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Observation of sunlight enhanced backscattering from the sea bottom near the beach

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Abstract

The paper describes a natural manifestation of the enhanced backscattering effect in conditions when sunlight is scattered by the sea bottom covered by shallow rippled water. In this system the water surface plays the role of a phase screen that focuses the light on the bottom, while the sandy bottom acts as a set of random single scatterers.

1. Observation

Enhanced backscattering (EBS) is a universal wave phenomenon, which manifests itself in a diversity of physical problems related to wave propagation and scattering of light in a random media. The EBS phenomenon arises due to the existence of coherent channels under multiple scattering (the phenomenon of weak localization) or due to the double wave passage through one and the same large-scale inhomogeneities (see review papers [1–3]).

One more manifestation of the EBS phenomenon can be observed under the conditions when the sunlight illuminates the sandy sea bottom near a beach. The rippled water surface serves as a phase screen, which is able to focus and defocus the sunlight, forming bright strips and dark spots on the sandy bottom. The photograph in figure 1 presents an example of similar strips and spots. This photograph was taken by the authors on a beach in Cargese, Corsica, during the NATO School 'Wave Scattering in Complex Media: From Theory to Applications' (proceedings of this School has been published in [4]).

The photograph in figure 1 shows the authors' long shadows of 8–10 m length on the sandy sea bottom covered by very shallow water: a typical depth h did not exceed 15–25 cm. The photograph was made in the early morning, just after sunrise. Cargese is situated on the western coast of Corsica, so the morning shadows fall on the water surface right near the beach.

Figure 1. Photograph of the authors' shadows lying on the sand under shallow rippled water. The shadow of the author who has taken this photo is on the right. The area of the halo that arises due to enhanced backscattering is shown as a ring around his head.

In the photograph (figure 1) one can observe the area of enhanced intensity of the backscattered sunlight, which is marked by the black circle. The EBS phenomenon forms something like a 'holy halo' around the head of the photographer whose shadow is on the right in figure 1, whereas the left shadow has no evidence of this.

2. Theory

In an attempt to explain the observed phenomenon in the simplest way, we suppose that the sunlight falls normally on the water surface, as shown in figure 2. All the wave fields scattered by individual sand particles, lying on the bottom, are in fact incoherent, because correlation radius $\boldsymbol{\rho}_c$ of the sunlight ($\boldsymbol{\rho}_c \approx \lambda/\theta_S \approx 2.5 \times 10^{-3}$ cm, $\theta_S \approx 1/200$ rad is an angular radius of the Sun) is significantly smaller as compared to the typical radius of randomly distributed sand grains (about 1 mm in diameter). Therefore, the interference phenomena are negligibly weak and one can consider the wave field intensities only.

Let us consider a small scattering element, centred at point $\boldsymbol{\rho} = (x, y)$ on a bottom surface $z = -h$. Let $I_0 = \text{const}$ be the intensity of the primary sunlight, falling on the water surface. The intensity of light, scattered by the selected scattering element $\boldsymbol{\rho} = (x, y)$ in

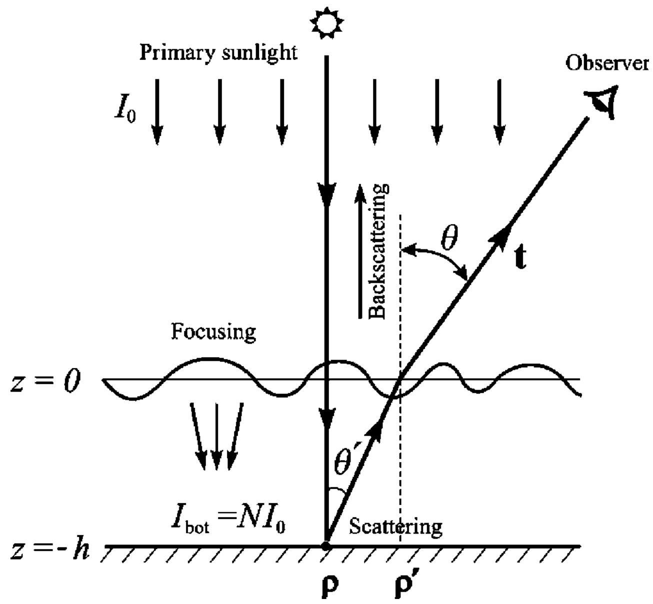

Figure 2. Scheme of sunlight focusing by a rippled water surface and backscattering from a sandy bottom.

the direction $\mathbf{t} = (\cos\phi\cos\theta, \sin\phi\cos\theta, \sin\theta)$, θ and ϕ being polar and azimuthal angles correspondingly, and registered by a remote observer (figure 2) is denoted as $I_{sc}(\boldsymbol{\rho}, \mathbf{t})$. We restrict our analysis to the case of small angle scattering, when $\theta \ll 1$, $\sin\theta \approx \theta$, $\cos\theta \approx 1$ and $\mathbf{t} \approx (\cos\phi, \sin\phi, \theta)$.

The scattered light intensity $I_{sc}(\boldsymbol{\rho}, \mathbf{t})$ takes on the value $I_{sc}^{\text{rippled}}(\boldsymbol{\rho}, \mathbf{t})$ in the case of rippled water surface and the value $I_{sc}^{\text{plane}}(\boldsymbol{\rho}, \mathbf{t})$ in the case of a plane surface. It is convenient to characterize the influence of the double passage of light through the rippled air–water interface by the *factor of enhancement*, which we define as a ratio

$$K(\boldsymbol{\rho}, \mathbf{t}) = \frac{I_{sc}^{\text{rippled}}(\boldsymbol{\rho}, \mathbf{t})}{I_{sc}^{\text{plane}}(\boldsymbol{\rho}, \mathbf{t})}. \tag{1}$$

The factor $K(\boldsymbol{\rho}, \mathbf{t})$ can be presented in the form of a product of two multipliers, each of them corresponding to a single crossing of the rippled water surface:

$$K(\boldsymbol{\rho}, \mathbf{t}) = K_1(\boldsymbol{\rho})K_2(\boldsymbol{\rho}'). \tag{2}$$

The first multiplier in equation (2) is *a focusing factor* $N(\boldsymbol{\rho})$:

$$K_1(\boldsymbol{\rho}) = N(\boldsymbol{\rho}). \tag{3}$$

It describes fluctuations of the primary sunlight intensity on a bottom:

$$I_{bot}(\boldsymbol{\rho}) = N(\boldsymbol{\rho})I_0. \tag{4}$$

The factor $N(\boldsymbol{\rho})$ exceeds a unit in the area of focusing, while value $N(\boldsymbol{\rho}) < 1$ corresponds to an area of defocusing.

The second factor in equation (2) describes focusing or defocusing of the scattered wave, when it crosses the rippled water surface on its way from the selected scattering element $\boldsymbol{\rho} = (x, y)$ to a remote observer. In virtue of the reciprocity theorem and under the conditions of small angle scattering this factor coincides with the focusing factor $N(\boldsymbol{\rho}')$, but taken at a point $\boldsymbol{\rho}' = \boldsymbol{\rho} + \tilde{\boldsymbol{\rho}}$, somewhat displaced with respect to $\boldsymbol{\rho}$ towards the observation point:

$$K_2(\boldsymbol{\rho}) = N(\boldsymbol{\rho}') = N(\boldsymbol{\rho} + \tilde{\boldsymbol{\rho}}). \tag{5}$$

The displacement $\tilde{\boldsymbol{\rho}} = \boldsymbol{\rho}' - \boldsymbol{\rho}$ can be estimated from the following consideration. Let us imagine a broken ray, which links an observer with the selected bottom scattering element. This ray propagating at a polar angle θ' in water and at an angle θ in the air, crosses the plane $z = 0$ at point $\boldsymbol{\rho}' = \boldsymbol{\rho} + \tilde{\boldsymbol{\rho}}$, where $\tilde{\boldsymbol{\rho}} = h \sin\theta'(\cos\phi, \sin\phi)$. The angles θ and $\theta'$are related by the Snellius law $\sin\theta/\sin\theta' = n$, where n is the water refractive index. For sufficiently small angles θ and θ' the Snellius law takes a simplified form $\theta/\theta' \approx n$, so that $\theta' \approx \theta/n$ and $\widetilde{\boldsymbol{\rho}} = h\theta(\cos\phi, \sin\phi)/n$.

With $K_1 = N(\boldsymbol{\rho})$and $K_2 = N(\boldsymbol{\rho}')$ relation (2) takes the form

$$K(\boldsymbol{\rho}, \mathbf{t}) = N(\boldsymbol{\rho})N(\boldsymbol{\rho}'), \tag{6}$$

and one is able to describe the basic features of the EBS phenomenon in a way similar to the results of [5]. This paper was devoted to the phenomenon of enhanced backscattering from a body placed in the turbulent medium (see also review papers [1–3]). In this case the factor $N(\boldsymbol{\rho})$ describes relative fluctuations of the wave intensity due to turbulence.

According to (6) the average value $\langle K(\boldsymbol{\rho}, \mathbf{t})\rangle$ of the enhancement factor equals

$$\langle K(\boldsymbol{\rho}, \mathbf{t})\rangle = \langle N(\boldsymbol{\rho})N(\boldsymbol{\rho}')\rangle = \langle N(\boldsymbol{\rho})\rangle^2 + \langle \widetilde{N}(\boldsymbol{\rho})\widetilde{N}(\boldsymbol{\rho}')\rangle, \tag{7}$$

where $\widetilde{N} = N - \langle N\rangle$ is the fluctuating part of the focusing factor N. Integrating the left-hand and right-hand parts of equation (4) over a sufficiently large bottom area S and taking into account the energy conservation law one has

$$(1/S) \int_S I_{\text{bot}}(\boldsymbol{\rho})\, \mathrm{d}^2\boldsymbol{\rho} = (1/S) \int_S I_0 N(\boldsymbol{\rho})\, \mathrm{d}^2\boldsymbol{\rho} = (1/S) \int_S I_0\, \mathrm{d}^2\boldsymbol{\rho} = I_0, \tag{8}$$

so that the spatial average of $N(\boldsymbol{\rho})$ happens to be equal to unity:

$$\langle N\rangle_{\text{spat}} = (1/S) \int_S N(\boldsymbol{\rho})\, \mathrm{d}^2\boldsymbol{\rho} = 1. \tag{9}$$

For ergodic fluctuations $\widetilde{N}$ the same is true for the statistical average $\langle N(\boldsymbol{\rho})\rangle$:

$$\langle N(\boldsymbol{\rho})\rangle = 1. \tag{10}$$

Thus, for statistically homogeneous fluctuations equation (7) takes the form

$$\langle K(\boldsymbol{\rho}, \mathbf{t})\rangle = 1 + \langle \widetilde{N}(\boldsymbol{\rho})\widetilde{N}(\boldsymbol{\rho}')\rangle = 1 + g_{\widetilde{N}}(\boldsymbol{\rho} - \boldsymbol{\rho}') = 1 + g_{\widetilde{N}}(\widetilde{\boldsymbol{\rho}}), \tag{11}$$

where

$$g_{\widetilde{N}}(\widetilde{\boldsymbol{\rho}}) = \langle \widetilde{N}(\boldsymbol{\rho})\widetilde{N}(\boldsymbol{\rho} + \widetilde{\boldsymbol{\rho}})\rangle \tag{12}$$

is a covariance of the focusing factor fluctuations.

In a backward direction, where $\theta = 0$, $\mathbf{t} = 0$ and $\widetilde{\boldsymbol{\rho}} = 0$, the average backscattering enhancement factor $\langle K(\boldsymbol{\rho}, 0)\rangle$ always exceeds unity:

$$\langle K_{\text{bsc}}\rangle \equiv \langle K(\boldsymbol{\rho}, 0)\rangle = \langle N^2(\boldsymbol{\rho})\rangle = 1 + g_{\widetilde{N}}(0) > 1, \tag{13}$$

because variance $g_{\widetilde{N}}(0) = \langle \widetilde{N}^2\rangle$ cannot be negative.

This factor takes the maximum value when the typical focal length for a rippled surface is comparable with a depth h. Analysis of a similar EBS phenomenon for coherent laser light, illuminating the scattering subsurface layer, located under large-scale gravity waves in the open ocean, was described in [6, 7] (see also [2]). In a deep ocean the fluctuations of the light intensity might be significantly larger (phenomenon of gigantic backscattering) as compared with shallow water.

3. Discussion

It is worth noting that figure 1 shows only an individual, but not an averaged picture of the scattered intensity. Nevertheless we can observe the EBS phenomenon due to peculiarities of human visual perception: our eye performs spatial integration over a picture thereby revealing an average increase of the light intensity in a backward direction. Owing to the ergodicity property of the water surface fluctuations, the spatial averaging of the observed small-scale picture in the EBS area in fact is equivalent to the statistical ensemble averaging. That is why we are able to observe the statistical features of the EBS phenomenon at the single realization, as presented in figure 1.

Enhanced backscattering might be observed within some angular sector, restricted by the characteristic scale (correlation radius) $\widetilde{\boldsymbol{\rho}}_c$ of the covariance function $g_{\widetilde{N}}(\widetilde{\boldsymbol{\rho}})$: the EBS phenomenon disappears at $\widetilde{\boldsymbol{\rho}} > \widetilde{\boldsymbol{\rho}}_c$, when incident and scattered waves cross *different* inhomogeneities of the rippled surface. One can see from figure 1 that the half-width $\Delta\theta_c$ of the EBS sector is about 2° and the dominant wavelength λ_{dom} of water ripples is about 3–5 cm. Supposing that the correlation radius $\widetilde{\boldsymbol{\rho}}_c$ is comparable with a quarter of the dominating wavelength in the wave spectrum, the angular width $\Delta\theta_c$ can be estimated from the relation

$$\widetilde{\boldsymbol{\rho}}_c \approx h\Delta\theta_c/n \approx \lambda_{\text{dom}}/4. \tag{14}$$

Strictly speaking, this relation corresponds to sunlight, normally falling on the sea surface, but qualitatively it is also true for the oblique case. It follows from equation (14), that at $\lambda_{\text{dom}} \approx$ 3–5 cm and at $h \approx$ 20–30 cm the angular width of the EBS sector is about 2–4°, which is in qualitative agreement with figure 1.

It should be pointed out that the covariance function $g_{\widetilde{N}}(\widetilde{\boldsymbol{\rho}})$ obeys the condition

$$\int_S g_{\widetilde{N}}(\widetilde{\boldsymbol{\rho}})\,\mathrm{d}^2\widetilde{\boldsymbol{\rho}} = 0, \tag{15}$$

which stems from the conservation law (8). According to equation (15) positive values of $g_{\widetilde{N}}(\widetilde{\boldsymbol{\rho}}) \approx g_{\widetilde{N}}(0)$ at $\boldsymbol{\rho} < \boldsymbol{\rho}_c$ or, which is the same, at $\theta < \Delta\theta_c$, are accompanied by negative values at $\boldsymbol{\rho} > \boldsymbol{\rho}_c$ (at $\theta > \Delta\theta_c$). It means that at angles $\theta > \Delta\theta_c$ the average enhancement factor (11) becomes less then unity. Unfortunately, such a decrease of K is not visible in figure 1 because the difference $|K - 1|$ is a comparatively small value: magnitudes $K < 1$ are distributed in a sufficiently wide angle range.

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