PROBABILITY OF DETECTION OF PULSE OPTICAL SIGNALS TRANSMITTED THROUGH A CLOUDY ATMOSPHERE

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A simple model of the optical communication channel with an account of clouds is proposed which allows one to calculate the probability of detection of a pulse optical signal transmitted through a cloud layer. The integral characteristics of the radiation are calculated using the relations obtained as a result of fitting the data of numerical experiments. The actual impulse response of the receiving device is taken into account in the calculations. The developed programs have high portability and allow one to operate in the interactive mode. The conditions of detection of pulsed optical signals for typical parameters of the receiving-transmitting system are found.

The atmospheric-optical systems of communication, monitoring of the environment, vision, and laser detection and ranging have continued to develop apace in recent years.[1–5] Therefore, the problem of elaboration of models of the optical channel and the corresponding software arises.[6]

The propagation of the pulsed optical radiation in the visible range in the cloudy atmosphere is accompanied by significant distortions of its spatio–temporal structure. These distortions determine or restrict the potentialities of the above-mentioned optical systems. Computer calculation of the radiation parameters by means of a rigorous solution of the transfer equation is a complicated mathematical problem which is available only for a narrow circle of specialists. Practical activity (engineering design) requires a rather simple model which will enable one to calculate the basic parameters of the optical channel with acceptable accuracy.

A model of the atmospheric–optical communication channel with an account of clouds, fitted to the data of numerical experiments was proposed in Refs. 7 and 8. In the calculations we took into account not only the energetic attenuation of radiation[4] but also variations in the amplitude and the signal pulse duration,[9] which are important for communication systems.

DESCRIPTION OF THE MODEL

The signal source is a laser with wavelength λ and peak power P which is located at a great distance above the Earth's surface and can be observed at a certain zenith angle. The cross-sectional area of the beam at the upper atmospheric boundary is such that the beam can be considered to be infinitely wide. The noise source (the Sun or the Moon, in general) is characterized by its spectral irradiance at the upper atmospheric boundary and by its zenith angle. The energetic attenuation of the signal and noise during their propagation through the clear atmosphere up to the cloud top determined on the basis of the model of the clear atmosphere described, e.g., in Ref. 10 (chapter 10), according to which the pulse energy is concentrated mainly in the unscattered component of the beam and spatio–temporal distortions of the signal are negligible.

The integral characteristics (the first and second spatio-temporal moments) of the optical radiation transmitted through the cloud layer and the section of the path from the cloud layer to the Earth's surface is determined by the fitting relations described in Refs. 7 and 9. Let us note the principal features of construction of these relations. The entire range of optical thicknesses of the cloud layer τ is divided into three regions: τ_1 bounds the region of applicability of the small–angle approximation, where the variance of the single scattering angle γ^2 is calculated on the basis of the elongated part of the scattering phase function; τ_2 ($\tau_2 > \tau_1$) bounds the diffuse scattering region, where the variance of the single scattering is calculated on the basis of the total scattering phase function. In the intermediate region from τ_1 to τ_2 the variance γ^2 varies linearly. The variance of the single scattering angle, which depends in such a way on τ, is substituted into the well–known relations for calculating the transmission of the scattering layer T,[11,12] the angular divergence of the beam Θ_b (Ref. 10, chapter 3), and the time–dependent variance of the pulse duration upon exit from the cloud layer.[1,12,13] Using these relations we set the scattering coefficient $\sigma = \sigma_m$, where σ_m is its mean value for a given cloud type (see, e.g., Ref. 14). Correspondingly, the geometric thickness of the cloud Z is equal to τ/σ. The scattering coefficient and the microstructure of the clouds determine the values of the parameters τ_1, τ_2, γ_1, and γ_2. The variance t_p^2 of the duration of the pulse incident on the photocathode takes account of additional pulse stretching on the section of the path from a cloud base to the Earth's surface. We assume that the height H of the cloud base is equal to H_m, where H_m is its mean value for a given cloud type. The amplitude P_{pa} of the pulse incident on the photocathode is obtained from the fitting relation:

$$P_{pa} = F_H T t_{p0}/t_p P_{p0} , \qquad (1)$$

where the angular factor F_H depends on the incident beam Θ_b and the field–of–view angle of the detector Θ_d. The fitting of the results of the numerical simulations was performed in Ref. 7 for the single–layer water–droplet cloud with scattering coefficient $\sigma = 33.33$ km^{-1}, cloud base height $H = 1$ km, and the scattering phase function for Deirmendjian's *C1* cloud model at $\lambda = 0.45$ μm. It was shown that in this case $\tau_1 = 4.5$, $\tau_2 = 15$, $\gamma_1 = 0.07$, and

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$\gamma_2 = 0.55$ and the accuracy of fitting the pulse amplitude relative to the results of numerical simulation is about 20–40%.

On the basis of the data of Refs. 14–16, two types of distribution of the cloud optical thickness are chosen:

$$\begin{cases} q_\tau = 1/(\tau_{20} - \tau_{10}), \ \tau_{10} \le t \le \tau_{20}, \\ q_\tau = 0, \ \tau > \tau_{20}, \ \tau < \tau_{10}, \end{cases} \tag{2a}$$

$$q_\tau = A/\tau \exp\,[-B \ln^2(\tau/\tau_m)]. \tag{2b}$$

Relation (2b) was derived in Ref. 17 by fitting the data of Refs. 15 and 16. In this relation τ_m is the median value of the optical thickness. B is the variance of the optical thickness distribution, and A is a normalization constant. Let τ_c be the critical value of the optical thickness of the cloud layer at which a specified value of the signal–to–noise ratio is still guaranteed. Then the probability of the absence of the signal during its propagation through a continuous cloud layer is

$$Q_s = \int_{\tau_c}^{\infty} q_\tau(\tau')d\tau'. \tag{3}$$

Until now the cloud layer was assumed to be continuous and infinite in extent. The description of the propagation of the optical radiation through the broken clouds is based on the results of Refs. 18 and 19, where, in particular, it was shown that under the condition

$$Z \ll L, \tag{4}$$

where Z is the thickness of the cloud layer and L is its characteristic horizontal dimension, the following approximate approach is valid. If the observation line–either the straight line V_s which links the detector and the signal source or the straight line V_N which links the detector and the noise source–intersects the cloud layer, then the radiation field is described by the relation which is valid for the continuous layer. If the observation line does not intersect the cloud layer, then the approximation of a clear atmosphere is used. It should be noted that if condition (4) is not satisfied, this approach to calculating the intensity may lead to great errors (approximately 100%).[18] The probability of covering the observation line is determined by the cloud cover index. Statistically reliable data are now available only on the recurrence of various gradations of cloudiness and mainly in the daytime. We used long-standing satellite data,[20] where the cloud gradations are combined into the following groups according to the value of the cloud cover index: the first group is from 0 to 2, the second is from 3 to 7, and the third is from 8 to 10. In each group the distribution of gradations is taken to be uniform, i.e., the probability of covering the observation line is determined by the relations $q_1 = 0.1$, $q_2 = 0.5$, and $q_3 = 0.9$, where the index $i = 1, 2, 3$ corresponds to the given gradation group. For the fixed ith group of gradation, the situation arises with probability q_i^2 in which the straight lines V_s and V_N intersect the cloud layer simultaneously. In this case $\tau_c = \tau_{c1}$ and $Q_{\tau 1} \equiv Q_\tau|_{\tau_c = \tau_{c1}}$ is the value of Q_τ given by Eq. (3) at $\tau_c = \tau_{c1}$. Only the straight line V_s intersects the layer with the probability $q_i(1 - q_i)$, where $\tau_c = \tau_{c2} < \tau_{c1}$, $Q_{\tau 2} \equiv Q_\tau|_{\tau_c = \tau_{c2}}$. And finally, the straight line V_s intersects the layer with probability q_i. It is natural to assume that in this case signal detection is guaranteed. Then the total probability of the signal detection is defined by the relation

$$Q_s = \sum_{i=1}^{3} Q_i[1 - Q_{\tau 2}q_i - q_i^2(Q_{\tau 1} - Q_{\tau 2})], \tag{5}$$

where Q_i is the recurrence of the ith group of cloud gradations.

The radiation transmitted through the atmosphere is incident on the photodetector, which transforms the light pulse energy into electrical energy and a decision is made whether there is a pulse or not. The receiving antenna is characterized by the transmission factor η_r, effective area S_r and spectral bandwidth $\Delta\lambda$. These characteristics determine the power of the signal $P_s(t)$ and the power of the noise P_N which are incident on the photocathode. In the calculation of $P_s(t)$ and P_N, the real spatio-temporal structure of the field is approximated by effective functions. The power $P_s(t)$ is determined by the relation

$$P_s(t) = P_{pa}F(t/t_p)\ , \tag{6}$$

where P_{pa} is the amplitude, t_p^2 is the variance of the pulse duration, and $F(t/t_p)$ is the effective function, which can be represented in terms of various dependences: rectangular, exponential, and the gamma function.

In addition, the photodetector is characterized by the quantum efficiency of the photocathode η_q and by the noise factor of the photomultiplier $1 + \beta$. The transmission spectrum of the video amplifier is assumed to be determined by an RC–circuit with response time t_r and bandwidth $\Delta f = 1/4t_r$. At the video amplifier output, the random process $\xi(t)$ includes the signal component $S(t) = \langle\xi(t)\rangle$ and the noise, which, in turn, consists of the signal fluctuations $\Delta_s(t)$ and the variance of the stationary noise Δ_N. If the response time of the photodetector is much smaller than t_p, then taking advantage of the conclusions of Ref. 21 (pp. 113 and 119) and Ref. 22 (p. 500) we obtain the following relations for $S(t)$, $\Delta_s(t)$, and Δ_N:

$$\begin{cases} S(t) = \eta P_{pa}\Phi(t)\,\hbar\,\nu, \\ \Delta_s(t) = 2(1 + \beta)\eta\Delta f P_{pa}\varphi(t)\,\hbar\,\nu, \\ \Delta_N = 2(1 + \beta)\eta\Delta f P_N, \end{cases} \tag{7a}$$

where

$$\begin{cases} \Phi(t) = \exp(-t/t_r)\displaystyle\int_0^{t_r}\exp(t'/t_r)F(t'/t_p)dt', \\ \varphi(t) = 4t_r\exp(-2t/t_r)\displaystyle\int_0^{t_r}\exp(t'/t_r)F(t'/t_p)dt', \end{cases} \tag{7b}$$

$\eta = \eta_r - \eta_q$, $\hbar$ is Planck's constant, and ν is the frequency of the incident signal. Then for the signal–to–noise ratio at the time t_{max}, at which the signal power reaches its maximum, we have the following equation:

$$P_m = \frac{\eta P_{pa}^2 \Phi_m^2}{2(1 + \beta)\, \hbar\, \nu (P_{pa} \varphi_m + P_N) \Delta f}, \qquad (8)$$

where $\Phi_m = \Phi(t = t_{max})$ and $\varphi_m = \varphi(t = t_{max})$. Using the well–known results on the probability of false detection signal as a function of the signal–to–noise ratio taken from Ref. 21 and the results that have been obtained here enables us to numerically calculate the energy of the channel and the probability of establishing communication with given reliability. Two ways of calculating the communication probability are included in the algorithmic implementation. In the first way, the pulse amplitude P_{pa} given by Eq. (1) and the noise power P_N considred as functions of t_p are substituted into relation (8). In addition, the pulse duration t_p, which enters into the expressions for Φ_m and φ_m, also depends on τ. As a result, we obtain a nonlinear equation for τ. The critical optical thickness, which defines the probability Q_S (given by Eq. (3)) and the probability of signal detection Q_s (given by Eq. (5)), is the solution of this equation. In the second way, incidence into the cloud and the cloud optical thickness (separately for the signal and the background noise sources) are simulated by the Monte Carlo method. The signal–to–noise ratio is then estimated by Eq. (8). If it exceeds a given value, then the counter n_1, initially equal to zero, is incremented by one. The final magnitude n_1 after n histories estimates the probability of signal detection: $Q_s \simeq n_1/n$. The algorithm also makes it possible to analyze multilayer cloudiness. In this case various combinations of clouds are simulated. For each cloud layer the optical thickness is simulated, and the scattering coefficient is estimated. However, to calculate the integral characteristics of the radiation under conditions of multilayer cloudiness, further improvement in the accuracy of the fitting relations is required.

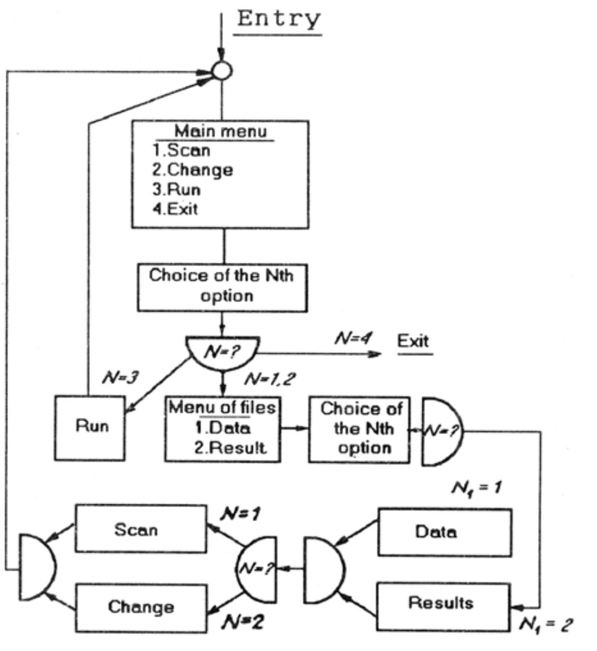

FIG. 1. The block diagram of the interactive mode of operation.

The programs written in FORTRAN and are completely portable. The driver occupies about 80 kilobytes of IBM PC memory. The execution time for calculating one value of Q_s by simulating the cloudiness parameters by the Monte Carlo method is equal to 1.4 min for an ES–1045 computer, 3.5 min for the IBM PC/AT, and 13 min for an IZOT–1016C computer for 10^4 histories. Using standard software, the algorithm is implemented interactively. The corresponding block diagram is shown in Fig. 1.

RESULTS OF CALCULATIONS

Let us find the conditions of detection of pulsed optical signals for typical parameters of the receiving–transmitting system. Let us consider a transmitter with wavelength $\lambda = 0.693$ μm, pulse energy $E_{s0} = 0.1$ J, pulse duration $t_{p0} = 20$ ns, and beam divergence $\Theta_{b0} = \pm$ 10 minutes[23] which is located at the altitude $R = 300$ km above the Earth's surface. The pulses are received by a detector with an interference optical filter. The detector has field–of–view angle $\Theta_r = \pm 10°$ and spectral bandwidth $\Delta\lambda = 40$ Å (Ref. 24). The transmission factor of the optical antenna η_r is equal to 0.6 and its effective area S_r is equal to 0.1 m^2. The photomultiplier with quantum efficiency $\eta_q = 0.1$ is located behind the optical filter.[25] The signal–to-noise ratio ρ_m is assumed to be equal to 100. This corresponds to the probability of false detection of a single pulse of the order of 10^{-5}–10^{-6} (Ref. 21). The calculations performed in daytime and for stratiform cloudiness with scattering coefficient $\sigma = 0.03$ m^{-1} indicate the critical value of the cloud optical thickness τ_c in Eq. (3) to be equal approximately to 90. In this case the optimum response time of the RC–circuit t_r is found to be of the order of 40 μs. With the uniform optical thickness distribution (2a) in the range from $\tau_{10} = 5$ to $\tau_{20} = 255$ (Ref. 14) the average annual probability of signal detection Q_s over Moscow district is equal approximately to 0.67. For the same optical thickness distribution averaging over the various areas of the global ocean gives $Q_s = 0.74$. This value of Q_s seems to estimate the lower limit of the probability, since the optical thickness distribution (2b) for which $Q_s \simeq 1$ is more typical over the ocean.

It is possible to significantly reduce the requirements on the transmitted power (energy) at the expense of using a narrow–band wide–angle filter, for instance, one based on the photoeffect of spectral hole-burning.[26] In this case $\Delta\lambda$ is equal to $5 \cdot 10^{-2}$ Ð and the field–of–view angle is limited only by the details of construction of the receiving antenna. For constant values of τ_c and the initial pulse duration, the required energy turns out to be smaller by a factor of 100 than when the interference filter is used.

CONCLUSIONS

A simple model of the optical communication channel with an account of clouds is proposed, which enables one to calculate its principal integral characteristics. The fitting relations used in the model provide satisfactory agreement with the results of numerical simulation. In the calculation of the signal–to–noise ratio, the mismatch between the spectra of the incident pulse and of the video amplifier of the photodetector is taken into account. The communication probability is determined by the condition that the signal–to–noise ratio does not exceed its assigned value. A block which enables one to simulate the stochastic channel is included in the algorithm. The portability of the programs to different computers and the dialog option of the algorithm are among its salient features. A requirements on computation time are given.

For typical parameters of the receiving–transmitting system, the critical value of the cloud optical thickness τ_c, for which the specified signal–to–noise ratio is yet guaranteed is shown to be equal to 90. For this value of τ_c under conditions of uniform optical thickness, the probability of signal detection Θ_s is equal approximately to 0.7. The use of a narrow–band wide–angle filter can decrease the required transmitted power by two orders of magnitude.

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