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# Laser rangefinder architecture as a cost-effective platform for lidar fire surveillance

Andrei B. Utkin [a,*], Alexander Lavrov [a], Rui Vilar [a,b]

[a] INOV, Rua Alves Redol, 9, 1000-029, Lisbon, Portugal
[b] Instituto Superior Técnico, DepMat, Av. Rovisco Pais, 1049-001, Lisbon, Portugal

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ABSTRACT

The possibility of early fire detection via lidar (light detection and ranging) technology implemented through a low-cost rangefinder is investigated. The evaluation is based on the variation of signal-to-noise ratio (*SNR*) with distance calculated on the basis of a theoretical model and determined experimentally. The theoretical *SNR* is obtained by combining a hydrodynamic model of the smoke plume taking into consideration the effect of wind (which enables calculation of smoke–particle distribution) and a lidar model that enables backscattered radiation intensity, detected power and, eventually, *SNR* to be assessed using Mie theory. The calculated values of *SNR* agree reasonably well with the experimental results obtained using small-scale experimental fires and show that in favourable conditions detection ranges up to about 4 km are achievable.



## 1. Introduction

Theoretical and experimental investigations concerning the possibility of forest fire detection using elastic [1–7] and Doppler [8] lidar and differential absorption lidar (DIAL) [9] have been carried out for more than a decade. However, wide application of lidar technologies in this area is severely restrained by the high cost and complexity of the equipment, the need for periodic maintenance by specially trained personnel and, in some cases, radiation hazard: the Nd:YAG laser technology mainly used for laser detection and ranging operates at 1064 and 532 nm wavelengths, both of which are dangerous to the eye. On the other hand, mass-production laser rangefinders are also based on time-of-flight technology for distance measurements and are much cheaper, more robust, and compact. In addition, they are eye-safe, more suitable for standalone functioning and do not need frequent servicing [10–13]. The problem of constructing a lidar smoke sensor based on an industrial rangefinder architecture, in which the distance measuring electronics is replaced by a system of acquisition of the retroreflected power signal, is therefore of considerable interest.

This paper presents a computational and experimental assessment of available rangefinder instruments for fire detection via laser-radiation retroreflection from the particulate matter in smoke plumes. The main parameters characterising the detection process and their interrelationships are discussed in Section 2. The numerical model of lidar operation is based on simulation of the smoke plume structure discussed in Section 3. Mixing of the smoke plume with ambient air and its displacement under the crosswind is described by a system of Reynolds-averaged three dimension Navier–Stokes equations [14], a model widely used for various physical and technological applications [15,16]. The smoke–particle distribution obtained is used for estimation of the smoke plume detecting efficiency for two configurations representing the most popular emitter technologies: diode laser and *Q*-switched solid-state laser. Experimental and theoretical results are presented in Section 4.

## 2. Basic relations

### 2.1. Retroreflected power and lidar signal

The power of retroreflected radiation $P_{rec}$ collected by a lidar or a laser rangefinder can be written as [2–4,17–19]

$$P_{rec}(R) = E_l \frac{\pi D_{rec}^2}{8R^2} \tau_{rec}\tau_{tr} \exp\left(-2\int_0^R \alpha(R')dR'\right) c\beta(R) \quad (1)$$

for a distributed target characterised by the backscattering coefficient $\beta(R)$ and

$$P_{rec}(R) = E_l \frac{\pi D_{rec}^2}{8R^2} \tau_{rec}\tau_{tr} \exp\left(-2\int_0^R \alpha(R')dR'\right) \frac{\sigma}{4\tau} \quad (2)$$

for a solid target of reflectivity $\sigma$. In these equations $R$ is the distance to the target, $E_l$ the laser-pulse energy, $c$ the speed of light, $D_{rec}$ the receiver optics diameter, $\tau_{rec}$ and $\tau_{tr}$ the receiver and

* Corresponding author. Tel.: +351 213100426; fax: +351 213100401.
*E-mail address:* andrei.utkin@inov.pt (A.B. Utkin).

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transmitter efficiencies, $\alpha(R)$ the extinction coefficient and $\tau$ the laser-pulse duration. The lidar signal $P_{sig}$ also depends on the light power measuring device in the receiver channel which transforms the retroreflected radiation into an electrical signal. For an avalanche photodiode (APD), traditionally used for this purpose in the configurations under consideration, $P_{sig}$ is related to $P_{rec}$ by the equation [18,20]

$$P_{sig}(R) = (G_{APD} R_{APD} P_{rec}(R))^2 R_L, \quad (3)$$

where $G_{APD}$ and $P_{APD}$ denote APD gain and responsivity, while $R_L$ stands for load resistance.

### 2.2. Detection parameters

According to Measures [17], Overbeck et al. [18], and Youmans et al. [20], the signal-to-noise ratio ($SNR$) of the lidar signal resulting from the accumulation of $n_a$ lidar returns is given by the equation

$$SNR(R) = \frac{P_{sig}(R)\sqrt{n_a}}{P_{th} + P_{amp} + P_{dark} + P_{shot} + P_{bgnd}} \equiv \frac{P_{sig}(R)\sqrt{n_a}}{P_{noise}}, \quad (4)$$

where $P_{th}$ is the thermal-noise power, $P_{amp}$ the electronic postdetection amplifier noise power, $P_{dark}$ the detector dark-current noise power, $P_{shot}$ the signal shot-noise power, $P_{bgnd}$ the background illumination shot-noise power and $P_{noise}$ the total noise power.

In contrast to lidar, laser rangefinding is based on time-of-flight measurement rather than on signal accumulation. Rangefinder performance can be assessed on the basis of the probability of target detection

$$\eta_D = \lim_{N_M \to \infty} \frac{N_D}{N_M}, \quad (5)$$

where $N_D$ is the number of successful measurements of the distance to the indentified target and $N_M$ is the total number of measurements and the accuracy of the distance measurement [21] is

$$\Delta R = \frac{c\tau}{2\sqrt{SNR}}. \quad (6)$$

To determine the criterion of smoke–plume detection, we use an algorithm suggested by Pal et al. [22] that includes calculation of the following values: (*i*) the lidar signal at the point of maximum particle concentration $P_{sig(\max)}$; (*ii*) the signal at the smoke/air boundary $P_{sif(bnd)}$; (*iii*) the noise at the point of maximum particle concentration $P_{noise(\max)}$ and (*iv*) $SNR$ in accordance with the formula

$$SNR = \frac{P_{sig(\max)} - P_{sig(bnd)}}{P_{noise(\max)}} \sqrt{n_a}. \quad (7)$$

It is assumed that reliable detection is conditioned by

$$SNR \geqslant 2. \quad (8)$$

### 2.3. Estimation of the threshold and signal values for specific probabilities of false alarms and misdetection

A possible scenario of forest fire surveillance assumes the detectors will be installed in watchtowers and the laser beam will scan in the horizontal plane. The detection efficiency is characterised by the probability of smoke detection against the adjusted value of the false-alarm probability (the probability of triggering an alarm in the absence of smoke). The detector noise presents a Gaussian distribution (see, for example, Andreucci and Arbolino [1], Bufton [21], Scolnik [23], and Gavan [24]). In this case the probability density function is

$$pb(s) = \frac{1}{\sqrt{2\pi n^2}} \exp\left(-\frac{(s - s_{ave})^2}{2n^2}\right)$$

with the average signal $s_{ave} = \int_{-\infty}^{\infty} s\, pb(s) ds$ and the mean square deviation $n^2 = \int_{-\infty}^{\infty} s^2 pb(s) ds - s_{ave}{}^2$.

The false-alarm probability is given by [1,21,23]

$$pb_{FA} = \int_{S_T}^{\infty} \frac{1}{\sqrt{2\pi n^2}} \exp\left(-\frac{t^2}{2n^2}\right) dt = 0.5 - \mathrm{erf}\left(\frac{s_T}{n}\right),$$

where

$$\mathrm{erf}(\zeta) = \frac{1}{\sqrt{2\pi}} \int_0^{\zeta} \exp\left(-\frac{t^2}{2}\right) dt$$

is the error function [25] and $s_T$ is the threshold value of target detection.

For the chosen value of $pb_{FA}$ (and consequently $s_T$), the probability of smoke detection is [1,21]

$$pb_D = 0.5 - \mathrm{erf}\left(\frac{s_T - s}{n}\right).$$

## 3. Numerical model of the smoke plume

The three-dimensional numerical model of the smoke plume is based on the Reynolds-averaged Navier–Stokes equations [26]

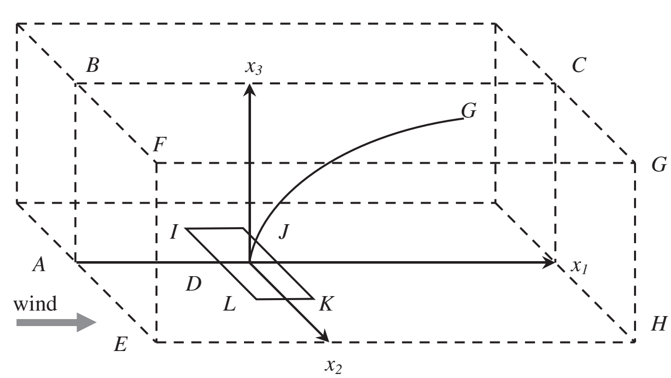


**Fig. 1.** Computational scheme.

**Table 1**
Diffusion and source coefficients for the conservation equations.

| $\phi$ | $\Gamma(\phi)$ | $S(\phi)$ |
|---|---|---|
| 1 | 0 | 0 |
| $u_1$ | $\mu_{eff}$ | $(-\partial p/\partial x_1)+(\partial/\partial x_1)(\mu_{eff}(\partial u_1/\partial x_1))(+(\partial/\partial x_2)(\mu_{eff}(\partial u_2/\partial x_1)+(\partial/\partial x_3)(\mu_{eff}(\partial u_3/\partial x_1))-g_1(\rho-\rho_{ref})$ |
| $u_2$ | $\mu_{eff}$ | $(-\partial p/\partial x_2)+(\partial/\partial x_1)(\mu_{eff}(\partial u_1/\partial x_2))+(\partial/\partial x_2)(\mu_{eff}(\partial u_2/\partial x_2))+(\partial/\partial x_3)(\mu_{eff}(\partial u_3/\partial x_2))-g_2(\rho-\rho_{ref})$ |
| $u_3$ | $\mu_{eff}$ | $(-\partial p/\partial x_3)+(\partial/\partial x_1)(\mu_{eff}(\partial u_1/\partial x_3))+(\partial/\partial x_2)(\mu_{eff}(\partial u_2/\partial x_3))+(\partial/\partial x_3)(\mu_{eff}(\partial u_3/\partial x_3))-g_3(\rho-\rho_{ref})$ |
| $h$ | $\mu_{eff}/\mathrm{Pr}$ | 0 |
| $k$ | $\mu_{eff}/\sigma_k$ | $P_1+G-\rho\varepsilon$ |
| $\varepsilon$ | $\mu_{eff}/\sigma_\varepsilon$ | $c_1(\varepsilon/k)(P_1+c_3G)-c_2\rho(\varepsilon^2/k)$ |