

APPLICATION OF THE BACKSCATTER NEAR-END SOLUTION FOR THE INVERSION OF SCANNING LIDAR DATA

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ABSTRACT

The significant issue of the classic multiangle data-processing technique is that the upper boundary height, up to which the multiangle data processing technique allows reliable extraction of optical parameters of the searched atmosphere, is always significantly less than the operative range of the scanning lidar. The existing inversion methodology yields poor accuracy when inverting the far-end data points of the signals measured in and close to zenith. In the report, the data processing technique is considered which allows using the zenith-measured signal to increase the maximal heights of profiling of the atmosphere. Simulated and experimental data are presented that illustrate the specifics of such a technique.

1. INTRODUCTION

The classical Kano-Hamilton multiangle method allows extracting the vertical extinction-coefficient profile from elastic lidar data without an a priori assumption on the vertical profile of the lidar ratio [1, 2]. However, the method requires fulfilling two conditions. First, the total backscatter coefficient should be invariable along the horizontal direction, that is,

$$\beta_{\pi,\Sigma}(h) = \text{const.} \quad (1)$$

The requirement in Eq. (1) means that the total backscatter coefficient, $\beta_{\pi,\Sigma}(h)$ at the height h , which is the sum of the molecular and particulate components, $\beta_{\pi,m}(h)$ and $\beta_{\pi,p}(h)$ respectively, should be the same for any slope direction used during scanning. The second condition is the validity of the unanimous correlation between the total optical depth, $\tau_\phi(0, h)$, measured along the elevation angle, ϕ , and the vertical optical depth, $\tau_{\text{vert}}(0, h)$. The dependence can be written as,

$$\tau_\phi(0, h) \sin \phi = \tau_{\text{vert}}(0, h), \quad (2)$$

where $\tau_{\text{vert}}(0, h)$ is the total (molecular and particulate) optical depth of the layer from ground

level to the height h in the vertical direction.

To extract the optical parameters of the searched atmosphere, the classic Kano-Hamilton inversion method requires determining the set of functions $y_\phi(h) = \ln[P_\phi(h)(h/\sin \phi)^2]$, calculated from the lidar signals, $P_\phi(h)$, measured in different slope directions ϕ . If the conditions in Eqs. (1) and (2) are met, these functions can be written as,

$$y_\phi(x, h) = \ln[C\beta_{\pi,\Sigma}(h)] - 2\tau_{\text{vert}}(0, h)x, \quad (3)$$

where C is the lidar equation constant and $x = 1/\sin \phi$. The function $[C\beta_{\pi,\Sigma}(h)]$, which is used in the below inversion method, is found after determining the intercept of the linear fit of the functions $y_\phi(x, h)$ versus x with the vertical axis.

A significant issue of the Kano-Hamilton method, as compared with the one-directional zenith profiling, is the restricted altitude range where required inversion accuracy can be achieved [3]. The maximal height, h_{up} , of the atmospheric layer up to which the acceptable inversion accuracy can be achieved is always less than the maximum ranges of the lidar signals measured in and close to zenith (Fig. 1). In the conventional multiangle

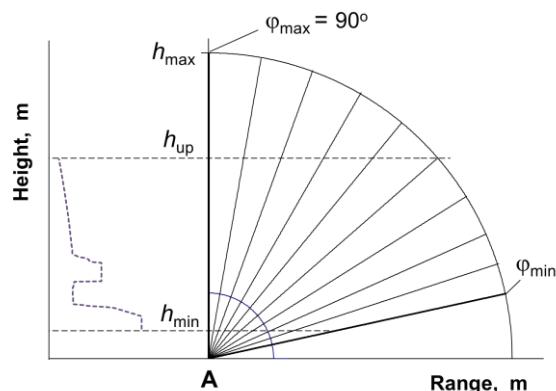


Fig. 1. Right side: Schematic of the scanning lidar operation. Left side: The vertical profile of the function $[C\beta_{\pi,\Sigma}(h)]$ derived from the Kano-Hamilton solution.

inversion method, the backscatter signals, $P_\phi(h)$, measured within the altitude range from h_{up} to h_{max} do not provide accurate determination of the optical parameters of the atmosphere within this altitude range. The only possibility to increase the profiling height is to combine the multiangle and one-directional data processing methodologies.

Below, the methodology for processing the multiangle data is discussed that allows increasing the maximum height of the profiling of the atmosphere as compared with the conventional Kano-Hamilton method.

2. METHODOLOGY

The algorithms for the backscatter near-end solution for a zenith-directed lidar data were considered in the study by Sassen and Cho [4]. In our study, an advanced version of this methodology is adopted for multiangle measurements. The first step of the processing procedure, after performing the initial Kano-Hamilton inversion, is the selection of the height h_{up} and determination of the product $[C\beta_{\pi,\Sigma}(h_{up})]$ at this height. This quantity, same as the particulate extinction coefficient, $\kappa_p(h_{up})$, found from the initial inversion, will be used as the input parameters for the next one-directional backscatter near-end solution. The vertical profile of the extinction coefficient, $\kappa_p(h)$, for the heights $h > h_{up}$ will be extracted from the square-range-corrected zenith signal, $P(h)h^2$, measured at these heights. Thus, the height h_{up} is the upper height for the Kano-Hamilton solution, and at the same time, the near-end boundary point for the backscatter solution. The inversion procedure is similar to that in Ref. [4]. Initially the ratio of the square-range-corrected lidar signals within the altitude range from h_{up} to h_{max} is determined,

$$F_{sign}(h) = \frac{P(h)h^2}{P(h_{up})h_{up}^2}. \quad (4)$$

The function $F_{sign}(h)$ is then transformed into another function, $Z(h)$, with the following structure,

$$Z(h) = [C\beta_{\pi,\Sigma}(h)] \exp \left[-2B \int_{h_{up}}^h \beta_{\pi,\Sigma}(h') dh' \right], \quad (5)$$

where B is a constant.

Such a transformation of $F_{sign}(h)$ into $Z(h)$ is achieved by multiplying the function $F_{sign}(h)$ by an auxiliary function $Y(h)$. The issue is that the profile of the required $Y(h)$ is a function of the unknown particulate lidar ratio, $S_p(h)$, within the altitude range from h_{up} to h_{max} . Therefore, the solution in the form in Eq. (5) can only be obtained using the assumption of invariable lidar ratio, $S_p(h) = S_p = \text{const.}$, for all the heights $h > h_{up}$. After taking the condition $B = S_p$, as proposed in [4], the function $Y(h)$ can be written in the form,

$$Y(h) = [C\beta_{\pi,\Sigma}(h_{up})] \exp \left\{ -2(S_p - S_m) \int_{h_{up}}^h \beta_{\pi,m}(h') dh' \right\}, \quad (6)$$

where $S_m = 8\pi/3$ is the molecular lidar ratio.

The ratio of $[C\beta_{\pi,\Sigma}(h)]$ to $[C\beta_{\pi,\Sigma}(h_{up})]$ for the height interval $h_{up} - h_{max}$ can be written as,

$$F_\beta(h) = \frac{Z(h)}{Z(h_{up}) - 2[\kappa_p(h_{up}) + S_p \beta_{\pi,m}(h_{up})] \int_{h_{up}}^h Z(h') dh'}. \quad (7)$$

The particulate extinction coefficient for the heights $h > h_{up}$ can be obtained in the form,

$$\kappa_p(h) = S_p \left\{ F_\beta(h) \frac{[C\beta_{\pi,\Sigma}(h_{up})]}{C} - \beta_{\pi,m}(h) \right\}. \quad (8)$$

Thus, two issues aggravate obtaining the reliable profile of $\kappa_p(h)$ for the heights $h > h_{up}$. First, the solution may be accurate enough only over the height intervals where the lidar ratio, S_p , is constant. Second, for obtaining the most accurate inversion result, the constant C should be somehow determined. Note that if the quantity $\beta_{\pi,\Sigma}(h_{up})$ can be determined accurately from the initial Kano-Hamilton inversion results, the constant can be found as $C = Z(h_{up}) / \beta_{\pi,\Sigma}(h_{up})$.

If the constant C cannot be determined, the solution for $\kappa_p(h)$ can be found with the formula,

$$\kappa_p(h) = F_\beta(h) \kappa_p(h_{up}) \left\{ \frac{\frac{S_p \kappa_m(h_{up})}{S_m \kappa_p(h_{up})}}{1 + \frac{S_p \kappa_m(h)}{S_m \kappa_p(h)}} \right\}. \quad (9)$$

When the molecular component is significantly less than the particulate one, the term in braces is close to unit, accordingly,

$$\kappa_p(h) \approx F_\beta(h) \kappa_p(h_{up}). \quad (10)$$

With the increase of the relative level of the molecular component, the simplified solution in Eq. (10) yields less accurate inversion results.

3. ANALYSES OF SIMULATED AND EXPERIMENTAL DATA

In Fig. 2, the dashed curve is the test profile $[C\beta_{\pi,\Sigma}(h)]$ used in the below simulations; the open circles show the bottom part of this profile within the altitude range from h_{min} to h_{up} , which is obtained from the data of artificial scanning lidar. The lidar operates at the wavelength 355 nm in the synthetic atmosphere where, for the heights $h > h_{up}$, the lidar ratio S_p is equal to 30 sr; the maximum range of the synthetic lidar signal measured in the zenith direction is $r_{max} = 8000$ m.

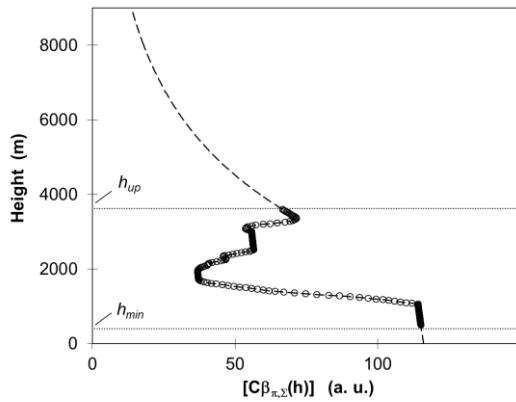


Fig. 2. Test profile $[C\beta_{\pi,\Sigma}(h)]$ used in the simulations (dashed curve) and the bottom part of that (open circles) obtained from the artificial scanning lidar; the height $h_{up} = 3600$ m.

The results of determining the profile of the extinction coefficient $\kappa_p(h)$ with Eq. (8) when the constant C is known are shown in Fig. 3. The model extinction coefficient is shown as the dashed curve; the profiles of the restored $\kappa_p(h)$ when assuming the lidar ratio equal to 20, 30, and 40 sr are shown as dotted, thick and thin solid curves, respectively. One can see that when the constant C is known, the selection of an incorrect S_p significantly shifts the location of the derived $\kappa_p(h_{up})$ from its starting point at h_{up} shown in the figure as the filled circle. Thus, the knowledge of the constant C significantly improves the accuracy of determining the profile of the extinction coefficient for the heights $h > h_{up}$.

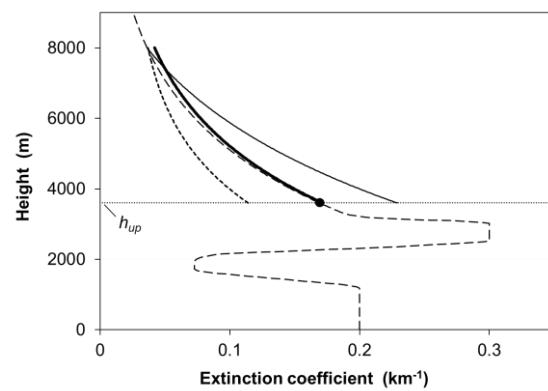


Fig. 3. Test profile $\kappa_p(h)$ used in the simulations (dashed curve) and the extinction coefficient profiles derived with Eq. (8) within the altitude range from h_{up} to $h = 8000$ m

The alternative profiles of the extinction coefficient for the same synthetic atmosphere but obtained with Eq. (10) are shown in Figs. 4 and 5.

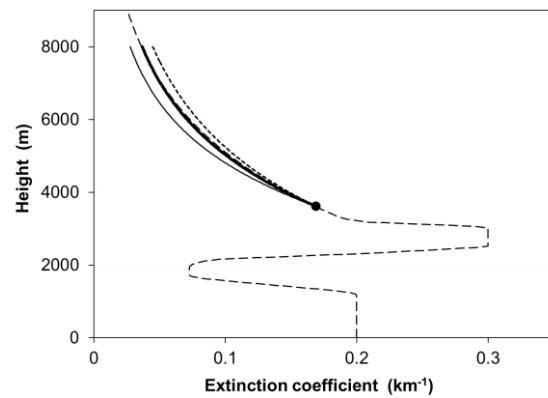


Fig. 4. Dashed curve is the test profile $\kappa_p(h)$ at 532 nm. The profiles derived with S_p equal to 10, 30, and 60 sr are shown as the dotted, thick and thin solid curves, respectively.

The profiles are calculated for the lidar signals, measured at the wavelengths 532 and 355 nm, respectively. The profiles of the extinction coefficient derived at the wavelength 532 nm, where the molecular component is relatively small, do not depend dramatically on the selected lidar ratio S_p . At the wavelength 355 nm, where the level of the molecular component is higher, the unbiased profiles of the extinction coefficient can be extracted only using an extremely restricted scope of the lidar ratios; in particular,

the retrieval can be made using only small values of the lidar ratio, $S_p < 15$ sr. The use of the higher values yields unphysical profiles of the corresponding particulate transmittance.

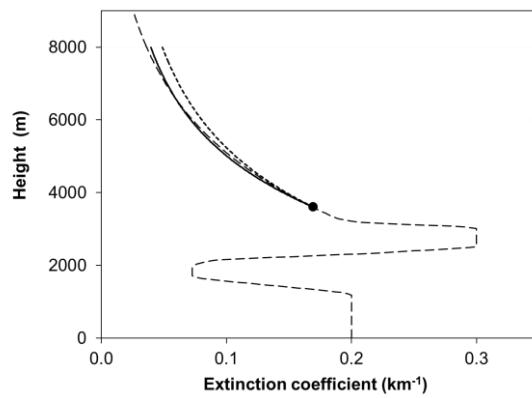


Fig. 5. Same as in Fig. 4 but calculated for the wavelength 355 nm. The profiles derived with S_p equal to 10 and 14 sr are shown as the dotted and solid curves, respectively.

In Figs. 6 and 7, the real lidar signal measured at 355 nm in clear-sky conditions and its inversion result is shown. For deriving the profiles $\kappa_p(h)$ at the heights $h > h_{up}$, the signal measured at $\varphi = 80^\circ$ was used. One can see that the square-range-corrected signal, shown in Fig. 6, monotonically decreases with height, so that the assumption $S_p \approx \text{const.}$ for the altitude interval from 4000 to 10,000 m looks sensible. The inversion results of the scanning lidar data combined with the

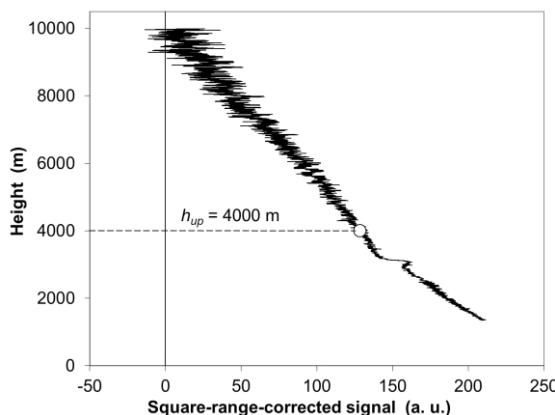


Fig. 6. Square-range-corrected signal measured with scanning lidar close to zenith direction.

backscatter near-end solution are shown in Fig. 7. The profile of $\kappa_p(h)$ derived from the Kano-Hamilton solution is shown as the dashed curve.

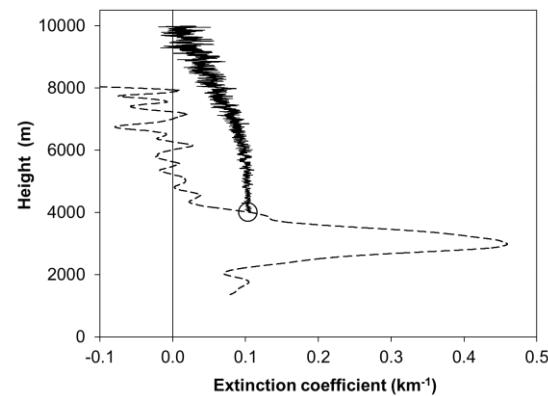


Fig. 7. Inversion results of the scanning lidar data.

The inversion result obtained with the backscatter near-end solution is shown as the solid curve. The analysis shows that the selected $S_p = 15$ sr is most adequate to the optical situation that took place during the lidar signal recordings.

4. SUMMARY

The new measurement methodology is presented which allows using the far-end zenith measured signal of scanning lidar to increase the maximal heights of determining vertical parameters of the searched atmosphere as compared to the classical Kano-Hamilton solution.

REFERENCES

- [1] Kano, M., 1968: On the determination of backscattering and extinction coefficient of the atmosphere by using laser radar, *Papers Meteorol. and Geophys.* **19**, 121-129.
- [2] Hamilton, P. M., 1969: Lidar measurement of backscatter and attenuation of atmospheric aerosol, *Atmos. Environ.* **3**, 221-223.
- [3] Kovalev, V. A., 2015: *Solutions in Lidar Profiling of the Atmosphere*, J. Wiley & Sons Inc., pp. 195-199.
- [4] Sassen, K. and Cho, B. S. 1992: Subvisual-thin cirrus lidar dataset for satellite verification and climatological research, *J. Appl. Meteorol.*, **31**, 1275-1285.