IMAGE IRRADIANCE STRUCTURE IN THE SENSING OF THE SEA SURFACE THROUGH THE ATMOSPHERE

M.L. Belov and V.M. Orlov

All-Union Scientific-Research Institute of Marine Fisheries and Oceanography, Moscow
Received February 27, 1989

This paper presents a study of the spatial structure of the irradiance behind the receiving lens in the sensing of the sea surface by a narrow laser beam through the atmosphere. Analytical expressions are derived for the mean irradiance in the image plane of the receiving lens for the cases of a clear atmosphere and an optically dense aerosol atmosphere. It is shown that sea surface roughness can increase the image size significantly.

At present it can be said that, along with the traditional techniques for sea surface sensing, laser techniques, which enable one to measure sea surface roughness, chlorophyll concentrations, and so on,[1–3] are in a state of rapid development. One of the first problems to be solved in the development of remote laser sensing techniques is that of defining the relationships between the lidar return parameters and the parameters of the sea surface which are to be determined. The problem of determining the power of the lidar return received from the sea surface through the atmosphere was considered in Ref. 4. In the analogous scheme below we discuss the irradiance distribution of the image which is formed behind the receiving lens.

First, we assume that the sensing is performed using IR radiation, which is strongly absorbed by liquid water so that lidar return is formed mainly as a result of specular reflection of the sensing beam from the air-water interface, while the contribution due to backscattering from the water column can be neglected. We will also neglect the contribution from light scattering by foam and take into account the fact that the radiation wavelength is much smaller than radii of curvature and heights of the sea surface roughness. In addition, we shall assume that the sea surface roughness remains unchanged during the radiation pulse, and that the spatial length of the pulse is much larger than the diameter of the beam spot on the sea surface. This assumption allows us to study the structure of the image irradiance without having to take account of the pulsed character of the sensing radiation.

Let us write down the expression for the brightness $I_0(\mathbf{m},\ \mathbf{R})$ of the radiation reflected from the sea surface, neglecting the effect of shadowing,

$$I_0(\mathbf{m},\mathbf{R}) = V^2(\theta) I_b(\mathbf{s},\mathbf{R}), \tag{1}$$

where $\mathbf{m} = \mathbf{s} - 2\mathbf{n}(\mathbf{n}\cdot\mathbf{s})$; n is the unit normal vector to the randomly rough surface S at the point $\mathbf{R}$; $V^2(\theta)$ is the Fresnel reflection coefficient, whose value depends on the local angle of incidence θ of the sensing beam (in our further discussion we shall assume only the case $V^2(\theta) = V^2$); $I_{SR}(\mathbf{s},\ \mathbf{R})$ is the brightness of the sensing radiation incident upon the surface S at the point $\mathbf{R}$ in the direction $\mathbf{s}$; $\mathbf{s}$ is the unit direction vector of incidence of the sensing beam.

From the distribution $I_0(\mathbf{m},\ \mathbf{R})$ on the surface S one can determine the brightness of the radiation arriving at the receiver aperture[2] and then using the principle of reversibility applied to the scattering medium[2] and the results from Refs. 3 and 4 one can also obtain an integral relation for the mean irradiance $E(\mathbf{R}_i)$ in the image plane of the receiving lens (assuming that the beam incident on the surface is narrow, and the transmitter and receiver are located in the same plane XOZ)

$$E(\mathbf{R}_1) \propto \frac{V^2 q^4}{4q_z^4} \int\limits_{S_0} d^2R_0 \int\limits_{-\infty}^{\infty} d\xi W(\xi) E_s[(R_{0x}\,\mathrm{tg}\psi + \xi(\mathbf{R}_0))\cos\psi, R_{0y}] \times$$
$$\times\ E_r[(R_{0x}\,\mathrm{tg}\chi + \xi(\mathbf{R}_0))\cos\chi, R_{0y};\ R_s] \times$$
$$\times\ W\left[\gamma_x = -\frac{q_x}{q_z} + \frac{R_{0x}k}{q_z}\left(\frac{\sin^2\psi}{L_s} + \frac{\sin^2\chi}{L_r}\right);\right.$$
$$\left.\gamma_y = \frac{R_{0y}k}{q_z}\left(\frac{1}{L_s} + \frac{1}{L_r}\right)\right], \tag{2}$$

where $E_s(\mathbf{R}_0)$ and $E_r(\mathbf{R}_0,\ \mathbf{R}_s)$ are the irradiances produced in the atmosphere by the surface and pseudosource (having the parameters of the receiver)[3] in the planes perpendicular to their optical axes; S_0 is the projection of the randomly rough surface S onto the plane $z = 0$; $\zeta(\mathbf{R}_0)$ is the height of this randomly rough surface $\mathbf{S}$ at the point $\mathbf{R}_0$; ψ and χ are the angles which the incident beam and the reflected radiation arriving at the receiver aperture make with respect to the OZ axis, respectively; $W(\zeta)$ and $W(\gamma_x, \gamma_y)$ are the height and slope distributions of the randomly rough surface S; $\mathbf{R}_i$ is a vector in the image plane; L_i and L_r are the distances from the center of the observed sector on the surface S_0 to the radiation source and to the receiver, respectively; $q_z = k(\sin\psi + \sin\chi)$; $q_x = -k(\cos\psi + \cos\chi)$; $q^2 = q_x^2 + q_z^2$.

By integrating Eq. (2) one can find an analytical formula for the mean irradiance of the image. In particular for the height and slope distributions we have

$$E(R_s) = \frac{V^2 q^4}{8 q_z^4} \cdot \frac{a_s a_r b_y^{-1/2} b_x^{-1/2}}{L_s^2 L_r^2 (\overline{\gamma_x^2}\,\overline{\gamma_y^2})^{1/2}} \times$$

$$\times \exp\left\{-\frac{q_x^2}{q_z^2 2\overline{\gamma_x^2}} \frac{C_p}{d_x} - \left[R_{sy}\frac{L_r}{F}\right]^2 C_r d_y b_y^{-1} - \right.$$

$$\left. -\left[R_{sx}\frac{L_r}{F}+\delta\right]^2 C_r \sin^2\psi d_x b_x^{-1}\right\}, \qquad (3)$$

where

$$b_x = C_s\sin^2\psi + C_r\sin^2\chi + 2\sigma^2 C_s C_r \sin^2(\psi-\chi) + \bar{\mu}\nu_x;$$

$$b_y = C_s + C_r + \nu_y;\ d_x = C_s + \frac{\mu\nu_x}{\sin^2\psi};\ d_y = C_s + \nu_y;$$

$$\tilde{\mu} = 1 + 2\sigma^2 C_s \frac{\cos\psi\sin(\chi-\psi)}{\sin\chi};$$

$$\delta = \frac{q_x \sin\chi |\nu_x^{1/2}| \tilde{\mu}}{\sin^2\psi (2\overline{\gamma_x^2})^{1/2} |q_z| d_x};$$

$$\bar{\mu} = 1 + 2\sigma^2(C_s\cos^2\psi + C_r\cos^2\chi);\ \mu = 1 + 2\sigma^2 C_s\cos^2\psi;$$

$$\nu_x = \frac{k^2}{2\overline{\gamma_x^2} q_z^2}(\sin^2\psi L_s^{-1} + \sin^2\chi L_r^{-1})^2;$$

$$\nu_y = \frac{k^2}{2\overline{\gamma_y^2} q_z^2}(L_s^{-1} + L_r^{-1})^2.$$

For a low-optical-density aerosol atmosphere[3]

$$a_s = \frac{P_0}{\pi\alpha_s^2}\exp(-\tau_1);\ a_r = \frac{r_r^2}{r_{1ca}^2}\exp(-\tau_2);$$

$$\tau_1 = \int_0^{L_s}\sigma(z)dz;\ \tau_2 = \int_0^{L_r}\sigma(z)dz;$$

$$C_s = (\alpha_s L_s)^{-2};\ C_r = F^2(L_r r_{1ca})^{-2}.$$

In the case of an optically dense aerosol atmosphere we have the following expressions for a_s, a_r, C_s, and C_r (Ref. 3)

$$a_s \propto P_0\pi^{-1}C_s L_s^2 \exp\left\{-\int_0^{L_s}(1-\lambda)\varepsilon(z)dz\right\};$$

$$a_r \propto r_r^2 F^{-2} C_r L_r \exp\left\{-\int_0^{L_r}(1-\lambda)\varepsilon(z)dz\right\};$$

$$\lambda = \frac{\tilde{\sigma}}{\varepsilon};$$

$$C_s \propto [\alpha_s^2 L_s^2 + \mu_s L_s^2]^{-1};\ C_r \propto [r_{1ca}^2 L_r^2 F^{-2} + \mu_r L_r^2]^{-1};$$

$$\mu_{s,r} = L_{s,r}^{-2}\int_0^{L_{s,r}} \times \tilde{\sigma}(z)\langle\gamma^2(z)\rangle(L_{s,r}-z)^2 dz,$$

where α_s is the divergence of the beam emitted by the source; P_0 is the power of the radiation emitted by the source; r_r is the effective diameter of the receiving aperture; r_{ica} is the effective diameter of the least circle of aberration of the receiving optical system; σ^2 and $\overline{\gamma}_{x,y}^2$ are the variances of the heights and slopes of the sea surface; $\varepsilon(z)$ and $\tau(z)$ are the extinction and scattering coefficients of the medium; F is the focal length of the receiving lens; $\langle\gamma^2(z)\rangle$ is the variance of the beam deviation angles during an elementary scattering act; $\tilde{\sigma}(z)$ is the effective scattering index; $\tilde{\sigma} = \sigma(1 - x_0)$, where x_0 is the isotropic part of the scattering phase function.[6]

In the limiting case σ^2, $\overline{\gamma}_{x,y}^2 \to 0$ Eq. (3) transforms into a formula for the irradiance distribution behind the receiving lens in the case of sensing a planar specular surface.

Figure 1 illustrates the effect of sea surface roughness on the size of the image of the illuminated spot on the surface; here N is the ratio of the radius of the illuminated spot on the sea surface ρ_{ix} (defined as the e^{-1} level of image brightness as a function of R_{ix}) to the radius of the image ρ_{ix} ($\sigma = 0$) when no roughness is present on the sea surface. Calculations of N as a function of the angle ψ were made using Eq. (3) for the case $C_r \ll C_s$ (i.e., the sensing beam divergence is much smaller than the field of view of the receiver); for the case $\gamma_{x,y} \ll \alpha_{r,s}$ (i.e., when the effective slope angles of the sea surface significantly exceed the sensing beam divergence and the field of view of the receiver); $2\sigma^2(L_s\alpha_s)^{-2} = 1$; curves 1 . and 3 were calculated for $\mu / \alpha_r^2 = 0$ (clear atmosphere); curves 2 and 4 were calculated for $\mu / \alpha_r^2 = 0.5$ (optically dense atmosphere; the sensing beam divergence here is increased due to atmospheric influence by a factor of $(1.5)^{1/2}$); curves 1 and 2 were calculated for $\chi = 45°$ while curves 3 and 4 were calculated for $\chi = 90°$.

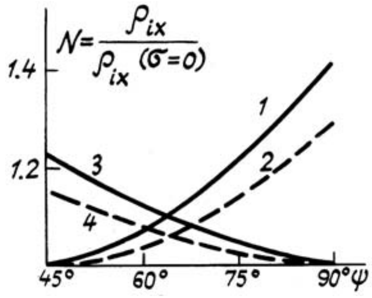

FIG. 1. Image size as a function of angle ψ.

As can be seen from the figure, random roughness can strongly increase (by a factor of up to 1,5) the size (i.e., diameter) of the image of the illuminated spot on the sea surface both in a clear and in an optically dense atmosphere. Physically this is explained by the fact that for the values of the parameters used in the calculations the dimensions of the image of the illuminated spot are comparable with those of the sea surface roughness and, therefore, strongly depend on the latter. This effect depends also on the sensing geometry. In the monostatic or strictly single-ended sensing scheme, when the radiation source and the receiver are spatially coincident, this effect is not observed, i.e., sea surface roughness does not disturb the image irradiance. At the same time, increasing the separation between the source and receiver results in an increasing distortion of the image, whose size then becomes more strongly dependent on the surface roughness.

It is interesting to note that the dependence of ρ_{sx} on the sea surface roughness is much stronger in a clear atmosphere (an optically dense atmosphere blurs the sensing beam and smoothes the distortions caused by the sea surface roughness).

The results obtained in this work can be applied to the design of laser remote sensing systems as well as to the analysis of their operation.

REFERENCES

1. A.I. Abramochkin, V.V. Zanin, I.E. Penner et al., Optika Atmosfery **1**, No. 2, 92 (1988).
2. I.M. Levin and K.S. Shifrin, Issledovanie Zemli iz Kosmosa, No. 4, 12 (1987).
3. F.V Bunkin, K.I. Volyak, A.I. Malyarovskii et al., Trudy Inst. Fiz. Akad. Nauk SSSR **1**, 3 (1986).
4. M.L. Belov, V.M. Orlov, and I.V. Samokhvalov, Optika Atmosfery **2**, No. 2, 218 (1989).
5. K. Case and P.F. Zweifel, *Linear Transport Theory* (Addison-Wesley, Reading, Mass., 1967).
6. V.M. Orlov, I.V. Samokhvalov, and G.G. Matvienko, *Elements of the Theory of Light Scattering and Optical Location* (Nauka, Novosibirsk, 1982).
7. F.G. Bass and I.M. Fuks, *Wave Scattering from a Statistically Rough Surface* (Nauka, Moscow. 1972).