Elastic-lidar wavelength-dependent detectability of dense aerosol objects through clear and hazy atmospheres

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EGU General Assembly Vienna | Austria | 7–12 April 2019

Introduction

The laser radiation wavelength is one of the factors that may influence the strength of the elastic-lidar return signal from clear and hazy atmospheres, either in the presence or in the absence of specific dense aerosol objects, such as cirrus clouds, Saharan dust or volcanic ash layers, etc. At a stronger signal and, respectively, higher measurement signal-to-noise ratio (SNR), the images of characteristic features along the lidar line of sight (LOS), including dense aerosol objects, would be, in general, brighter and clearer and better detectable.

To reveal purposely and systematically the role of the sensing laser wavelength, at equal other factors, in achieving good images by elastic lidar, we recently began developing an approach consisting in numerical and statistical modeling, comparison and analysis of single-scattering mean lidar and SNR profiles and the corresponding noisy profile estimates obtained at different sensing wavelengths. The signal and background fluctuations are generated as due to the prevailing Poisson shot noise.

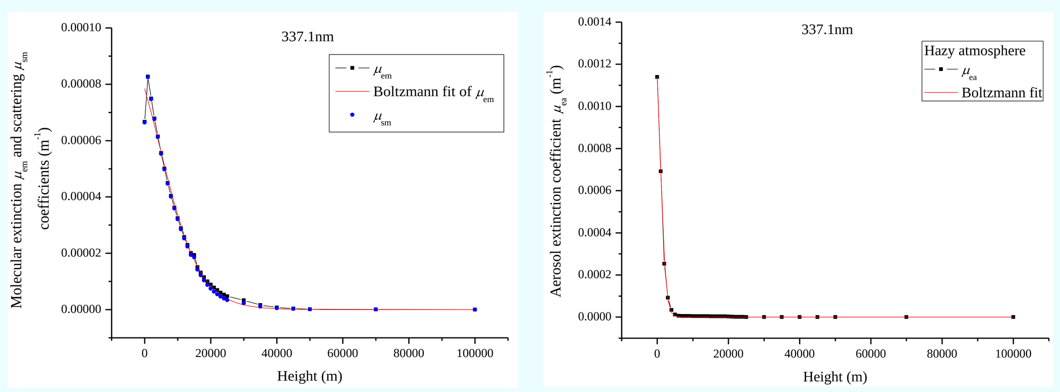
The **purpose of this work** is to demonstrate the performance and efficiency of the above-mentioned investigatory approach by applying it to aerosol stratification models of clear (23 km visibility) and hazy (5 km visibility) atmospheres containing simultaneously structures resembling a Saharan-dust layer and a cirrus cloud. The sensing radiation wavelengths considered belong to the UV (337.1 nm), VIS (514.5 nm), and NIR (1060 nm) spectral ranges.

Basic Equations and Models	Formula	Parameters
Single-Scattering Lidar Equation	$N_s(\lambda,z)=(A/z^2)\eta(z)C_L\beta(\lambda,z)\exp\left\{-2\int_0^z\mu_e(\lambda,z')dz'\right\}$	λ - laser radiation wavelength $z = ct/2$ coordinate of the scattering volume along the line of sight t - time period after the pulse emission A - receiving aperture area $C_L = cE_0S\tau_e/2e^-$, c is the speed of light, E_0 is the pulse energy, S is current-to-power detection sensitivity, τ_e is the integration (response) time of the receiving electronics, and e^- is the electron charge $\eta(z) = \Omega/(\Omega+A/z^2)$ - receiving efficiency function, Ω is the solid angle of view of the receiving optical system $\beta(\lambda, z)$ - line-of-sight profile of the atmospheric backscattering coefficient $\mu_e(\lambda, z)$ - line-of-sight profile of the atmospheric extinction coefficient $N_s(\lambda, z)$ - number of photoelectrons produced in a photon detector during a τ_e-long interval
Signal-to-Noise Ratio	$SNR(\lambda,z)=\xi N_s(\lambda,z)\left\{\xi F\left[N_s(\lambda,z)+N_b+N_d\right]\right\}^{-1/2}$	ξ - the photomultiplier photoelectron collection ability F - the noise excess factor $N_b(\lambda)$ - mean number of background-due photoelectrons N_d - mean number of dark current-due electrons
Clear and Hazy Atmosphere	$\mu_{pq}(\lambda,z)=A_{pq}(\lambda)/\left\{1+\exp\left[(z-z_{0,pq}(\lambda))/w_{pq}(\lambda)\right]\right\}$	A_{pq}, $z_{0,pq}$, and w_{pq} - best-fit least-squares approximation parameters p ≡ e or s when q = m p ≡ e when q = a e - extinction, s - scattering, m - molecular and a – aerosol
Saharan Dust Layer / Cirrus Clouds	$\mu_{e,sd(c)}(\lambda,z)/\mu_{e,sd(c)}(\lambda,z_0)=\beta_{sd(c)}(\lambda,z)/\beta_{sd(c)}(c)(\lambda,z_0)=[1+(z-z_0)^p/w^p_{sd(c)}]^{-1}$	$\mu_{e,sd(c)}(\lambda, z_0)$ and $\beta_{sd(c)}(\lambda, z_0)$ - peak values of the bell-shaped modes symmetric with respect to the position z_0, for a Saharan dust layer (sd) and/or a cirrus cloud (c) $w_{sd(c)}$ - characteristic width p - integer equal to 4

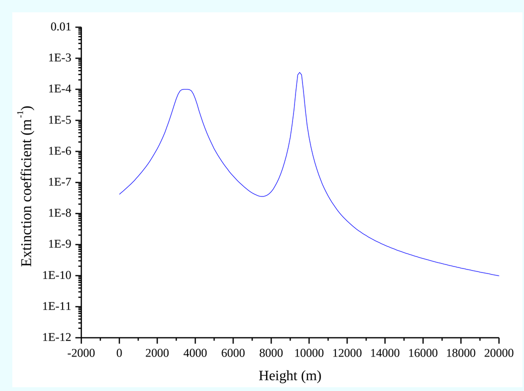
Parameter	Value			
	Case 1		Case 2	
A	$\pi 10^{-2}$ m^2		$\pi 10^{-2}$ m^2	
Ω	$\pi 10^{-6}$ sr		$\pi 10^{-6}$ sr	
E_0	30mJ		750mJ	
S	0.5A/W		0.5A/W	
τ_e	1ns		5ns	
N_d	3 (at a dark current of 5×10^{-10}A)		3 (at a dark current of ~10^{-10}A)	
N_b	302, 437 and 72 (at λ = 337.1, 514.5 and 1060nm for 10-nm interference filter)		302, 437 and 72 (at λ = 337.1, 514.5 and 1060nm for 2-nm interference filter)	
$z_{0,sd}$ $z_{0,c}$	3500m 9500m		3500m 9500m	
w_{sd} w_c	500m 150m		500m 150m	
$\mu_{e,sd}(\lambda, z_0)$ $\mu_{e,c}(\lambda, z_0)$	0.1.10^{-3}m^{-1} 0.075.10^{-3}m^{-1} 0.35.10^{-3}m^{-1}		0.1.10^{-3}m^{-1} 0.075.10^{-3}m^{-1} 0.35.10^{-3}m^{-1}	
$b_{sd}(\lambda, z)$ $b_c(\lambda, z)$ $b_m(\lambda, z)$	0.025sr^{-1} 0.02sr^{-1} 0.03sr^{-1} 0.1sr^{-1} 0.119sr^{-1}		0.025sr^{-1} 0.02sr^{-1} 0.03sr^{-1} 0.1sr^{-1} 0.119sr^{-1}	
$b_a(\lambda, z)$ λ = 337.1nm λ = 514.5nm λ = 1060nm	**Clear** 0.023sr^{-1} 0.032sr^{-1} 0.056sr^{-1}	**Hazy** 0.012sr^{-1} 0.016sr^{-1} 0.028sr^{-1}	**Clear** 0.023sr^{-1} 0.032sr^{-1} 0.056sr^{-1}	**Hazy** 0.012sr^{-1} 0.016sr^{-1} 0.028sr^{-1}

Results

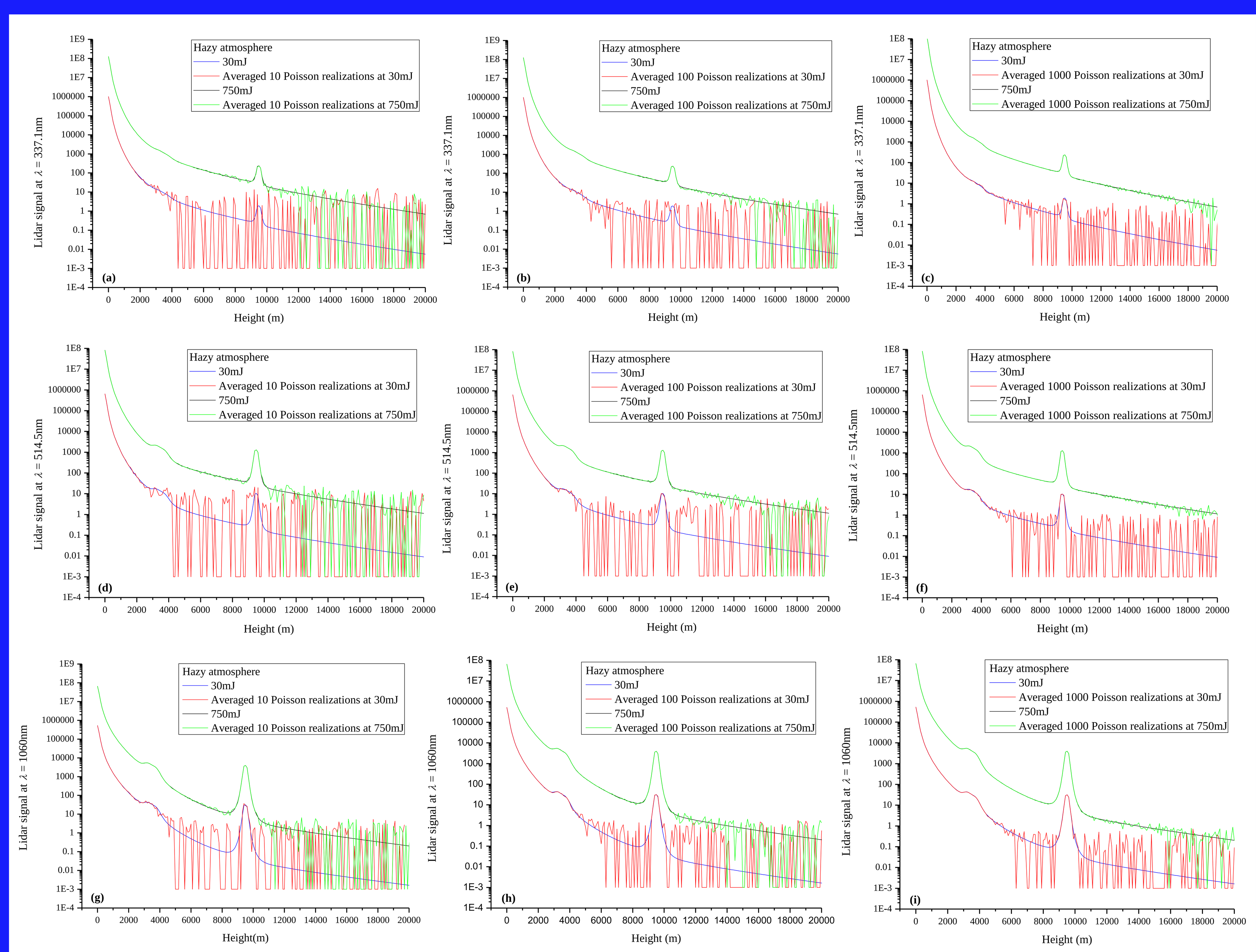
Model data for the molecular and aerosol extinction coefficients in hazy atmosphere at λ = 337.1nm and the corresponding approximating curves



Extinction coefficient profile of a Saharan dust layer and a cirrus cloud



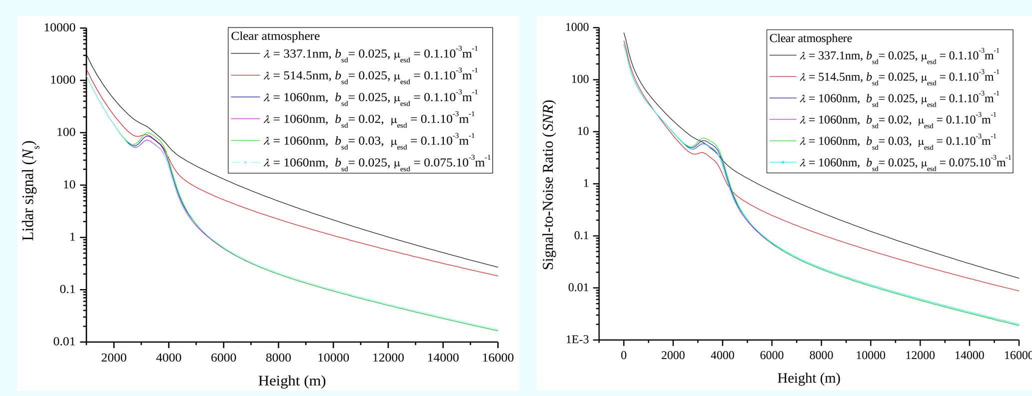
Mean lidar signal profiles at pulse energies of 30mJ and 750mJ, and the corresponding Poisson-fluctuating profiles averaged over 10, 100, and 1000 realizations, at λ = 337.1, 514.5 and 1060nm and a hazy atmosphere containing a Saharan dust layer and a cirrus cloud



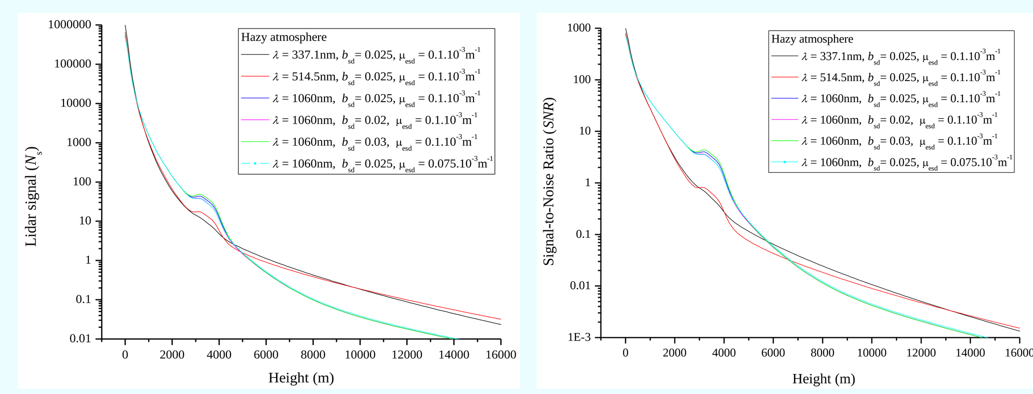
Results

Lidar signal and SNR profiles at E_0=30mJ from clear and hazy atmospheres containing a Saharan dust layer

Clear

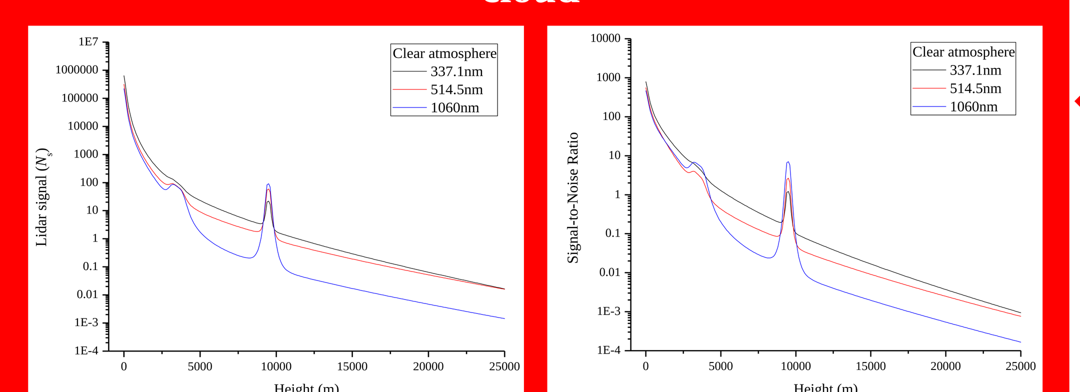


Hazy



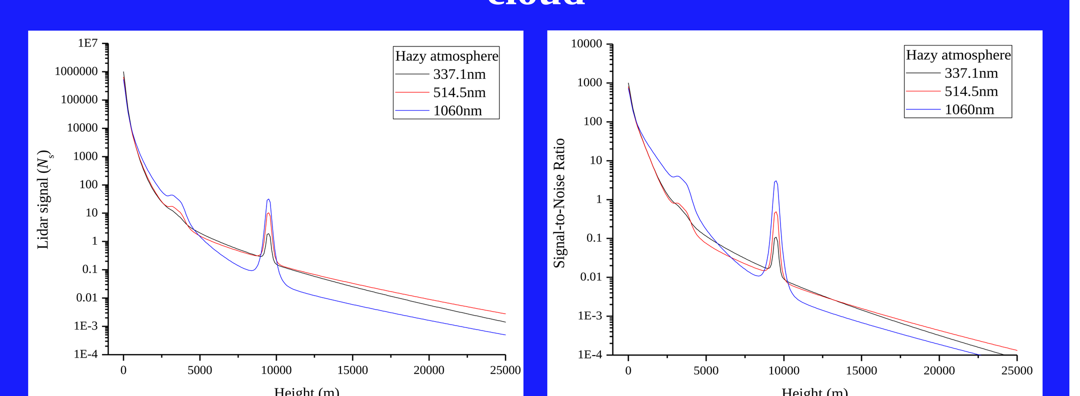
Results

Lidar signal and SNR profiles at E_0 = 30mJ from a clear atmosphere containing a Saharan dust layer and a cirrus cloud

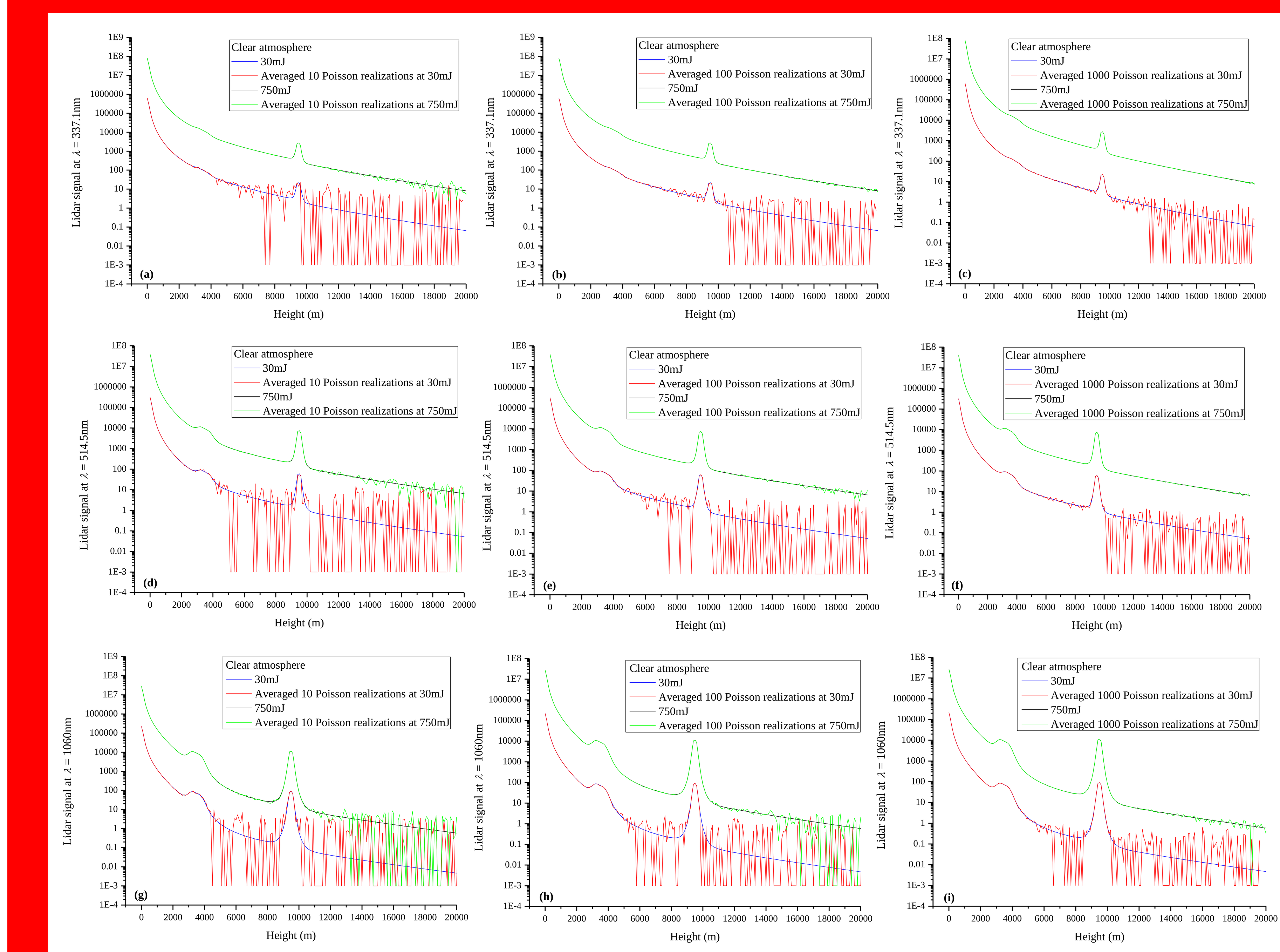


Results

Lidar signal and SNR profiles at E_0 = 30mJ from a hazy atmosphere containing a Saharan dust layer and a cirrus cloud



Mean lidar signal profiles at pulse energies of 30mJ and 750mJ, and the corresponding Poisson-fluctuating profiles averaged over 10, 100, and 1000 realizations, at λ = 337.1, 514.5 and 1060nm and a clear atmosphere containing a Saharan dust layer and a cirrus cloud



Conclusion

An approach is developed to evaluating the atmospheric elastic lidar sensing efficiency, depending on the lidar radiation wavelength.

The results obtained show:

- **Shorter (UV) wavelengths** are advantageous in clear atmosphere due to stronger backscattering and lower extinction. In a hazy atmosphere their advantage decreases and even vanishes at some altitudes, because of the additional increase in the attenuation.
- **Longer (NIR) wavelengths** ensure better detectability (brightest, clearest and most contrasting image) of relatively larger-particle aerosol objects (cirrus clouds and Saharan dust layers) because of the lower optical background, lower attenuation and backscattering outside of the object and the nearly wavelength-independent attenuation and backscattering inside the object.
- **The SNR** of detecting dense objects is maximum when using **NIR wavelengths** and an acceptable image quality is achievable at a smaller statistical volume and not so severe smoothing along the LOS, thus ensuring better temporal and spatial sensing resolutions.

Acknowledgements

This research is funded by the Bulgarian Academy of Sciences (BAS) Program for supporting young scientists and PhD students in BAS – 2017, under the project "Optimal effective elastic lidar sensing of aerosol atmosphere containing strongly scattering compact objects" (Contract No DFNP-17-4/24.07.2017). A partial financial support from the Bulgarian Ministry of Education and Science under grant D01-151/28.08.2018 is also acknowledged.