First prototype of a Lidar-Dial system for the automatic detection of harmful and polluting substances

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Lidar-Dial Techniques

The Lidar–Dial techniques are widely recognized as a cost–effective approach to monitor large portions of the atmosphere and, for example, they have been successful applied, by our group, to the early detection of forest fires.

At the University of Tor Vergata, a mobile Lidar/Dial station based on CO2 laser source has been designed and built.

The aim of our work was to prove the effectiveness of a remote sensing system in both configurations, Lidar and Dial, for reducing false alarms in the detection of forest fires.
Lidar-Dial Techniques: Forest Fires

A Lidar measurement is performed first to evaluate the aerosol mass fraction dispersed in the atmosphere, using the non-absorption wavelength of the water molecule. If the returned signal reveals a backscattering peak, the presence of a fire is highly probable. A second measurement is then necessary to establish the concentration of water; this is achieved by emitting a secondary laser pulse at the wavelength corresponding to the absorption line of the same molecule.

The combined detection of the two laser wavelengths, together with the choice of water, a characteristic emission during the first combustion stages, has allowed reducing significantly the occurrence of false alarms.

Figure – Visual output of the signal processing software for the case of a fire detected about 1.2 km from the mobile station in the north direction.
Lidar-Dial system for pollutants: main elements

- Specifications and Conceptual Design
- Lidar system
- Dial system
- Minimum detectable concentrations
- Conclusion
Specifications

- Continuous monitoring of the area under surveillance
- Identification of the released chemicals
- A very compact system with a range of at least 600-700 m in urban area
- Optical wavelengths in an eye-safe range for humans
- Low cost
The proposed system consists of:

a) continuous monitoring the area to be surveyed with the Nd:YAG laser

b) after detection of variations in the aerosols, accurate concentration measurements with the CO₂ laser

**Diagram:**

- **LIDAR**
  - Nd:YAG laser
  - Acquisition 1064 nm

- **DIAL**
  - CO₂ laser
  - Acquisition 9-11 μm

- **Remote Control**
- **Monitoring And Maintenance**
- **Local Storage**
- **AI Alarm Manager**
The Lidar system, for the continuous monitoring of the area to be surveyed, is based on a Nd:YAG laser and an Avalanche PhotoDiode (APD). The choice of these components is mainly dictated by the need of developing a compact system, robust enough to guarantee continuous (24/7) operation in hostile environments.

For the transmitter, a CFR (Compact Folded Resonator) laser has been chosen, due to, mainly, its reliability.

### Transmitter

**Laser**
- **Active medium**: Nd:YAG
- **Emission type**: Pulsed (Q-Switched)
- **Wavelengths**: 1064 nm, 532 nm, 355 nm
- **Pulse repetition rate**: 10 Hz
- **Beam divergence**: 1.5 mrad
- **Beam waist diameter**: 7 mm
- **Pulse duration**: 8 ns @ 1064 nm
- **Pulse energy**: 330 mJ @ 1064 nm
- **Power supply**: 100/240 V, 10 A, 50/60 Hz

**Telescope**
- **Focal length**: 1030 mm
- **Primary mirror diameter**: 210 mm
- **Primary-secondary mirrors distance**: 820 mm

### Receiver

**APD (model 1647 – New Focus)**
- **Spectral response**: 800 nm ÷ 1650 nm
- **3-db bandwidth**: 15 kHz – 1GHz
- **Peak response**: 0.6 A/W
- **NEP**: 1.6 pW/√Hz
- **Output impedance**: 50 Ω
- **Power supply**: +/- 15 V
- **Active area**: 0.8 mm²
Lidar system: Signal-to-noise Ratio

The SNR is mostly determined by the optical detector and the signal power incident on the detector element. According to Keiser (1983) the SNR for an avalanche photodiode is given by:

\[
SNR = \frac{(1/2 \cdot R \cdot m^2 \cdot P_r)^2}{2 \cdot q \cdot (R_d(P_r + P_B) + I_D) \cdot F(M) \cdot B \cdot \frac{4 \cdot k_B \cdot T \cdot B}{R_{eq} \cdot M^2} \cdot F_{\text{AMPL}}}
\]

- \(P_r\) is the received optical power
- \(P_B\) is the received optical power of background signal
- \(m\) is the modulation index
- \(M\) is the avalanche gain
- \(I_D\) is the primary bulk dark current
- \(F(M)\) is the excess photodiode noise factor = \(M^x\) with \(0 < x \leq 1\)
- \(B\) is the effective noise bandwidth
- \(k_B\) is the Boltzmann’s constant
- \(T\) is the absolute temperature
- \(R_{eq}\) is the equivalent resistance of photodetector and amplifier load
- \(F_{\text{AMPL}}\) is the noise figure of the amplifier
- \(R\) is the responsivity calculated as: \(R = M^* (\eta^* q)/(h^* \nu)\)

with \(\eta\) the quantum efficiency, \(q\) the electron charge, \(h\) the Planck’s constant and \(\nu\) the frequency of a photon.
Lidar system: SNR calculation

SNR simulation for the Nd:YAG system, varying the APD gain between 2 to 10.
Dial system

The design of the Dial system, for the accurate measurement of the pollutant concentrations, is based on the physical parameters of a working ground-based Lidar–Dial station which has been built and continuously upgraded at the University of Calabria. A similar set-up has been improved and mounted on a mobile station at the University of Rome – “Tor Vergata”.

<table>
<thead>
<tr>
<th>Transmitter TEA CO₂ laser</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>10⁹ W</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>0.77 mrad</td>
</tr>
<tr>
<td>Spectral range</td>
<td>9 ÷ 11 μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary ROC</td>
<td>2400 mm</td>
</tr>
<tr>
<td>Primary diameter</td>
<td>400 mm</td>
</tr>
<tr>
<td>ZnSe lens focal length</td>
<td>50 mm</td>
</tr>
<tr>
<td>Total Focal length</td>
<td>576.6 mm</td>
</tr>
<tr>
<td>F.O.V.</td>
<td>0.88 mrad</td>
</tr>
<tr>
<td>Detector type</td>
<td>HgCdTe</td>
</tr>
<tr>
<td>Detector sensitivity D*</td>
<td>3.38 · 10¹⁰ cmHz⁷/₂/W</td>
</tr>
<tr>
<td>Detector size</td>
<td>1mm²</td>
</tr>
</tbody>
</table>
Dial system

This set–up allows rapid tuning of the two lines (on and off) and keeps the misalignment within a range of 0.1 mrad, moderately below the beam divergence.

The values used to evaluate the SNR, and later the average minimum concentrations, which can be revealed by our mobile Dial system, are reported in the following table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active surface</td>
<td>A</td>
<td>1260 cm²</td>
</tr>
<tr>
<td>Noise eq. power</td>
<td>NEP</td>
<td>2.35*10⁻⁸</td>
</tr>
<tr>
<td>Reflectivity target</td>
<td>ρ</td>
<td>0.1</td>
</tr>
<tr>
<td>Receiver efficiency</td>
<td>k</td>
<td>0.1</td>
</tr>
<tr>
<td>Constant term</td>
<td>ΔP_r/P_r</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Dial system: SNR simulation

In this case the SNR remains above 4 over the distance range of 1.5 km.

SNR simulation for the CO2 system. Wavelength: 9P14 ($\lambda_{ON}$ Ammonia molecule)
Dial system: minimum detectable concentrations

For the greater distances the minimum concentration can be evaluated setting the difference in the backscattered return at two frequencies equal to the noise of the detector (NEP):

\[ n_{\text{min}} = \frac{(NEP) \pi R}{2 \zeta \cdot \rho \cdot A \cdot P_0 \left( \Delta \sigma \right) \exp(-2\alpha R)} \]

At shorter ranges a more restrictive limitation may occur due to the inability of the measurement system to distinguish between the fractional change in the Lidar signal due to real variations of the species concentration and random fluctuations caused by atmospheric turbulence:

\[ n_{\text{min}} = \frac{5 \cdot 10^3 \cdot (\Delta P_r / P_r)}{(\Delta \sigma) \cdot R} \]
Dial system: minimum detectable concentrations

Ozone minimum detectable concentration.
About 4 ppb @ 1Km

Ammonia minimum detectable concentration.
About 2 ppb @ 1 Km
Conclusions

The simulations reported in the previous sections indicate that both lasers can provide measurements with a more than acceptable SNR over the whole distance range required by the specifications.

The sensitivity of the measurements seems also to be adequate to the application of pollutant detection.

The positive results of the calculations therefore motivate the full design and the procurement of the system.

We are also considering the application of the same approach to automatically recognize and identify substances used in chemical weapons.
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