Eye-safe lidar measurements for detection and investigation of forest-fire smoke

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Abstract. The problem of eye safety in lidar-assisted wildland fire detection and investigation is considered as a problem of reduction of the hazard range within which the laser beam is dangerous for direct eye exposure. The dependence of this hazard range on the lidar characteristics is examined and possible eye-safety measures discussed. The potential of one of the cheapest ways of providing eye safety, which is based on placing the lidar in an elevated position and using a 1064-nm laser beam with increased divergence, is also investigated experimentally. It is demonstrated that a lidar system operating with wider beams maintains its ability to detect smoke plumes efficiently. Providing eye-safe conditions allows scanning of the internal 3D structure of smoke plumes in the vicinity of fire plots. Examples are given as layer-by-layer smoke concentration plots on the topographic map.

Additional keywords: Gestosa; remote sensing.

Introduction

Lidar (light detection and ranging) uses pulses of laser radiation that are partially backscattered from possible targets (e.g. solid obstacles, particle clouds, aerosols, molecules). The intensity of back-scattered radiation is recorded as a function of time. Experimental (Pershin \textit{et al}. 1999; Utkin \textit{et al}. 2002\textsuperscript{a,} 2003) and theoretical (Andreucci and Arbolino 1993; Lavrov and Vilar 1999; Vilar and Lavrov 2000; Lavrov \textit{et al}. 2003) investigations have demonstrated that lidar is a promising technique for the detection of the tenuous smoke plumes produced by forest fires at an early stage of development, when the fire is still easy to extinguish. Being an active detection technique, lidar presents better sensitivity than conventional fire surveillance systems based on visible or infrared imaging (Thomas and Nixon 1993; Rauste \textit{et al}. 1997). Field experiments, described previously by Utkin \textit{et al}. (2002\textsuperscript{a}), demonstrated that fires with a burning rate as small as 0.03 kg of wood per second can be detected reliably from a distance of 6.5 km. Another advantage of lidars is that, instead of visualising the flames (Barducci \textit{et al}. 2002), they function by interacting with smoke, so that they do not need line-of-sight observation of flames. Raw lidar signals resulting from smoke plumes of developed fires may be analysed by the so-called inversion techniques (Klett 1981, 1983, 1985; Fernald 1984; Matsumoto and Takeuchi 1994; Wei \textit{et al}. 2001). The application of these techniques yields the distribution of the extinction and back-scattering coefficients along the laser beam path and, finally, the concentration of smoke particles along the same line. Thus, by using an appropriate scanning procedure, the spatial distribution of smoke density around the lidar measurement site can be reconstructed, enabling the observer to analyse the internal plume structure (Utkin \textit{et al}. 2002\textsuperscript{b}). This characteristic makes lidar methods an invaluable tool for the investigation of fire and smoke behaviour in natural conditions and the experimental verification of atmospheric gas dynamics models.

One negative aspect of active laser sensing in free space is its potential danger to the eye. According to American National Standard Institute and International Electrotechnical Commission standards (Carnuth and Trickl 1992), the most popular lasers used in lidars, such as Q-switched Nd:YAG, produce in the near zone a pulsed output radiation at 1064-nm and 532-nm wavelengths with an energy density four to five orders of magnitude greater than the maximum permissible single-pulse exposure of the human eye. In traditional lidar applications, such as investigation
of the ozone layer and the study of aerosols in the upper atmosphere, the laser beam is directed vertically or nearly vertically to the sky, so that the risk of eye injury is minimal. This is not the case in wildfire surveillance applications, where the laser pulses travel along predominantly horizontal atmospheric paths, at a low height above the ground. The eye-hazard problem was partially considered by the present authors from a theoretical standpoint in Utkin et al. (2003). Due to the primary importance of this issue, the present work extends those considerations and provides some experimental results. The lidar will be treated as a prototype of a handy commercial instrument for autonomous fire surveillance, for which the requirements of low cost, high overall efficiency, reliability and simplicity are much stricter with respect to those imposed on laboratory equipment.

The problem of eye safety is considered first, from the viewpoint of how to reduce the eye-hazard range—a distance where the laser beam is dangerous for direct eye exposure. Experimental results of lidar measurements, where eye safety was achieved by placing the lidar in an elevated position and using a 1064-nm laser beam with increased divergence, are then reported. It is demonstrated that a lidar system operating with wider beams maintains its capacity of efficient detection of the smoke plumes. Finally, the ability of this system to reveal the internal structure of smoke plumes is demonstrated and examples of plots providing smoke concentration on the topographic maps are given. The results are summarised in the final section.

**Eye safety considerations**

For a properly aligned single-wavelength direct-detection lidar, the signal \( P(R) \), corresponding to the operational zone \( R > R_{far} \), in which the laser beam lies completely within the telescope field of view (Fig. 1), is defined by the lidar equation (Measures 1984: 243; Carnuth and Reiter 1986)

\[
P(R) = E\lambda A\lambda \frac{d_{ec}^2}{R^2} \beta(R) \exp \left( -2 \int_0^R \alpha(R')dR' \right),
\]

where \( E\lambda \) is the output laser pulse energy for the operating wavelength \( \lambda \), \( A\lambda \) a coefficient characterising the overall efficiency of the lidar system, \( d_{ec} \) the diameter of the entrance pupil of the receiver's optical train (in the majority of lidar systems, the diameter of the primary, light-gathering mirror of a receiving telescope), \( \alpha(R) \) and \( \beta(R) \) denote back-scattering and extinction coefficient distributions respectively, and \( R \) is the distance measured along the laser beam. At the same time, the eye-hazard factor for the distance \( R \), \( EHF(R) \), is defined by the ratio of the laser beam energy density within the illuminated spot of effective diameter \( d_R \), \( E\lambda/(1/4\pi d_R^2) \), to the maximum permissible single-pulse eye exposure for looking directly into the laser beam \( MPE\lambda \), corresponding to a 1–100 ns pulse duration, typical for lidar measurements:

\[
EHF(R) = \frac{4E\lambda}{\pi d_R^2 MPE\lambda} = \frac{4E\lambda}{\pi(d_0 + 2R \tan(\gamma/2))^2 MPE\lambda},
\]

where \( d_0 \) is the waist of the laser beam (which in practice can be estimated by its effective diameter at the receiver’s output) and \( \gamma \) is the laser-beam divergence; for eye-safe distances, \( EHF(R) \leq 1 \).

In accordance with equation (2), a lidar presents no danger outside the eye-hazard range

\[
R_{ehr} = \frac{1}{\gamma} \left( \frac{4E\lambda}{\pi MPE\lambda} - d_0 \right),
\]

for which the eye-hazard factor equals 1. In the simplest lidar emitters no beam-formation optics are used, so the raw laser beam is emitted directly to the atmosphere. The waist of the laser beam is defined by the design of the laser cavity and does not exceed a few millimetres, so the beam is well approximated by a cone with the vertex at the output pupil of the emitter. In this case, corresponding to

\[
d_0 \ll \frac{4E\lambda}{\pi MPE\lambda},
\]

the eye-hazard range is defined by a simpler relationship

\[
R_{ehr} = 1.13\gamma^{-1}(E\lambda/MPE\lambda)^{1/2}.
\]

The values of \( R_{ehr} \) for an Nd:YAG laser beam with a divergence of 0.5 mrad, used in previous work (Utkin et al. 2003), are given in Table 1 for different laser-pulse energies. This beam corresponds to a typical direct-detection lidar capable of detecting smoke and, as can be seen from the table, the hazardous zone is unacceptably large (more than 1 km) even for laser-pulse energies so low (10 mJ for 1064 nm and 3 mJ for 532 nm wavelength) that the smoke detection range is limited to ~0.5 km. The last column of Table 1 also illustrates the significant decrease of \( R_{ehr} \) for a more divergent laser beam of \( \gamma = 2 \) mrad.

The dependence of the eye-hazard factor on lidar parameters, given by equation (2), is the basis for diminishing \( R_{ehr} \)
Apart from Er:glass, many other promising active media, such as Co:MgF$_2$, Cr,Ho,Tm:YAG, Cr,Tm,Ho:YSGG, and Cr,Tm:YAG, are currently being investigated and corresponding laser systems developed (Vaidyanathan and Killinger 1994; Huflacker and Reveley 1998; Hellström et al. 2001). However the performance of all these lasers is less than desirable for one or more of the following characteristics that are important in high-resolution long-range lidar systems: pulse energy, pulse width, pulse repetition frequency, maintenance of reliable single-pulse operation, stable wavelength operation, efficiency, compactness and reliability, especially with respect to optical damage (Q-Peak 1998).

Preference is given to schemes that combine a traditional neodymium laser (Nd:YAG or Nd:YLF) with an optical parametric oscillator (Harrell-Klein et al. 1995; Hutchinson et al. 1999) or Raman cell (Patterson et al. 1989; Karning et al. 1998), which converts the output wavelength to an eye-safe wavelength.

Expansion of the laser beam as an independent tool to achieve eye-safety is rarely considered in the literature. However, it is a popular approach to improving laser-beam quality and reducing the radiation power density below the threshold of possible non-linear self-focusing and heat-related hazardous effects (Kent and Hansen 1999; Moorgawa et al. 2000). Beam expansion can readily reduce the radiation power density to an eye-safe level, provided that laser-energy reduction or an eye-safe wavelength is used (NASA 1989; Spinhirne 1993). The efficiency of both beam expansion and detection of the retroreflected light grows rapidly with transition to large-diameter optics (note the presence of $d_{	ext{rec}}$ in equation (1) and $d_0$ in equation (2) to the second power). Thus, in order to build a compact expanded-beam lidar, the same telescope must be used for the dual purpose of beam formation and collection of the retroreflected light. This results in a single coaxial emitter/receiver optical system with $d_0 \approx d_{	ext{rec}} = d_{	ext{tel}}$, where $d_{	ext{tel}}$ is the diameter of the primary mirror of the telescope. Although designs of this type are well described (Harms et al. 1978; Measures 1984; NASA 1989; Brown de Colstoun et al. 1990), they rarely result in efficient and, at the same time, simple and inexpensive detection systems. This is predominantly due to near-field back-scattered radiation saturating the photodetectors, and the need for beam separation. As discussed by Harms et al. (1978), the straightforward use of beam splitting planes results in 50% power loss for both transmitted and collected radiation. Significant reduction of these losses is possible due to the fact that both emitted and retroreflected radiation is highly polarised. Advances in the manufacture of polarisation transmit–receive switches, in which a polarising beam-splitter, a quarter-wave plate, and circular polarised laser light are used in order to avoid the power loss by turning the polarisation state between the emitted and the received radiation (Duck et al. 2001), can open new prospects for using this monostatic architecture in simple middle-range lidars as well as in lidars working in autonomous conditions (Eloranta and Ponsardin 2001).

High-power laser lidars based on direct generation of eye-safe radiation have not gained widespread acceptance. Apart from Er:glass, many other promising active media, such as Co:MgF$_2$, Cr,Ho,Tm:YAG, Cr,Tm,Ho:YSGG, and Cr,Tm:YAG, are currently being investigated and corresponding laser systems developed (Vaidyanathan and Killinger 1994; Huflacker and Reveley 1998; Hellström et al. 2001). However the performance of all these lasers is less than desirable for one or more of the following characteristics that are important in high-resolution long-range lidar systems: pulse energy, pulse width, pulse repetition frequency, maintenance of reliable single-pulse operation, stable wavelength operation, efficiency, compactness and reliability, especially with respect to optical damage (Q-Peak 1998).

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Table 1. Threshold eye-safe distance for an Nd:YAG lidar system without beam expander

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>$MPE_\lambda$ (J m$^{-2}$)</th>
<th>$E_\lambda$ (mJ)</th>
<th>$R_{d_{	ext{rec}}}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1064</td>
<td>0.05</td>
<td>150</td>
<td>3.91</td>
</tr>
<tr>
<td>120</td>
<td>3.49</td>
<td>80</td>
<td>2.85</td>
</tr>
<tr>
<td>40</td>
<td>2.02</td>
<td>20</td>
<td>1.43</td>
</tr>
<tr>
<td>10</td>
<td>1.01</td>
<td>10</td>
<td>0.80</td>
</tr>
<tr>
<td>532</td>
<td>0.005</td>
<td>50</td>
<td>7.13</td>
</tr>
<tr>
<td>60</td>
<td>4.38</td>
<td>30</td>
<td>5.53</td>
</tr>
<tr>
<td>20</td>
<td>4.51</td>
<td>20</td>
<td>4.51</td>
</tr>
<tr>
<td>10</td>
<td>3.19</td>
<td>10</td>
<td>3.19</td>
</tr>
<tr>
<td>3</td>
<td>1.75</td>
<td>3</td>
<td>1.75</td>
</tr>
</tbody>
</table>

and, finally, making the lidar eye-safe. The corresponding measures are described briefly in Table 2.

In most lidars used in forestry for fire safety applications, the lack of sensitivity due to the small laser-pulse energy needed to assure eye-safety is compensated by high-pulse repetition frequency (Laseroptronix 2003), which provides means for efficient data accumulation and increasing the signal-to-noise ratio. Some airborne lidar imaging systems (Bélanger et al. 2000; Riaño et al. 2002; Toposys 2003) achieve additional eye safety by operating at a wavelength of 1540 nm. Other lidar applications, such as laser-induced fluorescence imaging (Saito et al. 2000), require ultraviolet radiation. Here the third harmonic of an Nd:YAG laser ($\lambda = 355$ nm) is usually used (Takeuchi et al. 2001). In contrast, lidar-assisted mapping of vegetation and geological features is based primarily on far-infrared radiation (Foy et al. 2001). In both cases eye-safety is provided at the expense of high cost and complexity of the equipment.

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As well as eye-safe radiation, 1064-nm radiation is invisible signals due to atmospheric phenomena for lidar wildfire detectors, so one can anticipate that spurious doses of visible radiation from laser light shows can cause flash blindness. The blindness may last from several seconds.

Table 2. Eye-safety measures

<table>
<thead>
<tr>
<th>Description</th>
<th>Related parameter</th>
<th>Advantages and drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducing the laser pulse energy</td>
<td>$E_0$</td>
<td><strong>Advantage:</strong> The most straightforward way of diminishing the eye hazard that does not involve modification of the lidar system. <strong>Drawback:</strong> The decrease in the threshold eye-safe distance $R_{th}$, which is proportional to $E_0^{1/2}$, is accompanied by a linear decrease in the lidar signal and a corresponding degradation of smoke-recognition efficiency.</td>
</tr>
<tr>
<td>Operating at an eye-safe wavelength</td>
<td>$\lambda$, $MPE_0$</td>
<td><strong>Advantage:</strong> Radiation at eye-safe wavelengths ($\lambda &lt; 400$ nm and $\lambda &gt; 1400$ nm) does not penetrate into the eye and focus on the retina. Thus, the values of $MPE_0$ for these wavelengths are at least four orders of magnitude greater than for 532 nm (Eberhard 1983), which makes operating at eye-safe frequencies the most efficient way of eliminating the laser hazard. <strong>Drawback:</strong> The problem of developing powerful, but simple, cheap and reliable eye-safe lasers is not yet solved. The best so far, an Er:glass laser with fundamental harmonic at 1540 nm, has far worse characteristics (e.g. efficiency, reliability, cost, laser-beam quality and divergence) than an Nd:YAG. The alternative scheme involving conversion of the fundamental harmonic of an Nd:YAG laser into eye-safe IR radiation is linked with the introduction of an optical parametric oscillator or Raman convertor, which makes the lidar less simple, less reliable, and much more expensive. Using the third harmonic of an Nd:YAG laser (355 nm) is restricted by the low efficiency of radiation conversion.</td>
</tr>
<tr>
<td>Expansion of the laser beam</td>
<td>$R_0$</td>
<td><strong>Advantage:</strong> In the case $d_0 \geq (4E_0/(\pi MPE_0))^{1/2}$ provides a system that is eye-safe at any distance. In general, beam expansion increases the laser-beam quality and facilitates radiation transport through the turbulent atmosphere (Ready 1997). <strong>Drawback:</strong> The laser-beam expander must be introduced into the optical train of the receiver. For typical laser-pulse energies, 120 mJ at 1064 nm and 30 mJ at 532 nm, the minimum eye-safe beam diameter $d_0 = (4E_0/(\pi MPE_0))^{1/2} = 1.7$ and 2.8 m respectively, which results in heavy, bulky and costly systems.</td>
</tr>
<tr>
<td>Increasing the laser-beam divergence</td>
<td>$\gamma = d_0/R_0$</td>
<td><strong>Advantages:</strong> For a fixed distance $R_0$, a transition to laser-beam divergence $d_0$ provides the same effect as expansion of the laser beam up to diameter $d_0$. In many laser systems increasing $\gamma$ to values $\sim 3$ mrad may be effected without additional optical elements, simply by re-tuning the laser cavity. Sometimes this even results in a multi-mode generation with better efficiency than that producing quasi-Gauss, low-divergence beams. Wider angular laser-beam divergence means wider coverage of the surveillance area by a single shot, that is, faster scanning. <strong>Drawbacks:</strong> The laser beam remains narrow and, consequently, hazardous in the near zone. Conversely, as the distance increases, the high-divergent beam illuminates a rapidly increasing spot with less and less density. The diameter of the beam cross-section reaches the characteristic width of the smoke plume and, starting from this distance, degradation of the lidar sensitivity to the smoke is more dramatic than in the case of a small-divergence laser beam.</td>
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</table>

beam divergence of $\gamma = 2$ mrad operating at the fundamental harmonic was used. The telescope diaphragm was changed in order to increase the field of view to $\sim 3$ mrad. Although not intrinsically eye-safe, the fundamental harmonic 1064 nm has a maximum permissible direct eye exposure one order of magnitude greater than that for 532 nm. Moreover, the fundamental wavelength is closer to the eye-safe wavelength of 1540 nm that, according to Lavrov et al. (2003), is the most promising for the future development of hazard-free lidar wildfire detectors, so one can anticipate that spurious signals due to atmospheric phenomena for $\lambda = 1540$ nm will be similar to those revealed experimentally at 1064 nm. As well as eye-safe radiation, 1064-nm radiation is invisible, which in most eye-safety manuals is considered an additional dangerous factor. This is an incontrovertible truth for laboratory conditions, in which the view of the bright laser beam is a warning to personnel who are well aware of the current laser experiment. In field tests, however, the opposite situation occurs: the visible laser beam attracts the attention of occasional observers, who are stimulated to look directly to the light source. Although the authors are unaware of any serious discussion on this topic, their opinion is that in field experiments the visibility of the laser light results in greater danger rather than safer conditions. This is supported by an essay from the NASA Aviation Safety Reporting System (Patten 1995) asserting that even eye-safe doses of visible radiation from laser light shows can cause flash blindness. The blindness may last from several seconds.
to several minutes and, by decreasing the visual capability and attention level of the pilot or driver, may cause an accident.

Experiments on forest-fire detection

As can be seen from the last column of Table 1, increasing the divergence of the laser beam up to 2 mrad and using the fundamental harmonic result in a significant reduction of $R_{eh}$: while the laser beams ($\lambda = 532$ nm, $E_{\lambda} = 20$ mJ) used in the Gestosa 2001 tests (Viegas et al. 2002) were dangerous to the eye up to $R = 4.5$ km, the radius of the eye-hazard zone for the modified lidar system does not exceed 1 km even for $E_{\lambda} = 150$ mJ at 1064 nm. In order to provide experimental evidence for the fact that the modified lidar system, operating with wider beams at 1064 nm, maintains its ability to detect smoke plumes efficiently, new tests were carried out within the framework of the Gestosa 2003 campaign. The location of the personnel igniting and controlling the experimental fire, the fire plots and the lidar position are shown schematically in Fig. 2. The lidar was situated at a distance of 1150 m from the nearest plot, on the opposite slope of a deep valley. Thus in the eye-hazard zone, corresponding to $R < 980$ m, the laser beam always passed well above the ground, guaranteeing eye safety for the experimenters.

Notably, in forest-fire surveillance, the lidar must be placed at an elevated position to provide unimpeded line of sight within the range of the instrument. In mountainous regions the sensors can be placed in fire surveillance towers, generally at the top of mountains. In Portugal, large and rapidly growing forest fires often occur in valleys or on hillsides and in this case fire detection is more complicated because often the plume must be detected against the hillside rather than against a clear sky. In their previous work (Utkin et al. 2003), the authors demonstrated that a 532-nm lidar with beam divergence $\gamma = 0.5$ mrad can successfully detect forest-fire smoke plumes in the above conditions; a typical lidar signal is illustrated in Fig. 3a. The laser radiation is retroreflected by a hillside from a compact illuminated spot and the corresponding peak in the lidar curve is high and narrow. The new series of tests with $\lambda = 1064$ nm and $\gamma = 2$ mrad revealed a peculiarity that is inherent in detection with wider lidar beams: as is shown schematically in Fig. 2, radiation is reflected from a wider region of the hillside, at different distances from the lidar, leading to wider peaks. Sometimes only a few areas, perpendicularly oriented with respect to the

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**Fig. 2.** Scheme of the experimental site.

**Fig. 3.** Detection of the smoke plume against the hillside: $\lambda = 532$ nm, $\gamma = 0.5$ mrad (a) and $\lambda = 1064$ nm, $\gamma = 2$ mrad (b, c).
laser beam, contribute effectively to the retroreflection, and two or more separate peaks are observed (Fig. 3b). When a part of the laser beam hits the crowns of the trees covering the hillside, the structure of the retroreflected signal becomes even more complicated, as observed in Fig. 3c. However, hillsides and other solid targets of this kind may be distinguished easily from smoke plumes, as they always result in more time-stable retroreflected signals. The evolution of signatures of the smoke plume and of the hillside is illustrated in Fig. 4 for 10 groups of five successive lidar signals containing peaks due to both smoke and hillside retroreflection. The laser pulse energy was $E_p = 150 \text{ mJ}$ and each lidar signal resulted from the accumulation of 32 laser pulses. The temporal behaviour of the peaks was characterised by two standard deviations (SD), calculated within each group for the peak distance $R_p$ and the peak value of the signal $P_p = P(R_p)$. In Fig. 4 they are represented in a dimensionless form, as $\text{SD}(R_p)/\delta R$ and $\text{SD}(P_p)/\overline{P}_p$, where $\delta R = 6 \text{ m}$ is the lidar space resolution (defined by the data acquisition rate $25 \times 10^9$ samples/s) and $\overline{P}_p$ the average peak value. The points corresponding to smoke signatures appear in the upper part of the plot while those corresponding to hillsides tend to concentrate in the left bottom corner. The two groups can be separated easily from each other by a straight line or a simple curve, so the mathematical separation criterion can be readily defined. As could be anticipated, the variation of the measured distance to hillside peaks does not exceed the space resolution of the instrument. This means that in automatic, computer-assisted scanning it is possible to construct a database of background signals for each pair of azimuth and elevation angles and create a filter eliminating corresponding false alarms within the framework of traditional or fuzzy logic.

A complementary advantage of using more divergent laser beams is the decrease in duration of the complete scanning cycle that covers some prescribed solid angle $\Omega$. For a laser beam with divergence $\gamma$, the effective diameter of the illuminated spot can be estimated as $\gamma R$. This means that if no data accumulation is made, in one shot the lidar covers the solid angle $\delta\Omega = \frac{1}{4}\pi(\gamma R)^2/R^2 = \frac{1}{4}\pi\gamma^2$, so the number of laser pulses required for covering the entire solid angle $\Omega$ is given by the ratio $N_\Omega = \Omega/\delta\Omega = 4/\pi \cdot \Omega/\gamma^2$. If each lidar signal is obtained with accumulation of $n_p$ laser pulses, the total scanning time $t_\Omega$ is given by the equation

$$t_\Omega = \frac{4}{\pi} \frac{n_p}{\nu_p} \frac{\Omega}{\gamma^2}, \quad (3)$$

where $\nu_p$ is the pulse repetition rate. The scanning time is proportional to $\gamma^{-2}$, so increasing the divergence from 0.5 to 2 mrad can speed up scanning 16 times.

**Investigation of spatial structure of smoke plumes**

Apart from early detection of forest fires, lidar enables the investigation of the structure of smoke plumes and clouds. A sequence of layer-to-layer lidar scans provides information on the 3D configuration of distributed targets and can reveal the configuration of the smoke plume providing reliable information about the position of the plume boundaries and areas of significant concentration gradient within the bulk of the smoke. The latter information cannot be obtained with the help of cameras; however, it is extremely important for the experimental verification of gas dynamic models of fire propagation and smoke dispersion (notably, the same approach may be used for investigating dispersion of pollutants) as well as for chiefs of fire brigades and supporting air forces: in the case of sufficiently dense smoke covering the fire area and the surroundings, rapid evaluation of lidar scans allows them to ‘see’ the core of the smoke masked by its outer layers.

This method of structure analysis is based on a simple stable inversion algorithm first published by Klett (1981), which, with some subsequent modifications, has been used successfully for retrieval of the extinction $\alpha(R)$ and backscattering $\beta(R)$ profiles along the scanning beam direction $R$. Within the scope of this approach, the problem of simultaneous evaluation of two unknown functions, extinction and backscattering, is resolved by the assumption that the backscattering is proportional to $\alpha^k$, where the constant $k$ depends on the dominant extinction type. In the case of a smoke plume, the main contributions to extinction and back-scattering come from interaction with smoke particles; therefore, both $\alpha$ and $\beta$ are supposed to be proportional to particle concentration and the choice for $k$ is unity. The data evaluation scheme includes signal background elimination, representation of the
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As mentioned previously, both back-scattering and extinction were assumed to be proportional to the particle concentration. Estimation of the factor that transforms the extinction coefficient into particle concentration was made with the Wiscombe Fortran Code for Mie scattering calculations (Wiscombe 1980) on the assumption that the particle size distribution is known and corresponds to one measured \( \alpha_0 \) (Stith et al. 1981); analysis of different experimental distributions and their applicability to the present case is made by Lavrov et al. (2003). Thus, combining results of lidar scans from several levels, the description of the smoke plume structure in terms of three-dimensional particle distribution is achieved. It should be noted that the resulting concentration profiles represent a very rough estimation of real particle concentration, especially with respect to absolute values in particle number per cubic metre. More reliable lidar data evaluation schemes, such as those described by Ezcurra et al. (1985) and Benech et al. (1988), are connected with complicated calibration procedures that usually include airborne particle measurements and require an extraordinary amount of sophisticated equipment and manpower.

In recent measurements from the Gestosa 2003 experimental wildfire campaign, more accurate and complete eye-safe scans, carried out against clear sky and hillsides, enabled the whole structure of the plumes to be reconstructed. During scanning, the objects in the lidar field of view were filmed by a coaxial digital camera that facilitated the topographic tie-in of the lidar data.

To achieve the signal-to-noise ratio required for reliable restoration of concentration profiles, 16 laser pulses were accumulated in each recorded raw signal curve. With a pulse-repetition rate of 10 Hz, it took 1.6 s to measure the retroreflection curve corresponding to a fixed position of the scanning beam, from 90 to 215 s to scan one layer with fixed beam elevation, and \( \sim 10 \) min to record the whole plume structure as a set of three to five layers. In order to provide similar conditions for each scan, the retroreflected power in so-called logarithmic range-adjusted form, reduction of the lidar equation to Bernoulli (homogeneous Riccati) differential equation yielding an analytical solution for \( \alpha(R) \), and the choice of the reference extinction value, \( \alpha_0 = \alpha(R_0) \), for the reference distance \( R_0 \) that according to Klett is chosen at the farthest point of the extinction restoration domain, just behind the smoke plume, ensuring stability of the solution with respect to errors in lidar data and definition of \( \alpha_0 \). The stages of data processing needed for obtaining the analytical solution \( \alpha(R) \) are described in detail elsewhere (Lavrov et al. 2003). The calibration value \( \alpha_0 \), corresponding to the extinction of ambient air, was estimated with a series of lidar measurements of smoke-free atmospheric retroreflection with accumulation of \( \sim 1000 \) lidar returns and data processing according to the slope method (Klett 1981).

10-min record period corresponded to the most stable phase of development of the experimental fires whose duration was \( \sim 20–30 \) min. Higher frequency laser equipment with automatic, computer-controlled scanning systems would allow the same scanning to be performed within a much shorter time, enabling nearly instantaneous images of the plume to be observed.

With respect to their shape, the recorded smoke plume structures can be subdivided into three types; typical representatives of each one are depicted schematically in Fig. 5. Type 1 corresponds to the classical case of a smoke plume developing in a still atmosphere or in the presence of a weak wind. The cone-like plume rises freely to a height of \( \sim 300 \) m or more, until the buoyancy force becomes close to zero due to cooling and mixing with ambient air. As discussed by Benech et al. (1988), the vertical force acting on the smoke flow depends on many factors and, in certain circumstances, the initial upward motion caused by buoyancy acceleration can be stopped at a much lower height, resulting in plumes that rise only to a certain height (type 2) or even in those propagating downward (type 3).

The internal structure of the buoyancy-dominated plume of type 1, resulting from intense burning in moderate wind conditions, is shown in Fig. 6 as a sequence of five layers, each obtained by lidar scanning in the azimuth angle, with a step \( \Delta \varphi \approx 45^\circ = 13 \) mrad at constant beam elevation. The parameters characterising each layer—beam elevation angle, \( \theta \), and height of the beam above the fire, \( h \)—are defined in Fig. 6a. The relatively large fire corresponding to Fig. 6b,c was characterised by intense burning; according to Lavrov et al. (2003), the burning rate was assessed at \( \sim 20 \) kg/s. The smoke plume rose vertically to a height of 100 m. Above \( \sim 120 \) m, the plume drifted progressively by the wind blowing towards the lidar position (Fig. 6d–f). Up to \( \sim 180 \) m, the density of the smoke increased with height, as the vertical velocity of smoke particles decreased due to loss of buoyancy.
Fig. 6. Space structure of a buoyancy-dominated plume (type 1) from fire plot No. 523.

Similar effects are observed in Fig. 7a–d for a smoke plume resulting from a fire with a burning rate two to three times lower than in the previous example. Here the smoke plume was of type 2; its ascending motion was interrupted at a height of ~90 m, so scans with greater elevation did not reveal any smoke signature in the corresponding retroreflection curves. Figure 7c,d reveals a complicated internal structure in the top of the plume, consisting of a core surrounded by
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Fig. 7. Space structure of a low-height plume (type 2) from fire plot No. 614.

Fig. 8. An image of smoke partially propagating downwards captured by a video camera installed on the lidar in line with the receiver optics.

In the Gestosa 2003 experiments, the complicated local relief and particular meteorological conditions led to stable downward propagating smoke flows. A photograph of one of these flows is shown in Fig. 8. The structure of the type 3 smoke plume is represented in Fig. 9a,b. The low smoke density and observation conditions enabled only two layers of the plume to be scanned and restored. Both layers were located below the level of the fire plot, so the parameter \( h \) is not given as the layer characteristic. Instead, lines of equal height (that for the case of \( \theta = \text{const} \) are concentric arcs) with a step of 10 m are shown on the map for each scan. The numbers labelling the curves correspond to height above sea level, so the absolute height of any point of the plume can be estimated easily.

Interpolation of smoke particle concentration data restored from raw lidar signals can produce even more useful but less illustrative images of smoke plumes in a rectangular three-dimensional grid.
**Conclusion**

The main peculiarities of forest-fire detection with wide laser beams remain the same for the case of providing eye safety by expanding the laser beam rather than by increasing its divergence. Beam expansion may be useful for developing compact lidars in which the same telescope is used for beam formation and for collecting the retroreflected radiation. As far as large-diameter optics are designed for a single wavelength, here the application of ultra-thin and light interference lenses similar to the Fresnel zone plate lens (Watanabe et al. 2003) is possible.

The results obtained testify to the practicality of this simple method of providing eye safety for lidar measurements using wider beams. The lidar system was capable of early detection of smoke plumes and provided the basis for automatic recognition of smoke signatures in the raw lidar signal even in the presence of a hillside in the background. With such a lidar system it was possible to record the space structure of the smoke plumes without restrictions on the angle and altitude scanning ranges that are essential with an eye-hazard laser beam. This work justifies further extension of lidar-assisted fire surveillance and smoke-plume measurements that includes development of a compact lidar unit with the system of fast automatic scanning and signal recognition.

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