Low-cost Lightweight Airborne Laser-based Sensors for Pipeline Leak Detection and Reporting

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Tunable Diode Laser Absorption Spectroscopy (TDLAS)

TDLAS is an active optical method for detecting and quantifying one or more analyte gases mixed with other gases.

**Competitive Features**
- Selective; generally insensitive to cross-species interference
- Sensitive; sub-ppm detection of many gas species
- Fast; sub-second response time
- Configurable; point, open-path, or standoff sensor
- Non-contact; only the probe beam need interact with the analyte

Accepted as rugged, reliable, accurate commercial industrial sensors and analyzers
- *Thousands currently in use*
Like a flashlight, laser beam illuminates a surface

- Senses analyte gas between transceiver and illuminated surface
  - Standoff range ~100 ft with handheld transceiver

> 2000 RMLD™ units in use for natural gas leak surveying
Physical Sciences Inc.

Gas Pipeline Leak Surveying

- The US natural gas transmission and distribution comprises
  - Transmission: 250,000 miles of pipeline, 1,700 transmission stations, 17,000 compressors
  - Local Distribution: 500 to 1,000 gate stations, 132,000 surface metering and pressure regulation sites, 1,000,000 miles of distribution pipeline, 61,000,000 end-user customer meters
- The pipeline system continues to develop around fracking gathering fields and biogas-producing landfills
- Minimizing leaks and ruptures is essential for limiting emissions of greenhouse gases, reducing loss of valuable gas product, and preventing explosions
- Maintaining the system’s security and integrity is a continual process of identifying, locating, and repairing leaks by:
  - Monitoring pipeline flow conditions to flag abnormal conditions
  - Scheduled periodic walking, driving, or aerial surveys
- The San Bruno explosion has increased national emphasis on improving leak and rupture detection
  - *Highlights needs for cost-effective widely-deployed real-time leak sensors and surveying systems*
Aerial Mapping of Landfill Emissions

- **Landfills produce about 22 % of all methane emissions** (U.S. EPA, 2010)
  - Locating and quantifying methane sources is needed to improve gas collection systems
  - Currently deployed technologies, e.g. flux chamber, are time consuming, require data collected in a grid of sampling points, and may underestimate flux from hot spots

- **Optical remote sensing technologies estimate the total emission from soil by concentration measurements in the downwind plume**
  - EPA Method OTM-10 uses a ground-based laser and a set of retroreflectors positioned on a line downwind of the emitting area

- **Backscatter TDLAS deployed on a small unmanned quadrotor aerial vehicle, described here, scans the emitting surface and downwind plume from above**
  - Enables computing crosswind concentration, emitted flux, and concentration contour mapping
Technology Features

- **Based Near-IR Tunable Diode Laser Absorption Spectroscopy (TDLAS)**
  - Established non-contact trace gas sensing technique used for industrial safety and process control
  - Utilize telecommunications-style room temperature diode lasers
  - Yields the path-integrated concentration (ppm-m)

- **Molecules of the target gas in the laser light path absorb specific wavelengths (colors) of infrared light**
  - A wavelength is chosen where methane is the only absorbing gas – other gases in the air are invisible
  - Insensitive to cross-species interference

- **Wavelength Modulation Spectroscopy (WMS) signal processing measures the methane absorption**
  - Highly-sensitive; sub-ppm detection of many gas species
  - Fast; offering sub-second response time
Wavelength Modulation Spectroscopy

- A frequency agile (i.e., tunable) laser beam transits a gas sample
- The laser frequency (inverse of wavelength) scans repeatedly across an absorption line that uniquely identifies the target gas
- Absorption of the laser beam by the target gas creates an amplitude modulated signal at the detector
- Phase sensitive demodulation (i.e., lock-in amplification) provides target gas concentration output
  - Senses absorbances \( \sim 10^{-5} \); \( \sim 1 \) ppm-m \( \text{CH}_4 \)
Sensor Features

- Weight <9 lbs (Controller: 6 lbs and Transceiver: 3 lbs)
- Rugged, splash-proof and weather resistant
- Detection range: 2 feet to 100 feet
- Sensitive to <5 ppm-m
- Built in self test and calibration
- IR laser: Eye-safe (EN 60825-1), always on
- Spotter laser: Class IIIa; operator controlled
- Rechargeable battery lasting over 8 hours
- User friendly interface with audible tones
- Operating temperature from 0°F to 120°F
- Ergonomic design with shoulder harness
**Sensor Internals**

- **Single-Board Control Platform**
  - Complete WMS system
  - 10 kHz modulation
  - Incorporates laser control and data processing on battery-operated board
  - Digital signal processor for high-speed data acquisition and processing
  - Embedded microcontroller for laser operation, data reduction, communication
  - Serial (RS-232) data output stream and setup interface
  - SPI communication available for interface with other microcontrollers

- **Transceiver**
  - Lightweight, compact, rugged handheld unit
  - Co-linear laser transmitter and receiver
  - Rejects sunlight
  - Integrated visible pointing laser

- **User Interface**
  - Visual:
    - LCD display in controller unit
  - Audio
    - Variable tone: frequency = 10 x methane concentration
    - Fluctuation algorithm: leaks indicated by rapid concentration changes
## Measured Range Limits

<table>
<thead>
<tr>
<th>Surface</th>
<th>Range (m)</th>
<th>Surface</th>
<th>Range (m)</th>
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<tbody>
<tr>
<td>Woodshed</td>
<td>41</td>
<td>Painted Metal Door</td>
<td>14</td>
</tr>
<tr>
<td>Old White Paint</td>
<td>35</td>
<td>Dirty Snow Bank</td>
<td>23</td>
</tr>
<tr>
<td>Brick</td>
<td>50+</td>
<td>Clean(er) Snow Bank</td>
<td>19</td>
</tr>
<tr>
<td>Concrete</td>
<td>43</td>
<td>Clean Asphalt</td>
<td>25</td>
</tr>
<tr>
<td>Stucco</td>
<td>46</td>
<td>Sand</td>
<td>33</td>
</tr>
<tr>
<td>Boulders</td>
<td>43</td>
<td>Sand on Asphalt</td>
<td>34</td>
</tr>
<tr>
<td>Tree</td>
<td>46</td>
<td>Wet Sand</td>
<td>14</td>
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<tr>
<td>Shrub</td>
<td>43</td>
<td>Clean Standing Water</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Grass (on hill)</td>
<td>40</td>
<td>Dirty Water</td>
<td>3</td>
</tr>
<tr>
<td>Metal Post</td>
<td>&gt;39</td>
<td>Bag w/CH$_4$ on Snow*</td>
<td>50</td>
</tr>
<tr>
<td>Wooden Stockade</td>
<td>55</td>
<td>Oblique Bag w/CH$_4$ on Ground</td>
<td>50</td>
</tr>
</tbody>
</table>
Quadrotor sUAV Platform

- Total weight 4.6 kg
  - TDLAS 1.4 kg, < 1.5 W
- Zigbee 2.4 GHz digital radio system provides remote-control and real-time data download
- The On-Board Control Unit manages the TDLAS sensor, stores raw data, and transmits to the control station
  - All samples are geo-referenced, marked with GPS position and barometric altitude
- Operator may pre-program a survey route as a set of latitude, longitude, altitude waypoints
Sensor evaluated in laboratory using optical cell filled with CH₄ / N₂ mixtures of 5-1000 ppm-m

Validated in open field by simulating diffuse methane emission from soil

Rubber pipelines distribute methane over a 20m x 20m area at 43 g/s = 93 g/m² - day
- High range of methane landfill emissions
- Low range of methane concentration due to the small emitting area
Aerial Pipeline Leak Surveillance

- Aerial natural gas pipeline leak surveillance, from fixed or rotary winged aircraft or helicopters, has been routine for many years.
- In-situ methane sensors, requiring the aircraft to fly through a leak plume to detect it, are often utilized
  - Speeds ~ 150 mph, altitudes ~ 750 feet
- Backscatter laser sensor systems are gaining acceptance
  - Capital costs, maintenance, and weight have limited deployment to a small number of operators

<table>
<thead>
<tr>
<th>Platform</th>
<th>Technology Package</th>
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<tbody>
<tr>
<td>Fixed Wing</td>
<td>RMLD</td>
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<tr>
<td>Fixed Wing</td>
<td>CRDS</td>
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<tr>
<td>Helicopter</td>
<td>Gas-Filter Correlation Radiometry</td>
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<tr>
<td>Helicopter</td>
<td>Reference Channel Laser</td>
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<tr>
<td>Helicopter</td>
<td>DIAL</td>
</tr>
<tr>
<td>4X4 Vehicle</td>
<td>CRDS</td>
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</tbody>
</table>
High Altitude Aerial Backscatter TDLAS

Combining EDFA and WMS provides long-range (6000 ft), robust and modest cost standoff sensor

Remove EDFA for low-altitude (<1200 ft) survey
Aerial RMLD™ Implementation

- Backscatter TDLAS is combined with automated data reduction, alerting, GPS, and video imagery, integrated into a single-engine single-pilot light aircraft platform.
- Detects plumes from natural gas leaks smaller than 10 SCFM
  - Corresponds to the flow through a sub-millimeter (<0.04 inch) hole in a 800 PSIA transmission pipeline.
- Advantages: Cost, Simplicity, Size, Weight, Power, Manufacturability, Data and Graphic User Interfaces
  - Real-time notification of leak coordinates
  - Cockpit alert enables maneuvering for verification and examination.
aRMLD™ Example Data

~1000 scfh leak rate

17:14:50
Heading South
~ 800 ft AGL

~ 17:17:11
Heading North
~ 1000 ft AGL
~ 100 ft east of leak
Maneuvering
No Joy

17:20:22
Heading South
~ 600 ft AGL
~ 400 ft NE of leak

17:22:47
Landfill
~ 3000 ft ESE of rwy 10
~600 ft AGL
Turning base-to-final
Conclusion

- Backscatter TDLAS is a cost-effective method for aerial detection and mapping of methane emitted by pipelines and landfills

- Demonstrated on small unmanned quadrotor, single engine-fixed wing, and lightweight helicopter

- Commercial package for pipeline leak surveying in use for several years
Acknowledgments

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