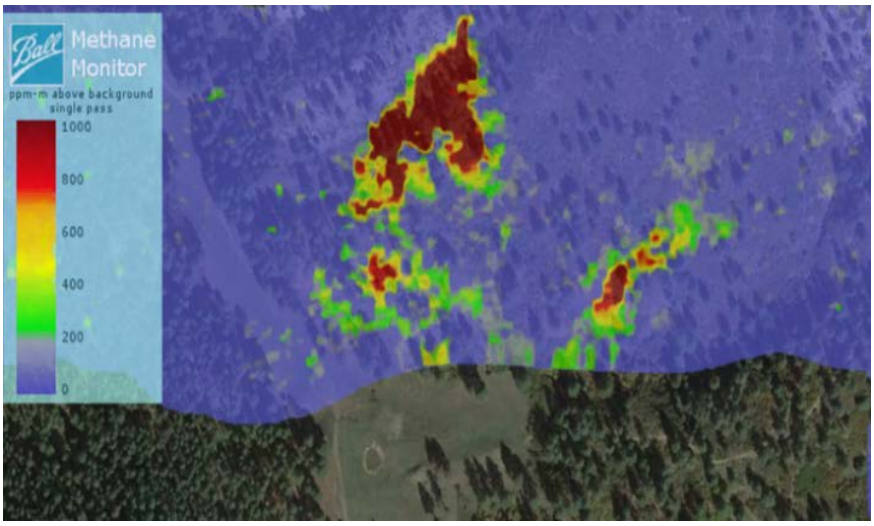
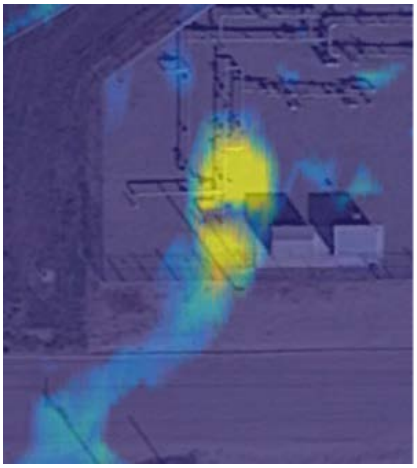
Rapid Aerial Small Methane Leak Sensor (RASMLS) Final Report, Public Version

by the Ball Aerospace Methane Monitor Team

for DOT/PHMSA R&D Project: Rapid Airborne Sensor for Methane Leak Survey (RASMLS)

OTA # DTPH5615T00016 with Period of Performance from September 2015 through March 2018





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Summary of Project Results

The key technology advancement of the Rapid Aerial Small Methane Leak Sensor (RASMLS) project is increased sensor swath capability.

Swath width enables area mapping: The Ball Aerospace team increased swath width to approximately 300 meters by increasing average output laser power, laser pulse repetition rate and aircraft flight altitude. This technology now enables efficient area-mapping of prospective methane sources, effectively doubling flight altitude and increasing swath width by three times.

Figures 1 and 2 show examples of methane emissions observed with the advanced wide-swath sensor .

Figure 1, Example of two plumes from a single oil and gas production facility located in the San Juan Basin. This data was collected during final flight testing in February 2018. Data from over 50 facilities was shared with Colorado State University (CSU). CSU is performing ground-based assessments of emissions from a few facilities in various production basins for the U.S. DOE.

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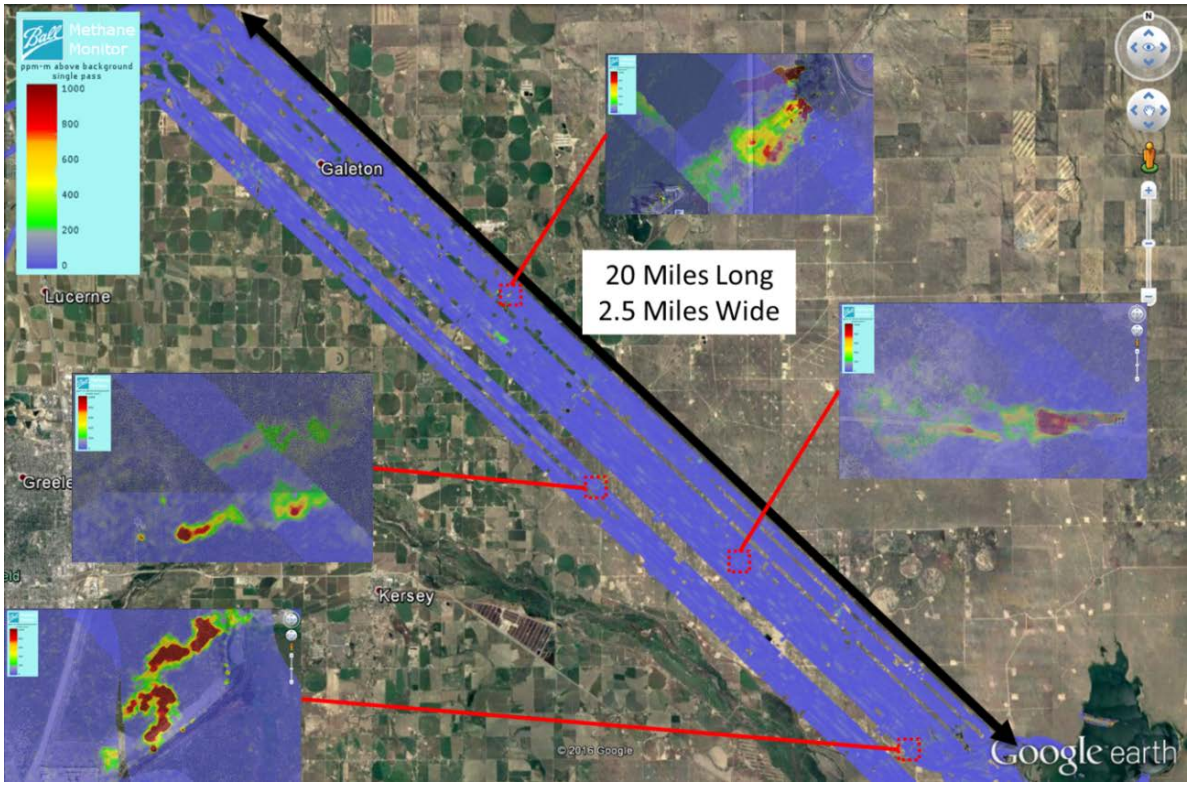

Figure 2, Rapid aerial survey efficiently identifies sources of emissions. Survey of regions near Greeley, Colorado, was performed in May of 2017 as an intermediate flight test of the sensor. Numerous sources of emissions were identified. Table 1 provides information to illustrate the power of rapid, wide-area surveys.

Chemical sensitivity and leak rate detection threshold held constant: The sensitivity and detection threshold was held constant while the swath width and flight altitude was increased. Ball Aerospace is currently funding internal research and development efforts to further improve sensitivity performance under the increased swath width and flight altitude parameters. For example, Ball is upgrading amplification and signal processing on the sensor receive-path using a custom design to reduce the amount of noise from these elements of the system. This improves the signal to noise ratio, thereby improving overall performance.

Table 1, More than 1,300 oil & gas production facilities were surveyed within a 4.5 hour flight time over targeted areas. Total flight time was 7.5 hours and 68 square miles (175 sq km) were surveyed.

Parameter	Performance
Nominal Aircraft speed	55 m/s
Nominal flight altitude (AGL)	1000 m (3280 ft)
Swath width	300 m (984 ft)
Overlap between adjascent swaths	30 m (10%)
Area covered	**175 km^2 (68 mi^2)**
Total flight time	**7.5 hours**
Flight time over target areas	**4.5 hours**
Data volume (GB)	85 GB (over flight area)
Data collection rate (GB/Hr)	45
Number of active wells surveyed	**1,300+**

***Commercialization*:** Several demonstrations were performed for target end customers. These have included area-mapping of natural gas storage facilities and gas gathering pipe systems. A survey of 400-500 miles of high pressure natural gas transmission pipeline was performed for PG&E in October of 2017. Transmission pipeline leak surveys benefit from higher flight altitudes and wider swaths because it is easier to track minor changes in pipeline direction than if the overall field-of-regard is smaller.

Ball continues soliciting leak survey business directly from facility operators while we learn end-customer's operational needs and establish competitive pricing. In the long run, we intend to engage with an oil and gas service provider with existing business ties to facility owners. This collaboration serves as a means to accelerate market penetration of this technology.

***Stanford EDF Mobile Monitoring Challenge*:** A key test and demonstration for this technology is planned for May 21-25, 2018. This technology will be tested in comparison to a dozen other means for observing methane emissions in a "challenge" conducted by Stanford University and funded by the Environmental Defense Fund. This is an opportunity to showcase the technology and generate additional commercial interest.

***Patents*:** Ball Aerospace has filed a U.S. patent application titled, "DIFFERENTIAL ABSORPTION LIDAR", Application No. 2017-04-06, WO201705890141, for this technology.

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Development History

Figure 3 presents the overall development history of Differential Absorption LiDAR (DIAL) technologies at Ball Aerospace for aerial leak survey. Development has been ongoing for more than four years. The methane-specific sensor is now ready for wide-scale deployment.

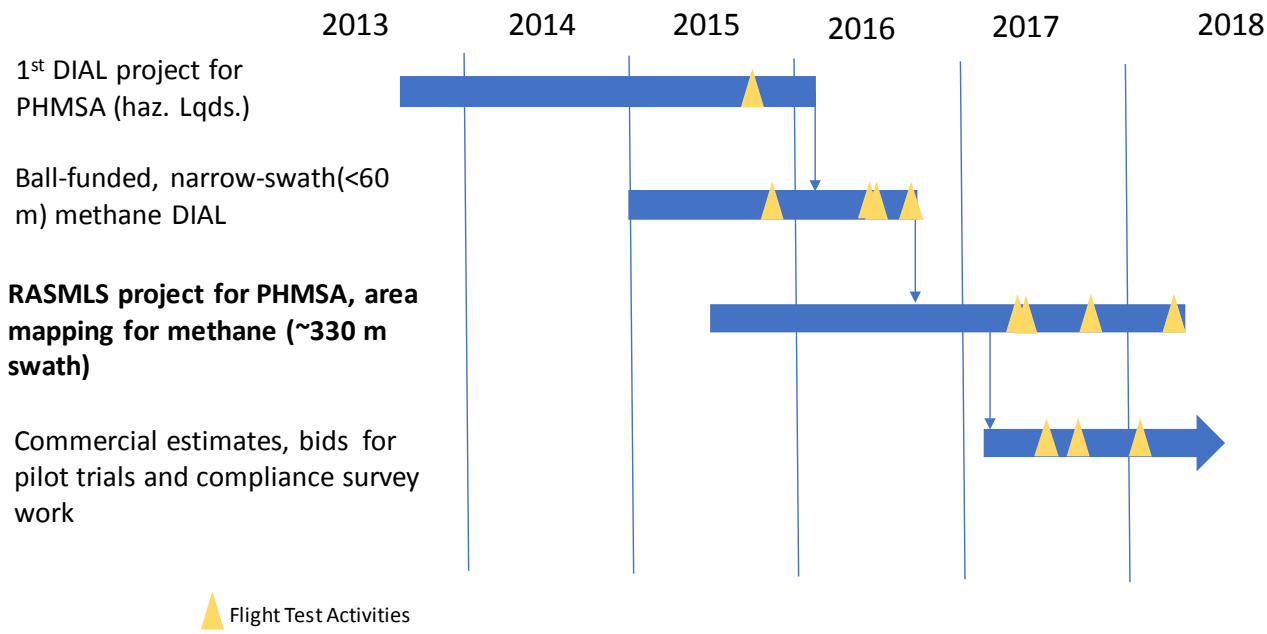

Figure 3, History of DIAL technology at Ball Aerospace for aerial leak survery.

Technology Overview

***IPDA/DIAL Technique*:** The Integrated Path Differential Absorption (IPDA) LiDAR is a well-established method for measuring atmospheric gas concentrations. In its simplest form, the method employs laser emissions at two different wavelengths. As shown in **Figure 4**, an "On-line" laser is tuned to an absorption feature in the spectroscopy of the target gas. A second, "Off-line" laser is at a nearby wavelength not absorbed by the target gas. Both wavelengths are separated from the absorption features of the normal atmosphere: nitrogen, water vapor. For natural gas detection, our Off-line and On-line wavelengths are locked to 1645.40 and 1645.55 nm as shown in **Figure 4**.

The Methane Monitor system is configured for downward (near nadir) view making a full column measurement using the ground as a target that reflects the laser beams back to the lidar. The difference between the received laser intensity of the two wavelengths, after transmission to the ground, reflectance from the ground's surface, and transmission back to the aircraft correlates to the amount of the target gas present.

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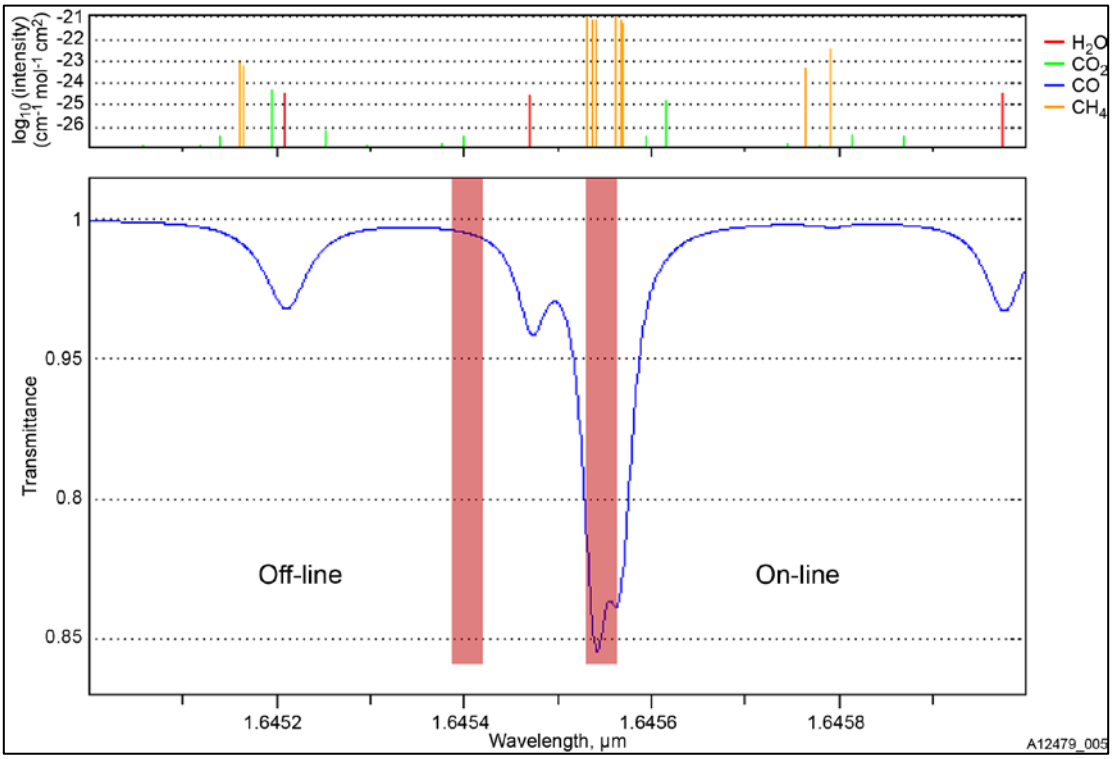

Figure 4, Spectral features of the most common atmospheric gases are shown (above) and for methane on an expanded scale (blue curve). A difference in the return between the on-line and off-line wavelengths (shown notionally by the red bars) indicates the presence of the target gas.

High Level Sensor Design and Concept of Operations: Figure 5 (next page) presents a block diagram of the sensor components and **Figure 6** shows the physical arrangement of the sensor. In operation, the laser generates two pulses, one at each wavelength with a repetition rate of 10 kHz. The flight computer and signal processing electronics has been pre-loaded with coordinates of targets to be surveyed. As the aircraft overflies the targets, pointing actuation is used to scan the target. This pointing actuation also compensates for aircraft motion (roll, pitch and yaw) and accounts for imprecise aircraft navigation. Precision GPS data and data from an Inertial Measurement Unit provide a reference for pointing control and allow geolocation of methane concentration data (and associated context camera imagery).

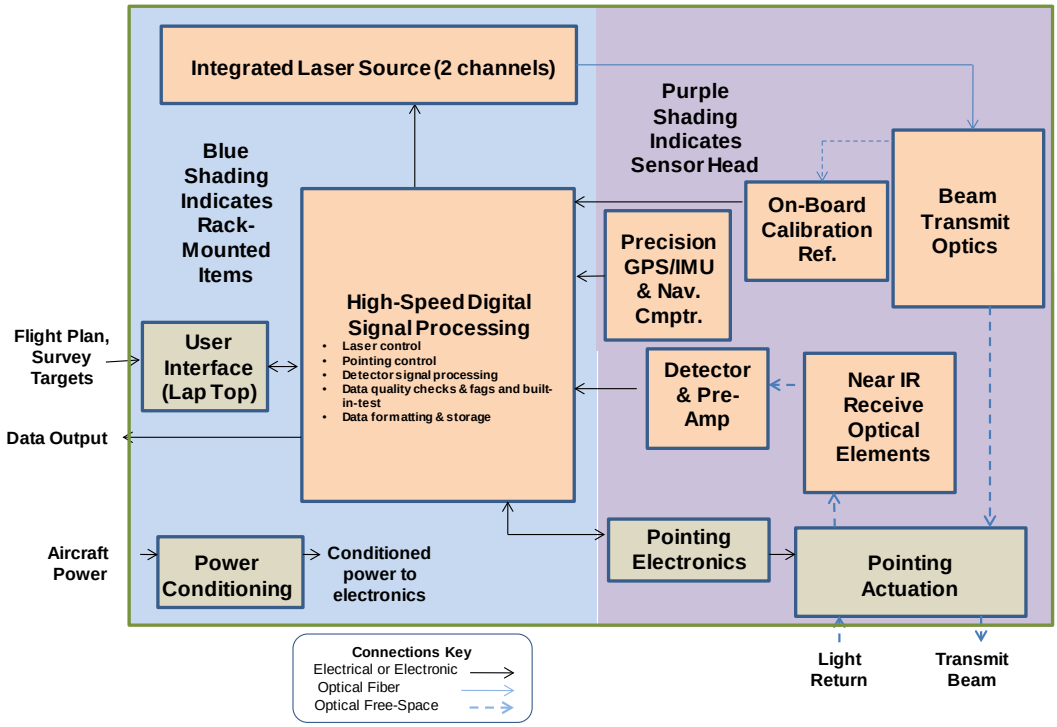

Figure 5, Key components of the IPDA Lidar (DIAL) sensor system are grouped into those items requiring good relative optical alignments (within the purple shading) and those that can be mounted within a standard equipment rack.

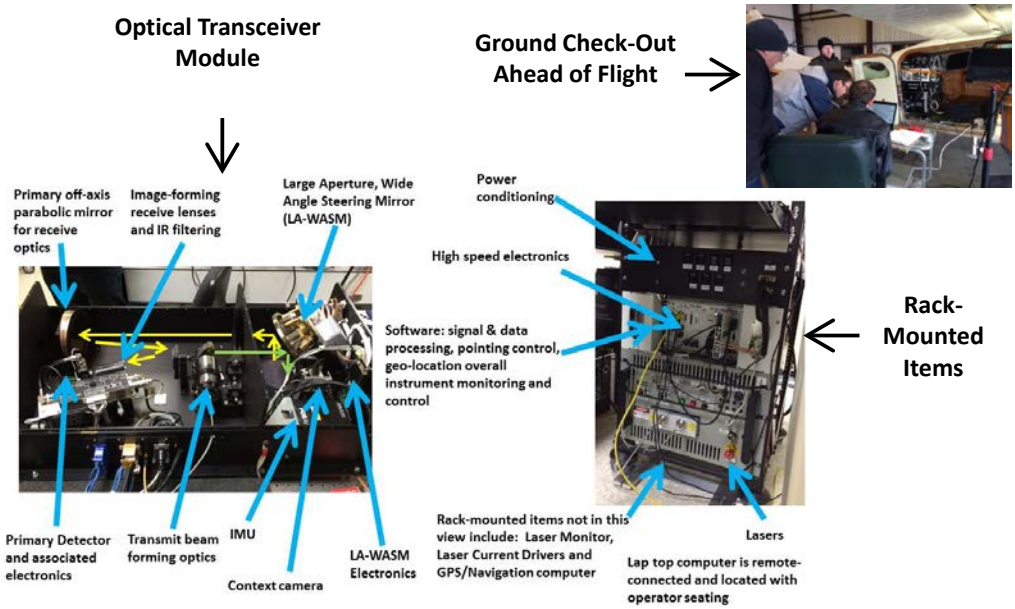

Figure 6, The Methane Monitor instrument fits within the Cessna 206, a single engine, fixed-wing aircraft. The transceiver module on the left above contains all of the optically-aligned elements and the 19-inch rack on the right contains the remaining components of the system.

Operator Interfaces: A laptop computer provides the sensor operator with a display of output data during flight. This interface also allows the operator to adjust various sensor parameters – either during power-on or in-flight. **Figure 7** shows an example of in-flight data with added call-outs to show specific observations (in orange).

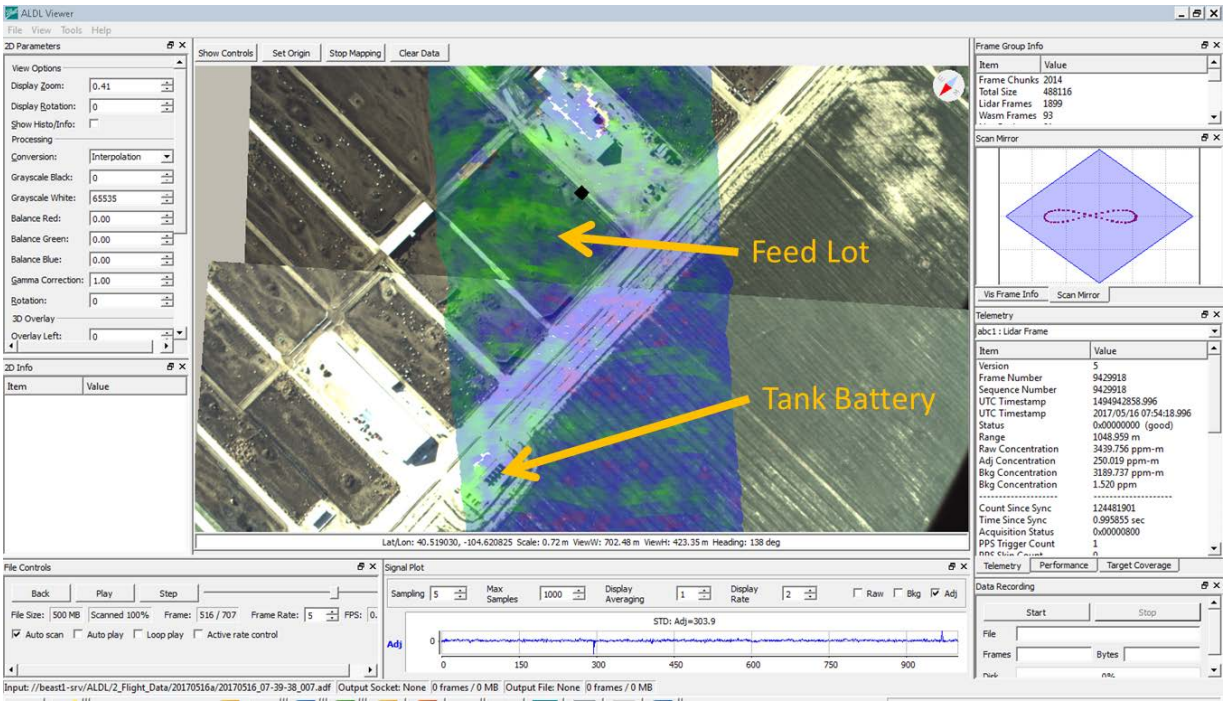

Figure 7, Display of Ball's "Viewer" software. The screen is in playback mode for post-flight review. The scene shows flight over multiple common methane sources: a tank battery and a cattle feed lot.

Advantages of Active Sensing (Laser Sensing): Illuminating the atmosphere by projecting laser light offers a substantial technical advantage over passive remote sensing techniques. Conceptually, the difference is like using flash photography in a low-light setting as compared to taking photographs without supplemental light. **Figure 8** illustrates the difference between passive and active sensing and the following bullets summarize the fundamental difference and resulting benefits.

- DIAL laser illumination exceeds 15,000 W/m2 (during a short pulse) with all light concentrated near a wavelength of interest.
- Sunlight is <1,000 W/m2 with light spread across the entire spectrum; mostly at visible wavelengths
- <u>Net result is >1,000,000X more signal strength per unit area for DIAL vs. passive sensors</u>
- DIAL sensors can take data throughout the day but passive systems are typically limited to a few hours around local noon.

- DIAL sensors maintain sensitivity on cloudy days (fly under cloud deck) but full and partial cloud cover reduces the sensitivity of passive sensors

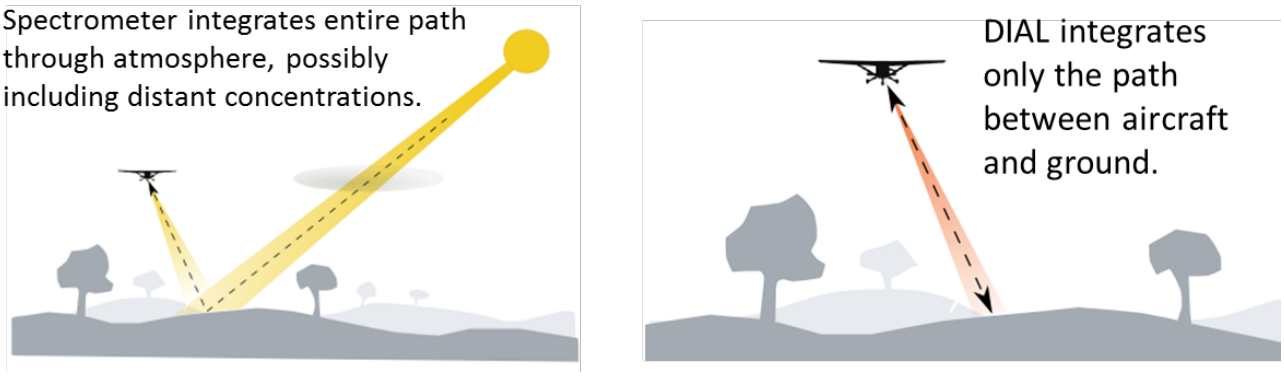

Figure 8, Sunlight used by passive sensors is affected by large quantities of background methane which interfere with observations by absorbing light at the wavelengths of interest. DIAL provides 1,000,000X the power of sunlight during brief pulses at the wavelengths of interest and integrates a relatively short path between the aircraft and ground.

Acknowledgements

PHMSA: The RASMLS team appreciates the R&D investment by PHMSA and looks forward to commercializing this technology to improve pipeline safety and reduce the impact of methane emissions from a broad range of sources. We appreciate the guidance and feedback from Dustin Hubbard, the Project Manager and also James Merritt.

Pacific Gas and Electric (PG&E): We would also like to thank PG&E for supporting this technology, including direct support for testing in October of 2017.

NOAA: NOAA provided access to their Table Mountain Test Facility in Boulder County, Colorado. This facility was used both for ground-base, horizontal testing of the sensor at full range and also as a site for controlled release of methane to simulate leaks during flight testing.

Staff

A total of 43 Ball Aerospace employees worked the RASMLS effort. Twenty people worked at least 10 hours on the project. They are shown in the table below from those working the most hours to those working the least.

RASMLS Contributors
Bartholomew, Jarett L
Karcher, Stephen L
Sipos, Ryan A
Solga, Stephen G
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Craner, Jeremy A
Lyman, Philip C
Hanson, Teresa C
Webster, Kaloni I
Donahoo, Elizabeth A
Warrington, Richard M
Devaud, Genevieve
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Farris, Betsy M
Newman, Michael R
Adkins, Mike M
Teckenbrock, Renee B

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Appendix A – Publications & Presentations

The Methane Monitor team has presented at numerous conferences to promote the technology and engage with stakeholders. This included one of the Methane Monitor software engineers submitting a paper to NIWeek. The paper won the High Impact Award in the energy sector and Ball Aerospace was given the opportunity to present a keynote address at the conference. The keynote was recorded and live streamed. The IEEE Spectrum magazine covered the conference and wrote an article on the sensor development. See: https://spectrum.ieee.org/tech-talk/at-work/test-and-measurement/catching-fugitive-methane-on-the-fly. Methane Monitor team members also attended a number of public events without presenting and held a number of private, face-to-face meetings with potential customers and collaborators. Public events are listed below.

Date	Event Details
November 2016	*Rocky Mountain AIAA Conference* *Poster Presentation and Paper* *Lead Presenter/Author: Jarett Bartholomew*
January 2017	*API Inspection Summit* *Presentation* *Lead Presenter: Phil Lyman*
January 2017	*AIAA SciTech* *Presentation and Paper* *Lead Presenter/Author: Jarett Bartholomew*
May 2017	*NIWeek* *Paper and Keynote Presentation* *Lead Author: Steve Karcher* *Presenters: Steve Karcher & Phil Lyman*
August 2017	*SPIE Optics & Photonic Conference* *Presentation and Paper* *Lead Presenter & Paper: Jarett Bartholomew*
November 2017	*OSA Optics & the Environment Conference* *Presentation and Paper* *Lead Presenter/Author: Bill Tandy*

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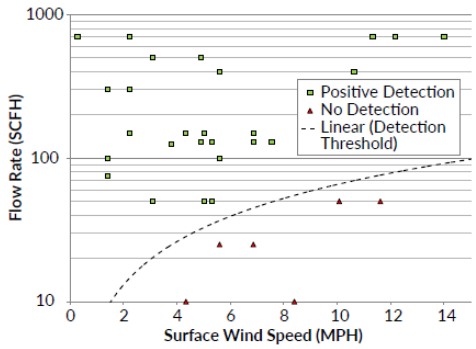
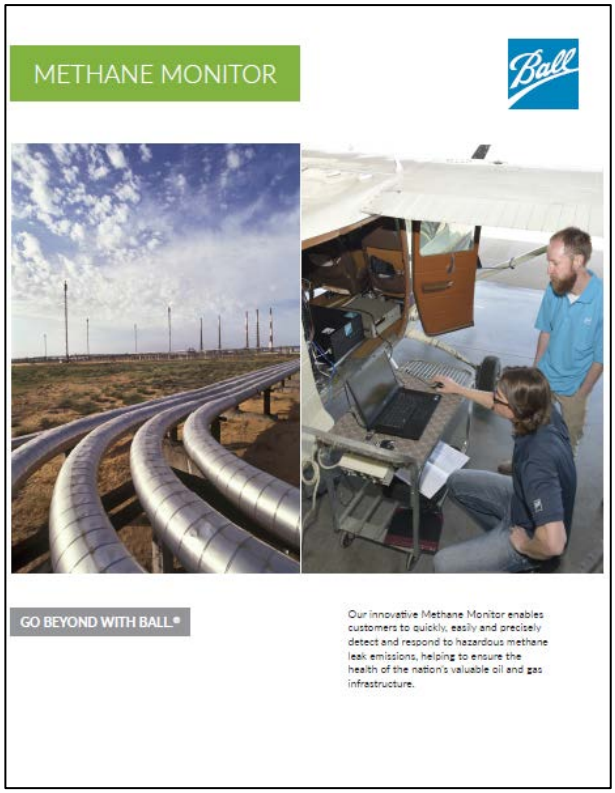
Appendix B – Marketing Brochures

Two marketing brochures were developed for the Methane Monitor system. Unlike other remote sensing technologies, the Methane Monitor team has presented system sensitivity in terms of detection threshold as a function of leak rate and wind speed. The detection threshold plot and the two-sided brochure are shown below. The information in the brochures has been reviewed for compliance with export law and approved for release to both US citizens and foreign nationals.

Nominal performance: emission rate vs wind speed scatter-gram shows detection threshold.





METHANE MONITOR

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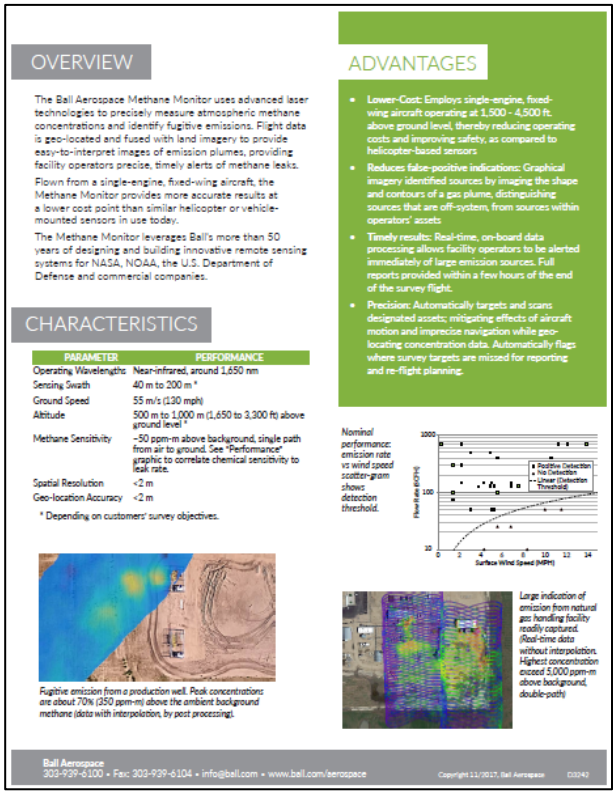
Our innovative Methane Monitor enables customers to quickly, easily and precisely detect and respond to hazardous methane leak emissions, helping to ensure the health of the nation's valuable oil and gas infrastructure.



OVERVIEW

The Ball Aerospace Methane Monitor uses advanced laser technologies to precisely measure atmospheric methane concentrations and identify fugitive emissions. Flight data is geo-located and fused with land imagery to provide easy-to-interpret images of emission plumes, providing facility operators precise, timely alerts of methane leaks.

Flown from a single-engine, fixed-wing aircraft, the Methane Monitor provides more accurate results at a lower cost point than similar helicopter or vehicle-mounted sensors in use today.

The Methane Monitor leverages Ball's more than 50 years of designing and building innovative remote sensing systems for NASA, NOAA, the U.S. Department of Defense and commercial companies.

CHARACTERISTICS

PARAMETER	PERFORMANCE
Operating Wavelengths	Near-infrared, around 1,650 nm
Sensing Swath	40 m to 200 m *
Ground Speed	55 m/s (130 mph)
Altitude	500 m to 1,000 m (1,650 to 3,300 ft) above ground level *
Methane Sensitivity	~50 ppm-m above background, single path from air to ground. See "Performance" graphic to correlate chemical sensitivity to leak rate.
Spatial Resolution	<2 m
Geo-location Accuracy	<2 m

* Depending on customers' survey objectives.

Fugitive emission from a production well. Peak concentrations are about 70% (350 ppm-m) above the ambient background methane (data with interpolation, by post processing).

ADVANTAGES

- Lower-Cost: Employs single-engine, fixed-wing aircraft operating at 1,500 - 4,500 ft. above ground level, thereby reducing operating costs and improving safety, as compared to helicopter-based sensors
- Reduces false-positive indications: Graphical imagery identified sources by imaging the shape and contours of a gas plume, distinguishing sources that are off-system, from sources within operators' assets
- Timely results: Real-time, on-board data processing allows facility operators to be alerted immediately of large emission sources. Full reports provided within a few hours of the end of the survey flight.
- Precision: Automatically targets and scans designated assets; mitigating effects of aircraft motion and imprecise navigation while geo-locating concentration data. Automatically flags where survey targets are missed for reporting and re-flight planning.

Nominal performance: emission rate vs wind speed scatter-gram shows detection threshold.

Large indication of emission from natural gas handling facility readily captured. (Real-time data without interpolation. Highest concentration exceed 5,000 ppm-m above background, double-path)

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