# Essentials of LIDAR multiangle data processing methodology for smoke polluted atmospheres

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**Abstract** Mobile scanning lidar is the most appropriate tool for monitoring wildfire smoke-plume dynamics and optical properties. Lidar is the only remote sensing instrument capable of obtaining detailed three-dimensional range-resolved information for smoke distributions and optical properties over ranges of 10+ km at different wavelengths simultaneously.

Lidar allows continuous monitoring of smoke-polluted atmospheres, providing information about diurnal and spatial variation of aerosol properties, plume heights and dynamics, as well as direction and rate of smoke plume movement in near real-time. It is a prospective instrument for monitoring downdrafts, which transport the smoke particulates downward, worsening air quality at ground level.

The two-wavelength lidar, developed at The Fire Sciences Laboratory (Missoula, MT, USA) utilizes two ways for data processing, specified here as Program 1 and Program 2. Program 1 is used to study the dynamics of smoke layering and plumes and investigate changes of their heights in time and space at the 1064 nm wavelength. With this program, no lidar signal inversion into the optical parameters is made. Program 2 is used to extract the optical parameters of the atmosphere from signals measured at the 355 nm wavelength. With Program 2, signal inversion yields vertical profiles for the smoke particulates' optical depth, the extinction coefficient profile, and the lidar ratio. This program is used to investigate optical characteristics of smoke particulates in the vicinity of wildfires.

## Essentials of investigating smoke-layering and smoke-plume dynamics using Program 1

Smoke plumes exhibit large temporal and spatial changes in their concentration, especially in areas of their boundaries. To study smoke plume dynamics, the regions with high level of smoke backscattering must be separated from regions of clear atmosphere, and the distance from the lidar to the smoke-plume boundaries should be established. However, the use of an automated method to determine such boundaries is always an issue. The exact boundary of any heterogeneous layer is not well specified, and a large amount of interpretation is generally involved in the determination of, for example, the boundary layer or the cloud height. Different methodologies have been proposed to discriminate layering with increased particulate loading. In all methods, the shape of the lidar signal is analyzed, and a sharp increase or decrease in the backscatter signal intensity is considered a boundary of the aerosol plume, the cloud, or the boundary layer.

When analyzing our experimental data from smoke-polluted atmospheres, we commonly observed the strong diffusion of smoke plumes at distant ranges. This dramatically reduced the intensity and gradients of the backscatter-signal at the smoke boundaries, impeding their reliable determination. Moreover, analysis shows that false spikes, originated by noise at the far-end of the range-corrected signal, often mask the slight changes in the backscattering at the smoke-plume edges, making it impossible to discriminate them. This forced us into looking for alternative methods that would provide an increased gradient of the analyzed function at the edges of smoke plumes.

Two methods were developed for our lidar operating in the multiangle mode. In study [1], a method for automatic determination of the near-edge boundaries of smoke plumes was proposed for the scanning lidar that performs an azimuthal scan at a fixed slope direction. A special ratio function provided increased gradients at the near-edge of the smoke, as well as strong suppression of false noise spikes over the far end of the measurement range.

Recently we proposed a new principle for identifying smoke plume and layer heights for lidar that operates in a vertical scanning mode [2]. This methodology allows for creating the atmospheric Heterogeneity Height Indicator (HHI), which shows all heights at which the smoke plume heterogeneity was detected by vertically scanning lidar. HHI allows one to determine the heights of smoke plumes and layers and their temporal changes using data from the whole vertical scan, that is, using the information obtained for the whole area searched by a scanning lidar. The determination of the smoke boundaries is made through specifying the number of heterogeneity events, that is, the number of cases when the increased gradient is revealed at different heights. The HHI plot allows easy distinguishing between a vertically developing smoke plume and a horizontally stratified smoke layer created by a morning inversion. It makes it possible to identify smoke plume vertical boundaries and their temporal changes using automated data processing.

## Essentials of the investigation of the stratified-smoke-layering optical properties using Program 2 of the data processing

Our consideration of the multiangle mode with Program 2 is restricted by analysis of the Kano-Hamilton multiangle method [3, 4]. This method allows for calculating the particulate extinction coefficient from elastically scattered signals without an a priori selection of the particulate extinction-to-backscatter (lidar) ratio.

Program 2 for the Kano-Hamilton method of the multiangle data processing can be utilized only under favorable conditions, sometimes only from lidar data obtained from restricted areas. This method requires the condition of a measurable difference for the optical depths under different slope directions. In clear atmospheres, this requirement can be met only if the lidar operates at short wavelengths where the molecular and particulate extinction coefficients are at least comparable. Therefore, for processing data with Program 2, only the lidar signals measured at 355 nm are used. These signals yield much more accurate inversion results than signals measured at longer wavelengths.

Distortions in the measured lidar signal are a significant issue with multiangle measurements [5]. Systematic distortions in experimental data can be a significant source of large measurement uncertainties. The near-end distortions may occur due to inaccuracies in determining the length of the incomplete overlap zone, low-frequency noise components in the signal, distortions due to the restricted frequency range of the photoreceiver, and receiving optics aberrations. Another type of systematic distortions in lidar data is found in the signal offset that remains after subtraction of the signal background component. These distortions are extremely influential over distant ranges, where the useful signal is always determined as a small difference of two large quantities.

### ***Specifics of the signal offset subtraction***

Even a minor shift remaining in the lidar signal after the subtraction of the estimated offset can result in significant systematic distortions in the inversion results, especially when the lidar operates in multiangle mode. To improve measurement accuracy, we developed a new principle for determining the total offset in the lidar signal created by a daytime background-illumination and electrical or digital offsets [6]. The analysis made using both the new and conventional techniques for accounting the offset in lidar signals can allow proper estimates for the upper and lower uncertainty limits in the retrieved optical depth in the multiangle measurement.

### ***Specifics of the optical depth retrieval***

Before the optical depth profile can be extracted from multiangle measurements, the examination of the systematic and random distortions in the inversed data should be performed. The knowledge of the distortions is required for determining the minimum and maximum ranges and heights within which the level of the measurement uncertainty is acceptable.

Different procedures should be applied when investigating the multiplicative and additive distortion components in the measured signal [7]. The multiplicative distortion is dominant at the near range. Accordingly, minimal acceptable lidar ranges and corresponding heights should be determined, below which the multiangle measurement data produce inaccurate or even unphysical measurement results. The optical depth profile below minimal heights can be interpolated by relating data of the lidar and a ground-based nephelometer. At the distant range, the procedure should be focused on determining additive distortion. The level of the systematic distortions at these ranges is estimated by comparing characteristics of the shaped and non-shaped profiles of the retrieved optical depth.

### ***Retrieval of the extinction coefficient and column-integrated lidar ratio using established uncertainty boundaries of the optical depth as a constraint***

The straightforward extraction of the extinction coefficient from the optical depth profile requires the use of numerical differentiation. Because the real signals are always corrupted by random and systematic noise, this procedure can yield unacceptably poor measurement accuracy, especially in clear atmosphere.

The principal drawback of conventional retrieval techniques used in the multiangle measurement technique (the same as in Raman, and High Spectral Resolution lidar data-processing techniques) is that only the optical depth profile is used for extracting the extinction coefficient. The information concerning particulate loading contained in the backscattering term is generally not used to put constraints on the extracted extinction coefficient.

In study [8], an alternative technique is introduced that calculates the extinction coefficient without using numerical differentiation. The extinction coefficient is derived from the particulate backscatter coefficient while using an estimate of uncertainty boundaries of the optical depth as a constraint. The extinction coefficient is extracted by assuming a stepwise profile of the particulate column-integrated lidar ratio. The stepwise lidar ratios for different zones are found that provide the best agreement between the initial (inverted) profile of the optical depth and that obtained by the inversion of the backscatter-coefficient profile.

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*September 30th - October 2nd, 2009*
*Bucharest, Romania*

**Optoelectronic Techniques for Environmental Monitoring**
**http://inoe.inoe.ro/OTEM2009**

Published by INOE

409 Atomistilor St., P.O. BOX MG-5, Bucharest - Magurele, 77125, România
Tel: (4021) 457.45.22, 457.57.58
Fax: (4021) 457.45.22

Director of Publication: Roxana Savastru

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| Editors: | Doina Nicolae, Upendra Singh, Gelsomina Pappalardo |
| Technical Manager: | Doina Nicolae |
| Publishing Board: | Jeni Vasilescu, Florica Toanca |
| Cover | Florica Toanca |

With the support of: Ministry of Education, Research and Innovation, Romania

Supported by a grant from Norway through the Norwegian Cooperation Programme for Economic Growth and Sustainable Development with Romania



Printed in Romania.