Measurement of Mount Etna plume by CO_2-laser-based lidar

Luca Fiorani,* Francesco Colao, and Antonio Palucci

Laser Applications Section, ENEA, Via Enrico Fermi 45, 00044 Frascati, Italy
**Corresponding author: luca.fiorani@enea.it*

Received November 20, 2008; revised January 19, 2009; accepted January 27, 2009;
posted February 12, 2009 (Doc. ID 104309); published March 11, 2009

The CO_2 laser-based agile tuner lidar for atmospheric sensing has been used to profile the volcanic plume of Mount Etna during its most recent eruption. Owing to the transmitted wavelength, this system is practically insensitive to air molecules while it detects aerosol loads, and thus the path attenuation of the laser beam is strongly affected by volcanic particulate. Vertical profiles of extinction coefficient were retrieved up to an altitude above ground level of 5000 m. The observed extinction coefficient ranges from 10^{-5} to 5×10^{-4} m^{-1}. The lidar was able to accurately track the spatiotemporal evolution of the volcanic plume thanks to a spatial resolution of 15 m and a temporal resolution of 1 min. © 2009 Optical Society of America

OCIS codes: 010.1100, 010.1300, 280.1350, 280.3640.

Volcanic particulate can strongly affect stratospheric and tropospheric temperatures, thus contributing to climate change. Although lidar [1] soundings of volcanic particulate have been carried out in the lower stratosphere after major eruptions [2], lidar measurements of volcanic plumes [3] are quite unusual, even if they offer the attractive capability of retrieving flux rates [4]. Moreover, to our knowledge, it is the first time that a CO_2-laser-based lidar is used to profile a volcanic plume. According to Mie theory, a CO_2-laser-based lidar, because of its wavelength of operation around 10 μm, has the advantage of efficiently detecting the relatively large aerosols that form volcanic plumes and, at the same time, being practically insensitive to molecules and small aerosols of a different origin.

Recently, the agile tuner lidar for atmospheric sensing (ATLAS) [5] has been developed and mounted on the ENVIronmental LABoratory (ENVILAB), hosted in a small truck. ATLAS (Table 1) can be decomposed into four subsystems: transmitter, receiver, detector, and analog-to-digital converter (ADC). The main parts of the transmitter are a tunable transverse excited atmospheric CO_2 laser (WH-20, Scientific Development & Integration, South Africa) and an off-axis reflective beam expander consisting of two oxygen-free high-conductivity copper mirrors manufactured in our laboratory. The laser is tunable thanks to the agile tuner consisting of a diffraction grating and a scanning mirror actuated by a computer-controlled galvo motor. The receiver is based on a Newton telescope. A liquid-nitrogen-cooled mercury-cadmium-telluride photodiode (PV-12-1, Fermionics, United States), coupled with a preamplifier designed to compliment it (PVA-500-10, Fermionics, United States), has been chosen as the detector.

The most recent eruption of Mount Etna started on May 13, 2008. Lidar measurements were carried out on July 14, 2008, while the volcano was still active. ATLAS was located in Santuario Magazzeni (latitude, 37.75986; longitude, 15.10459; altitude, 1025 m), i.e., about 10 km east from the main craters (altitude, 3329 m), and was pointed vertically. A strong wind came from the west, blowing the plume just over the system so that it remained around the altitude level of Mount Etna and thus above the top of the planetary boundary layer (PBL). An approximate position and altitude of the plume were visually checked from the system site and from locations some kilometers away from Santuario Magazzeni before, during, and after the data acquisition.

Within the CO_2 laser spectrum (9–11 μm), the beam is weakly attenuated by the atmosphere, i.e., the extinction coefficient is of the order of 10^{-4} m^{-1} for visibility larger than 5 km [6], unless the emission wavelength is tuned at the absorption line of an air molecule as in differential absorption lidar [1] experiments. The spectral stability is not critical in elastic backscatter lidar [1] experiments, because in this case the phenomena dominating the extinction and the backscattering coefficients depend weakly on the wavelength [6]. Nevertheless, it was checked, and there was no difference observed between the wavelength computer controlled by the galvo motor and the wavelength measured with a spectrum analyzer.

An example of the lidar signal is given in Fig. 1. The repetition rate was 5 Hz, and ATLAS was operated in the elastic backscatter lidar mode, transmitting a wavelength of 10.591 μm corresponding to the 10P20 emission line of the CO_2 laser. The experiment started at 10:45 a.m. (local civil time, i.e., universal time coordinated+2) and 3000 lidar returns were averaged corresponding to a temporal resolution of 10 min. The spatial resolution depends on the sampling rate and is 15 m.

The experimental points are compared with a calculation [1] assuming a constant extinction coefficient of 0.25 km^{-1} (this value has been retrieved from the signal slope between 500 and 1000 m) and with the level corresponding to the specified noise equivalent power (NEP) of the detector. The assumption of a constant extinction coefficient is very crude, as demonstrated by the not negligible discrepancy between experimental points and the calculated intensity of the signal, and was used only to estimate the maximum theoretical altitude of measurement as the altitude where the calculated intensity of the signal is

Table 1. Main Specifications of ATLAS

	Pulse Energy	750 mJ (at the 10P20 emission line)
Transmitter	Pulse duration	60 ns (FWHM)
	Repetition rate	$2 \div 20$ Hz
	Transmitted wavelength	$9.2 \div 10.8$ μm
	Beam divergence	0.7 mrad
Receiver	Mirror coating	Au
	Diameter	310 mm
	Focal length	1.2 m
Detector	Diameter	1 mm
	Specific detectivity	4×10^{10} cm Hz$^{1/2}$ W^{-1}
	Gain	200
	Linear dynamic range	$0.1 \div 1000$ mV
	Bandwidth	$0 \div 10$ MHz
Analog-to-digital converter	Dynamic range	8 bit
	Sampling rate	10 Ms s^{-1}

equal to the specified NEP of the detector (slightly beyond 5000 m).

The maximum of the signal around 150 m is well explained by the overlap function. The altitude of complete overlap is about 300 m, in good agreement with an analysis of the receiver response [7]. Between 1800 and 3300 m of altitude, the laser beam intercepts the volcanic plume and the number of backscattered photons rises accordingly. Beyond 4000 m signal and noise are hardly distinguishable, in reasonable agreement with the maximum theoretical altitude of measurement.

Starting from 300 m, the extinction coefficient was retrieved from the lidar signal (Fig. 2) with an inversion method [8], derived from the algorithms published by Klett [9] and Fernald [10], assuming a constant backscatter-to-extinction ratio of the order of 10^{-3}–10^{-1} sr^{-1}, in good agreement with aerosol measurements and models [6,11–13]. The reference range was 300 m, and the reference extinction was evaluated with the slope method using the 14 signal points from 300 to 495 m (owing to the incomplete overlap, it was impossible to extend the evaluation below 300 m).

Except the double peak from 1800 to 3300 m, the extinction coefficient shows a behavior in agreement with the roughly exponential decrease already observed in similar studies [11–13]. After a more careful inspection, two nearly linear decays can be distinguished; the first one is stronger and extends between 300 and 1000 m, and the second one is weaker and extends between 1000 and 4300 m. The most probable explanation of this behavior is that in the intervals 300–1000 m and 1000–4300 m the lidar probes PBL and free troposphere (FT), respectively, while the double peak from 1800 to 3300 m is due to the volcanic plume. The difference in the slope of the extinction coefficient in the intervals 300–1000 m and 1000–4300 m implies that the optical properties and the aerosol loads of PBL and FT are dissimilar. As far as we know, all published profiles measured by CO_2 lasers start at about 2000 m [11–13], and they cannot be compared with this study below that altitude. Nevertheless, the different optical properties of PBL and FT are routinely exploited to observe the temporal evolution of the PBL height by ultraviolet, visible, and near-IR lidars [8].

After the extinction profile of 10:45 a.m., three more measurements were carried out in the same experimental conditions at 12:38 p.m., 13:19 p.m., and 14:00 p.m. (Fig. 3). Note that at 12:38 p.m. the profile extends up to 5000 m, thus approaching the maximum theoretical altitude of measurement. The fact that different signals do not have the same maximum

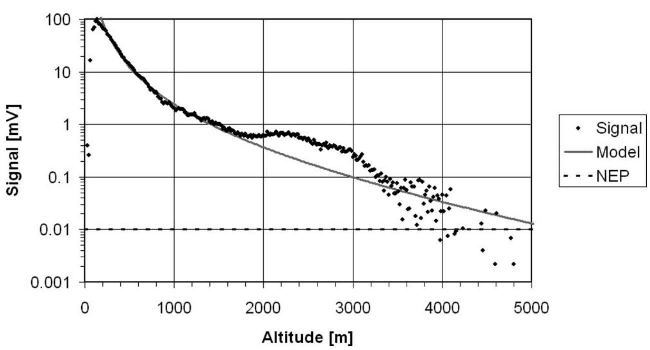

Fig. 1. Lidar signal compared with a theoretical model and the detector noise. The altitude in all figures is above ground level.

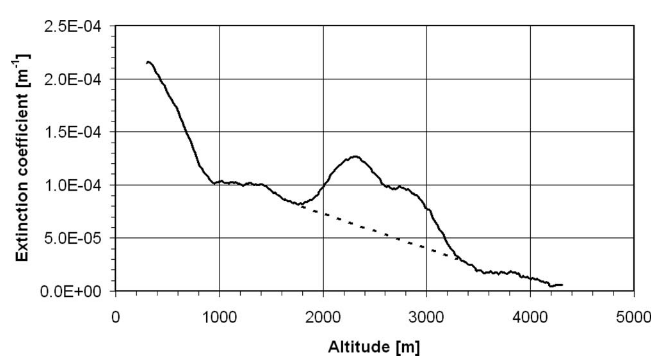

Fig. 2. Extinction coefficient retrieved from the lidar signal of Fig. 1. The double peak from 1800 to 3300 m appears to superimpose on a nearly linear decay and has been ascribed to the volcanic plume (the dashed curve has been added for the convenience of the reader).

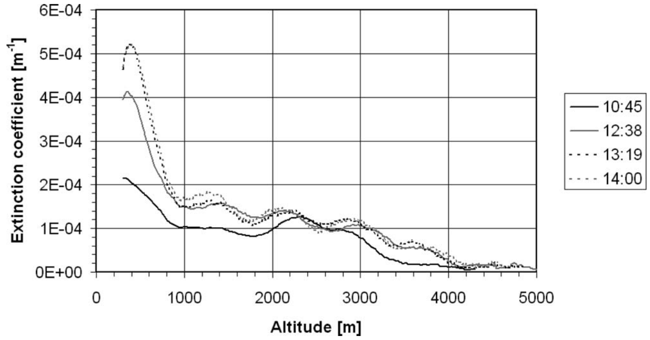

Fig. 3. Extinction coefficient retrieved at 10:45 a.m., 12:38 p.m., 13:19 p.m., and 14:00 p.m. in the same experimental conditions of Fig. 1. The volcanic plume appears to spread and stratify with time.

altitude of measurements is not surprising, because the signal-to-noise ratio can vary somewhat according to the change in atmospheric conditions. While the general behavior remains more or less the same, the extinction coefficient between 300 and 1000 m increases with time and the volcanic plume spreads and stratifies after 10:45 a.m. The increase in extinction coefficient between 300 and 1000 m in the warmest hours of the day can be explained by the convective activity that mixes the PBL. As soon as the Sun's radiation heats the Earth's surface, the aerosols that are below 300 m in the early morning start to be raised above that altitude by thermal columns [8], thus falling in the measurement range of ATLAS.

A moving aerosol plume may spontaneously undergo different microphysical processes that include condensation, evaporation, coagulation, sedimentation, and diffusion [13]. During this study, owing to the strong wind blowing the plume, it is likely that the change in extinction coefficient beyond 1000 m is related to transport phenomena, and thus the lidar observation of the spatiotemporal evolution of the volcanic plume gives information on the air mass dynamics of the FT.

Although the extinction profiles of Fig. 3 were acquired with a spatial resolution of 15 m and a temporal resolution of 10 min, ATLAS can follow the spatiotemporal evolution of the volcanic plume with a higher temporal resolution. To demonstrate this, the sample of 3000 lidar returns acquired at 10:45 a.m. was divided into ten consecutive subsamples of 300 lidar returns; then each set of 300 lidar returns was averaged, corresponding to a temporal resolution of 1 min, and the extinction coefficient was retrieved per each subsample. Eventually, the extinction profiles were combined in a contour plot of the extinction coefficient as a function of time and altitude (Fig. 4) showing in detail the spatiotemporal dynamics of the volcanic plume. It is clear that the optical thickness of the plume increases with time and the second peak develops at the end of the observation period.

In conclusion, the CO_2-laser-based lidar ATLAS has been used to profile the volcanic plume of Mount Etna. According to Mie theory, ATLAS is particularly sensitive to volcanic particulate. Extinction coefficient profiles have been retrieved up to an altitude above ground level of 5000 m with a spatial resolution of 15 m and a temporal resolution of 1 min. These performances are adequate to follow the spatiotemporal dynamics of the volcanic plume.

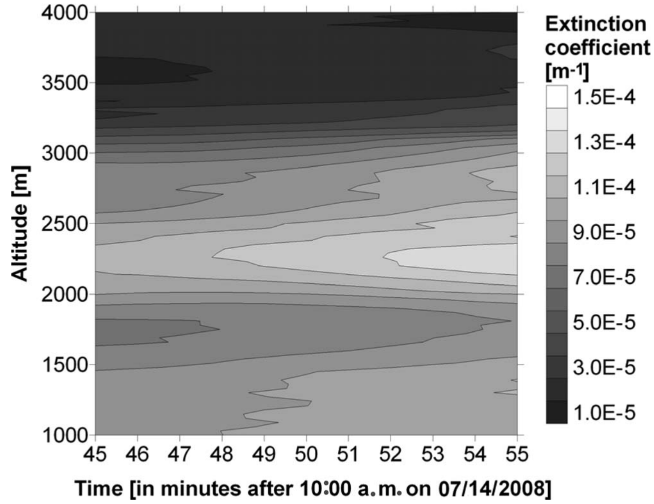

Fig. 4. Contour plot of the extinction coefficient as a function of time and altitude.

The authors are deeply grateful to R. Fantoni for her constant encouragement and A. Aiuppa, G. Giudice, and C. Spinetti for fruitful discussions. We extend a special thank you to D. Del Bugaro for his important involvement, N. du Preez and F. Lamattina for laser assistance, and R. Giovagnoli for mechanical parts. We gratefully acknowledge the valuable support at Mount Etna by G. Giuffrida, R. Guida, and M. Liuzzo. We also deeply appreciated the helpful suggestions of the referees.

References

1. R. M. Measures, *Laser Remote Sensing* (Krieger, 1992).
2. H. Jaeger, Geophys. Res. Lett. **19**, 191 (1992).
3. P. Weibring, H. Edner, S. Svanberg, G. Cecchi, L. Pantani, R. Ferrara, and T. Caltabiano, Appl. Phys. B **67**, 419 (1998).
4. J. N. Porter, K. A. Horton, P. J. Mouginis-Mark, B. Lienert, S. K. Sharma, E. Lau, A. J. Sutton, and T. Elias, Geophys. Res. Lett. **29**, 1783 (2002).
5. L. Fiorani, M. Aglione, I. Okladnikov, and A. Palucci, in *Proceedings of the First 'Atmospheric Science Conference'* (ESA, 2006).
6. A. Ben-David, Appl. Opt. **38**, 2616 (1999).
7. R. Velotta, B. Bartoli, R. Capobianco, L. Fiorani, and N. Spinelli, Appl. Opt. **37**, 6999 (1998).
8. L. Fiorani, in *Lasers and Electro-Optics at the Cutting Edge* (Nova, 2007).
9. J. D. Klett, Appl. Opt. **20**, 211 (1981).
10. F. G. Fernald, Appl. Opt. **23**, 652 (1984).
11. A. Deepak, G. S. Kent, and G. K. Yue, *Atmospheric Backscatter Model Development for* CO_2 *Wavelengths* (NASA, 1982).
12. M. J. Post, F. F. Hall, R. A. Richter, and T. R. Lawrence, Appl. Opt. **21**, 2442 (1982).
13. R. T. Menzies, M. J. Kavaya, P. H. Flamant, and D. A. Haner, Appl. Opt. **23**, 2510 (1984).