STRUCTURE OF THE SPACEBORNE LIDAR RETURN FROM THE UPPER LEVEL CLOUDS. PART II. OPTICALLY INHOMOGENEOUS CLOUDS

G.M. Krekov and M.M. Krekova

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
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Computation of spaceborne lidar returns is performed by the Monte Carlo method. The analysis of results has shown that identification of inhomogeneities in the cloud top is possible under particular optical conditions. The optical thickness of the cloud layer is not greater than $\tau \approx 2.5–3$. *The estimates are obtained for the lidar operating at* $\lambda = 0.532$ μm *at the distance from the cloud* $H \sim 400$ km.

INTRODUCTION

The possibility of detecting clouds of different optical density by means of a lidar is limited by the sensitivity of a recording system. It was shown in the first part[1] that the dynamic range of the signal magnitude $P(h)$ coming from the cloud layer of thickness $\Delta H = 100$ m is 1–2 orders of magnitude, and the signal amplitude $P(h)$ variation depending on the value σ_{ext} are also within this same interval (see Fig. 1 in Ref. 1). In this connection, the selection is evidently possible of inhomogeneous structure at least in the upper part of a cloud layer. However, this contradicts to the results we have presented earlier.[2] The matter is that the capabilities of computers at that time did not allow the calculations to be made with the sufficient level of statistical sample which is necessary at short time gate intervals. The calculations[2] were carried out with the depth resolution in the cloud of $\Delta h = c\tau/2$ of 20–50 m that made it impossible to reveal fine temporal structure of signals. In this paper we present results of calculations performed using the statistical sample of the order of 10 million photon histories with the cloud depth resolution $\Delta h \le c\tau_i$, where τ_i is the pulse duration.

The initial and boundary conditions of the problem corresponded to the data described in the first part.[1] Calculations were performed for the wavelength $\lambda = 0.532$ μm. The divergence angle of a sounding beam was $\varphi_i = 0.2$ mrad and the receiver field of view angle $\varphi_d = 0.4$ mrad. When setting the extinction coefficient profile, the cloud was divided into n layers. The extinction coefficient $\sigma_{ext}(h)$ varied from one layer to another, and was constant inside each layer. The cloud scattering phase function corresponded to the C1 cloud type,[3] the optical model of the atmospheric aerosol in the 30-km layer above the cloud was set according to Ref. 4. When setting the profiles $\sigma_{ext}(h)$ we had in mind the idea that the formation and transformation of clouds with the variety of their forms and types occur, in real atmosphere, under the action of different dynamical processes. Apart from the typical mean profiles $\sigma_{ext}(h)$ increasing or decreasing with the distance down from the cloud top,[5] we considered more complicated profiles as well.

CALCULATED RESULTS

Calculations were carried out for the upper part of a cloud layer of the thickness of $\Delta H = 80–120$ m and total optical depth of $\tau \sim 3$. In the majority of figures the extinction coefficient as a function of depth into the cloud is shown in the left-hand side figures. Figures 1 and 2 illustrate the change of the total power of a lidar return from a cloud, $P(h)$, as a function of the depth into the layer sounded. Figure 1 shows the signal change for two examples of the profiles $\sigma_{ext}(h)$ decreasing monotonically (Fig. 1*a*) and sharply decreasing and then remaining constant with depth (Fig. 1*b*). The mean value σ_{ext} in the layer did not exceed 20 km^{-1}, and τ was ~ 2.2 in both cases.

The calculated signals $P(h)$ noticeably differ from each other. They repeat the behavior of $\sigma_{ext}(h)$ variation. The sharp decrease in the signal $P(h)$ in Fig. 1*b* stops practically simultaneously with the stop in the extinction coefficient decrease, and then the signal change becomes monotonic. Figure 2 shows the results of calculating $P(h)$ for the monotonically increasing profiles $\sigma_{ext}(h)$ differing from each other in the gradients of the change with the cloud depth.

Figure 2*a* shows the behavior $P(h)$ at a relatively slow increase of the extinction coefficient value, its mean value in the inhomogeneous layer being ~ 27 km^{-1}, and $\tau \sim 1.2$. Figure 2*b* shows the dependence $P(h)$ for a sharply increasing profile $\sigma_{ext}(h)$ with the mean value in the inhomogeneous layer being $\sigma_{ext} \sim 30$ km^{-1} and $\tau \sim 0.9$. The qualitative behavior of the signals $P(h)$ in these examples corresponds to the behavior of $\sigma_{ext}(h)$. The positions of maxima in $P(h)$ and $\sigma_{ext}(h)$ practically coincide or are quite close to each other.

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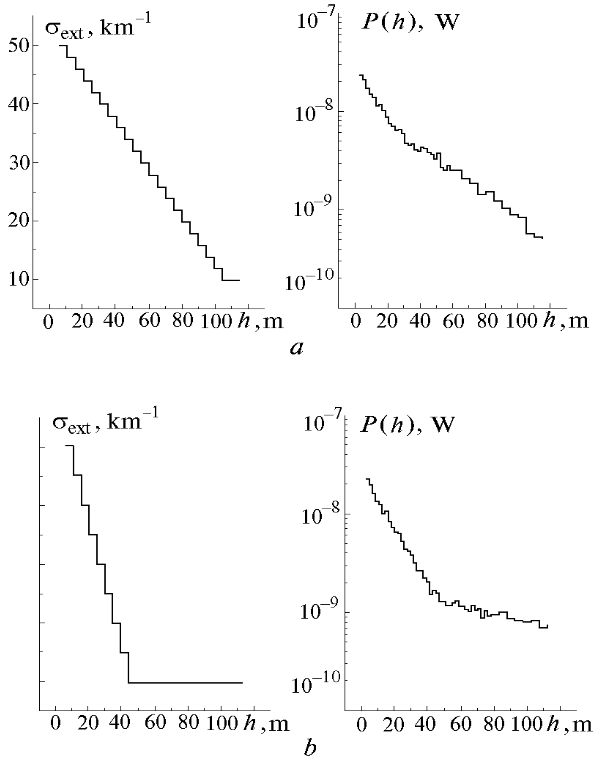

FIG. 1. Lidar return P(h) as a function of the extinction coefficient profile $\sigma_{\text{ext}}(h)$.

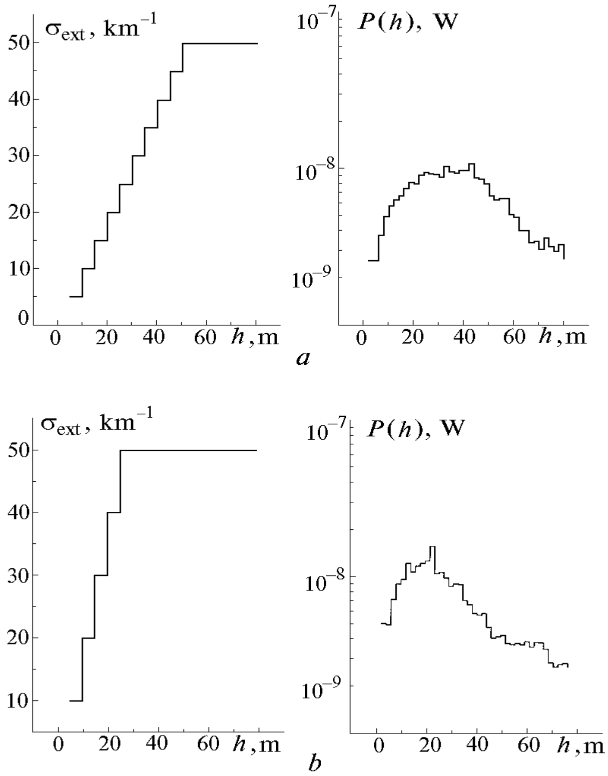

FIG. 2. The same function P(h) as in Fig. 1 for two types of the profiles of $\sigma_{\text{ext}}(h)$, *increasing with the depth.*

There arises the question on whether is it possible or not to reproduce the profile $\sigma_{\text{ext}}(h)$ by involuting in space the $P(h)$ at the presence of some extreme values in the depth of the cloud layer, or the pattern will be washed out due to the multiple scattering background? Signal power $P(h)$ calculated for the clouds with more complicated profiles of the extinction coefficient is presented in Figs. 3*a* and *b*.

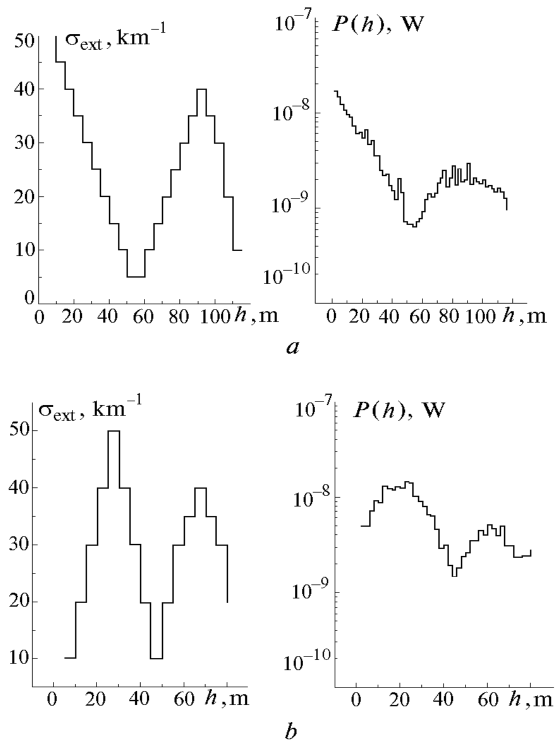

FIG. 3. The return signal power P(h) for the shape of $\sigma_{\text{ext}}(h)$ *profile with several maxima.*

The mean values of σ_{ext} in the cloud layers did not exceed 24– 30 km^{-1}, and τ was ~ 2.5– 3.

The results presented in this figure illustrate the existence of correlation between the signal profile shape and the shape of the extinction coefficient profile. The positions of maxima in $P(h)$ and $\sigma_{\text{ext}}(h)$ practically coincide, though the maxima in $P(h)$ are more diffuse and can be displaced a little bit to the lower or higher optical thicknesses. The displacement of the signal maxima as well as the degree of their spread are only determined by the behavior of the background component of the signal. It is confirmed by the data shown in Fig. 4, on the distribution of radiation $P(h)$ over the scattering orders for the extinction coefficient profile shown in Fig. 3*a*.

As to a homogeneous cloud, radiation of the low orders of multiple scattering are determining in the formation of signal up to the optical thickness of $\tau \le 2.5$–3. Redistribution of their power occurs at the optical depths of $\tau \approx 1$–1.5. If the position of the maximum $\sigma_{\text{ext}}(h)$ corresponds to the optical thickness of $\tau > 1.2$ or $\tau < 1.2$, the signal maximum $P(h)$ is displaced to lower optical thickness in the first case and to the higher ones in the second case. The results shown in Fig. 4 make it possible to note quite an important feature: the low scattering orders can keep information on the extinction coefficient profile even when using a spaceborne lidar

Calculations of the lidar return signal for an inhomogeneous cloud of high optical density are shown in Fig. 5. The extinction coefficient profile has the parabolic shape, the mean value of the extinction coefficient in the layer is $\sigma_{\text{ext}} \approx 43$ km^{-1}, its maximum is at the depth of $\tau \sim 3.5$. The signal $P(h)$ decreases monotonically and no correlation with the extinction coefficient profile occurs.

This can be explained as follows. The single scattering signal $P_1(h)$ has no maximum in this optical situation because the extinction of radiation is not compensated for by an increase of the backscattering coefficient according to the profile $\sigma_{\text{ext}}(h)$.

In addition, formation of the multiple scattering of low orders finishes at the depths of $\tau \sim 1.5-2$ (see Ref. 1), so the positions of their maxima do not coincide with the position of the extinction coefficient maximum. The main role of the low orders of scattering in the formation of reflected signal keeps up to $\tau \sim 2-2.5$. As a result, the structure of signal $P(h)$ at the depth corresponding to the maximum value of $\sigma_{\text{ext}}(h)$ is practically completely determined by contributions from high orders of multiple scattering. They do not have well pronounced maxima, because their formation starts at higher levels of the cloud and is superposed in the signal formed at large depths due to the accumulated travel path.

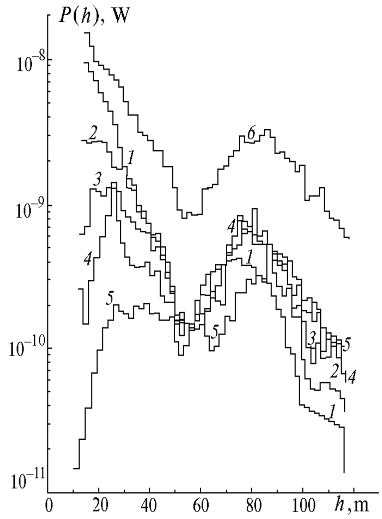

FIG. 4. Distribution of the reflected radiation power over the multiple scattering orders. Numbers of the curves 1–5 correspond to the order of multiple scattering and 6 is the total signal power $P(h)$.

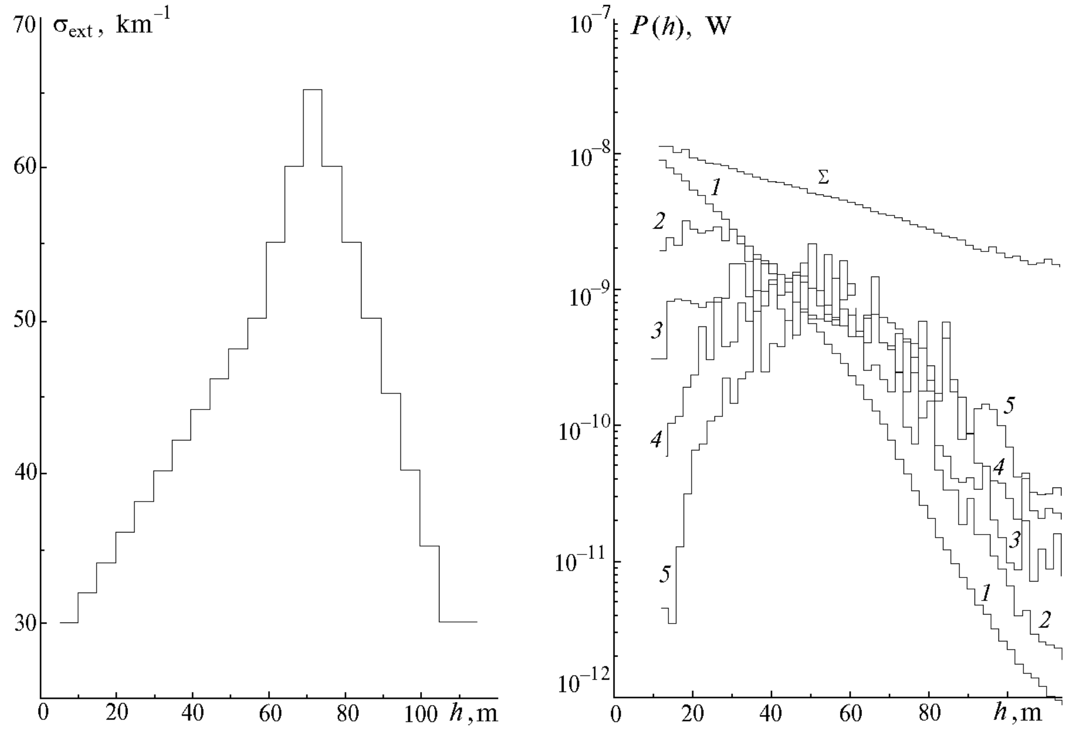

FIG. 5. Dependence of $P(h)$ and distribution over the orders of multiple scattering calculated for a cloud with high optical density and parabolic shape of the extinction coefficient profile. Curves 1–5 show the order of multiple scattering, Σ corresponds to $P(h)$.

CONCLUSION

The series of calculations of lidar return signals with different kinds of the extinction coefficient profiles, optical thickness τ, and mean value σ_{ext} has shown the following. Qualitatively the behavior of the return signal from an inhomogeneous cloud coincides with the shape of the profiles $\sigma_{ext}(h)$, if the optical thickness of the layer under investigation is below $\tau \sim 2.5$–3, and the mean value $\sigma_{ext} < 30$ km^{-1}. If the qualitative behavior of the return signal from clouds exhibits the cloud inhomogeneity, it is expedient to apply the methods based on a more general approach.[6,7] These methods make it possible to process the total lidar return, because the background component due to multiple scattering is the carrier of useful information, that is confirmed by the results of calculating contributions to $P(h)$ coming from multiple scattering of different orders as shown in Fig. 4. However, it is necessary to note that only low orders of scattering keep information on $\sigma_{ext}(h)$. Probably, this fact is indicative of the existence of limitations on the efficiency of the methods for inverting the lidar signal proposed by the authors of Refs. 6 and 7. It is expedient to examine their stability in a closed numerical experiment as it was done, for instance in Ref. 8.

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