Comparison of eye-safe UV and IR lidar for small forest-fire detection

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ABSTRACT

Lidar is a promising tool for forest-fire monitoring because this active detection technique allows efficient location of tenuous smoke plumes resulting from forest fires at their early stages. For the technique to be generally usable, instrumentation must be eye-safe, i.e., it must operate within the spectral range 0.4 < λ < 1.4 μm. In this paper the lidar efficiency at the wavelengths 0.3472 μm (second harmonic of the ruby laser) and 1.54 μm (Er:glass laser) are compared using a theoretical model. The results of calculations show that the energy required for smoke-plume detection using 0.3472 μm becomes greater than the corresponding value for 1.54 μm when the distance exceeds some threshold, which ranges between 2 and 6 km depending on other parameters. Being caused by relatively higher absorption of the UV radiation in the atmosphere, this result is valid for any wavelength in the vicinity of 0.35 μm, for example, the third harmonic of Nd:YAG laser and the second harmonic of Ti:sapphire laser.

Keywords: lidar, forest fire, detection, eye safety, photomultiplier, avalanche photodiode

1. INTRODUCTION

Forest-fire detection using lidar has great potential for fire prevention as the high sensitivity of this active technique allows for efficient detection of tenuous smoke plumes resulting from early-stage fires. Since forest-fire monitoring covers inhabited areas, instrumentation must be safe to the eye, i.e., the wavelength of the laser beam used must be within the ranges 0.4 < λ < 1.4 μm and λ > 1.4 μm (see, e.g., Carmuth and Trickl). Some examples of the application of eye-safe lidar to smoke and fog detection exist in the literature: The detection of forest fire smoke by a direct backscattering lidar operating at 0.884 μm (GaAs diode laser) was recently demonstrated by Pershin et al. while Eberhard detected oil fog using a 0.3472 μm direct-backscattering lidar (the second harmonic of the ruby laser). Detection of forest fire smoke by a 2 μm heterodyne lidar was demonstrated by Targ et al.

There are two main parameters that are estimated to compare the lidar efficiency in the two eye-safe spectral regions:

- Atmospheric extinction of the probing laser beam. According to Collis and Russel, for shorter wavelengths molecular extinction increases as λ^4, affecting significantly the total extinction in the UV range.

- Efficiency of the radiation backscattering by the smoke plume. According to Srivastava et al., the backscattering efficiency of the forest-fire smoke sub-micron aerosol for wavelengths near 0.35 μm is from 3 to 17 times higher than that in the range 1.5 – 2 μm, the ratio depending on aerosol composition and particle size distribution.

In this paper we compare the detection efficiency of lidars operating at the second harmonic of the ruby laser (0.3472 μm) and at a wavelength near 1.54 μm (Er:Yb:glass laser, Er:glass laser, or Nd:YAG laser with an optical parametric oscillator). The results obtained for 0.3472 μm are also valid for the third harmonic of the Nd:YAG laser or the second harmonic of Ti:sapphire laser.

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2. MAIN EQUATIONS

It is assumed that the fire has a circular form with radius \( r_f \) and a fuel mass burned per unit time \( M_b \). An ash density in the burning products of \( C_{as}=0.3 \text{ g/m}^3 \) was used in accordance with Patterson and McMahon \(^{11} \) and Gueglfin et al. \(^{12} \). The details of the problem formulation were presented in a previous publication. \(^{3} \) The mean initial vertical velocity and the temperature of the smoke plume are calculated on the basis of thermodynamic arguments. The one-dimensional "top hat" Morton's approximation \(^{13} \) is used to model mixing of the smoke plume with the ambient air. In this approximation, the profiles of the mean vertical velocity \( U \) and the mean buoyancy are supposed to have the form

\[
\begin{align*}
U(x, y) &= U_i(x), \quad \theta_i(x, y) = \theta_i(x) \quad \text{for} \quad 0 \leq y \leq Y_{\text{max}}(x), \\
U(x, y) &= 0, \quad \theta_i(x, y) = 0 \quad \text{for} \quad y > Y_{\text{max}},
\end{align*}
\]

(1)

\[
g(\rho_e - \rho_i)/\rho_i = g(T_i - T_e)/T_e = \theta_i(x, y),
\]

where \( x, y \) are the cylindrical coordinates, \( T_i \) and \( T_e \) the average plume and air temperatures, \( \rho_i \) and \( \rho_e \) the average plume and air densities, \( Y_{\text{max}} \) the smoke plume radius, and \( g \) the acceleration of gravity. In Eq. (1) the pressure and molecular weight of the medium in the plume and in the ambient air are similar. In general, when the gases mix, the temperature boundary layer is wider than the velocity boundary layer, but in the "top hat" approximation the thickness of these layers is considered to be the same. Within these assumptions, the mass, momentum, and heat equations describing the plume have the form suggested by Morton \(^{13} \)

\[
\frac{d}{dx}(\rho_i Y_{\text{max}}^2 U_i) = 2\rho_i E U_i,
\]

\[
\frac{d}{dx}(\rho_i Y_{\text{max}}^2 U_i^2) = g(\rho_e - \rho_i) Y_{\text{max}}^2,
\]

\[
\frac{d}{dx}(\rho_i Y_{\text{max}}^2 U_i \theta_i) = 0,
\]

(2)

where \( E \) is the entrainment coefficient. According to Ricou and Spalding \(^{14} \) and Bejan \(^{15} \), for a buoyant plume \( E = \delta \sqrt{\rho_i / \rho_e} \), where \( \delta \approx 0.12 \) is the entrainment constant.

The backscattering coefficient, \( \beta \), was calculated using the formula \(^{16} \)

\[
\beta = \pi \int_0^\infty r^{2}\theta_B(r, \lambda, n) N(r) dr,
\]

where \( r \) is the particle radius, \( N(r) \) the particle size distribution in the smoke (estimated using the experimental data of Stith, Radke, and Hobbs \(^{17} \)), \( \theta_B(r, \lambda, n) \) the backscattering cross section, and \( n \) the complex refraction index of smoke particles. A computer code developed by Vilar and Lavrov \(^{2} \) was used to calculate \( \theta_B(r, \lambda, n) \) on the basis of Mie theory.

The power of the backscattered radiation received by the lidar is given by \(^{16} \)

\[
P_r = \zeta E_l \frac{c \pi D^2}{8 R^2} \tau_{RX} \tau_{TX} \exp(-2\alpha R) < \beta(R) >,
\]

(3)

where \( P_r \) is the power collected by the lidar receiver, \( E_l \) the laser pulse energy, \( c \) the speed of light, \( D \) the diameter of the input pupil of the receiver, \( R \) the distance to the lidar, \( \tau_{RX} \) and \( \tau_{TX} \) the efficiencies of the receiver and transmitter, respectively, \( \zeta \) the overlap factor (assumed to be 1), and \( \alpha \) the air extinction coefficient (distance independent). The mean backscattering coefficient, \( < \beta(R) > \), was calculated taking into account the mixing of the smoke plume with the ambient air.
and averaging over the volume illuminated by the laser beam, defined as the product of the transverse cross-section of the beam by the distance $c t_p / 2$, where $t_p$ is the laser pulse duration.

The comparison of the UV and IR lidar efficiencies was carried out on the basis of the analysis of the signal-to-noise ratio (SNR). The detector of the 1.54 μm lidar was assumed to be an avalanche photodiode. According to Overbeck et al. \textsuperscript{18} and Vilar and Lavrov \textsuperscript{2}, the expression for the SNR in this case takes the form

$$SNR = \frac{P_{\text{sig}}}{P_{\text{th}} + P_a + P_{\text{dark}} + P_{\text{short}} + P_{\text{back}}},$$  \hspace{1cm} (4)

where $P_{\text{sig}}$ is the power of the output electric postdetection signal, $P_{\text{th}}$ the thermal-noise power, $P_a$ the power of the electronic postdetection amplifier noise, $P_{\text{dark}}$ the detector dark-current-noise power, $P_{\text{shot}}$ the signal shot-noise power, and $P_{\text{back}}$ the background illumination shot-noise power. Substituting the explicit expressions for these terms given by Overbeck et al. \textsuperscript{18} and Vilar and Lavrov \textsuperscript{2} into Eq. (4) and solving the resulting equation yield the expression for the required laser energy in terms of all parameters

$$E_1 = \frac{e \cdot \text{SNR} \cdot F_{\text{ex}} \cdot B}{\left(\frac{e \cdot \pi D^2 / 8 R^2}{R_p}\right) \cdot \tau_{RX} \cdot \tau_{TX} \cdot \exp(-2 \alpha R) \cdot \beta(R)} \left[1 + \left(1 + \frac{2}{e \cdot \text{SNR} \cdot F_{\text{ex}} \cdot B} \frac{2k(T + T_0)}{eG^2 R_l F_{\text{ex}} I_{\text{back}} R_p + I_{\text{dark}}} \right)^{0.5}\right]$$ \hspace{1cm} (5)

In the above equation $G$, $R_p$, and $F_{\text{ex}}$ are the current gain, responsivity, and excess-noise factor of the APD; $R_l$ is the load resistance, $k$ the Boltzmann's constant, $B=1/(2t_p)$ the effective bandwidth, $T_0$ the effective noise temperature, and $I_{\text{dark}}$ the dark current. $I_{\text{back}}$ is given by the equation

$$I_{\text{back}} = \frac{\pi D^2}{4} B_{\text{fil}} \tau_{RX} \frac{\pi F A^2}{4} L_\lambda,$$

where $B_{\text{fil}}$ is the receiver optical bandwidth, $F A$ the full angle of the field of view, and $L_\lambda$ the background solar radiance.

We assume that in the 0.3472 μm lidar radiation is detected with the help of a photomultiplier. In this case, the expression for the signal-to-noise ratio in the anode current, $\text{SNR}_a$, has the form\textsuperscript{16}:

$$\text{SNR}_a = \frac{I_{\text{sig}} G}{\sqrt{2eG^2 F B \left(\frac{2 \text{SNR}_a}{I_{\text{back}} + I_{\text{dark}} + I_{\text{dark(a)}}}\right)}},$$ \hspace{1cm} (6)

where $F$ can be thought of as a noise factor associated with the gain. According to Measures\textsuperscript{16}, usually $F=1$ and it may be omitted, $G$ is the photomultiplier gain, $I_{\text{sig}} = P_{\text{p}} P_{\text{p}}$, and $I_{\text{dark(a)}}$ is the anode dark current. By substituting the explicit expressions for $I_{\text{sig}}$ in Eq. (6) and solving it, the following equation for the laser energy required for achieving given SNR for radiation detection using a photomultiplier is derived:

$$E_1 = \frac{e \cdot \text{SNR}^2 \cdot B}{\left(\frac{e \cdot \pi D^2 / 8 R^2}{R_p}\right) \cdot \tau_{RX} \tau_{TX} \cdot \exp(-2 \alpha R) \cdot \beta(R)} \left[1 + \frac{2}{e \cdot \text{SNR} \cdot F_{\text{ex}} \cdot B} \left(I_{\text{back}} + I_{\text{dark}} + I_{\text{dark(a)}}\right)\right]$$ \hspace{1cm} (7)

3. MAIN PARAMETERS OF LIDAR, PLUME, AND THE ATMOSPHERE

The values of the lidar, smoke plume, solar radiance, and atmospheric parameters are presented in Table 1. A beam divergence of 10 mr was chosen for the 1.54 μm lidar in agreement with the experimental data of Georgiou, Musset, and Boquillon\textsuperscript{19} and Wu, Myers, and Myers\textsuperscript{20}. The lower limit set by diffraction for a Gaussian beam is

$$\gamma_{\text{min}} = \frac{4 \lambda}{\pi D_l},$$

where $D_l$ is the laser active media diameter. As the diameter of Er:glass crystal is of 1 to 2 mm, $\gamma_{\text{min}}$=1 to 2 mr.
The Er:glass lasers presently available have considerably higher divergence, but $\gamma = 2.5$ mr should be achieved in near future, so this value was used in calculations. The ruby laser used by Eberhard has the divergence of 1.2 mr, and larger divergence can be easily achieved using a simple optical device. It is necessary to emphasise that the choice of the laser beam divergence requires some compromise: to detect an isolated smoke plume, a low laser beam divergence is preferable because it provides higher sensitivity and positioning accuracy. On the other hand, in order to achieve reasonable surveillance time for a full-circle scanning, the divergence must be large. It is assumed that the telescope field of view is equal to the laser beam divergence. The parameters used are typical for the bialcali photocathode photomultiplier: the quantum efficiency for 0.3472 $\mu$m is 14%, the cathode responsivity 0.05 A/W, and the gain $5 \times 10^6$. The parameters of the avalanche photodiode are typical for an InGaAs APD: the gain is 20 and the excess noise factor 10. Following Youmans, Garner, and Peterson and Zenker et al., a 2 nm receiver optical bandwidth was used for both the UV and IR lidar. Forest fires preferably occur in dry weather conditions weather, thus the extinction coefficient was estimated for 15 km visibility. The extinction coefficient was calculated using the numerical data of Nilsson. The background solar radiance was estimated using data provided by Youmans, Garner, and Peterson and Pratt.

Table 1. Lidar, solar radiance, atmosphere, and plume parameters

<table>
<thead>
<tr>
<th>Parameter and units</th>
<th>UV eye-safe lidar</th>
<th>IR eye-safe lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength, $\mu$m</td>
<td>0.3472</td>
<td>1.54</td>
</tr>
<tr>
<td>Pulse duration, ns</td>
<td>20, 50</td>
<td>20, 50</td>
</tr>
<tr>
<td>Laser beam divergence, mr</td>
<td>2.5, 10</td>
<td>2.5, 10</td>
</tr>
<tr>
<td>Total optical efficiency</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Receiver:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope diameter, m</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Telescope field of view, mr</td>
<td>2.5, 10</td>
<td>2.5, 10</td>
</tr>
<tr>
<td>Receiver optical bandwidth, nm</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total optical efficiency</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Detector responsivity, A/W</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>Detector gain</td>
<td>$5 \times 10^6$</td>
<td>20</td>
</tr>
<tr>
<td>PMT anode dark current, A</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>APD dark current, A</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Detector noise factor</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>APD load resistance of, $\Omega$</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td><strong>Solar radiance, atmosphere, and plume parameters:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plume backscattering coefficient, m$^{-1}$sr$^{-1}$</td>
<td>$3.7 \times 10^2$</td>
<td>$6.6 \times 10^3$</td>
</tr>
<tr>
<td>Background solar radiance, Wm$^{-2}$sr$^{-1}$$\mu$m$^{-1}$</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>Rayleigh scattering coefficient, m$^{-1}$</td>
<td>$0.8 \times 10^4$</td>
<td>$=0$</td>
</tr>
<tr>
<td>Visibility, km</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Aerosol extinction coefficient, m$^{-1}$</td>
<td>$3 \times 10^4$</td>
<td>$1 \times 10^4$</td>
</tr>
<tr>
<td>Total extinction coefficient, m$^{-1}$</td>
<td>$3.8 \times 10^4$</td>
<td>$1 \times 10^4$</td>
</tr>
</tbody>
</table>
4. RESULTS

The variation of the laser-pulse energy required with distance for various lidar and plume parameters is shown in figure 1. All calculations were carried out for $SNR = 1.5$, the minimum value for satisfactory detection$^{16}$. The lidar is assumed to perform a full-circle rotation for inspection of the area with the help of a step change of the azimuth angle. In this case the
duration of an inspection circle depends on the field of view of the receiver, $\gamma$. To minimise the inspection time, a large value of the field of view angle must be chosen. However, the sun background radiation increases as the field of view increases, causing a decrease of $SNR$ if all other factors remain constant. Besides, if the smoke plume diameter in the point of intersection with the laser beam is smaller than the diameter of the area illuminated by the laser beam, the increase of laser beam divergence (and, correspondingly, of the field of view of the receiver) causes the average backscattering coefficient and $SNR$ to decrease.

The variation of the laser-pulse energy required for satisfactory detection with distance (assuming that the area illuminated by the laser beam is near the fire, at the ground level, and the fuel mass burned per unit time is 0.05 and 2 kg/s) is shown in figures 1a and 1b respectively. The laser pulse energy required to achieve $SNR = 1.5$ rises more steeply for the ruby laser than for the Er-glass laser. This is not unexpected, because for the 0.3472 $\mu$m wavelength of the second harmonic of ruby laser the air extinction coefficient is larger than for the IR laser. The comparison of the curves of figure 1 shows that the

Figure 1. Variation with distance of the laser energy $E_l$ required to achieve a $SNR \approx 1.5$ for a UV lidar with ruby laser and a PMT detector (curves 1 and 3) and for an IR lidar with an Er-glass laser and an avalanche photodiode detector (curves 2 and 4). Laser pulse duration is 20 ns, divergence 10 mr (curves 1, 2) and 2.5 mr (curves 3, 4). Figures 1a and 1b correspond to detection of the smoke plume near the fire while figures 1c and 1d correspond to a height of 100 m. Figures 1a and 1c correspond to a small-fire burning rate of 0.05 kg/s and fire radius of 0.5 m, figures 1b and 1d correspond to a larger fire with 2 kg/s burning rate and 2.5 m radius.
laser-pulse energy for the ruby laser becomes larger than the corresponding value for the Er:glass laser in the range of 2–6 km, depending on the value of other parameters. In all situations the average backscattering increases and the laser pulse energy decreases when the laser beam divergence decreases.

In Mediterranean regions, where forest fire detection is primarily necessary, forests grow in hilly territory. If the lidar is installed on top of a hill, it may detect fires in neighbouring valleys and hilltops. In this case the intersection of the laser beam with the smoke plume occurs at a significant height $X_b$ above the ground. In the point of intersection, the ash particle density is lower and the plume radius larger than at the ground level, near the origin of the fire. To estimate the laser-pulse energy required for detection in these conditions, calculations were performed for $X_b=100$ m, leading to the results presented in figures 1c and 1d. The shape of these curves depends on the ratio between the plume diameter and the diameter of the area illuminated by the laser beam at the intersection point. Values of these parameters are presented in Table 2.

**Table 2. Plume and laser beam parameters at the intersection point.**

<table>
<thead>
<tr>
<th>Fuel mass burned per unit time, kg/s</th>
<th>Plume diameter, m</th>
<th>Diameter of area illuminated by laser beam in the place of intersection, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_b=0$ m</td>
<td>$X_b=100$ m</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.05</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>30</td>
</tr>
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<td></td>
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</tbody>
</table>

For $X_b=0$ m, $R=2$ km, and $\gamma=10$ mr the radius of the spot illuminated by the laser beam is larger than the plume diameter. Therefore, a decrease of the laser beam divergence results in a decrease of $E_l$, due to the fact that as beam divergence decreases, a larger fraction of emitted radiation is backscattered by the plume.

For $X_b=100$ m, $R=2$ km, and $\gamma=10$ mr the smoke plume diameter is approximately equal to the laser-beam diameter. For a 1.54 $\mu$m lidar and a SNR varying from 1 to 2, the APD noise is mostly controlled by the thermal-noise power, which is independent from $\gamma$. Therefore, the decrease of laser beam divergence does not change $E_l$. The situation is a somewhat different for a 0.3472 $\mu$m lidar: for $1 < SNR < 2$ the PMT noise controlling factor is the shot-noise current of background solar radiance, so a decrease of laser beam divergence (and of the receiver field of view) causes a decrease of the background solar radiance and, as a consequence, a decrease of $I_{back}$ and $E_l$.

For $X_b=100$ m, $R=10$ km, and $\gamma=10$ mr, the smoke plume diameter is several times smaller than the local diameter of the laser beam, so a decrease of laser beam divergence causes an increase of the radiation backscattered by the smoke plume and, as might be expected, a decrease of $E_l$.

All previous calculations were made for a pulse duration $t_p=20$ ns. Calculations for $t_p=50$ ns were also carried out. There are two factors that may influence $E_l$ as $t_p$ increases: (1) the value of $<\beta>$ may decrease due to averaging along the laser beam within the range $c t_p/2$; (2) the dependence of $E_l$ on $1/\sqrt{t_p}$ exists. Finally, for the conditions corresponding to figure 1a, an increase of $t_p$ causes $<\beta>$ to decrease 2.5 times and $E_l$ to increase 10-30% approximately, whereas for the conditions of figures 1b, 1c, and 1d, the plume diameter at the intersection point with the laser beam is similar (or larger than 7.5 m, so $<\beta>$ does not change significantly, and $E_l$ decreases 30-40%.

Atmospheric turbulence affects the noise level, which should influence the results, but the modification is not expected to affect the main conclusions. All the calculations carried out for a UV lidar at a wavelength of 0.3472 $\mu$m (second harmonic of the ruby laser), should be valid for any wavelength of about 0.35 $\mu$m (for example, the third harmonic of Nd:YAG laser or the second harmonic of Ti:sapphire laser).

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