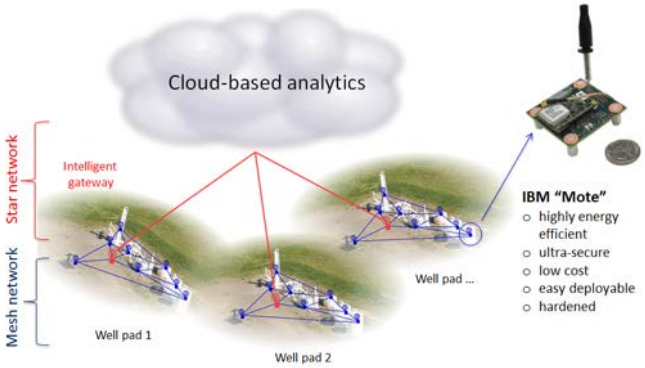
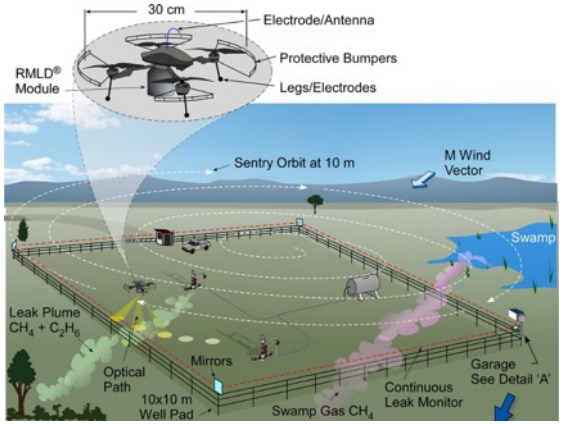
ENERGY
INSTITUTE
Colorado State University
Emerging Technologies
for Methane Quantification
May 15, 2018
Bryan Willson
Professor & Presidential Chair in Energy Innovation
Director, CSU Energy Institute
Former Program Director & Special Government Employee
DOE ARPA-E, Advanced Research Projects Agency - Energy

NG Emissions Monitoring Technology

Point sensor technologies

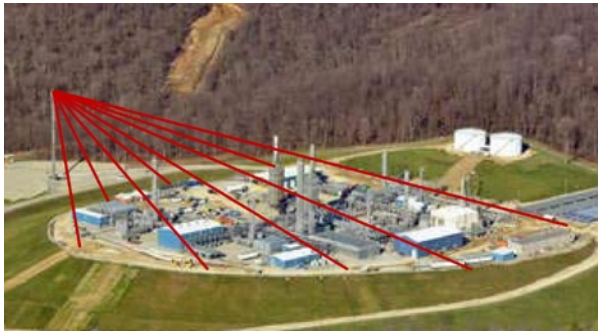


Aerial technologies



Optical imaging technologies

Long distance technologies



ENERGY INSTITUTE
Colorado State University

ARPA-E's MONITOR Program

Technology to Quantify Methane Emissions

Bryan Willson
Special Government Employee
Founding Program Director

arpa·e
CHANGING WHAT'S POSSIBLE

Complete & Partial Solutions to Detection

Complete measurement systems: *6 projects*

- Systems that include:
  1) Methane emission sensing
  2) Leak rate characterization and data analytics
  3) Provisions for data quality control
  4) Digital communication
  5) Enhanced functionality

parc, A Xerox Company — Palo Alto, CA

PSI Physical Sciences Inc. — Andover, MA

AERIS Technologies — Redwood City, CA

BRIDGER PHOTONICS — Bozeman, MT

IBM — Yorktown Heights, NY

REBELLION PHOTONICS — Houston, TX

Partial measurement systems: *5 projects*

- Nascent technologies that may be too early in the development process for incorporation into a complete system
- Could significantly contribute to meeting system-level objectives
- Primarily envisioned as advances in detector technology or data analytics

THORLABS — Jessup, MD

LI-COR — Lincoln, NE

GE — Niskayuna, NY

Duke University — Durham, NC

University of Colorado Boulder — Boulder, CO

The Portfolio: Four Approaches

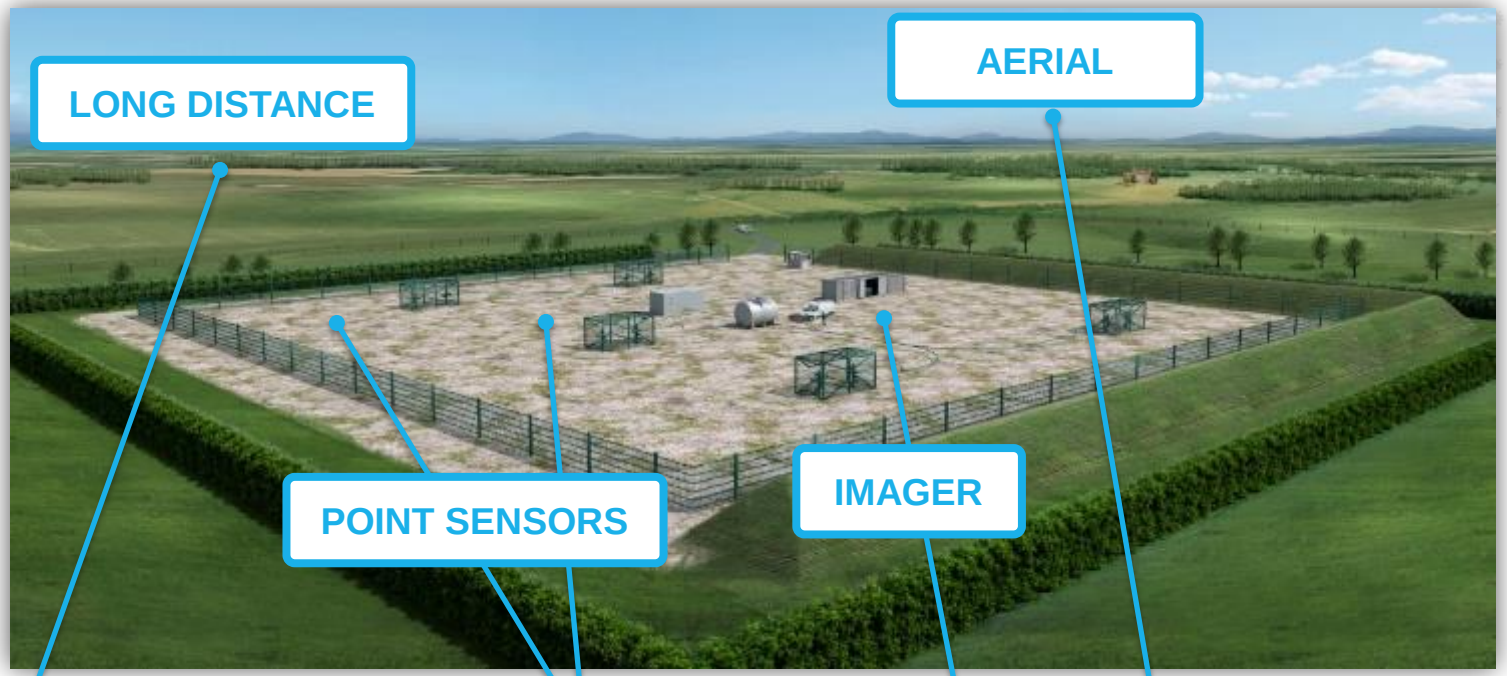


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Image courtesy of Cuadrilla Resources

Portfolio:
Five Point Sensing Technologies

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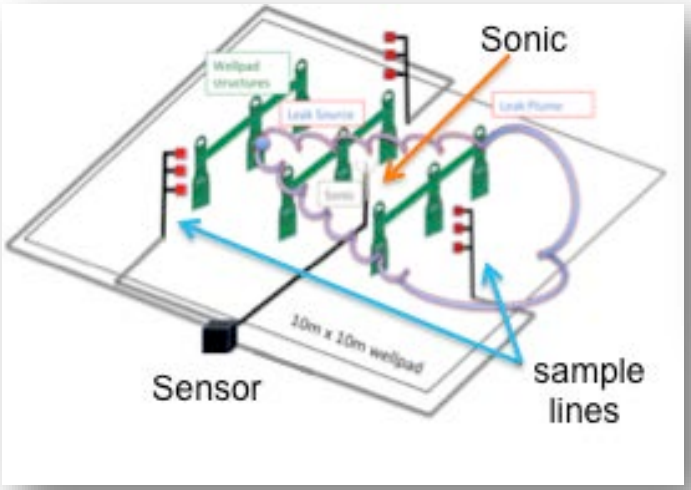
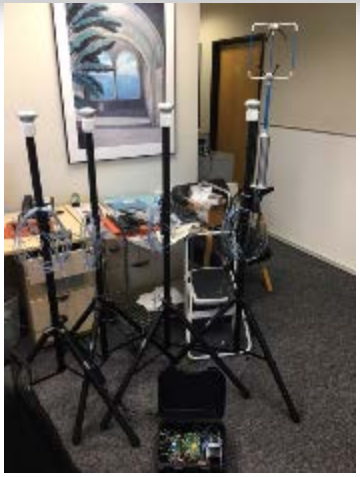
Image courtesy of Cuadrilla Resources

Miniature, High Accuracy Tunable Laser Spectrometer for CH_4/C_2H_6 Leak Detection





PROJECT HIGHLIGHTS

- Enables ppb/s sensitivity via simple and robust direct absorption spectroscopy
- Uniquely discriminates biogenic vs. thermogenic emissions
- Analyzer core is 2.9l volume, 1.5kg w/pump @12W total power consumption
- Rackmounted and handheld early units are available now
- Compatible with other industry applications that require high accuracy, real-time analyses (*e.g.* mobile applications)

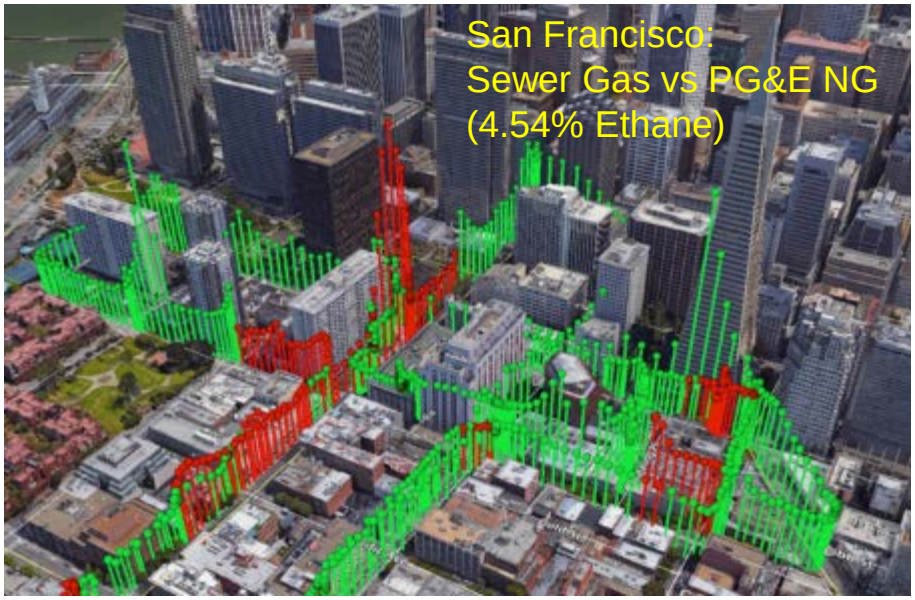
AWARD AMOUNT: $2.4 million

PROJECT PARTNERS: Los Alamos National Laboratory, Rice University

Miniature, High Accuracy Tunable Laser Spectrometer for CH_4/C_2H_6 Leak Detection

Thermogenic Methane:

- Vehicle samples taken while driving Red indicates correlated CH_4 + C_2H_6

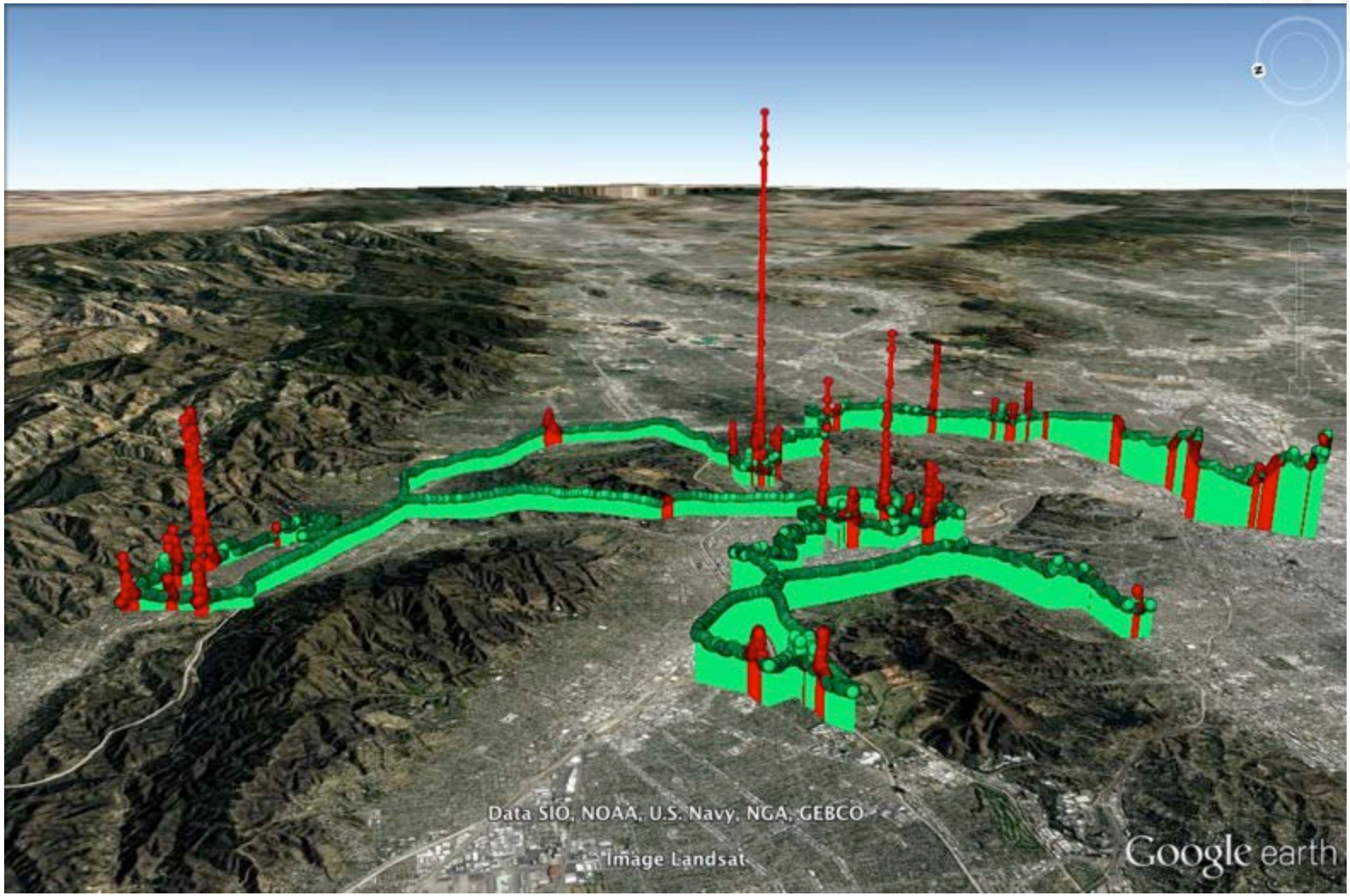


Biogenic Methane:

- Office Buildings located on former landfill
- Green= methane only; no ethane

Aeris *MIRA Pico Mobile LDS: Ethane*/Methane

2 dozen+ NG leaks detected with 99%+ confidence



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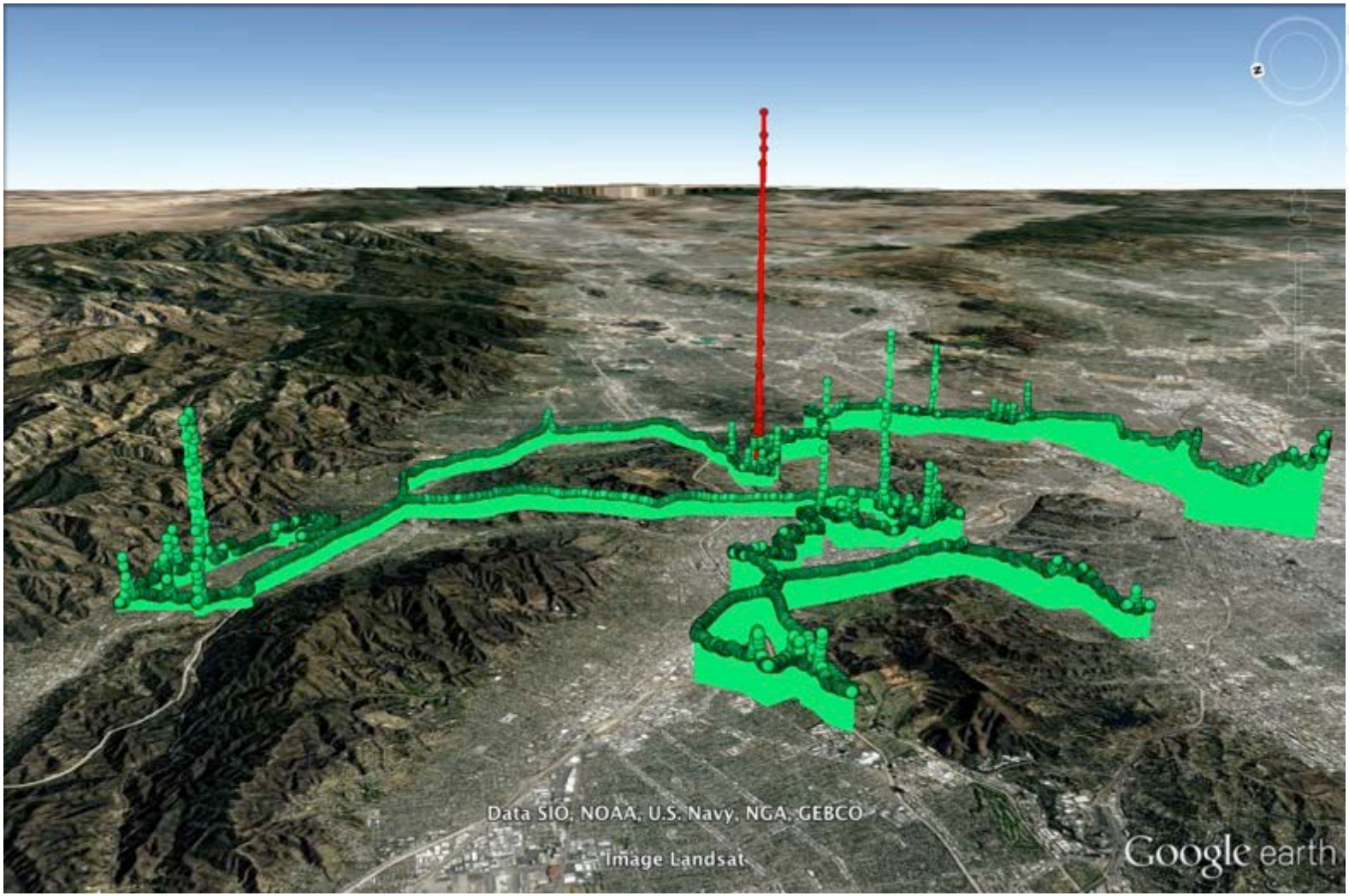
CHANGING WHAT'S POSSIBLE

Aeris ethane/methane vs. simulated LGR/Picarro:

Only 1 correlation detected (vs. 28 w/Aeris Pico Mobile LDS)



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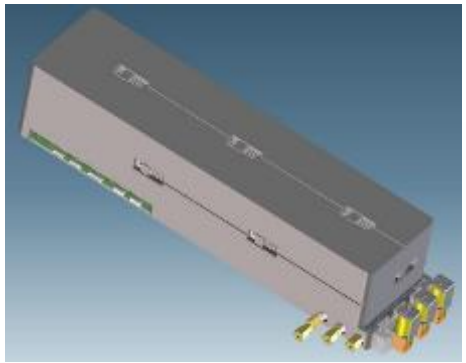
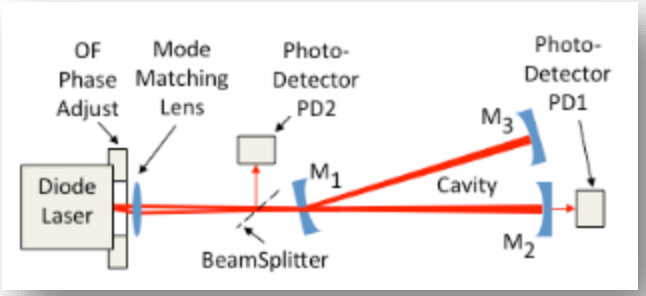
CHANGING WHAT'S POSSIBLE

Laser Spectroscopic Point Sensor for Methane Leak Detection





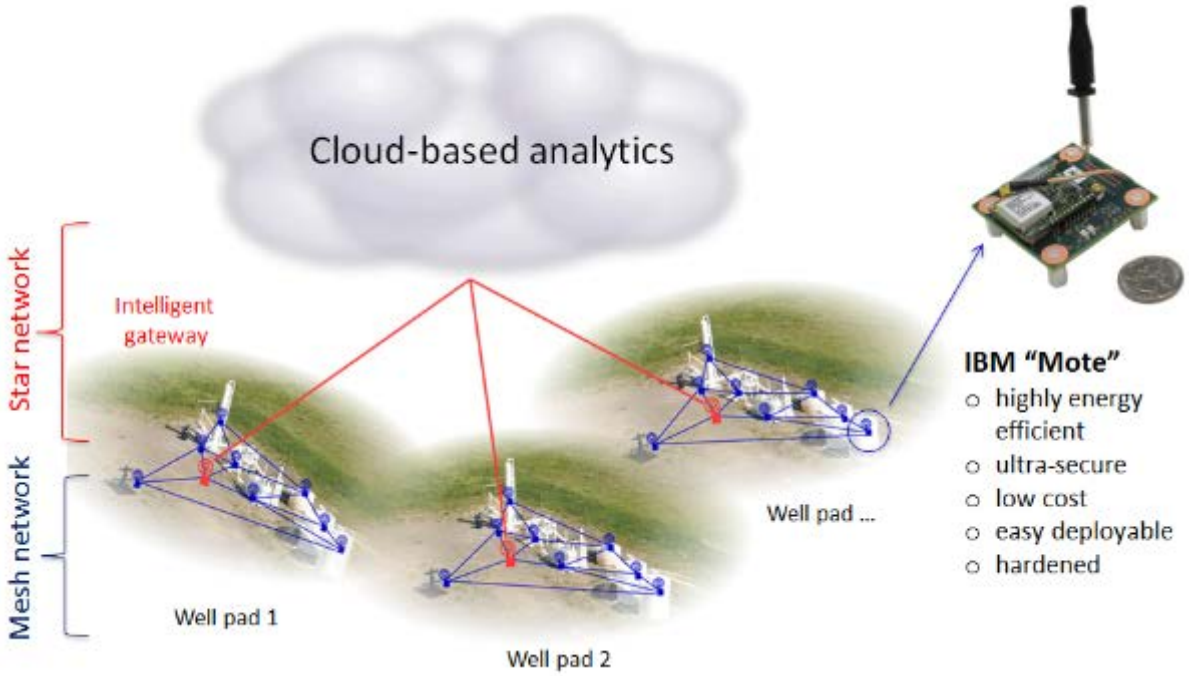
PROJECT HIGHLIGHTS

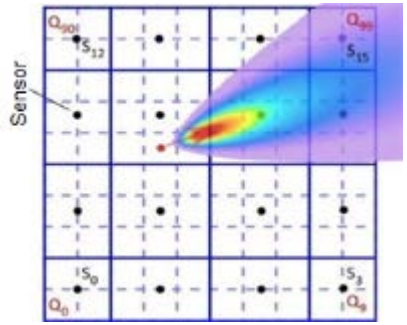
- Performance of state of the art cavity-based point sensors at reduced cost
- High sensitivity, selectivity, and stability measurements with low maintenance
- Closed path instrument is weather-proof, high-performance, and low power consumption
- Suitable for continuous or intermittent stationary and mobile applications
- Advanced spectral models and high instrument stability allow unattended operation
- Advanced manufacturing and novel design/alignment enable cost reductions

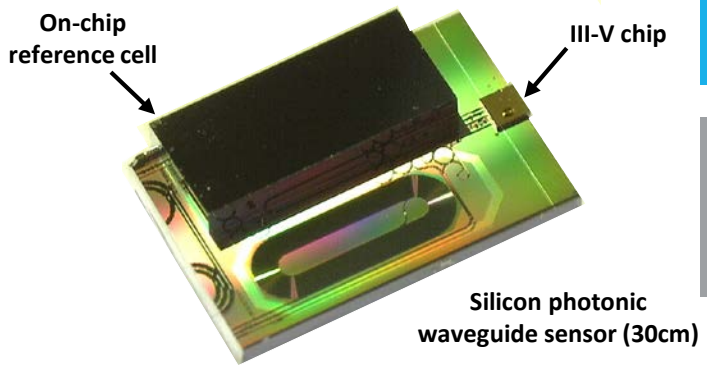
AWARD AMOUNT: $2.85 million

PROJECT PARTNERS: Colorado State University, Gener8

On-Chip Optical Sensors and Distributed Mesh Networks for Methane Leak Detection







PROJECT HIGHLIGHTS

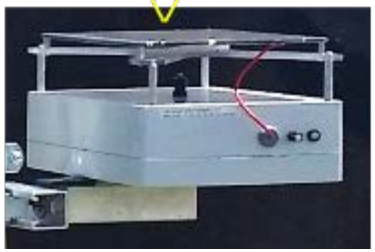
- Developing novel, low cost, on-chip optical sensors with high methane selectivity
- Distributed and modular system with self-organizing network of low-power motes
- State of the art silicon photonics technology for on-chip TDLAS
- Allows for selectivity to molecule of choice
- Orders of magnitude lower cost ($250/sensor target)
- Low power consumption (<1 Watt)
- Cloud-based analytics for source detection and localization

AWARD AMOUNT: $4.5 million

PROJECT PARTNERS: Princeton University, Harvard University, Southwestern Energy

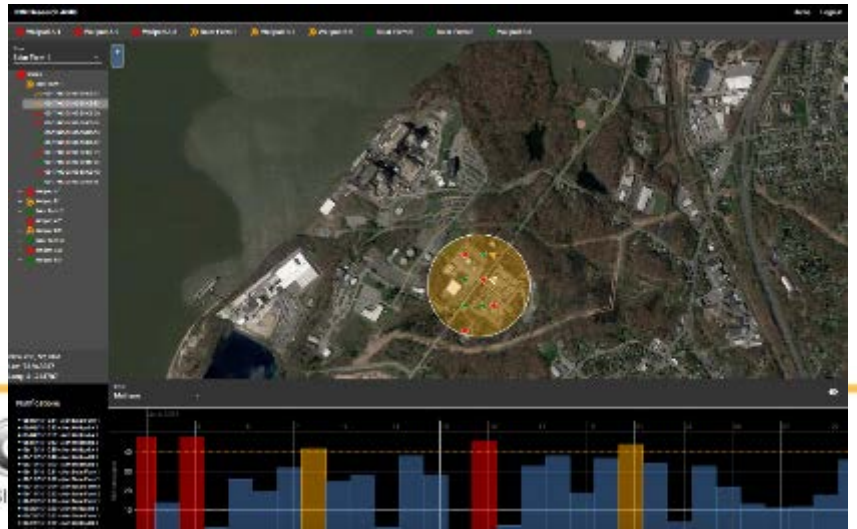
On-Chip Optical Sensors and Distributed Mesh Networks for Methane Leak Detection

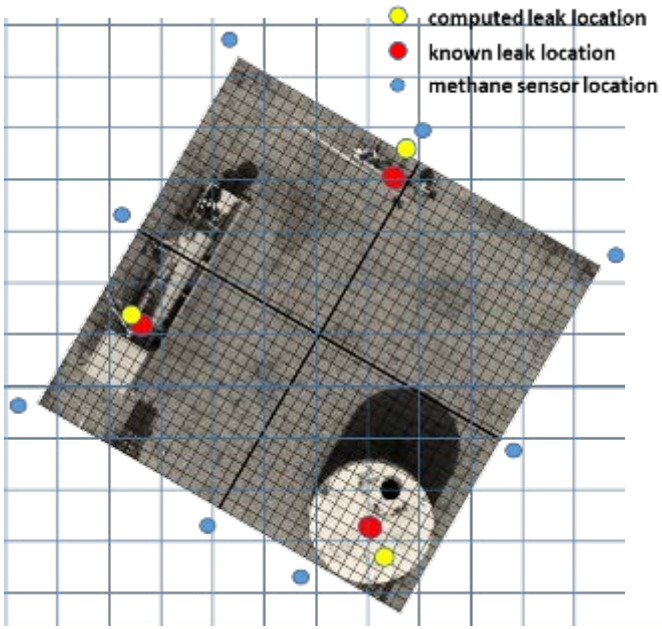
base station wind sensors methane sensors



IBM AIMS methane sensing system:

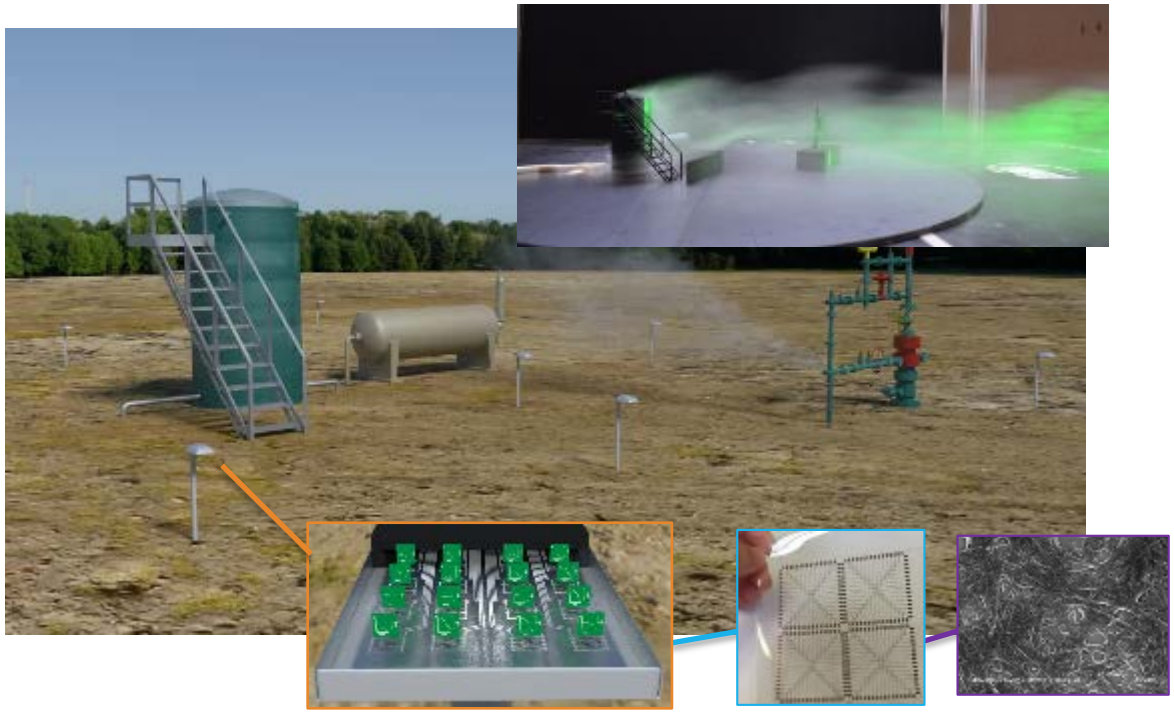
solar powered
low power mesh radio connectivity
ppm sensitivity





Printed Carbon Nanotube Sensors for Methane Leak Detection

parc
A Xerox Company



PROJECT HIGHLIGHTS

- Developing a mesh network of ultra-low-cost printed sensor arrays that can detect multiple gases
- Uses scalable low-cost, additive printing methods to print chemical sensor arrays based on modified carbon nanotubes
- Sensor elements with different responses to methane, ethane, propane and other wellhead gases
- Total system costs under $350 per site per year
- Wellpad, pipelines and refineries
- Sub-ppm sensitivity with leak localization within 1 m

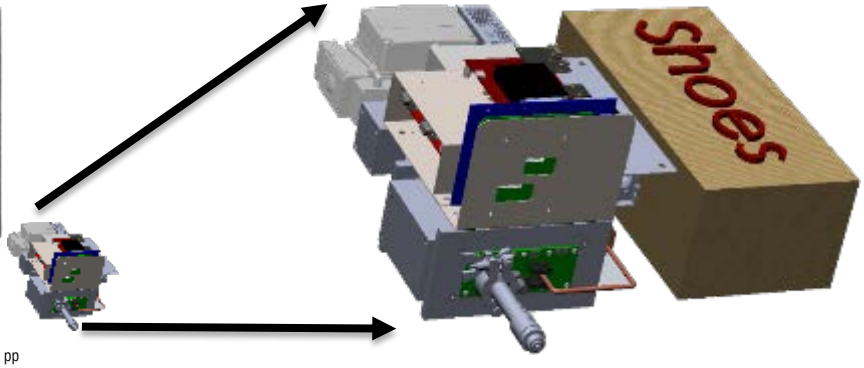
AWARD AMOUNT: $3.4 million

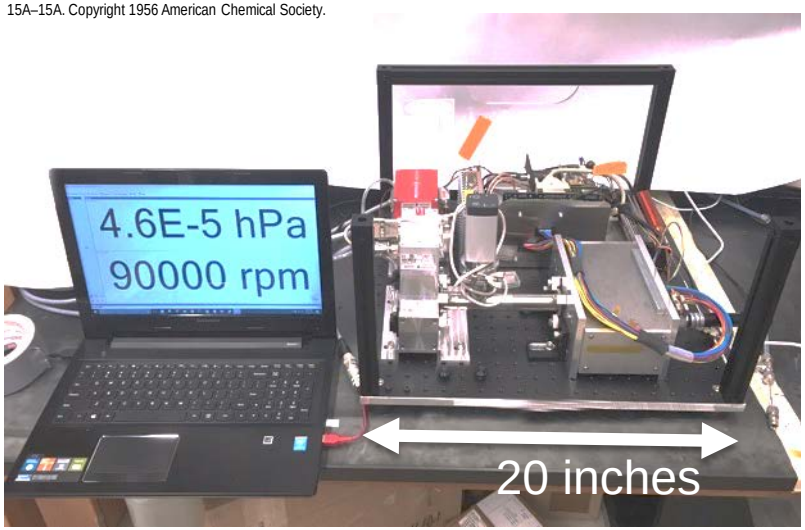
PROJECT PARTNERS: NASA Ames Research Center, BP, Xerox Corporation

Coded Aperture Miniature Mass Spectrometer for Methane Sensing

Image adapted with permission from: Consolidated Electrodynamics Corporation, Anal. Chem., 1956, 28 (4), pp 15A–15A. Copyright 1956 American Chemical Society.

CAMMS-ES mini prototype concept





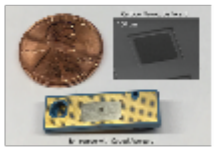
PROJECT HIGHLIGHTS

- Miniaturizing a mass spectrometer utilizing microfabrication and aperture coding
- High selectivity measurements at short detection times for methane as well as VOC's (such as benzene, C_2-C_7)
- Capable of thermogenic vs. biogenic differentiation
- Examining fence line monitoring at refineries and gas processing facilities

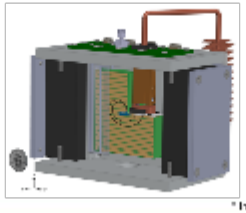
AWARD AMOUNT: $2.9 million

PROJECT PARTNERS: RTI International

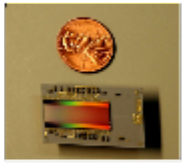
Microfabricated CNT field emission ion source



Cycloidal mass analyzer



Focal plane array detector



* Image courtesy Denton Group at University of Arizona

Portfolio:
Two Long Distance Technologies

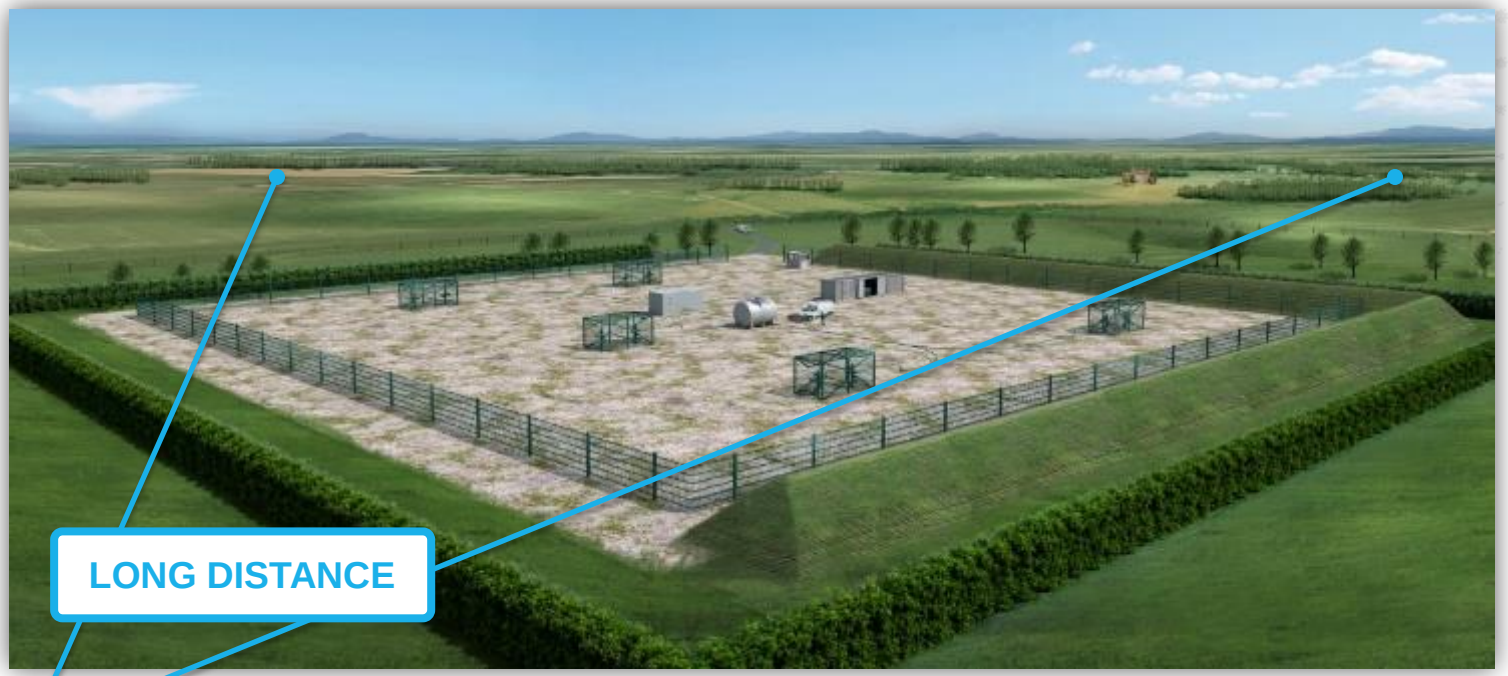


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Image courtesy of Cuadrilla Resources

Frequency Comb-based Methane Sensing Spectroscopy

University of Colorado Boulder

Monitor 100s of sites from a central location. Clients are charged an annual fee for monitoring.

- Large cost reduction over proof-of-concept

PROJECT HIGHLIGHTS

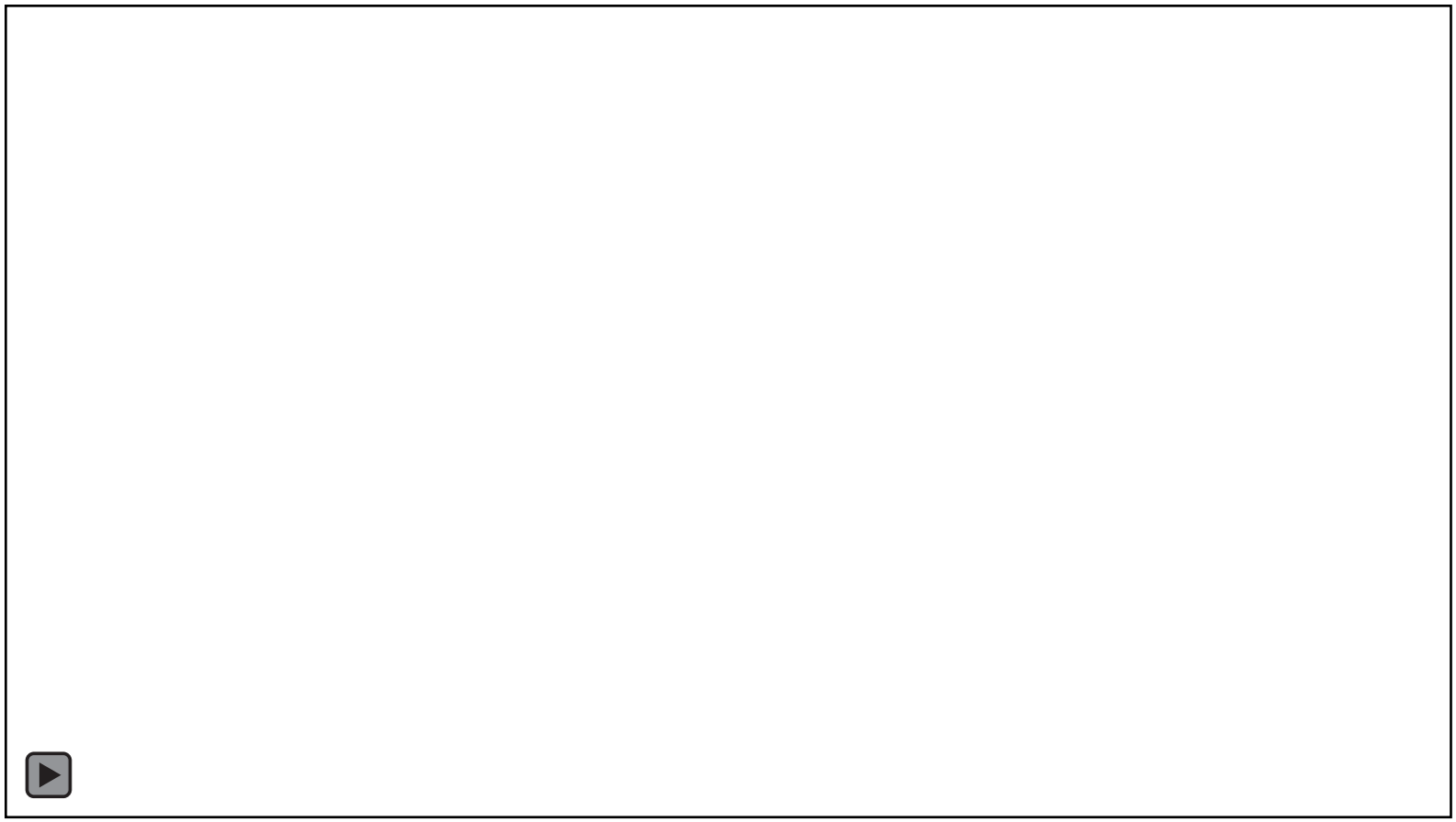
- High sensitivity (ppb-m) Regional laser frequency-comb absorption measurements over kilometer paths with inversion techniques
- Ability to monitor 100's of sites from a central location with thermogenic-biogenic differentiation
- Simplifying design to reduce the cost of phase locked dual comb spectroscopy
- Multispecies sensing includes CH_4, $^{13}CH_4$, C_2H_6, H_2O, CO_2, and propane
- Coupled to large eddy dispersion modeling to provide localization

AWARD AMOUNT: $2.1 million

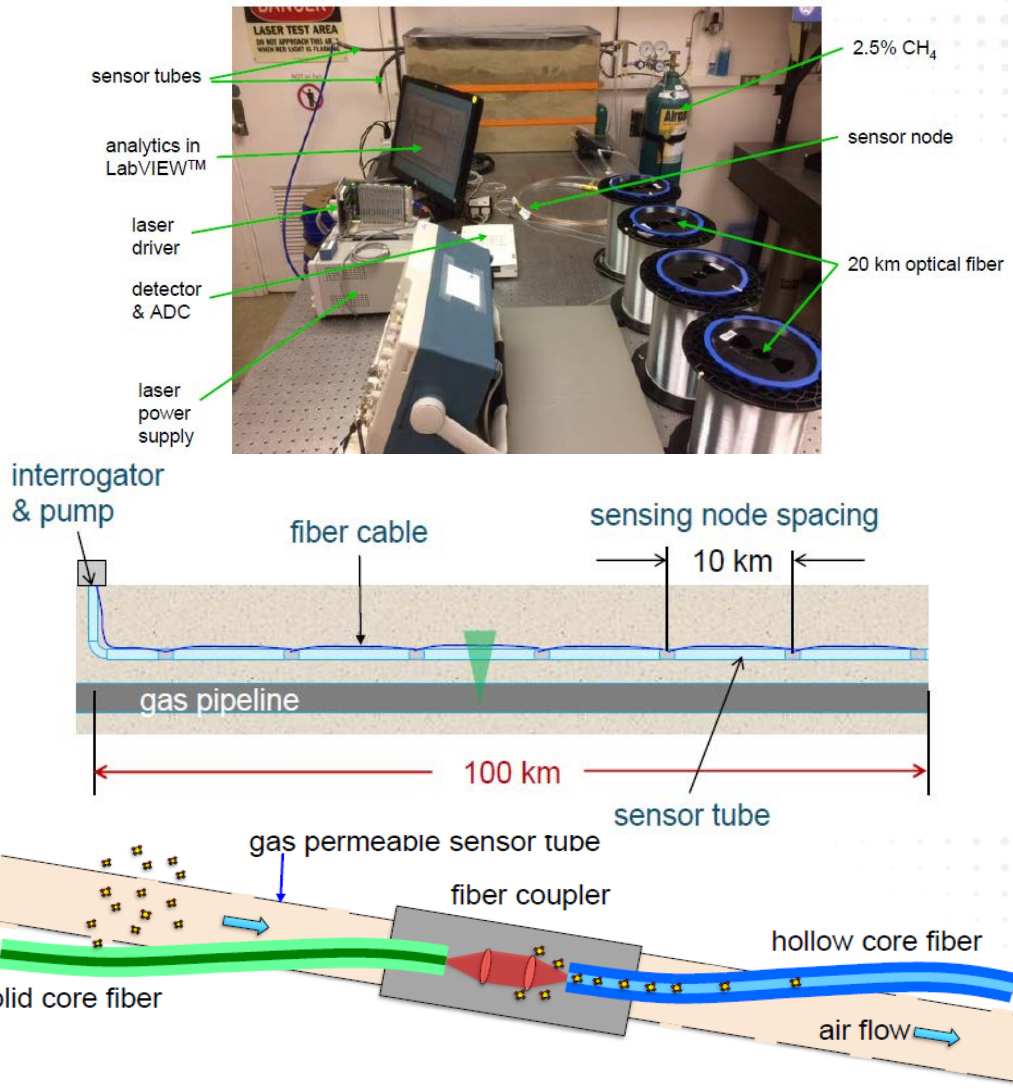
PROJECT PARTNERS: NIST, NOAA

Frequency Comb-based Methane Sensing

University of Colorado Boulder



Distributed Gas Sensor Using Hollow Core Fiber



PROJECT HIGHLIGHTS

- Modified tube + hollow core fiber sensing system in a design that can span over 100km and offer continuous pipeline monitoring
- Broadly applicable throughout the oil and gas industry, particularly for large-scale infrastructure (such as gathering lines and storage facilities)
- Near IR absorption enables remote TDLAS through standard telecom while leverageing conventional tube sensing

AWARD AMOUNT: $1.4 million

PROJECT PARTNERS: Virginia Tech

Portfolio:
Two Aerial Technologies

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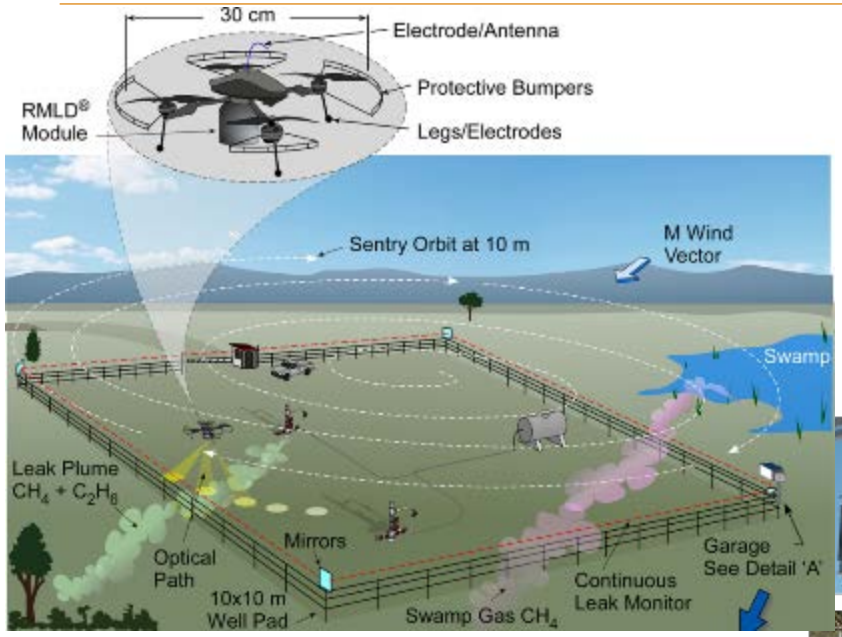
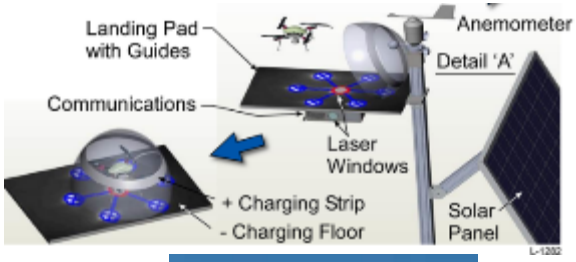
Image courtesy of Cuadrilla Resources

UAV-based Laser Spectroscopy for Methane Leak Measurement

Physical Sciences Inc.





PROJECT HIGHLIGHTS

- Continuous leak monitoring with leak quantification and real-time alarm notification
- Two modes of operation: continuous perimeter monitoring and search mode to pinpoint leak location
- Speciation of methane and ethane differentiates thermogenic vs. biogenic emission
- Improved production processes reduce costs of mid-IR Interband Cascade Laser (ICL) sources

AWARD AMOUNT: $2.9 million

PROJECT PARTNERS: Heath Consultants, Thorlabs, Princeton University, University of Houston, Cascodium

arpa·e
CHANGING WHAT'S POSSIBLE

UAV-based Laser Spectroscopy for Methane Leak Measurement

Physical Sciences Inc.

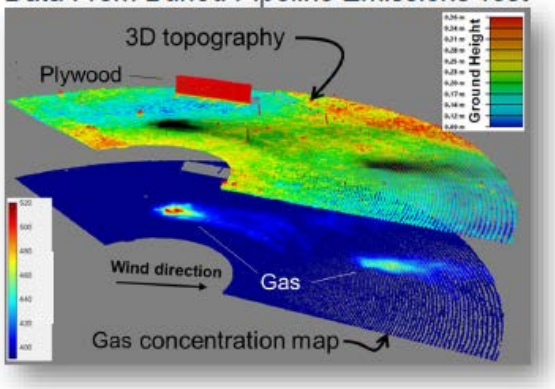
Mobile LiDAR Sensors for Methane Leak Detection

BRIDGER PHOTONICS

UAV sensor

Manned aircraft sensor

Data From Buried Pipeline Emissions Test

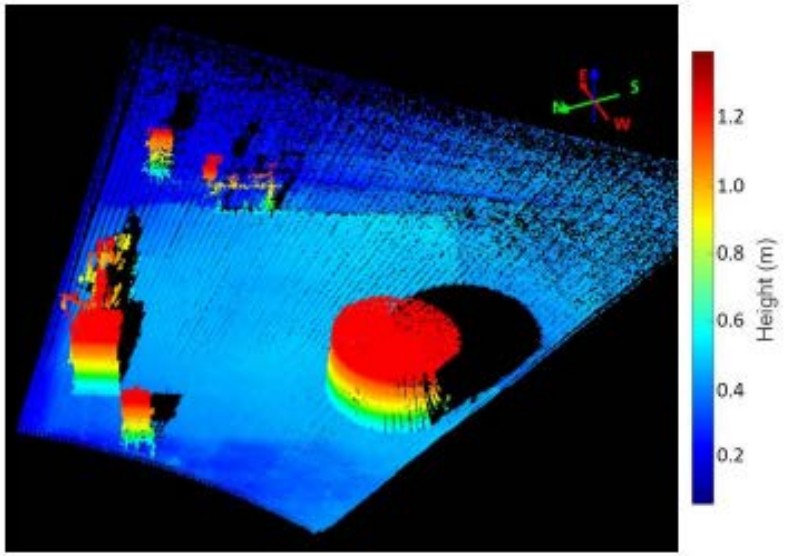


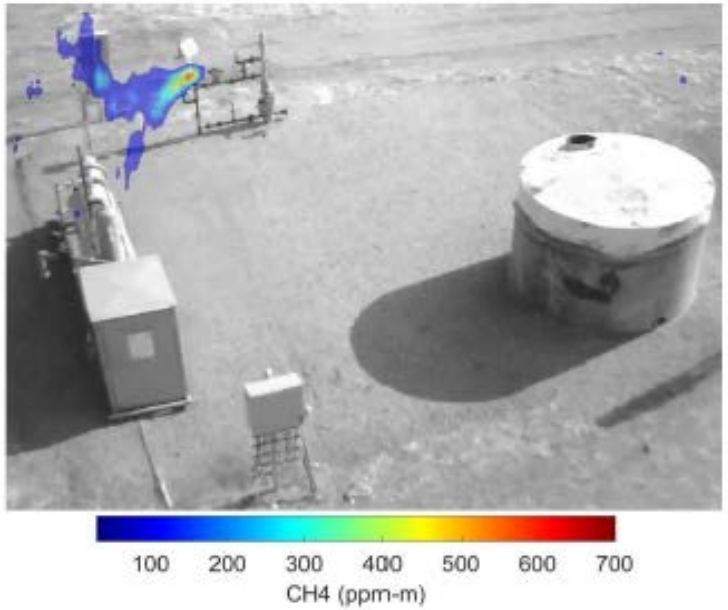
PROJECT HIGHLIGHTS

- Simultaneous, rapid, and precise 3D topography and methane gas sensing on fixed or mobile platform
- Produces detailed situational awareness reports derived from overlaid methane concentration, 3D topography, and RGB picture data
- UAV and manned aircraft platforms targeting well pads and pipelines
- Capable of covering a broad range: a frequency-swept laser beam is transmitted to a topographical target 1-300 m from the sensor
- Sensitivities from 5ppm-m and measurements from up to altitudes of 1000 ft

AWARD AMOUNT: $1.5 million

Mobile LiDAR Sensors for Methane Leak Detection





Mobile LiDAR Sensors for Methane Leak Detection

BRIDGER PHOTONICS

› Sensor status

- Gimbal sensor for fixed position monitoring is operational
- Telescoping mast provides downward-looking perspective and rapid deployment
- Real-time data streaming and processing for immediate results

Mobile LiDAR Sensors for Methane Leak Detection

Mobile LiDAR Sensors for Methane Leak Detection

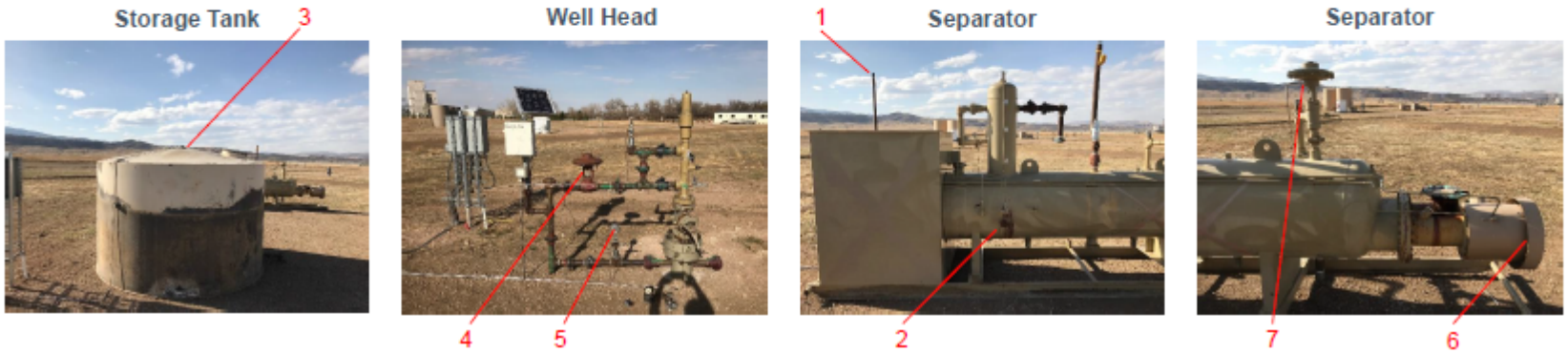
BRIDGER PHOTONICS

› Results summary

- Detected and quantified 7 leaks in 2.5 hours
- Localized 6 of 7 to within 1 m
- Estimated 6 of 7 leak rates to within 50%

Leak #	Leak Location	Time	Detected?	Location Error (m)	Actual Rate (cuft/hr)*	Measured Rate (cuft/hr)	Rate Error (%)
1	Separator PRV vent	9:30	yes	1.6 m	7	10	43%
2	Separator burner controller	9:49	yes	1 m	12	21	75%
3	Storage tank vent	10:06	yes	0 m	11	10	-9%
4	Well head pneumatic valve	10:20	yes	0 m	10.5	13	24%
5	Well head pressure guage	10:40	yes	0 m	4	6	50%
6	Separator burner gas line	11:10	yes	0.4 m	9	8	-11%
7	Separator pneumatic valve	11:52	yes	0 m	11	8	-27%

* flow meter uncertainty: 1.5 cuft/hr



Portfolio:
One Imaging Camera Technology

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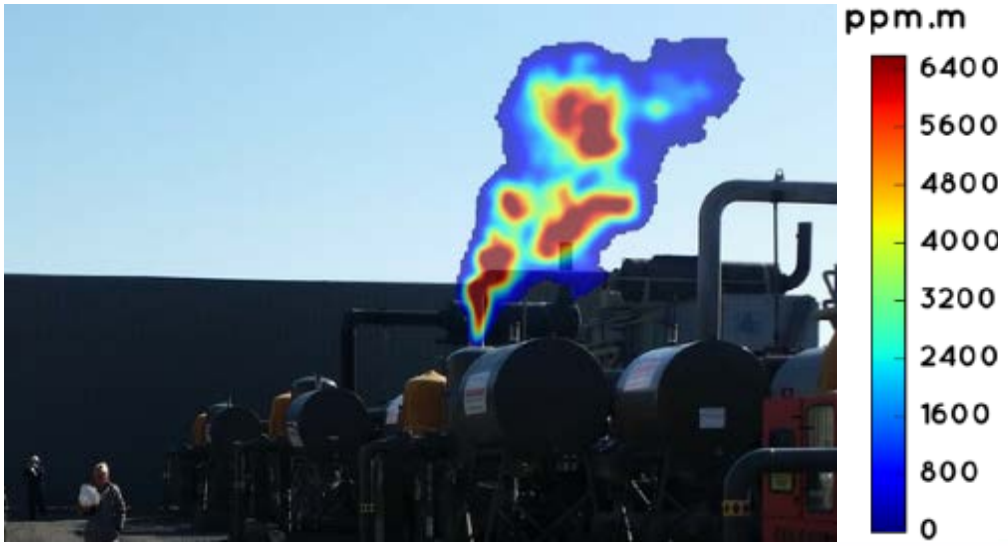
Image courtesy of Cuadrilla Resources

Portable Imaging Spectrometer for Methane Leak Detection

REBELLION PHOTONICS



PROJECT HIGHLIGHTS

- Miniaturization of Rebellion's Gas Cloud Imager (GCI), a long-wave infrared imaging spectrometer: 7-14µm
- Camera will be lightweight and portable – the size of a Red Bull can - and capable of being incorporated into personal protective equipment
- Data processing uses cloud-based computing architecture that streams results to mobile device

AWARD AMOUNT: $4.3 million

Portable Imaging Spectrometer for Methane Leak Detection

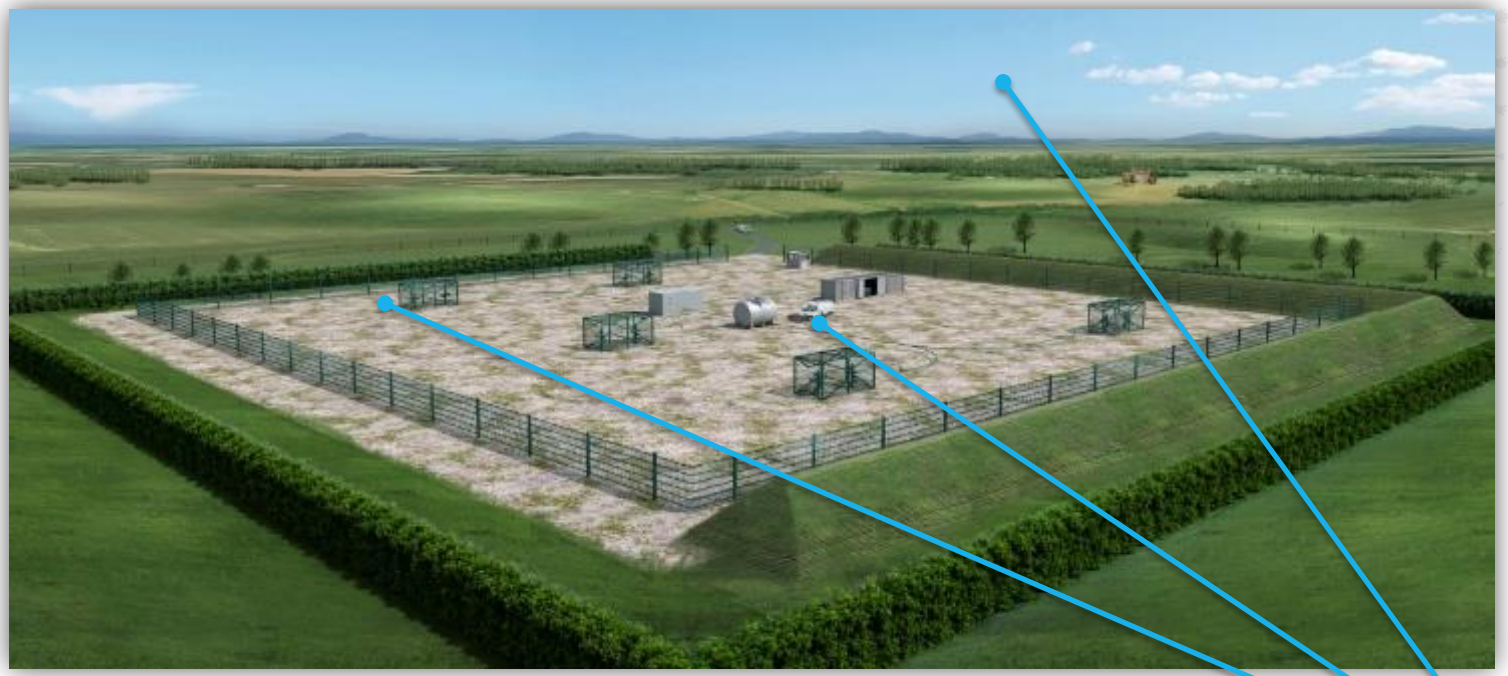
REBELLION PHOTONICS

Main panel with video stream and status bar

Event Log

Mosaic View

Portfolio:
One Enabling Technology



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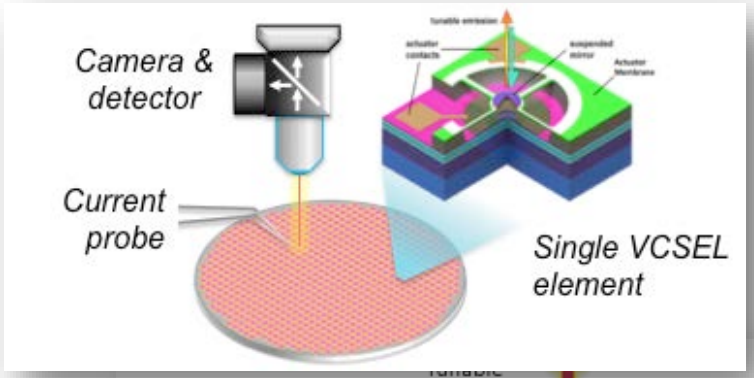
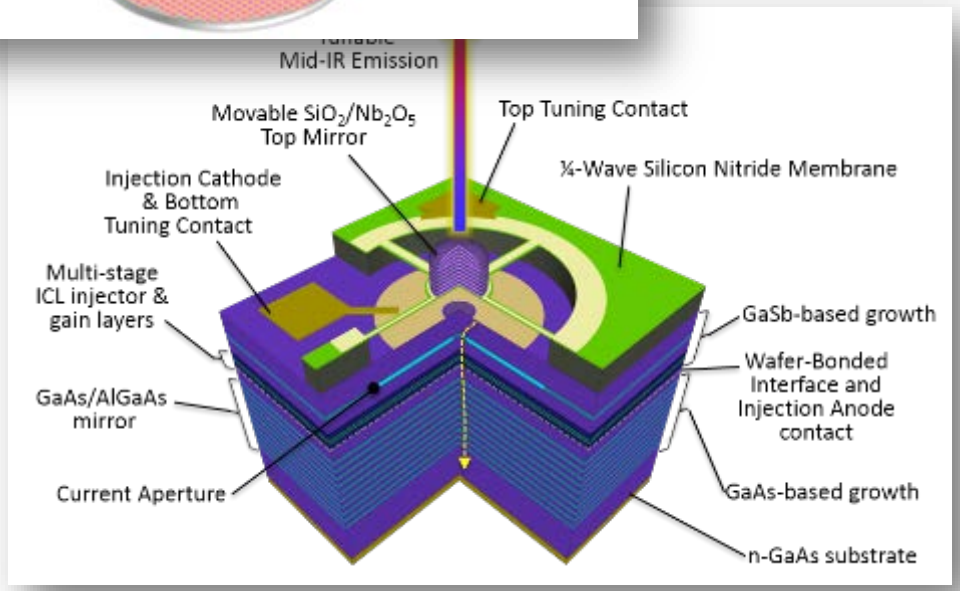
Tunable Mid-infrared Laser for Methane Sensing





PROJECT HIGHLIGHTS

- Innovative, low-cost mid-IR laser with VCSEL architecture
- Integrated micro-electro-mechanical system (MEMS) mirror enables a wide tuning range
- Approximately 40x reduction in laser cost, applicable across a wide array of sensors and applications

AWARD AMOUNT: $1.9 million

PROJECT PARTNERS: Thorlabs Quantum Electronics, Praevium Research, Rice University

METEC – Methane Emissions Test and Evaluation Center

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