Optimum efficiency lidar sensing of multilayer hydrometeors through a turbid atmosphere

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Abstract. The detected lidar return power is a basic factor determining the brightness of the detected lidar images and the signal-to-noise ratio (SNR) of a given measurement. At equal other characteristics, the laser radiation wavelength should influence the lidar return signal and assume an optimum value depending on the specificity of the objects investigated. As such a problem had not been considered systematically, we recently began developing a modeling approach to solving it, based on evaluating the mean and the noisy lidar profiles and the SNR profile of the measurement along the lidar line of sight by using the lidar equation and well known realistic models of the atmospheric objects and background. The main purpose of the present work is to estimate by numerical modeling the detectability of the lidar return from different distances and multilayer cirrus clouds, depending on the laser radiation wavelengths. The results obtained confirm the expectations that at a higher atmospheric turbidity, a relatively higher sensing efficiency (return power) is achievable by longer-wavelength laser radiation, within the NIR range.

1. Introduction

The lidar remote sensing of the atmosphere is an effective, non-disturbing and large-scale approach to studying the physical and chemical structure, state and dynamics of the atmosphere [1].

The detected lidar-return power is a basic factor determining the brightness and detectability of the “lidar images”, as well as the measurement signal-to-noise ratio (SNR), conditioning in turn the minimum detectable contrast. The corresponding lidar signal depends on the characteristics of the lidar system and the media investigated. At equal other characteristics, the laser radiation wavelength should influence the lidar return signal strength and have some optimum value in this sense, depending on the specificity of the investigated objects. As such a question had been investigated mainly for some concrete specific wavelength pairs [2, 3], rather than considered systematically, we began recently [4] developing a modeling approach to the problem, based on evaluating the mean and the noisy lidar profiles and the SNR profile of the measurement along the lidar line of sight (LOS).

A high atmospheric turbidity is unfavorable in view of express and vast-scale ground-based lidar sensing because of the strong light attenuation. At the same time, the sensing of specific contrasting objects under high-turbidity conditions may be of special research interest. Therefore, the main purpose of this work is to estimate by numerical modeling the possibility of successful sensing of such

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objects, depending on the wavelength of the laser radiation within the UV, VIS and NIR spectral ranges.

2. Basic expressions, approaches and models

2.1. Lidar equation

The optical thickness of the atmospheric layers of interest in this work may exceed unity in some cases. Nevertheless, we shall hereinafter employ the single-scattering lidar equation, assuming corrections performed for the multiple scattering [5], or not so extreme particulate-scattering-due turbidity and a sufficiently small angle of acceptance of the receiving optical system.

The single-scattering elastic lidar equation is convenient to be written in the form [4]

$$N_i(\lambda, z) = \left\{ A/z^2 \right\} \eta(z) C_i \beta(\lambda, z) \exp \left\{ -\frac{2}{n} \mu(\lambda, z) dz \right\},$$

where $\lambda$ is the laser radiation wavelength; $z = ct/2$ is the coordinate of the scattering volume along the LOS, and $t$ is the time period after the pulse emission; $A$ is the receiving aperture area; $\eta(z) = \Omega/(\Omega + A^2z^2)$ is the receiving efficiency function, where $\Omega$ is the solid angle of view of the receiving optical system; $C_i = cE_0S\pi c^2/2e^2$, $c$ is the speed of light, $E_0$ is the laser pulse energy, $S$ [A/W] is current-to-(light)power photodetection sensitivity, $\tau_e$ is the integration (response) time of the receiving electronics, and $e^+$ is the electron charge; $\beta(\lambda, z)$ and $\mu(\lambda, z)$ are the LOS profiles of the atmospheric backscattering and extinction coefficients, respectively; and $N_i(\lambda, z)$ is the number of photoelectrons produced in a photon detector during a $\tau_e$-long interval. In the numerical calculations we assume that $A = \pi 10^2 \text{ m}^2$, $\Omega = \pi 10^8 \text{ sr}$, $E_0 = 750 \text{ mJ}$, $S = 0.5 \text{ A/W}$, and $\tau_e = 5 \text{ ns}$.

2.2. Signal-to-Noise Ratio (SNR)

The SNR of measuring lidar signal profiles may be written as [1]

$$\text{SNR}(\lambda, z) = N_i(\lambda, z) \left\{ N_i(\lambda, z) + N_0(\lambda) + N_i(\lambda) \right\}^{-1/2},$$

where $N_i(\lambda)$ and $N_0$ are the mean numbers of background-due photoelectrons and dark current-due electrons, respectively. Equation (2) is derived [1], assuming Poisson statistics of the photoelectron and dark electron fluctuations. At a dark current of $\sim \pi 10^{-10} \text{ A}$ [6, 7], we obtain that $N_i = 3$ for $\tau_e = 5 \text{ ns}$.

Also, using experimental data [8], at a 2-nm interference filter, realistic values are determined of $N_0 = 302, 437, 221$ and 72 for wavelengths $\lambda = 337.1, 514.5, 694.3$ and 1060 nm, respectively.

2.3. Models of the extinction and backscattering coefficient profiles $\mu(\lambda, z)$ and $\beta(\lambda, z)$

The profiles of $\mu(\lambda, z)$ and $\beta(\lambda, z)$ consist of several components corresponding to the atmospheric molecular and aerosol constituents and strongly scattering compact objects, like clouds, etc. Each of these components has its own extinction and backscattering coefficient profiles, respectively, $\mu_{\text{em}}(\lambda, z)$ and $\beta_{\text{em}}(\lambda, z)$, $\mu_{\text{col}}(\lambda, z)$ and $\beta_{\text{col}}(\lambda, z)$, and $\mu_{\text{ab}}(\lambda, z)$ and $\beta_{\text{ab}}(\lambda, z)$. In turn, $\mu_{\text{em}}(\lambda, z)$, $\mu_{\text{col}}(\lambda, z)$ and $\mu_{\text{ab}}(\lambda, z)$ are sums of the corresponding absorption (index ab) and scattering (index s) coefficients: $\mu_{\text{em}}(\lambda, z) = \mu_{\text{abs}}(\lambda, z) + \mu_{\text{scat}}(\lambda, z)$, $\mu_{\text{col}}(\lambda, z) = \mu_{\text{abs}}(\lambda, z) + \mu_{\text{col}}(\lambda, z)$, and $\mu_{\text{ab}}(\lambda, z) = \mu_{\text{abs}}(\lambda, z) + \mu_{\text{scat}}(\lambda, z)$. The backscattering and extinction (scattering) coefficients are connected by the relations:

$$\beta_{\text{em}}(\lambda, z) = b_{\text{em}}(\lambda, z) \mu_{\text{em}}(\lambda, z), \quad \beta_{\text{col}}(\lambda, z) = b_{\text{col}}(\lambda, z) \mu_{\text{col}}(\lambda, z), \quad \beta_{\text{ab}}(\lambda, z) = b_{\text{ab}}(\lambda, z) \mu_{\text{ab}}(\lambda, z),$$

where $b_{\text{em}}(\lambda, z)$ and $b_{\text{col}}(\lambda, z)$ are the corresponding lidar ratios, and $b_{\text{ab}}(\lambda, z) = 3/8\pi \approx 0.119 \text{ sr}^{-1}$. The ratio $b_{\text{ab}}(\lambda, z)$ is considered here as constant along the vertical, i.e., $b_{\text{ab}}(\lambda, z) = b_{\text{ab}}(\lambda)$. It is estimated at visibilities $S_m$ of 23 km (clear atmosphere) and 5 km (hazy atmosphere), using an empiric procedure [9]. The values obtained for clear atmosphere and $\lambda = 337.1, 514.5, 694.3$ and 1060 nm are 0.023 sr$^{-1}$, 0.032 sr$^{-1}$, 0.041 sr$^{-1}$, and 0.056 sr$^{-1}$, respectively. The corresponding values for hazy atmosphere are...
0.012 sr$^{-1}$, 0.016 sr$^{-1}$, 0.021 sr$^{-1}$, and 0.028 sr$^{-1}$ (see also in [10, 11]). For cirrus clouds we assume that $b_\circ(\lambda, z) = \text{const} = 0.1$ sr$^{-1}$ [1, 5, 12]. The overall optical thickness is

$$Th(\lambda, z) = \int_0^\mu \mu(\lambda, z)dz = \int_0^\mu \mu(\lambda, z)dz + \int_0^\mu \mu(\lambda, z)dz + \int_0^\mu \mu(\lambda, z)dz.$$

(4)

2.3.1. Clear and hazy atmosphere. For an atmosphere without clouds we have $\mu(\lambda, z) = \mu(\lambda, z) + \mu(\lambda, z)$ and $\beta(\lambda, z) = \beta(\lambda, z) + \beta(\lambda, z)$, where the profiles $\mu(\lambda, z)$ and $\mu(\lambda, z)$ are basic for the numerical modeling and analysis. Realistic data concerning these profiles are taken from a report of McClatchey et al. [11], where the vertical sampling interval is 1 km and more. The cases of midlatitude clear and hazy atmospheres are considered corresponding to visibilities of 23 and 5 km [11]. For convenience, the data profiles are approximated here by simple analytical expressions:

$$\mu(\lambda, z) = \sum_0^\mu \mu(\lambda, z) / \left[1 + \exp \left((z - z_0(\lambda))/w(\lambda)\right)\right];$$

(5)

where $p = e$ or $s$ when $q = m$, and $p = e$ when $q = a$; $A(\lambda, z)$, $z_0(\lambda)$, and $w(\lambda)$ are best-fit least-squares approximation parameters. The values obtained of the parameters $A$, $z_0(\lambda)$, and $w(\lambda)$ are given in table 1. The model data [11] for $\mu = \mu(\lambda, z)$ and $\mu = \mu(\lambda, z)$ along with the corresponding approximating curves in the case of hazy atmosphere and wavelength 514.5 nm are illustrated in figures 1a and 1b, respectively.

| Medium | $\lambda$ [nm] | $A_\text{em}$ [m$^{-1}$] | $z_0\text{em}$ [m] | $w_\text{em}$ [m] | $A_\text{sm}$ [m$^{-1}$] | $z_0\text{sm}$ [m] | $w_\text{sm}$ [m] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Clear           | 337.1           | 1.1391E-4       | 4768.6191       | 6015.5248       | 3.20757E-4       | 901.34287       | 876.44783       |
| Atmosphere      | 514.5           | 3.11541E-5      | -377.72112      | 6654.69124      | 2.29634E-4       | 912.98854       | 895.10918       |
| Atmosphere      | 694.4           | 1.09915E-4      | 849.40119       | 1533.79435      | 1.76006E-4       | 890.48116       | 903.22858       |
| 23km visibility  | 8.72106E-6      | 139.1284        | 6555.60679      | 6777.02863      | 1.21505E-4       | 878.65179       | 906.27013       |
| Hazy            | 1060            | 1.64867E-6      | 46.13384        | 6577.02863      | 1.21505E-4       | 878.65179       | 906.27013       |
| Atmosphere      | 514.5           | 3.11541E-5      | -377.72112      | 6654.69124      | 0.00107          | 876.50855       | 738.06736       |
| 5km visibility   | 694.4           | 1.09915E-4      | 849.40119       | 1533.79435      | 9.17684E-4       | 611.12836       | 819.11022       |
| Hazy            | 1060            | 1.64867E-6      | 46.13384        | 6577.02863      | 9.39205E-4       | 202.60498       | 1169.59388      |

Table 1. Parameters of the curves approximating the vertical extinction profiles in clear and hazy atmosphere.

Parameters of the curves approximating only the molecular scattering profiles.

$b_\circ = A_\text{em} z_0\text{em} = z_0\text{em} w_\text{em}$, and $w_\text{em} = w_\text{em} at \lambda = 514.5$ and 1060 nm.

2.3.2. Clouds in the atmosphere. In the presence of clouds we have $\mu(\lambda, z) = \mu(\lambda, z) + \mu(\lambda, z) + \mu(\lambda, z)$ and $\beta(\lambda, z) = \beta(\lambda, z) + \beta(\lambda, z)$. The additional terms $\mu(\lambda, z)$ and $\beta(\lambda, z)$ describing the contribution of clouds may be modelled as superpositions,

$$\mu(\lambda, z) = \sum_0^\mu \mu(\lambda, z)$$

and $\beta(\lambda, z) = \sum_0^\mu \beta(\lambda, z)$, of bell-shaped modes

$$\mu(\lambda, z) = \sum_0^\mu \mu(\lambda, z) \beta(\lambda, z) / \beta(\lambda, z) \beta(\lambda, z) = [1 + (z - z_0) / \beta(\lambda, z)]^1$$

(6)
that are symmetric with respect to the corresponding positions $z_{0j}$ of their peak values $\mu_{ec}(\lambda, z_{0j})$ and $\beta(\lambda, z_{0j})$ and have characteristic widths $w_{ci}$; $p$ is some integer. We have considered here such a threefold cirrus cloud model with mode parameters: $z_{01} = 7500$ m, $\mu_{ec,1}(\lambda, z_{01}) = \mu_{ec,1}(z_{01}) = 0.5 \times 10^{-1}$ m$^{-1}$, and $w_{c,1} = 400$ m; $z_{0,2} = 8500$ m, $\mu_{ec,2}(\lambda, z_{0,2}) = \mu_{ec,2}(z_{0,2}) = 1 \times 10^{-3}$ m$^{-1}$, and $w_{c,2} = 250$ m; and $z_{0,3} = 9500$ m, $\mu_{ec,3}(\lambda, z_{0,3}) = \mu_{ec,3}(z_{0,3}) = 0.35 \times 10^{-3}$ m$^{-1}$, and $w_{c,3} = 150$ m. The value chosen of $p$ is 4. When considering cirrus clouds, we assume that their extinction and backscattering coefficients do not depend on the laser wavelength within the UV, VIS and NIR spectral ranges [12]. Physically, this is due to the much larger size of the scattering ice particles compared to the wavelength.

Figure 1. Model data and approximating curves for the molecular (a) and aerosol (b) extinction coefficients in hazy atmosphere at $\lambda = 514.5$ nm.

3. Numerical results and discussion of $N_s$ and SNR profiles obtained under different atmospheric conditions and laser wavelengths

All the models and approximations, equations, and concrete values of characteristic parameters described in section 2, as well as some expressions obtained in [4], were employed to evaluate and model profiles of the lidar return signal $N_s(\lambda, z)$ and the corresponding SNR$(\lambda, z)$ from clear and hazy atmospheres containing multilayer cirrus cloud structures. In figure 2, one can see the graphs of the lidar signal profiles from clear and hazy atmospheres with a three-layer cirrus cloud. In figure 2a it is seen that the signal from the space below the cloud is determined mainly by the process of backscattering, because at relatively low turbidity the influence of the attenuation is not so essential. Then, the signal is stronger at shorter wavelengths. The signal from the cloud zone however is stronger at longer wavelengths because of the lower attenuation at these wavelengths. At wavelengths $\lambda = 514.5$

Figure 2. Lidar profiles from clear (a) and hazy (b) atmosphere containing a three-layer cloud field.
and 694.3 nm, the signals are comparable because of the comparable attenuation. Above the cloud zone, the backscattering again becomes determinant and the shorter sensing wavelengths provide the stronger signals. If the analog detection threshold is \( N_N = N_{\text{th}} = 1000 \) (32 nA photocathode current), the aerosol stratification is detectable in analog mode up to \( z = 4 \) km.

The main fragments of the cloud are well detectable at \( \lambda = 1060 \) nm, and hardly, at \( \lambda = 514.5 \) and 694.3 nm. The detection of clouds through hazy atmosphere is illustrated in figure 2b. It is seen that the signals from the clouds at longer wavelengths are many times higher than those at shorter wavelengths. Besides, large intervals of altitudes appear, below the cloud field, from where the longer wavelengths (694.3 and especially 1060 nm) provide the highest return signals. These are the intervals where the aerosol optical thickness is mainly formed (see also in [3]).

The SNR profiles for clear and hazy atmospheres have a similar run as those of \( N_N(z) \). A minimum of about 3% signal variations is detectable, through clear atmosphere, from all the cloud layers at \( \lambda = 1060, 694.3 \) and 514.5 nm. In a hazy atmosphere, such variations are detectable only at \( \lambda = 1060 \) nm. Thus, the NIR wavelengths are advantageous for sensing cirrus clouds through a hazy atmosphere.

4. Conclusions

Using an approach we formulated recently, we investigated the efficiency of detecting multilayer cirrus clouds by elastic lidar, through clear (23 km visibility) and hazy (5 km visibility) atmospheres, depending on the sensing lidar radiation wavelength. The approach consists in modeling realistically the lidar signal and SNR profiles at wavelengths in the UV, VIS and NIR spectral ranges. Thus, we determined the optimum sensing wavelengths that ensure maximum signal and SNR levels and, respectively, maximum measuring and imaging sensitivity, accuracy and contrast. We showed that below the cloud base in a clear atmosphere, the shorter wavelengths are advantageous in the above sense because of the stronger (back)scattering and the weak attenuation. Because of the lower attenuation, however, the cloud fields are better detectable by the longer wavelengths. As the atmospheric turbidity increases in a hazy atmosphere, the advantages of the shorter wavelengths decrease and even vanish below the cloud base, because of the increased attenuation. In this case, the cloud layers are still relatively better imaged by the longer wavelengths.

The investigations will be continued with computer simulations of noisy profiles and statistical data processing, illustrating the wavelength influence under various atmospheric conditions.

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