DEPENDENCE OF THE AMPLITUDE AND TEMPORAL CHARACTERISTICS OF PULSED OPTICAL RADIATION TRANSMITTED THROUGH A CLOUDY MEDIUM ON THE CLOUDINESS PARAMETERS

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The problem of pulsed optical radiation transmitted through stratiform was examined for the case of normal incidence of a wide unidirectional beam. The amplitude and temporal characteristics (ATC) of pulses transmitted in the range of optical thicknesses from 0 *to* 50 *have been found by the Monte Carlo method.*

The dependence of the ATC on the extinction coefficient, photon absorption probabilities, the scattering phase function, and the distance from the receiver to the boundary of the cloud layer was investigated. Estimates of the characteristic values of the ATC were given for real stratiform clouds of different types, including multilayered.

With the aim of developing means of optical signaling and laser detection and ranging through the atmosphere, it is important to know the regularities of variation of the amplitude and temporal characteristics (ATC) of the received signals as a function of the optical properties, the geometry of the experiment, and the parameters of the receiving—transmitting system. The Monte Carlo method,[1] which allows one to consider all of the peculiarities of the experimental geometry and of the optical characteristics of the medium, is the most versatile method for a theoretical investigation of the problem. In particular, in Ref. 2 the ATC of the light pulses were studied by this method, directly at the exit from cloud layers of different optical thickness τ with different scattering phase functions.

In this paper the effect of a number of cloudiness parameters including the extinction coefficient σ, the probability of absorption of the photon, the scattering phase function, and the distance from the cloud layer to the receiver on the ATC of the pulses transmitted through the cloudy medium is studied. In addition ATC values are calculated for several models of continuous cloudiness of the stratus type including multistratus. It is supposed that a light source with small angular divergence is situated far from the Earth's surface, for instance, on a satellite orbit, with its optical axis directed vertically downward, and the size of the illuminated zone upon entering the cloud medium is significantly greater than the thickness of the cloud. The pulse duration at half maximum, disposed at t_p, is taken to be equal to 20 ns. A receiver with an aperture of $2\varphi_r$ was placed on the Earth's surface within the zone of illumination by the direct beam with its optical axis coincident with the source axis. In this case, assuming a sufficiently high position of the source, the incident beam can be regarded as infinitely wide, which substantially simplifies the numerical simulation. The method of direct simulation of the process of photon propagation in the layer has been used in this work. The number of trajectories used in the computations of a single variant of the problem was $(1–5)\cdot 10^5$. The error of the estimate did not exceed 15% for the amplitude and 30% for the temporal pulse characteristics, which increase with τ. The ATC of the transmitted pulses were analyzed: the maximum power or amplitude P_m of the pulse, the duration of the transmitted pulse at half maximum $\Delta_{0.5}$, and the energetic pulse duration Δ_ε, which is defined as the time interval at the end of which 70% of the total pulse energy has been transmitted (the start of the time count in the definition of Δ_ε corresponds to the moment when the first nonscattered photon arrives). The parameter $\Delta_{0.5}$ characterizes the duration of the most intense portion of the pulse. It determines the maximum attainable frequency of signaling, and also the optimum response time of the detector under conditions of intensive background illumination. The parameter Δ_ε is essential for selection of the response time of the detector when the background noise is low.

THE EFFECT OF THE OPTICAL PROPERTIES AND ALTITUDE OF THE CLOUD LAYER ON THE ATC OF THE PULSES

First let us consider how the distance from the receiver to the layer, which is equal to the altitude h_0 of the lower boundary of the uniform cloudy layer (or in dimensionless units $\tau_0 = h_0\sigma$) affects the ATC of the recorded pulses. The initial pulse duration in dimensionless units is $\delta = \sigma c t_p = 0{,}2$ (c is the speed of light), which corresponds to $t_p = 20$ ns when

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$\sigma = 33.3\ \text{km}^{-1}$. The computations were performed for the scattering phase function which corresponds to the Deirmendjian *C*-1 cloud model, and the radiation wavelength was taken to be $\lambda = 0.45\ \mu\text{m}$. The dependence of the ATC of the pulses on τ_0 is caused by the additional time delay of the radiation emanating from the cloud obliquely at angles $\varphi \neq 0$.

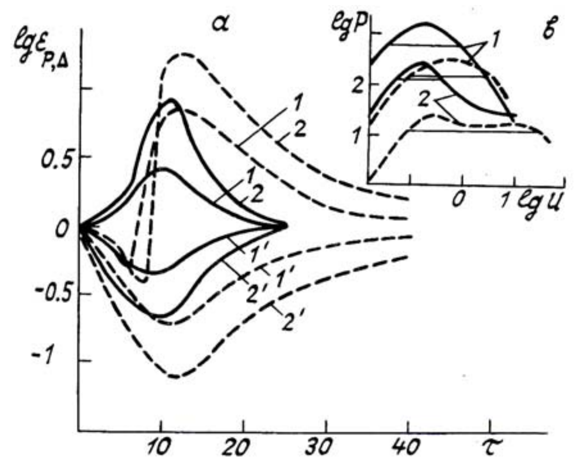

FIG. 1. Ratios of the amplitudes ε_p *(1′ and 2′) and durations* ε_Δ *(1 and 2) of the pulses when the detector is located at the distances* $\tau_0 = 33.33$ *(1 and 1′) and 166.7 (2 and 2′) from the layer and at the layer boundary for the receiving angles* 10° *(solid lines) and* 90° *(dashed lines).*

The value of this delay on the path from the lower cloud boundary to the receiver is estimated as $\Delta u_g = \tau_0[(\cos\varphi)^{-1} - 1]$. We shall characterize the effect of τ_0 on P_m and $\Delta_{0.5}$ by the ratios $\varepsilon_p = P_m(\tau, \tau_0)/ /P_m(\tau, 0)$ and $\varepsilon_\Delta = \Delta_{0.5}(\tau, \tau 0)/\Delta_{0.5}(\tau, 0)$. Figure 1a gives these values as functions of τ for the two values $\tau_0 = 33.3$ (1 and 1′) and 167 (2 and 2′) which were chosen noting that $0 \le \tau 0 \lesssim 200$ in the real atmosphere.

As follows from Fig. 1a, the increase in τ_0 results, as a rule, in a decrease in the pulse amplitude and an increase in the parameter $\Delta_{0.5}$. An exception is the region $\tau = 6$–8 for $\varphi_r = 90°$ where the value of $\Delta_{0.5}$ decreases, as calculations show, for all $\varphi_r \ge 30$. Such behavior of the value $\Delta_{0.5}$ is related to the peculiarities of the deformations of the pulse shape for different τ (Fig. 1b). Figure 1b shows the pulse shape in the vicinity of the maximum for $\tau = 6$ (solid lines) and $\tau = 10$ (dashed lines) when $\tau_0 = 0$ (curves 1) and 167 (curves 2). The quantity $\Delta_{0.5}$ is indicated by the horizontal segment on each pulse. It can be seen from Fig. 1b that the reason for the decrease of $\Delta_{0.5}$ for $\tau = 6$ in going from $\tau_0 = 0$ to 167 is the dip in the trailing edge of the pulse immediately behind the region of the pulse maximum.

Figure 1a shows that the maximum difference of the quantifies ε_p and ε_Δ from unity (by an order of magnitude for $\varphi_r = 90°$) takes place for $\tau = 10$–15, i.e., in the region where τ most greatly affects the ATC. At small or large τ the effect of the parameter τ_0 decreases. This is explained by the fact that when $\tau < 10$, the radiation emanates from the layer at small angles φ and as a result the value of Δu_g becomes small compared to the initial pulse duration. If τ is greater, the time delay Δu_g becomes shorter than the temporal spreading of the pulse in the cloud layer.

The given τ_0 — dependences, of the ATC can be used also to estimate the effect of changes in the quantity σ on the ATC when $h_0 = \text{const}$ and $\tau = \text{const}$, but in so doing one should take into account the changes of the unit $(\sigma c)^{-1}$ of dimensionless time. The effect of the last factor compensates the effect of τ_0 for $\tau \lesssim 20$ (excluding the above-indicated region $\tau = 6$–8 for $\varphi_r \ge 30°$).

Therefore, when $\tau \lesssim 20$, a change in σ has less of an effect on the ATC than a change in h_0. At the same time, for larger values of τ, when the effect of τ is smaller, the ATC will change mainly as a result of the scale factor $(\sigma c)^{-1}$ which gives $P_m \sim \sigma^{-1}$ and $\Delta_{0.5} \sim \sigma^{-1}$.

Let us now consider the ATC dependence on the scattering phase function, which is determined for water-droplet clouds by the particle size distribution and photon absorption probability in a cloudy medium. Numerical calculations have shown that for the dimensionless pulse duration $\delta = 0.2$, the effect of the particle size variation is insignificant. It was found that for the gamma distribution with the parameter $\mu = 4$ the variations in the ATC remain essentially within the limits of calculational error when the modal radius varies in the limits 4–8 μm and only for $\tau = 4$ are they somewhat greater ($\simeq$ 30%). For shorter pulses with $\delta = 0.01$, size changes result in more substantial ($\sim$ 100%) variation of the ATC, especially for $\varphi \le 20°$ and $\tau \le 20$.

Real absorption in clouds ($\omega_a > 0$) results in a decrease of both P_m and $\Delta_{0.5}$ and its effect becomes more pronounced as τ increases. As calculations show, when $\omega_a = 4 \cdot 10^{-3}$ (Ref. 2) the decrease of P_m and $\Delta_{0.5}$ compared to the case of a nonabsorbing cloud stands at tens of per cents at $\tau = 50$, and the energy is roughly 2–3 times lower.

The above-mentioned calculations pertain to the effect of individual parameters of single-layer cloudiness on the ATC of the transmitted pulses. Values of these parameters are substantially different for clouds of the types St, As, and Ci located at different altitudes. For this reason, it is of interest to estimate the ATC of light pulses for different types of clouds. In the case of multilayer clouds the number of possible parameters and their combinations increases,so we shall restrict ourselves to the examination of a few representative models of a multilayer cloudiness.

ATC OF LIGHT PULSES TRANSMITTED THROUGH DIFFERENT TIFFS OF CLOUDS

To carry out the numerical simulations a multilayer of cloudiness model was selected which includes up to three uniform layers located at different altitude tiers.

The cloudiness parameters for each layer of each type were selected on the basis of known data[2–8] including the results of measurements over both the continent and the ocean. The probability of absorption of a photon was taken in accordance with the data of Ref. 2 to be equal to $4 \cdot 10^{-3}$. The particle size spectrum for water-droplet clouds of St and As types was described by the gamma distribution with the parameters a_m (the modal radius) and μ.

For the multilayer cloudiness (Table II) the parameters of the separate layers were taken to be the same as for single-layer clouds (Table I). For fixed total optical thickness of the layers τ the quantities τ_I (i = 1, 2, and 3) were chosen for the individual layers taking into account the data[9,10] on the representativeness of τ for clouds of different types over the ocean. In particular, in the case of two-layer cloudiness the conditional probability density $F(\tau_2/\tau) = F(\tau - \tau_2) \cdot F_2(\tau_2)$ has been found from the known probability density of τ based on the assumption of the independence of $F_1(\tau)$ and $F_2(\tau)$. $F(\tau_2/\tau)$ represents the probability density of the second layer, which has the optical thickness τ_2 while the total optical thickness of the layers is τ. The median value of τ_{2m} for $F(\tau_2/\tau)$ was estimated, and this value was taken to be the optical thickness of the second layer. Correspondingly, we set $\tau_1 = \tau - \tau_{2m}$. .In the case of three-layer cloudiness the value of τ_3 for the layer C1 was set equal to 3, and τ_1 and τ_2 were estimated in analogy with the care of two-layer cloudiness. The values of τ_1 so obtained are shown in Table II.

TABLE I. Parameters of different types of clouds.

Cloudiness type	Altitude of the boundary h_0, km	Thickness L, km	Microstructure a_m, μ		Extinction coefficient σ, km^{-1}	Phase composition of the layer
Stratus, St	0.7	0.1-1.15	6	4	43	droplets
High--altitude stratus	3.5	0.25-1.4	5	4	15-22	droplets
Cirrus Ci	10	1	ice columns l = 300μm d = 120μm*		3	crystals

*l is the length and d is the diameter of the column

TABLE II. Models of multilayer cloudiness and τ_1 of the lower layer.

Type of multilayer cloudiness	Lower layer	Total τ						
		4	10	20	30	40	45	50
St+As	St	2	6	12	22	30	-	-
St+Ci	St	2	8	13	26	-	30	-
St+As+Ci	St	-	4	11	19	-	-	38
As+Ci	As	-	7	14	21	-	-	-

The results of the ATC calculations for the different types of cloudiness given in Tables I and II (except Ci) are displayed in Figs. 2–4. The calculations were performed for separate values of τ divisible by 5 in the range τ = 4–50 (except for τ = 4) and the two angles φ_r = 5° and 90°. In order not to superimpose the individual points in Figs. 2–4 corresponding to the different cloudiness types, they are slightly separated in the direction along the τ axis. For convenience in reading the figures the zones of point spreading for φ_r = 5 and 90° are indicated somewhat arbitrarily by the dashed lines. In addition, the points for φ_r = 90° always lie higher than those for φ_r = 5° for cloudiness of the same type with identical τ.

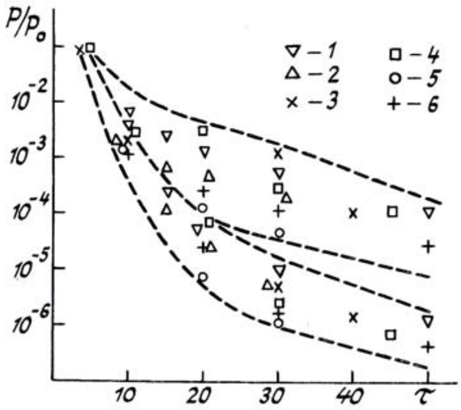

FIG. 2. Relative amplitude P_m/P_0 of the transmitted pulses (P_0 is the amplitude in the absence of cloudiness) as a function of cloud optical thickness for different types of cloudiness: St (1), As (2), St + As (3), St + Ci (4), As + Ci (5), St + As + Ci (6).

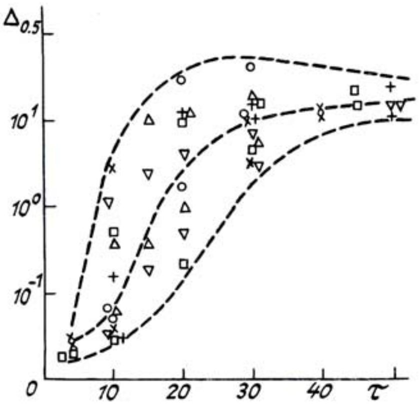

FIG. 3. Pulse duration $\Delta_{0.5}$ in units of 10^{-6} sec *as a function of the layer optical thickness* τ *for different types of cloudiness.*

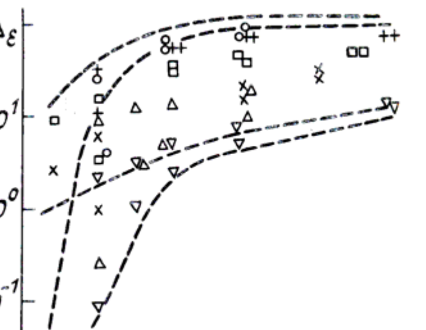

FIG. 4. Energetical pulse duration Δ_ε in units of 10^{-6} sec *as a function of the optical thickness τ of the layer for different types of cloudiness.*

As can be seen from Figs. 2–4 the effect of cloud type on the ATC is very strong, and the effect of the parameter Δ_ε even exceeds the effect of φ_r (Fig. 4). It should be noted that the value of Δ_ε is noticeably greater than that of $\Delta_{0.5}$ in a number of cases (for $\tau \le 30$ and $\varphi_r = 5°$ for single-layer clouds, and for each τ considered and $\varphi_r = 90°$ for multilayer clouds). This indicates that a large part of the pulse energy is contained in the delayed trailing edge of the pulse. Comparing the degree of pulse stretching (characterized by the rate of amplitude decrease, and pulse duration increase), we note that among single-layer clouds those of As type result in greater spreading. This is related to the high altitude of the lower cloud boundary and the relatively small value of the extinction coefficient for this type of cloud (Table I). But the greater degree of pulse stretching is observed for multilayer formations, especially of As + Ci type. Thus, the difference between the ATC for single-layer clouds of St type, on the one hand, and the multilayer clouds of St + As and St + Ci types, on the other, can be 8–10 times in amplitude, and 3–4 times in the duration $\Delta_{0.5}$. The reason for the strong pulse stretching in multilayer clouds is the additional time delay acquired by the photons during their propagation in the space between the layers.

CONCLUSIONS

The amplitude-temporal characteristics of pulses transmitted through a cloudy medium are determined primarily by the optical thickness of the cloudy medium. For identical optical thickness they also depend on the number and altitude of the cloudy layers and the values of their extinction coefficients. The variations in the size spectrum of real water – droplet clouds do not significantly affect the ATC of pulsed radiation. Among the different types of cloudiness multilayer formations with high-altitude location of their layers and small extinction coefficients give the greatest pulse stretching.

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