Photonics and the Evolution of Ultrasensitive Gas Analyzers: Past, Present, and Future

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aeris: “AYRis”, *air (latin)*

- The atmosphere (top O_3 layer) extent is only 1/400th the Earth’s diameter

-This thin, fragile shell supports all life and controls the climate.

- We can now monitor the atmosphere with sufficient resolution via photonics

-Wide use is limited by cost

-The future of atmospheric monitoring lies in the commoditization of emerging photonics technologies.

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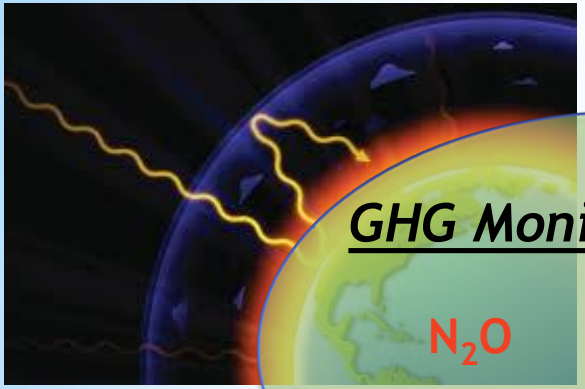
Markets



GHG Monitoring

N_2O

Air Quality

H_2CO
EtO

CH_4 CO

CO_2+isotopes

Energy, Natural Gas

C_2H_6, C_3H_8, C_2H_2, C_2H_4, C_6H_6

Critical environmental species drive many parallel markets

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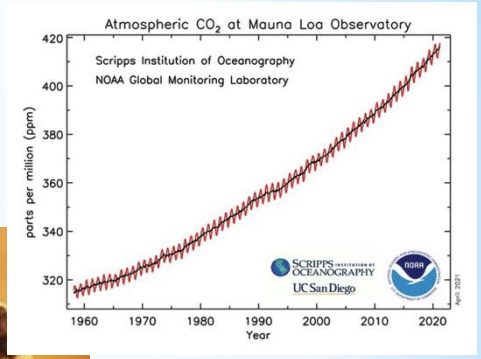
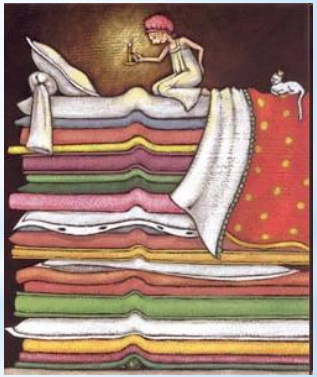
Tough Requirements: Greenhouse Gases, Pollutants

- GHG's: WMO/NIST target *accuracy*
  - CO_2: 100ppb (@ 400ppm)
  - CH_4: 2ppb (@1840ppb)
  - N_2O: 0.1ppb (@325ppb)



- Pollutants: regulatory (EPA, OSHA)
  - CO: 2ppb
  - HCHO: 2ppb (LEED is <20ppb abs.)
  - Ethylene Oxide: <1ppb



- >10^{-3} accuracy at *trace levels* is non-trivial! Traditional methods are inadequate
  - (e.g. NDIR, FTIR, Chemi-)

Ultrasensitive gas analysis methods are required!

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The Past: Ultrasensitive Cavity Technique Origins

- **1980's**: Cavity Ringdown methods (CAPS, **CRDS**) came from high R mirrors for defense
  - R=99.99% mirrors: laser-ring gyros for defense guidance (missiles, etc.)
  - Laser weapons programs: SBL and ABL at 3.7um (HF/DF) and 1.3 micron (COIL)
  - PVD, IBS, IAD methods all developed using metal-oxide and (redacted)-fluoride coatings.
- The need to kill or prevent yourself from being killed was a great motivator!
- What else were cavity methods good for?

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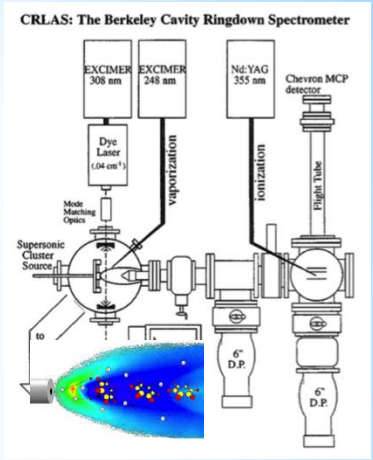
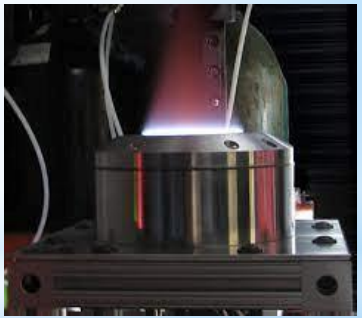
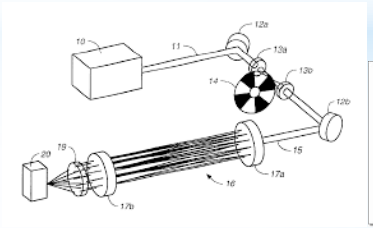
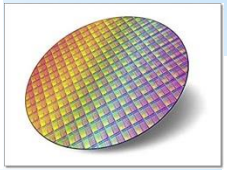
1989-2000: CRDS Evolution via Photonics

- Late 80's: *U.C. Berkeley* we used CRDS for for pure spectroscopy using large lasers:
  - Molecular beams, ss jets, plasmas: Dye Lasers
  - 5 miles through snow on foot to the lab
- 1994: (*Sandia Labs*) we extended CRDS to the MIR for flame research using tunable OPO's
- mid 1990's: *Los Gatos Research* (*LGR*) we invented new cavity methods for use with new NIR semiconductor lasers (ICOS and OA-ICOS)
  - Others also integrated NIR lasers with CRDS
- Mid 1990's: *LGR* we paid Sarnoff $200K for a single NIR wafer run
  - by 2000 NIR lasers commoditized for telecom









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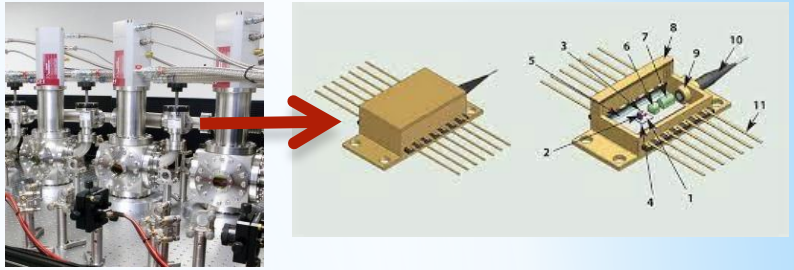
2000's: Commercialization of Cavity-based NIR Analyzers

- Revolution from cryogenic diode lasers to COTS room temperature devices was a game changer
- **$B telecom markets** commoditized NIR, single frequency, tunable semiconductor lasers
  - Wavelengths 1300 nm &1500-1600nm
- Cavity methods + telecom lasers=commercially viable ultrasensitive gas analyzers
- To date, 1000's of cavity-based gas analyzers sold, still considered by some state-of-the-art
  - LGR (ABB), Picarro, Tiger, AP2E, LiCor
- 201X-Present, … systems still relatively large, power hungry, mirrors remain weakest link

is there a better way….?



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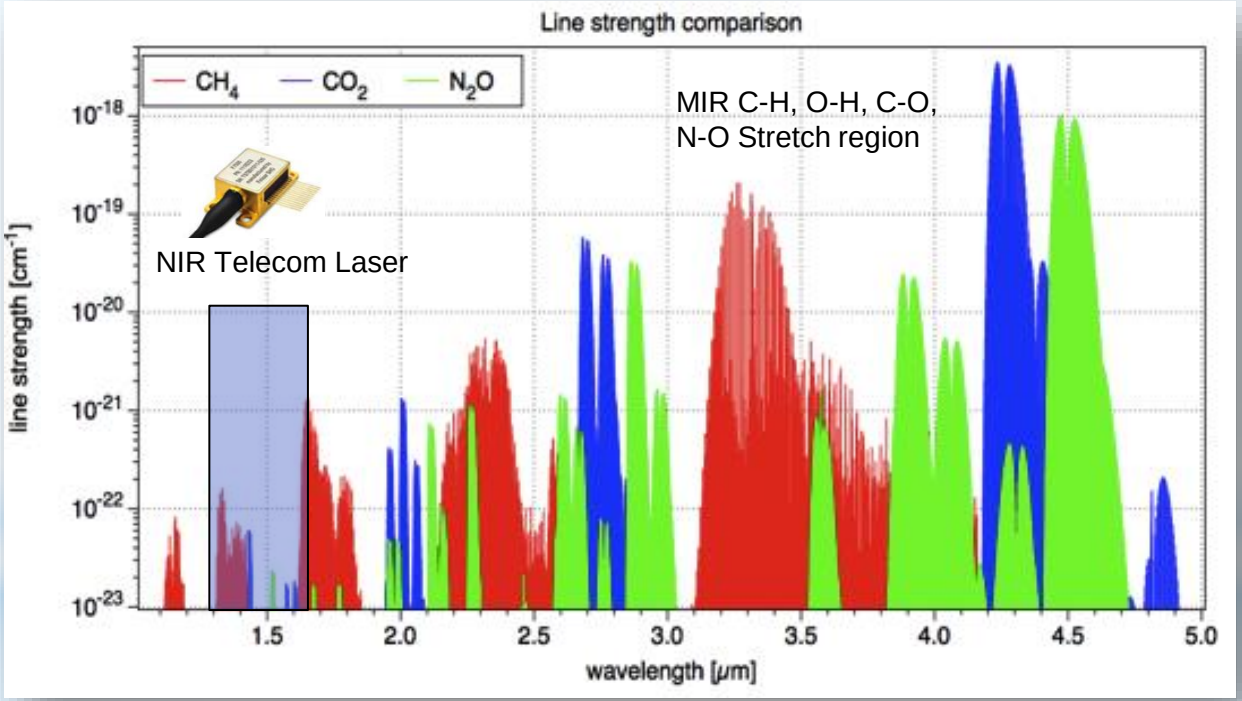
Transition to the MIR: Moving Away From Cavities

Absorption (Beer's Law) ≈ line strength x path length x concentration



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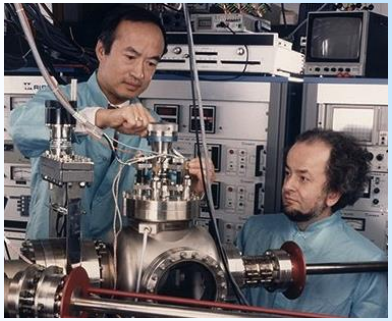
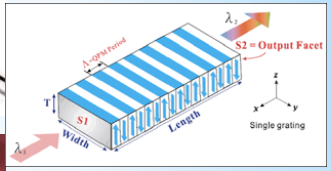
MIR: <u>Cavities no longer required</u> to achieve the same/superior sensitivity

Transition to the Middle Infrared (MIR)



- **Late-90's to 200X**: Quantum Cascade MIR lasers (QCL's)
  - expensive ($30K), limited supply, high power/heat
- **In 2002**, we founded *NovaWave*: Telecom lasers and NLO's to make MIR lasers using ***Difference Frequency Generation (DFG): Two Telco lasers+crystal***
  - Innovative Photonics Solutions: high power single-frequency diode lasers eliminated the need for fiber amplifiers in DFG
- DGF provided a path to high fidelity, tunable MIR-based gas analyzers, but prices still $50K+
- Acquired by Thermo-Fisher in 2010, NovaWave developed DFG-based products, e.g. *Delta-Ray* for isotope analysis



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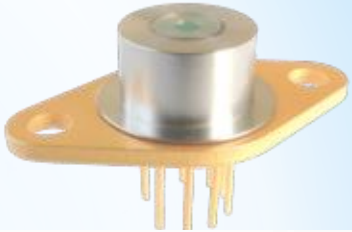
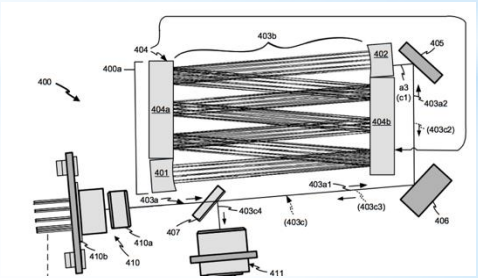
New MIR Enabling Photonics: Interband Cascade Lasers

- **<u>200X to Present</u>**: ICL MIR lasers successfully developed and commercialized (Nanoplus)
  - High heat load, high power of QCL's solved
  - It took 15+ years to maturity
- Other key photonics developments:
  - MCT and InAsSb photodetectors (Vigo)
  - Chalcogenide aspheres (Lightpath)
  - Novel multipass cell designs (Aeris)

We founded Aeris in 2013
Mission: commoditize MIR-based ultrasensitive gas analyzers





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The Present: Aeris MIRA: Middle InfraRed Analyzer

The World's Most Sensitive, Portable Laser-based Gas Analyzer

MIRA Pico: Ultrasensitive "Lab-in-a-Lunchbox"

- *ppb/s sensitivity and ppb level accuracy*
- *10x smaller, lighter, lower power*
- ***Currently ½ the price of comparable, 10x larger systems***
- *Unmatched economy of scale*
- *Three platforms:* ***Pico, Ultra, and Strato***

MIRA Redefines the State-of-the-Art in Laser-Based Analyzers

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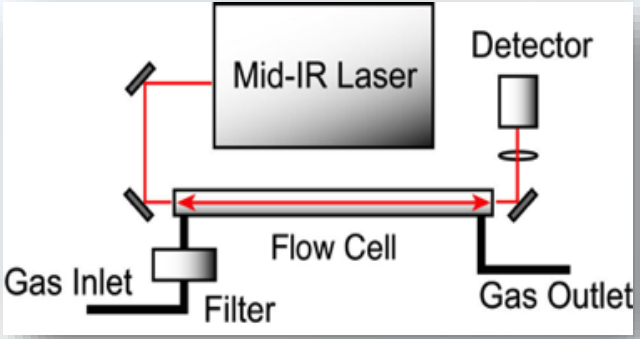
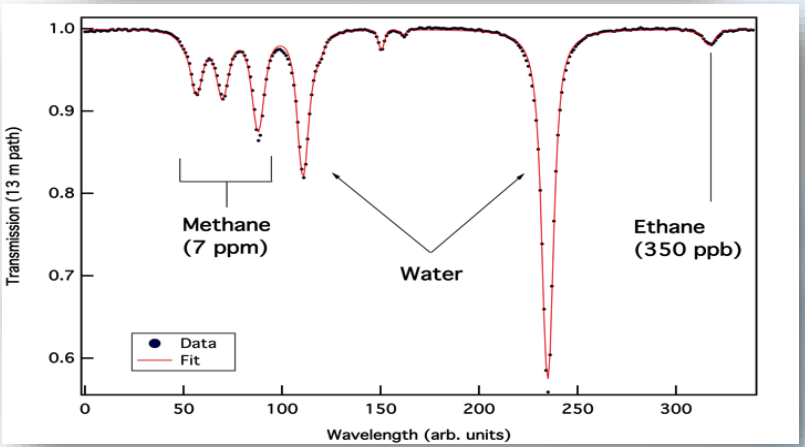
MIRA: Mid-IR Laser Absorption Spectroscopy

- ***Direct absorption spectroscopy***
  - ***Simple, quantitative, linear***
- Fingerprints are more discrete and ***stronger in the Mid-IR***
  - ***200x*** stronger for CH_4
  - ***6000x*** for C_2H_6
  - ***32,000x*** for N_2O
- No FM: scanned spectrum provides tracability

The robust nature of direct absorption provides unmatched scalability





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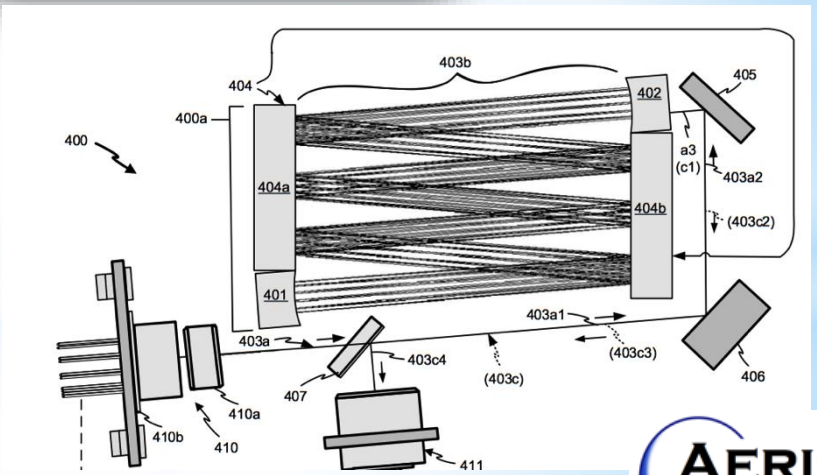
Aeris Patented, High Performance Sensor Engine

- **MIRA**: Disruptive, miniature sensor
  - Compact, **Patented** multipass cell
  - 13m path length in 60cc volume
  - ***<1ppb/s*** sensitivity typical.
  - 100x less susceptible to “dirty mirrors”
- Proprietary custom electronics
  - Low Power, miniature, lower cost
  - High A:D, fast digitizers, 8-layer design

10x reduction in analyzer size, weight, and power consumption at a disruptive price point



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The MIRA Platform: *Pico, Ultra, and Strato Series*

MIRA *PICO Series: "lab in a lunchbox"*

- 1ppb/s sensitivity typical for most species
- Lunchbox sized (5.7 l vol., 2.75kg/6lbs)
- AC/DC, 15W, 6hr battery, *GPS, WiFi, RS-232*

MIRA *Ultra Series: Low Drift*

- Same core technology as *Pico Series, except…*
- Low drift via ***temperature stabilized optical core***
  - *1-2ppb drift typical*
- *Portable and 3U Rackmount versions available*
- *Battery Option: 2-3 hours continuous operation*

MIRA *Strato Series: Drone*

- Same as Pico, but smaller and lighter (2.8l vol., 1.9kg)
- 1.5 hour battery

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Applications and Markets

- Environmental: Pollutants, Toxics, GHG
  - Formaldehyde: Indoor Air Quality, Low VOC products
  - **Carbon Dioxide**, Carbon Monoxide
  - **Nitrous Oxide**
  - Ethylene Oxide: Highly toxic carcinogen
  - Methane, ethane, ethylene, acetylene, propane…
- Oil and Gas:
  - **Natural gas** (Methane) leak detection
    - Fixed, Mobile, Drone: up-, mid-, and downstream

Monitoring these species in real-time using ultrasensitive systems will be commonplace in the future as costs/prices drop

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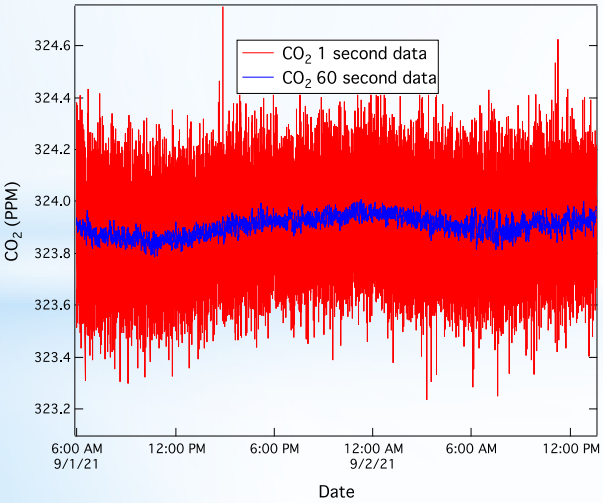
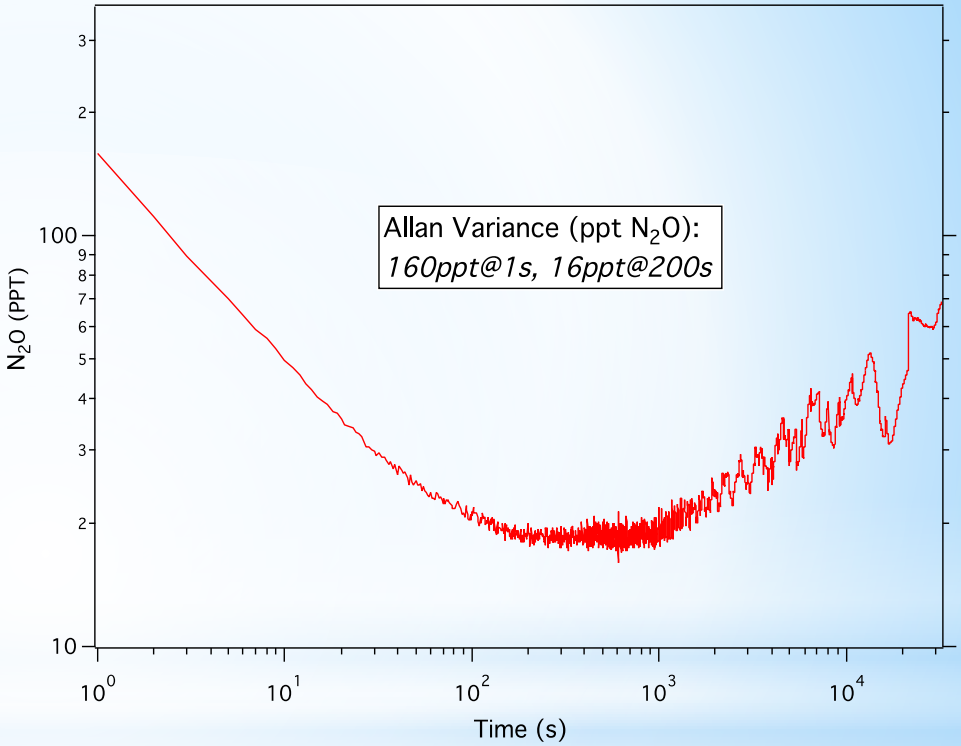
MIRA Ultra N_2O/CO_2

- CO_2 is the #1 GHG, N2O is #3
  - Global GHG monitoring networks
  - Meets/exceeds WMO/NIST targets
- solar powered capability will enable autonomous monitoring in remote locations





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Oil and Gas Markets : Up, Mid, and Downstream

Fixed CH_4 Monitoring:

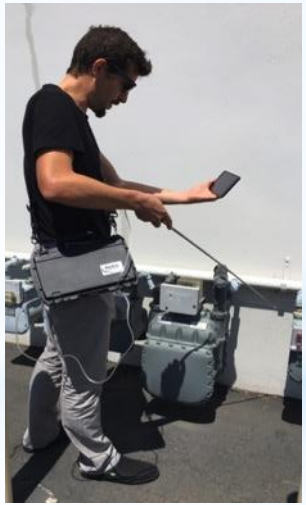
- 24/7/365 Wellpad monitoring: 1M wells in US alone
- Compressor stations: (1400 large in US)
- Storage facilities (414 underground in US)
- Biogenic Methane Sources:
  - Landfills (3100 active, 10,000 old in US),
  - Livestock operations, feed lots (26,000 in US)

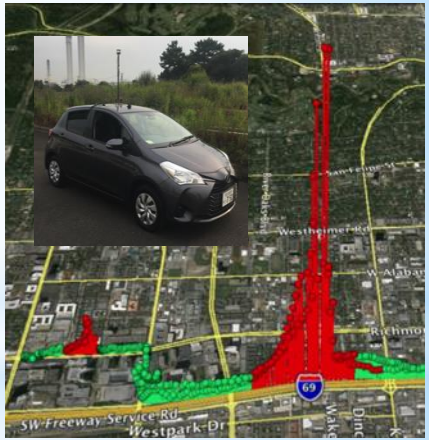
Mobile

- Utilities: ***mobile mapping***: 70M gas customers in US
- Pipeline inspection (500K miles in US)
- Wellpad surveys: rapid screening tool
- Drone-based leak detection: high value assets

Handheld

- Utility Leak surveys: “up to the meter”
- Wellpad/refinery/facility surveys





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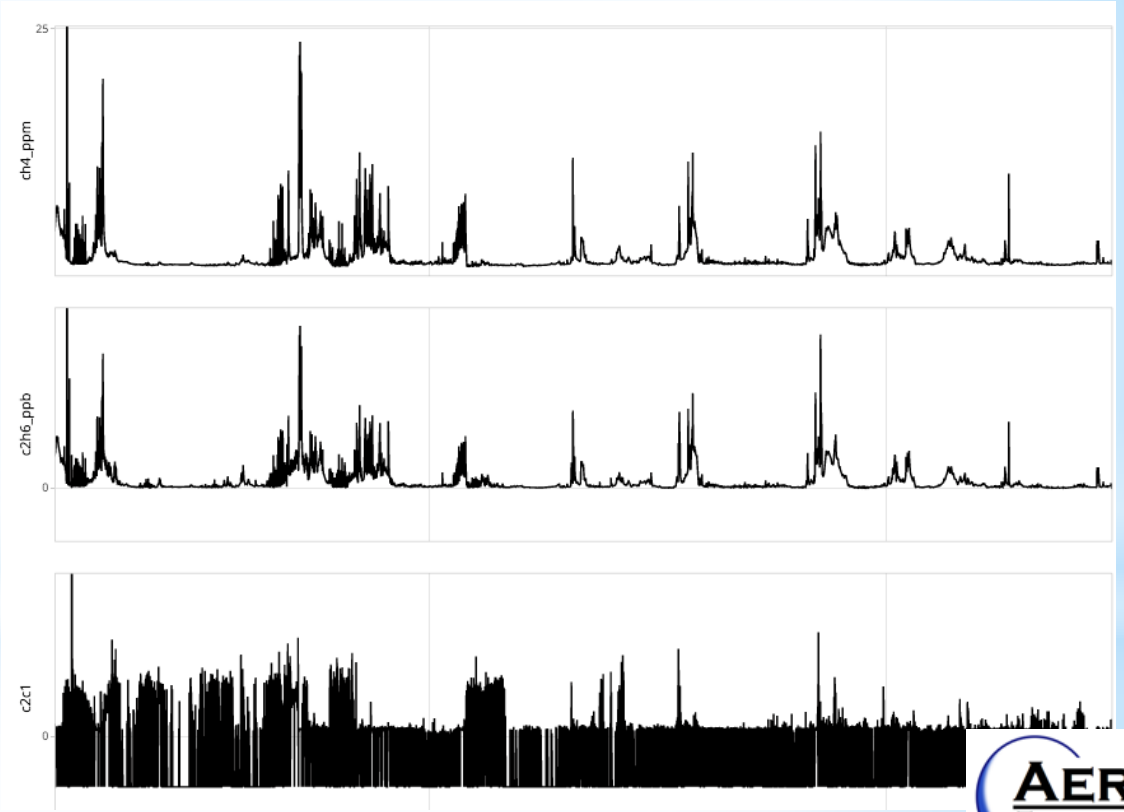
Autonomous (Fixed) Wellpad Monitoring: 24/7/365

- ***Solar Powered!***
- ***ID leaky operations***
- <1ppb/s CH_4/C_2H_6



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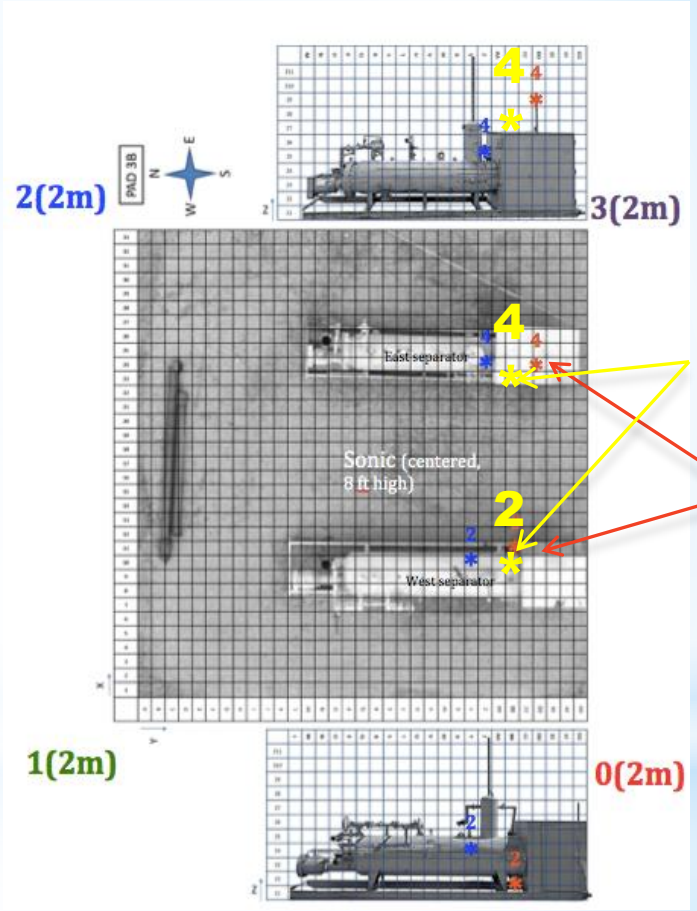
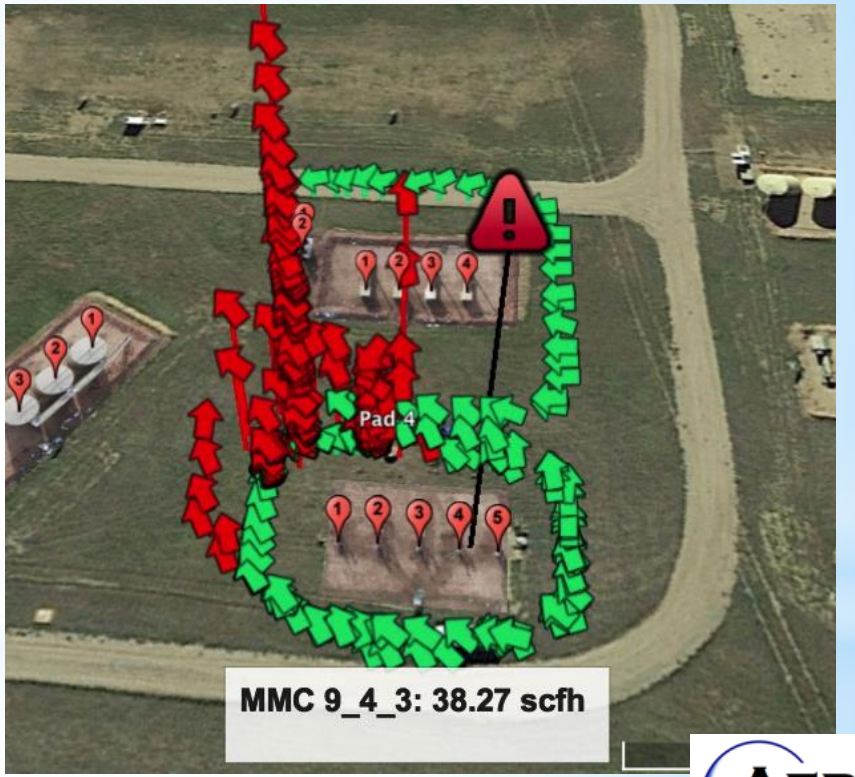
Wellpad Monitoring

ARPA-E MONITOR (DE-AR0000545)

- Aeris methane/ethane + wind + GPS + Neural Net Analytics=
  leak location and size
- Actual leak location is red, Calculated location yellow
- In the future, AI will be combined with this approach to autonomously monitor wellpads 24/7/365



Mobile Methane Leak Detection



- Wind + sensor data+analytics=

  leak location and size

- In the future, such systems will be commonly used to monitor urban pipeline health for gas utilities.

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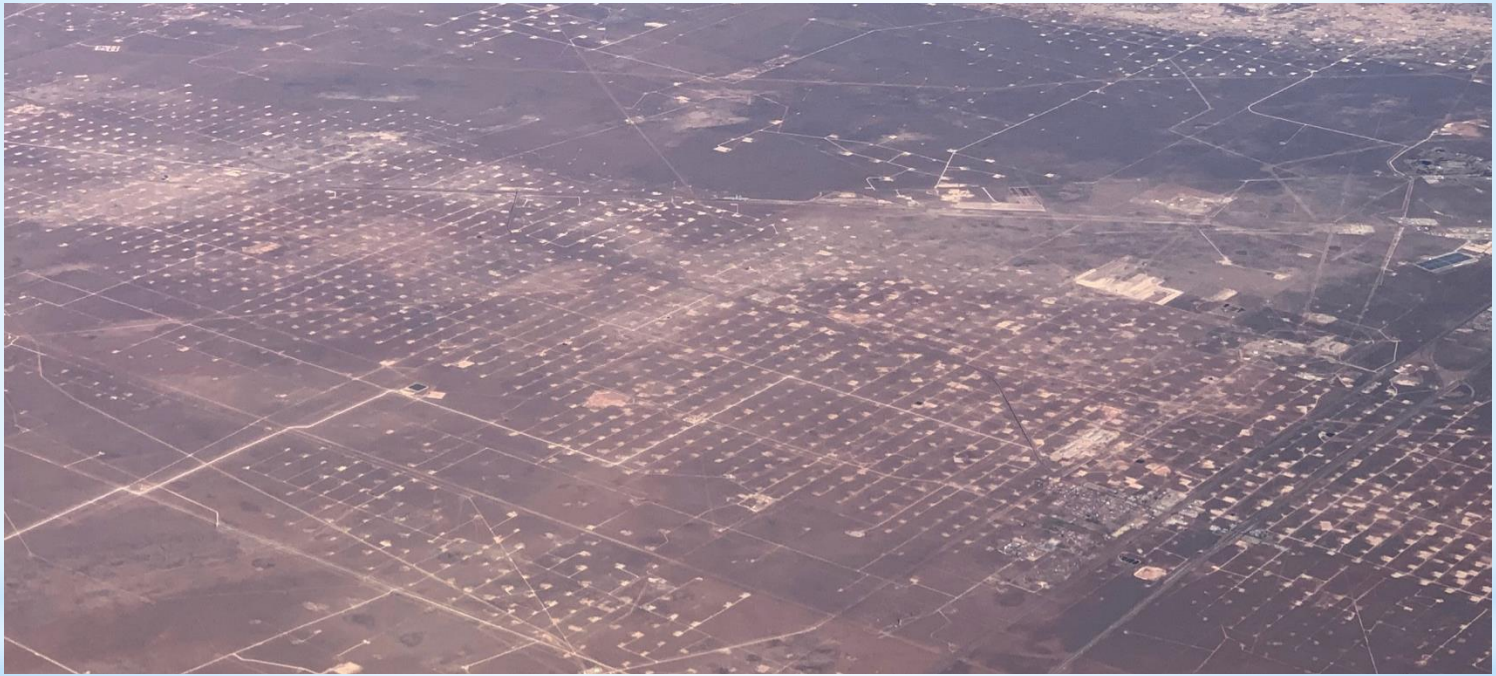
The Future: What market will commoditize MIR analyzers?



1,000,000 O&G wellpads in the US alone!
(Secret: They ALL leak methane)

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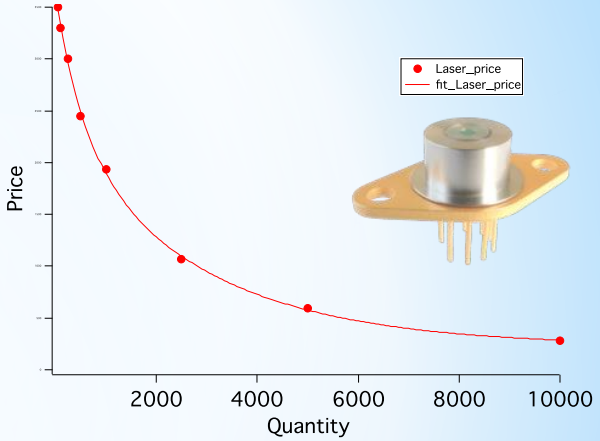
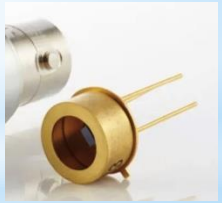
The Future: Commoditizing MIR Technologies

- **<u>Ultrasensitive MIR analyzers for <$8-10K is possible!</u>**
  - There is currently no parallel large market for components as was the case in the NIR
- The simplicity of the MIR platform reduces the BOM, build, operational and maintenance costs
  - No $$$ and fragile cavity optics, no wavemeters, no complicated fiber-coupled laser packaging, no piezo-scanned cavities, ultra-low power



- What is required of the component technologies?
  - Numbers- it's a numbers game!
  - more players and vendor sources



Can SAAS business models for sensor data remove the capex burden and change the game entirely?

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Summary

- *Ultrasensitive gas analysis has evolved in parallel with photonics technologies over the last 30 years: Telco NIR lasers + Cavities*
- *MIR Photonics have evolved significantly in the last 20 years*
- *Aeris has leveraged MIR Photonics advances to produce a disruptive gas analyzer platform, with 10x improvements in critical metrics: size, weight, power, performance. Enables new remote, handheld and mobile applications*
- *The future commoditization of MIR gas analysis is a numbers game, which could be realized in the near future by the need to monitor O&G operations*

***Acknowledgements** (over the decades)*

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