Multiwavelength lidar node development and simulation for a regional tropospheric aerosol monitoring network.

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Abstract. This work studies multiwavelength lidar node operation requirements to operate in a regional aerosol monitoring network. Some of the parameters taken into account are simplicity and robustness of the system in continuous and remote operation conditions. Sub-system modularity and accessibility is also contemplated. A numerical simulation is performed on a synthetic atmospheric signal to analyze the behaviour of this system in a) the visible (532 nm) and infrared (1064 nm) spectral regions; b) the main atmospheric compound Raman spectral region (nitrogen, oxygen water vapor). Adding depolarization channels in the 532 nm spectral region is also contemplated.

Keywords: lidar network, aerosol, water vapor

1. Introduction
The role that aerosols meet in the atmospheric system is very complex and still not well known. A deeper understanding of its temporal and spatial distribution and of the interaction with other geophysical variables, such as water vapor, are necessary to understand better the dynamics of global climate balance [1].

Several remote sensing instruments placed in ground based stations, aircrafts and satellites are being used to collect aerosols information. Among them, the lidar (acronym of LIght Detection and Ranging) technique has the ability to retrieve both spatial and temporal aerosol information by means of their optical properties [2]. This system operates as radar but instead of using radio waves it operates at the infrared to ultraviolet spectral region, in which particle and molecular scattering are more important. These instruments are usually classified by the type of scattered radiation detected by the system. The most common ones are the elastic and inelastic (Raman) backscatter lidars. Elastic lidars detects the same wavelengths as the ones emitted by the laser source [3]. For weak atmospheric aerosol loads, Rayleigh scattering prevails due to the presence of molecules, while in presence of aerosols aerosol (Mie) scattering is predominant. As the elastic lidar equation has two unknown terms (extinction and backscatter), the solution arrives from an a priori assumption that links them [4]. For the Raman case, the atmospheric scattering of the majoritarian atmospheric compounds is proportional to the molecular concentration. Knowing this profile the extinction can be retrieved. For this reason inelastic Raman scattering is measured when possible [5].

The multiwavelength lidar system (MWLS) operating at the Lidar Division at Villa Martelli [6], is a powerful instrument for aerosol characterization through the use of multiple emission and detection wavelengths as it combines all the above mentioned measuring techniques.
A new system is being developed to perform measurements at remote geographical areas. This lidar has similar capabilities than the MWLS and it also incorporates new features. Two photomultipliers (PMT) at different polarization angles will measure atmospheric-induced laser depolarization to retrieve aerosol geometry parameters for an additional aerosol characterization [7].

This technique contributes to discriminate liquid from solid aerosols, ice crystal presence in clouds, etc. Also a 32 channel spectrometer combined with a multi-cathode photomultiplier module and a photoncounting acquisition system [8] [9] will help to characterize aerosol composition from its range resolved spectra.

2. Lidar Objectives

The system will be able to retrieve the geophysical variables presented in Table 1. Among the main requirements for the design of the system are:

- **Mobility**: It has to be easily transported to a remote site in which the system must be able to operate for long periods of time.
- **Continuous and automatic operation**: It has to be able to perform long-term measurements with minimal human intervention.
- **Modularity**: It must be scalable design to allow new features to the system.
- **Node operation features**: Operation and data management are oriented to create a base design for an aerosol monitoring network in Argentina.
- **Scanning Capabilities (Optional)**: Capable to monitor aerosols profiles at different lines of sights.

### Table 1. Geophysical products to relieve the mobile lidar

| Lidar products                                      | Associated Wavelengths For the measurement |
|-----------------------------------------------------|---------------------------------------------|
| Elastic Backscatter attenuated                      | 355, 532, 1064 nm                           |
| Aerosol extinction - Fernald inversion              | 355, 532, 1064 nm                           |
| Aerosol extinction - Raman investment               | 580 \(^{a}\), 607 \(^{b}\) nm               |
| Water Vapour Mixing Ratio                           | 580, 607, 660 \(^{c}\) nm                   |
| Total molecular backscatter                         | 532, 580, 607 nm                            |
| Lidar ratio                                         | 532, 580, 607 nm                            |
| Depolarization Ratio                                | 532 nm                                      |
| Aerosol Optical Thickness,                          | 355, 532, 1064 nm                           |
| Cloud: Optical / Geometrical thickness              | 355, 532, 1064 nm                           |
| Atmospheric Boundary Layer, height                  | 355, 532, 1064 nm                           |
| Aerosol type discrimination.                        | Height dependent spectrum acquired using 32 channels |

\(^{a}\) Oxygen Raman scattering after 532 nm excitation.

\(^{b}\) Nitrogen Raman scattering after 532 nm excitation.

\(^{c}\) Water Vapour Raman scattering after 532 nm excitation.
3. Lidar Instrument Description

Figure 1 shows the lidar main modules as a block diagram.

3.1. System emission

The transmitter is a Quantel Brilliant 20, flash pumped Nd:YAG laser. It delivers short pulses (5 ns) of linearly polarized radiation (> 90%) at a repetition rate of 20 Hz. The energies at the fundamental, second and third harmonic are 350 mJ (1064 nm), 150 mJ (532 nm) and 90 mJ (355 nm) respectively. This laser was chosen because of its relative high energy per pulse at the visible wavelength (used for Raman backscatter detection) and its polarized emission (for aerosols depolarization studies).

The laser beam is redirected to the atmosphere by a broadband dielectric mirror having 99% reflection at the 320 to 1100 nm spectral range.

3.2. Receiver

The backscattered light is collected using a Celestron C8-A XLT Schmidt-Cassegrain telescope with a primary mirror diameter of 203 mm diameter and a focal length of 2032 mm. In operation conditions a diaphragm at its focal plane acts as a field stop to narrow the field of view (FOV) to 1 mrad. The reflective and antireflective coatings assures high transmission efficiency at visible wavelengths.

3.3 Polychromator setup

After reaching the focal plane, a convex lens collimates the incoming radiation. Depending on the type of measurement, the light can be redirected to the range dependent spectrum analyzer or continue to the filter based polychromator. This last discriminates the elastic backscattered wavelengths (Rayleigh and Mie scattering at 355, 532 and 1064 nm) and the Raman backscattered wavelengths created from the interaction of the the 532 nm laser emission and the atmospheric oxygen, nitrogen and water vapor molecules. The polychromator design scheme is presented in figure 2.
The dichroic and interference filters specifications for polychromator optical design are shown in table 2 and table 3 respectively.

Table 2. Dichroic beamsplitters

| Number | Reflectivity          | Transmission                      |
|--------|-----------------------|-----------------------------------|
| 0      | 70 @ 500 to 800 nm    | 30 @ 532 nm; 95 @ 355, 580, 607, 660 |
| 1      | 95 @ 1064 nm; 99 @ 355 nm | 98 @ 532, 580, 607, 660 nm       |
| 2      | 99 @ 355 nm           | 98 @ 1064 nm                      |
| 3      | 99 @ 532 nm           | 96 @ 580, 607, 660 nm            |
| 4      | 99 @ 580, 607 nm      | 94 @ 660 nm                       |
| 5      | 98 @ 580 nm           | 94 @ 607 nm                       |

Table 3. Filters

| Number | Wavelength (nm) | Peak transmission (%) | FWHM (nm) |
|--------|-----------------|-----------------------|-----------|
| A      | 1064            | 95                    | 4         |
| A1     | 1064            | 80 (Long pass 1000 nm)| NA        |
| B      | 355             | 80                    | 1.3       |
| B1     | 355             | 90 (Band pass, 377 nm center) | 50      |
| C      | 660             | 95                    | 1         |
| D      | 580             | 95                    | 1         |
| E      | 607             | 95                    | 1         |
| F      | 532             | 95                    | 2         |
The ideal polychromator efficiency, without taking into account losses from lens surface and their internal transmission, is 73.6% at 1064 nm, 95% at 532 nm, 72% at 355 nm, 90.25% at 580 nm, 83.60% at 607 nm and 83.6% at 660 nm. After this separation the beams are focused to the photodetectors which are described in table 4.

| Wavelength (nm) | Photodetectors                          |
|-----------------|-----------------------------------------|
| 355             | Hamamatsu PMT module H6780-03           |
| 532, 580, 607, 660 | Hamamatsu PMT module H6780-20          |
| 1064            | EG&G APD based Licel unit               |
| Spectrometer    | Licel Module based on an Oriel (MS125)  |
| (32 channels)   | spectrometer and a Hamamatsu linearly distributed multicathode PMT module (H7260-20). |

The lidar is designed to detect the polarization of the 532 nm elastic backscatter using a polarizing cube beam splitter placed inside the polychromator close to the corresponding photomultipliers.

All the signals are acquired using Licel TR-20-160 AP transient recorder modules operating at 20 MSPS. Raman signals are measured in photon-counting mode (bandwidth of 0 to 300 MHz and a maximum counting rate of 250 MHz) and elastic signals are measured in analog mode (12 bits, 20 MHz sampling frequency A/D converter). The module performs internal summation of multiple profiles up to a maximum of 4096. Final records are sent by an Ethernet connection to the main computer.

### 3.4 Spectrometer description

The Multi Spectral Lidar Detector (MSLD) from Licel Company collects a continuous spectrum divided in 32 equally separated bands (channels). Each one is a photosensitive area of a multianode photomultiplier module connected to a photon-counting unit acquiring 1024 bin profiles (15.36 km length, with a 15 m bin size). The configuration description is presented in Table 5.

| Spectrograph model | Oriel MS125, 77400. | Acquisition |
|--------------------|---------------------|-------------|
| - Design           | Crossed Czerny-Tuner| - Photon counting rate: 100 MHz |
| - F /number:       | 3.7                 | - Bin size: 100 ns |
| - Focal length:    | 120 mm              | - Bins: 1024 |
| Gratings           |                      | - Max. average: 4096. |
| - Grating A:       | 77464, Plane, Ruled, 500 nm Blaze, 280-1600 nm Spectral Range | - Max. rep. rate: 30 Hz |
| - Grating B:       | 77421, plane, holographic, 500 nm Blaze, Spectral range 300-840 nm. |
| Multi-Spectral Lidar Detector: | Multianode Hamamatsu 32 channel array - H7260-20. | Fiber Optic type: |

| Spectral resolution | <6 nm |
|---------------------|-------|
| - 1200 lines / mm grating: | <6 nm |
| - 1800 lines / mm grating: | <4 nm |
The polychromator uses a Raman edge filter (filter S, Figure 2) to remove the strong elastic backscatter lidar return at 532 nm, allowing the transmission of the weak inelastic backscatter lidar signals within visible spectrum range (537-750 nm) with an efficiency exceeding 90%.

4. System Overlap Function

The overlap function is the range-dependent fraction of the total illuminated air mass that is seen by the detector while the laser beam propagates through the atmosphere. This function can be simulated by means of optical ray tracing techniques. For this case the free version of OSLO (Optics Software for Layout and Optimization) [10][11] was used using the simulation parameters from table 6.

This lidar will use a coaxial configuration in which the laser emission axis coincides with the telescope line of sight.

| Table 6. Simulation parameters for the Overlap system |
|-------------------------------------------------------------------------------------------------------------------------------|
| **Receiver**                                                                                                                    | **Emitter**                                                                 | Simulation parameters |
| Telescope type: Schmidt-Cassegrain                                                                                               | Coaxial to the telescope axis.                                             | Beams per image pixel: 100                                           |
| Primary mirror diameter: 203 mm (8")                                                                                             | Laser divergence: 0.360 mrad                                               | Bin size: 7.5 m                                                     |
| Secondary mirror diameter: 68.58 mm (2.7")                                                                                                | Spot diameter: 6 mm                                                      |
| Focal ratio: F/10 (2032 mm)                                                                                                      |                                                                          |
| Field of view: 0.49 mrad to 0.98 mrad                                                                                                |                                                                          |

In the simulations, the lidar backscattered signals were projected on an 8 mm in diameter circular target, corresponding to the abovementioned Hamamatsu PMT module up to a distance of 3.75 km distance which can be considered as infinity. Two FOV were used giving an overall transmission of 89.5% and 82.5% with a FOV of 0.98 mrad (aperture 1.8 mm) and 0.5 mrad (aperture 1 mm), respectively.

Figure 3 shows the overlap functions. Maximum overlap is achieved at 450, 550, 900, 5500 m with aperture settings of 2, 1.8, 1.5 and 1 mm, respectively.

For lower altitudes the system starts to see the laser beam at 20, 40, 60 and 80 m, with this aperture settings.
5. Mobile Laboratory
The mobile laboratory is being built in a 20 feet's shelter and it has two rooms: one for the lidar instrumentation and the other for the acquisition computers, and eventually a lidar operator. This laboratory is shown on Figure 4.

6. Lidar Signal Simulation
Some a priori simulation are required to parameterize the laser source, telescope, polychromator and detector requirements and to study the system behaviour under different atmospheric conditions.

6.1. Lidar Equation
Equation (1) shows the elastic lidar signals under a given molecular scattering (Rayleigh) and aerosol (Mie) distribution. Equation (2) shows the same but for the Raman lidar signals.

\[
S(\lambda, z) = K(\lambda, \lambda, z)[\beta_{\text{aer}}(\lambda, z) + \beta_{\text{mol}}(\lambda, z)] \exp \left\{-2 \int_0^Z \left(\alpha_{\lambda}^{\text{aer}}(\zeta) + \alpha_{\lambda}^{\text{mol}}(\zeta) \right) d\zeta \right\}
\] 

(1)
\[ S^X_{\lambda,\lambda_R}(z) = K(\lambda_L, \lambda_R, z).N^X(z), \frac{d\sigma^X_{\lambda}(\pi)}{d\Omega}. \exp \left\{- \int_0^z [\alpha^\text{aer}_{\lambda}(\zeta) + \alpha^\text{mol}_{\lambda}(\zeta)]d\zeta - \int_0^z [\alpha^\text{aer}_{\lambda_R}(\zeta) + \alpha^\text{mol}_{\lambda_R}(\zeta)]d\zeta \right\} \] (2)

Where:
- \( S^X_{\lambda,\lambda_R}(z) \): Elastic lidar backscatter signal,
- \( S^X_{\lambda,\lambda_R}(z) \): Raman lidar backscatter signal for gas species X,
- \( z \): height range,
- \( \lambda \): laser wavelength,
- \( \lambda_R \): Raman laser wavelength for gas species X,
- \( \beta^\text{aer}(\lambda, z) \) and \( \beta^\text{mol}(\lambda, z) \) volume backscattering coefficients of aerosols and molecules in the wavelength \( \lambda \) for an incident radiation wavelength \( \lambda_L \),
- \( \alpha(\zeta) \): wavelength-dependent extinction coefficient.
- \( N^X(z) \): number of molecules for gas species X.
- \( d\sigma^X_{\lambda}(\pi)/d\Omega \): Raman backscattering cross section for gas species X.
- \( K(\lambda_L, \lambda, z) \): Instrumental factor in the system, expressed in the equations (3).

\[ K(\lambda_L, \lambda, z) = E_L \cdot \frac{A_0}{Z} \cdot \frac{c}{2}, k(\lambda_R).O(z) = [w.m] \] (3)

\[ .... = E_L \cdot \frac{A_0}{Z^2} \cdot \frac{c}{2\Delta z}, k(\lambda).O(z).Q.G.e.50\Omega = [V.m] \]

\[ .... = E_L \cdot \frac{A_0}{Z^2} \cdot \frac{c}{2\Delta z}, k(\lambda).O(z).Q.10^{-6} = [MCPS.m] \]

Where:
- \( E_L \): laser emission power,
- \( A_0 \): optical area of collection,
- \( c \): speed of light,
- \( e \): electron charge,
- \( k(\lambda_R) \): subsystem instrumental factor receptor,
- \( O(z) \): overlap factor between the section irradiated by the laser and the telescope's field of view,
- \( Q \): photomultiplier or avalanche photodiode quantum efficiency.
- \( G \): photomultiplier or avalanche photodiode current gain.
- \( \Delta z \): spatial resolution.

6.2. Simulation parameters
Simulations backscatter lidar signals are performed using the parameters in table 7 together with those already specified for the instrument.
Table 7. Simulation parameters for lidar backscatter signals

| Parameter                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Radiosonde (date)                              | August 24, 2009, Ezeiza, Argentina.       |
| Emission: Energy laser / wavelength:           | 350 mJ @ 1064 nm, 160 mJ @ 532 nm and 70 mJ @ 355 nm. |
| Instrumental: Telescope reflectivity:          | 0.8 @ 532 nm, 0.7 @ 1064 nm, 0.6 @ 355 nm. |
| FOV:                                           | 0.885 mrad                                 |
| Atmospheric boundary layer height:             | 2000 m                                    |
| Entrainment zone depth:                        | 150 m                                     |
| Aerosol extinction cross section:              | $8 \times 10^{-5}$ m$^{-1}$               |
| $K_p$ aerosol:                                 | $1 / 50$ @ 532, 1064, 355 nm.             |

6.2.1. Elastic lidar signal simulation. Figure 5 shows the elastic backscatter simulations results, according to the parameters in table 6.

![Figure 5](image)

**Figure 5.** Simulations of the backscatter lidar signals in the elastic backscatter 355, 532 (sum of two components, parallel and orthogonal) and 1064 nm.
6.2.2. **Simulations of elastic lidar signals.** Figure 6 shows the elastic backscatter simulations, according to table 6.

![Figure 6](image)

*Figure 6.* Simulation of Raman backscattering profiles of $\text{O}_2$, $\text{N}_2$ and water vapor.

7. **Monitoring Network**

The aim of developing a mobile lidar is to strengthen aerosol observation in Argentina held by the Lidar Division [12]. Figure 7 shows the geographic location of the current aerosol measurement sites. Some of them are equipped with aerosol lidars (Lidar at CEILAP - Buenos Aires and CEILAP - Rio Gallegos). The others can be potential sites for a network lidar applications as they have AERONET / NASA network (CEILAP - Buenos Aires, CEILAP - Rio Gallegos, CEITT at Cordoba and Trelew at the Universidad Nacional de la Patagonia San Juan Bosco) [13].

![Figure 7](image)

*Figure 7.* Measurement sites of aerosol used by the CEILAP Lidar Division.
8. Summary
The description of a new tropospheric aerosol lidar that will be operating as a monitoring network mobile node is presented. Main features include full Raman detection of the atmospheric majoritarian compounds (nitrogen, oxygen and water vapor) in the visible region, depolarization measurements at 532 nm, and the use of a spectrometer for range and wavelength resolved lidar measurements. The overlap function results shows that the system is appropriate for close-to-ground boundary layer studies, reaching overlap maximum at the 450 m with 1 mrad FOV. Simulations show the desired system lidar profile; absolute values are probably overestimates due to the fact that there is still not a measurement of the overall lidar system optical throughput at the detection stage. Finally possible lidar locations are suggested for a lidar network operation, which is the principal goal of this instrument.

Acknowledgements
The authors thank JICA (Japan International Cooperation Agency) for supporting this project.

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