# A portable LIDAR system for the early detection: FfED system - a case study.

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**ABSTRACT**

*Abstract* - Forest fires can be the cause of serious environmental and economic damage. For this reason considerable effort has been devoted to forest protection and fire-fighting. Experimental and theoretical investigations have already shown that the LIDAR (Light Detection and Ranging) technique is a powerful tool to detect the tenuous smoke plumes produced by forest fires at an early stage In this paper the capability of a LIDAR system to detect a forest fire is explained and an upgrade of the LIDAR technique to reduce the number of false alarms is described. It is based on the comparison between the backscattered signal due to the orography, acquired in absence of any fire, and the signal obtained during surveying.
The first experimental results, acquired by FfED (Forest fire Early Detection) system, will be shown.

*Key-Words* : LIDAR, Environment, Forest Fires, Early Detection, Portable

## 1 INTRODUCTION

The LIDAR technique is a quite powerful experimental method for the exploration of the atmosphere [1]. It is often used to acquire the information necessary to investigate various phenomena and to validate models relevant to different topics of atmospheric physics. Furthermore it can also be used in environmental surveys for monitoring particulate and gases.[1] [2]
Theoretical investigations by Andreucci and Arbolino [3] [4], experiments by Lavrov and Vilar [5], Pershin et al. [6] and Utkin at al. [7] [8] [9] have shown that LIDAR is a powerful technique to detect the tenuous smoke plumes produced by forest fires at an early stage.
In our previous works [10] [11] [12], the potential of the LIDAR/DIAL technique to detect forest fires, evaluating the increment of the particulate matter and/or the water vapor concentration in atmosphere, has been investigated numerically and with laboratory tests . In this paper the first results of extensive experimental campaigns ( in field and in cell) and numerical simulations results are reported. They demonstrate the capability of the developed portable and automatic system to detect the smoke plumes of even small amounts of combusted material equal to 1kg. Using a laser energy of 360 mJ, consistently with present safety regulations, the maximum range of operation is $1.16*10^{-7}$ J $cm^{-2}$.
Numerical simulations have been developed, by the mean of COMSOL Multhiphysics software, to analyse the behaviour of several vegetable substances during combustion process. At the same time measurements in cell with an uniform and controlled environment have been performed. The numerical output compared with the experimental ones has demonstrated the capability of FfED to detect a small forest fire. Since the presented LIDAR system has been designed to operate in complex orographies, particular attention has been devoted to the reduction of false alarms, one of the main issues for the extensive applications of this early detection technique. The main upgrade of the technique has been implemented to increase the immunity to false alarms. It consists in the discrimination of other types of smokes, which are not due to forest fires and therefore should not trigger any alarm (including the orographic peaks)

With regard to the structure of the paper, in section 2 a description of the mobile LIDAR system, its principal characteristics and the main design choices are given. The results of numerical simulation are shown in section 3 and the results of the first experimental campaigns are described in section 4 and the conclusions and future developments are drawn in the section 5.

# 2 THE AUTOMATIC PORTABLE LIDAR SYSTEM

## 2.1 Overview of the system

The LIDAR system, whose results are presented in this paper, consists of an optical apparatus of transmission/reception assembled in biaxial configuration. The unit is constituted of a transmitter system based on a compact Q-switched Nd:YAG laser source operating at three wavelengths: 1064 nm, 532 nm and 355 nm. The backscattered signal is collected by a Newtonian Telescope and then transferred by an optical guide to a photomultiplier tube (PMT). The signal acquisition is performed by a LeCroy digital oscilloscope communicating with the computer where the data are stored. A schematic of the set-up is reported in Figure 1 and the basic specifications of the main system's components are summarized in Table 1.

| | |
|---|---|
| ***Transmitter:*** | |
| Laser | Q-switch Nd:Yag |
| Energy pulse at 1064 nm | 360 mJ |
| Pulse time width | 5 ns |
| Divergence angle | 0,5 mrad |
| Pulse Frequency | 10 Hz |
| ***Receiver:*** | |
| Telescope type | Newtonian |
| Nominal focal length | 1030 mm |
| Primary mirror diameter | 210 mm |
| Detector | Photomultiplier (PMT) |
| Photocathode sensibility | 72 mA/W |
| Response time | 30 ns |

**Tab. 1**. *Specifications of our LIDAR system*

In order to guarantee eye-safety conditions, the laser beam output has been reduced so as to respect the standard maximum permissible exposure(ANSI Z136.1-1986),which is equal to $1.16*10^{-7}$ J $cm^{-2}$. The system can be operate remotely by means of a labview routine .The whole system is assembled in a small van that occupies a volume of 3,5 $m^3$ to permit an easy transportation to the required monitoring locations.

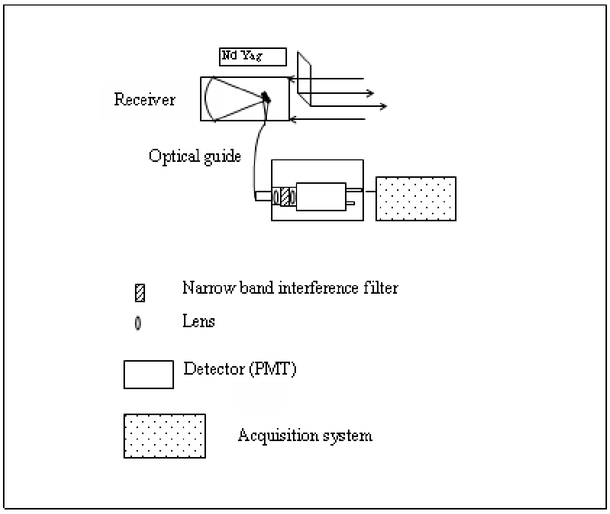


**Fig. 1** *Schematic of the Mobile LIDAR system*

The hardware and software components of system are placed inside a van hauled to a car to reach impervious location sited, for example, on the mountains.
The LIDAR system is placed on a support and it is possible to move it with two step-motors whose permit a movement on a horizontal plane (from 0° to 360°) and on a vertical plane (from -10° to 90°C) with a resolution of 1,25°.
The system can be managed in remote by a software in labview that allows to :

- open and close the windows of the van in 20 second to avoid, in case of impervious meteorological conditions, the damage of hardware and software components;
- test the laser functions to control if the laser works in the single shot mode and continuum shot mode and to line up the system;
- test the motors functions.

In the experiments it is necessary to adapt the system to the several situation and places. At the beginning of experiments, in the point in which the van with the system is placed, is necessary to measure the geographical coordination with a GPS (Global Positioning System) system. To consider the point of measurement at the beginning of experiment is possible plan, by the software, the follow parameters :

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- the north;
- the position of laser in comparison to the horizontal plane.

Another important input parameter that we can set by the software is the acquisition number (in our experiments fixed at 100) .

The system is placed (by an automatic control on the motor movements obtained by the encoders) on several positions, in correspondence to the coordinates elaborated by the software, and it starts to shot in continuum mode since to reach the number of acquisition set at the beginning of experiment. In case of alarm the system is automatically placed on the suspected position and it starts to shot again to validate or deny the alarm. In case of fire alarm confirmation the coordinates of fire are automatically send, by the software, to a environmental protection organization.

In conclusion the system output are:

- a complete control of the selected area;
- an advertise of dangerous (in case of fire) and the geographical coordinate of fire;
- a data storage of the all experiments for each position mapped by the system.

## 2.2 The optical design

Since one of the main difficulty of LIDAR system for atmospheric surveying is the low signal to noise ratio, the collection optics has to be treated with particular attention. In order to optimise the focalisation of the backscattered signals on the photomultiplier tube, an optical system (composed of two lenses and a narrow band interferential filter) has been designed with the ZEMAX software package with the aim to simulate the optical characteristics of the entire optical system. The expected backscattered radiation at 1064 nm, transferred by the telescope and optical system on the photomultiplier tube area, has been calculated as described in the following .

The energy focalized on the photomultiplier tube is given by the product of four terms:

$$E_{1064cathode} = \xi_{so}(\lambda) E_{1064accepted} = \\ = (\xi_{filter} \cdot \xi_{guide} \cdot (1-\xi_{dispersion}) \cdot \xi_{gated})_{1064nm} \cdot E_{1064accepted} = \\ = 0.37 E_{1064accepted} \quad (1)$$

where:

- $E_{1064,cathode}$ is the energy which arrives at the PMT cathode at 1064nm;
- $E_{1064,accepted}$ is the energy collected by the telescope;
- $\xi_{so}(\lambda)$ represents the spectral transmission factor of the receiver system;
- $\xi_{filter}$ =0.73% is the narrow band filter energy transmission at 1064 nm;
- $\xi_{guide}$ =60% is the optical guide energy transmission at 1064nm;
- $\xi_{dispersion}$ =11% is the energy fraction subjected to dispersion of the liquid light-guide;
- $\xi_{gated}$ =96% is the backscattered energy quantity focused into the PMT effective surface of 78.5 mm$^2$

The overlapping factor for a biaxial LIDAR system (Kuze et al., 1998) has been considered to analyse possible radiation losses due to an inadequate overlap between the area of the laser illumination and the receiver-optics field of view at the target area. A poor overlap leads to a weak backscattered signal irrespective of the size of the telescope or the power of the laser.

The radius of the receiver-optics field of view $r_T(R)$ and the radius of the laser pulse in the target plane $W(R)$ are given by [2]:

$$r_T(R) = r_0 + \phi R \quad (2)$$

$$W(R) = \{W_0^2 + \theta^2 R^2\}^{1/2} \quad (3)$$

where:

- $r_0$ represents the effective radius of the primary mirror telescope;
- $W_0$ is the laser output at beam waist;
- $\theta$ is the laser half divergence angle;
- $\phi$ is the receiver-optics half opening angle dependent on the focal distance ($f$ ) and on the light-guide radius ($rD$) by the relation: $\phi = rD/f$ .

The overlap probability along the measurement's range is called: *Geometrical Form Factor* $\xi(R)$ and can be expressed in the form [1]:

$$\xi(R) = \frac{A\{r_T(R); W(R); d(R)\}}{\pi W^2(R)} \quad (4)$$

where:

- $d(R)$ indicates the separation of the telescope and laser axes in the target plane;
- A represents the area overlap function.

The variation of the overlap factor $\xi(R)$ over the range of interest for our LIDAR system has been estimated

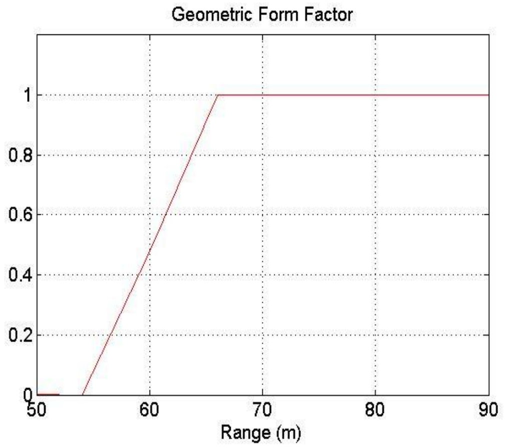


**Fig.2** *Behavior of FFED system Geometric Form Factor in function of the range in meters.*

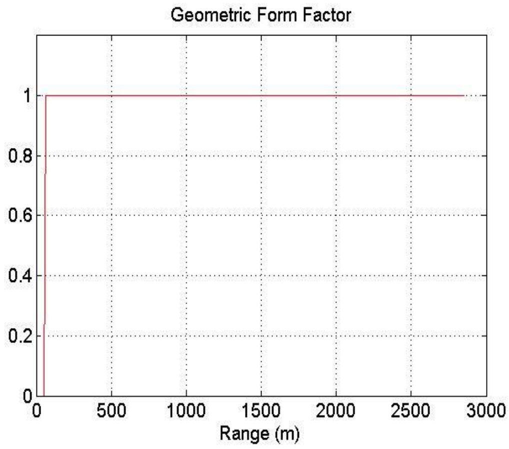


**Fig.3** *Behavior of FFED system Geometric Form Factor in function of the range in meters.*

As shown in Figures 2 and 3, when the laser and the telescope axes are approximately parallel, the geometrical probability factor increases in a very short range and saturates to unity up to large distances (superior to 2500 metres); this is due to the fact that the effective radius of the primary mirror telescope ($r_0$=105 mm) is about a factor of 2 larger than the laser output aperture ($Wo$=2.5mm). Therefore the signal intensity is zero only at short distances when there is not overlap between the receiver-optics field of view and the laser illumination area. At distances superior to 67 metres the backscattered signal value is independent from the Geometric Form factor and is equal to one.

## 3 NUMERICAL SIMULATION

A mathematical model to know the behaviour of several substances (that presents characteristics similar to those expected to be in the forest) during the combustion process in a measurement cell has been developed. The use of the measurement cell has been necessary to create an uniform and control lled environment where the smoke diffusion process is not influenced by weather conditions. The cell has a length of 8.6 meters and a diameter of 0,6 meter. A hole with a pipe in the bottom of the cell has been added in order to allow the smoke inlet (Figure 4).

**Fig.4** *Cell*

Numerical simulation have been developed by the mean of the software Comsol Multiphysics that uses the finite elements method to solve differential equation systems.

The starting equation is :

$$d_a \frac{\partial q}{\partial t} - \nabla(c\nabla q) = R - \overrightarrow{u}\,\nabla q \qquad (5)$$

Where:

- ***q*** : *represents the smoke concentration;*
- ***c*** : *represents the scatter term ;*
- ***R*** : *velocity of reaction ;*
- $\overrightarrow{u}$ : *velocity vector*

Once that the boundary conditions have been properly setted it is possible to solve equation (5) and know the combustion products behaviour inside the cell.

Figure 5 shows the trend of this concentration along the symmetry axes of the cell.

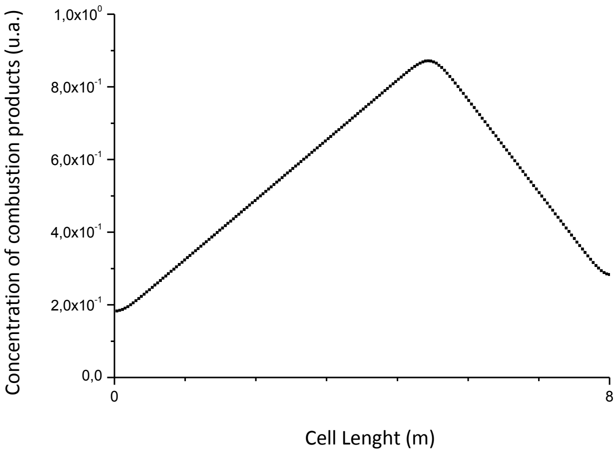


**Fig.5** *Simulation of combustion products behavior along the cell's central axis*

# 4 RESULTS OF THE EXPERIMENTAL MEASUREMENTS

## 4.1 Experimental campaign in cell

Experiments with the Nd:YAG laser source have been implemented for each typology of material burned and using each of the three characteristic wavelength of this source : 1064 nm, 532 nm, 355nm. Due to the fact that the special resolution of the laser pulse (75 cm) was lower than the length cell it has been possible calculate the backscatter coefficient profile of the smoke inside the cell. In the figure 4 the concentration profile of the combustion products obtained during the experiments is showed. By a comparison with the simulation results (Figure 6) it is evident that the experimental results match the numerical one.

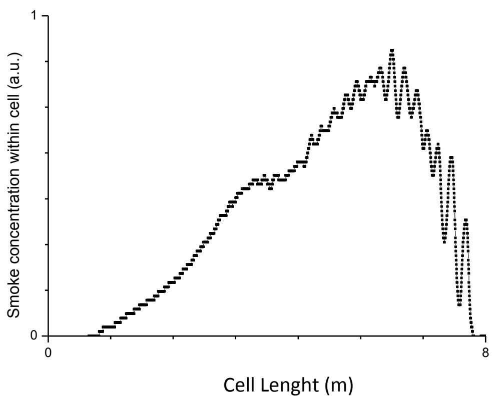


**Fig.6** *Normalized distribution of combustion products in cell*

After that experiments have been developed using a wavelength of 1064nm (the one used in the field campaign to detect smoke particles) and burning 10 g of eucalyptus and again the good agreement with numerical results is evident (Figure 5-6). An evaluation of backscattering values vs cell length has been done and the results are reported in Figure 7.

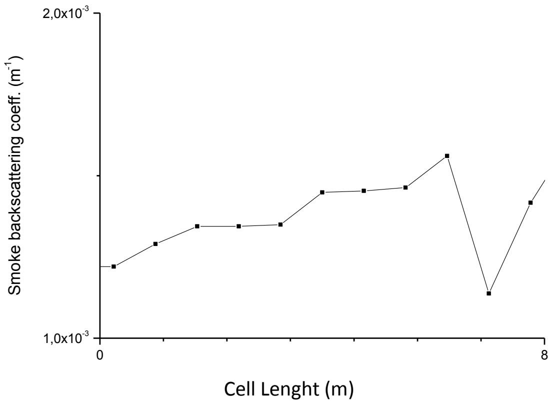


**Fig.7** *Backscatter coefficient profile of smoke from eucalyptus at 1064 nm*

So by the mean of these results the experimental campaigns in field have been organized and the results are showed in section that follow (4.2).

## 4.2 Experimental campaign in field

The purpose of the measurements performed is firstly to verify the capability of the FfED system to detect the tenuous smoke plumes produced by forest fires at an early stage, and secondly to test the methodology developed in the case of complex orography to distinguish the smoke plume backscattered signal from orographic peaks that otherwise would give rise to false alarms. A new signal processing method, able to discriminate peaks due to the fires from peaks due to the other factors, has been developed.

For this reason the experimental site selected is a place with a complex orography; it is located near Settefrati in the province of Frosinone (Italy) precisely in the Canneto valley surrounding the Meta massif's buttresses. This location remains at a height of 1030 m above mean sea level; its more high portion is wildlife reserve in the Abruzzo, Molise and Lazio National Park.

A quite small fire was lighted into a box at a distance of about 700 metres from the system; Figure 8 and Figure 9 show FfED positioning in course of action, the point of fire lighting, and Figure 10 the measures direction.

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**Fig.8** *Canneto Valley ( the red point visualizes the zone of fire lighting)*

**Fig.9** *FfED system positioning in course of action.*

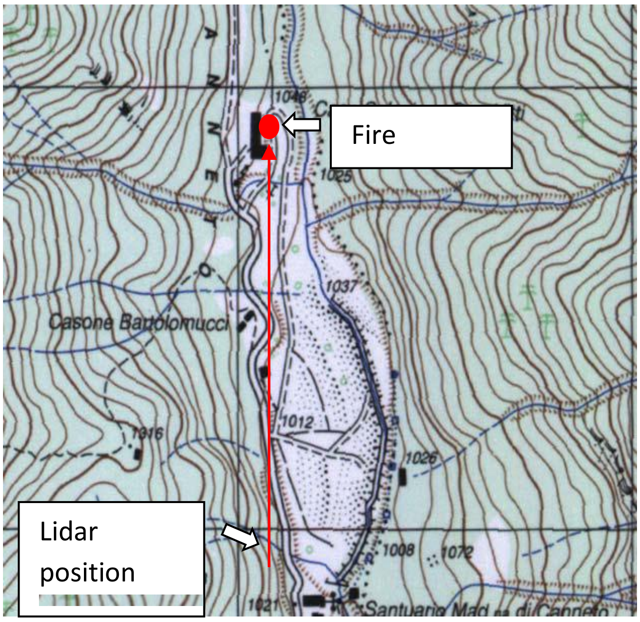


**Fig.10** *Measures direction in the first set of measurements*

If the site's orography remains unknown each peak will be owing to a fire; in order to reduce false alarms it is necessary have an information about the backscattered signal by the Orographic obstacles.
So the backscattered signal obtained in presence of a fire typically presents one peak due to the interaction of the laser beam with the smoke plume at a specific distance, and other peaks due to fixed orographic targets. LIDAR backscattered signals obtained have been analysed. Each acquisition data file is obtained by the average of 100 laser pulses every 10 seconds. Figure 11 shows the backscattered signal at 1064 nm.

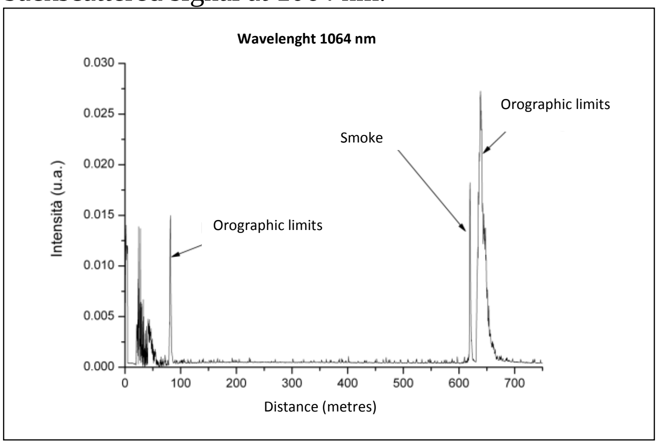


**Fig.11** *Backscattered LIDAR signal at 1064 nm obtained during a set of measurements.*

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# 5 CONCLUSION AND FUTURE DEVELOPMENTS

In this work a LIDAR system, capable of detecting forest fires at a very early stage but with low percentage of false alarms, has been presented. The main design choices and their implementations have been described.

The results obtained during by the experimental campaign in cell have confirmed the good agreement between the numerical results obtained by the mean of numerical simulation and the experimental ones obtained with the FfED LIDAR system implemented and they have demonstrate the capability of FfED system to detect small fire events.

The first experimental results in field have confirmed the capabilities of the system and have shown that it is able to localize a smoke plume recognizing if the peaks on the backscattering LIDAR signal, at different ranges, are due to the combustion of a small amount of vegetable fuel or to a fixed target.

In order to improve the ability of the method to locate the exact position of a fire, we intend to develop a dispersion model to simulate the smoke back trajectory; this will allow to send the exact alarm coordinates to the PC connected to an environmental protection organization and to minimize the time of intervention.

The first experimental results are encouraging but more specific tests have to be performed to fully characterize the potential of the proposed approach.

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