of the depth decrease of maximum focusing with decreasing sun altitude. This is also in qualitative agreement with experimental data showing the reduction of fluctuation intensity with the sun lowering to the horizon (Dera and Stramski, 1987). In the present simulation the intensity peaks reaching the levels $2\bar{E}-2.5\bar{E}$ were found only in about half-a-meter surface layer. The maximum intensity for a one-meter depth was only $1.4\bar{E}$. If we reasonably assume that the scattered light at small depths contributes 30-50 per cent to the mean value of total irradiance for the relatively low sun, the calculated maximum intensities at a half-a-meter depth would be below the $1.5\bar{E}$ level. Of course, somewhat larger waves would be needed to give stronger focusing effect penetrating more deeply. The dependence of a depth of maximum focusing on sun altitude with a wave steepness as a parameter was analysed numerically for a sinusoidal shaped wave by Khulapov and Nikolaev (1977).

Some final comments are needed on the wave profile pictures taken by Schooley (1958) from which one was used for our present purposes. Unfortunately, due to the thin water film clinging to the wall of the channel the true wave data could not be reproduced with sufficient accuracy from other photographs corresponding to higher wind velocities. It is interesting to note that by means of wave profile pictures Schooley confirmed Crapper's (1957) theoretical prediction of the shape of pure capillary waves with troughs peaked downward, which is the reverse of the gravity wave case. This geometrical feature may be important in the focusing problem. Another practical observation that is immediately forthcoming from Schooley's photographs is the fact that the existence of very short, steep capillary waves (a length less than 1 cm and the steepness extending to over 0.5) are unquestionable at higher wind velocities. This may be important in destroying the focusing under strong winds, and thus may partly account for the corresponding regularity evidenced by our *in situ* experiments (Dera and Stramski, 1987).

At this point it is of interest to recall once again the pioneering investigation of Schenck (1957) who demonstrated the focusing effect as a function of wave dimensions of water surface having a sinusoidal and trochoidal shape. In this way a more complete description relating the subsurface optical effects to waves will now be attained. In Schenck's theory the size of 'collector' is generally assumed to be one-sixteenth of a wavelength; in our numerical investigation the choice of this size has an experimental base. One can use Schenck's theory to deduce that strong flashes of irradiance observed by us in a one- to two-meter surface layer may be produced by relatively short, steep gravity waves being principally tenths of centimetres long and several centimetres high. As an example, the trochoidal wave 18 cm long and 1.3 cm high (the steepness of 0.07) gives a sharpest focus at a depth of 1 m. In this case the light intensity on a 'collector' slightly over 1 cm long is peaked to the value almost six times higher than the average one. As mentioned before, the wave may be regarded as a pure gravity one if a wavelength is greater than 17 cm, which corresponds to completely negligible effect of surface tension when compared with that of gravity force (Kraus, 1972). As another example, a very steep trochoidal wave having a length of over 0.5 m and a height of about 7 cm (the steepness approaching the maximum value of 0.14 for gravity waves without cresting) produces the maximum intensity of about five times greater than the average one at a depth of 1 m. It is to be noted that as the wavelength increases or the wave steepness decreases the point of maximum focus increases in depth. By virtue of this property, as an example, the steepest possible trochoidal wave of over 1 m length will produce on a 'collector' being over 6 cm long a sharpest focus with intensity about five times over the average value approximately 2 m below the water surface. For the same wavelength but the reduced steepness to 0.07 the peak of a similar maximum intensity occurs roughly at a depth of 4 m. This is to say that the maximum intensities predicted by Schenck's theory for 'collectors' being some centimetres in length (in consequence, for waves with length of tenths of centimetres or more) seem to be of no immediate practical use, since it is evident from experiments (Dera and Stramski, 1987) that high-intensity flashes are detectable only by very small collectors of a few millimetres in diameter. In spite of this and of the facts that in nature the waves are not of a single length and height and can, in general, deviate largely from the trochoidal form, the above examples are valuable in pointing out the waves being of interest in the problem of strong flashes of irradiance.

To attach more confidence to the theoretical predictions we now briefly present the water tank measurements on flashing light. The experimental apparatus consisted of a water tank in which surface waves were steadily generated, an irradiance meter which measured the fluctuations of downward irradiance an analog-to-digital converter, and a Commodore 64 microcomputer which controlled the light measurements and recorded the data. The water tank was about 1.1 m long, 0.7 wide and 0.8 m deep. Surface waves were generated by a flapper plate driven by a variable speed motor mounted in one end of the water tank. No measurements of waves have been made but, of course, only short waves having a length of tenths of centimetres at the most were present on the water surface. The irradiance meter with a flat cosine collector of 2.5 mm in diameter, optical filter (550 nm with a passband of 80 nm), and silicon photovoltaic detector was placed in the tank so that the collector was 0.5 m below the water surface and had the exposure to the sunlight. The detector output was digitized at a sampling interval of 1 msec in thirty-second segments. The digitized data were analysed by means of microcomputer to obtain frequency distribution of flash intensity $N(E)$. The final estimate of frequency distribution was calculated for ten 30 seconds long samples repeated in rapid succession, giving the 5 minutes of entire record. The measurements were made under clear sky at noon when the sun altitude was about 50°. The data in Figure 7 are typical of the results obtained in the water tank. It is seen that the frequency of flashes (N) decreases nearly exponentially with flash intensity E. The same regularity was noted in the field studies as shown in Figure 1 (see also Dera and Olszewski, 1978; Dera and Stramski, 1987). Furthermore, the simulation data are in good quantitative agreement with the results of the field experiments; hence, some confidence is achieved on the importance of short waves in the strong focusing effect. The fact that the measuring depth in the tank is somewhat smaller does not seem to be crucial for our comparative purposes because only slight differences should be expected in the statistical distributions $N(E)$ for a depth of 0.5 and 1 m in clear water under favourable weather conditions.

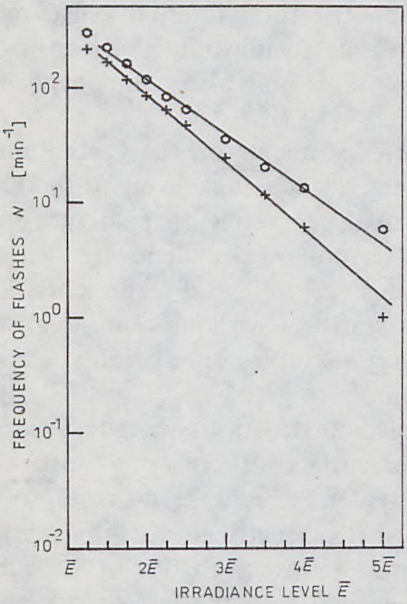

Fig. 7. Typical frequency distributions of flash intensity on a depth of 0.5 m measured in a water tank with generated surface waves exposed to the sunlight.
The solid lines are the least squares fit to the data by the exponential function: $N = N_0 \exp(-AE)$. The estimated regression parameters are as follows: $A = 1.11\bar{E}^{-1}$, $N = 1076.9 \min^{-1}$ for the upper line, and $A = 1.35\bar{E}^{-1}$, $N = 1284.5 \min^{-1}$ for the lower line

4. Concluding remarks

The numerical experiments presented here, the intuitive appeal to the wave crest acting as a converging 'lens', and the corresponding features of the light pattern observable in shallow water lend confidence that the focusing effect is indeed the most plausible explanation of the phenomenon in question. An attention is here concentrated on numerical examples showing the possible importance of small, smooth waves several centimetres long that have not been quantitatively interpreted before. This investigation is very elementary and omits many possible effects which could be seriously considered in a more general model. For example, the short waves, as measured in a wind-water tunnel, superimpose on the long waves in common situations on open water. Second, the sunlight refracted by a wind-ruffled sea is seen by an upward looking collector as a glittern pattern. Accordingly, the larger wave – having too complicated structure to act as an uniform 'lens' – may produce sparkles, each of which represents an image of the sun and contributes to a single focus, or more than one wavelet superimposed on larger wave may contribute to a single focus as well. According to Snell's law of refraction, from a depth of 1 to 2 m, the sea surface area of a few to over 16 m^2 is seen within the angle beyond which the total internal reflection takes place. As an idea advanced here serves only to illustrate the focusing produced by individual small wave, it may be usable only as a component of a more general model.

In this study we have also performed the experiments on the generation of flashing light by surface waves in a short-fetch water tank exposed to the sun. By a comparison between typical statistical properties of irradiance in the water tank and in the sea it is possible to have more confidence that only short waves are of practical interest in the focusing problem. Furthermore, it seems easily possible to model flashing light statistics without sophisticated wave generators. In particular, this may be very useful for simulation studies of photosynthesis response to fluctuating light.

Finally, we wish to point out that in practical situations the subsurface optical effects can be related to the actual sea surface structure in statistical terms only. In this context the concept presented here in itself is not too informative, but eventually upon coupling with presently inaccessible data relating the statistics of underwater irradiance to the statistics of surface slope and curvature, we would gain further insight into the focusing behaviour.

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