Broad-Area Emission Surveys with Airborne Remote Sensing

David M. Tratt, Kerry N. Buckland, Eric R. Keim, Jeffrey L. Hall,
Katherine M. Saad, Patrick D. Johnson
The Aerospace Corporation
Los Angeles, Calif., USA

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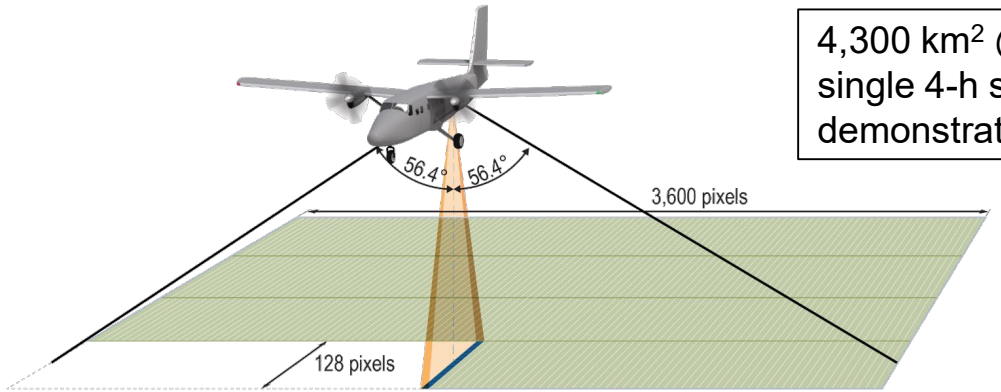
Introduction

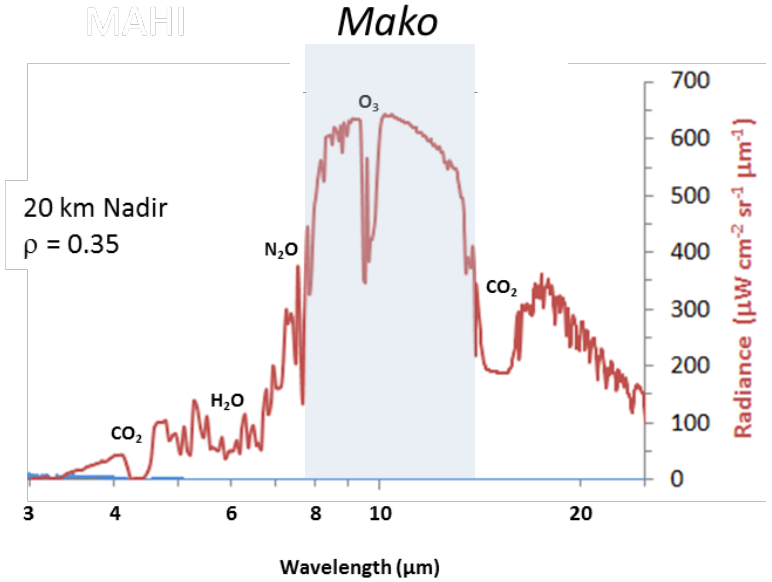
- Airborne hyperspectral longwave-infrared (LWIR) imaging is a powerful technique for detecting, identifying, and tracking/sourcing gaseous emissions from compact sources
- Hyperspectral resolution enables full characterization of the thermal radiance distribution and detection/identification of gaseous and solid materials within the scene
  - *Atmospheric Compensation (ISAC)*
  - *Spectral Matched Filter (SMF) or Adaptive Coherence Estimation (ACE)*
  - *Stepwise (forward) Generalized Least Squares (whitened space)*
- Urban-industrial environments are replete with gaseous emissions deriving from a wide variety of commercial and residential operations
- Broad-area surveys are important in regulatory monitoring, mitigation of public health concerns, post-disaster hazard evaluation, regional climate assessment
  - *Recovery from immediate effects of catastrophic events is often hampered by an array of latent dangers*
  - *Fugitive emissions of hazardous gases are an especially pernicious risk to first responders and nearby communities*
  - *Broad-area airborne LWIR surveys rapidly mounted provide flexible and unique capabilities for identification and monitoring of environmental hazards*

dtratt@aero.org

Airborne Wide-Swath LWIR Spectral Imager ("Mako")

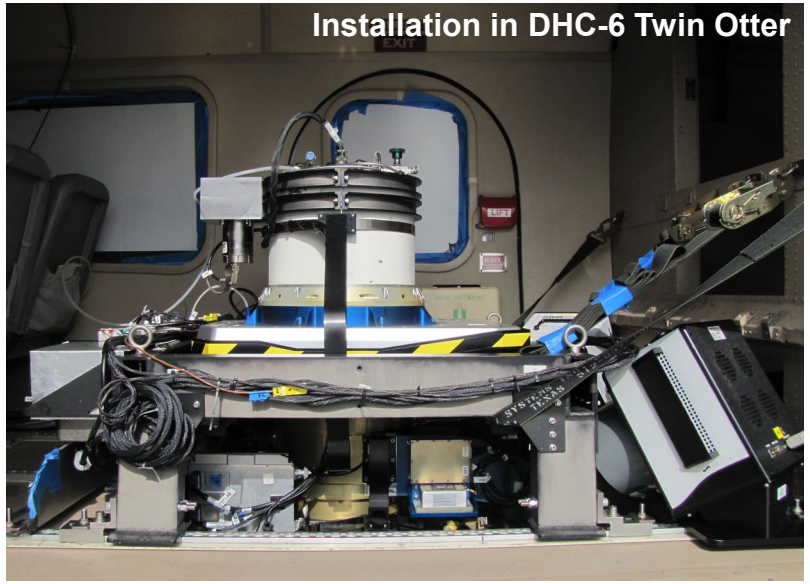


4,300 km^2 @ 2-m GSD in a single 4-h sortie has been demonstrated.



Whiskbroom scanning enables broad-area coverage and high areal rate

Parameter	Mako
Spectral coverage	7.6 – 13.2 μm
Spectral resolution	44 nm (128 channels)
IFOV	0.55 mrad
Along-track FOV	4.0°
Base frame rate	3255 Hz
Operational frame rate	814 Hz (4 co-adds)
Cross-track pixels	400 – 3600
Cross-track field-of-regard (relative to nadir)	±56.4° (max.)
FPA temperature	9.5 K
NESR (10 μm, 4 co-adds)	<0.4 μW cm^{-2} sr $^{-1}$ μm^{-1}
NEDT (10 μm, 300 K)	0.02 K
Scan type	Whiskbroom
Areal acquisition rate (2-m GSD)	33 km^2/min (max.)



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Spectral Detection and Identification

- Spectral Matched Filter (SMF):

$$\mathrm{SMF} = \frac{\mathbf{A}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{Y}}{\left(\mathbf{A}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{A}\right)^{1/2}}$$

- Adaptive Coherence Estimator (ACE):

$$\mathrm{ACE} = \frac{\mathbf{A}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{Y}}{\left(\mathbf{A}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{A}\right)^{1/2}\left(\mathbf{Y}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{Y}\right)^{1/2}}$$

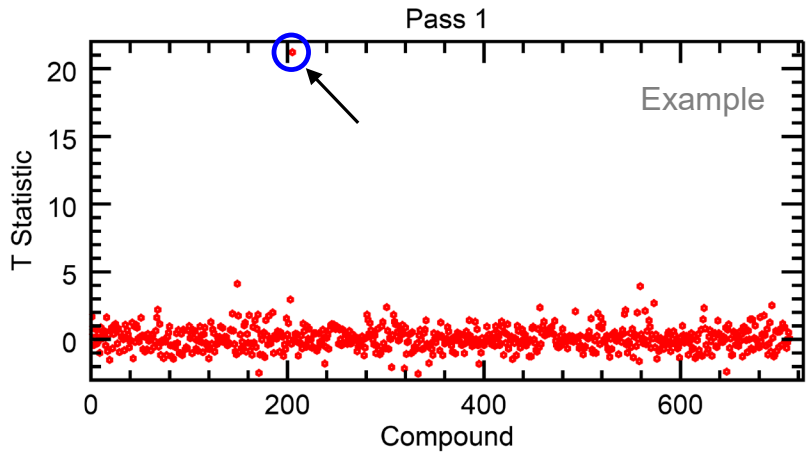
- *t*-statistic (used primarily for ID):

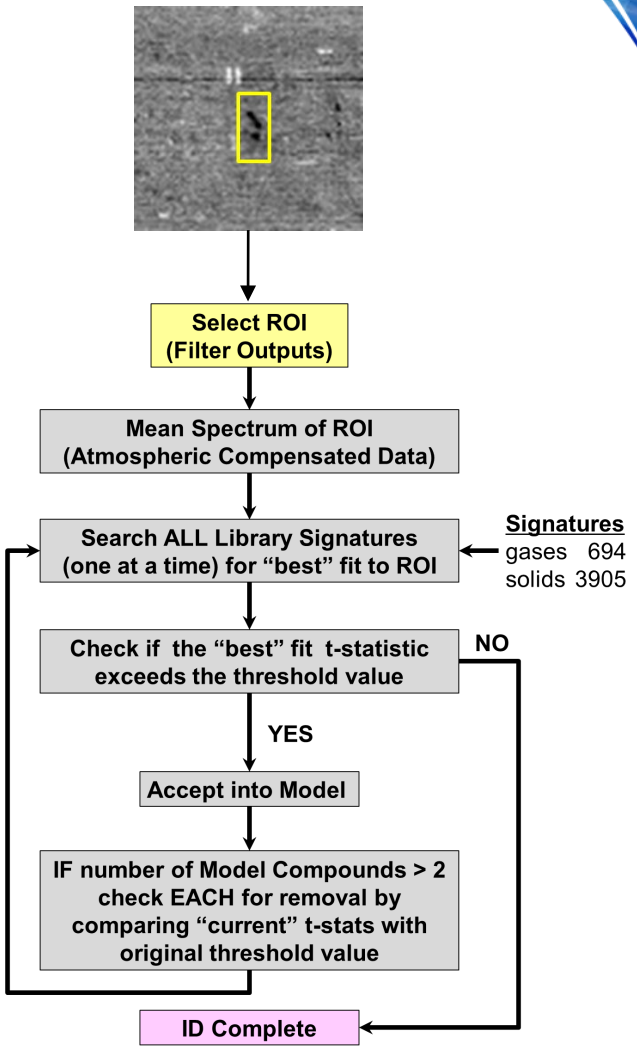
$$t = \frac{\mathbf{A}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{Y}}{\left(\mathbf{A}^{\mathrm{T}}\mathbf{C}^{-1}\mathbf{A}\right)^{1/2}\left((\mathbf{Y}-\mathbf{A}\mathbf{X})^{\mathrm{T}}\mathbf{C}^{-1}(\mathbf{Y}-\mathbf{A}\mathbf{X})\right)^{1/2}}$$

$$\mathbf{C} = \frac{1}{n-1}\sum_{i=1}^{n}\mathbf{Y}_i\mathbf{Y}_i^{\mathrm{T}}$$

	Source	Definition
Y	Data	**Pixel Spectrum** (mean removed) of compensated data; measurement of ground-leaving radiance
C	Data	**Covariance Matrix** Describes variance within each spectral channel and correlation between spectral channels
A	Spectral Library	**Target Signature** (resampled to sensor spectral response); gas absorption coefficient or solid material reflectance
X	Calculated	**Target Coefficient Matrix** Obtained from GLS regression

- Identification (ID) by stepwise generalized least-squares (GLS)
- Spectral fitting in "whitened space"
  - *Based on scene covariance matrix*
- Algorithm proven in multiple field tests
  - *Tested against ground-truth*
  - *Algorithm competitions and "blind" exercises*
  - *Up to 6 separate gases have been successfully unmixed and ID'd under test conditions*
- Confidence levels
  - *Assessed using t-stat strength and separation:*





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Tactical Processing: Urban-Industrial Environments

90 compounds of interest selected from a ~700-member spectral library

1,1,1,2-Tetrafluoroethane	Acrolein	Ethane	Methyl isobutyl ketone	Sulfur trioxide
1,1,1-Trichloroethane	Acrylonitrile	Ethanol	Methyl methacrylate	Sulfuryl fluoride
1,1,2-Trichloro-1,2,2-trifluoroethane	Ammonia	Ethene	Methylamine	tert-Butyl methyl ether
1,1-Dichloro-1-fluoroethane	Benzene	Ethyl acetate	Naphthalene	Tetrachloroethylene
1,1-Dichloroethane	Butane	Ethylbenzene	Nitric acid	Tetrahydrofuran
1,1-Difluoroethane	Carbon dioxide	Formaldehyde	Nitrogen dioxide	Toluene
1,2,4-Trimethylbenzene	Carbon tetrachloride	Heptane	Nitrogen dioxide and dimer	Trichloroethylene
1,2-Dichlorotetrafluoroethane	Carbonyl sulfide	Hexane	Nitrous oxide	Trichlorofluoromethane
1,2-Dibromoethane	Chlorodifluoromethane	Hydrogen peroxide	Octane	Vinyl chloride
1,2-Dichloroethane	Chloroform	Hydrogen sulfide	Ozone	a-Pinene
1,3-Butadiene	Chloropicrin	Isobutane	Pentane	d-Limonene
1,3-Dichloropropene	Cycloheptane	Isobutene	Peroxy acetyl nitrate (main bands)	m-Xylene
1,4-Dichlorobenzene	Cycloheptene	Isoprene	Phosgene	o-Xylene
1-Propanol	Cyclohexane	Isopropanol	Phosphine	p-Xylene
2,2-Dichlor-1,1,1-trifluorethane	Cyclohexene	Methane	Propane	
2-Butoxyethanol	Dichlorodifluoromethane	Methanol	Propene	
Acetaldehyde	Dichlorofluoromethane	Methyl bromide	Styrene	
Acetic acid	Dichloromethane	Methyl ethyl ketone	Sulfur dioxide	
Acetone	Diethyl ether	Methyl formate	Sulfur hexafluoride	

dtratt@aero.org

Tactical Analysis Output Sample

All emissions are time-stamped, geolocated, and chemically identified as illustrated in this excerpt from a typical automated tactical analysis report:

Plume Sources (LA Basin - 7/22/2014)				
Time (UTC)	**(LON, LAT)**	**ID**	**t-stat**	**Source Information**
17:40:24	-118.345305, 33.986106	1,1,1,2-Tetrafluoroethane	-14.8	Residence
17:41:24	-118.314280, 33.982817	Acetone	-26.9	Furniture and upholstery
17:41:33	-118.309144, 33.978966	Methanol	-14.6	Auto paint shop
17:43:02	-118.265361, 33.975626	Acetone	-13.8	Furniture factory
17:43:46	-118.242887, 33.992775	Acetone	-17.9	Iron worker
17:43:46	-118.243212, 33.972248	Acetone	-18.4	Screen printer
17:43:46	-118.242184, 34.010894	Chlorodifluoromethane	-10.2	Metal salvager
17:43:55	-118.237554, 34.002014	Ammonia	-23.6	Cold storage
17:43:59	-118.236606, 34.002475	Ammonia	-9.2	Cold storage
17:43:59	-118.235838, 33.990606	Ammonia	-27.4	Clothing store (probable furnace flue)
17:44:04	-118.234248, 33.986740	Ammonia	-11	Fabric finishing and lamination (probable furnace flue)
17:44:17	-118.226988, 33.995651	Ammonia	-24.6	Galvanizing
17:44:25	-118.223949, 34.000360	Ammonia	-15	Galvanizing
17:44:25	-118.223321, 34.006222	Ethanol	-22	Foods warehouse
17:44:30	-118.220774, 33.999024	Carbon dioxide	11.7	Waste handling/incinerator
17:44:30	-118.220774, 33.998867	Carbon dioxide	13.1	Waste handling/incinerator
17:44:34	-118.217737, 34.006523	Ammonia	-19.4	Produce warehouse
17:44:34	-118.217199, 33.996992	Carbon dioxide	11.3	Glass foundry
17:45:00	-118.204839, 33.982193	Ammonia	-24.6	Thermal processing of metals
17:45:00	-118.204715, 33.981642	Ammonia	-22.1	Thermal processing of metals
17:45:25	-118.191401, 33.997515	Ethene	-16.1	Produce Supplier
		Methane	-6	

dtratt@aero.org

Greenhouse Gas Focus: The Kyōto Basket

- The “Kyōto Basket” comprises five specific gases and two classes of halocarbons
- LWIR hyperspectral sensors address most of the Kyōto Basket gases:

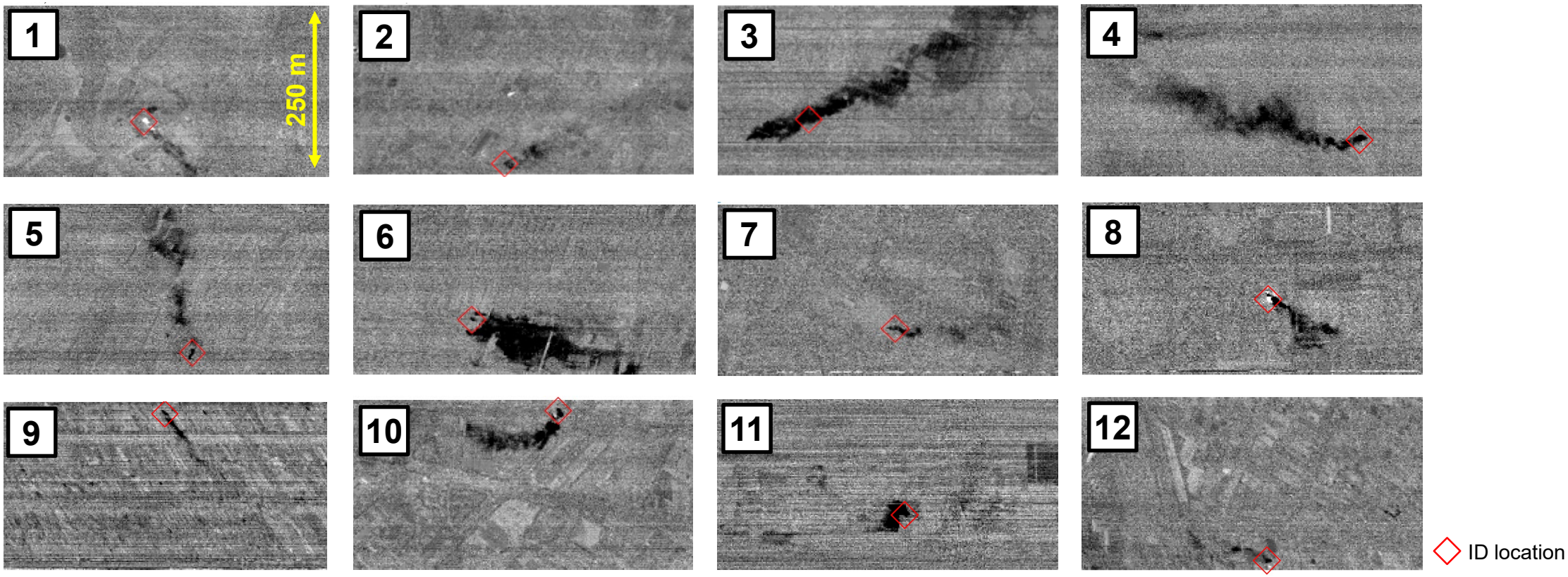
Kyōto Basket Gas	Mako Sensitivity (kg/h)*
Carbon dioxide (CO_2)	Very low (4800)
Methane (CH_4)	Moderate (10)
Nitrous oxide (N_2O)	Moderate (10)
Hydrofluorocarbons (HFCs)	Very high/high (0.2–2.0)
Perfluorocarbons (PFCs)	Very high/high (0.2–1.0)
Sulfur hexafluoride (SF_6)	Very high (0.1)
Nitrogen trifluoride (NF_3)	Very high (0.5)

* Minimum detectable point-source emission flux assuming 5-m/s wind, 5-K thermal contrast, 2-m GSD, and urban/industrial spectral clutter statistics.

dtratt@aero.org

Kyōto Basket Species Observed in Urban Settings

Selected ACE detection filter images



1: Carbon dioxide (landfill flare)

2: Carbon dioxide (oil refinery)

3: Methane (international airport)

4: Methane (landfill)

5: Nitrous oxide (industrial gas supplier)

6: Nitrous oxide (industrial gas supplier)

7: Sulfur hexafluoride (aerospace plant)

8: Sulfur hexafluoride (research facility)

9: 1,1-Difluoroethane, HFC-152a (residential building)

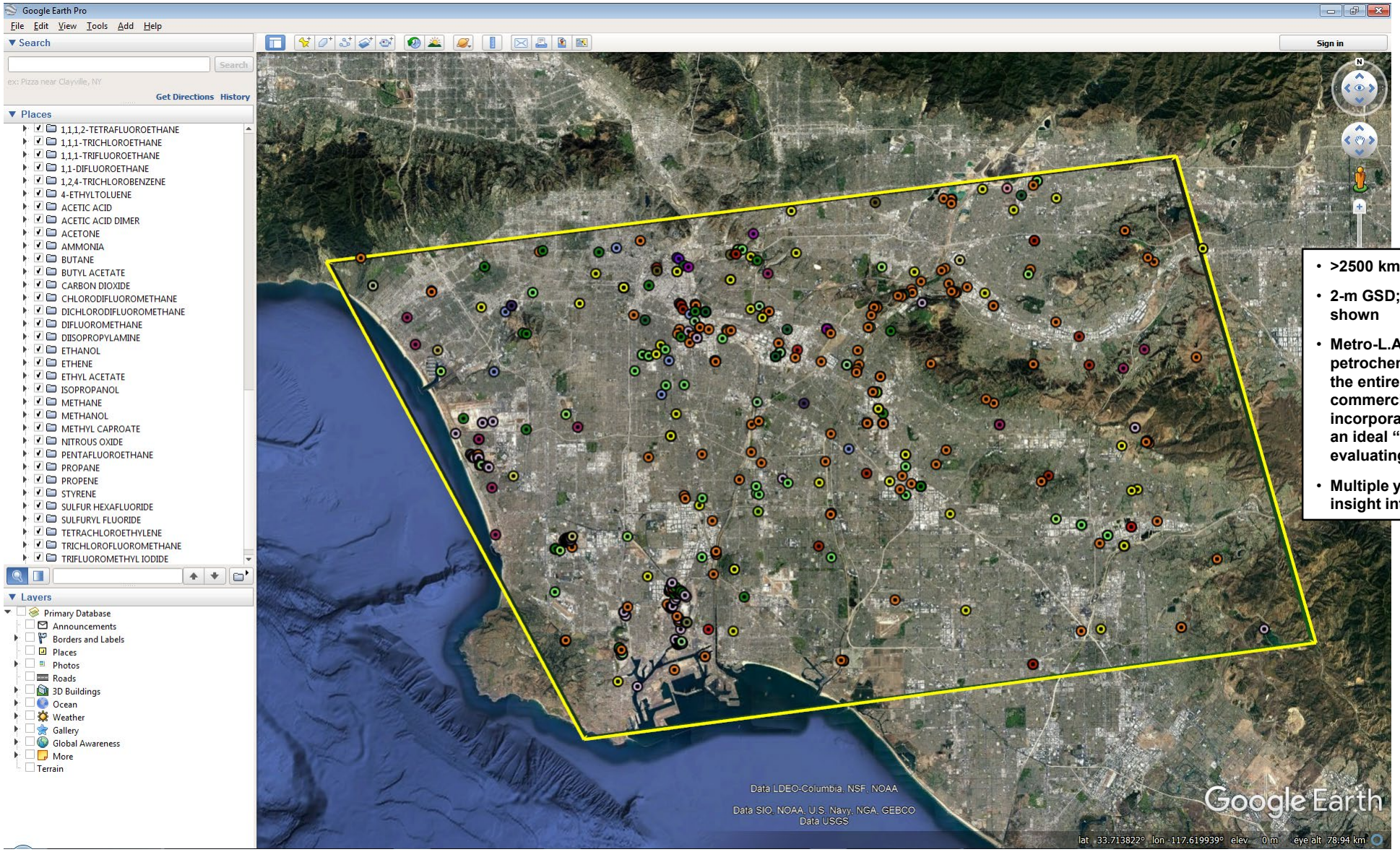
10: 1,1,1,2-Tetrafluoroethane, HFC-134a (water dept. depot)

11: Pentafluoroethane + Difluoromethane, R-410 (office bldg.)
(HFC-125) (HFC-32)

12: Pentafluoroethane + 1,1,1,2-Tetrafluoroethane + Difluoromethane, R-407 (gas station)
(HFC-125) (HFC-134a) (HFC-32)

dtratt@aero.org

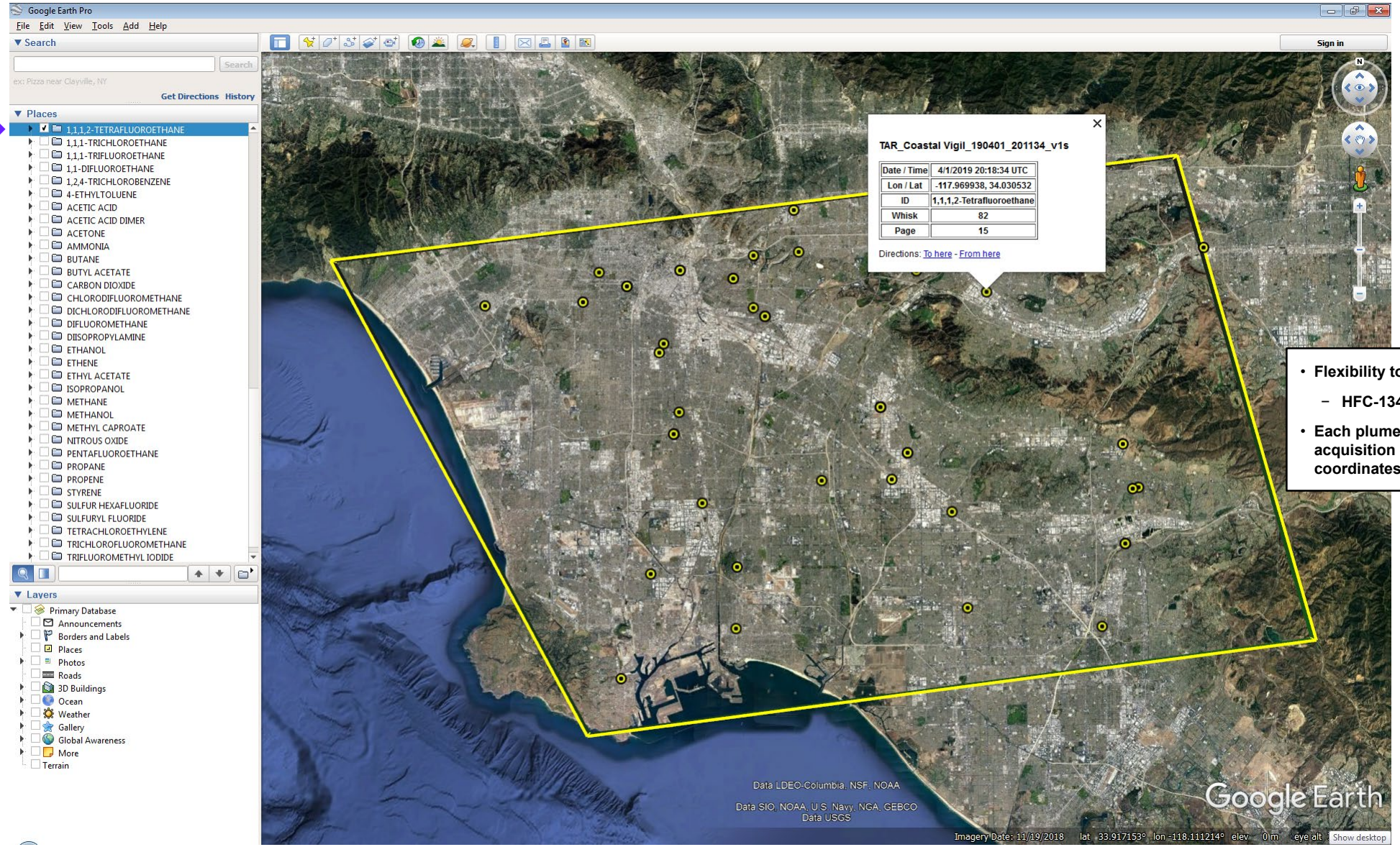
Broad-Area Survey of the Los Angeles Basin, 1 April 2019



- **>2500 km^2 acquired in 3 hours**
- **2-m GSD; all detected emission sources shown**
- **Metro-L.A. contains a major portion of petrochemical refining capacity serving the entire western U.S. and its combined commercial and residential areas incorporate >18 x 10^6 persons. It offers an ideal "laboratory" for testing and evaluating gas sensing techniques.**
- **Multiple years of collections provide insight into emission trends**

dtratt@aero.org

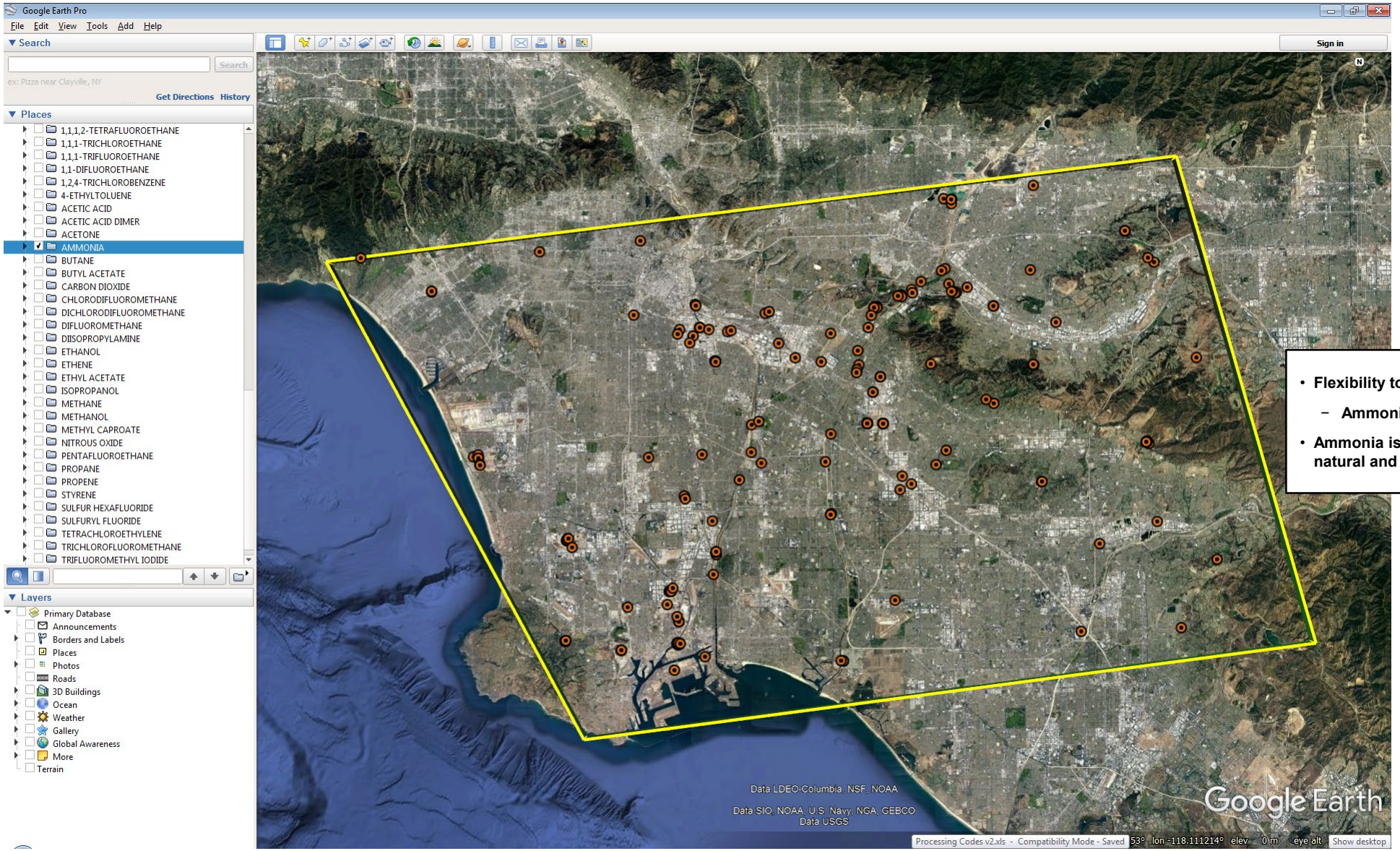
Broad-Area Survey of the Los Angeles Basin: HFC-134a



- **Flexibility to select individual gases**
  - **HFC-134a shown**
- **Each plume location point is tagged with acquisition date/time, geographical coordinates, and gas ID**

dtratt@aero.org

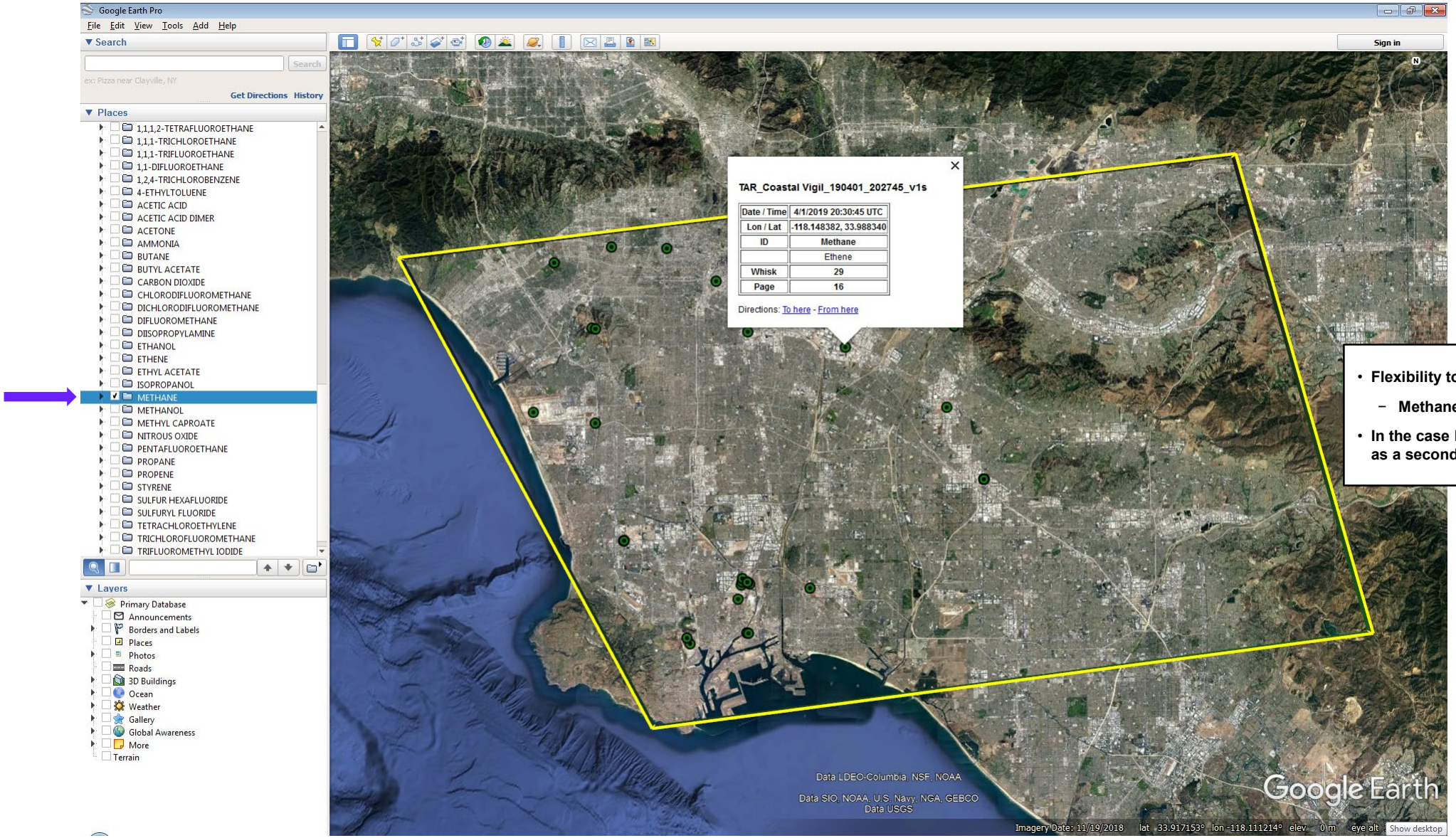
Broad-Area Survey of the Los Angeles Basin: Ammonia



- **Flexibility to select individual gases**
  - **Ammonia shown**
- **Ammonia is produced by a great many natural and anthropogenic sources**

dtratt@aero.org

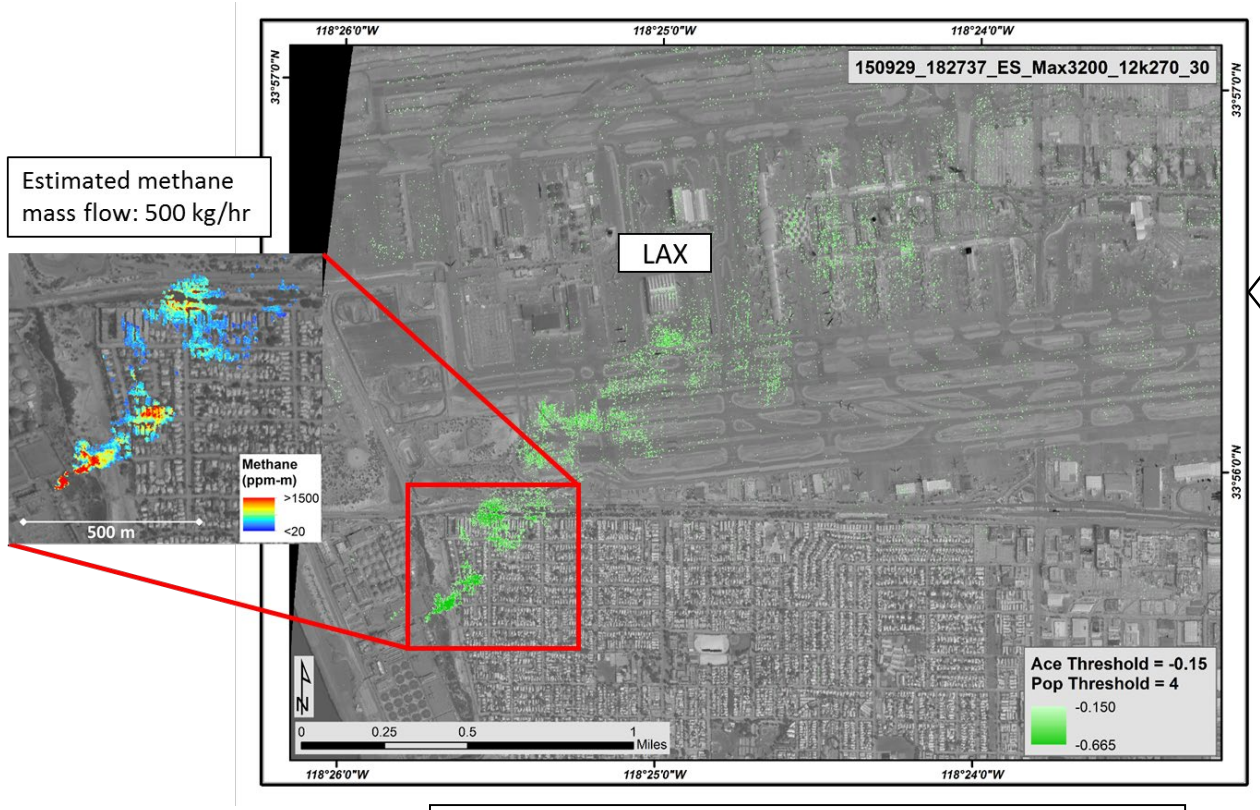
Broad-Area Survey of the Los Angeles Basin: Methane



- **Flexibility to select individual gases**
  - **Methane shown**
- **In the case highlighted, ethene is identified as a secondary plume component**

dtratt@aero.org

Long-Range Plume Tracking



Methane release from wastewater treatment plant; plume length ~4 km

Methane generated at the plant supplies a nearby power generating station. Gas excess to capacity is usually flared.

False color ACE overlain on thermal radiance mosaic

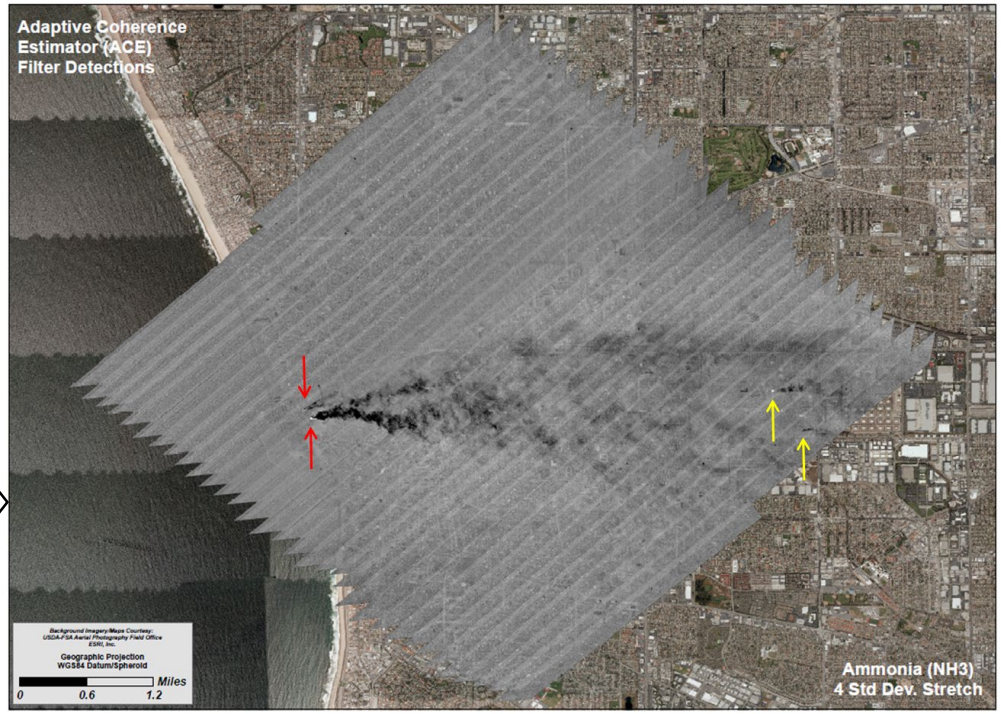
Area Covered: ~52 km^2
Collection Time: ~2.3 min

Ammonia slip from NO_x emission control system (SCR reactor) at gas-fired power plant; plume length ~8 km

Plume sources are two power plant stacks (red arrows). Note the well-defined bifurcate structure.

Additional plume sources downwind from primary sources (yellow arrows) are from oil refinery

Grayscale ACE overlain on satellite imagery



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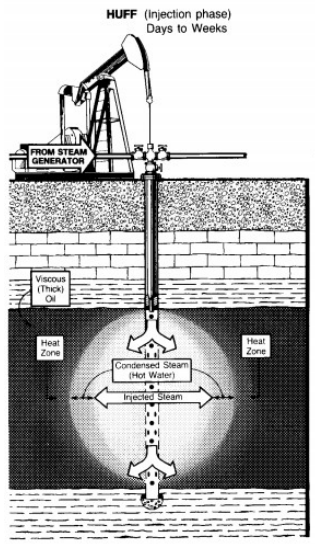
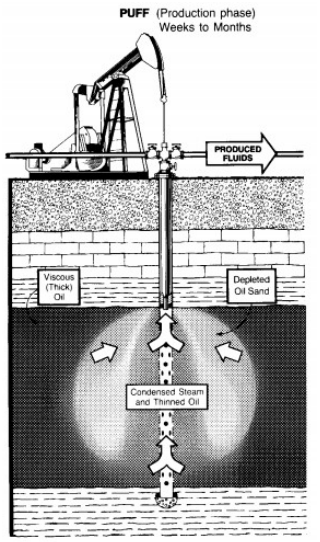
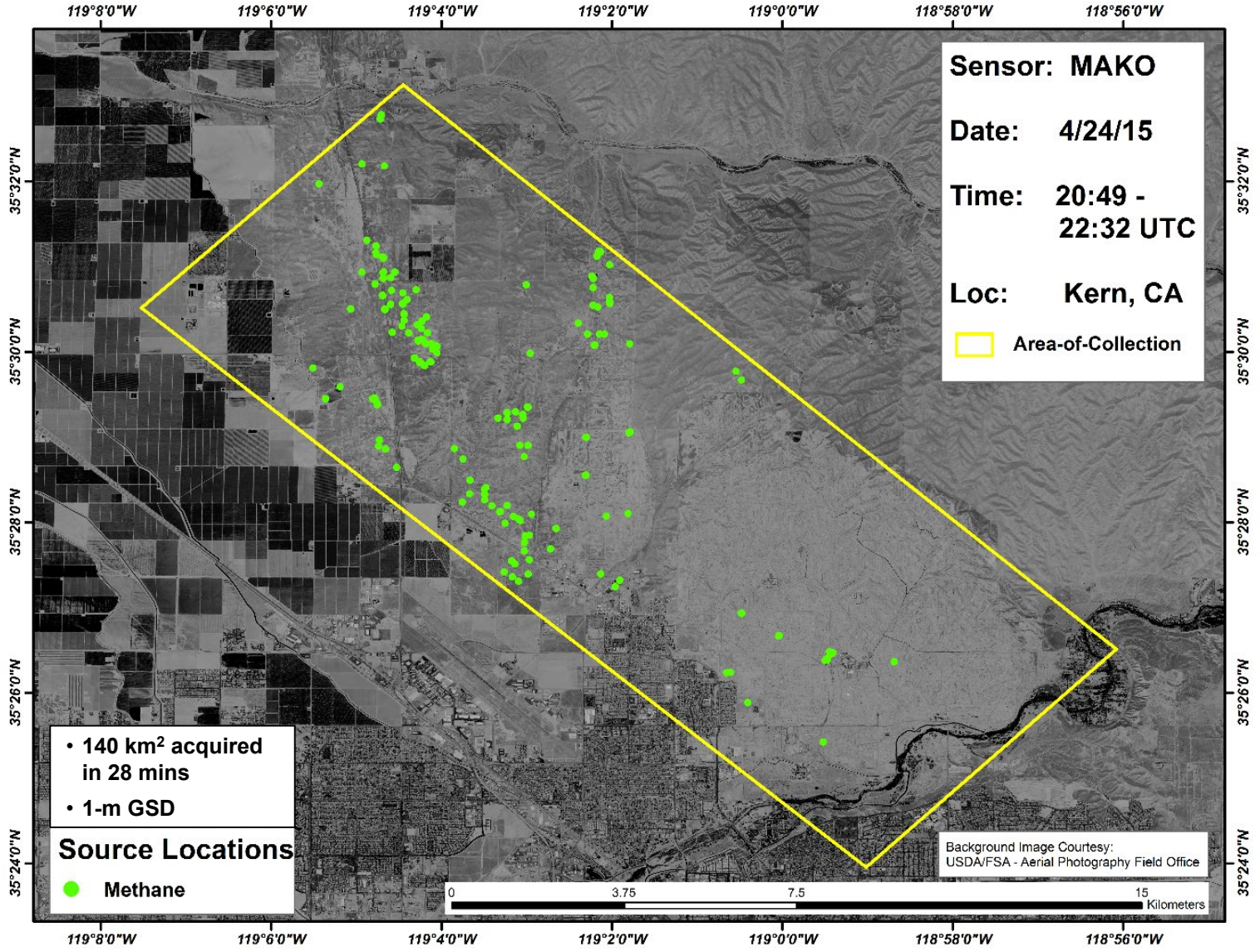
Kern Oil Fields, Bakersfield, CA

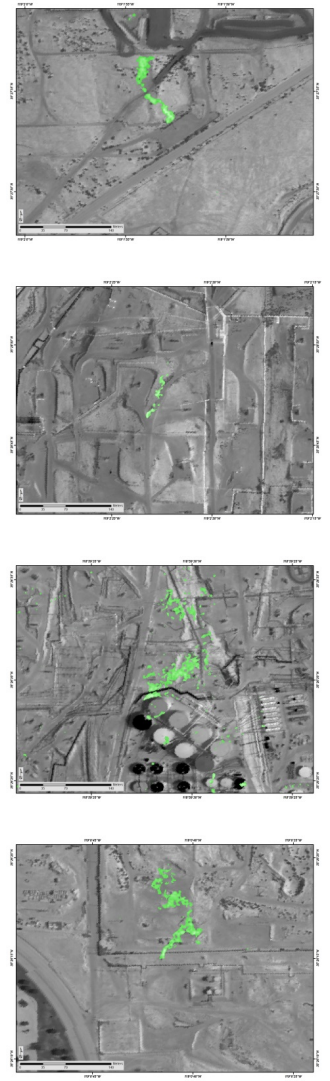
Venerable production field with enhanced recovery (steam injection)





Source: DOE





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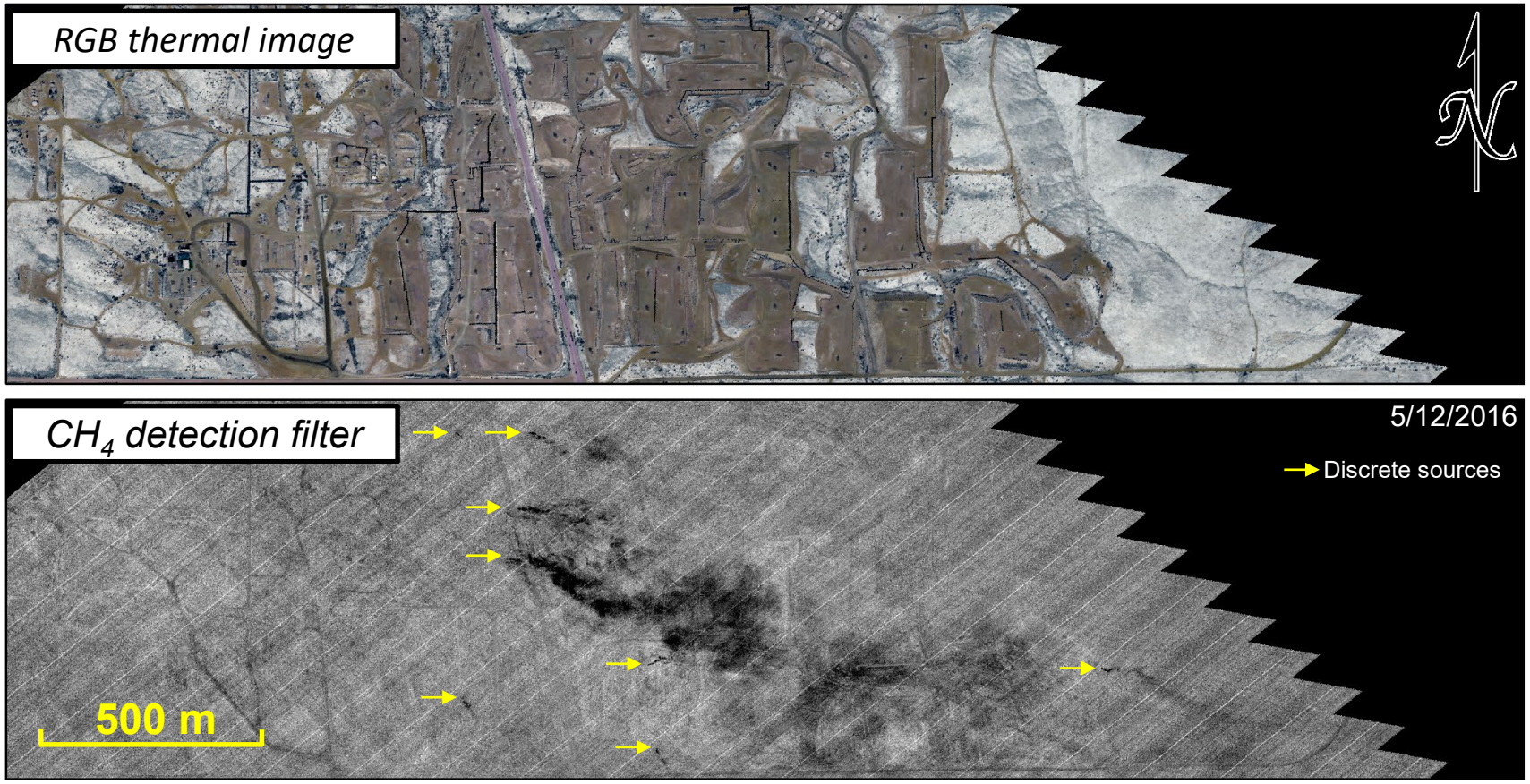
Kern Oil Fields, Bakersfield, CA

Broad-area context with high spatial resolution



Thermal radiance scene image encoded in false color to clarify structural details on the ground

Multiple methane plumes from several sources coalesce into a diffuse haze detectable more than 1 km downwind

(GSD: 1 m)

dtratt@aero.org

Topical Question of the Day

Resurgence in atmospheric abundance of CFC-11 (trichlorofluoromethane)

LETTER

Nature, Vol. 569, pp. 546-550 (2019)

https://doi.org/10.1038/s41586-019-1193-4

Increase in CFC–11 emissions from eastern China based on atmospheric observations

M. Rigby[1,15], S. Park[2,15]*, T. Saito[3,15], L. M. Western[1,15], A. L. Redington[4,15], X. Fang[5,15], S. Henne[6], A. J. Manning[4], R. G. Prinn[5], G. S. Dutton[7,8], P. J. Fraser[9], A. L. Ganesan[10], B. D. Hall[7], C. M. Harth[11], J. Kim[11], K.-R. Kim[2], P. B. Krummel[9], T. Lee[2], S. Li[12], Q. Liang[13], M. F. Lunt[14], S. A. Montzka[7], J. Mühle[11], S. O'Doherty[1], M.-K. Park[12], S. Reimann[6], P. K. Salameh[11], P. Simmonds[1], R. L. Tunnicliffe[1], R. F. Weiss[11], Y. Yokouchi[3] & D. Young[1]

- LWIR HSI is highly sensitive to halocarbons
- Broad-area airborne surveys enable identification and geolocation of emission hotspots on regional scales
- Facilitates improved regulatory compliance

Foam blowing at construction site

HVAC unit "in distress"

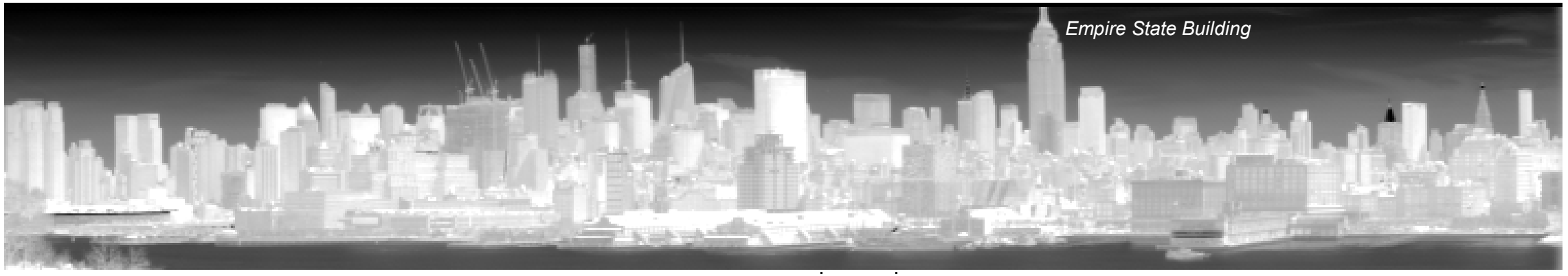
Vehicle dismantler

dtratt@aero.org

Persistent Observations of Built Environments

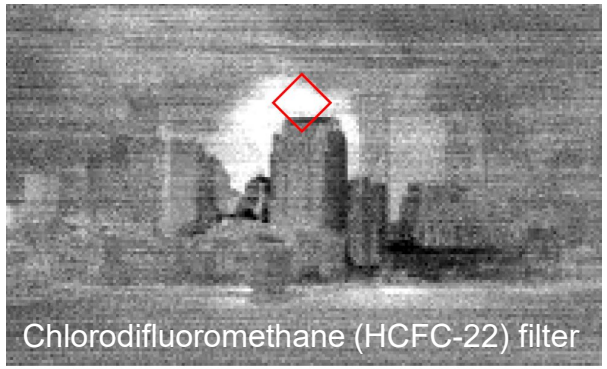
- **Background**
  - Collaborative venture with New York University's Center for Urban Science and Progress
  - Near-continuous operation from a static vantage point over a period of 8 days in April 2015
  - 5402 data cubes collected (accompanied by context camera imagery)

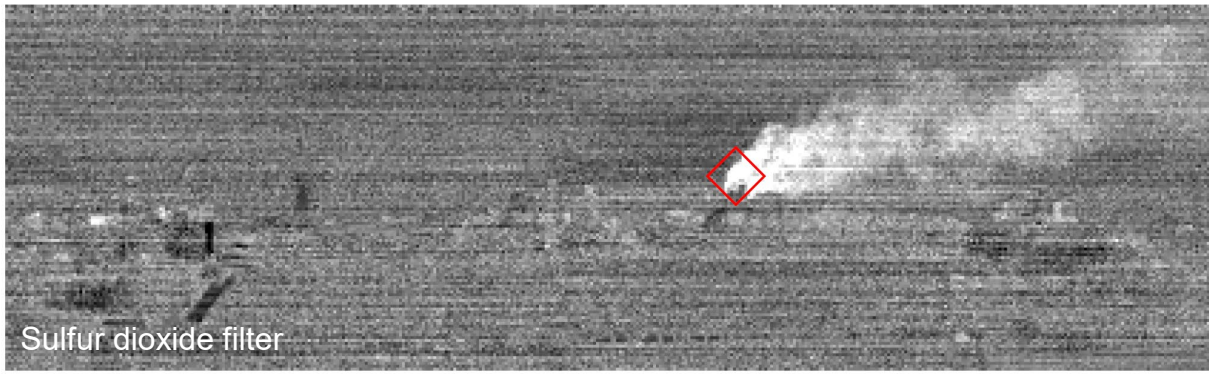
- **Synopsis**
  - Large clouds of HCFC-22 (chlorodifluoromethane), sometimes occupying more than 6 city blocks, persisting for several minutes, and disappearing/reappearing as the gas migrates through the urban canyons
    - HCFC-22 is being phased out due to its ozone depletion potential and its listing as a potent greenhouse agent with a global warming potential ~1800 times that of CO_2
  - Large clouds of a mixture of difluoromethane (HFC-32) and pentafluoroethane (HFC-125), which is sold as R-410 and was designed to replace HCFC-22
    - These plumes were also large, but not as prominent as the HCFC-22 plumes
  - Smaller plumes of 1,1,1,2-tetrafluoroethane (HFC-134a) were occasionally observed
  - Also observed plumes of methane, ethene, CO_2, and NH_3 emanating from many buildings

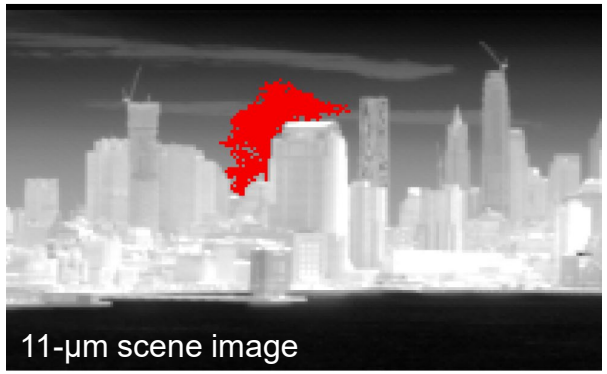


Sample Gas Detection Images

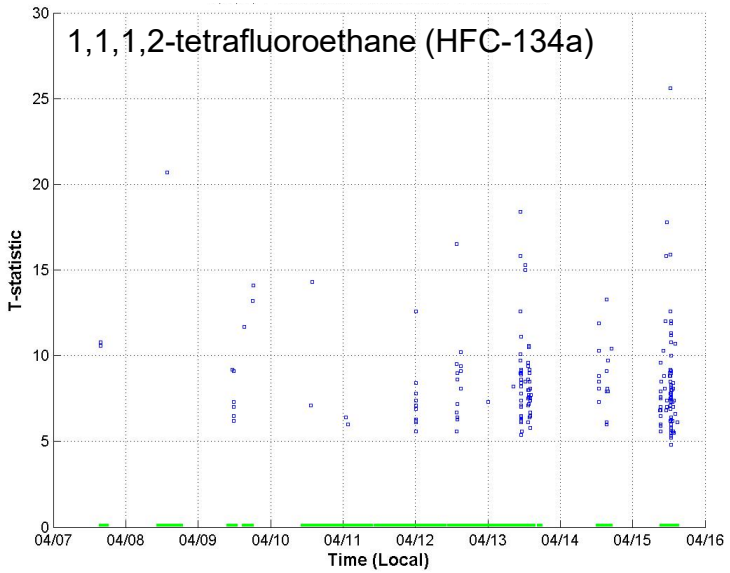
- In these examples the upper panel shows the ACE-filter gas detection image, while the lower panel shows the same scene in the LWIR with the pixel ensemble of strongest SNR overlain in red
- The HCFC-22 case at left shows how this prominent plume switches between observation in emission (when viewed against the cold sky) and observation in absorption (when viewed against warmer buildings) as it diffuses throughout the scene
- The SO_2 case at right depicts a cruise ship progressing up the Hudson River while burning sulfur-rich fuel

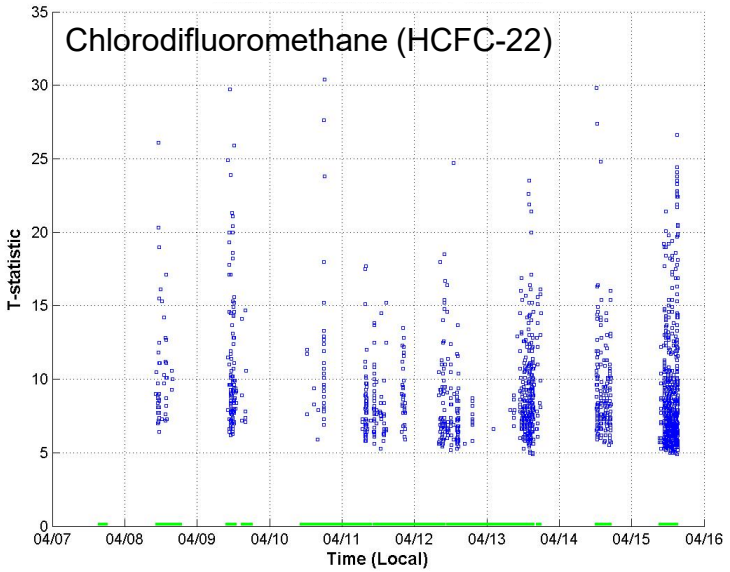






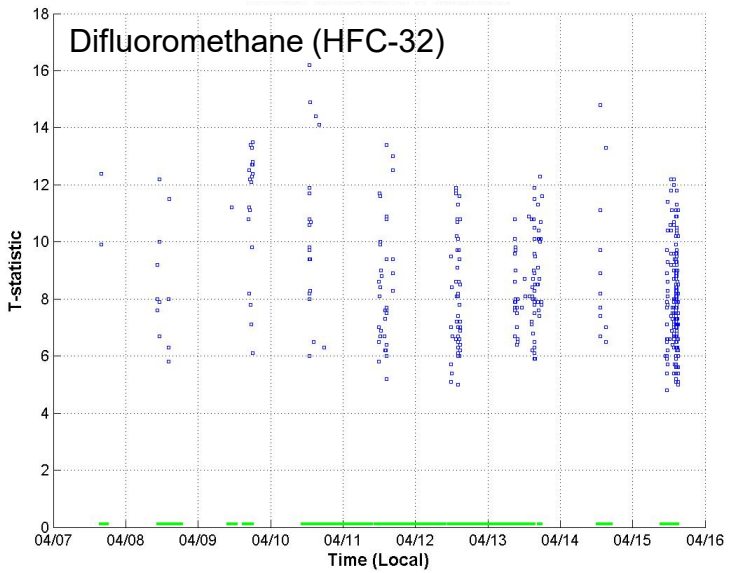
Time Series Analyses Expose "Rhythms of the City"

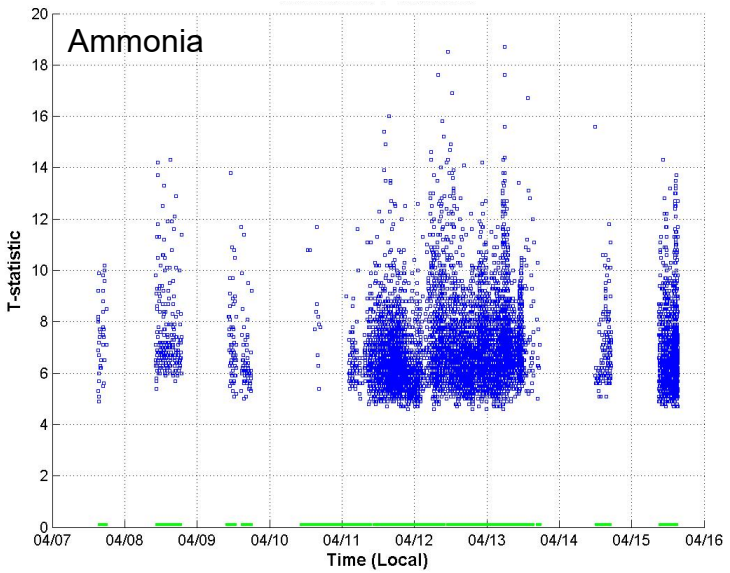




HCFC-22 is being phased out *per* the Montreal Protocol. All production and import is scheduled to be eliminated by 2020, although recycled HCFC-22 remains in circulation to service existing air conditioners.

Sensor operational periods





Observations suggest that venting of overpressured HVAC systems is synchronized within a few hours of local noon

Summary

- High spatio-spectral resolution airborne LWIR imaging spectrometry is a versatile tool for detecting and tracking GHG and other emissions within urban and non-urban environments
- High spatial resolution (1-2 m) permits trace-back of emission plumes to their source
  - *Plumes can range in size from a few pixels to several km in extent*
- High spectral resolution enables precise identification and discrimination of mixed gas plume components through the application of SMF and/or ACE algorithms
  - *Quantification of emission rate is possible with knowledge of prevailing meteorology*
- Application to multiple sectors
  - *Regulatory monitoring*
  - *Mitigation of public health concerns*
  - *Post-disaster hazard evaluation*
  - *Regional climate assessment*
- Operation in the emissive LWIR spectral region avoids reliance on solar illumination, allowing operations to be conducted day and night
- Further information: psl-isd@aero.org

Further Reading

- "Tracking and quantification of gaseous chemical plumes from anthropogenic emission sources within the Los Angeles Basin," K. Buckland *et al.*, *Remote Sensing of Environment*, **201**, 275-296 (2017), doi:10.1016/j.rse.2017.09.012
- "Mapping refrigerant gases in the New York City skyline," M. Ghandehari *et al.*, *Scientific Reports*, **7**, 2735 (2017), doi:10.1038/s41598-017-02390-z
- "MAHI: An airborne mid-infrared imaging spectrometer for industrial emissions monitoring," D. Tratt *et al.*, *IEEE Transactions on Geoscience and Remote Sensing*, **55**, 4558-4566 (2017), doi:10.1109/TGRS.2017.2693979
- "Remote sensing and *in situ* measurements of methane and ammonia emissions from a megacity dairy complex: Chino, CA," I. Leifer *et al.*, *Environmental Pollution*, **221**, 37-51 (2017), doi:10.1016/j.envpol.2016.09.083
- "Airborne visualization and quantification of discrete methane sources in the environment," D. Tratt *et al.*, *Remote Sensing of Environment*, **154**, 74-88 (2014), doi:10.1016/j.rse.2014.08.011
- "High areal rate longwave-infrared hyperspectral imaging for environmental remote sensing," D. Tratt *et al.*, *Proceedings of SPIE*, **10639**, 1063915 (2018), doi:10.1117/12.2303834

dtratt@aero.org