High Spectral Resolution LIDAR Receivers, to Measure Aerosol to Molecular Scattering Ratio in Bistatic Mode, for use in Atmospheric Monitoring for EAS Detectors

E. Fokitis¹, P. Fetfatzis¹, A. Georgakopoulou¹, S. Maltezos¹
A. Papayannis¹, A. Aravantinos²

¹ NATIONAL TECHNICAL UNIVERSITY OF ATHENS
² TECHNOLOGICAL EDUCATIONAL INSTITUTION OF ATHENS
OUTLINE

- SIGNAL CORRECTION IN THE NITROGEN FLUORESCENCE TECHNIQUE
- DESIGN OF A HIGH SPECTRAL RESOLUTION LIDAR (HSRL) IN BISTATIC MODE
- STUDY AND SIMULATION OF THE TWO F ABRY - PEROT ETALONS
- LABORATORY PERFORMANCE TESTS OF THE FABRY – PEROT AND FRINGE ANALYSIS METHODS
- CONCLUSIONS AND PROSPECTS
Scattering process in the atmosphere

An aerosol is non-gaseous substances that divided into solid particles or liquid droplets and held in suspension in the atmosphere. Atmospheric aerosols include particle sizes that range over at least 4 orders of magnitude.

There are three scattering processes of the light depending on the size (diameter D) of the particle:

If \( D \ll \lambda \) Rayleigh scattering

If \( D \sim \lambda \) Mie scattering

If \( D \gg \lambda \) Geometrical scattering

The scattered signal

\[
S = \frac{I_o T}{r^2} \left[ \frac{1}{1} \frac{1}{1} \frac{d\sigma_m}{44^2 \sigma_m^4} + \frac{1}{1} \frac{1}{1} \frac{d\sigma_a}{44^2 \sigma_a^4} \right]
\]

\( I_o \): Light source intensity

\( T \): Transmission

\( r \): Range

\( \Lambda_m / \Lambda_a \): Extinction length ratio

The vertical axis is the number of particles per cm³ per logarithmic radius (µm) interval. The horizontal axis is the particle size radius in µm and the aerosol size distribution shown here ranges from 10-3 µm to 103 µm.
The atmospheric fluorescence technique is widely used in the Ultra High Energy Cosmic Ray experiments.

To correct the Extensive Air Shower signal of air fluorescence for the air Cherenkov contamination, caused mainly by the aerosols, accurate data for the aerosol phase function are needed.

We focus on the design principles of a HSRL receiver, for recording the aerosol to molecular scattering ratio, as a function of height.
• The High Spectral Resolution Lidar (HSRL) is a device based on a narrow-band laser and a pair of high resolution Fabry-Perot etalons to separate the aerosol (Mie) and molecular (Rayleigh) scattering.

• The HSRL can give simultaneously, for each atmospheric height layer, both the aerosol and the molecular scattered intensity which can be recorded by a ground based detector.

• This type of LIDAR is used in CALIPSO Mission in NASA and is planned in mission ADM-DAEDALUS of ESA operated at 2010 using as transmitter a laser Nd:YAG at 355 nm.
How the aerosol phase function could be measured

With fixed: $\theta_{\text{laser}}, L$ \quad and chosen: $h$

$$\omega = \frac{\pi}{2} - \theta_{\text{laser}} + \arctan \left( \frac{h}{L - h \tan \left( \frac{\pi}{2} - \theta_{\text{laser}} \right)} \right)$$
LIDAR IN BACKSCATTERING MODE

- In this mode the emitter (laser) and the receiver (telescope and detector) are located at the same position.

- This mode is widely used but requires a pulsed laser to determine the height. A such type of Lidar is used in NTUA (Physics Dep.) for atmospheric monitoring in the frame of environmental research.
MEASUREMENTS IN NTUA

This Lidar uses a pulsed laser Nd:Yag at 532 nm and typically measures backscattering coefficient.

The plot illustrated concerns a measurement of the above quantity taken in NTU in Athens on 30-7-2008.
The lidar equation in bistatic mode has the following form:

\[ P = P_0 K \frac{A}{r^2} d\theta \beta (\theta_{\text{scat}}) T \]

The laser path length is given by:

\[ ds = \frac{r \theta_{\text{FOV}}}{\sin \theta_{\text{scat}}} \]

Where:

- **P**: Received Power
- **P₀**: Transmitted power
- **K**: Optical efficiency of the receiver
- **A**: Effective area of main mirror
- **r**: Range to the target
- **ds**: Laser path length viewing from the telescope
- **β(θ_{\text{scat}})**: Scattering coefficient
- **Tₜ**: Transmittance from laser to target
- **Tᵣ**: Transmittance from target to telescope
- **T**: Total Transmittance
- **θ_{\text{FOV}}**: Field of View for the telescope
- **θ_{\text{scat}}**: Scattering angle

\[ T = T_T T_R = e^{-\tau \left( \frac{1}{\sin(\theta_T)} + \frac{1}{\sin(\theta_R)} \right)} \]

Detected rate: \(4 \times 10^4\) ph/s

Total efficiency: \(1.6 \times 10^{-13}\)

The transmission of the atmosphere:
• The maximum percentage of aerosol exists in planetary boundary layer at around 2 km height.

• For molecular channel because of high velocities we have greater Doppler broadening compared with that of aerosol channel.

• The two receivers, one for the aerosol channel and the other for the molecular channel, is based on Fabry-Perot etalon prototypes.

**Aerosol channel**
- \( d = 50 \text{ mm} \)
- \( \text{FSR} = 0.1 \text{ cm}^{-1} \)
- \( T = 85\% \)

**Molecular channel**
- \( d = 5 \text{ mm} \)
- \( \text{FSR} = 1 \text{ cm}^{-1} \)
- \( T = 85\% \)

**Free Spectral Range:**
\[
\text{FSR} = \frac{1}{2nd}
\]

**Finesse:**
\[
F = \frac{\text{FSR}}{\delta\lambda}
\]
Characterization of the HSRL receivers

• **Aerosol channel:** It is made by using well known spectral lines with such as He-Ne lasers with resolved longitudinal modes.

• **Molecular channel:** We study the spectral distribution of atomic spectral lines at known temperatures.

  The sharpness of the fringes depends also on the instrumental characteristics of the etalon.
THE INSTRUMENTS USED AND THEIR MAIN SPECIFICATIONS

• A solid state CW laser (OEM manufacturer) 120 mW at 532 nm, with coherence length exceeding 50 meters corresponding to $\delta k \sim 0.02$ cm$^{-1}$.

• A colored CCD camera (Nikon D40) with 6 Mpixel image analysis (3040x2014) and pixel size 7.8 $\mu$m.

• Two different Fabry-Perot etalons (spacer thickness: 5 mm and 50 mm) with verified overall finesse of 17.5.

• Newtonian telescope of diameter $D=250$ mm and $f$-number $f/#=5.5$. 
Test with micro particles

Scatterers particles diluted in water
The fringe pattern obtained with the etalon of 50 mm from the beam of the laser scattered by the microparticles.

The intensity plots have been derived from the accumulated data along a hypothetical horizontal narrow pixel strip (2 pixel wide).
A fringe pattern obtained by the etalon of 50 mm using a white paper as scatterer of the laser beam.
For the finesse determination we used an appropriate transformation of the radial variable of the fringe pattern, pixel number or mm to $1/\cos\theta$. This transformation leads to an interferogram obtained with variable wavelength.

$$\delta = \frac{4\pi nd \cos\theta}{\lambda} = \frac{4\pi nd}{\lambda(1/\cos\theta)}$$
The intensity plot of the fringe pattern is obtained along a narrow line (2 pixel wide) rotating over the whole polar angle (2π) by a software algorithm in steps of Δθ. With an improved method we use a circular rotated sector instead of line.
Fitting of the fringe diameter as a function of the order number for comparison with theoretical expectations

The analytical formula between $R^2$ and integer $n$ is:

$$R^2 = \frac{D^2 \lambda}{d} n + (2 - m_0 \frac{\lambda}{d}) D^2$$

where:
- $R$ : the radius of the 4 rings for the circular pattern on the CCD
- $D$ : the focal of the lens towards the CCD
- $d$ : the spacer thickness of the Fabry–Perot etalon ($d = 5$ cm),
- $\lambda$ : the diode laser wavelength ($\lambda = 532$ nm)
- $n$ : the fringe order,
- $m_0$ : the order of central fringe.

From the linear fit of $R^2 = f(n)$ we found that:

- These points are in a linear correlation (linear correlation coefficient $R^2 = 0.99941$)
- Slope = $0.123 \pm 0.002$ cm$^2$ and
- Intercept point = $-0.03 \pm 0.005$ cm$^2$

- $D^2 = 0.123$ cm$^2$ ($5$ cm / $532$ nm) = $1.156$ m$^2$ and thus $D = 1.08$ m which is in a good agreement with the true value of $1.10$ m for the distance of our geometry.
How the interferogram of the molecular channel changes with phase $\delta$

How the interferogram of the aerosol channel changes with phase $\delta$
CONCLUSIONS

- A High Spectral Resolution Lidar in bistatic mode has been studied and simulated. In this work we were concentrated mostly on the optimization of the receiver’s performance.

- From laboratory performance tests we verified the resolving capabilities of the two etalons designed for using in the two channels of HSRL.

- Analyzing and transforming appropriately the fringe pattern we were able to estimate the laser line spectral width. We are developing an improved fringe pattern analysis taking into account existing geometrical deformations. A multi-parametric least square method from the literature could be used appropriately in our application.

Our next steps are:

- To introduce a very narrow optical filter around 532 nm to reduce the optical noise (mainly night-sky background and artificial light).

- To optimize the design of a 100 mm etalon by means of its absorption coefficient using thin film deposition method.