How Cities Breathe: Ground-Referenced, Airborne Hyperspectral Imaging Precursor Measurements To Space-Based Monitoring

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Abstract: Methane's (CH_4) large global warming potential (Shindell et al., 2012) and likely increasing future emissions due to global warming feedbacks emphasize its importance to anthropogenic greenhouse warming (IPCC, 2007). Furthermore, CH_4 regulation has far greater near-term climate change mitigation potential versus carbon dioxide CO_2, the other major anthropogenic Greenhouse Gas (GHG) (Shindell et al., 2009). Uncertainties in CH_4 budgets arise from the poor state of knowledge of CH_4 sources - in part from a lack of sufficiently accurate assessments of the temporal and spatial emissions and controlling factors of highly variable anthropogenic and natural CH_4 surface fluxes (IPCC, 2007) and the lack of global-scale (satellite) data at sufficiently high spatial resolution to resolve sources.

Many important methane (and other trace gases) sources arise from urban and mega-urban landscapes where anthropogenic activities are centered – most of humanity lives in urban areas. Studying these complex landscape tapestries is challenged by a wide and varied range of activities at small spatial scale, and difficulty in obtaining up-to-date landuse data in the developed world – a key desire of policy makers towards development of effective regulations. In the developing world, challenges are multiplied with additional political access challenges. As high spatial resolution satellite and airborne data has become available, activity mapping applications have blossomed–i.e., Google maps; however, tap a minute fraction of remote sensing capabilities due to limited (three band) spectral information. Next generation approaches that incorporate high spatial resolution hyperspectral and ultra-spectral data will allow detangling of the highly heterogeneous usage megacity patterns by providing diagnostic identification of chemical composition from solids to gases.

To properly enable these next generation technologies for megacity include atmospheric radiative transfer modeling the complex and often aerosol laden, humid, urban microclimates, atmospheric transport and profile monitoring, spatial resolution, temporal cycles (diurnal and seasonal which involve interactions with the surrounding environment diurnal and seasonal cycles) and representative measurement approaches given traffic realities. Promising approaches incorporate contemporaneous airborne remote sensing and in situ measurements, nocturnal surface surveys, with ground station measurements.

References

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Approach considerations

Hyperspectral Imaging: Land Use and Strong Trace Gas Sources

High Resolution Remote Sensing: Trace Gas Column Abundance

Key urban considerations revolve around 1. atmospheric corrections including high and temporally and spatially variable aerosol loads, atmospheric heterogeneity in terms of profiles of atmospheric parameters, and **2.** high and varied levels of surface spectral clutter, often at sub-pixel scales.

Ground Reference Airborne Reference

Key urban ground reference considerations include traffic and access, micrometeorology, boundary layers comparable to building size at times, extremely strong diurnal and seasonal variability, and in coastal cities, imposition of coastal weather cycles. Airborne in situ measurements often are restricted at low altitudes, and for megacities, size scales can be huge.

Land Use Reference (ancillary data)

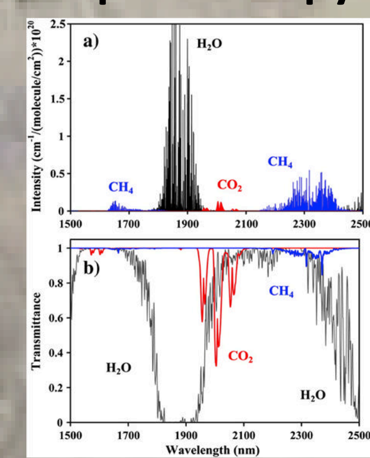
Key consideration is availability for the developing world, and up to date accuracy for the developed world.

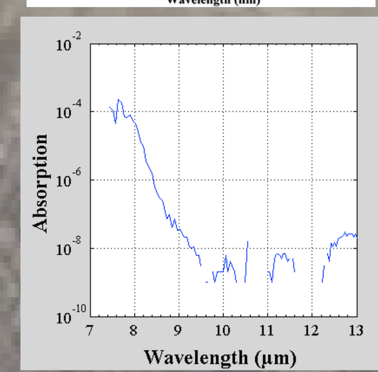
Emission Derivation (Plume Inversion Modeling)

Key considerations are collection of adequate data for plume derivation, boundary layer height, and accurate wind profile trajectories.

Application to surface, air, and remote sensing data.

Underlying Spectroscopy



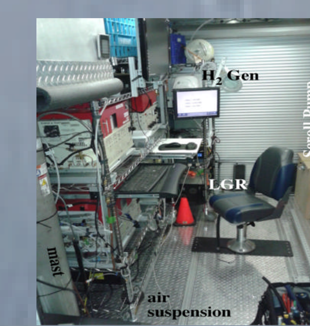


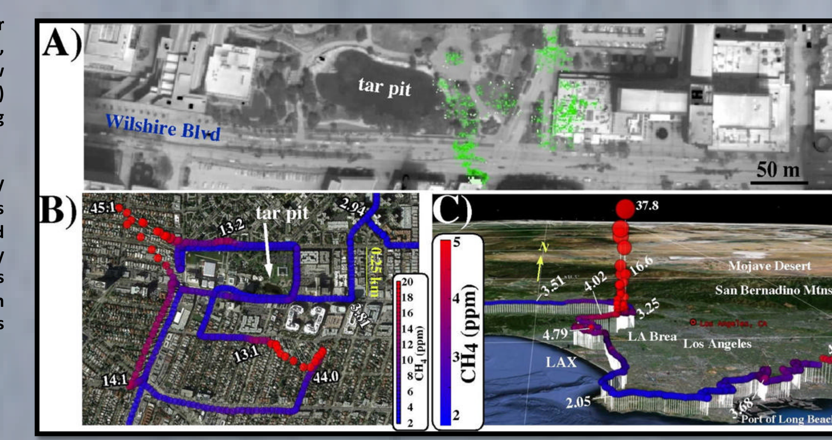
Methane exhibits strong spectral features in the shortwave infrared (SWIR) and the thermal (TIR). These features are useful for spectroscopic analysis of methane. These features are broad and gentle at the resolution of spectral imagers, but in reality are comprised of numerous fine-scale spectral features.

Mobile Measurement Trace Gas Remote Sensing Surface Reference Measurements

AMOG Surveyor (AutoMObile Greenhouse gas), which is an ordinary commuter car (Nissan Versa) with a trunk science package including an inverter/charger, solar battery, cavity ringdown spectrometer (Fast GHG Sensor, Los Gatos Research (LGR)), high flow scroll vacuum pump, ultrasonic anemometer/weather station, GPS, incident (UV-SWIR) radiation, thermal radiometer, solar spectrometer, continuous video recording (aiding post-processing interpretation), and internal network.

MACLab (Mobile Atmospheric Composition Laboratory) is a 12-ton, 37' diesel RV Toyhauler, with a garage converted for air chemistry analysis, including 4 gas chromatographs (SRI GC) on an independent air suspension rack, ultrapure air and hydrogen generators, 8.5 kw generator, 18-m pneumatic mast, greenhouse gas cavity ringdown spectrometer, high flow vacuum lines. The internal Ethernet network allows access between all computers, instruments, server, and video streams. The habitation module supports a 4-person team, enabling round-the-clock data collection in areas without accommodations, rest stops.

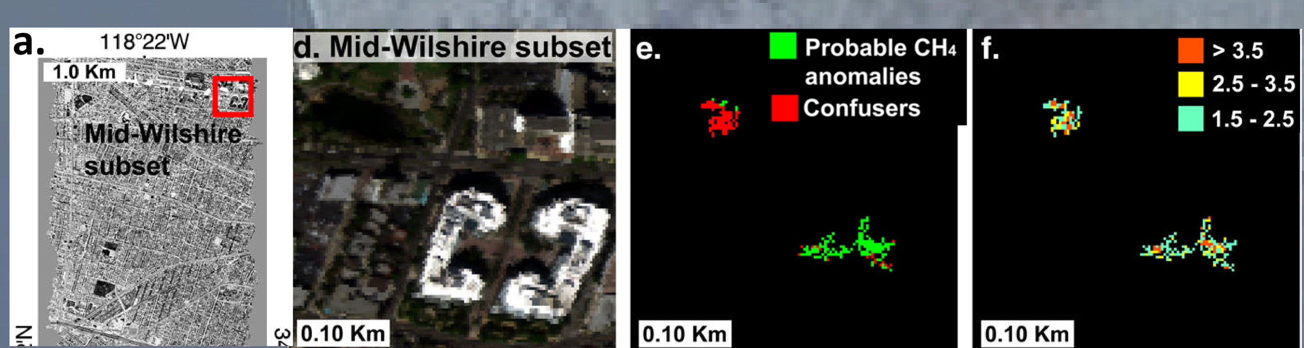




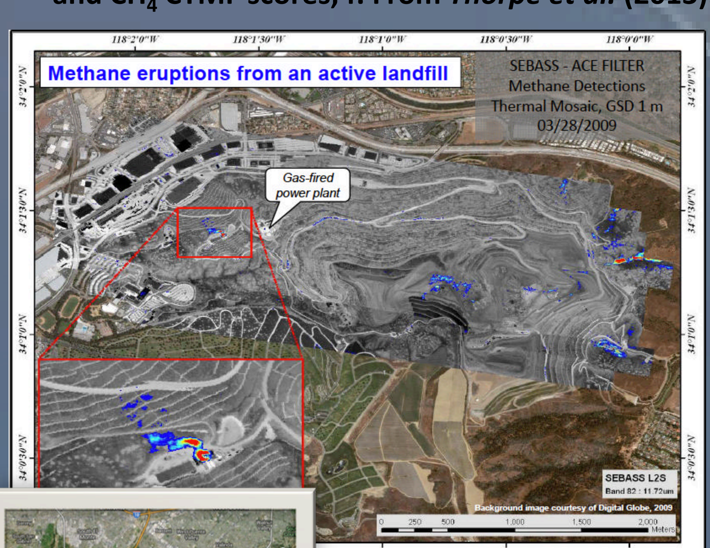
La Brea Tar Pit. A) SEBASS TIR image of La Brea Tar Pit area (Wilshire Area) in the Los Angeles Basin showing methane, CH_4, plumes. Data acquired at 2049 UTC, 27 Mar. 2009. (Aerospace Corp.) B) CH_4 survey data collected 1100 UTC, 21 Feb. 2012 in the immediate vicinity of the Tar Pit area, height and symbol size proportional to concentration. Color scales are stretched to capture finer CH_4 structure close to ambient; symbol height and size are proportional to CH_4 concentration. C) *In situ* nocturnal CH_4 survey data of North Los Angeles, La Brea area noted. From *Leifer et al.* (2012).

Nocturnal MACLab (2013) Houston mapping of methane plumes from extensive FFI facilities. Transect sequence took ~7 hrs to complete. Nocturnal measurements provide effective urban mobility (traffic) and decreased (road-biased) vehicular emissions compared to daytime surveys.

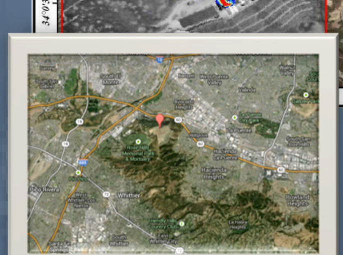
Airborne Shortwave Infrared (AVIRIS) and Thermal Infrared (SEBASS) Methane Imaging Spectroscopy in the LA Basin



AVIRIS image of Los Angeles, 18 Sept. 2008, showing d. Mid-Wilshire subset, e. CTFM classification and CH_4 CTMF scores, f. From *Thorpe et al.* (2013).

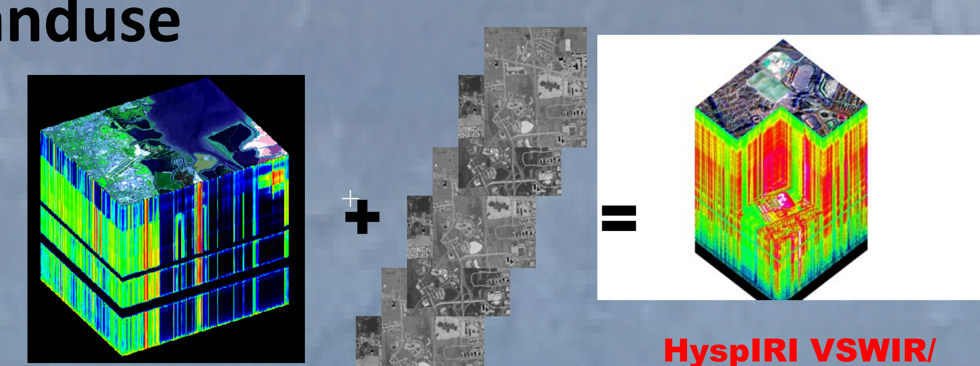


There are multiple challenges to urban trace gas remote sensing from aerosols and water vapor, which can vary on sub-urban dimensions. For TIR, thermal contrast is important, and thus, variable thermal profiles and surface temperatures lend complexity. The relatively broad spectral resolution of imaging spectrometry adds complexity from complex sub-pixel surface reflectance, typical addressed by spectral mixing models, and from interference by water vapor and aerosols. Greater spectral resolution addresses the latter, while higher spatial resolution aids the former.



Puente Hills Landfill is surrounded by Los Angeles, and emits CH_4 signatures, which exhibit puffiness due to variable thermal contrast and likely unsteady emissions.

Landuse

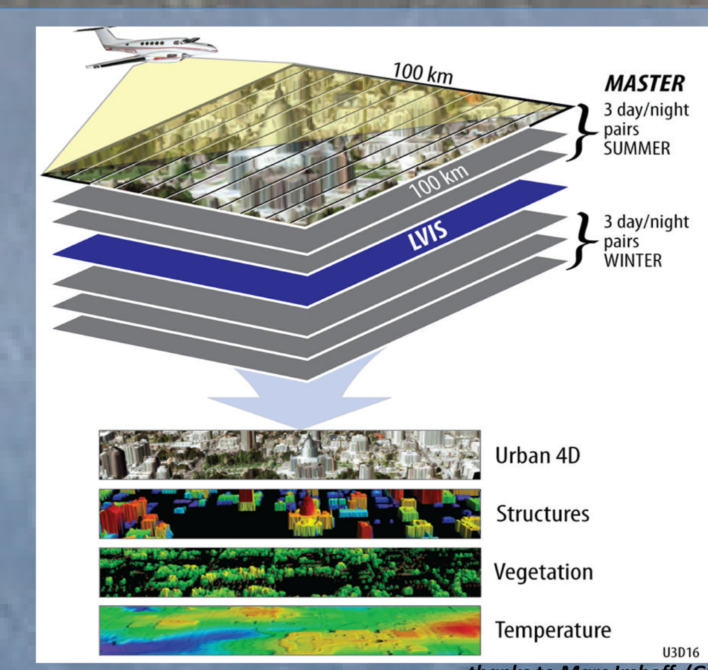


HyspIRI Hyperspectral VSWIR Level II Product (NDVI, fPAR, surface reflectance characteristics)

HyspIRI TIR multispectral Level II product (8 TIR Bands) (surface temperature, radiance, [day/night], emissivity)

HyspIRI VSWIR/ TIR composite data set (quantitative integrative measurement of urban surface reflectances, temperatures, and emissivity across the urban ecosystem)

The synergistic capability of collecting hyperspectral VISWIR and multispectral TIR data with HyspIRI, provides unique opportunities for developing level II products for enhanced land use assessment that can be integrated into composite datasets that are unavailable with current NASA Earth observing satellites. Moreover, the HyspIRI high revisit time offers opportunities to visualize and quantify land use changes at frequencies that cannot be attained at this time with satellite data. This is particularly important for urban areas where the land covers that comprise the city surface have surface reflectances that are in many cases, similar and cannot be spectrally separated using only multispectral VISWIR data. These surfaces also have differing TIR and albedo responses which can change over time, as a function of both human-induced land cover changes or in response to atmospheric conditions.



thanks to Marc Imhoff (GSFC)

HyspIRI data can ultimately be used to develop urban '4 dimensional' (4D) models within the perspective of space, spectral responses, land cover condition, and time. An example of this is the simulation of HyspIRI data as derived from day/night MASTER collected over multiple seasons. A vertical dimension can also be added and integrated via by the collection of Lidar data.

CO_2 and Methane EXperiment "COMEX"

instruments and aircraft

COMEX will calibrate / validate plume inverse-model derivation of greenhouse gas source emissions for future remote sensing satellite missions (HyspIRI and CarbonSat) that use Short Wave InfraRed absorption features for trace gas retrievals.

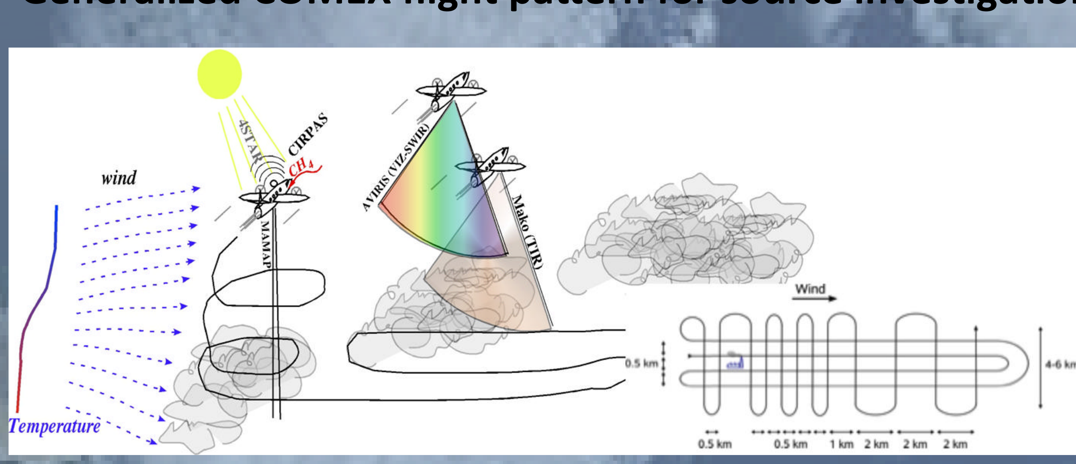
Airborne – HyspIRI ER2 with AVIRIS swath maps sources
MAMAP methane and carbon dioxide (Bremen)
CIRPAS, in situ GHG (Ames), atmospheric characterization
Mako TIR methane (Aerospace)
H211 in situ methane and carbon dioxide (Ames)

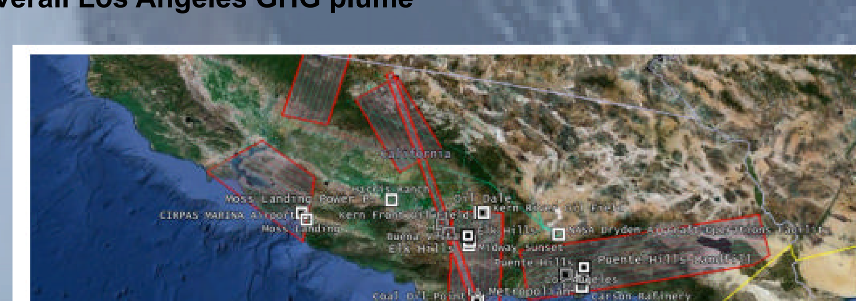
Surface – AMOG Surveyor and MACLab – Temporal GHG, trace gas characterization, and satellite data comparison

Large localized anthropogenic and natural GHG (mainly CH_4) emitting areas inside the swath mapped areas covered during the HyspIRI/AVIRIS deployment in spring 2014:

- California fossil fuel and gas extraction areas near Bakersfield,
- oil an natural gas refineries (Carson Refinery …),
- natural marine geologic CH4 emissions from the Coal Oil Point area,
- terrestrial geologic emissions from the La Brea Tar Pits in Los Angeles ,
- large landfills (Puente Hills, Santa Barbara Landfill,…),
- power plants (Moss Landing),
- cattle (Harris Ranch)
- overall Los Angeles GHG plume

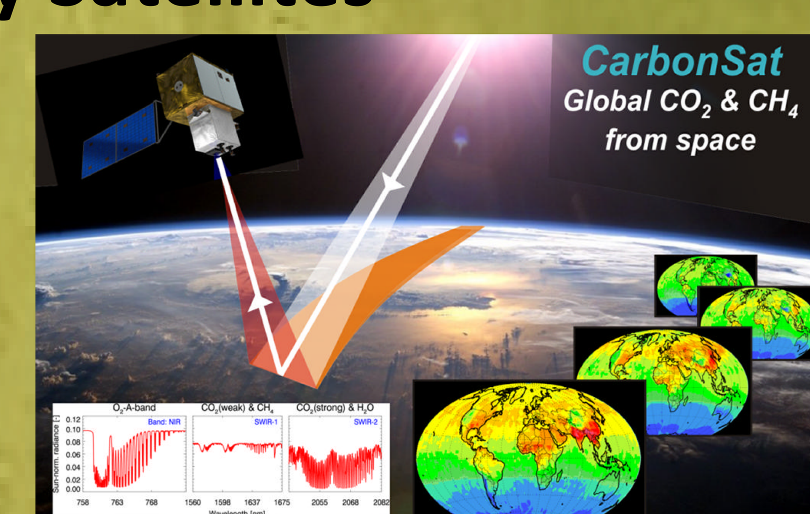
Generalized COMEX flight pattern for source investigation





COMEX has applications for remote sensing space-borne TIR and SWIR Sensors (e.g., VIIRS, IASI, AIRS, etc.)

Complementary Satellites

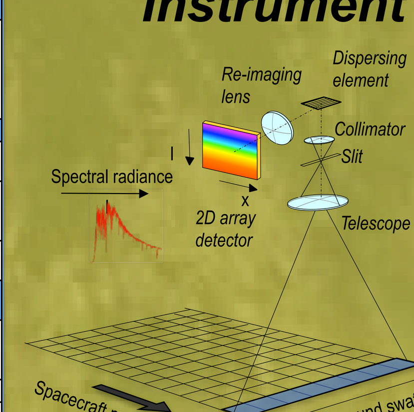


The HyspIRI mission includes two instruments mounted on a satellite in Low Earth Orbit.

- Imaging spectrometer measuring from the visible to short wave infrared (VSWIR: 380 nm
- 2500 nm) in 10 nm contiguous bands
- Multispectral imager measuring from 3 to 12 um in the mid and thermal infrared (TIR).
- VSWIR and TIR instruments have 60-m spatial resolution at nadir.
- VSWIR revisit of 19 days
- TIR revisit of 5 days.

	Band		
	NIR	SWIR-1	SWIR-2
Data Products	aerosol, cloud, p_{surf}, fluorescence	CO_2, , CH_4,	CO_2, H_2O scattering correction, cirrus
	spectral requirements		
Spectral range [nm]	747 – 773	1590 – 1675	1925 – 2095
Spectral resolution [nm]	0.1	0.3	0.55
Spectral Sampling	3 – 6	3 - 6	3 – 6
	parameters for the SNR requirement		
L_{ref} [phot/s/nm/ cm^2/sr]	3.0×10^{12}	1.0×10^{12}	3.0×10^{11}
SNR_{ref} (T)	150	160	130
SNR_{ref} (G)	300	320	260

Instrument



- Pushbroom (across track), along track scanning via spacecraft motion
- 3 imaging grating spectrometers with good spatial and spectral imaging capabilities
- 2-D detectors cooled
- High SNR
- High performance on-board calibration sources (diffusers, lamp, LED, etc.)

Main Points

- COMEX will combine airborne, surface, TIR and SWIR imaging spectroscopy and high spectral resolution spectroscopy for greenhouse gas source derivation from a number of S. California sites as a part of the HyspIRI campaign, with a focus on the Los Angeles megacity.
- Combined airborne and surface reference data are richer for source identification and characterizing the complex urban meteorology.
- Synergies and insights could be derived from analyzing Hyperspectral Imaging data for Los Angeles land-use during the COMEX campaign.
- Combined TIR and SWIR provides improved land-use characterization.