

# New prototype of very compact LIDAR for atmospheric particulate monitoring

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CO.RI.S.T.A. led a research project funded by the Italian Ministry of University and Research to realize a portable lidar system to monitor atmospheric particulate. The main goal of the project is to get a very compact, inexpensive, easy-and-safe use system. The designed lidar system is provided with an optical apparatus of emission/reception assembled in bistatic configuration. Thanks to its limited size (height 1m, width 1m) and light weight (less than 50 Kg), the system can be easily moved for in situ measurements. To maintain a high efficiency and guarantee reliability we use a pulsed Nd:YAG laser emitting at 532nm and 355nm. The radiation is sent into the atmosphere by a remote alignment beam-steerer. The receiving telescope has a Cassegrain configuration with a spherical primary mirror and an elliptical secondary mirror. Two acquisition channels were realised for analog and digital acquisition. Both the telescope and the optical acquisition channel have been modelled and deeply analysed with Zemax, a 3D simulation program which allows to design optical systems and to investigate their performance. Intercalibration measurements of the prototype and aerosols backscattering measurements will be presented.

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## 1. Introduction

Actually there is a growing interest in the study of aerosol in the troposphere because of their established influence in many atmospheric processes. In fact the aerosol particles are directly involved in the radiation budget control by absorption and scattering processes. Moreover they are involved in the atmospheric chemistry because they can modify the concentration of important atmospheric constituents as ozone and, at ground level, are harmful to man, animals and plants.

The monitoring of aerosol particles in the atmosphere can be realised in real time with lidar systems using optical backscattering for the study of atmospheric properties. Among remote sensing systems, lidar technique represents a powerful tool for atmospheric aerosol study giving vertically resolved measurements of aerosol optical and microphysical parameters, with high spatial and temporal resolutions. Moreover, lidar systems provided for a mobile mirror scanning system allows to build a 3-D map of atmospheric aerosol and pollutants distributions.

Finally, with recent technological advances in lasers and detectors, lidar technology has great promise for future observations from platforms such as unattended airborne vehicles or commercial airlines because the systems can be very compact.[1,2]

In this context, CO.RI.S.T.A. (Consortium for Research on Advanced Remote Sensing Systems) led a research project funded by MIUR (Italian Ministry for University and Research), with Quanta System and Kayser

Italia as partners, to realize a lidar system for monitoring of particulate in atmosphere. The main goal of the project (named LAPMI) is to get a compact, inexpensive, user friendly lidar system. The LAPMI project is part of the European research program EUREKA, where INOE 2000 (National Institute of Research and Development for Optoelectronics, ROMANIA), CEPIEM (Institute for Employment Protection, Health and Ergonomics, ROMANIA), Prefecture of Bucharest, and CO.RI.S.T.A. are working together to develop techniques to monitor particulate in atmosphere by means of lidar systems.

This paper reports on the realisation of a portable lidar prototype for *in situ* measurements of aerosol. The lidar system realised by CO.RI.S.T.A. and its partners is provided with an optical apparatus of emission/reception in bistatic configuration composed by a Cassegrain telescope and a beam-steerer, a Nd:YAG laser and two acquisition channels at two different wavelengths. The prototype can perform 3D measurements by scanning the atmosphere along the azimuth and the zenith angles, by means of two step motors. Thanks to its limited size (height 1m, width 1m) and light weight (less than 50 Kg), the system can be easily moved for *in situ* measurements. Both the telescope and the optical acquisition channels have been modelled and deeply analysed with Zemax [3], a 3D simulation program which allows to design optical systems and to investigate their performance. Intercalibration measurements of the prototype with a fixed lidar system and aerosols backscattering measurements will be presented.

## 2. Experimental set-up

A lidar is essentially composed of a transmitter (laser) and a receiver (telescope). Its principle of operation is illustrated in fig. 1: the backscatterers (molecules, aerosols) at the distance  $R$  from the system send back part of the laser pulse toward A, active surface of the telescope. Consequently, the analysis of the detected signal as a function of  $t$ , the time interval between emission and detection, allows the study of the optical properties of the atmosphere along the beam, since the simple relation between  $t$  and  $R$  is given by:

$$R = \frac{ct}{2} \quad (1)$$

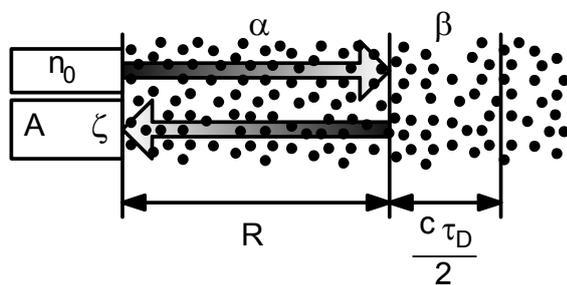


Fig. 1. Lidar principle of operation. The points represent generic atmospheric scatterers (molecules, aerosols).

The photons detected within  $\tau_D$ , the detector response time, are backscattered from the layer delimited by the distances  $R$  and  $R + c\tau_D/2$ . Their number  $n$  is proportional to the thickness  $c\tau_D/2$  and to the backscattering coefficient  $\beta$  of the involved air volume. Furthermore, in its round trip, the original pulse consisting of  $n_0$  photons is attenuated by the atmosphere. This phenomenon is quantified by the extinction coefficient  $\alpha$ . Moreover,  $n$  is proportional to the solid angle  $A/R^2$  and the efficiency  $\zeta$  of the detection system. Finally the lidar equation can be written [4]:

$$n(R, \lambda) = n_0(\lambda) \zeta(\lambda) \frac{A}{R^2} \beta(R, \lambda) \frac{c\tau_D}{2} \exp\left[-2 \int_0^R \alpha(R', \lambda) dR'\right] \quad (2)$$

Table 1. Characteristics of the laser source for Lapmi project.

Wavelength	Energy per laser pulse	Beam polarisation	Pointing stability	Beam divergency	Repetition rate	Pulse length
532 nm	$500 \pm 50 \mu\text{J}$	TEM <sub>00</sub>	$\leq 100 \mu\text{rad}$	1 mrad	1kHz	50 ns
355 nm	$300 \pm 30 \mu\text{J}$	TEM <sub>00</sub>	$\leq 100 \mu\text{rad}$	1 mrad	1kHz	50 ns.

The pulse lengths are about 50 ns for both wavelengths, leading spatial lidar resolution of 7.5 m. In table 1 the laser source characteristics are summarised.

Our prototype has been designed to characterise the aerosols distribution in urban areas by measuring the elastic aerosols backscattering coefficient at two different wavelengths. In this way it is possible to calculate the backscattered-related Angstrom coefficient allowing a characterisation of the chemical/physical properties of the aerosols distribution by using an algorithm for the lidar equation retrieval such, e.g. Klett method [5].

Basically the functional scheme of our lidar system is the following: the laser signal, sent into the atmosphere by a remote alignment beam steerer, is collected by the telescope, passes through a diaphragm and then it is collimated on a narrow-band interference filter. The backscattered radiation is detected by means of a photomultiplier and is acquired by means of a multichannel board. The two wavelengths can be remotely selected but they can not be used simultaneously.

In fig 2a and 2b a layout and a picture of the prototype are respectively shown.

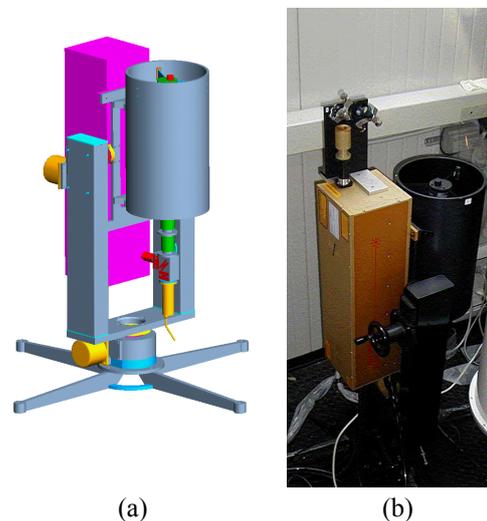


Fig. 2. (a) layout and (b) picture of the lidar prototype.

In order to maintain a high efficiency and compactness of the system, a diode pumped Nd-YAG laser source has been realised by Quanta System [6]. The laser source is equipped with crystals for second and third harmonic generation and works at a repetition rate of 1 KHz with pulse energy of 500  $\mu\text{J}$  and 300  $\mu\text{J}$  at 355 and 532nm respectively.

The prototype has been designed in a bistatic configuration with a minimum observable height of 170 m. To send the laser radiation into the atmosphere a hand-operating beam

steerer has been designed made up by two plane mirrors, with a coating for both 355 nm e 532 nm, mounted at  $45^\circ$  on two hand-operating gimbal mirrors, as showed in fig.3.

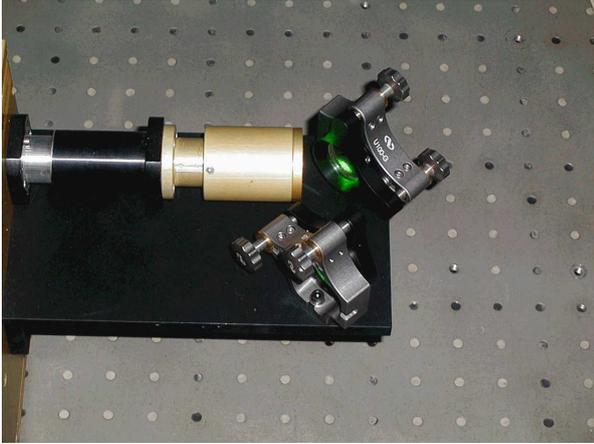


Fig. 3. The beam steerer.

The telescope has a Cassegrain configuration with a spherical primary mirror and an elliptical secondary mirror (see fig. 4). To achieve this configuration we performed simulations with Zemax optical design software [3], looking for the best compromise between compactness, low cost, good aberration correction and good backscattering radiation retrieval. The primary mirror has a diameter of 20 cm with a central aperture of 3 cm, while the secondary mirror has a diameter of 6 cm. A 17 cm baffle has also been realised to avoid the detection of the light that enters the tube without being reflected by the mirror [7]. The effective telescope focal length is 140 cm and a diaphragm with a variable aperture of 2, 3, 4 mm, has been used to change the field of view of telescope and thus observe different atmospheric heights.



Fig. 4. A top view of the lidar Cassegrain telescope.

Spectral selection is made by two narrow band interference filters centred at 355 and 532nm, with 0.5nm FWHM and center transmittance  $> 50\%$ . By performing simulations we also calculated the beam divergence  $\theta$  due to the backscattering radiation coming from different range of atmosphere. We estimated the wavelength shift  $\Delta\lambda$  on the interference filters due to the beam divergence and the effective refractive index of the filters using the following equation

$$\Delta\lambda = (\lambda_s - \lambda_0) = \frac{\lambda_0(n_{eff}^2 - \sin^2\theta)^{1/2}}{n_{eff}} - \lambda_0 \quad (3)$$

where

$$\begin{cases} n_{eff}(\lambda_0 = 355nm) = 2.124 \\ n_{eff}(\lambda_0 = 532nm) = 1.841 \end{cases} \quad (4)$$

are the refractive index values for  $\lambda_0 = 355$  nm and  $\lambda_0 = 532$  nm, respectively

In table 2 and in table 3 we report divergence angles and  $\Delta\lambda$  calculated as follows for different atmosphere heights and with a 3 mm diaphragm for the two different wavelengths.

The wavelength shift introduced by the beam divergence and the effective refractive index of the filters is always smaller than the filter bandwidth for both the 532nm and 355 nm. To detect the backscattered radiation two acquisition channels were designed for analog and photon-counting acquisition model. The photon-counting detector is a Hamamatsu photomultiplier H6180 with a discriminator and a preamplifier stage, while the analog detector is a Hamamatsu analogue photomultiplier H6780. The analogue and photon-counting signals are acquired by a 14 bits digitizer and a standard multichannel scaler board.

Table2. Divergence angles and  $\Delta\lambda$  for different atmosphere heights at 355 nm.

Atmosphere height (meter)	$\Delta\lambda$ (nm)	$\theta$ (mrad)
170 (minimum observable height)	-0.017	4.6
467 (full overlap height)	-0.025	18
100000	-0.009	15

Table3. Divergence angles and  $\Delta\lambda$  for different atmosphere heights at 532 nm.

Atmosphere height (Meter)	$\Delta\lambda$ (nm)	$\theta$ (mrad)
170 (minimum observable height)	-0.015	14
467 (full overlap height)	-0.03	18
100000	-0.03	18

### 3. Results and discussion

The prototype was calibrated by performing simultaneous backscattering measurements with a fixed lidar of the INFN (National Institute for the Physics of Matter) laboratory of Naples. This lidar system is based on a XeF Excimer laser ( $\lambda=351\text{nm}$ ) working at a repetition rate of 50 Hz with a pulse energy of 50 mJ. The backscattered radiation is collected by a Newtonian telescope, in monostatic configuration, with a primary mirror of 30 cm diameter and focal length of 120 cm. The detection and data analysis system includes two acquisition channels corresponding to the elastic backscattered radiation and Raman shifted echoes from  $\text{N}_2$  molecules. Data acquisition will be performed through a composite system which includes both analog digitizing and photon counting techniques simultaneously to extend the sounded range from 100 meters to 20 Km [8]. In fig. 5 and in fig. 6 the results of analogue and digital intercalibration measurements performed at 355nm on 13<sup>th</sup> and 15<sup>th</sup> of May 2002 are sketched. The measurements have been performed with 3 mm diaphragm, an energy laser of 300  $\mu\text{J}$  over a range from 500 m to 7000 m where the backscattering radiation still permits to reach a good value of the signal to noise ratio according to the performances simulation of the lidar prototype. The reported measurements refer to lidar signals averaged over 4000 laser shots corresponding to 30 minutes. acquisition time. The raw data were binned over 8 points leading to a 60 m spatial resolution. The profiles of fixed and portable lidars show a good agreement from 500 m up to 7 Km.

The slightly data departures below 500 m are due to the fact that effective area correction [9] has not been taken in account for the portable lidar data while the fixed lidar one is corrected by its effective area: so portable lidar signal is always undervalued until all the backscattered lidar signal is completely in the telescope field of view.

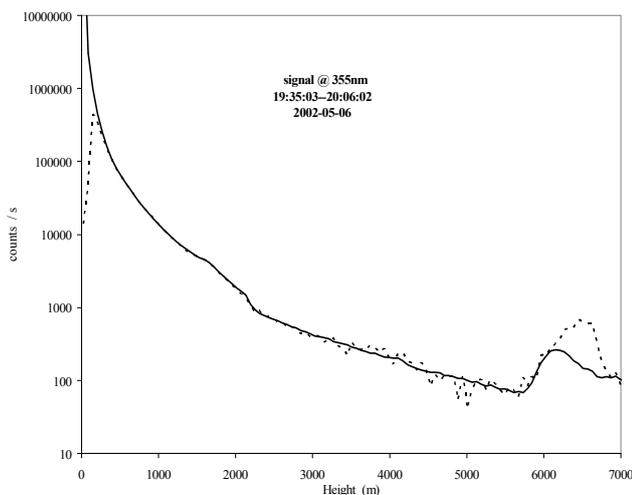


Fig. 5. Photoncounting intercalibration measurements. The fixed lidar signal is the continuous line while the portable lidar signal is the dashed line.

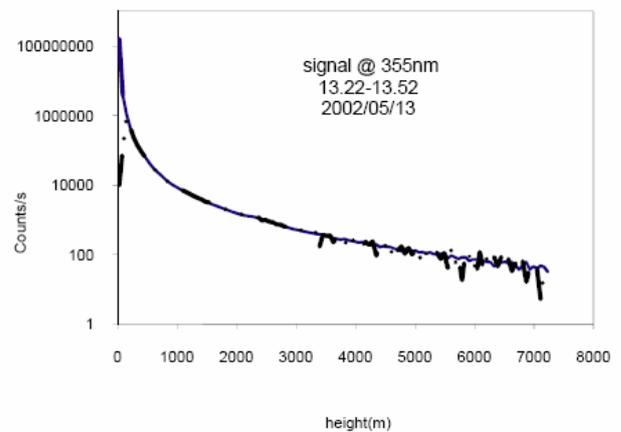


Fig. 6. Analogue intercalibration measurements. The fixed lidar signal is the continuous line and the portable lidar signal is the dashed line.

Moreover, a measurement at 532 nm has been compared with a simultaneous measurement performed with INFN fixed lidar at 351 nm showing a consistent lidar data behaviour, reported in fig. 7.

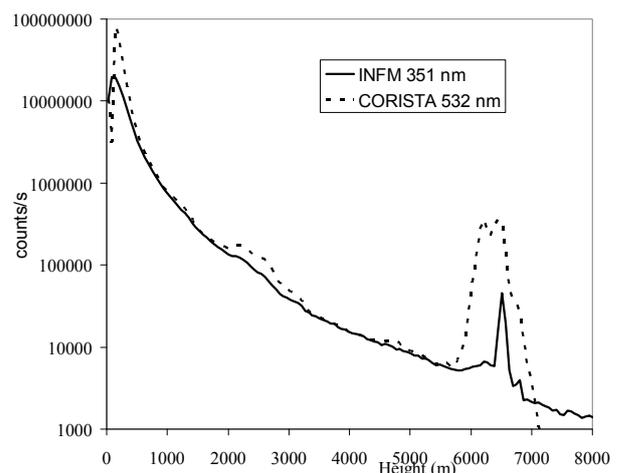


Fig. 7. A comparison between the portable analogue lidar signal at 532 nm (dashed line) and the fixed lidar signal at 351 nm (continuous line).

Lidar elastic backscattered signals allowed us to obtain profiles of aerosol backscattering coefficient following the procedure suggested by Klett-Fernald [5].

We show in fig. 8 the comparison between the aerosol backscatter coefficient profiles obtained with the two systems. The observed layering in the troposphere is correlated to a Saharan dust transport phenomena occurred during the measurement campaign. As we can observe comparing fig.8 and fig.9 a rather good agreement have been found between lidar data and forecasts based on DREAM (Dust Regional Atmospheric Module) model that predict desert aerosol load over the measurement area.

Furthermore the measurements of aerosol backscattering coefficients at two wavelengths ( $\lambda_1=351$  nm e  $\lambda_2=532$  nm) allowed us to estimate the backscatter related Angstrom coefficient,  $\delta(z)$ , typical of the exponential law characterising the backscattering coefficient in terms of the wavelength  $\beta_p \propto \lambda^{-\delta}$ .

The backscatter-related Angstrom coefficient,  $\delta(z)$  as a function of the height can be obtained from the expression:

$$\delta(z) = \frac{\ln(\beta_p(532, z) / \beta_p(351, z))}{\ln(351/532)}, \quad (1)$$

where  $\beta_p(351, z)$  and  $\beta_p(532, z)$  represents the aerosol backscattering coefficient profiles at 351nm and 532nm respectively.

In order to minimise the uncertainty on  $\delta$  parameter, we have taken into account the measurements up to a 3500m above the lidar station, because above this height  $\beta_p$  profiles show larger statistical fluctuation and also because the aerosols concentration is less.

The  $\delta(z)$  profile shows values ranging from 0.2 to 1.6. Zero closest values, typical of larger aerosols dimensions, lie below 1400 m corresponding to the measured PBL height and usually are rural and /or urban aerosols [10]; while above this height there are aerosols with different dimensions. Particularly, for height ranging between 1400 m and 2300m,  $\delta$  values range between 0.8 and 1.6, indicating aerosols having smaller dimensions. Above 2300m and up to 3500m a greater content in the aerosol size distribution of dust particles with larger dimension corresponds to an increase in the  $\delta$  parameter. These results are in agreement with the LR (Lidar Ratio) mean values obtained in these layers and calculated from aerosols extinction and backscattering independent and simultaneous measurements performed at 351 nm. In fact, LR values calculated in these different atmospheric regions resulted to be characteristic of different typology of aerosol and in the range 2300-3500 resulted typical of desert dust particles (LR=40sr).

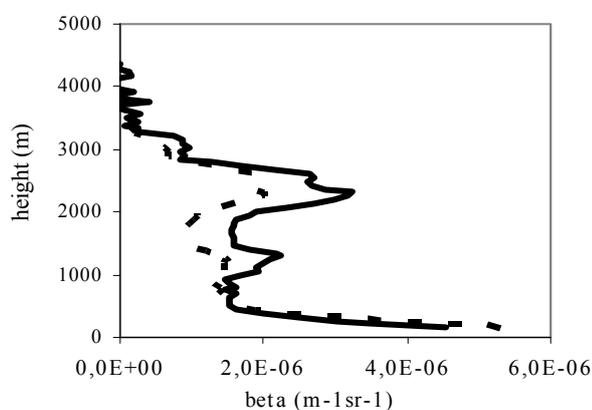


Fig. 8. Beta profiles at 532 nm (continuous line, CO.RI:S.T.A. portable lida) and 351 nm (dashed line INFM fixed lidar).

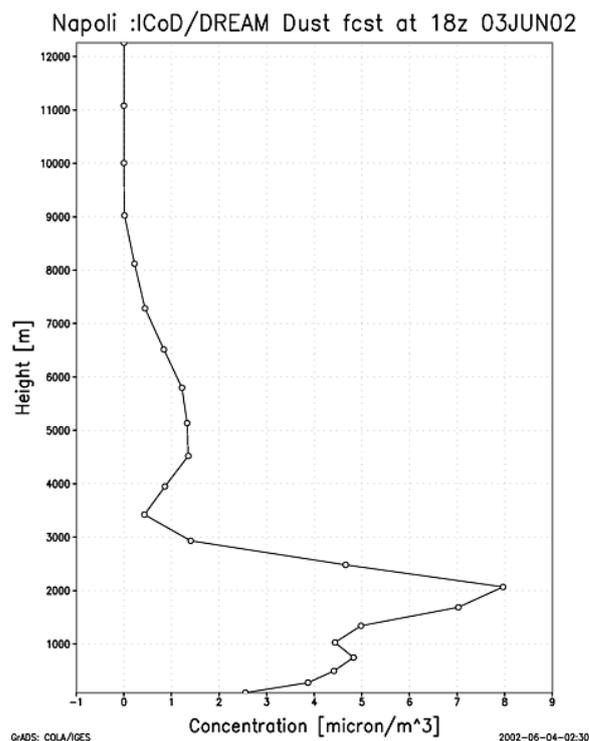


Fig. 9. Forecast based on DREAM model for the city of Naples at June 6<sup>th</sup>, 2002.

#### 4. Conclusions

A new prototype of portable lidar for aerosols measurements has been realised. The prototype is provided with an optical apparatus of emission/reception in bistatic configuration composed by a Cassegrain telescope and a beam-steerer, a Nd:YAG laser and two acquisition channels. The prototype can perform 3D measurements by scanning the atmosphere along the azimuth and the zenith angles. Thanks to its limited size (height 1m, width 1m) and light weight (less than 50 Kg), the system can be easily moved for *in situ* measurements. Intercalibration measurements with a fixed lidar have been performed showing very reliable performance of the prototype. Moreover backscattering coefficient measurements at two different wavelengths have been performed in order to evaluate the backscatter -related Angstrom coefficient, which is related to the aerosols particles dimension.

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