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EXPERIMENTAL STUDY OF SHORT-PERIOD IRRADIANCE FLUCTUATIONS UNDER AN UNDULATED SEA SURFACE *

Contents:

1. INTRODUCTION

The results of the experimental investigations presented in this paper describe the phenomenon of the fluctuations of underwater irradiance caused by the refraction of sun rays on a rough sea surface. The first simplified model of this phenomenon was presented by Schenck (1957), who explained the mechanism of the fluctuations of underwater irradiance as a focusing effect of sun rays by wave crests. Experimental studies and further theoretical considerations in this direction were conducted by Dera and Olszewski (1967), Dera and Gordon (1968), Snyder and Dera (1970), Gordon et al. (1971), Nikolaev et al. (1972), Mullamaa and Nikolaev (1972), Jakubenko et al. (1973), Nikolaev and Maštakov (1973), Severnev (1973), Sudbin et al. (1974), Neujmin and Tolkačenko (1974), Prokopov et al. (1975). Dera and Druet (1975), Ivanov (1975), Li et al. (1975), Chulapov and Nikolaev (1976), Prokopov and Nikolaev (1976) and others.

The above papers elucidate much of the physical mechanism of underwater light field fluctuations, propose several simplified mathematical models, and present experimental data together with results of statistical analysis based on these data. However, in view of the complexity of the fluctuations, the existing descriptions require further research, in particular, fuller experimental confirmation under different natural conditions.

The results of most studies devoted to irradiance fluctuations indicate

* Some of the results of this paper were submitted at the Marine Optics Symposium organized by the International Association for the Physical Sciences of the Ocean IAPSO in Grenoble, 1975.

that, among the controlling factors, the focusing of sun rays by wave crests plays a dominant role in the effect of surface oscillations on underwater light field, in sunny weather and at shallow depths. As the result of this focusing, a transient concentration of solar energy in small areas of water occurs, this being manifested in the form of light flashes. The intensity of the flashes, their frequency and duration depend upon the existing environmental conditions, in particular the external irradiance conditions, spectrum of sea surface oscillations and the optical properties of sea water. The quantity of experimental data illustrating this dependence is still modest.

This paper includes another experimental analysis of the fluctuation phenomenon, basing on a comparison of changes in the power spectrum of irradiance fluctuations and changes in the power spectrum of waves causing the fluctuation in the inshore zone. A preliminary assessment of the distribution of intensities and duration of the transient concentrations of solar energy in open oceanic waters is also given. These phenomena were studied as to their effect on the conditions of photosynthesis of organic matter and other photochemical reactions possible in the sea. Hence, the main subject of the studies was irradiance fluctuations of very high intensity, often attaining amplitudes 2—3 times higher than the existing mean value of irradiance at the site of investigations. Such strong fluctuations were found only to depths of several metres below the water surface, and it is to this surface layer of water that the present investigations were limited. Experiments were conducted at the University of Leipzig's Baltic oceanographical coastal station at Zingst (G.D.R.) during the international scientific expedition EKAM-73 in May and June 1973 (Dera and Druet 1975), and during a survey cruise on the Polish m.s. "Antoni Garnuszewski" from the Merchant Navy Academy in Gdynia, to the waters of E.C. Atlantic and the Mediterranean in March and April 1975.

2. DESCRIPTION OF EXPERIMENTS

The first part of the work was conducted at the coastal station at Zingst and was basically limited to recording and statistical processing of the fluctuations of downwelling irradiance, as well as the recording and analysis of the respective power spectra of wind waves studied by Druet (1975).

Standard irradiance meters fitted with flat Lambert collectors 4.5 cm in diameter, vacuum photocells and colour glass filters with maximum transmission at $\lambda = 530$ nm were used to detect the irradiance fluctuations. The detectors were installed on a measuring mast about 200 metres from the shore at depths of 1 m and 2 m below the water surface. A digital wave recorder described in the paper by Śpiewak (1975) was fixed very close to the light detectors. Irradiance fluctuations were recorded simultaneously at the two depths mentioned, by means of a Hewlett-Packard 7100 type, two channel strip chart recorder. The analogue recordings of irradiance fluctuations were converted into digital form with quantization step of $\Delta t = 0.079$ sec., their power spectra being calculated by Fast Fourier Transform, over 4000 data being taken into account in each series. These spectra were then smoothed out 3 times by means of a Hamming filter. A description of these experiments, together with some results of investigations, is contained in the paper by Dera and Druet (1975), wherein other studies conducted at the same time during the expedition at Zingst, are also presented.

The second part of the investigations was conducted from the "Antoni Garnuszewski" (5500 tons), during the cruise to the E.C. Atlantic and Mediterranean. The purpose of this part of the experiment was the preliminary determination of the range and scale of transient concentrations of solar energy under a rough sea surface in favourable insolation and wave conditions, in the optically differentiated waters of the open sea.

An apparatus of special design was used in these investigations (Dargiewicz 1975). The irradiance meter, fitted with a photomultiplier, green interference filter (535 nm) and a small diameter (2.5 mm) downwelling-irradiance collector, was connected to a special 10-channel threshold analyzer with quartz clock. With this measuring system, direct recording of the intensity and duration of light flashes, related automatically to the mean irradiance level at the site of the investigations, was possible.

3. RESULTS AND DISCUSSIONS

The power spectra of the most typical irradiance fluctuations observed in shallow inshore water with a moderate shoreward wind, are shown in Fig. 1. For comparison, the power spectrum of surface waves recorded at the site of the investigations simultaneously with the irradiance, is also entered into the drawing.

The most obvious feature of the irradiance fluctuation spectra presented in Fig. 1 is their complexity, which is manifested in the large number of peaks. The main maximum of these spectra is clearly shifted towards higher frequencies, as compared with the maximum power spectrum of the prevailing surface waves. This means that most of the irradiance fluctuation power in these shallow waters falls in the high frequency range, in which the wave spectrum generally attains the asymptotic form, which can be expressed in the approximate form by Phillips' law: $S(\omega) = \eta g^2 \omega^{-5}$ (where $\omega = 2\pi f$ — circular frequency, g — acceleration due to gravity, $\eta = 6.5 \cdot 10^{-3}$ — universal constant).

With the lowering of the sun's altitude (Fig. 1 curve for 14.40 GMT i.e. 15.40 local time) a substantial drop in the irradiance fluctuation power

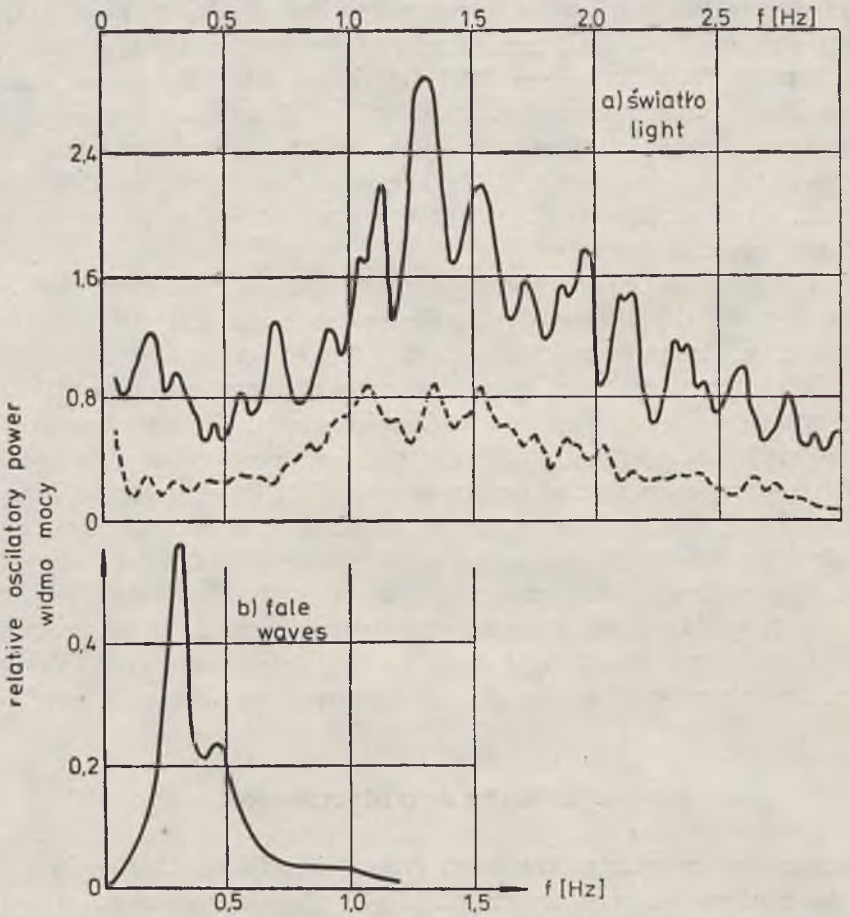


Fig. 1. Power spectra of underwater irradiance fluctuations for two solar altitudes α_H (part a) and for a steady-state power spectrum of surface waves (part b). Baltic at Zingst, depth z = 1 m, June 9th, 1973

————————	10.30 GMT	$\alpha_H = 57°$	$\sigma_E / \overline{E} = 0.13$
- - - - - - - - -	14.40 GMT	$\alpha_H = 37°$	$\sigma_E / \overline{E} = 0.07$

Ryc. 1. Widma mocy fluktuacji podwodnego oświetlenia dla dwóch wysokości słońca α_H (rys. a) przy ustalonym widmie mocy falowania powierzchni morza (rys. b). Bałtyk-Zingst, głębokość z = 1 m, 9 VI 1973

————————	10^{30} GMT	$\alpha_H = 57°$	$\sigma_E / \overline{E} = 0{,}13$
- - - - - - - - -	14^{40} GMT	$\alpha_H = 37°$	$\sigma_E / \overline{E} = 0{,}07$

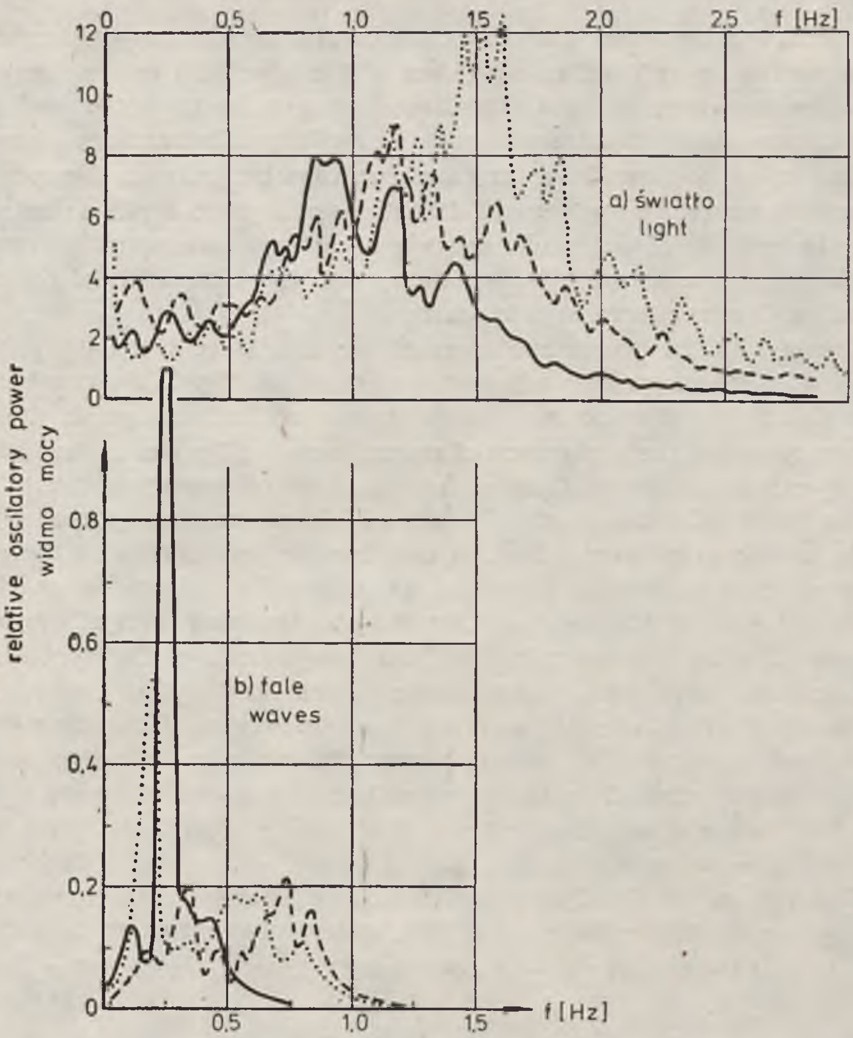


Fig. 2. Underwater irradiance fluctuation spectra (part a) for various spectra of surface waves (part b).

Baltic at Zingst, $z = 2$ m

———————	June 5, 1973	8.45 GMT	$\alpha_H = 49°$	$\sigma_E / \bar{E} = 0.10$
- - - - - - - - -	June 7, 1973	10.30 GMT	$\alpha_H = 57°$	$\sigma_E / \bar{E} = 0.12$
....	May 30, 1973	8.30 GMT	$\alpha_H = 46°$	$\sigma_E / \bar{E} = 0.32$

Ryc. 2. Porównanie widm fluktuacji podwodnego oświetlenia (rys. a) przy różnych widmach mocy falowania powierzchni morza (rys. b).

Bałtyk-Zingst, $z = 2$ m

———————	5 VI 1973	8^{45} GMT,	$\alpha_H = 49°$,	$\sigma_E / \bar{E} = 0{,}10$
- - - - - - - - -	7 VI 1973	10^{30} GMT,	$\alpha_H = 57°$,	$\sigma_E / \bar{E} = 0{,}12$
....	30 V 1973	8^{30} GMT,	$\alpha_H = 46°$,	$\sigma_E / \bar{E} = 0{,}32$

was observed over the whole spectral band studied, the position of the main maximum and individual peaks of the spectrum in the frequency scale remaining unchanged. This result was to be expected under the assumptions that the frequency of irradiance fluctuations does not depend upon the incidence angle of sun rays but only on the spectrum of surface waves. The power of fluctuations at a given depth z diminishes with the increase of the incidence angle of sunrays on a rough sea surface, this being due to the surface geometry and the elongation of the mean optical path of scattered rays in water.

Changes in the power spectrum of the irradiance fluctuation due to changes in the wave spectrum, are presented in Fig. 2. As can be seen from this figure, the increase of the power of fluctuations in the high frequency range, the occurrence of several new high peaks in the fluctuation spectrum and the shifting of the main spectral maximum towards the higher frequencies are observed when additional maxima appear or grow in the spectrum of wind waves. It can thus be concluded that the direct cause of the considerable growth of irradiance fluctuations observed was the short waves of frequencies above 0.5 cps; the main part of the power of these fluctuations belonging to finer components of the spectrum of free surface oscillations, whose share in the wave power spectrum is negligible. It could also be assumed that the shape of the short-period waves had a strong effect on the power of fluctuation, as complex wave spectra usually result from the superposition of two or more wave systems (e.g. following a change in wind direction), which is connected with major changes in the wave profile.

Changes in the level and distribution of irradiance fluctuations are closely related to the changes in such statistical parameters as standard deviation of the actual value of irradiance E from its mean value $\bar{E}$:

$$\sigma_E = \sqrt{\frac{\sum_1^n (E - \bar{E})^2}{n - 1}}$$

and the probability (density) distribution P (E) of given instantaneous values of irradiance E.

The standard deviations are given in all drawings for the Zingst experiment. In all cases the deviations are the greater and the main maximum of fluctuation spectrum is shifted towards the higher frequencies when the wave spectrum expands towards the higher frequencies.

This relationship is confirmed in the subsequent drawings in which the probability distribution of particular irradiance level E is given together with the standard deviations, thus enabling one to compare them with the corresponding wave spectra (Fig. 3) and irradiance fluctuation spectra

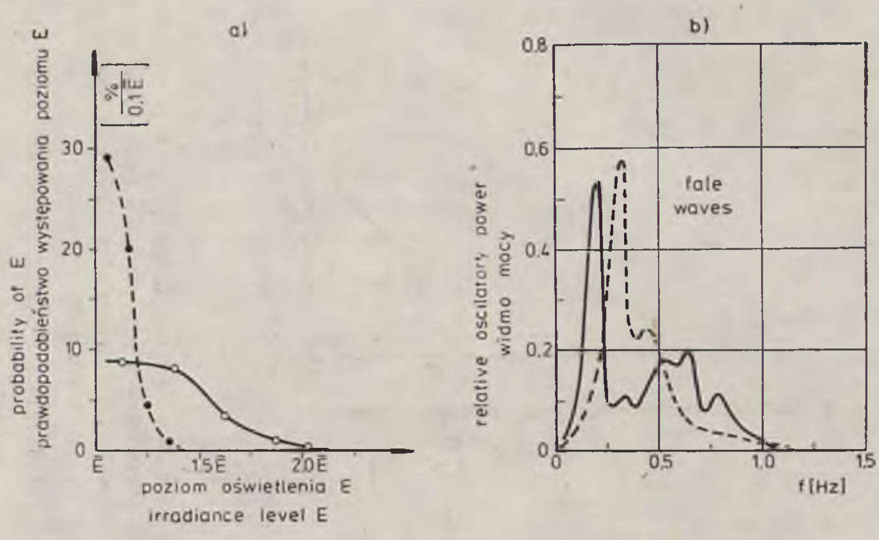


Fig. 3. Irradiance probabilities E (part a) for two different surface waves spectra (part b).

Baltic at Zingst, z = 1 m

——————— May 30, 1973 8.30 GMT $\alpha_H = 46^\circ$ $\sigma_E/\bar{E} = 0.56$

- - - - - - - - - June 9, 1973, 10.30 GMT $\alpha_H = 57^\circ$ $\sigma_E/\bar{E} = 0.13$

Ryc. 3. Porównanie rozkładów prawdopodobieństwa występowania poziomu E oświetlenia (rys. a) przy dwóch różnych widmach mocy falowania powierzchni morza (rys. b).

Bałtyk-Zingst, z = 1 m

——————— 30 V 1973 8^{30} GMT, $\alpha_H = 46^\circ$ $\sigma_E/\bar{E} = 0{,}56$

- - - - - - - - - 9 VI 1973 10^{30} GMT, $\alpha_H = 57^\circ$ $\sigma_E/\bar{E} = 0{,}13$

(Figs. 4—6). In the cases illustrated in Figs. 3 and 4, the differences in probability distribution are due to the details of wave spectra shown in Fig. 3 and to those in fluctuation spectra shown in Fig. 4, and are related to the change in wave conditions. In both cases, the irradiance probability distribution is much flatter when the wave, as well as the fluctuation spectra are better developed at higher frequencies. In such situations the probability of actual irradiance E of about two mean values $\bar{E}$ is different from zero, whereas in the remaining cases this probability already drops to zero for $E = 1.5\,\bar{E}$.

Figs. 5 and 6 show the spectra of fluctuations and probability distributions P (E) for two depths: z = 1 m and z = 2 m. Fig. 5 illustrates a typical situation where the maximum fluctuation amplitude decreases with depth, while Fig. 6 shows the reverse situation — less frequently found in water with such a high degree of turbidity [K_d (530 nm) $\geqslant 0.3\ m^{-1}$]. In both cases, however, the increase in maximum fluctuation amplitude is

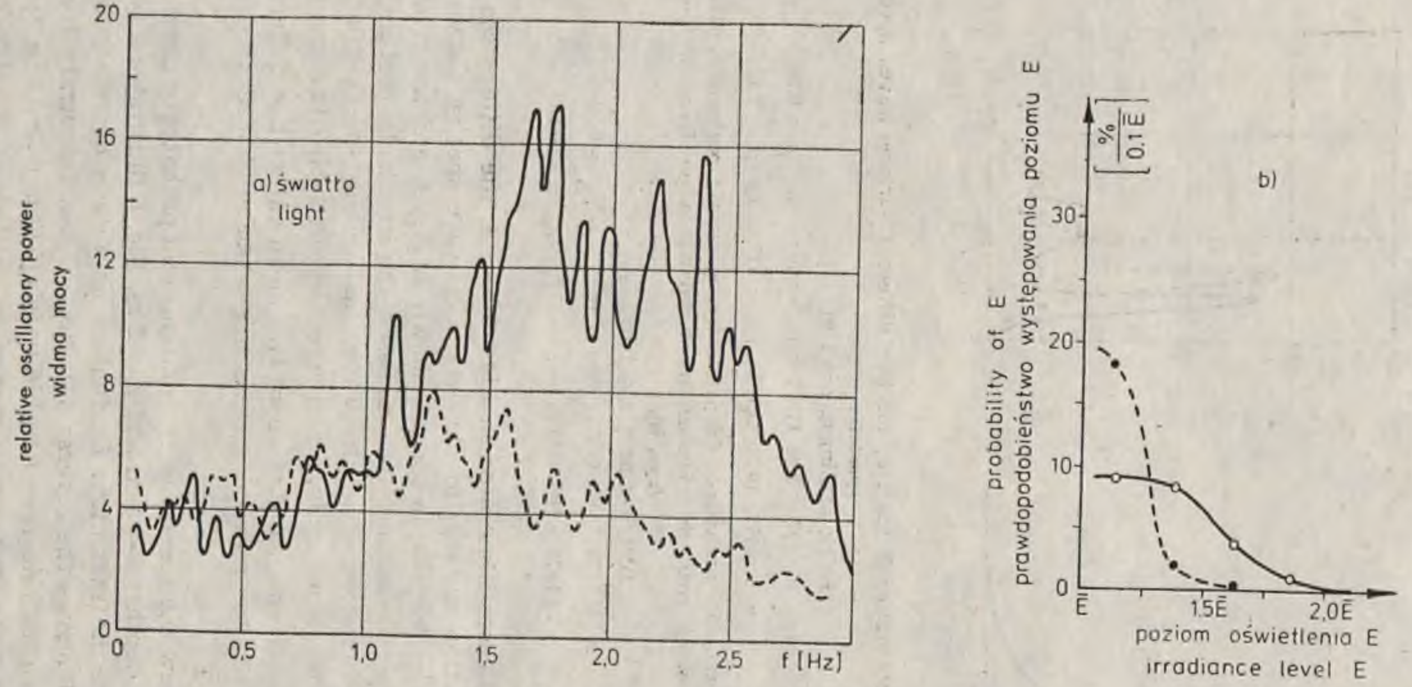
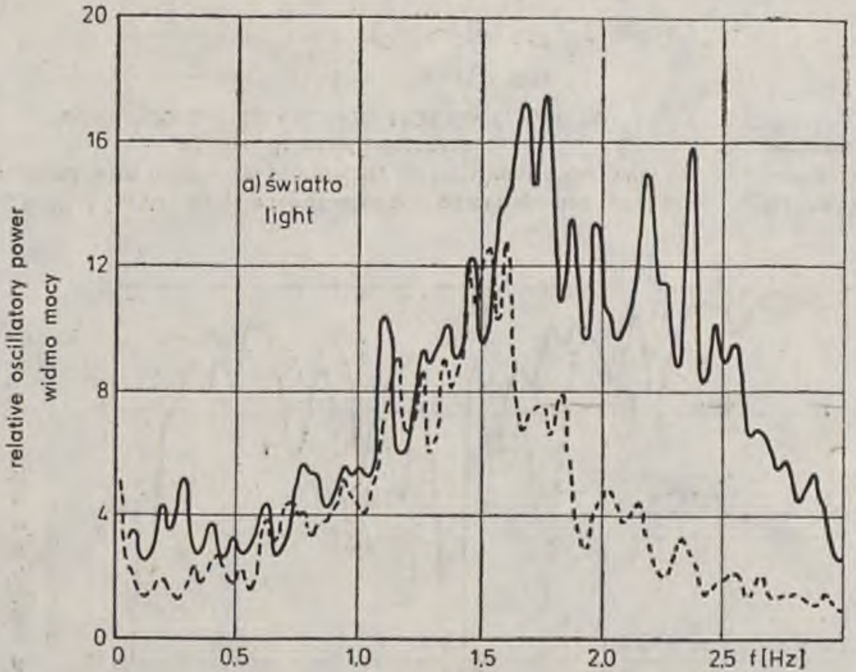


Fig. 4. Two different underwater irradiance fluctuation power spectra (part a) compared with respective irradiance probability distributions P (E) (part b).
Baltic at Zingst, z = 1 m

———————	May 30, 1973	8.30 GMT	$\alpha_H = 46°$	$\sigma_E/\bar{E} = 0.56$
- - - - - - - -	June 7, 1973	10.30 GMT	$\alpha_H = 57°$	$\sigma_E/\bar{E} = 0.16$

Ryc. 4. Dwa różne widma mocy fluktuacji podwodnego oświetlenia (rys. a) porównane z odpowiednimi rozkładami prawdopodobieństwa występowania poziomu E oświetlenia (rys. b).
Bałtyk-Zingst, z = 1 m

———————	30 V 1973	8^{30} GMT,	$\alpha_H = 46°$	$\sigma_E/\bar{E} = 0{,}56$
- - - - - - - -	7 VI 1973	10^{30} GMT,	$\alpha_H = 57°$	$\sigma_E/\bar{E} = 0{,}16$



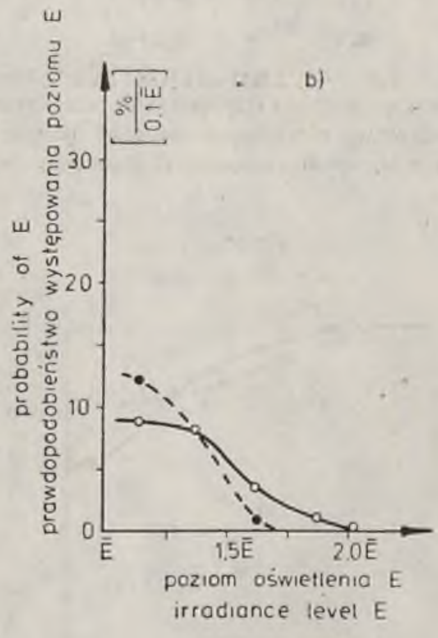


Fig. 5. Underwater irradiance fluctuation power spectra (part a) compared with irradiance probability distributions P (E) (part b) at two different depths z.

Baltic at Zingst, May 30, 1973, 8.30 GMT, $\alpha_H = 46°$

——————— z = 1 m $\sigma_E / \bar{E} = 0.56$

- - - - - - - - - z = 2 m $\sigma_E / \bar{E} = 0.32$

Ryc. 5. Widma mocy fluktuacji podwodnego oświetlenia (rys. a) porównane z rozkładami prawdopodobieństwa występowania poziomu E oświetlenia (rys. b) na dwóch różnych głębokościach z.

Bałtyk-Zingst, 30 V 1973, 8^{30} GMT, $\alpha_H = 46°$

——————— z = 1 m $\sigma_E / \bar{E} = 0,56$

- - - - - - - - - z = 2 m $\sigma_E / \bar{E} = 0,32$

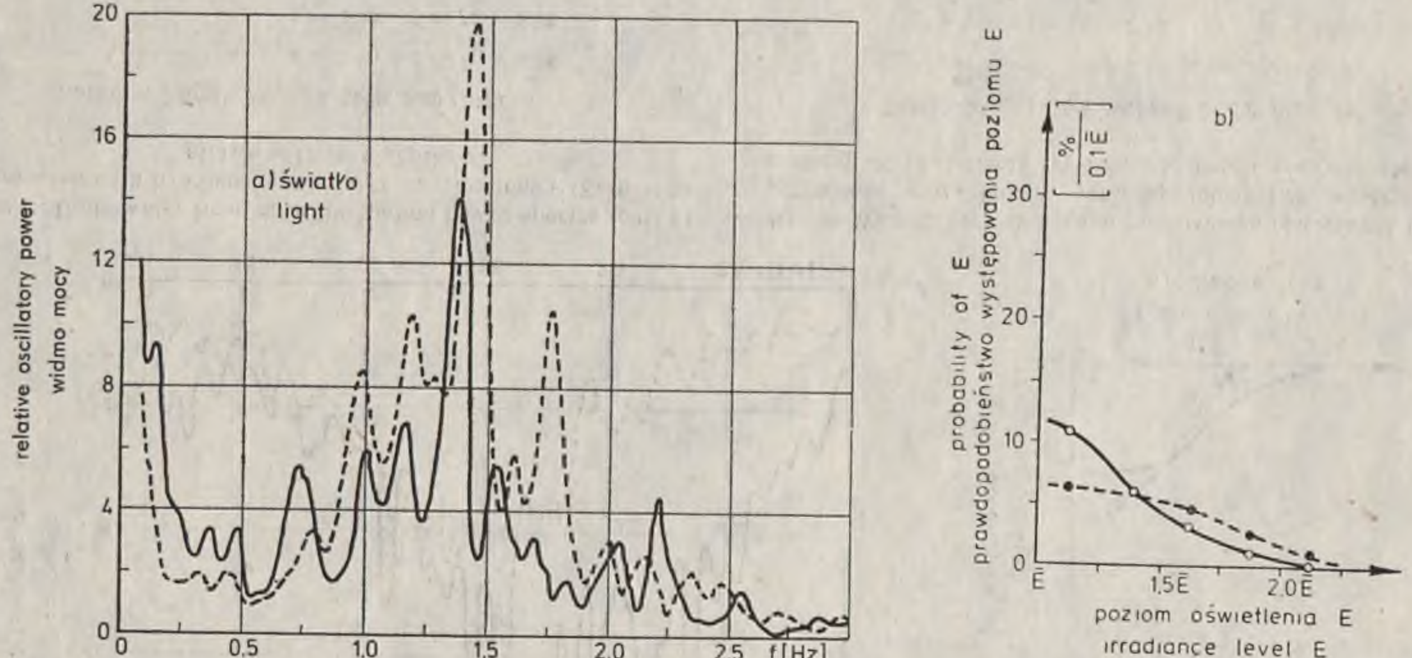


Fig. 6. Underwater irradiance fluctuation power spectra (part a), compared with irradiance probability distributions P (E) (part b) at two different depths z.

Baltic at Zingst, June 3, 1973, 10.30 GMT, $\alpha_H = 56°$

———	$z = 1$ m	$\sigma_E/\bar{E} = 0.39$
- - - - -	$z = 2$ m	$\sigma_E/\bar{E} = 0.57$

Ryc. 6. Widma mocy fluktuacji podwodnego oświetlenia (rys. a) porównane z rozkładami prawdopodobieństwa występowania poziomu E oświetlenia (rys. b) dla dwóch różnych głębokości z.

Bałtyk-Zingst, 3 VI 1973, 10^{30} GMT, $\alpha_H = 56°$

———	$z = 1$ m	$\sigma_E/\bar{E} = 0,39$
- - - - -	$z = 2$ m	$\sigma_E/\bar{E} = 0,57$

accompanied by a rise in the level of the short-term part of the fluctuation power spectrum.

The drawings indicate that the probability of irradiances greater than 2 $\bar{E}$ is insignificant. However, the fact of the existence, under certain conditions, of non-zero values of this probability indicates the possibility of very intense light pulses occurring under a rough sea surface. It is worthwhile recalling that the irradiance recorded was averaged to a certain extent both spatially (by means of collector with a relatively large diameter of 4.5 cm), and in time, by a recorder with a certain mechanical inertia.

With emphasis on the study of the intense light pulses, which we called light flashes, a different measuring technique was adopted in the second part of the experiment, which permitted the averaging mentioned to be avoided. After several simple experiments with collectors of various-sizes, the diameter of the downwelling irradiance collector was reduced to 2.5 mm, taken as the optimum size of "point" collector in the water. A digital threshold analyzer, by which millisecond light pulses with a repetition frequency of up to 50 cps could be recorded without distortion, was used to record the data. The relatively clear waters of the Mediterranean and E.C. Atlantic were chosen as the survey region.

Fig. 7 gives an example of an irradiance fluctuation recording (with the recorder used in Zingst), in which the parameters measured during the second part of the investigations are drawn. The analyzer counted the number of times the irradiance exceeded a certain level E in relation to its mean value $\bar{E}$, automatically averaged with a time constant of about 30 seconds. The computed number N (per unit of time) will be referred to the frequency of light flashes stronger than a given irradiance x $\bar{E}$ (where: $\bar{E}$ = mean value of downwelling irradiance in situ).

The thresholds of the analyser determining ten irradiance levels simultaneously, were chosen experimentally, most frequently as follows: 1.25 $\bar{E}$, 1.5 $\bar{E}$, 1.75 $\bar{E}$, 2 $\bar{E}$, 2.25 $\bar{E}$, 2.5 $\bar{E}$, 3 $\bar{E}$, 3.5 $\bar{E}$, 4 $\bar{E}$ and 5 $\bar{E}$. The duration of the individual actual irradiance values exceeding particular levels is recorded on two arbitrarily chosen channels simultaneously with the number of flashes exceeding the particular irradiance with an accuracy of up to about 1 ms.

A suitably ballasted light meter was submerged about 3 m from the sunlit side of the ship. The movement of the ship, although insignificant, slightly disturbed the recording of signals, by causing variation of the depth at which the meter was submerged. Measurements of the diffuse attenuation coefficient of irradiance indicate, however, that such disturbance could only have reached the first of the thresholds analyzed (1.25

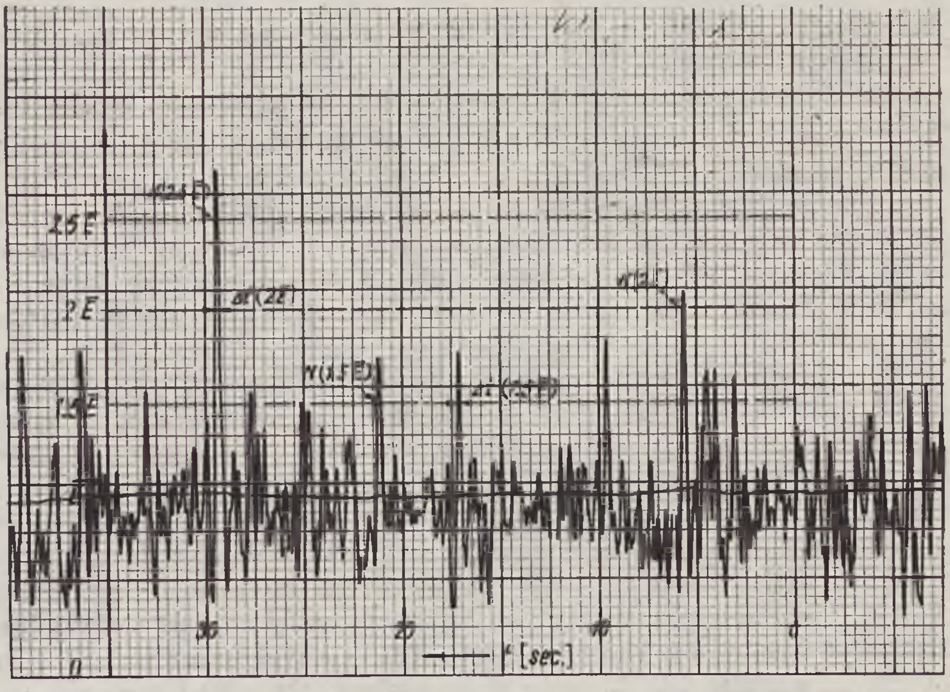


Fig. 7. Example of an analogue record of underwater irradiance fluctuations, with parameters measured in the second part of experiment:

$\overline{E}$ — mean irradiance E (t) on site,

N (x $\overline{E}$) — number of time increments, i.e. frequency of light flashes,

Δ t (x $\overline{F}$) — duration of a light flash above the reference level x $\overline{E}$.

The values x are chosen in the drawing as 1.5, 2.0 and 2.5. Ten thresholds were employed in the investigations, for x = 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 3.00, 3.50, 4.00 and 5.00

Ryc. 7. Przykład analogowego zapisu fluktuacji podwodnego oświetlenia z zaznaczonymi parametrami mierzonymi w drugiej części eksperymentu:

$\overline{E}$ — średnia wartość oświetlenia E (t) w miejscu badań,

N (x $\overline{E}$) — ilość błysków świetlnych silniejszych niż (x $\overline{E}$) w jednostkowym przedziale czasu, tj. częstość błysków,

Δ t (x $\overline{E}$) — czas trwania poszczególnego błysku powyżej poziomu x $\overline{E}$.

Wartości x wybrano na rysunku przykładowo równe 1,5; 2 i 2,5; w badaniach stosowano 10 progów dla x = 1,25; 1,50; 1,75; 2,0; 2,25; 2,50; 3,00; 3,50; 4,00; 5,00

$\overline{E}$), as oscillations in the thickness of the water layer up to about $\pm$ 1 m, might have caused changes in the irradiance level from $\pm$ 7% in the Mediterranean to about $\pm$ 30% in some of the investigated areas of the Atlantic. In fact, the light pulses recorded exceeded the mean irradiance value by two, three and even occasionally five times.

Fig. 8 gives the probability distribution of irradiance and flash frequencies recorded as above, at a depth of 2 m in the Mediterranean. The

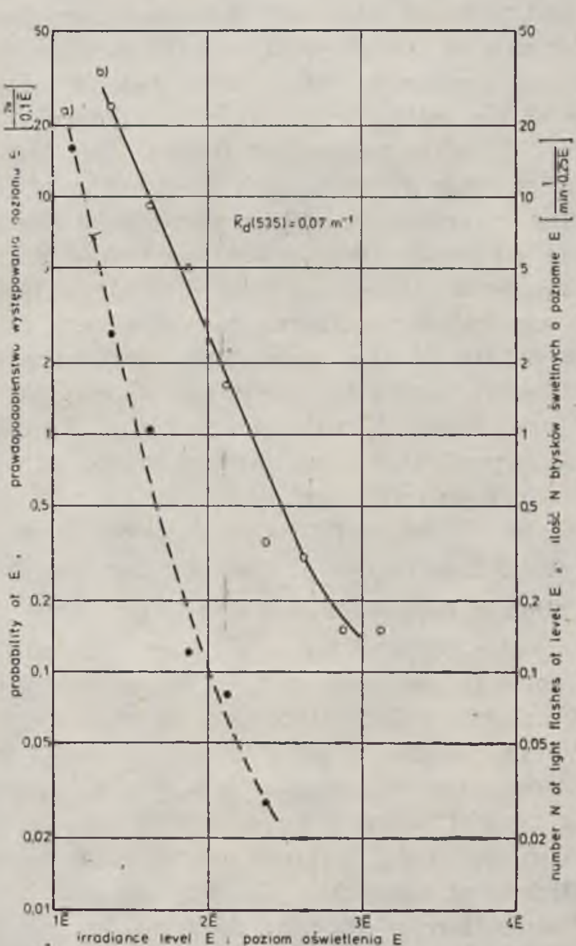


Fig. 8. Comparison of probability distributions P (E) (curve a) with the frequency of light flashes at level E (curve b). Mediterranean off Spain, z = 2 m, April 11, 1975 13.00 GMT $\overline{K}_d$ (535) = 0.07 m^{-1}, wind ENE 3, wave height h_{max} ca 0.5 m

Ryc. 8. Porównanie rozkładu prawdopodobieństwa E (krzywa a) z częstością błysków świetlnych o poziomie E (krzywa b).
Morze Śródziemne koło Hiszpanii, z = 2 m, 11 IV 1975, 13[00] GMT,
$\overline{K}_d$ (535) = 0,07 m^{-1}, wiatr ENE 3, fala $h_{max} \approx$ 0,5 m

results presented were obtained in a moderate sea (wave height not exceeding 1 m), in perfectly sunny weather and clear waters, where the attenuation coefficient of downwelling irradiance K_d (535 nm) attains the value of 0.07 m^{-1}. The frequency of light flashes in the 1.25 — 1.5 $\bar{E}$ ranges is of the order of 20 $min.^{-1}$, but their quantity decreases sharply with increasing intensity, according, approximately, to an exponential law, down to about 5 $min.^{-1}$ for the instantaneous irradiances in the 1.75 — 2.0 $\bar{E}$ range and to about 0.1 $min.^{-1}$ for irradiances higher than 3 $\bar{E}$. However, the decrease of the probability P (E) is much faster than the decrease of flashing frequency. This means that the share of high — intensity flashes in the total energy of the irradiance studied is lower than would appear from the number of flashes. This fact might be due to the shortening of flash duration with the growth of flash intensity. Hence, the flashing frequency, N, and the duration of flashes Δ t, seem to be the parameters, which describe the phenomenon of fluctuations at the highest amplitudes better than the probability (density) P (E).

It is easy to see that these flashes, rare and very intensive, which characterize the nature of the underwater environment, will not be detected by an observer using the methods of spectral analysis, the results of which are presented in the discussion of the first part of our experiments. This is particularly true because of the very short duration of the flashes, to which we refer later.

The distributions of the duration of flashes above the reference irradiances 2 $\bar{E}$ and 3 $\bar{E}$ at depths of 1 m and 2 m are shown in Fig. 9. The average duration of flashes above 3 $\bar{E}$ is 20 ms, while that for flashes above 2 $\bar{E}$ is 26 ms at a depth of 1 m and 33 ms at 2 m. The most probable duration of these flashes is about 2 ... 3 times shorter than the mean values indicated, this being due to the clear asymmetry of the distributions presented. The secondary peak in the flashing duration curve observed in some cases (see drawing) is most probably due to the effect of a certain component of the surface wave spectrum.

The diagrams shown in Fig. 9 refer to fairly clear waters, where the attenuation coefficient of irradiance, K_d (535 nm) assumes the value of 0.16 m^{-1}. The distributions of flashing duration for much more turbid waters, where K_d (535 nm) = 0.29 m^{-1}, have a similar form, which is illustrated in Fig. 10. It can thus be presumed that the most probable flashing duration above 2 $\bar{E}$ and 3 $\bar{E}$ is from several to tenths of milliseconds, while the frequency of these flashes ranges from a few cycles to tenths of cycles per minute. Longer durations and lower frequencies were usually observed at the greater of the two depths. This must depend on the surface wave spectrum, which has not been analyzed in this study.

Nevertheless, basing on the assumptions mentioned above we conclude that the irradiance flashes observed are caused basically by the short-wave part of the surface wave spectrum, whose share in the total energy is very small.

The frequency and mean duration of flashes above a certain irradiance level, measured at depths of 1 m and 2 m in the Atlantic, are shown in Fig. 11, versus the reference level. Again, a rapid decrease in the flashing frequency with increasing intensity can be noted. This

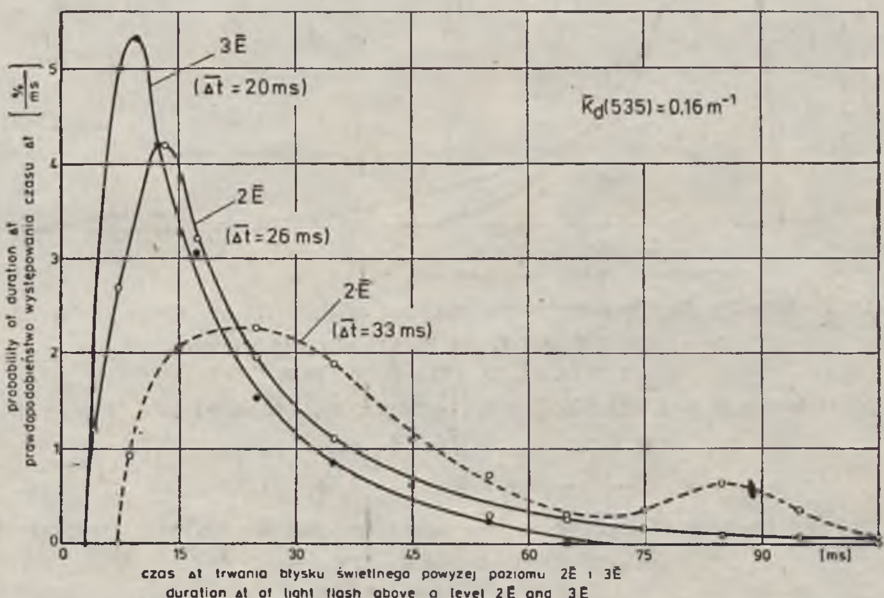


Fig. 9. Probability distributions for the duration of light flashes above irradiance levels E, for two different depths z. Atlantic off Morocco:

April 14, 1973, 10.00 — 14.00 GMT, $\overline{K}_d$ (535) = 0.16 m^{-1}

wind NNE 2, wave height h_{max} ca 0.15 m + 1 m swell

——●—— z = 1 m E = 3 $\overline{E}$ $\overline{\Delta t}$ (3 $\overline{E}$) = 20 ms

——○—— z = 1 m E = 2 $\overline{E}$ $\overline{\Delta t}$ (2 $\overline{E}$) = 26 ms

- - - -○- - - z = 2 m E = 2 $\overline{E}$ $\overline{\Delta t}$ (2 $\overline{E}$) = 33 ms

Ryc. 9. Rozkłady prawdopodobieństwa czasu trwania błysku świetlnego powyżej różnych poziomów oświetlenia E i dla dwóch różnych głębokości z. Atlantyk w rejonie Maroka:

14 IV 1973, 10^{00}—14^{00} GMT, $\overline{K}_d$ (535) = 0,16 m^{-1}

wiatr NNE 2, fala h_{max} ≈ 0,15 + 1 m martwa fala

——●—— z = 1 m E = 3 $\overline{E}$ $\overline{\Delta t}$ (3 $\overline{E}$) = 20 ms

——○—— z = 1 m E = 2 $\overline{E}$ $\overline{\Delta t}$ (2 $\overline{E}$) = 26 ms

- - - -○- - - z = 2 m E = 2 $\overline{E}$ $\overline{\Delta t}$ (2 $\overline{E}$) = 33 ms

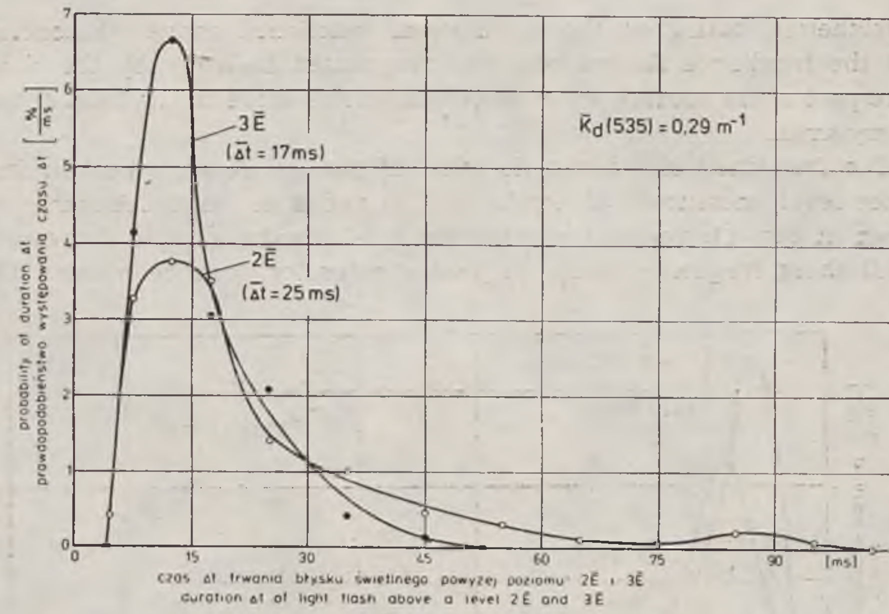


Fig. 10. Probability distributions of the duration of light flashes above the irradiance level $E = 2\bar{E}$ and $E = 3\bar{E}$. Atlantic off Morocco:
z = 1 m, April 15, 1975, 10.00—14.00 GMT
K_d (535) = 0.29 m^{-1}, wind NNE 1, wave height h_{max} ca = 0.1 m + 1 m swell

——●—— $E = 3\bar{E}$ $\bar{\Delta t}(3\bar{E}) = 17$ ms
——○—— $E = 2\bar{E}$ $\bar{\Delta t}(2\bar{E}) = 25$ ms

Ryc. 10 .Rozkłady prawdopodobieństwa czasu trwania błysku świetlnego powyżej poziomów oświetlenia $E = 2\bar{E}$ i $E = 3\bar{E}$.
Atlantyk w rejonie Maroka:
z = 1 m, 15 IV 1975, 10^{00}—14^{00} GMT
$\bar{K}_d$ (535) = 0,29 m^{-1}, wiatr NNE 1 fala $h_{max} \approx 0,1$ m + 1 m martwa fala

——●—— $E = 3\bar{E}$ $\bar{\Delta t}(3\bar{E}) = 17$ ms
——○—— $E = 2\bar{E}$ $\bar{\Delta t}(2\bar{E}) = 25$ ms

decrease is almost exponential: from several flashes per minute for a level of 1.5 $\bar{E}$ to about one flash per ten minutes for a level of 3.5 $\bar{E}$. The mean duration of flashes is about tenths of milliseconds and exposes a clear, although fairly irregular, tendency to drop with an increasing irradiance reference level.

The findings for waters of different turbidities, analogous to those of Fig. 11, are shown in Fig. 12. It can be seen that the decrease of flashing frequency with increasing intensity is faster for more turbid water, with higher values of K_d. It is also worthwhile noting that flashes with an intensity higher than 5 $\bar{E}$, although at a frequency of only about 0.1 min^{-1},

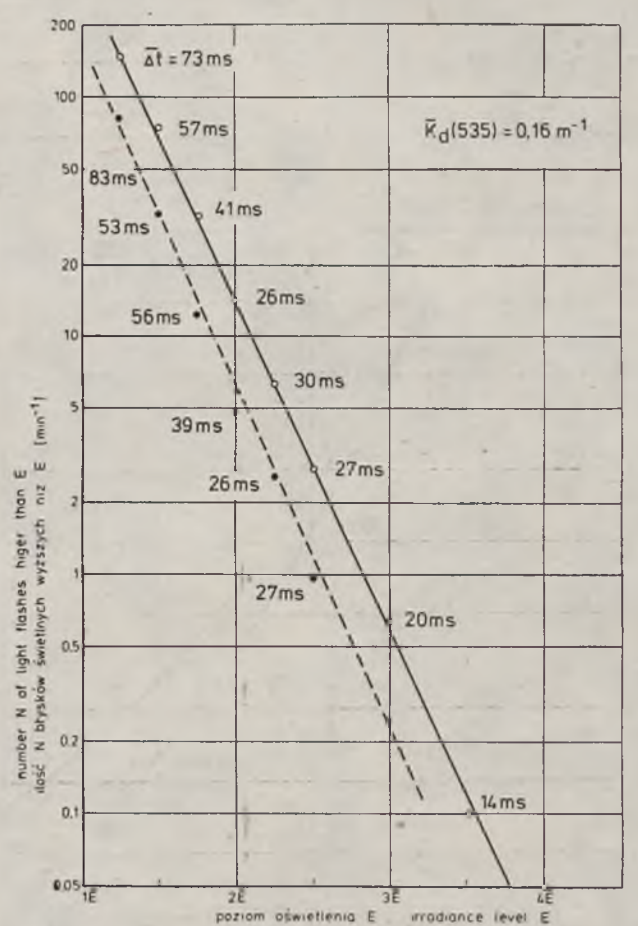


Fig. 11. Distribution of freguencies N of underwater flashes above E, at two depths z. Atlantic off Morocco, April 14, 1975, 12.00 GMT

$\overline{K}_d$ (535) = 0.16 m^{-1} wind NNE 2, wave height h_{max} ca 0.15 m + 1 m swell

——————— z = 1 m

- - - - - - - - - z = 2 m

Ryc. 11. Rozkład częstości N podwodnych błysków świetlnych wyższych od E, na dwóch głębokościach z.

Atlantyk w rejonie Maroka: 14 IV 1975, 12^{00} GMT

$\overline{K}_d$ (535) = 0,16 m^{-1}, wiatr NNE 2, fala $h_{max} \approx$ 0,15m + 1 m martwa fala

——————— z = 1 m

- - - - - - - - - z = 2 m

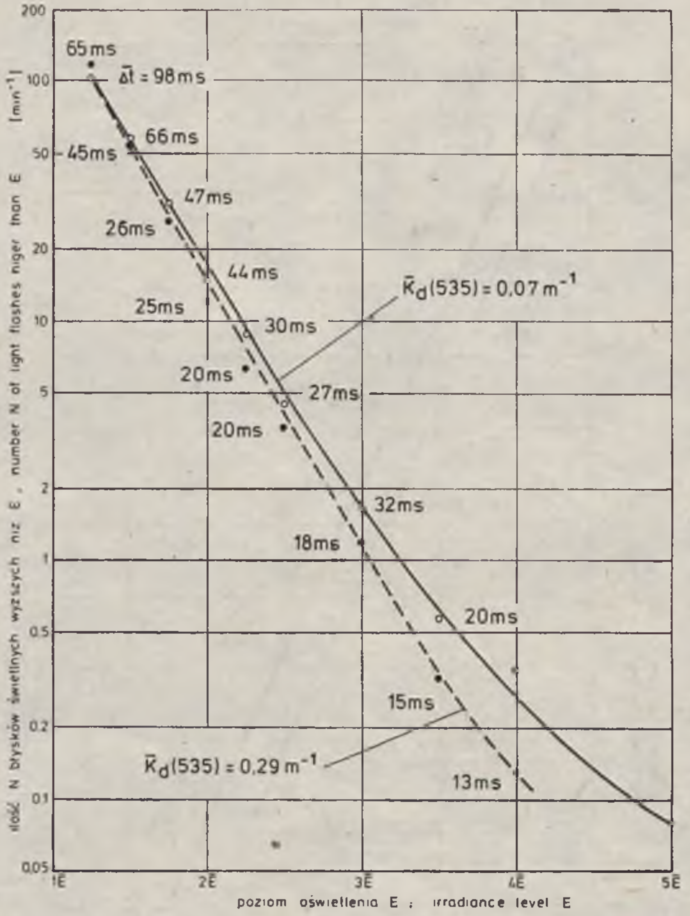


Fig. 12. Distribution of frequencies N of underwater light flashes above E, at a depth of 1 m, for two different water turbidities.

——— Mediterranean off Spain:

April 11, 1975, 14.00 GMT, $\overline{K}_d$ (535) = 0.07 m^{-1}
wind ENE 3, wave height h_{max} ca 0.5 m

- - - - - Atlantic off Morocco:

April 15, 1975, 10.00 GMT, $\overline{K}_d$ (535) = 0.29 m^{-1}
wind NNE 1, wave height h_{max} = 0.1 m + 1 m swell

Ryc. 12. Rozkład częstości N podwodnych błysków świetlnych wyższych od E, na głębokości z = 1 m, dla dwóch różnych stopni zmętnienia wody.

——— Morze Śródziemne koło Hiszpanii:

11 IV 1975 14^{00} GMT $\overline{K}_d$ (535) = 0,07 m^{-1}
wiatr ENE 3, fala h_{max} ≈ 0,5 m

- - - - - Atlantyk w rejonie Maroka:

15 IV 1975 10^{00} GMT $\overline{K}_d$ (535) = 0,29 m^{-1}
wiatr NNE 1 fala h_{max} ≈ 0,1 + 1 m martwa fala

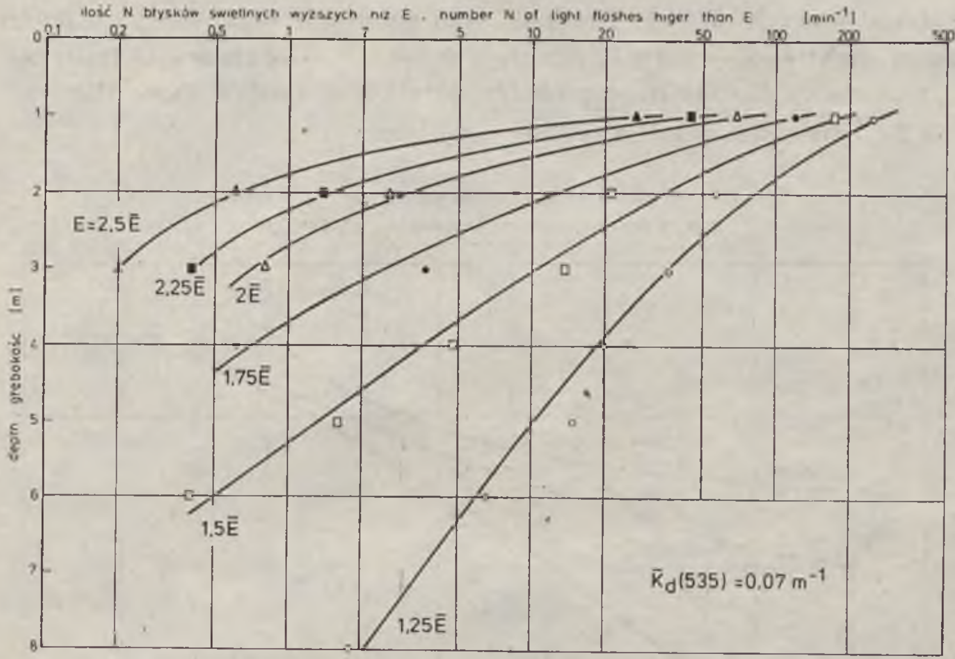


Fig. 13. Frequency N of underwater light flashes above E as a function of depth z, for various levels of E.
Mediterranean off Spain:
April 11, 1975, 12.00 GMT, $\bar{K}_d$ (535) = 0.07 m^{-1}
wind ENE 3, wave height h_{max} ca 0.5 m
E = 1.25 $\bar{E}$ (○) 1.50 $\bar{E}$ (□) 1.75 $\bar{E}$ (●) 2.00 $\bar{E}$ (△) 2.25 $\bar{E}$ (■) 2.50 $\bar{E}$ (▲)

Ryc. 13. Częstość N podwodnych błysków świetlnych wyższych od E w funkcji głębokości z, dla różnych poziomów E.
Morze Śródziemne koło Hiszpanii:
11 IV 1975, 12^{00} GMT, $\bar{K}_d$ (535) = 0,07 m^{-1},
wiatr ENE 3, fala h_{max} = 0,5 m
E = 1,25 $\bar{E}$ (○), 1,50 $\bar{E}$ (□), 1,75 $\bar{E}$ (●), 2,00 $\bar{E}$ (△), 2,25 $\bar{E}$ (■), 2,50 $\bar{E}$ (▲)

were observed in the clear Mediterranean waters in one case only, shown in Fig. 12.

The changes in the frequencies of irradiance flashes are shown in Figs. 13 and 14 as functions of depth. Fig. 13 illustrates these changes for various flashing amplitude levels, moderate waves and sunny weather, for the clear waters of the Mediterranean. The frequency of high-intensity flashes drops rapidly with depth. There was a slightly slower drop in frequency for lower intensities, but even in very clear water [K_d (530 nm) = 0.07 m^{-1}] flashes higher than 1.5 $\bar{E}$ were noted only to a depth of 8 m. Flashes with amplitudes between 2.5 $\bar{E}$ and 3 $\bar{E}$ were found at a depth of 3 m. The maximum amplitude of flashes at a depth of 1 m slightly exceeded 5 $\overline{E}$, but their frequency was about one flash per 10 minutes, while the most probable duration of flashes above the level of 5 $\overline{E}$ mentioned was a few milliseconds.

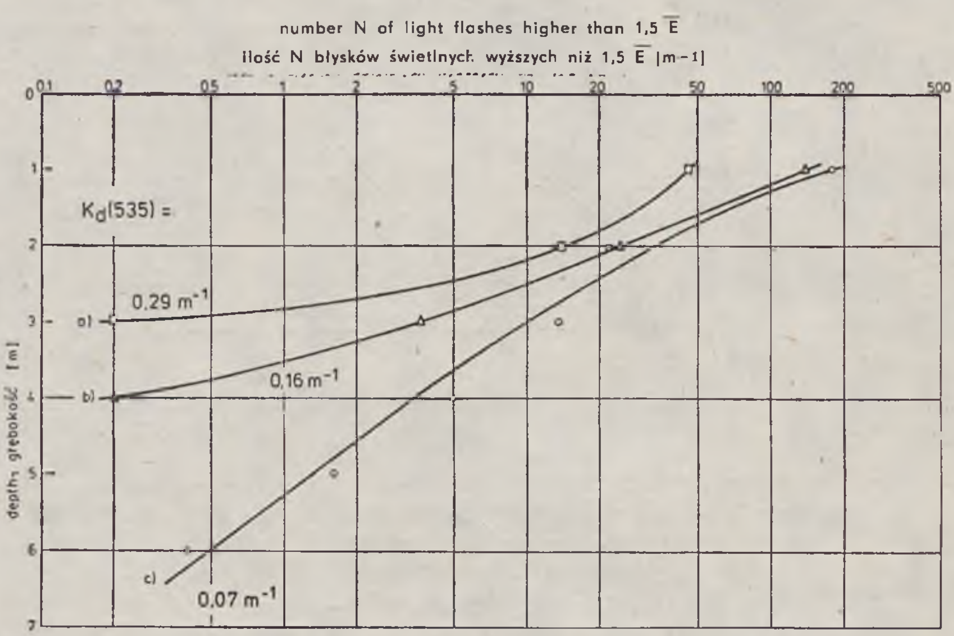


Fig. 14. Frequency N of underwater light flashes above E = 1.5 $\overline{E}$ as a function of depth, for different turbidities.
Atlantic off Morocco:
curve a, April 15, 1975, 13.00 GMT, $\overline{K}_d$ (535) = 0.29 m^{-1}
wind NNE 1, wave height h_{max} ca 0.1 m + 1 m swell
curve b, April 14, 1975, 11.00 GMT, $\overline{K}_d$ (535) = 0.16 m^{-1}
wind NNE 2, wave height h_{max} ca 0.15 m + 1 m swell
Mediterranean off Spain
curve c, April 11, 1975, 12.00 GMT, $\overline{K}_d$ (535) = 0.07 m^{-1}
wind ENE 3, wave height h_{max} ca 0.5 m

Ryc. 14. Częstość N podwodnych błysków świetlnych wyższych od E = 1,5 $\overline{E}$ w funkcji głębokości, dla różnych stopni zmętnienia wody.
Atlantyk w rejonie Maroka:
krzywa a, 15 IV 1975, 13^{00} GMT, $\overline{K}_d$ (535) = 0,29 m^{-1},
wiatr NNE 1, fala h_{max} ≈ 0,1 m + 1 m martwa fala
krzywa b, 14 IV 1975, 11^{00} GMT, $\overline{K}_d$ (535) = 0,16 m^{-1},
wiatr NNE 2, fala h_{max} ≈ 0,15 m + 1 m martwa fala
Morze Śródziemne koło Hiszpanii:
krzywa c, 11 IV 1975, 12^{00} GMT, $\overline{K}_d$ (535) = 0,07 m^{-1},
wiatr ENE 3, fala h_{max} ≈ 0,5 m

The changes in flashing frequency above the reference level of 1.5 E versus depth are illustrated in Fig. 14 for waters of various turbidities. It can be seen that the decrease of flashing frequency with depth is faster in more turbid water than in clear water. This means that a fairly wide interval of depths (down to about 10 m) with light flashes, i.e. with very strong irradiance fluctuations, which may strongly affect biological and photochemical processes in the water environment can be anticipated only in the clearest waters.

4. CONCLUSIONS AND SUMMARY

It can be noted in the summary of the results of investigations presented herein that a thorough knowledge and possible modelling of the phenomenon of irradiance fluctuations under an undulated sea surface requires further experimental studies. It appears that such statistical characteristics as standard deviation and probability distributions of various irradiance levels are insufficient to describe the fluctuations of the highest amplitudes. Because of the very short (in milliseconds) duration of the strongest flashes and their relatively low power (i.e. contribution to the total irradiance) it seems appropriate to complete the information about the phenomenon of fluctuations by studying both the frequencies of the strongest flashes and their duration under various weather conditions and for different water turbidities. The effect of the inherent optical properties of water seems to be as important as that of wave spectrum.

The rare occurrence of the strongest flashes (about 5 $\bar{E}$ i.e. 500 per cent of the mean irradiances, with frequency of about one flash per ten minutes) indicates the very slight probability of obtaining the best focusing forms by surface wave profiles. It can be suggested that the respective optimum form requires the superposition of several elementary waves, which is observed very rarely under natural conditions, although at certain regular intervals. It is the observation of this regularity which qualifies us to treat the flashes of the highest amplitudes as a phenomenon which can affect certain physico-chemical and biological processes in the sea.

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EKSPERYMENTALNE BADANIA KRÓTKOOKRESOWYCH FLUKTUACJI OŚWIETLENIA POD SFALOWANĄ POWIERZCHNIĄ MORZA

STRESZCZENIE

Wykonano pomiary i analizę statystyczną fluktuacji odgórnego oświetlenia naturalnego pod sfalowaną powierzchnią morza w warunkach słonecznej i bezchmurnej pogody, dla różnych stopni zmętnienia wody i stanów dynamicznych jej powierzchni. Eksperymenty przeprowadzono w dwóch seriach, z których pierwsza obejmowała badania w strefie przybrzeżnej południowego Bałtyku, a druga — badania na Atlantyku w rejonie Maroka i na Morzu Śródziemnym w rejonie Hiszpanii.

W części opisującej wyniki pierwszej serii badań porównano widma mocy fluktuacji i statystyczne rozkłady ich amplitud z odpowiednimi widmami falowania powierzchni morza w miejscu pomiarów (ryc. 1—6). Stwierdzono przy tym szereg prawidłowości dotyczących charakteru widma fluktuacji oświetlenia i jego zmian pod wpływem zmian zarówno falowania, jak i wysokości słońca na niebie.

W części odnoszącej się do drugiej serii eksperymentów przedstawiono wyniki statystycznej analizy fluktuacji o dużych amplitudach, badanych w otwartych, dobrze nasłonecznionych wodach oceanu i Morza Śródziemnego, przy zastosowaniu specjalnie do tego celu opracowanej techniki pomiarowej. Rejestrowane parametry procesu ilustruje i wyjaśnia ryc. 7, ryc. 8—14 przedstawiają natomiast wyniki uzyskane w drugiej części eksperymentu. Wykazano tu m.in. występowanie pod sfalowaną powierzchnią morza chwilowych oświetleń przekraczających trzy, cztery, a czasem nawet pięć razy wartość średnią, o czasie trwania od kilkudziesięciu do kilku milisekund. Podano statystyczne rozkłady częstości takich „błysków" świetlnych oraz ich czasów trwania w wodach o różnym zmętnieniu i na różnych głębokościach, przy różnym, zawsze jednak niezbyt silnym falowaniu powierzchni morza.

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