OPTICAL SIGNAL POWER FROM A RANDOMLY ROUGH SURFACE SOUNDED THROUGH THE ATMOSPHERE

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The energy characteristics of radiation scattered by a randomly rough surface has been discussed previously (see, e.g. , Refs. 1 to 3), but only for monostatic sounding and taking no account of the atmosphere. Below, lidar return power is investigated for the case of bistatic sounding of a randomly rough surface in the atmosphere using a narrow laser beam.

Let us consider the reflection from a S composed of randomly oriented orientied small plane specular areas. These small areas are significantly larger than the wavelength of the radiation. Such a model is typical of a sea surface with waves but no foam and with no light scattering inside the water. We may then write the expression for the brightness $I_0(m, R)$ of radiation specularly reflected by an elementary area of a randomly rough surface S, assuming that the sounding angles are large compared with the characteristic slope angles of the surface, i.e., mutual shadowing of elements is negligible:

$$I_0(m, R) = A(R) I_{\text{rad}}(S, R), \tag{1}$$

where $m = S - 2n(nS)$; $A(R)$ is the reflection coefficient: $I_{\text{rad}}(S, R)$ is the brightness of the radiation incident on the surface along the direction S at the point R; n is the unit vector of the normal to the surface S at the point R.

Using the distribution $I_0(m, R)$ one can determine the brightness $\tilde{I}(m, r)$ of radiation at the receiver[4], and then using the reciprocity theorem[4] and the results from Ref. 5, one can find the expression for the power of the received signal. By averaging this expression over an ensemble of surfaces and changing the integration over the rough surface S to an integration over the surface S_0 (projection of S onto the plane $z = 0$)[6] one obtains for a narrow sounding beam (assuming the surface S_0 to be homogeneous, $A(R) = A$, and the source of radiation and the receiver being in the same plane XOZ)

$$P \simeq \frac{Aq^4}{4q_z^4} \int_{-\infty}^{\infty} d\xi W(\xi) \int_{S_0} dR E_r(\mathbf{R}'_\xi) E_r(\mathbf{R}''_\xi) W\left[\gamma_x = -\frac{q_x}{q_z} + \frac{R_x k}{q_z}\left(\frac{\sin^2\psi}{L_s} + \frac{\sin^2\chi}{L_r}\right); \gamma_y = \frac{R_y k}{q_z}\left(\frac{1}{L_s} + \frac{1}{L_r}\right)\right], \tag{2}$$

where $q_z = k(\sin\psi + \sin\chi)$; $q_x = -k(\cos\psi + \cos\chi)$;

$$q^2 = q_x^2 + q_z^2;$$

$$\mathbf{R}'_\xi = \{[R_x \operatorname{tg}\psi + \xi(R)]\cos\psi, R_y\};$$

$$\mathbf{R}''_\xi = \{[R_x \operatorname{tg}\chi + \xi(R)]\cos\chi, R_y\};$$

$\mathbf{R} = (R_x, R_y)$ is the vector in the plane S_0; $k = 2\pi/\lambda$ is the wave number; $\xi(\mathbf{R})$ is the height of the randomly rough surface S at the point $\mathbf{R}$; $\gamma = \nabla\xi(\mathbf{R})$ is the vector of random slopes of the surface S; $W(\gamma_x, \gamma_y)$, $W(\xi)$ are the probability densities of the slopes and heights of the randomly rough surface S, respectively; $E_s(\mathbf{R})$, $E_r(\mathbf{R})$ are the illuminations produced by the actual source and by a virtual one having the parameters of the receiver, in the planes perpendicular to the optical axes of the source and the receiver[5]; ψ, χ are the angle of incidence and the angle of observation reckoned with respect to OX axis); L_s, L_r are the distances from the centre of the area observed to the source and receiver, respectively.

The integrals entering into Eq. (2) can be evaluated, and one can obtained an analytical expression for P. In particular, for the mean received power in the case of sounding of a randomly rough, locally specular surface in clear atmosphere, one obtains (the heights and slopes of random roughness are assumed to have a Gaussian distribution, as is typical for sea surface, with waves[7]

$$P \simeq \frac{q^4}{q_z^4} \frac{a_s a_r A}{4L_s^2 L_r^2} \frac{1}{\sqrt{2}} \frac{1}{2(\bar{\gamma}_x^2 \bar{\gamma}_y^2)^{1/2}} \times \left[C_s + C_r + 1/R_0^2 + \frac{k^2}{2\gamma_y^2 q_z^2}\left(1/L_s + 1/L_r\right)^2\right]^{-1/2} d^{1/2} \times d^{1/2} \exp\left\{-\frac{q_x^2}{2\bar{\gamma}_x^2 q_z^2}\left[1 - \frac{n}{n+m} \times \left(1 + \frac{(C_s \sin\psi\cos\psi + C_r \sin\chi\cos\chi)^2}{d}\right)\right]\right\}, \tag{3}$$

where

$$d = \frac{1}{2\sigma^2}(n + m) + C_s C_r \sin^2(\psi - \chi) +$$

$$+ (C_s \cos^2\psi + C_r \cos^2\chi)(1/R_0^2 + n);$$

$$n = \frac{1}{2\bar{\gamma}_x^2}\left[\frac{\sin^2\psi}{L_s} + \frac{\sin^2\chi}{L_r}\right]^2 \left[\frac{k}{q_z}\right]^2;$$

$$m = C_s \cos^2\psi + C_r \cos^2\chi + 1/R_0^2;$$

$$a_s = \frac{P_0 \exp(-\tau_1)}{\pi\alpha_s^2}; \quad C_s = \frac{1}{\alpha_s^2 L_s^2}; \quad \tau_1 = \int_0^{L_s} \sigma(z)\, dz;$$

$$a_r = \pi r_r^2 \exp(-\tau_2); \quad C_r = \frac{1}{\alpha_r^2 L_r^2}; \quad \tau_1 = \int_0^{L_r} \sigma(z)\, dz;$$

P_0 is the emitted laser power; σ^2, $\bar{\gamma}^2_{x,y}$ are the variances of heights and slopes of the rough surface S, respectively; r_n, R_0 are the effective sizes of the receiving and sounded areas; $2\alpha_s$, $2\alpha_r$ are the beam divergence angle and the receiver's field of view; $\sigma(z)$ is the extinction coefficient of the medium.

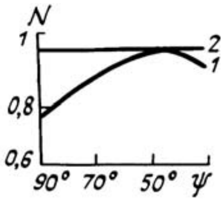

FIG. 1. The value of N as a function of the angle at which the surface is illuminated.

If the size of the beam's spot on the surface sounded and of the area viewed by the receiver on the surface S_0 are much larger than cr then for the case of backscattering ($\psi = \chi$, $L_s = L_r$), then for R_0^{-2} 0 the expression (3) can be simplified, and neglecting the atmosphere, it is identical with the result of Refs. 2, 3.

The figure presents the dependence of the ratio N of power P actually received to that for $\sigma = 0$ ($P(\sigma = 0)$, as a function of the angle ψ at which the beam irradiates the surface. Calculations were made using expr. (3), with the following parameters:

$$C_s = C_r = C; \quad C \gg R_0^{-2}; \quad C\sin^2\psi \gg \frac{1}{2\bar{\gamma}_{x,y}^2}\left[\frac{1}{L_s} + \frac{1}{L_r}\right]^2 \left[\frac{k}{q_z}\right]^2;$$

$\chi = 45°$; $\sigma C^{1/Z} = 1$ (curve 1); $\sigma C^{1/2} = 0.1$ curve 2).

As is clear from the figure, in contrast to the monostatic scheme, in the bistatic scheme for sounding a randomly rough surface, the mean received power depends strongly on σ when the laser beam spot on the surface sounded and the area viewed by the receiver are comparable with r.m.s. values of heights on the randomly rough surface.

The results obtained in this paper can be used to analyze lidar operation.

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