ON THE EFFECT OF INCREASING THE VISIBILITY RANGE OF THE UNDERWATER OBJECTS WITH INCREASE OF THE HEIGHT OF THE OBSERVER ABOVE THE SEA SURFACE

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This paper explains the reasons for the well–known effect of anomalous vision of the underwater objects from space. It is shown that the visibility range of the large high–contrast objects from space through the clearest ocean water can reach 500 m *under the most favourable conditions.*

The effect of increasing the visibility range with increase of the height of the observer above the surface of the water reservoir has long been known and is widely discussed in the literature (see Refs. 1–4). The bottom can be seen better from onboard the aircraft than from onboard the ship. Cosmonauts have succeeded in observing the sea bottom up to the depths of the order of 400 m (see Ref. 2) while the visibility range of the underwater objects from the surface or from underwater does not exceed 100 m even through the clearest ocean water according to the theoretical estimates and field observations.[5]

What is the physical nature of the examined effect? In our opinion, the dependence of the visibility of the bottom on the height H of the observer can be explained by several reasons.

1. The surface roughness strongly interferes with the observations from onboard the ship. The roughness engenders the spatial fluctuations of the surface image which superimposes on the bottom image. In addition, the structure of the received image undergoes distortions caused by the refraction of the light coming from the object at the sloping sections of the rough surface. Photography[5] of the underwater test objects from the platform located above the water surface (at $H = 8$ m) showed that even at high transparency of water (for the visibility of the Secchi disk $z_d = 20$ m) and relatively low heights of the sea surface roughness (the wind velocity $v = 2.5$ m/s) the visibility range of small details of the instantaneous image of the object can be very small and with increase of the immersion depth (L) at first (at $L = 1$ m) the shape of the elements is distorted, then (at $L = 5$ m) the gaps can be seen in the image, and at $L = 10$ m the information about the object structure is lost completely.

With increase of the height of observations the spatial fluctuations of the bottom and surface images are smoothed and decreased (this effect was considered in detail in Refs. 6 and 7). In addition, the distortion of the instantaneous images decreases. Really, one can show[8] that if l is the displacement of the image point caused by the roughness (counted off in the objective plane), then its variance is

$$\sigma_l^2 = \frac{L^2\sigma^2(n-1)^2}{n^2}, \tag{1}$$

where σ^2 is the variance of the slopes of the sea surface and n is the refractive index of water. The roughness practically does not distort the image when the size of the element to be resolved $D_{el} \gg l$. As far as the displacement $l \lesssim 2.5\,\sigma_l$ with a probability of 0.99, the condition of the absence of the distortions is

$$D_{el} \gg 2.5\sigma_l \tag{2}$$

or, using the relation[8] $\sigma^2 = 3.16{\cdot}10^{-3}\,v$ for the variance of the slopes of the sea surface and the value $n = 1.34$, we derive from Eqs. (1) and (2) $D_{el} \gg 0.035L\sqrt{v}$. For example, for $v = 10$ m/s at $L = 20$ m we can neglect the distortion of the image due to roughness for $D_{el} \gg 2$ m. Thus, sufficiently large objects can be seen through the rough surface practically without distortions. But the resolution of the large–scale structures is the most often encountered problem in observations from great heights.

It should be noted that the effect under consideration does not increase the visibility range in comparison with the underwater observation. In the last case the visibility is maximum.

2. With increase of H the visibility range increases due to a more perpendicular observation of the sections of the object plane located at the periphery of the field of view (the distance "along the ray" from the surface to the periphery of the field of view decreases). Due to this effect the maximum increase of the visibility range L for observations from air in comparison with the visibility range L' of the same object from underwater is equal to $\cos^{-1}\varphi$, where 2φ is the angle of the field of view (in water). For example, at $2\varphi = 90°$ the visibility range increases by 40%.

3. In our opinion, the main reason for improving the visibility with increase of H is that the large objects are observed from great heights (for example, the large sandbanks with homogeneous reflection coefficient against the background of dark sections of the bottom covered with seaweeds), and they do not "get" completely in the field of view and for this reason, they are invisible ("the largeness can be seen at a distance"). They also can be invisible due to the small–scale inhomogeneities of the reflectance. The contrast of these inhomogeneities (disregarding the backscatter interference) decreases in water according to the law $K \sim \exp(-\sigma L)$ (σ is the scattering coefficient). In addition, for sufficiently great heights H the observer begins to perceive as a whole the large–scale inhomogeneities of the reflectance or the large–scale roughness of the local topography of the bottom whose image is transferred through the water layer without decrease of the contrast due to their large size (the frequency–contrast characteristic of water, as a rule, tends to unity with increase of the element size D_{el} and

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to $\exp(-\sigma L)$ with decrease of D_{el} according to the data of Refs. 1 and 5). When observing the bottom roughness the brightness image of the large–scale local topography of the bottom is engendered by the variations of the water layer thickness through which the different elements of this local topography are observed.

When explaining the phenomenon of anomalous vision from space one should possibly take into account the tendency of increase in the water transparency with depth (below the seasonal thermocline).

The papers published in due time about the observations of the underwater ridges by cosmonauts lead to the hypothesis[3,4] of forming the false image of these ridges by the layers of enhanced turbidity rising up at a distance of several kilometers from the bottom and dublicating the shape of this local topography.

In conclusion let us determine the maximum visibility range of the large underwater objects from space. Let us use the formula of the apparent contrast for observation of the large objects[5]

$$K = \frac{K_0\, k k_a}{1 + B_{bg}/\bar{B}}\,, \qquad (3)$$

where K_0 is the real contrast, k and k_a are the frequency–contrast characteristics of the water and atmosphere, B and B_{bg} are the mean brightnesses of the object and background. Then

$$B = \pi^{-1} n^{-2} E T_a R \exp(-\kappa L) \exp[-(\kappa + \varphi_0 \sigma) L \mu^{-1}]\,,$$

$$B_{bg} = \pi(E\rho_a + E T_a^2 \rho n^{-2} + E T_a^2 \rho_s)\,, \qquad (4)$$

where E is the irradiance at the upper boundary of the atmosphere; T_a is the atmospheric transparency; R is the mean reflection coefficient of the object; κ is the absorption coefficient; φ_0 is the parameter of the scattering phase function of water (the fraction of the backscattered light); μ is the cosine of the solar zenith angle; ρ_a, ρ, and ρ_s are the brightness coefficients of the atmospheric haze, water, and surface.

We may set $k = k_a = 1$ for the large objects. Since we estimate "from above", we also take $K_0 = 1$, $T_a = 1$, $\varphi_0 = 0$, and the maximum value $R = 0.15$. Then we derive from Eqs. (3) and (4)

$$K = \left[1 + \frac{\rho + n^2(\rho_a + \rho_s)}{0.15 \exp[-(1 + \mu^{-1})kL]}\right]^{-1}\,. \qquad (5)$$

Let us further take the typical value[5] $\rho = 0.02$ for clear water, and let us set $\mu = 0.88$ (the solar zenith angle $\theta_0 = 40°$). For this value of θ_0 and the clearest atmosphere[9] $\rho_a = 0.04$ and $\rho_s = 0.01$ for $v = 10$ m/s (see Ref. 5).

By substituting these values into Eq. (5), taking $K = K_{th}$ ($K_{th} = 0.01$ is the threshold contrast sensitivity of the receiver[5]), and solving Eq. (5) for L, we obtain $L \approx 2.3/\kappa$.

For the minimum value[10] $\kappa = 0.004\ \text{m}^{-1}$ (in the wavelength range 470–490 nm) the threshold visibility L is 575 m. Thus, the visibility range $L = 400$ m reported by cosmonauts is quite real.

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