ON ESTIMATION OF THE RADIATION SCATTERING COEFFICIENT AT THE CLOUD BOUNDARY

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The criteria for characterization of the scattering coefficient at the cloud boundary are proposed. The scattering coefficient averaged over the laser beam path is calculated. Averaging is performed to one of several specific points in the lidar return from the cloud. The most suitable averaging turned out to be that measured over the interval from the point of the sign modification of the derivative of the signal when the beam enters the cloud to the point of the maximum signal.

In laser sounding of clouds the necessity constantly arises to determine the radiation scattering coefficient. It is typical of subsatellite sounding, aeronautical meteorological service, climatology, etc. The depth of sounding can practically reach tens and hundreds of meters. The natural question arises about the depth which characterises the cloud in the sense of the scattering coefficient with adequacy most completely corresponding to the posed problems and technical capatilities of a lidar.

Certainly, it would be interesting to use the entire depth profile of the scattering coefficient $\sigma(r)$, providing a user with maximum body of information. But, first, during the long runs of measurements such information may be redundant. Second, the lidar systems with limited potential (for example, the airborne ones) may have insufficient storage volume. Third, due to the well–known peculiarities of the laser sounding equation (LSE) its solution starts to diverge after reaching some depths,[1] the accuracy of retrieving $\sigma(r)$ sharply decreases, and the resultant information content of the sounding process decreases after all.

In many cases when sounding the clouds with not only ground–based but also airborne lidars, it is the boundary external part of clouds that is of interest, rather than their central regions. The notion of the cloud boundary, in its turn, can be defined on several criteria.

Figure 1 explains these criteria based on the analysis of a lidar return signal (proposed previously in Ref. 2). The profile of the scattering coefficient $\sigma(r)$ (curve *1*) is constant in the atmosphere under the cloud and is equal to σ_0. Starting from the distance r_0 (it is the cloud microphysical boundary) $\sigma(r)$ linearly increases in the first approximation and grad $\sigma(r) = \mu$. The return signal power varies depending on the variation in parameters of cloudiness (μ) (curve *2*). At the distance r_0 the sign of the derivative reverses for the first time. The derivative reaches its maximum value F_{max} at the distance r_{max}. Here the derivative reverses its sign for the second time. The distances r_1 and r_2 correspond to the threshold value of $0.5\,F_{max}$ (in general other thresholds can be chosen). The distance r_a appears due to asymptotical processing of the lidar signal and is equal to half the maximum depth of beam penetration into the cloud reached in the given sounding event. The values r_0, r_1, r_{max}, and r_2 are independent of the parameters of the lidar. The value r_a directly depends on the energy potential of the lidar.

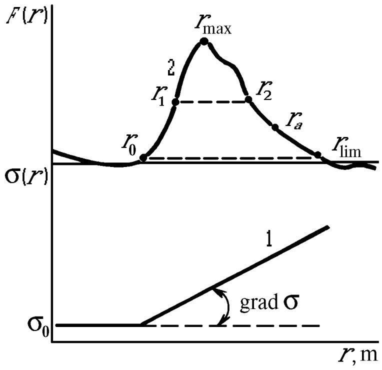

FIG. 1. Lidar determination of the cloudiness boundary: 1) model profile of the scattering coefficient and 2) generalized shape image of the lidar signal; r_0, r_1, r_2, r_{max}, and r_a are the points characterizing various criteria for the cloud boundary and r_{lim} is the limiting depth of cloud sounding.

There are two ways of choosing the characteristic values of the scattering coefficient. The first is to measure the values of $\sigma(r)$ at the points r_1, r_{max}, r_2, and r_a. It has no evident difficulties, since the given points are taken from the precalculated profile $\sigma(r)$. The second is to perform an averaging over the sounding path. For this purpose it is reasonable to select the intervals $r_0 - r_1$, $r_0 - r_{max}$, $r_0 - r_2$, and $r_0 - r_a$. This paper is devoted to the numerical check of these criteria for the cloud boundary. Its concrete goal is the aspects regarding the method of performance of the subsatellite cloud lidar.[4] Here it is necessary to take into account the specific features of the onboard automated system of signal recording and processing, namely, the discrete character of the real signal in time and amplitude and inapplicability of too complicated algorithms of data processing due to the limited energy resources of an aircraft.

To calculate the lidar return signals $F(r)$, I used the equation of laser sounding in the single scattering approximation, which is adequately given at the stage. The scattering coefficient was taken to be the piecewise–continuous constant up to the cloud microphysical boundary r_0 and then linearly increasing with the fixed gradient μ. The experiments performed previously by the author and the data published elsewhere[3] have shown that such an assumption is

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real. The parameter μ was chosen in such a way that in the cloud at a depth of 50 m the scattering coefficient reached 12.5 ... 50 km^{-1} (which are close to real values).

The profile $\sigma(r)$ was retrieved using the Kovalev asymptotic method (its foundations were given in Ref. 5) in its simple form

$$\sigma(r) = \frac{F(r)}{2\int_r^{r_{lim}} F(x)x^2 dx} . \qquad (1)$$

In this algorithm the concentration of particles can vary along the beam path but the scattering phase function is assumed to be constant.

The limiting distance r_{lim}, i.e., the asymptotic distance to which the signal is integrated, was calculated from the condition $F(r_{lim}) \le 0.01\, F_{max}$, where F_{max} is the maximum signal and $r_{lim} > r_{max}$. This magnitude is approximately adequate to the operation conditions of a 7–digit ADC. The physical boundary of the cloud r_0 was calculated accordingly, for $F(r_0) \le 0.01F_{max}$, where $r_0 < r_{max}$.

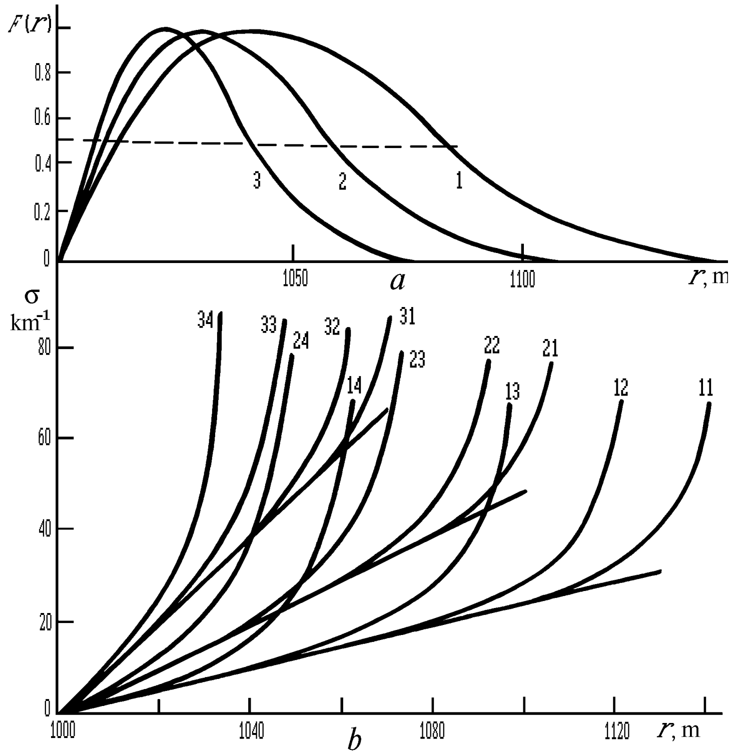

FIG. 2. Retrieval of profiles of the scattering coefficient. Curves 1, 2, and 3 show the lidar signals scaled to unity with the scattering coefficient gradient $\mu = 2.5\cdot10^{-4}$, $5.0\cdot10^{-4}$, *and* $1.0\cdot10^{-3}$ m^{-2}*; curves 11, 12, 13, and 14 are for* $\mu = 2.5\cdot10^{-4}$ m^{-2} *and the optical thickness used for retrieving* σ *is equal to* 1.0, 0.8, 0.5, *and* 0.25 *of the maximum sounded thickness; curves 21, 22, 23, and 24 are for* $\mu = 5.0\cdot10^{-4}$ m^{-2}*; curves 31, 32, 33, and 34 are for* $\mu = 1.0\cdot10^{-3}$ m^{-2}.

It is well known that the Kovalev algorithm in the form of formula (1) must meet the asymptotic condition at infinity. For this purpose it is necessary to obtain the optical thickness of the cloud, at least, equal to two (to the natural base) at the distance $r_0 - r_{lim}$. The larger is the thickness, the greater is the depth of the reliably retrieved profile $\sigma(r)$. In the real experiment the sounded depth is never exactly known preliminary. To check the effect of the deficiency of the optical depth on the averaged scattering coefficient, the following procedure was used. In every model profile $\sigma(r) = \sigma_{mi}(r)$ for its eigenvalue r_{limi} the sounded optical depth was determined from the formula $\tau_i = \int_{r_0}^{r_{limi}} \sigma_{mi}(x)\, dx$. The deficiency of the optical depth was determined as $\tau_d = 0.8\tau_i$, $0.5\tau_i$, and $0.25\tau_i$. The distances in the cloud r_{di}, were calculated correspondingly to these reduced optical depths. Subsequently, in the retrieval of the $\sigma(r)$ profile the asymptotic integral in the denominator of Eq. (1) was taken to the reduced limit r_{di}, rather than to the limiting value r_{limi}. But the signals $F(r)$ used for processing on the shortened beam path were the same. Such a procedure enabled one to imitate cloud sounding with the sounded optical depth deficient for the fully adequite application of asymptotic equation (1) and to estimate the degree of deviation of the retrieved values of $\sigma(r)$ from the model values σ_m under different conditions.

The next step was the derivation of the value of the scattering coefficient averaged over the beam path. The averaging was performed up to the points r_1, r_{max}, r_2, and $r_a = 0.5\, r_{lim}$, i.e., the values

$$\overline{\sigma}_1 = \frac{1}{r_1 - r_0}\int\limits_{r_0}^{r_1}\sigma(x)dx\ ;\ \overline{\sigma}_m = \frac{1}{r_{\max} - r_0}\int\limits_{r_0}^{r_{\max}}\sigma(x)dx\ ; \quad (2)$$

$$\overline{\sigma}_2 = \frac{1}{r_2 - r_0}\int\limits_{r_0}^{r_2}\sigma(x)dx\ ;\ \overline{\sigma}_a = \frac{1}{r_a - r_0}\int\limits_{r_0}^{r_a}\sigma(x)dx$$

were calculated.

To obtain the measure of deviation from the real values, the same average values were calculated for the model profiles $\sigma_m(r)$. The averaging in model calculations was performed to the same points r_1, $r_{\max}$, r_2, and r_a, respectively.

Let us consider the obtained data as an example of analysis of the results of numerical study of cloud sounding at the distance $r_0 = 1000$ m (Fig. 2). Results of sounding at distances of 250, 500, and 2000 m are given in the text.

It can be seen from curves *1–3* that the position of $r_{\max}$ at which the signal is maximum shifts toward the greater cloud depth with decrease of $\mu = \text{grad}\ \sigma$. On the basis of this effect the algorithm of estimating the gradient of the cloud scattering coefficient can be constructed,[2] when

$$\mu = \frac{1}{2(r_{\max} - r_0)}\frac{2r_0 - r_{\max}}{r_{\max}}\ . \quad (3)$$

For the examined cases we have $r_1 = (10 \pm 3)$ m, $r_{\max} = (32 \pm 13)$ m, $r_a = (55 \pm 15)$ m, and $r_2 = (62 \pm 22)$ m. They are also the depths of the spatial averaging of the profiles of the scattering coefficient.

The family of curves shown in Fig. 2*b* is the profiles of the scattering coefficient retrieved using Eq. (1) in its discrete representation. Thus, curve *11* is retrieved under the optimum conditions, when the depth taken into account is equal to the maximum sounded depth $r_{\lim 1} = 140$ m, i.e., $\tau = 2.48$. Curve *2* is retrieved under worse conditions, when the signal $F(r)$ was the same but the depth $\tau = 1.98$ was taken into account, that is, 0.8 of the maximum depth. Curves *11* and *14* were analogously retrieved at the depths $\tau = 1.24$ and 0.62.

From the shape of the curves and measure of their deviation from the model profiles (straight lines) we can see that the scattering coefficient by the Kovalev method is retrieved with a good quality when the sounded thickness exceeds unity. In this case it is possible to average $\sigma(r)$ over the laser beam path up to very great cloud depths. However, the general optimistic picture is affected by entering the optically weak sections of the beam path which is illustrated by curves *14*, *24*, and *34* (Fig. 2) and analogous results obtained at different distances to the cloudiness.

Let us consider the deviations of the values σ calculated from the signals from their model analogs summarized in Table I. Given in the second column are the standard deviation of the calculated mean values of σ from their model analogs being equal, e.g., $\overline{\sigma}_m = \sigma_0(r_{\max} - r_0) + 0.5\mu(r_{\max} - r_0)^2$. (All the errors are taken with the positive sign.)

Thus, using the criterion $\overline{\sigma}_m$ for a dense cloud we obtain its standard deviation from the model value of only 6%. True, the variation of this deviation reaches 84% here. For the deficiency of the optical thickness being less than unity the deviation from the model reaches 48%, however its variation decreases down to 32%.

It is significant that in the "good", i.e., dense cloud for all the criteria the deviations from the model values are within 4–10%. But already for $1 < \tau < 2$ for the deepest values of $\overline{\sigma}_a$ and $\overline{\sigma}_2$ it tends to 20% (the lower rows of the table).

For the deficiency of the optical thickness being less than unity the deviations of $\overline{\sigma}_a$ and $\overline{\sigma}_2$ from the model reach 80%. Hence, $\sigma_{\max}$ is the most suitable criterion for the scattering coefficient. If we take into account the principal uncertainty of retrieval the profile $\sigma(r)$ as well as deviation of its real shape from the linear model, than the 50% deviations from the model may be considered not too large. When necessary we can go over from $\overline{\sigma}_{\max}$ to $\overline{\sigma}_a$ or $\overline{\sigma}_2$. They are correlated and for the entire sets of the parameters $\overline{\sigma}_a/\overline{\sigma}_{\max} = 2.2 \pm 0.5$. In the case of another criterion $\overline{\sigma}_2/\overline{\sigma}_{\max} = 1.7 \pm 0.5$.

TABLE I. Deviations of the values of σ_i averaged over the laser beam path and calculated using asymptotic equation (2) from the calculated model profiles $\sigma(r)$.

Averaging criterion	Standard deviation of the scattering coefficient $\overline{\sigma}_i$ averaged over the laser beam path from the average model profiles σ_{mi} (%)	Data spread (%)	Geometric depth of averaging (m)	Sounded optical thickness
$\overline{\sigma}_1$	7	74		
	36	42	10 ± 3	τ > 1
$\overline{\sigma}_m$	6	84	32 ± 13	τ < 1
	48	32		
$\overline{\sigma}_a$	10	90	55 ± 15	τ > 1
	82	32		
$\overline{\sigma}_2$	6	87	62 ± 22	τ < 1
	72	26		
$\overline{\sigma}_a$	5	93	–	2 < τ < 3
$\overline{\sigma}_2$	4	72	–	
$\overline{\sigma}_a$	19	38	–	1 < τ < 2
$\overline{\sigma}_2$	10	67	–	

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