ON EXTRAPOLATION OF LIDAR DATA IN DETERMINING THE ATMOSPHERIC VISIBILITY ALONG THE SLANT PATHS

V.A. Kovalev, E.E. Rybakov, M.B. Zakharyan, and V.M. Ignatenko

A.I. Voeikov Main Geophysical Observatory, Leningrad
State Committee on Hydrology and Meteorology (Goskomgidromet) of the USSR, Leningrad

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High–intensity runway lights became invisible when the optical thickness τ *of the atmospheric layer between the light and an observer attains 3 and more (up to 10 and more at nighttime) whereas the lidar range of action corresponds to the values of* τ = 1.5–2. *In this case the assumption seems to be justified that the mean extinction coefficient measured in an atmospheric layer h is independent of the elevation angle. This basic assumption has been checked with the help of a large series of lidar observations.etc.*

In accordance with recommendations of IKAO and Conferences on Air Navigation there exists the requirement to make the data on the slant visibility range (SVR) available for the pilot before landing. These data allow the pilot to estimate if he would be able to make in advance the required visual reference to a fixed number of landmarks. Though the concrete meaning of the SVR is not defined, it must indicate the altitude at which the pilot expect visual reference to the ground-based light signaling system; he must receive an acknowledgement that this visual reference will last till the end of landing.[1]

To estimate the SVR or the altitude of visual reference (AVR) the data on the mean extinction coefficient or the transmittance as functions of altitude are required. These data can be derived from the data obtained with the help of devices based on the methods of laser detection and ranging of the atmosphere. Unfortunately, an essential disadvantage of these devices (lidars) when they operate under conditions of low visibility is their small range of action in comparison with the visibility range sought of the runway light landmarks (the approach lights or the high-intensity runway lights). It is well known that the distance at which these lights can be detected is relevant for the optical thickness of the atmospheric layer between the observer and the light which is equal to 3 and larger and is amounted to ~ 10–12 at nighttime. At the same time the range of action of lidars is limited by the optical depths about 1.5–2 (Refs. 2–4). The natural way to avoid this difficulty appearing in measuring the slant visibility range of the airport lights is to use one or another method of extrapolation of lidar data outside the limits of the observed layer. This paper is devoted to the aspects of practical applicability of extrapolation technique to lidar sounding along the slant paths.

The simplest approach to the problem of determining the slant visibility range is to use the condition of the stratified atmosphere according to which the lower ground atmospheric layer is represented as a set of the thin horizontal layers with the constant extinction coefficients.[5] If this condition is virtually satisfied, the problem of determining the SVR is solvable. It should be also noted that this condition can be used as an a priori assumption which eliminates the uncertainty in the solution of the equation of laser sounding.

However, the first experimental investigations, which we performed, testified to the validity of suspicions which were expressed in the papers at different times that the model of the homogeneously stratified atmosphere is not satisfied under real conditions; even if this condition is satisfied with essential reservations, its practical use for determining the slant visibility range is seriously impeded. As an illustration, Fig. 1 shows the profiles of the extinction coefficient $\bar{\mu}$ as a function of an altitude h, which were derived from the data of an Electronika–03 lidar with an analog–digital converter in the process of sounding a relatively stable, weakly turbid, and cloudy atmosphere at angles 8° and 12° with the horizon. The given profiles fiih) of the backscattered signals were derived from a 5–10–shot average. Curves *1* and *2* were obtained by the ordinary proceeding methods,[4] the broken lines 3 – by the Kano method,[6] which is based on the direct application of the condition of the homogeneously–stratified atmosphere. As can be seen from Fig. 1, the usage of the last leads to quite significant variations in the calculated values of the extinction coefficient (in a number of cases even the negative values of $\bar{\mu}(h)$ can be obtained). This can be attributed to not only the high sensitivity of the method[6] to the instrument errors, but also the violation of the starting a priori assumption about the homogeneously–stratified atmosphere. It should be

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noted that the measurements which were carried out over the course of a few hours gave the profiles analogous to those presented in Fig. 1, curves *1* and *2* which were plotted ignoring the condition of homogeneously–stratified atmosphere, were of quite stable character.

Thus, extrapolating the lidar data outside the limits of the observed layer, one should use less rigorous *a priori* assumptions than the condition of the homogeneously–stratified atmosphere. In our opinion, such a condition is given in Ref. 7, where it was assumed that the mean value of the extinction coefficient is independent of the observation angle in the layer h of interest. In other words, for measuring of the visibility range in a fixed layer h, the optical thickness of this layer for the arbitrary elevation angles φ and ψ with the horizon must satisfy the condition

$$\frac{\tau_\varphi(h)}{\tau_\psi(h)} = \frac{\sin\psi}{\sin\varphi} . \qquad (1)$$

Another form of writing Eq. (1) is

$$\int_0^h \mu_\varphi(h')\mathrm{d}h' = \int_0^h \mu_\psi(h')\mathrm{d}h', \qquad (1a)$$

where $\mu_\varphi(h')$ and $\mu_\psi(h')$ are the local values of the extinction coefficient along the path of the sounding beam for the observation angles φ and ψ, respectively.

In Fig. 2 the profiles of the local (Fig. 2a) and mean (Fig. 2b) extinction coefficients are presented as a function of the altitude h for different elevation angles, which illustrate the above statements. Each profile is derived from the backscattered light signal average, as well as in Fig. 1. The conditions of sounding (November 20, 1987) are shown in Table I.

The profiles shown in Fig. 2 represent, apparently, quite typical atmospheric situation in which the structure of a haze under the cloud layer, whose general tendency of increasing the extinction coefficient in the direction toward the cloud base remains unchanged, at the same time undergoes continuous spatiotemporal variations. It can be easily seen that in this case the choice of the condition (1) (or (1*a*)) is preferable than the use of the traditional condition of equality of the local values of $\mu_\varphi(h')$ and $\mu_\psi(h')$ within the limits $0 \le h' \le h$.

TABLE I. Conditions of sounding the atmosphere on November 20, 1987.

No.	Time of sounding	Observation angle, deg.	Horizontal MVR*, km	Cloud altitude, m
1	18.38	3	5.2	–
2	18. 43	6	5.8	–
3	18. 48	11	6.0	–
4	18.53	17	6.0	340
5	19. 10	11	6. 4	440
6	19. 15	6	6.4	–
7	19. 19	3	6.6	–

*) Meteorological visibility range.

Naturally, there are quite probable situations in the real atmosphere in which the condition (1) or (1*a*) may be also violated (e.q., in the process of forming or dissipating the fog, in the presence of individual large–scale inhomogeneities along the observation path, etc.). In these cases the results of lidar measurements of the SVR appears to be dependent on the observation angle. Respectively, the optimum way to check up in practice the fact that the condition (1) or (1*a*) is satisfied is to find one or another parameter, which determines the slant visibility range in the surface layer derived from the lidar signals at different observation angles: if this condition is satisfied, the results of lidar measurements are independent of variations in the observation angle.

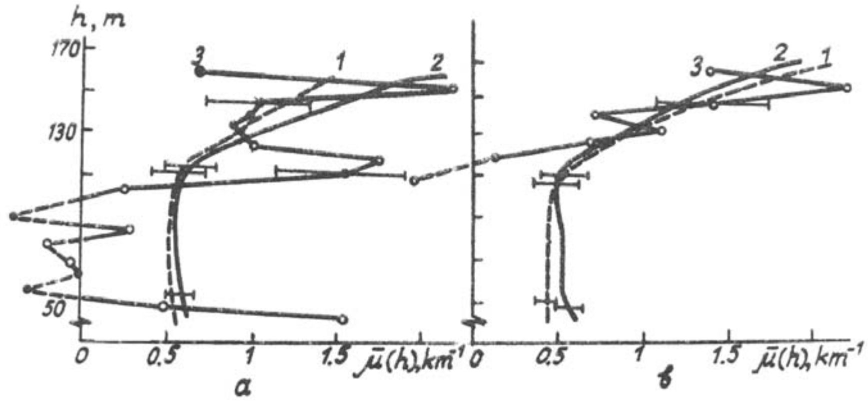

FIG. 1. The profiles of the extinction coefficient obtained by the different methods for processing of the backscattered signals.

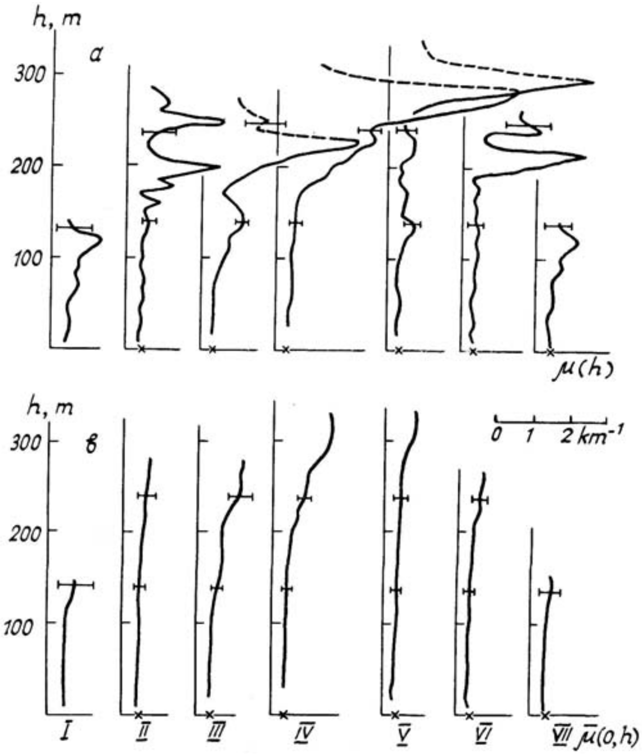

FIG. 2. The profiles of the extinction coefficient (μ(h) *denotes local and* $\bar{\mu}(0,h)$ – *average coefficients) derived from the lidar data for different elevation angles. The crosses on the horizontal axis denote the values of the extinction coefficient at the height of the Earth's surface derived from the readings base recorder at the moment of sounding.*

The practical applicability of the condition (1) or (1*a*) in the real atmosphere was examined using a lidar with conventional configuration (the receiving–transmitting system, the analog–digital converter, and the computer). The lidar operated at a wavelength of 0.694 μm. As the parameters that characterize the visibility in the surface layer[8-12] the following quantities connected with it were investigated:

– the altitude of detection of the high–intensity lights (h_1) in the starting zone of the runway from the glide path;

– the altitude of visual reference to a group of approach lights (h_2), which is needed for the pilot's altitude control;

– the altitude $h_{om} = S_{om} \cdot \sin \upsilon_0$ defined as the projection of the meteorological visibility range S_{om} measured at angle υ_0 of a glide path onto the vertical axis.

The temporal behavior of the parameters h_1, h_2, and h_{om} derived from the data of lidar sounding at different angles with the horizon are shown in Fig. 3.

The given curves are typical of all the set of the data that have been obtained here. The characteristic features of the curves are, first, the correlation between the values of altitude h and the visibility range in the lower atmospheric layer; the correlation coefficient in a number of atmospheric situations amounts to 0.91. Second, in the majority of cases the relatively good stability of these quantities with time and the absence of their sharp changes from measurement to measurement were observed (the exceptions are the cases of sharp changes in visibility with time or the presence of the broken multilayer cloudiness).

The experimental results show that altitudes h_1, h_2, and h_{om} derived from the lidar data as a rule are independent of the observation angle (naturally, if the sounding range at the chosen angle is relevant for the altitude sought) that testifies to the expediency of the use of the assumption of the form (1) or (1*a*) for lidar determination of the slant visibility. Moreover, the reproducibility of results of measurements with changing the observation angle can be considered as the criterion of reliability of these results.

For illustration of the above statement, Fig. 3*c* shows the false temporal behavior of parameters h_1 and h_{om}. They were observed during the measurements of the visibility characteristics on November 4, 1989. The obvious proof of the fact that these dependences are false is a stable correlation between the observation angle and the values of the measured altitudes h_1 and h_{om}. Analysis shows that these false dependences are caused by the so-called edge effect,[4] but not by the violation of condition (1) or (1*a*), or in a more wide sense, by inadequacy of the algorithm for processing the lidar signals and the observed atmospheric–optical situation.

Resulting systematic trend in the behavior of the parameter sought with the change in the observation angle can be interpreted as an incorrect choice of the boundary conditiozis in the solution of the equation of laser sounding. In other words, the stability of the parameter sought with the change of observation angle can be considered to be one of the criteria for an a posteriori estimate of the correctness of the chosen algorithms for processing the lidar signals.

In 1989 the lidar measurements of the characteristics of the slant visibility range were performed over the airport. The lidar was placed on the near actuator of the working start at a distance of about 1 km from the start of the runway. The temporal behavior of altitudes h_1 (curve 1) and h_{om} (curve 2) are shown in Fig. 4. They were derived from the data of lidar sounding of three elevation angles (9°, 14°, and 20°). Curve 3 shows the temporal behavior of the lower cloud boundary recorded with a standard cloud—range meter in the vicinity of the near actuator. The actual values of altitudes of visual detection of the runway recorded onboard airplanes entering the glide path are indicated by figure 4.

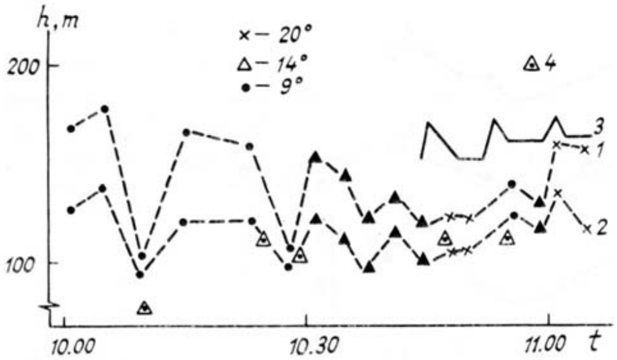

FIG. 4. The time dependence of the characteristics of the slant visibility derived from the data of lidar measurements over the airport and the results of the visual observations performed onboard airplanes.

The given results are typical of the data set obtained. During the comparison, 73 altitudes of the visual reference were recorded onboard the airplanes and 1300 counts of lidar were obtained. The results of comparisons testify to the expediency of using the starting assumption (1) or (1*a*) in lidar determining characteristics of the slant visibility.

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