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Effects of intrinsic fluorescence on biological aerosols detection accuracy of lidar

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ABSTRACT

The objective of this work was to investigate the effects of intrinsic fluorescence on the detection capability for biological aerosols of an UV fluorescence lidar with selected design parameters. Numerical simulations, based on the fluorescence lidar equation, were performed for fluorescence spectra ranging from 300 nm to 800 nm, where the fluorescence was induced by a pulsed laser at 266 nm. Simulation results show that the minimal detectable concentration of biological aerosols increases with detection range at different rates for different solar zenith angles, and that the uncertainties of the minimal detectable concentrations increase sharply with ranges. Lowest concentrations of biological aerosols are expected to be detectable during the night. In the day-time, aerosols emitting intrinsic fluorescence wavelengths are expected to be detectable at larger distances, with a relatively large uncertainty of the minimal detectable concentration.

1. Introduction

These decades, driven by healthy, environmental, agricultural, and defensive concerns, have been growing interests in lidar that offers the capabilities of detecting and analyzing biological aerosols in real-time. A wide variety of biological aerosol particles with the diameters ranging from 0.001 μm to 100 μm, such as bacteria, fungal, pollens, viruses and algae are dispersed in the atmosphere. The particles can directly affect human, animal and plant health [1] as well as indirectly influence the weather conditions, as they may act as ice nuclei (IN) and cloud condensation nuclei (CNN) [2–4]. Biological aerosols tend to absorb more light than most of inorganic aerosols, especially at short wavelength levels, thereby heating and cooling of the atmosphere [5]. It was estimated that the number concentrations of biological aerosol particles remain at around 30% as the environmental and seasonal changes in the atmosphere [6,7]. Moreover, there is an enormous range of biological aerosol particle mass concentrations of about 55–95% in the tropics [8,9].

Intrinsic fluorescence is an important basis to discriminate biological aerosols from non-biological aerosols [10]. In principle, fluorescent effects of biological aerosols could be induced by ultraviolet (UV) laser, while most of the non-biological aerosols could not be, and different types of biological aerosols have their own absorption and emission spectra. Ultraviolet absorption and fluorescence emission peaks of biological aerosols were explored, and found that there is an obvious difference fluorescence wavelength peak with the same excitation wavelength level [11]. Thus, we could easily classify different types of biological aerosols based on the intensity of the fluorescence spectrums [12]. Furthermore, research on the verification of a LIF-LIDAR technique for stand-off detection and classification of biological agents, indicate that the laser induced fluorescence lidar was able to measure biological aerosols up to a distance of 700 m [13]. UV laser induced fluorescence lidar, as a power tool with a real-time and high spatial resolution [14], has a good prospect in the field of the atmospheric biological aerosol detection.

In this work, an ultraviolet laser induced fluorescence lidar was designed to investigate the effects of intrinsic fluorescence on biological aerosol detection. Based on the chosen design specifications of a fluorescence lidar, we performed numerical simulations to evaluate its detection capabilities for different concentrations of biological aerosol particles. The minimal detectable concentrations of the system were also evaluated under different fluorescence wavelength levels. In addition, we further estimated the errors of the minimal detectable concentrations at different solar zeniths and nighttime operation, respectively.

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2. Principle of laser induced biological aerosols fluorescence lidar

2.1. Fluorescence

Fluorescence is the spontaneous emission of a photon following excitation into an excited state by absorption of incident light at a frequency within a specific absorption line or band of molecules. The re-emitted light measured at the appropriate frequency, is useful for identifying the molecular species responsible for the fluorescence. It has a longer wavelength and lower energy than the absorbed light in general. Most of biological materials contain natural fluorophores, which include aromatic amino acids (such as tryptophan, tyrosine and phenylalanine), NADH, riboflavin and chlorophyll, and they show strong absorption bands in the spectral region ranging from 260 nm to 380 nm and emitting bands ranging from 300 nm to 800 nm, which can be used as characteristic tracers of their biological nature.

2.2. UV-LIF lidar

Since most aerosols are non-biological particles suspended in the atmosphere, it is hard to identify the relatively low concentrations those with biological origin. An established identification method uses aerosol fluorescence in the 300–800 nm spectral range [15], as in contrast to biological aerosols, non-biological particles emit practically no fluorescent light when irradiated with an UV laser.

Fluorescence lidar based on the fluorescent effects induced by UV lasers, is capable of detecting the concentrations of biological aerosols effectively. UV laser pulses are emitted into the atmosphere, and then interact with the biological aerosols (if exist). The fluorescence signals are collected and further analyze to obtain various physics-chemical information of the biological aerosols. A conceptual configuration of ultraviolet laser induced fluorescence lidar for the rapid detection of biological aerosol concentrations in the atmosphere is shown in Fig. 1.

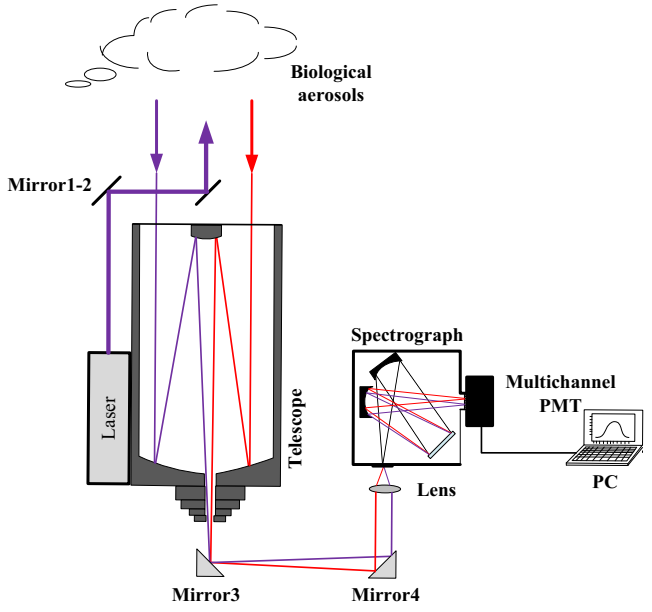

Fig. 1. A conceptual configuration of ultraviolet laser induced fluorescence lidar.

3. Numerical modeling

The number of photons in the fluorescence lidar return $N(\lambda_1, R)$ was simulated using the fluorescence lidar equation [16], which describes the characteristics of biological aerosol detection and the principles of laser induced fluorescence lidar,

$$N(\lambda_1, R) = n_0 \frac{E_0 \lambda_0}{hc} \frac{A_0}{R^2} \xi(R) \eta_0 \Delta R N(R) T_{\lambda 0} T_{\lambda 1} T(\lambda_0, R) T(\lambda_1, R) \times \int_{\lambda_1 - \frac{\Delta\lambda}{2}}^{\lambda_1 + \frac{\Delta\lambda}{2}} \frac{d^2\sigma}{d\Omega d\lambda}(\lambda_1, \lambda) d\lambda, \quad (1)$$

where n_0 is the pulse count, E_0 the laser pulse energy, λ_0 the excitation wavelength, λ_1 the fluorescence wavelength, h the Planck's constant, c the velocity of light, A_0 the received area of telescope, R the cloud distance, $\xi(R)$ the overlap factor, η_0 the detection efficiency, ΔR the cloud depth, $N(R)$ the concentration of biological aerosol particles, $T_{\lambda 0}$, $T_{\lambda 1}$ the optical transmittance of excitation wavelength and fluorescence wavelength, respectively, and $T(\lambda_0, R)$, $T(\lambda_1, R)$ the atmospheric attenuation, respectively, $d^2\sigma/d\Omega d\lambda(\lambda_0, \lambda)$ is the differential scattering cross-section,

$$\frac{d^2\sigma}{d\Omega d\lambda}(\lambda_0, \lambda) = \frac{\Psi(\lambda_0) A_1}{4\pi} L(\lambda_0, \lambda), \quad (2)$$

where $\Psi(\lambda_0)$ is the quantum yield of fluorescence, A_1 the average of effect area, $\Delta\lambda_1$ the full half-high width of characteristic line, the

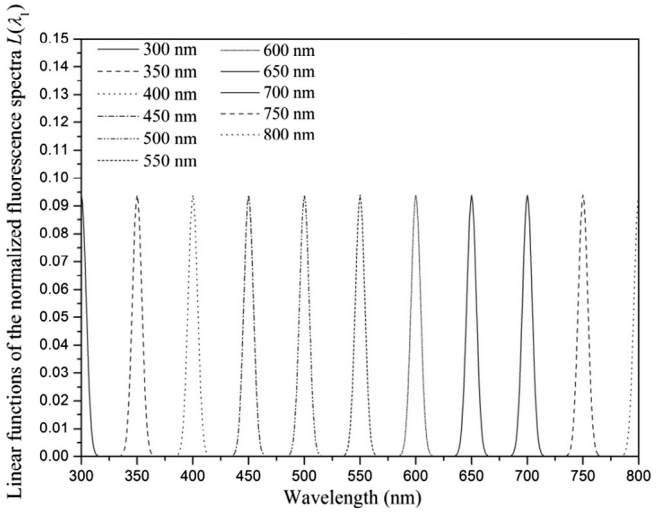

Fig. 2. The linear functions of normalized spectra from 300 nm to 800 nm with a maximum value of 0.094 to any fluorescence wavelength.

Table 1
The main parameters of the fluorescence lidar.

E_0	Pulse energy (mJ)	60
λ_0	Excitation wavelength (nm)	266
λ_1	Fluorescence wavelength (nm)	300–800
$\Delta\lambda$	Filter bandwidth (nm)	20
f	Pulse repetition frequency (Hz)	10
A_0	Received area of telescope (m^2)	0.051
θ	Field of view (mrad)	0.5
A_1	The average of effect area (m^2)	1×10^{-12}
ΔR	Cloud depth (m)	20
η_0	Quantum efficiency of the detector	0.2
$T_{\lambda 0}$	Transmission of laser emission optical train	0.8
$T_{\lambda 1}$	Transmission of receiving optical train	0.3
$\Delta\lambda_1$	Full half-high width of characteristic line (nm)	10
$\Psi(\lambda_0)$	Quantum yield of fluorescence	0.1
CSP	Dark noise current (s^{-1})	500