Author: Dr. Michael B. Frish
Position/Organization: Area Manager, Industrial Sensors, Physical Sciences Inc.
Session Title: RD&I: 4(II): Innovation: Effectively characterizing and addressing methane emissions
Paper Title: Scanning, standoff laser-based leak imaging and quantification
Co-authors: Nicholas F. Aubut, Richard T. Wainner, Matthew C. Laderer,
Physical Sciences Inc.
Paul D. Wehnert, James Rutherford, Heath Consultants Inc.

SUMMARY/CONCLUSIONS

This paper reports a novel quantitative methane plume imaging tool, based on active near-infrared backscatter laser sensing technology. It integrates a laser sensor with a video camera in a future handheld package to create a highly sensitive imager that also quantifies emission rate. It provides colorized quantified images of path-integrated methane concentration independent of background. The images depict methane plumes overlaid on a visible camera image of the background. This new tool addresses the need for reliable, robust, low-cost sensors to detect, image, and quantify fugitive methane emissions, enabling operators to prioritize repairs. We built a prototype platform that demonstrated quantitative performance in the laboratory and municipal field tests. Based on measured signal-to-noise ratios, it can quantify emissions as small as 0.25 scfh in seconds.

BACKGROUND

Natural gas leakage poses safety hazards, contributes to greenhouse gas loads, and costs customers the price of lost gas.[1] Leak detection practices include walking, driving, or aerial surveys. Detection tools locate leaks by: 1) measuring the local methane concentration (ppm) vs position; or 2) measuring the concentration integrated over the length of a line-of-sight path (ppm-m); or 3) visualizing leak plumes using optical imaging equipment. The underlying technologies include gas chromatography (GC), flame ionization detection, non-dispersive infrared spectroscopy, laser absorption spectroscopy in various configurations, and infrared imaging.

In US upstream operations, surveys for Leak Detection and Repair (LDAR) using optical gas imaging (OGI) are required periodically at well and compressor sites to visualize leak plumes emanating from various components. The EPA defines OGI as an “instrument that makes visible emissions that may otherwise be invisible to the naked eye,” and requires that “the imaging instrument must provide the operator with an image of the leak and the leak source.”[2] However, because there is no convenient technology, optical or otherwise, for measuring leak rate, the current EPA rules make no accommodation for prioritizing repairs based on emission rate, despite common understanding of a need for such prioritization. Indeed, no current leak survey tools directly quantify emission rate, a technology gap that this work addresses.

Active backscatter lasers sensors and passive OGI instruments provide remote or standoff leak detection, meaning that the detector need not be inserted into the emission plume to detect the emission. They rely on optical spectroscopy to detect target gases that absorb infrared light passing through leak plumes.

In passive OGI, the source of infrared light is broadband thermal radiation from background objects, terrain, or sunlight. Because passive OGI relies on differences in temperature between the leak plume and the background to visualize the plume, it is inherently non-quantitative: its detection sensitivity varies with ambient background conditions.

Figure 1 illustrates the principles of active backscatter laser sensing.[3,4] The laser beam projected through the plume carries a signal that is analyzed to accurately deduce the amount of methane in the path the beam traverses, independent of background characteristics. The scanned-laser survey tool described in this paper meets and exceeds the OGI requirements; it is more sensitive than passive OGI, quantitative, and independent of ambient conditions. These measurement virtues enable quantitative plume visualization in individual images (Figure 2), each of which may be processed to estimate emission rates (flux).

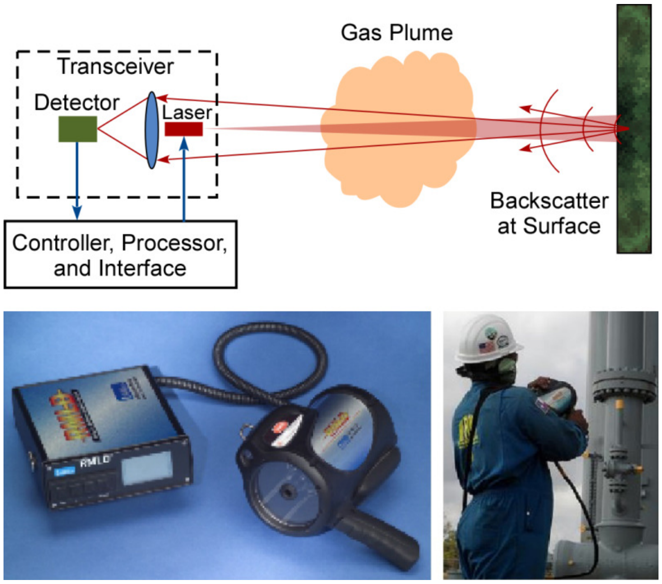


Figure 1. Backscatter laser detector principles and illustration of use in natural gas pipeline leak surveying.

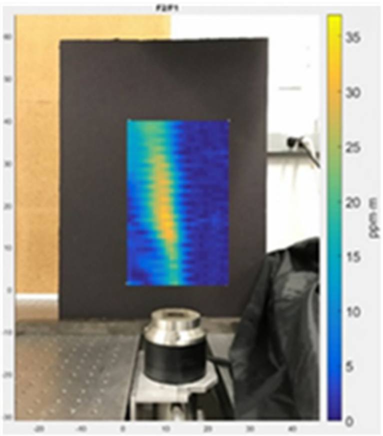


Figure 2. Single frame of a ~7 scfh methane plume image captured in 1 second via scanned backscatter laser sensing.

AIMS

In current practice, laser sensors locate leak sources by manual or mobile scanning, and provide quantitative measurements of path-integrated concentration. The new tool described herein adds fast mechanical raster scanning, visible camera imaging, and colorized visualization to the handheld laser detector package, thus functioning as an OGI while providing quantitative methane concentration data for calculating emission rates.

METHODS

The envisioned lightweight portable tool (Figure 3) provides quantitative images of path-integrated methane concentration. Software produces a colorized quantitative image of the methane plume overlaid on visible imagery. Emission rates are calculated from the image information complemented with wind vector values deduced from the images or by supplemental measurement.

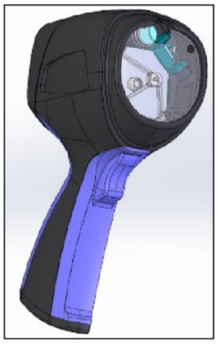
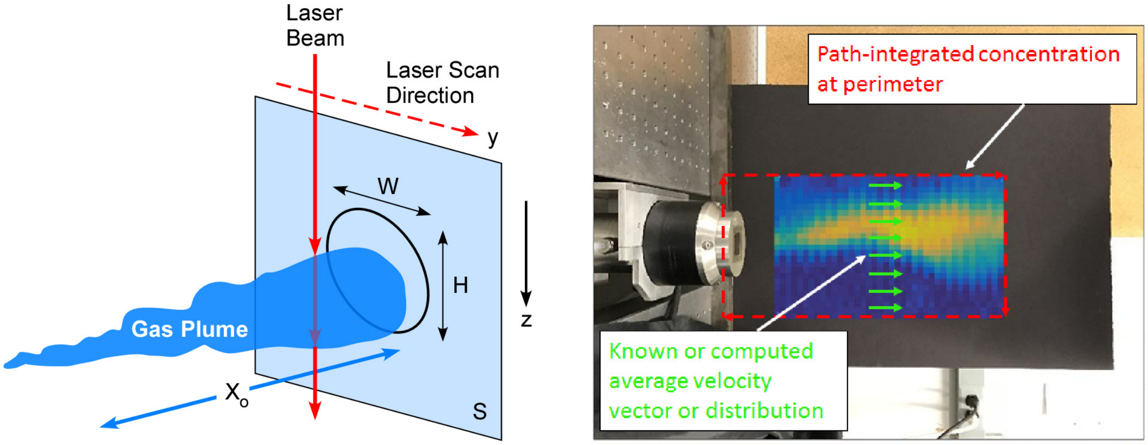


Figure 3. Laser-based Quantitative Gas Imager (QGI) package concept.

The emission rate Q is deduced by a mass-balance approach.[5] The laser sensor measures the path-integrated methane plume concentration $<c(x_o, y)>$ flowing at wind speed $\hat{u}$ through a surface downwind of the source (Figure 4a):

$$Q = \hat{u}(x_0) \int_{-W}^{W} < c(x_0, y) > dy \quad (1)$$

The surface may be a depicted in the imaged scene as a line or perimeter circumscribing the emission source (Figure 4b).



(a) (b)

Figure 4. (a) Flux calculation schematic. The linear laser beam measures column concentration integrated along z-direction and temporally scans the S-plane in the y-direction. (b) Illustration of flux calculation as applied to a laboratory methane plume. The red line illustrates a perimeter for calculation that would enclose the source.

Using off-the-shelf components, we built a benchtop breadboard prototype pictured in Figure 5.. We deployed it in three successive tests, each increasing the level of challenge:

1) Calibration and testing using a ‘bump’ cell
2) Quantitative plume imagery and flux estimation of methane flow from an unlit burner.
3) Visualization and flux estimation of municipal natural gas distribution pipeline leaks

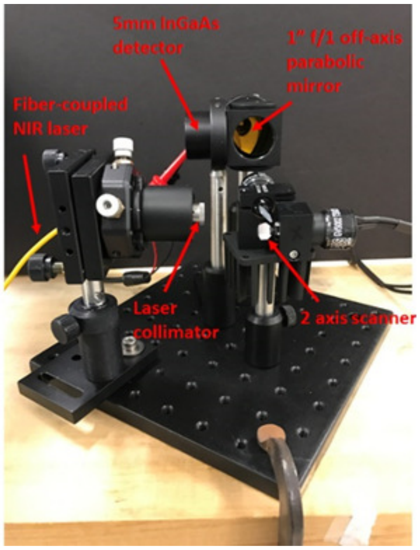
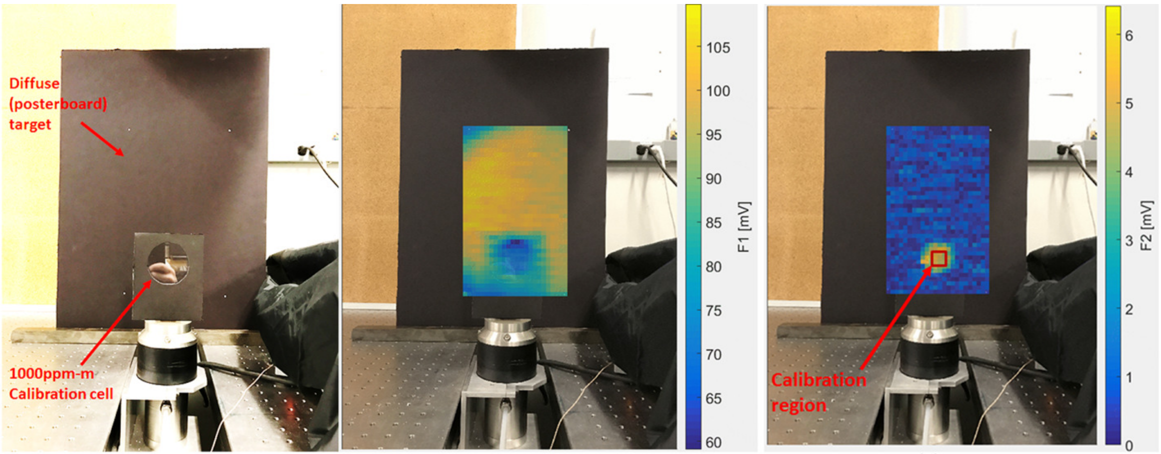


Figure 5. Breadboard prototype RMLD-QGI Optical Head. Support electronics are not shown.

RESULTS

1) Bump cell tests and calibration

Figure 6 illustrates the procedure for calibrating path-integrated methane concentration by inserting into the TDLAS region of interrogation a 'bump' cell, which is a standard RMLD® accessory for periodic calibration check. This accessory is comprised of a ~2cm wide glass cylinder containing ~50,000ppm CH_4 (thus ~1000ppm-m path-integrated concentration), held in a gray PVC block. Figure 6b shows that the PVC block provides less backscattering than the background target, due primarily to absorption of the laser beam by the PVC. The picture also shows that the glass cylinder provides even less backscattering; this is due to the specular reflection of the laser beam at the eight glass/air interfaces it transits (theoretically providing 72% transmission, comparable to the values measured). Nevertheless, the methane cell is clearly visible in the map of Figure 6c. The ratio of 6c/6b is proportional to path-integrated CH_4 concentration and independent of backscattered power. A calibration constant is deduced from these images and utilized in subsequent calculations; nominally, Concentration = 14000(5c/5b) ppm-m.



(a) (b) (c)

Figure 6. (a) Photo of 1000ppm-m methane "bump" cell. (b) Map of 40x25 received laser power signals acquired in 1sec. (c) Map of 40x25 methane concentration signals acquired in 1sec.

2) Quantitative Plume Imagery.

We used the Hencken burner shown in Figure 7 to interrogate a 7.2 Lpm (15 scfh) methane plume, creating one image frame per second illustrated by video frames 1 through 9. The methane flow exits from 173 0.5 mm ID tubes in the central 5/8" x 5/8" (2.52 cm^2) region. For a 120 cm^3/s (15scfh) flow an approximate flow speed above the burner exit is 47 cm/s, calculated by assuming uniform flow through the cross-section of the central region. The pixel noise on the images was ~73 ppm-m, while the measured concentration values are ~5000 ppm-m. The signal-to-noise ratio of ~70 indicates potential to measure fluxes as low as 0.25 scfh.

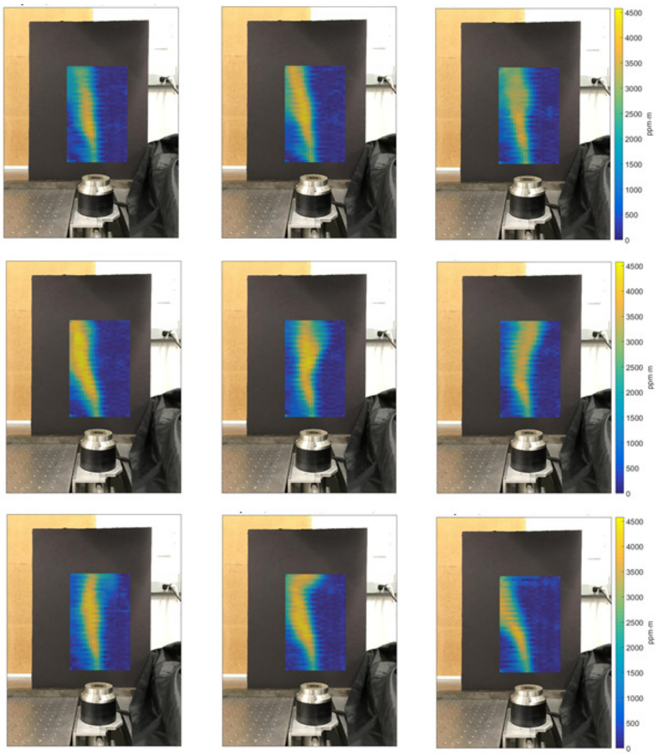


Figure 7. Video Frames 1 – 9: Nine 1sec scans of a methane "leak" plume at 7.2 Lpm (15scfh).

We note that both the measured path-integrated concentration and the plume width increase with elevation (i.e. distance from the source). As the plume flows into and mixes with the stagnant ambient air, its speed slows while conserving flux by increasing width and concentration. Figure 8 plots the product of integrating the path-integrated concentration (ppm-m) with the horizontal span (m), yielding the ppm-m^2 product for each row (40 rows) and comparing three different frames. The metered flux of 15 scfh (120 cm^3/s) indicates local plume speed diminishes from ~80 cm/s near the burner exit to ~35 cm/s near the top of the scanned region (340 ppm-m^2 * 35 cm/s = 120 cm^3/s). These plume speeds are qualitatively consistent with the 47 cm/s estimated in Section 5.2 above.

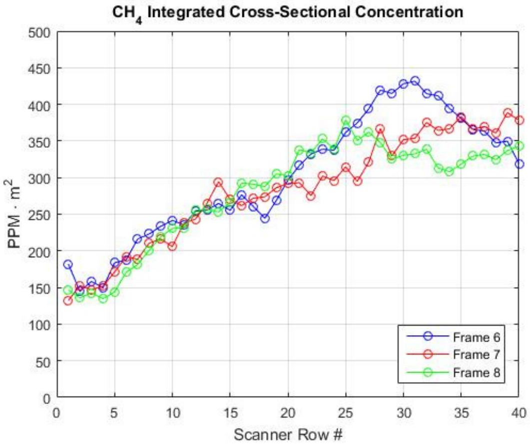


Figure 8. Row by row plot of area-integrated concentration (ppm-m^2) for three frames of the 1Hz TDLAS imagery of the 7.2Lpm methane plume.

3) Visualization and flux estimation of municipal natural gas distribution pipeline leaks

The benchtop prototype RMLD-QGI was deployed from a mini-van (Figure 9) to capture the first-ever video images of small fugitive leaks from municipal distribution pipelines, and to quantify the leak rates. Figure 10 shows one example of leakage exiting the ground through a water meter box. The test campaign similarly visualized more than 60 leak sites.

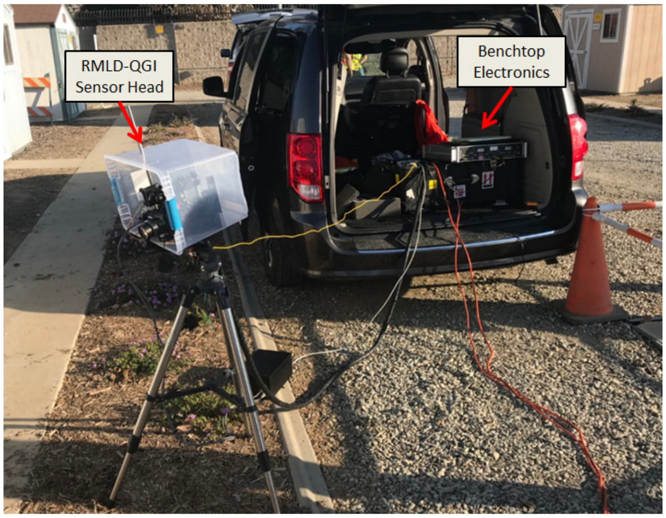


Figure 9. Breadboard RMLD-QGI Transceiver and electronics support van.

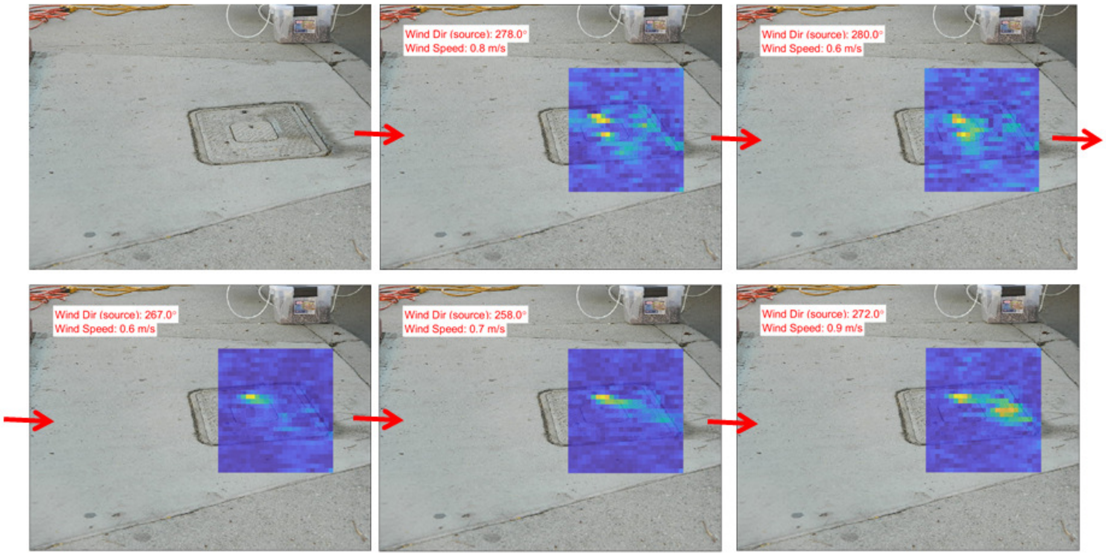


Figure 10. An uncontrolled, fugitive emission stemming from a hole in the lid of a water box. Estimated flux =4 .2 ± 0.7 scfh.

REFERENCES

[1] "America Pays for Gas Leaks", Report Prepared for Senator Edward J. Markey, July 2013.

[2] Federal Register, Vol. 81, No. 107, 40 CFR Part 60; Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources; Final Rule; June 3, 2016.

[3] Frish, M.B., Wainner, R.T., Stafford-Evans, J., Green, B.D., Allen, M.G., Chancey, S., Rutherford, J., Midgley, G., and Wehnert, P., "Standoff Sensing of Natural Gas Leaks: Evolution of the Remote Methane Leak Detector (RMLD)," Photonic Applications Systems Technologies (PHAST) Conference, Baltimore, MD, 24-26 May 2004.

[4] Frish, M.B., Wainner, R.T., Green, B.D., Laderer, M.C., and Allen, M.G., "Standoff Gas Leak Detectors Based on Tunable Diode Laser Absorption Spectroscopy," SPIE Paper No. 6010-13, Optics East, Boston, MA, 23-26 October 2005.

[5] Frish, M.B., Wainner, R.T., Laderer, M.C., Allen, M.G., Rutherford, J., Wehnert, P., Dey, S., Gilchrist, J., Corbi, R., Picciaia, D., Andreussi, P., and Furry, D., "Low-cost Lightweight Airborne Laser-based Sensors for Pipeline Leak Detection and Reporting," SPIE Defense Security + Sensing, Baltimore, MD, 29 April – 3 May 2013, Paper No. 8726-12, PSI/SR-1487, April 2013.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Chicago Operations, under Award Number DE-SC0015779.

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000547. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The authors gratefully acknowledge the support and technical contributions of the US Department of Transportation Pipeline and Hazardous Materials Safety Administration, NYSEARCH, SoCalGas, Heath Consultants Inc., and Physical Sciences Inc.