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Fugitive Methane Leak Detection Using sUAS and Miniature Laser Spectrometer Payload: System, Application and Groundtruthing Tests

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***Abstract*—A miniature *in-situ* CH_4 concentration measurement instrument based upon tunable laser spectroscopy (TLS) was developed and applied in numerous field campaigns. The instrument, a $3.4\ \mu m$ laser spectrometer developed at NASA Jet Propulsion Lab (JPL), is lightweight ($250g$), low power ($< 8\ W$), and high sensitivity ($10\ ppb\ s^{-1}$). The payload was further developed and integrated onto a small UAV at UC Merced, rendering an overall payload weight of $400\ g$ and real-time data acquisition. The remarkable characteristics of the instrument and prior investigative work regarding sensor placement yielded excellent trial and field results, which are presented in this work.**

I. INTRODUCTION

Miniature natural gas sensors weighing a few hundred grams with $10\ ppb\ s^{-1}$ sensitivity present the energy industry with cost effective and unobtrusive ways to improve safety, comply with state and federal regulations, and decrease natural gas emissions. Oil and gas (O&G) companies lose an estimated $30B annually due to fugitive emissions [1]. Fugitive emissions may occur along any portion of the natural gas production road-map - upstream, midstream or downstream; therefore, reinforcing the need for a reliable methane concentration instrument (CMI) and leak analysis method. While several gas detection technologies exist on the market today, few are small enough to be flown on a small unmanned aerial system (sUAS), and those that do exist tend to be retrofitted from hand-held instruments, lending to bulky systems and decreases in precision and accuracy of the measurements[2], [3], [4].

One particularly promising implementation of this technology is on small unmanned aerial systems (sUAS) flown by service providers, energy providers, or even more ambitiously as part of larger network conducting autonomous, continual monitoring. Current methane sensing and measurement technologies can be split into three main categories: electro-optical infrared gas imaging, laser spectroscopy [5] [6], gas flame ionization [7], and sample extraction. These technologies range drastically in applicability on sUAS, their sensitivity, weight and price range are outlined in Table I. While these four forms of methane sensing technologies are currently being flown by some research groups, the most promising results are obtained utilizing electro-optical infrared imaging and laser spectroscopy.

In this work, a miniature methane sensor developed at JPL Caltech that has been integrated into a concise UAV payload is presented and three research areas are identified. The technology is derived from a field of spectroscopy called Open Path Laser Spectroscopy (OPLS), in which a Herriott cell is in the free-stream of air and allows molecules to freely pass throughout the cell. This not only yields an extremely small time constant (1.2 s), but also adds a critical implication that the measured air is unimpeded and thus undisturbed - essentially an accurate ‘snapshot’ of the environment is taken. Leveraging work completed in 2015 by the Mechatronics, Embedded Systems and Automation (MESA) Lab in collaboration with Pacific Gas & Electric (PG&E), it was determined that there are “certain operating conditions in which the influence of propellers can be ignored” [8].

A year-long experimental campaign was executed to properly characterize payload functionality in:

1) Detection,
2) Localization,
3) Quantification.

Key emphasis was placed upon detection and localization, with quantification still a major research focus to be presented in future works.

The remainder of this work is organized with system overview and integration discussed in Section III, Section IV reviews the two controlled release experiments conducted in 2016, alternate application are introduced in Section V, the future of this research at UC Merced and JPL is discussed in Section VI, followed by concluding remarks in Section VII.

II. PLATFORM SELECTION

In the preliminary stages of this study both fixed wing and vertical take-off and landing (VTOL) sUAS platforms were considered. Ultimately it was decided that VTOL aircraft would offer more degrees of freedom for flight planning with detection and localization in mind. This is due to there ability to hover in a single location, operate at much lower airspeeds, and fly complex flight plans that fixed wing aircraft can not. It should also be noted that fixed wing platforms are also being used in this research, but that they present their own unique challenges that will not be discussed in this paper.

TABLE I

CURRENT INDUSTRY ACCEPTED METHANE SENSING TECHNOLOGIES

Manufacturer	Description	Cost
Picarro	Cavity Ring Down Spectroscopy (CRDS)	>$50,000
Los Gatos Research (LGR)	Cavity enhanced spectroscopy	<$25,000
Rebellion Photonics Inc.	Electro-optical imaging	N/A
Heath Consultants	Gas Flame Ionization	<$10,000
Heath Consultants	RMLD	<$10,000

III. SYSTEM INTEGRATION

As stated previously the technology employed is based in Open Path Laser Spectroscopy (OPLS) in which measurements are taken with a Herriott cell being placed in a free stream of air allowing for molecules to pass through the cell. A key concern when implementing this technology on VTOL sUAS is that the propeller wash of the propulsion system would disrupt this free stream flow of molecules and negatively impact detection. In a previous study[8], performed on a quad-rotor aircraft it was proven that their exists a region in which the propeller wash can be considered negligible. As long as the following conditions are satisfied; the sensor must be placed outside of the adjacent propeller wash region, specific to the power system combinations (propeller and motor) of the sUAS and have wind speeds of at least $2\frac{m}{s}$ relative to the optical head of the sensor. With these results it was determined that this technology could be adapted to any quad-rotor aircraft and still serve as a valuable tool for detection, localization and quantification of natural gas plumes.

With these results in mind an OPLS sUAS payload was developed and integrated with two separate VTOL platforms, the 3D Robotics (3DR) Iris+ and it's successor the 3D Robotics (3DR) Solo. The first iteration of this payload was integrated to the IRIS+ platform. Approximately 5 months of testing was performed using this platform before switching to the Solo. These specific platforms were selected due to their open source autopilots. Utilization of an open source autopilot was critical to this research as it allowed for the OPLS sensor data to be fused into the autopilot data stream. It also enabled measurements to be geo-tagged with precise (2 cm) altitude information and allowed for the integration of other sensors like LIDAR into the flight control that in turn enabled terrain-following modes of flight to be carried out.

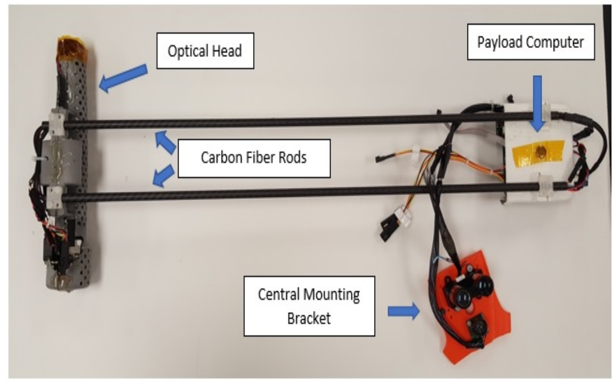

Fig. 1. Fully assembled OPLS payload designed for easy integration to the 3DR Solo sUAS. assembly displays all the neccessary components of the payload.

The integration of the OPLS payload was conducted on two fronts, hardware and software. These efforts are summarized in the following subsections.

A. Hardware Design and Integration

The methane sniffing payload was designed to remain consistent across multiple platforms for ease of use and integration as well as being relatively lightweight (<400 g). The payload consists of three main components: an optical head, payload computer and central mounting structure. These components are all mounted to supporting carbon fiber rods. The central mounting bracket then meshes with the belly of the aircraft as seen in Figure 1 and secures the entire payload to the sUAS. Each part seen in Figure 1 aside from the the carbon fiber rods is 3D-printed using a polylactic acid (PLA) material and a MakerBot Replicator printer. The sensor itself is comprised of both the Herriott cell or optical head and a Gumstix computer which are housed within these 3D printed components.

The carbon fiber rods can be cut to any size to reflect the UAS dimensions and the position of each component is adjustable as to balance the payload about the aircraft's center of gravity. In current implementations of the payload the central mounting bracket must be redesigned for each platform integration. In future efforts a universal mounting bracket should be implemented so that a payload can be easily swapped between aircraft.

Figure 2 shows the JPL/PRCI OPLS sniffer mounted on UC Merceds 3DR Solo. In order to ensure that the OPLS payload was secured to the sUAS and would support the sniffer throughout flight operations, the entire payload was tested to meet NASA standards for structural design and test factors of safety for spaceflight hardware NASA-STD-5001 [9].

The central mounting bracket was designed not only to support the two carbon fiber rods and bear the weight of the payload, but also to contain small cm-sized ground-ranging LIDAR and SONAR units. The utility of ground-ranging is twofold. One, it provides a relatively accurate (±

Fig. 2. OPLS Integration with Solo

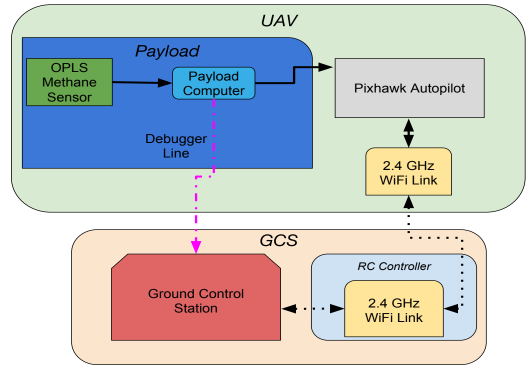

Fig. 3. OPLS Integration with Solo

12 cm) altitude above ground measurement in comparison to the default GPS and barometer measurements which can drift by many meters in the course of minutes. Two, the LIDAR ground-ranging information can be integrated into the autopilot control system so that the platform can be flown safely to as low as 50 cm in terrain following mode.

B. Software Integration

Utilizing an open source autopilot enabled integration of the methane data directly into the autopilot data stream, thus allowing for critical location information (latitude, longitude, altitude) and GPS time to be packeted with the concentration information. Furthermore, all the data was packeted into a MAVLink message and relayed over a 2.4 GHz Wi-Fi link to a custom written ground control station (GCS) software. This is outlined in system integration flow chart in figure 3. These integration efforts were beneficial in maintaining a lightweight payload as no alternative GPS or telemetry was necessary for real-time data visualization.

As mentioned previously, a custom ground control software was also developed under the scope of this research project. Developing a functional GUI has many advantages to this research as it allows for the software to be completely customized and offers and wide range of benefits for real time analysis specific to natural gas detection.

IV. Controlled Release Experiments

Many experiments were conducted over the course of the year to develop payload functionality in the three key areas described above. These experiments were exploratory in nature, as we sought to understand the real-world dynamics of methane flow in the lower atmosphere. The understanding of these dynamics is essential to detection methods and a key tool in path planning of the UAS. In this paper we will identify some key observations of these experiments and present data from a few select flights.

In order to fully understand these dynamics all experiments were conducted with two ancillary instruments. These included a 3D ultrasonic anemometer for measuring wind speed and direction and a Pyranometer for measuring the solar irradiance to be used for quantifying convection of the plume. These measurements are essential for plume estimation efforts and will play a key factor in future localization.

During these experiments multiple flight paths were flown and serve as a foundation for optimal future detection patterns. The flexibility of these plans is essential to methane detection efforts. The nature of the plume dynamics are heavily dependent on rapidly changing wind effects and topography. Flight patterns should be flown that are conducive to gas detection in response to the following factors: wind direction, wind speed and topography.

A. Detection

Leak detection is the preliminary step in localization or quantification. Many sensors on the market provide adequate sensitivity and reliability, but are not feasible for sUAS applications. In order to ensure the methane detecting sUAS is effective in detection of a plume it is compared to other similar ”lightweight” sensors employed in both hand held and ground vehicle surveillance operations. These sensors include those such as Remote Methane Leak Detectors (RMLD^{TM})[10] or Standoff Tunable Diode Laser Absorption Spectroscopy (sTDLAS) sensors[11]. RMLDs are advantageous for their standoff sensing capabilities. Comparatively the OPLS requires sufficient airflow and to be in the direct path of the plume. While RMLDs eliminate this limitation they do not compare to many aspects of an OPLS sensor.

In a study done by Physical Sciences Inc. a ”miniaturized ultra-lightweight” sTDLAS sensor was flown on a 3.2kg quad rotor aircraft carrying a 1.4kg sTDLAS sensor[11]. In this experiment they were able detect leaks as small as $1\frac{m^3}{h}(35.31SCFH)$ from an altitude of approximately 50m. While impressive it does not satisfy the needs of the gas industry. Gas industry leaders are interested in detecting leaks ranging as small as $0.0028\frac{m^3}{h}$ (0.1SCFH). It should also be noted that the OPLS payload is much lighter than the sTDLAS described above currently weighing <400g. This drastic difference in weight gives an sUAS equipped with the OPLS payload a huge advantage in flight time and surveillance duration. This is representative of the fact that the OPLS sensor was completely redesigned for sUAS integration and not simply gutted and mounted on an aircraft. Two rounds of

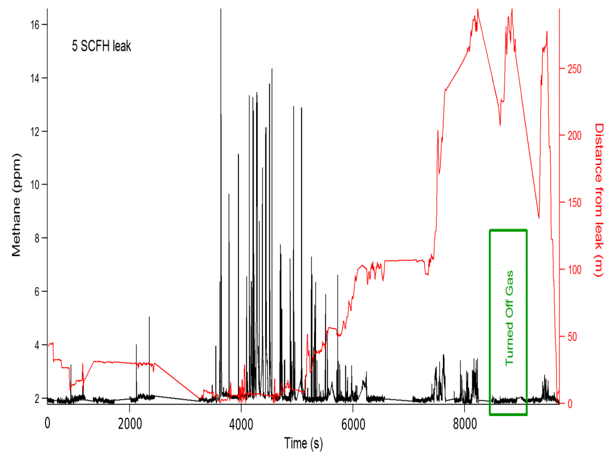

Fig. 4. Measurements downwind of a $0.142\frac{m^3}{h}$ (5 SCFH) controlled methane leak. Black is methane; Red is distance from leak.

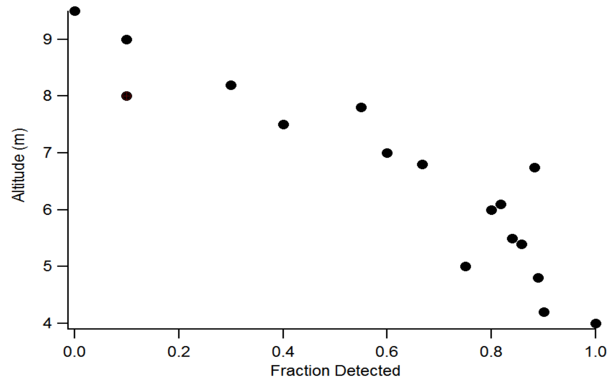

Fig. 5. August test flights

experiment were performed to test the detection capabilities of the OPLS payload targeting this much smaller leak rate.

In the first round of controlled release experiments the focus was to determine the downwind extent in which the sUAS payload was capable of measuring small leaks. These experiments were conducted using automated flight plans at distances from the leak ranging between 50 - 250m and under manual flight control at distances greater than 250m. At a distance of 280m from the leak source the sUAS payload was capable of clearly measuring a $0.142\frac{m^3}{h}$ (5 SCFH) leak as shown in Figure 4.

In later rounds of intermediate testing the sUAS payload was flown with wind information integrated into real time software analysis to provide live back-trajectory analysis. These tests also included LIDAR and SONAR systems for altitude verification and provided key information regarding lower atmospheric plume characteristics as well as observations of the OPLS performance and calibration.

Key observations of these tests were:

1) The atmospheric stability class (D and F), which were driven mainly by high winds (gusts $>10\ \frac{m}{s}$), kept the plume <10 m at 150 m despite high insulation and convection potential.
2) The OPLS measurements display 100s *ppb* drift primarily due to opto-mechanical thermal changes. This highlighted the importance of developing a data analysis methodology that removes this drift as well as determine 'natural' background changes in methane concentration from other methane sources. This 'non-drift' signal helps in the identification of plume indications.

The second controlled release experiments considered here had greatly improved signal-to-noise from the previous experiment and thus it was easier to detect leaks. This increase in signal-to-noise was mainly due to better mechanical alignment within the OPLS optical head. A main goal of these experiments were to understand the effect of altitude on discovering a $0.142\frac{m^3}{h}$ ($5\ SCFH$) leak at a downwind distance of 30 m under typical summer conditions in California. Data of flight altitude versus fraction per pass that the controlled emission was detected are shown in Figure 5 Above 7 m, the chance of discovering a leak drops dramatically. At 3 m altitude, nearly 100% of traverses downwind of the $0.142\frac{m^3}{h}$ ($5\ SCFH$) leak were discovered.

Twice weekly flights were flown at UC Merced to debug issues like understanding the telemetry range and field of view, test the autopilot stability and verify the fidelity of the open-source code, characterize OPLS noise and signal drift as a function of height and temperature, and investigate the time dependence and variance in methane signal at different distances from the emission source, as shown in Figure 6. This variance often masked itself as noise in the signal,but may serve as valuable additional metric used to detect the presence of methane. The main observation that can be taken away from this figure, is that upwind from methane leak sources a rather steady background oscillation can be seen. Moving downwind of the leak source results in an increase in signal variance. Given these observations, which are highly repeatable, a qualitative assessment of the environment can be made. 'If an increase in signal variance is observed, then a leak upwind of the measurements is present.' The one caveat to this hypothesis is that a good observation of the background methane signal must be obtained prior to drawing any conclusion of detection.

While detection can be qualitatively drawn from variance signal analysis, more definitive quantitative assessments can be drawn. For example, it was observed that the signal decreased exponentially as a function of distance from the leak, which will be discussed further in Section IV-B.

B. Localization & Quantification

While there is an abundance of research performed on active source localization of diffusion-driven processes, there is limited research in active localization of emissions sources that are overwhelmingly advection-driven in literature. Localization is an important intermediate step between detection and quantification. Temporal Flux measurements are needed to accurately quantify leaks from a single source. In order to take longer durations samples the plume source needs to be localized and wind direction must be considered.

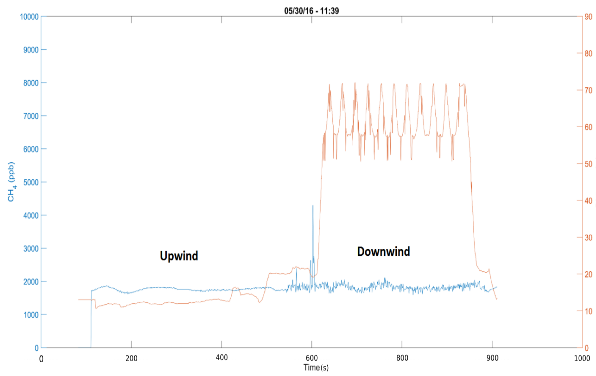

Fig. 6. OPLS signal variance

Throughout the field experiments, it became apparent that qualitative source localization became a relatively easy task with an Operator in the loop; however, the repeatability of such results vary from operator to operator, depending mainly on experience. A deeper look into variance vs. distance (Figure 7) shows that a quantifiable increase in the variance of the signal is apparent. While the baseline of variance remains relatively the same, the distribution of variance values broadens as the source is approached.

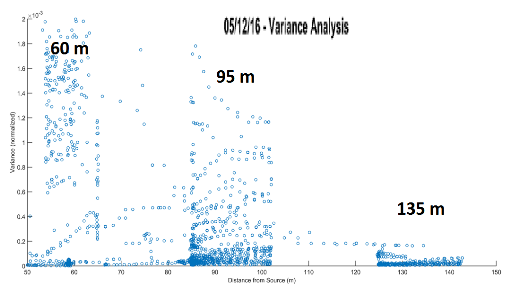

Fig. 7. Variance Analysis

The OPLS equipped sUAS exhibited promising results in flights in which a hidden controlled leak was localized using random searches under manual flight controls. In these flights, the pilot acted as a leak surveyor and cooperatively used the custom GCS software to identify and localize the leak with ± 5m accuracy. However, attempting to implement automation to the localization problem it becomes inherently complex. Thus far autonomous localization of the leak source was not a main development of this project. It will, however, be a main focus in all future work including the development of necessary algorithms and plume estimation efforts.

The current industry standard for 'quantification' is grading. Grading is essentially triaging detected emissions leaks into three categories:

1) Grade 1 - roughly 80% or greater of the lower explosive limit (LEL);
2) Grade 2 - roughly 20% or greater of the LEL;
3) Grade 3 - any leak detected.

Estimating emissions measurements by confining them to the above categories are subject to human error in sample collection/assessment and do not offer a qualitative assessment of the leaking infrastructure; however, they do offer a starting point for automated emissions quantification.

Much research has been dedicated to calculating fugitive emissions and/or flux rates. Thoma et al studied the ability to detect and quantify emissions using the plane integrated concentration method based on measurements taken from a mobile CMI [12], [13], [14].

During the year of controlled release experiments, the most promising approach to utilizing an sUAS for methane emission quantification is by means of a flux plane. A flux plane is a vertical plane downwind of the leak source composed of several horizontal transects at incremental altitudes. During post processing, these planes are interpolated utilizing a scattered-interpolant algorithm and flux rates can be extracted. This is similar to the manned-aircraft work performed by Cambaliza et al during their emission flux assessment of the city of Indianapolis [15]. During this experiment, measurements were collected several kilometers downwind of Indianapolis.

Another work utilized a CMI that has been mechanically multiplexed with multiple inlets to take several samples from one vehicle [16]. The result is a sliding flux plane.

V. Alternative Applications

Methane gas is both naturally occurring and produced largely due to the development of industries. Methane emissions occur far and wide, many of these sources include utility companies, livestock farming, agriculture, and waste disposal infrastructure. These sources all represent industries in which the OPLS payload is highly applicable and can add great value to methane monitoring efforts.

While the majority of methane production can be attributed to human influence, naturally occurring methane is also of great interest to environmental researchers. The majority of naturally occurring methane is produced by wetlands and microbial life in the large bodies of water. The OPLS sUAS could serve as a valuable tool for environmental researches in their own efforts to measure methane emissions from wetlands and bogs.

VI. Future Work

Current efforts are made to improve localization and quantification techniques. Resources at the Jet Propulsion Lab and UC Merced are invested in the "Rapid Flux Quantification".

It is also important moving forward to develop standard detection practices and success metrics to create systematic procedures for plume detection by means of sUAS. This is important to successful implementation of the technology for methane leak surveillance. Similar detection practices are being developed by the Environmental Protection Agency (EPA) for Geospatial Measurement of Air Pollution-Remote Emissions Quantification (GMAP-REQ) in a drafted report OTM-33A. OTM-33A proposes guidelines for inspections to ensure leak surveyors are providing accurate and meaningful results. Similar procedures should be developed and amended to OTM-33A to encompass sUAS applications in air pollutant and emissions detection.

VII. CONCLUSIONS

In Conclusion, the OPLS technology developed at NASA JPL has proved promising in sUAS applications for pipeline surveillance and fugitive emission detection. Having redesigned the sniffer for easy integration into sUAS platforms it offers incredible advantages over similar sensors on the market. The OPLS is an extremely light weight sensor ($<$400 g) and is capable of detecting very small leaks below $0.142\frac{m^3}{h}$ ($5\ SCFH$) from hundreds of meters away as long as the sUAS traverses through the plume path.

After performing numerous controlled release experiments over the course of a year many observations were made. It was discovered that the most promising approach to utilizing sUAS for methane emission quantification is by means of a flux planes downwind of the leak source. Another key discovery, was the added value of signal variance to methane detection. A conditional hypothesis is proposed and supported by multiple experiments with strikingly repeatable results: 'If an increase in signal variance is observed, then a leak upwind of the measurements is present.' This result is perhaps the most important finding as it will shape future localization and quantification efforts.

Future work is also needed from an industry perspective. In order for utility companies to find value in this technology it is necessary to develop standardized success metrics. These metrics should me specialized for sUAS in leak surveillance applications similar to those proposed by the EPA in OTM-33A for GMAP-REG techniques employing ground vehicles.

REFERENCES

[1] "Methane leaks: The opportunity paris climate negotiators can't afford to miss." [Online]. Available: https://www.edf.org/blog/2015/04/24/methane-leaks-opportunity-paris-climate-negotiators-cant-afford-miss

[2] T. I. Yacovitch, S. C. Herndon, G. Ptron, J. Kofler, D. Lyon, M. S. Zahniser, and C. E. Kolb, "Mobile laboratory observations of methane emissions in the barnett shale region," *Environmental Science & Technology*, vol. 49, no. 13, pp. 7889–7895, 2015, pMID: 25751617. [Online]. Available: http://dx.doi.org/10.1021/es506352j

[3] A. Khan, D. Schaefer, L. Tao, D. J. Miller, K. Sun, M. A. Zondlo, W. A. Harrison, B. Roscoe, and D. J. Lary, "Low power greenhouse gas sensors for unmanned aerialvehicles," *Remote Sensing*, vol. 4, no. 5, pp. 1355–1368, 2012. [Online]. Available: http://www.mdpi.com/2072-4292/4/5/1355

[4] T. F. Villa, F. Gonzalez, B. Miljievic, Z. D. Ristovski, and L. Morawska, "An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives," *Sensors*, vol. 16, no. 7, 2016. [Online]. Available: http://www.mdpi.com/1424-8220/16/7/1072

[5] "Picarro surveyor." [Online]. Available: http://picarrosurveyor.com/

[6] "Greenhouse gas, isotope and trace gas analyzers: Lgr." [Online]. Available: http://www.lgrinc.com/

[7] H. C. I. www.heathus.com, "Gas, electric, water, utility — damage prevention." [Online]. Available: http://heathus.com/

[8] B. Smith, G. John, B. Stark, L. E. Christensen, and Y. Chen, "Applicability of unmanned aerial systems for leak detection," in *2016 International Conference on Unmanned Aircraft Systems (ICUAS)*, June 2016, pp. 1220–1227.

[9] N. NASA, "Std-5001," *Structural Design and Test Factors of Safety for Space flight Hardware*, vol. 6, p. 21, 1996.

[10] L. Tao, D. Pan, L. Golston, K. Sun, S. Saripalli, and M. A. Zondlo, "Uav-based laser spectrometer to quantify methane from agricultural and petrochemical activities," in *2015 Conference on Lasers and Electro-Optics (CLEO)*, May 2015, pp. 1–2.

[11] M. B. Frish, R. T. Wainner, M. C. Laderer, M. G. Allen, J. Rutherford, P. Wehnert, S. Dey, J. Gilchrist, R. Corbi, D. Picciaia, P. Andreussi, and D. Furry, "Low-cost lightweight airborne laser-based sensors for pipeline leak detection and reporting," pp. 87 260C–87 260C–9, 2013. [Online]. Available: http://dx.doi.org/10.1117/12.2015813

[12] E. D. Thoma *et al*, "Detection and quantification of fugitive emissions from colorado oil and gas production operations using remote monitoring," *103^{st} Annual Conference of the Air & Waste Management Association*, Jun 2010.

[13] H. L. Brantley, E. D. Thoma, W. C. Squier, B. B. Guven, and D. Lyon, "Assessment of methane emissions from oil and gas production pads using mobile measurements," *Environmental Science & Technology*, vol. 48, no. 24, pp. 14 508–14 515, 2014, pMID: 25375308. [Online]. Available: http://dx.doi.org/10.1021/es503070q

[14] T. A. Foster-Wittig, E. D. Thoma, and J. D. Albertson, "Estimation of point source fugitive emission rates from a single sensor time series: A conditionally-sampled gaussian plume reconstruction," *Atmospheric Environment*, vol. 115, pp. 101 – 109, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S135223101530114X

[15] M. O. Cambaliza, P. Shepson, J. Bogner, D. Caulton, B. Stirm, C. Sweeney, S. Montzka, K. Gurney, K. Spokas, O. Salmon *et al.*, "Quantification and source apportionment of the methane emission flux from the city of indianapolis," *Elementa*, vol. 3, 2015.

[16] C. W. Rella, T. R. Tsai, C. G. Botkin, E. R. Crosson, and D. Steele, "Measuring emissions from oil and natural gas well pads using the mobile flux plane technique," *Environmental Science & Technology*, vol. 49, no. 7, pp. 4742–4748, 2015, pMID: 25806837. [Online]. Available: http://dx.doi.org/10.1021/acs.est.5b00099