Jet Propulsion Laboratory
California Institute of Technology

Spectroscopic Detection and Monitoring of Environmental Hazards

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… and countless collaborators including R. Green, A. Thorpe, C. Frankenberg, R. Duren, C. Miller, E. Middleton, S. Ungar, L. Guanter, A. Hollstein, and others.

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Agenda

1. Survey of environmental hazard detection
2. GHG point sources and the Aliso Canyon Leak
3. Prospects for future GHG monitoring campaigns

Oil Spills

Wildfires

Earthquakes

Gas leaks

Drought and disease

Algal blooms

Volcanoes / landslides

Search and rescue

Environmental crime

wikimedia

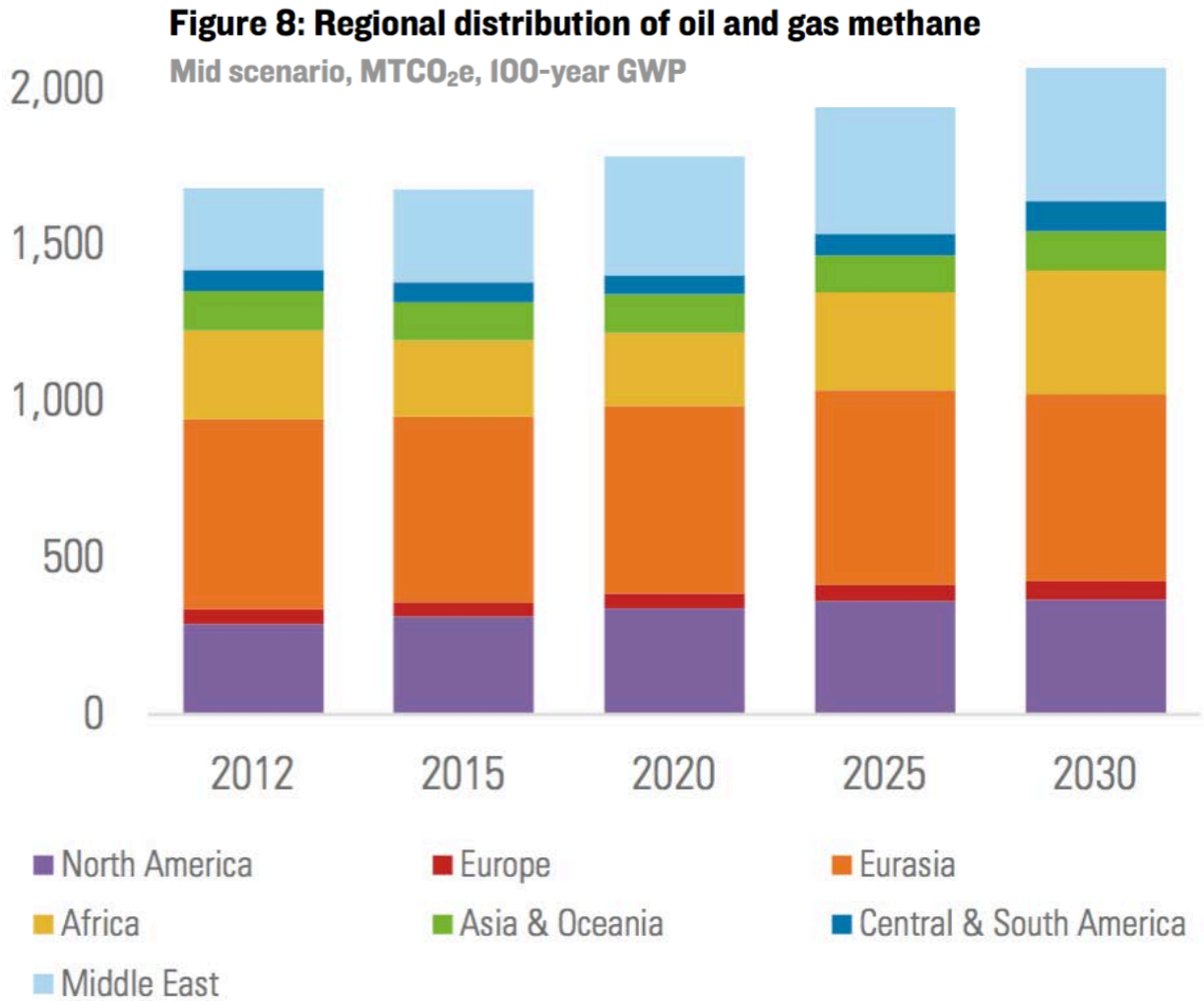
Remote spectroscopy can…

- **Predict** to enable prevention
- **Detect** to enable early action
- **Monitor** to assist evacuation & response
- **Quantify** to assist remediation & cleanup
- **Understand** with process studies

Magnitude of the CH_4 leak issue

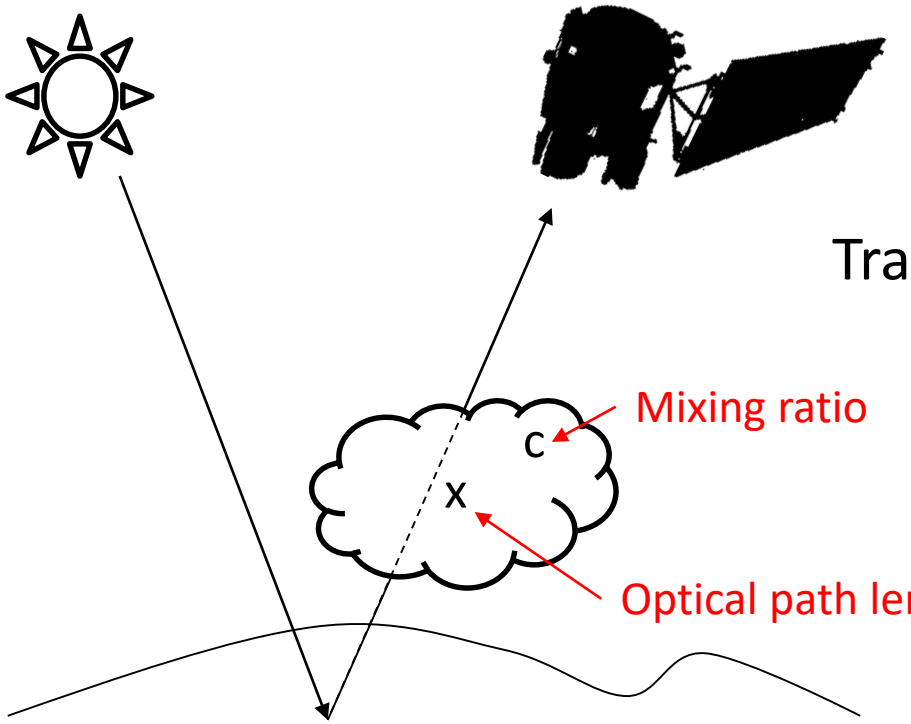
Potential global societal impacts in the **multiple billions of $USD, before accounting for gas revenue**, at $6.6 USD/t-$CO_2$ [2]

A growing burden of aging gas transmission infrastructure will require leak & explosion hazard monitoring.



[1]: Larsen et al., Rhodium Report 2015 (image)
[2]: Waldhoff et al., Economics 2015

Measuring point source greenhouse emissions remotely

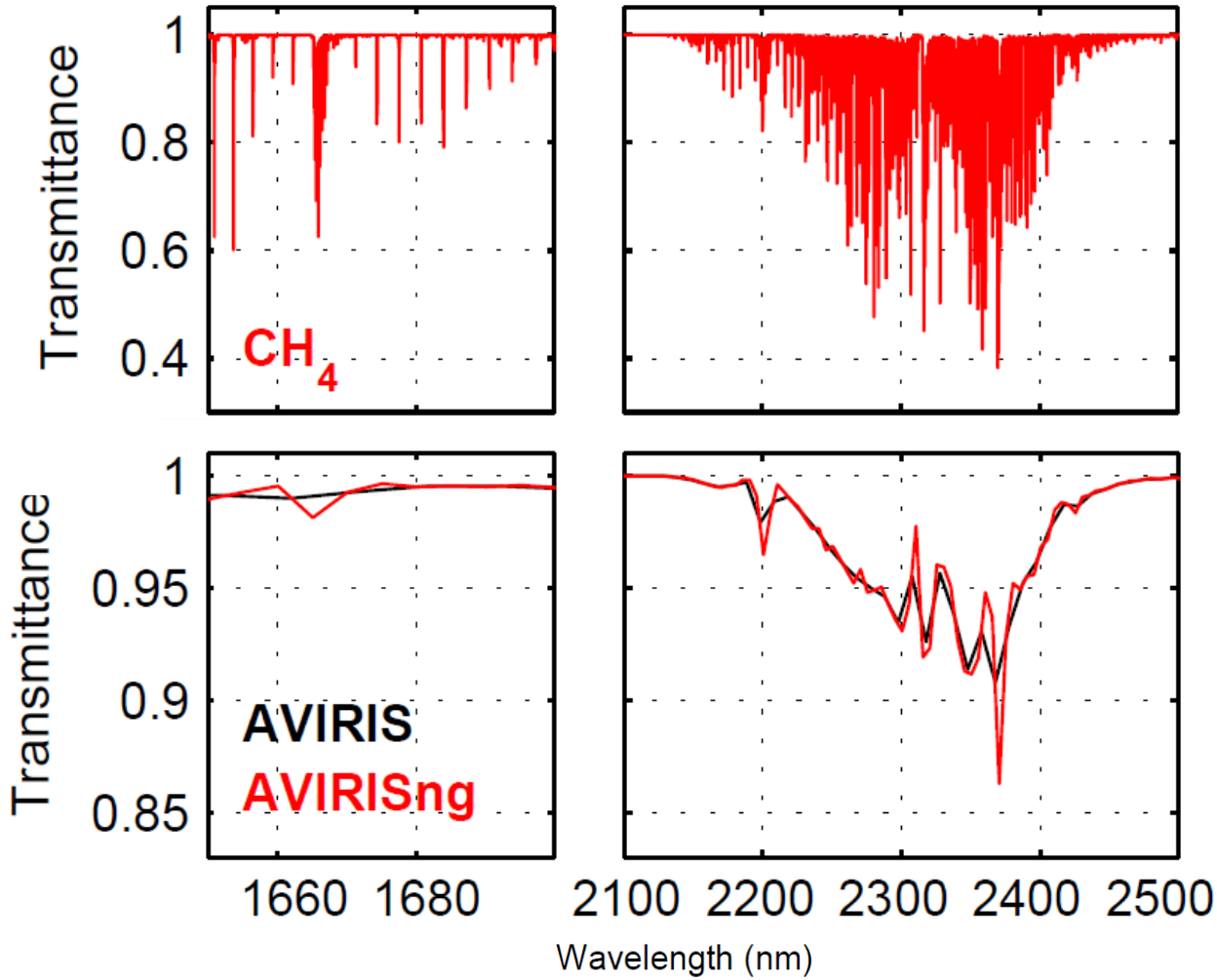


Mixing ratio
length in ppm m

$$\text{Transmission} \;\alpha\; e^{-\kappa c x}$$

Absorption coefficient

CH_4 absorption signatures



Detection via matched filter

Matched filter applied independently in each column

$$\hat{\alpha}(\mathbf{x}) = (\mathbf{x} - \mu)^T \Sigma^{-1} \mathbf{t} / (\mathbf{t}^T \Sigma^{-1} \mathbf{t})$$

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Mixing ratio length

Tested spectrum

Background mean

Background covariance

target

Detection via matched filter

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Using the target signature

$$\mathbf{t} = \partial \mathbf{x} / \partial \ell = -\mu e^{-\kappa \ell} \kappa = -\mu \kappa$$

Detection via matched filter

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Background covariance

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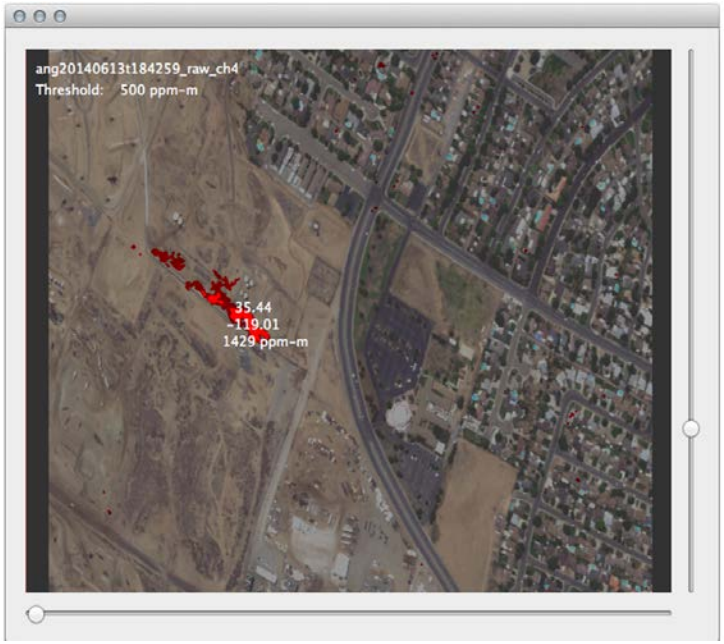
Using the target signature

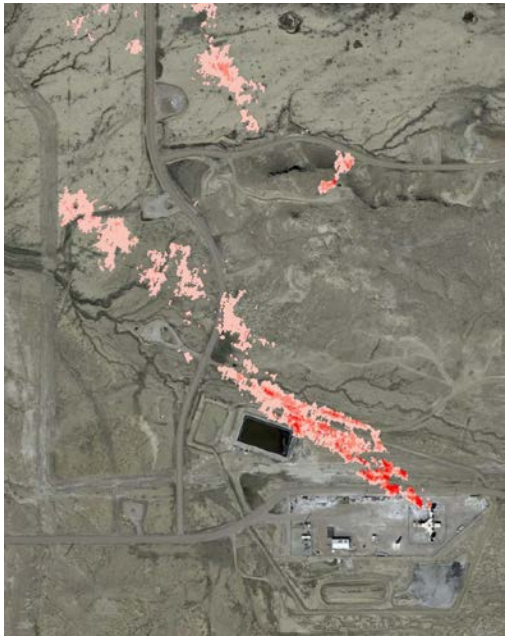
$$\mathbf{t} = \partial \mathbf{x} / \partial \ell = -\mu e^{-\kappa \ell} \kappa = -\mu \kappa$$

Unit absorption coefficient

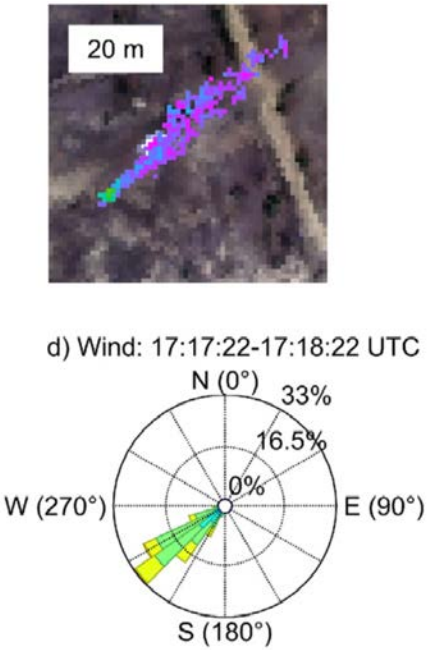
Many prior examples of airborne CH_4 detection



Real-time plume detection and mapping
(Thompson et al., AMT 2015)

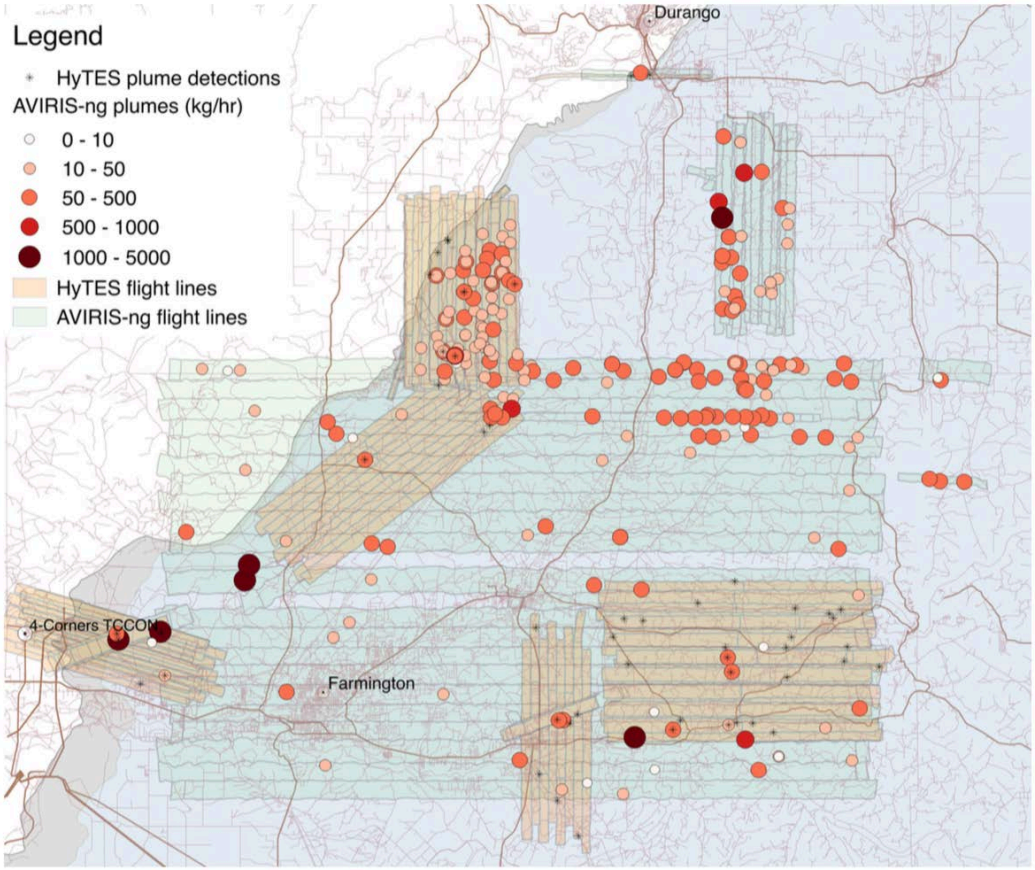


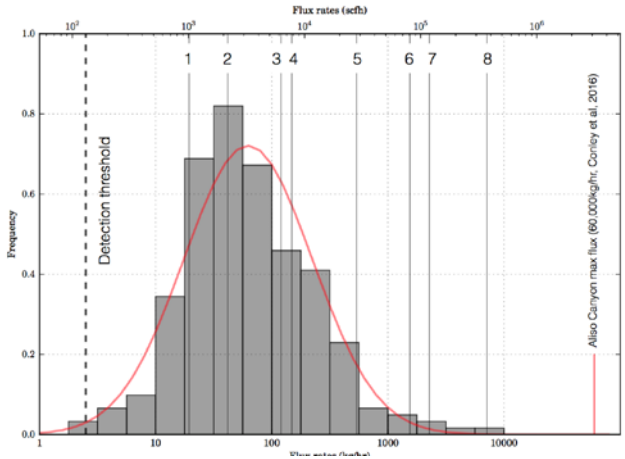
Four Corners airborne campaign
(Frankenberg et al., PNAS 2016)



REMOTC sensitivity study
(Thorpe et al., RSE 2016)

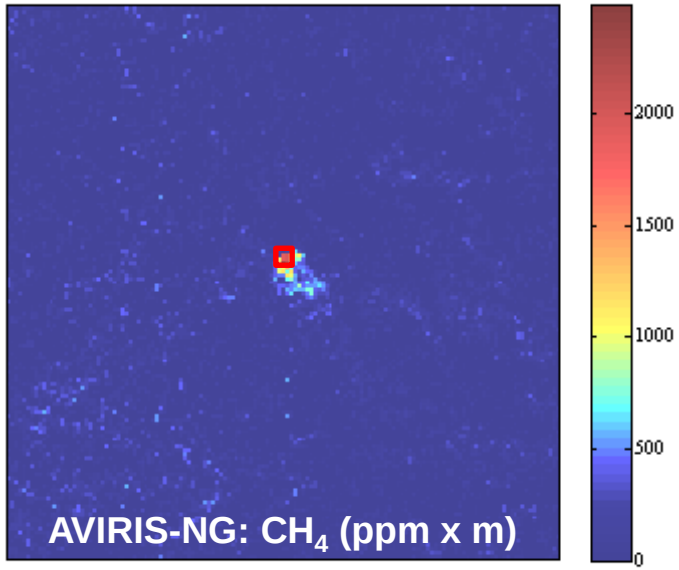
Distribution of AVIRIS-NG measured leaks at Four Corners





- Over 200 sources [Frankenberg et al., PNAS 2016]
- Log-normal distribution
- Total is 0.23–0.39 Tg/yr.
- Sources > 1000 kg hr^{-1} contribute 20-40% of total

Pipeline leaks discovered with AVIRIS-NG



Pipeline leaks discovered with AVIRIS-NG

USA relative impacts

Annual Harmful Algal Blooms

$0.6B via "Economic Impact of HABs in the U.S." Woods Hole Institute tech. rept. 2000-11

Annual Oil & Gas Production CH_4 leaks

$3.1B Includes lost revenue and global warming potential. Waldhoff et al., "The Marginal Damage Costs of Different Greenhouse Gases," *Economics* Vol. 8, 2014-31; and Larsen et al., "Untapped Potential: Reducing Global Methane Emissions from Oil and Natural Gas Systems," Rhodium group report, 2015.

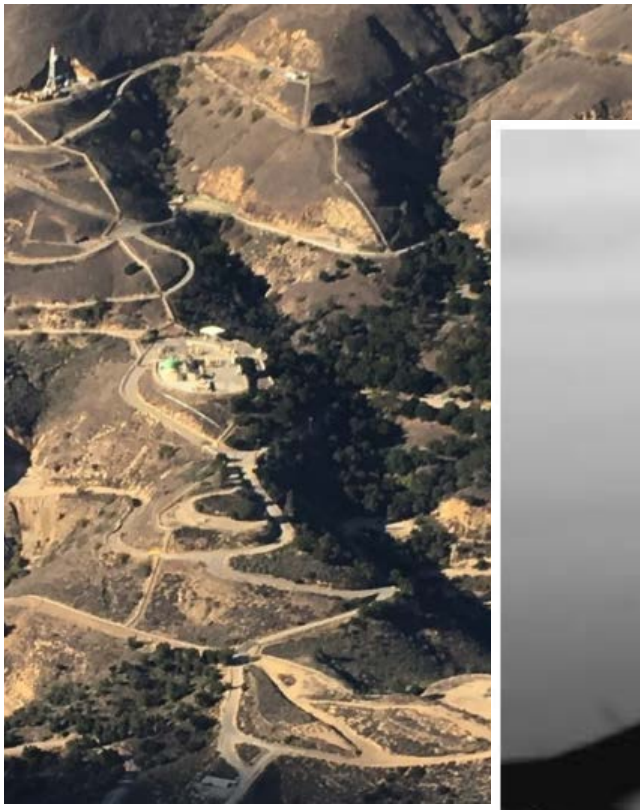
Exxon Valdez spill

$7.4B via Cohen, "A zonomy of Oil Spill Costs," rff.org report, 2010.

All values ($USD 2016)

… Key question: what fraction is remediable?

The Aliso Canyon CH_4 release

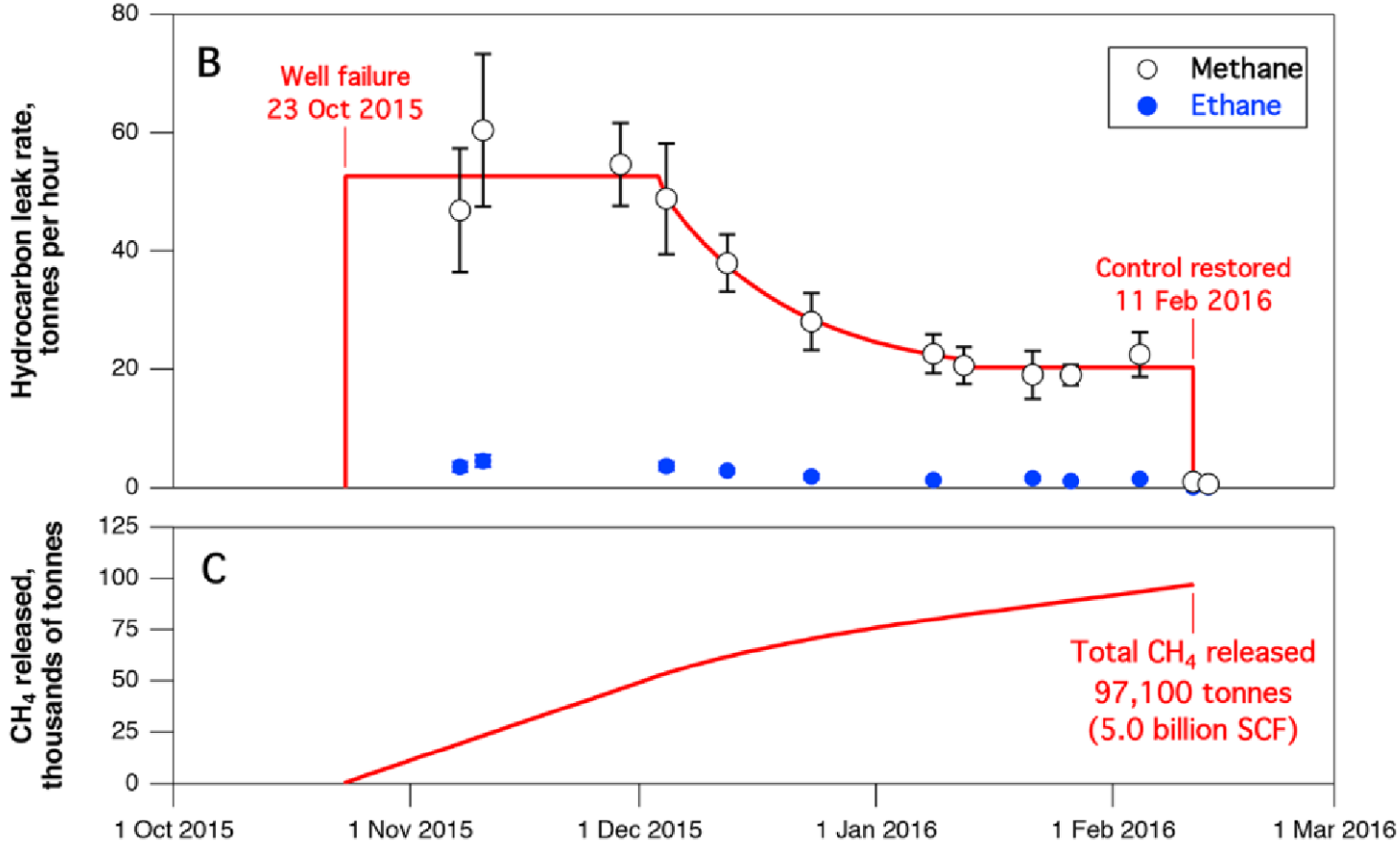


(NOAA)

http://blogs.edf.org/

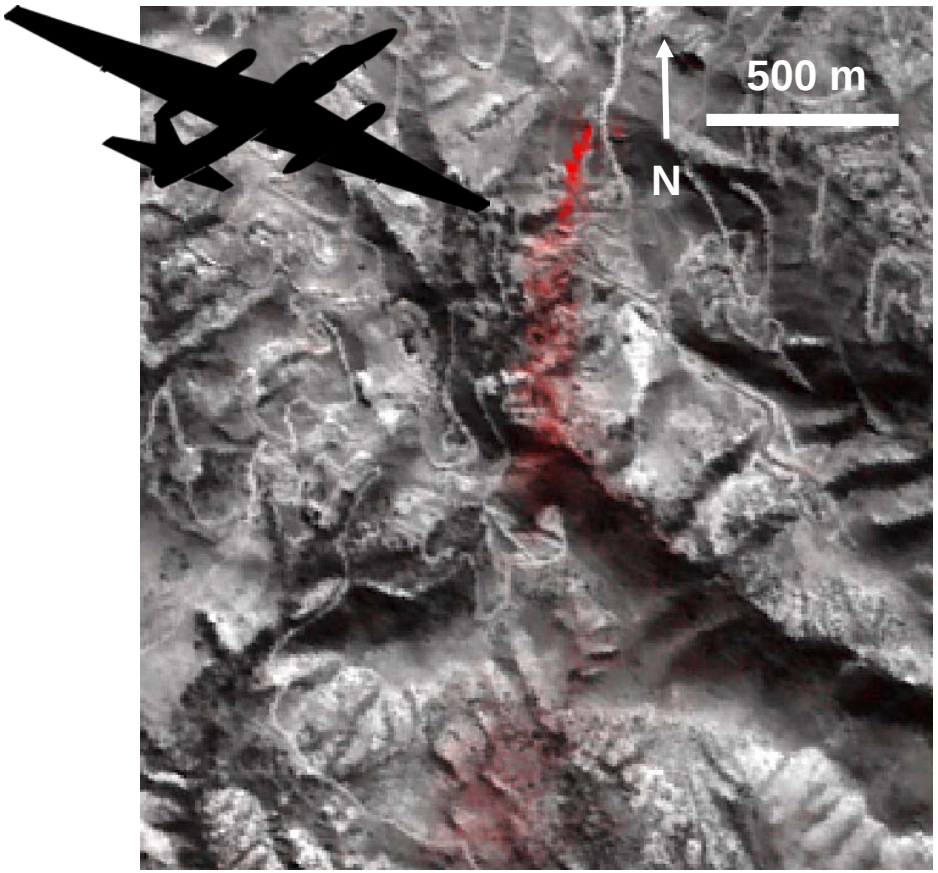
Leak rate estimated from airborne mass balance

Conley et al., *Science* 2016

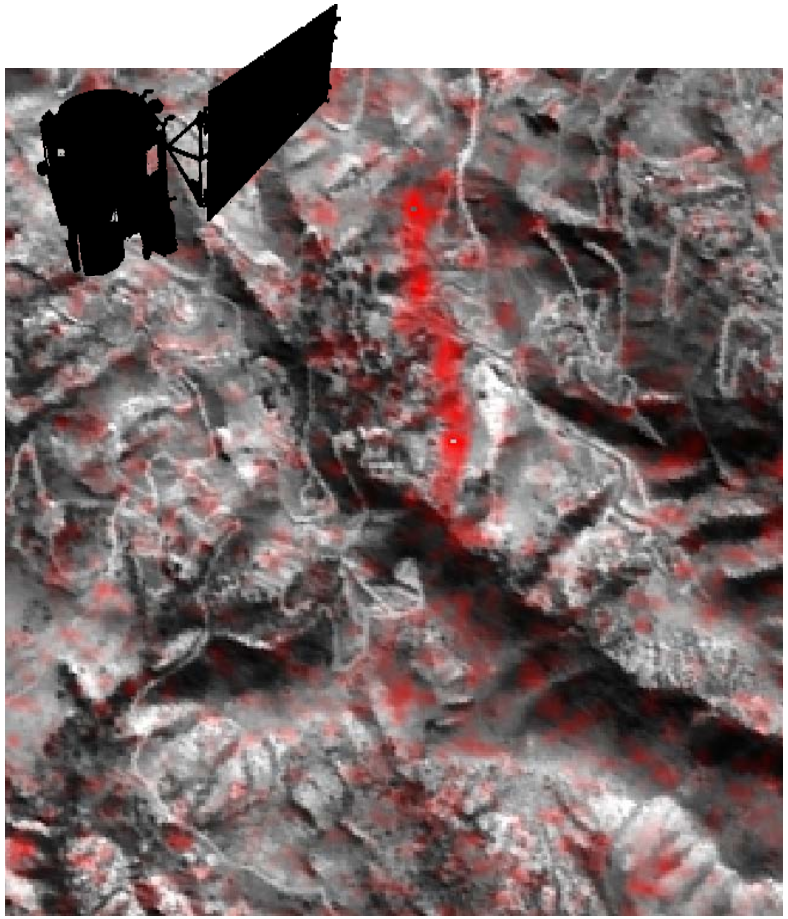


“Next morning” post-flight results

ER-2 at 6.6 km altitude, 1/12/2016



EO-1 Spacecraft at LEO, 1/1/2016



Thompson et al., *Geophys. Res. Lett.* (2016, accepted)

Integrated methane enhancement

- Total estimated above-background methane mass
- Inversely proportional to windspeed (Green et al., 1980)

$$IME = k \sum_{i=0}^{n} \hat{\alpha}(i) S(i)$$

Integrated methane enhancement

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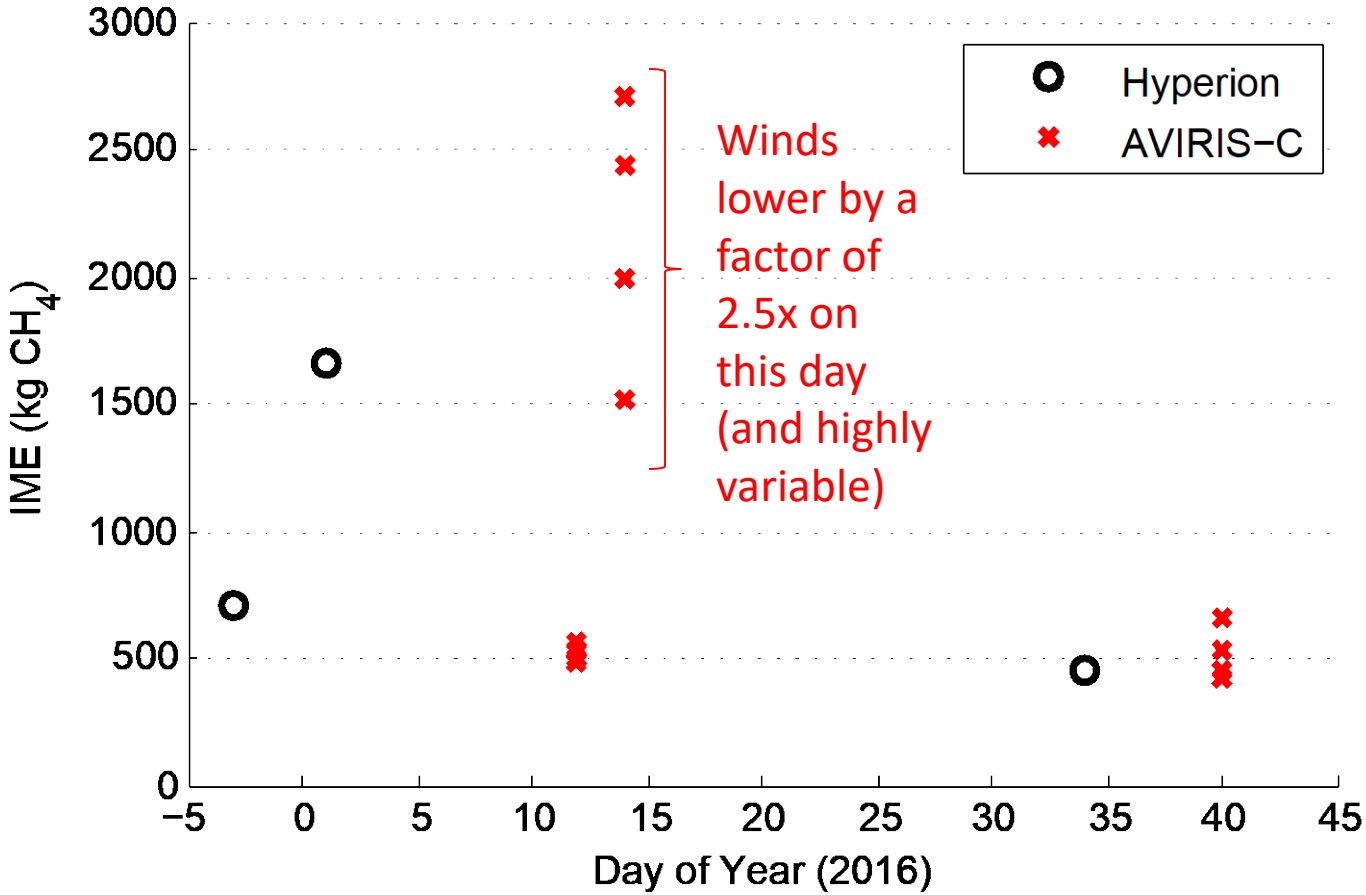
$$IME = k \sum_{i=0}^{n} \hat{\alpha}(i) S(i)$$

constant

Estimated mixing ratio length for pixel i

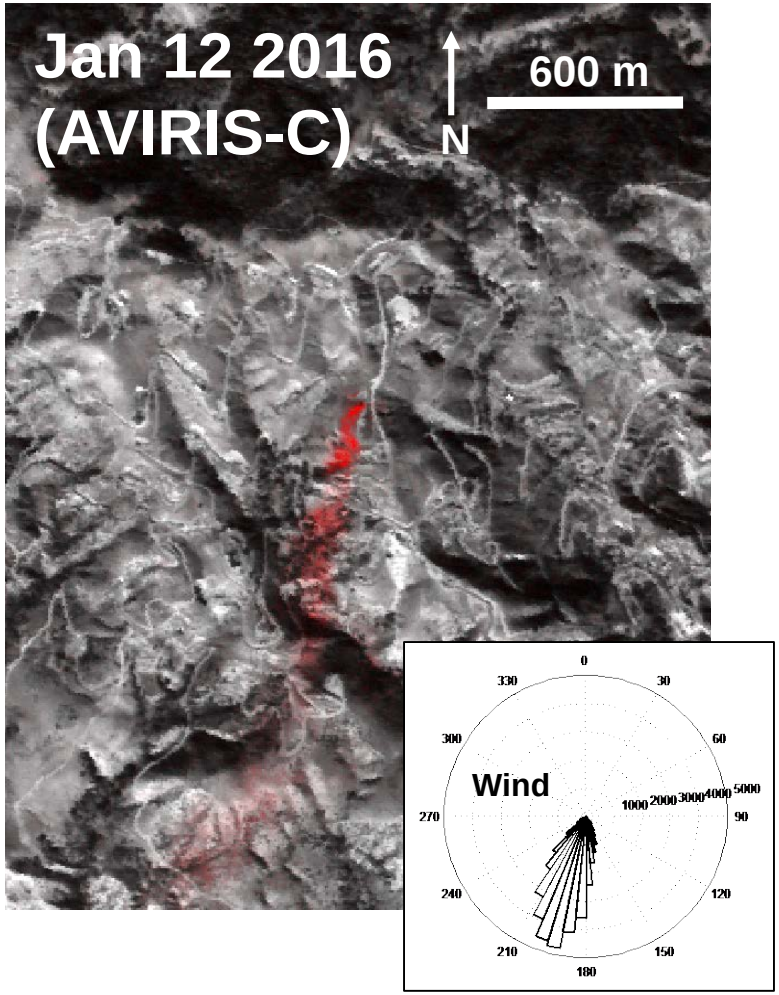
Pixel area

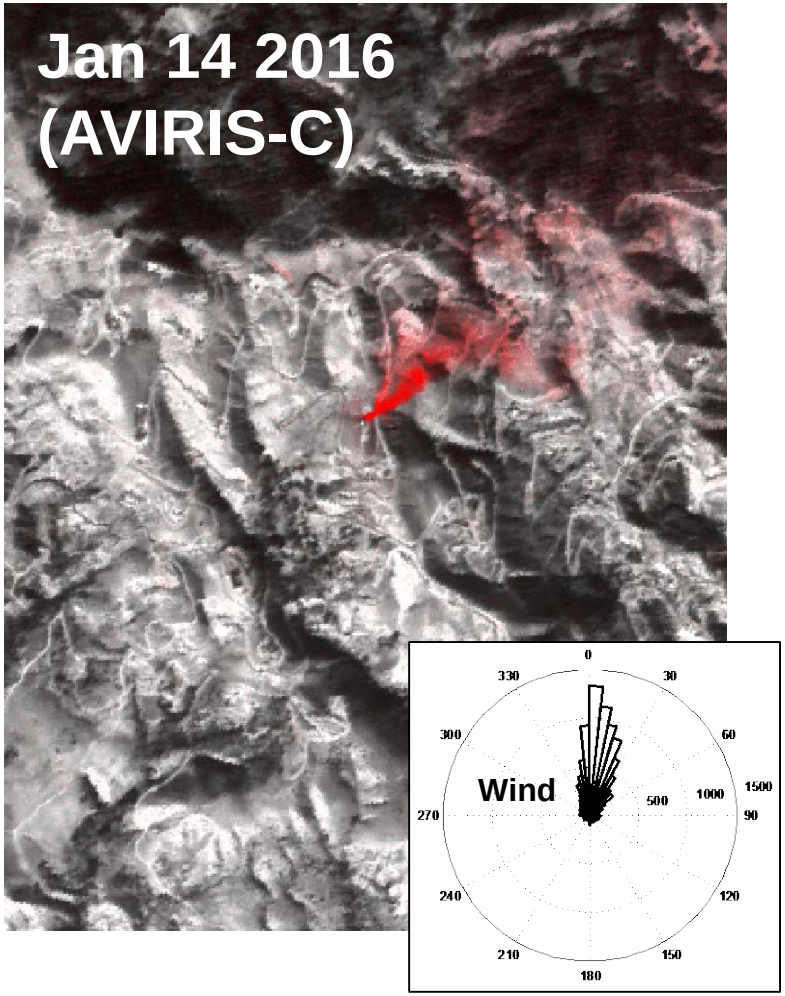
Integrated Methane Absorption



Thompson et al., *Geophys. Res. Lett.* (2016, accepted)

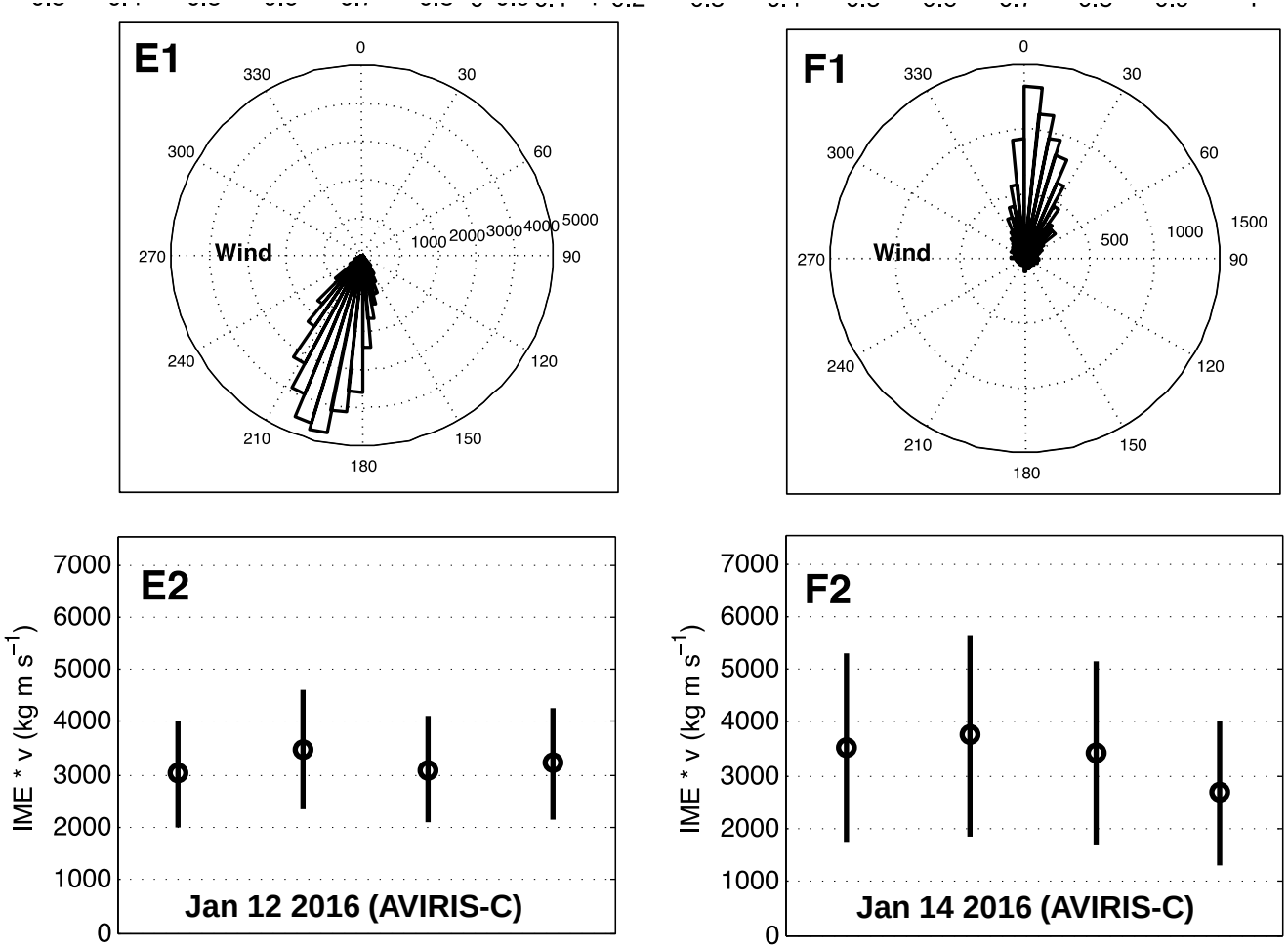
Wind directions





Thompson et al., *Geophys. Res. Lett.* (2016, accepted)

Wind-corrected IME



Thompson et al., *Geophys. Res. Lett.* (2016, accepted)

Agenda

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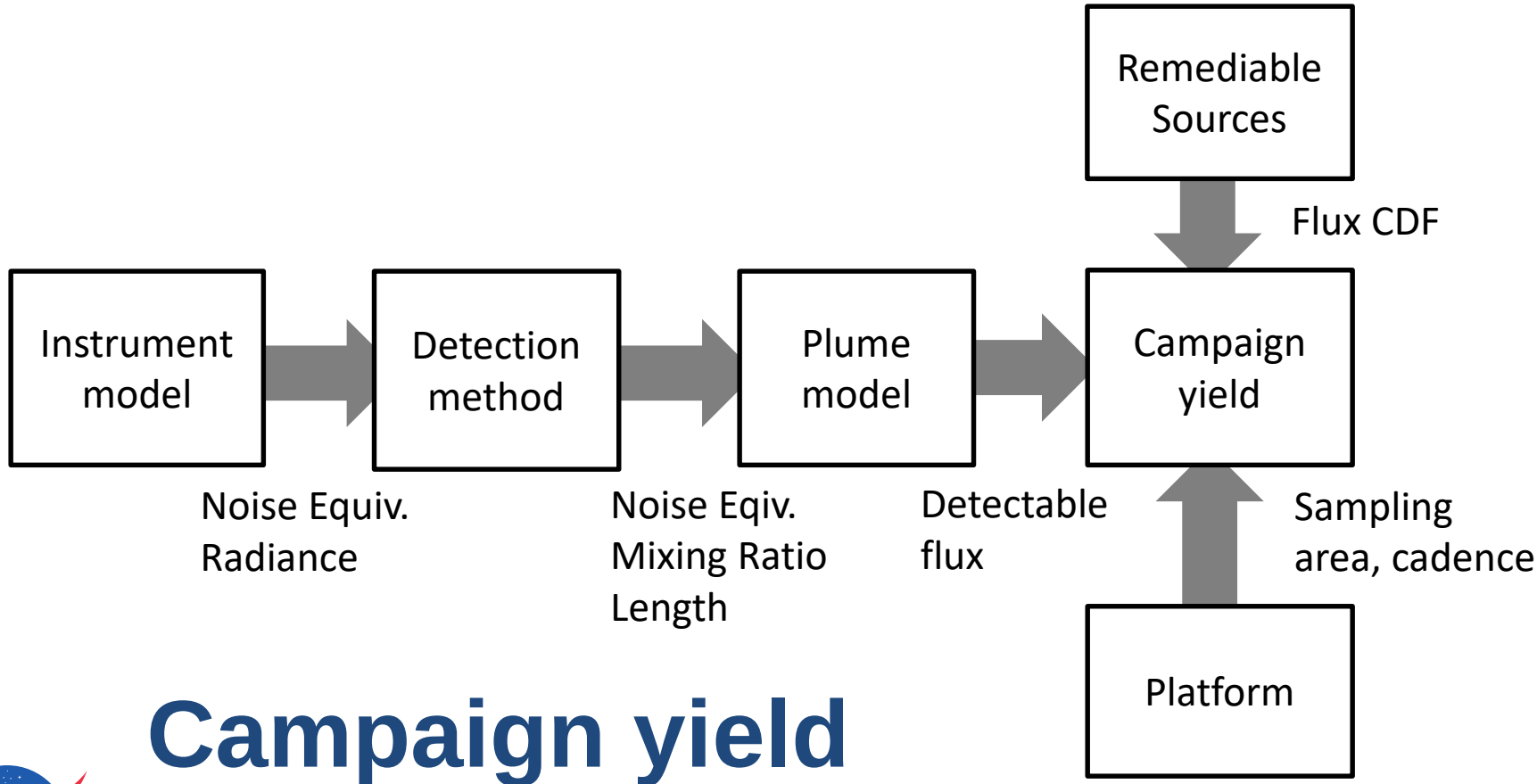
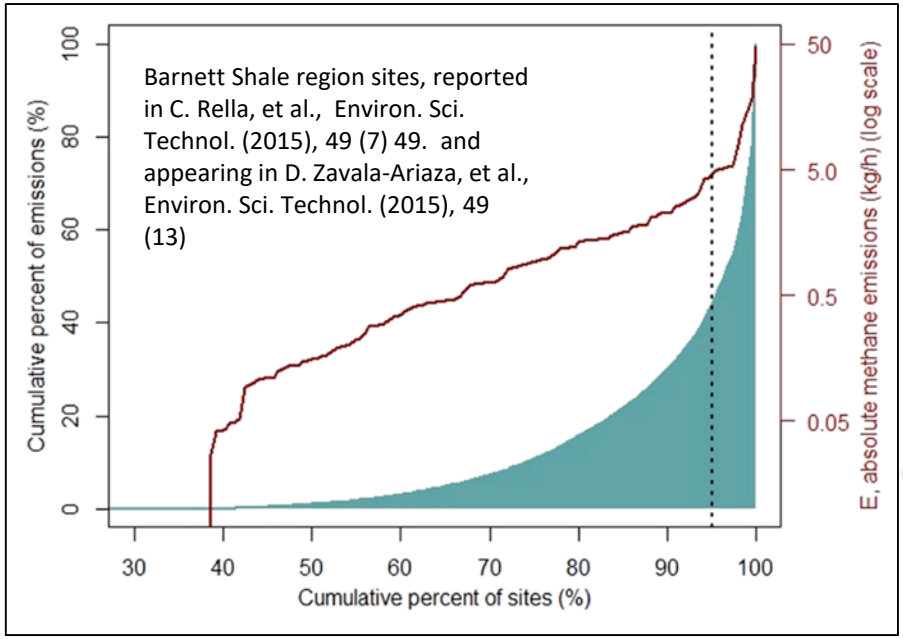
2. The Aliso Canyon leak
3. **Prospects for future GHG monitoring campaigns**



Campaign yield



Remediable Sources

Flux CDF

Instrument model → Detection method → Plume model → Campaign yield

Noise Equiv. Radiance

Noise Eqiv. Mixing Ratio Length

Detectable flux

Sampling area, cadence

Platform

Campaign yield

The Broad View

[Duren et al., NASA Earth Science Decadal Survey RFI, http://sites.nationalacademies.org/DEPS/esas2017

	System	Source population	Fraction sampled	Emissions above threshold	Detectable flux (kg/hr)	GSD (m)	Cadence (days)
Sources	Tier1	CO2: tens of thousands of facilities (global)	99%	>80%	200,000	30	30
		CH4: 10,000,000 facilities (global)	99%	30%	1,000	30	30
	Tier2	Ch4: 1,000,000 facilities (key regions)	>90%	90%	10	5	730
	Tier3	CO2: tens of thousands of facilities1a (global)	>50%	>90%	20,000	10	15
		CH4: 10,000,000 facilities (global)	>50%	50-90%	50	10	15
Instruments	OCO-2	CO2: tens of thousands of facilities (global)	<1%	<1%	2,000,000	~2,000	30
	TROPOMI	CH4: 100,000 known large facilities (global)	~20%	<10%	20,000	7,000	10
	EnMAP	CH4: 100,000 known large facilities (global)	0.20%	<1%	1,700	30	30
	Carbon-Sat	CO2: tens of thousands of facilities1a (global)	~20%	99%	2,000,000	2,000	3
		CH4: 100,000 known large facilities (global)	~25%	30%	2,300	2,000	3

Preliminary Conclusions (1/3)

- Targeted orbital VSWIR imaging spectroscopy at 30m resolution is useful for testing and cataloguing super-emitters
- Global mapping at 30 m GSD could image 30% of CH_4 and > 80% CO_2 emissions.
- *Operationally-useful* hazard detection & remediation would probably require dedicated instruments with higher sensitivity, cadence

Preliminary Conclusions (2/3)

- Conservative estimates of the “remediable leak fraction” suggest widespread comprehensive monitoring could recover **order billion $USD worth of lost revenue and radiative forcing potential**
- **The monitoring challenge will increase** with the growing burden of new & aging gas infrastructure – suited to regional efforts that include airborne platforms.

Preliminary Conclusions (3/3)

- For both GHGs and oil spills, mission support for “rapid response” could capture new, transient high-interest events (e.g. Aliso, Exxon Valdez or Deepwater Horizon).

Thanks!

- Robert O. Green, Michael Eastwood, Andrew Thorpe, Riley Duren, the AVIRIS team, Brian Bue, Christian Frankenberg, Charles Miller and Andrew Aubrey, all from JPL & Caltech;
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