Transmitting properties of optical communication channels above a reflecting surface

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Received February 1, 1999

Pulse responses of optical communication channels with reflections from underlying surfaces have been investigated by the Monte Carlo method together with the radiation fluxes reflected from and transmitted through a scattering medium. The effect of reflection model, geometric parameters of transmitting and signal recording systems, and optical density of the medium on the responses have been analyzed.

Introduction

Optical communication systems can be schematically divided, by their purpose and peculiarities in operation in the open atmosphere, into the lines of long-range communication (out of open sight, for example) and land communication lines within the limits of open sight. The idea of creation of the lines of optical communication capable of operating behind the horizon, based on light scattering by clouds and some other scattering formations, was discussed, for example, as early as in 1970s.[1] A possibility of using the forward scattering optical radiation for transmitting the information through short-range land communication lines was proposed in Ref. 2. Some aspects of such systems operation were treated in the monograph by V.E. Zuev, V.V. Belov, and V.V. Veretennikov.[3]

The interest of investigators in solving the problem of transporting optical information through scattering channels is connected with the necessity of increasing reliability of such systems and extending their capability of operating under poor atmospheric-optical conditions.

In most cases the path of short-range communication line is located at a small height above the underlying surface. It is obvious, that the radiation, retroreflected by the surface (which may vary in structure and type), should be taken into account in the communication schemes, which use the forward-scattered optical radiation.

The angular features of the reflectivity of natural and artificial rough surfaces are often characterized by the directional pattern of the reflectance defined as a ratio of the surface brightness, measured in the given direction, to its illuminance within a given spectral range (angular pattern of spectral brightness). The dimensionless analog of this parameter is the coefficient of brightness defined as the ratio of surface brightness in the corresponding direction to the brightness of absolutely white surface reflecting according to Lambert law.[4]

Most vast material on the ground-based field measurements of different objects' angular reflectivity has been accomplished for the spectral range from 0.4 to 1.0 μm (aerospace photography region). To a lesser degree these investigations cover the spectral range from 1.0 to 2.5 μm.[5–8]

A peculiarity of the ground-based and even in a larger degree, of the airborne measurements of the coefficient of brightness of landscape elements is their significant spatial averaging over objects' surfaces. For the most part, thus obtained information does not allow one to estimate the fine angular structure of scattering from an underlying surface.

There is a complicated dependence between the reflectivity characteristics of natural objects and the direction of radiation incidence and the observation angle. Experimental and calculated data show that the Lambert law does not work practically for all natural surfaces. The examples of the measured angular pattern of brightness for some natural surfaces can be found in Refs. 7 and 9. The calculated results on angular distribution of the radiation reflected from model surfaces are presented in Ref. 8.

Statement of the problem and the method of its solution

This paper deals with the influence of reflectivity of a surface, under some operating communication line, and scattering properties of a medium on the reflected and transmitted light fluxes and pulse response of an optical communication channel.

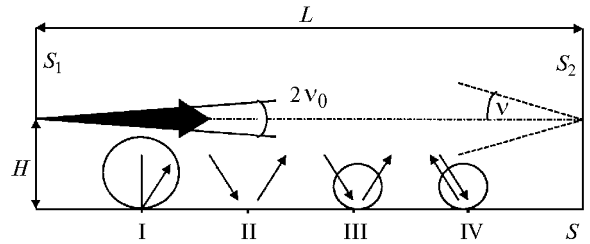

Fig. 1. Geometry of the experiment.

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A source of laser radiation (Fig. 1) is at a height H above a homogeneous plane reflecting surface S. It emits a monochromatic radiation of the wavelength λ. We will consider some variants of a point source emitting to a single direction within the angular divergence cone ν_0. Its optical axis is parallel to the reflecting surface. The radiation receiver is oriented toward the source, i.e., their optical axes coincide; the receiver's field of view angle is 2ν.

Optical properties of the surface are given by angular diagram of reflection $f(\Theta, \varphi)$ and by the absorptance α. Both these characteristics do not depend on the coordinates of a point on the surface, that is, $f(\rho, \Theta, \varphi) = f(\Theta, \varphi)$, $\alpha(\rho) = \alpha$ (here ρ is the radius-vector of a point on the surface S). We will consider (see Fig. 1) four models of reflecting properties of a surface (as some limiting cases): Lambert (I), specular (II), Lambert + specular (III), and Lambert + retroreflection (IV). The combination of the reflection laws is chosen so that the reflected components have same energy. This means that in the interaction of a photon with the surface the reflected energy is distributed between the elements of the combination equally, i.e., 0.5/0.5. For example, in the case (III) the photon has the probability of being reflected according to Lambert law of 0.5 and the probability of specular reflection is also 0.5.

The homogeneous scattering and absorbing medium fills the space between the reflecting surface S and the planes perpendicular to it and passes through the entrance pupils of the receiving and emitting optical devices. Optical properties of the medium are determined by the scattering phase function $g(\Theta)$ as well as by the coefficients of absorption β_{ab} and scattering β_{sc} and correspond to the disperse media formed by spherical particles.

The investigations were performed by the Monte Carlo method in the frames of linear system approach.[3] In the procedure, developed for this purpose, the methods of direct modeling and local computation have been realized.[10] The following characteristics of optical radiation were considered:

– the flux of radiation P_1 reflected by the medium and surface and crossing the plane S_1;

– the flux of radiation P_2 crossing the plane S_2;

– the flux of photons P_{1s} reflected by the surface and crossing the plane S_1;

– the pulse response $h(t)$ of the communication channel (Fig. 1);

– the components $h_s(t)$ and $h_{1s}(t)$ of the pulse response $h(t)$ formed, correspondingly, by radiation due to multiple and single scattering reflected from the surface.

In our numerical experiments, the optical thickness of the medium τ took the values from 0.5 to 10, the distance H was from 1 to 50 m. The results given below were obtained for $\lambda = 0.85$ μm. The medium models were found with the use of the LOWTRAN-7 program complex.[11]

The results of statistical modeling

Typical calculated results for the reflected fluxes P_1 as functions of optical thickness of the medium for a source emitting in a single direction are presented in Fig. 2. Let us pay attention to the dependence $P_1 = P_1(\tau)$ for (II)–(IV) reflection models (Fig. 1). The monotonic growth of the radiation flux reflected by the scattering medium at an increase of its optical thickness, with no reflecting surface present or that only absorbs (Fig. 1), is well known and easily explicable. Suppose, that $\tau = 0$, then $P_1 = 0$. Let $\tau = \tau_1 > 0$ and $P_1 = P_{11} > 0$. Suppose also, that some layer with the optical thickness $\Delta\tau$ is added to the medium. Then the total optical thickness of the medium will be $\tau_2 = \tau_1 + \Delta\tau$. Obviously, the flux, reflected by it, will be $P_{12} = P_{11} + \Delta P$. Inasmuch $\Delta P \geq 0$, then $P_{12} \geq P_{11}$. Consequently, the dependence $P_1(\tau)$ in such cases is always monotonic.

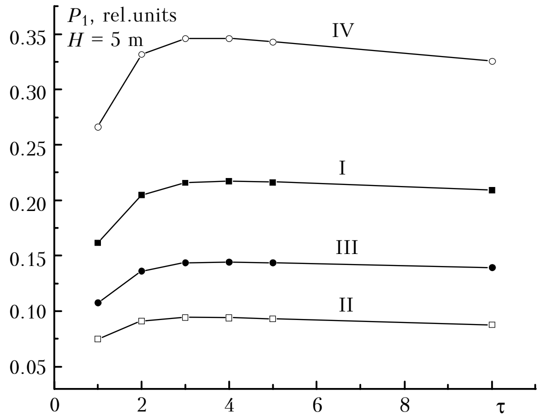

Fig. 2. Magnitude of reflected flux vs. optical length of the communication line.

Non-monotonic behavior of $P_1(\tau)$ in Fig. 2 may be explained in the following way. First of all, one has to keep in mind that the results shown in it have been obtained for fixed values of the geometric parameters L and H. That means that the increase in the optical thickness was stipulated by an increase in the extinction coefficient (and, first of all, of its scattering component). We present the flux P_1 as a sum of two components: P_{1m} and P_{1s}, where P_{1m} is the radiation flux, reflected by the medium and not interacting with the surface S, and P_{1s} is the radiation flux reflected by S. Dividing the flux P_1 into two components, we suppose that the first component corresponds to the scheme of the experiment shown in Fig. 1, only assuming that the surface S is absolutely absorbing and the component P_{1s} is due to reflection of radiation incident onto S from the medium. It is clear, that $P_{1s}(\tau)$ is a monotonic function. It is easy to show that this function has a maximum. If $\tau = 0$, then, obviously, $P_{1s} = 0$. Let $\tau \to \infty$, then (at least, in supposition that the medium slightly absorbs the radiation) we may state that as well $P_{1s} \to 0$. Since for $0 < \tau < \infty$ the reflected flux $P_{1s} > 0$, the function $P_{1s}(\tau)$ has a maximum.

The calculated results presented in Fig. 3 confirm this conclusion. They show the influence of the reflection law on the magnitude of the flux P_{1s} depending on τ at H = const and L = const. As expected, the minimum values of the flux correspond to specular reflection, the maximum values – to a combination of the Lambert scattering and retroreflection. This can be explained by the fact, that at a low height H (in the given case H = 5 m) the most probable angles of the scattered photons incidence on the plane S are such that the specular reflection takes place in the direction toward the plane S_2 and retroreflection toward the plane S_1.

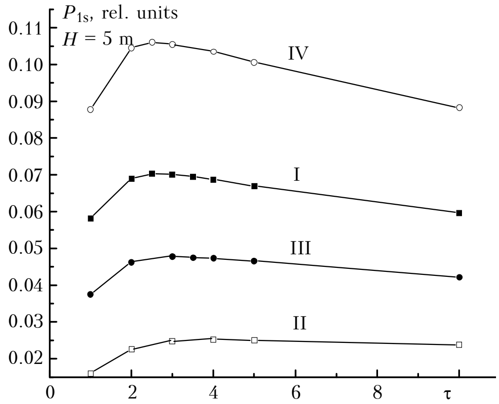

Fig. 3. Dependence of $P_{1s}(\tau)$ on the reflection model.

Although an increase in the extinction coefficient of a medium results in a growth of the optical thickness of the layer separating the communication line from the reflecting surface (what, in turn, should lead to a more homogeneous and diffuse illumination of the surface S), but it somewhat damps the influence of the reflection diagram $f(\Theta, \varphi)$ on P_{1s}. Thus, a tenfold increase of τ results here in a change of this influence from 5 (at $\tau \approx 1$) to 3 (at $\tau \approx 10$) times (if to characterize it by the ratio $P_{1s}(\text{IV})/P_{1s}(\text{II})$, where (IV) and (II) are the models of $f(\Theta, \varphi)$ shown in Fig. 1).

The influence of the height of the communication line above surface S on τ_{max} value is shown in Fig. 4, where fluxes P_{1s} at $1 \le H \le 50$ m are depicted for the Lambert model. If the reflecting surface approaches the emitter's axis this results in an increase in P_{1s} and τ_{max} values, what can be easily explained by some transformation of the spatial-angular structure of the scattered radiation incident onto the plane S at a change of the parameter H.

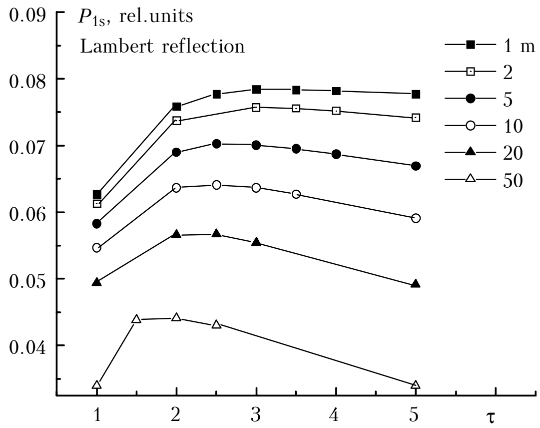

Fig. 4. Dependence of $P_{1s}(\tau)$ on the altitude of the light source.

The influence of the reflecting surface on the transmitted fluxes is shown in Fig. 5 for H = 5 m. On the whole, this influence weakens with increasing optical density of the medium and the distance between the surface and the light beam axis. It is due to the increase in the optical thickness of the scattering layer, which screens the surface from the source.

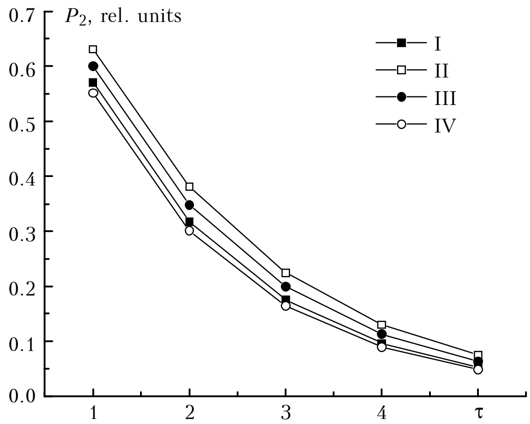

Fig. 5. Dependence of transmitted flux P_2, reflected by surface S, on the medium optical thickness.

The shape of the surface S response $h_s(t)$ to $\delta(t)$-pulse (or the pulse transient characteristic of the system "emitter-surface-receiverB) as well as the influence on it of the communication line's height and the reflection diagram are shown in Figs. 6–9. The shape of the response $h_s(t)$ allows us to distinguish between the leading edge, a region of maximum response, and the trailing edge. It is also characterized by time t_{max}, at which $h_{max} = h_s(t_{max})$ and the value t_{max} itself are determined by the reflection angular pattern $f(\Theta, \varphi)$ and the optical density of the medium (see Fig. 6).

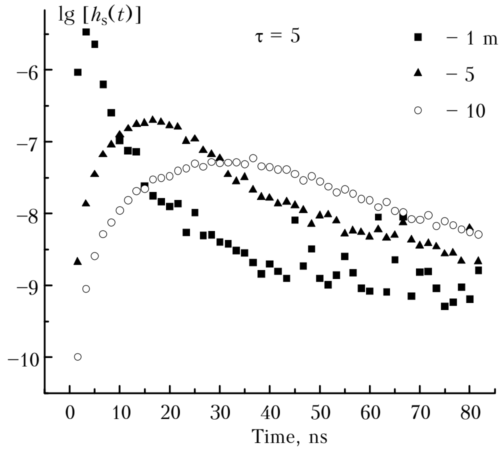

Fig. 6. Shape of the pulse response $h_s(t)$ for the Lambert model.

In the case of specular reflection, shown in Fig. 7, the shape of the pulse transient characteristic strongly differs from that in the preceding case. A specular surface allows photons to move after reflection in the same direction with respect to the communication channel axis. Since the medium has the forward peaked scattering phase function, the probability for the photons, reflected from the surface and undergone a few scattering interactions, to conserve the direction onto receiver's plane is in this case higher than in others. Therefore, on the given time scale the maximum of pulse transient characteristic is achieved in the very beginning of the process, and then a slow fall off of its magnitude occurs. The source's height affects only the magnitude of maxima and the values closest to them.

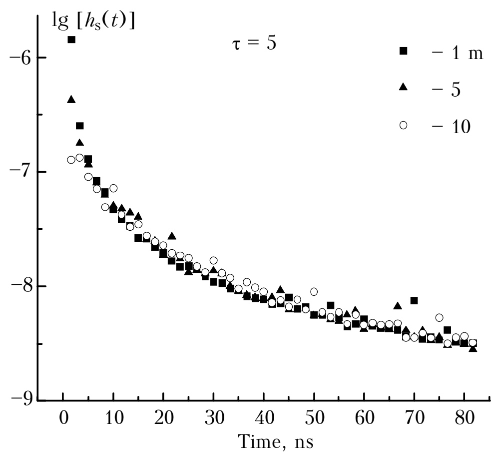

Fig. 7. Shape of the pulse response $h_s(t)$ for the specular reflection model.

As seen from Fig. 8, the combination of Lambert and retroreflection models produces the functions close to those, characteristic of the first case. The difference is only in a little bit lower values of the surface pulse response.

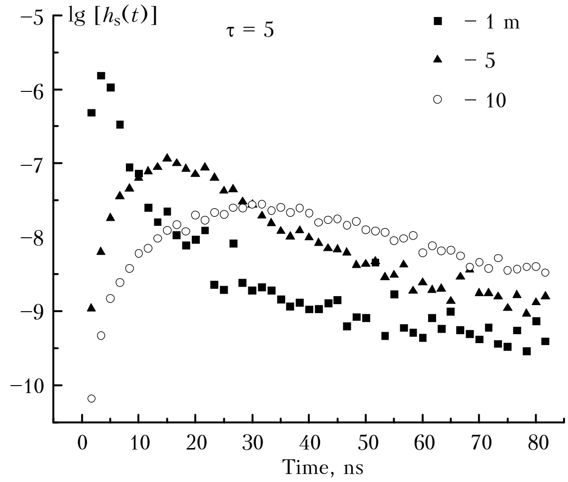

Fig. 8. Shape of the pulse response $h_s(t)$ for Lambert+retroreflection reflection model.

The most interesting result among these for a surface characterized by a mixed (Lambert + specular) reflection has been obtained for the height of 5 m. A contribution of different reflection laws resulted in appearance of two pronounced maxima, the first of which was produced by the specular reflection from surface and the other appeared due to the effect of diffuse reflection (see Fig. 9).

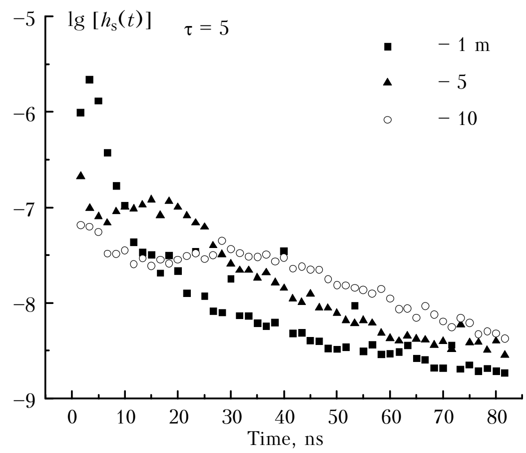

Fig. 9. Shape of the pulse response $h_s(t)$ for the Lambert + specular reflection model.

Thus, the results of the statistical experiments, have revealed the possibility of observing a non-monotonic dependence of the fluxes reflected by some scattering medium on its optical density for the cases when optical communication lines are located above some reflecting surface. The causes and the conditions for appearance of this peculiarity in the function $P_1(\tau)$ have been clarified. Besides, the estimates of the pulse transient characteristics of a communication channel were obtained, and the influence on them of geometrical and optical conditions for the radiation propagation and recording investigated.

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