The Airborne Methane Plume Spectrometer (AMPS): Quantitative imaging of methane plumes in real time

Andrew K. Thorpe*, Christian Frankenberg, Robert O. Green, David R. Thompson, Andrew D. Aubrey, Pantazis Mouroulis, Michael L. Eastwood, Georgios Matheou

Jet Propulsion Laboratory, California Institute of Technology

*Andrew.K.Thorpe@jpl.nasa.gov
- Large uncertainties in CH$_4$ emissions from oil and gas systems
- Atmospheric observations consistently suggest higher emissions than predicted by inventories (Kort et al., 2008; Miller et al., 2013; Brandt et al., 2014)
Detection of emissions requires:
- Surveys of a large fraction of producing areas
- Unequivocal detection and attribution

Measuring concentrations at the surface to pinpoint emissions is:
- Impractical/costly
- Requires monitoring equipment is installed at each wellhead
Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and next generation instrument (AVIRIS-NG)

- Grating spectrometers
- 380 to 2,500 nm
- 34° field of view
- High spatial resolution

<table>
<thead>
<tr>
<th>AVIRIS-NG(^1) and AVIRIS(^2) key measurement characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>Response</td>
</tr>
<tr>
<td>Calibration</td>
</tr>
<tr>
<td><strong>Radiometric</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Precision (SNR)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td><strong>Spatial</strong></td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Sampling</td>
</tr>
<tr>
<td>Response</td>
</tr>
<tr>
<td>Sample distance</td>
</tr>
<tr>
<td>Geom. model</td>
</tr>
<tr>
<td><strong>Uniformity</strong></td>
</tr>
<tr>
<td>Spectral cross track</td>
</tr>
<tr>
<td>Spectral IFOV variation</td>
</tr>
</tbody>
</table>

\(^1\)Green et al., 1998, \(^2\)Hamlin et al., 2011
AVIRIS and AVIRIS-NG have been used to characterize Earth’s surface and atmosphere.
AVIRIS and AVIRIS-NG were not designed for CH$_4$ mapping

Quantitative CH$_4$ retrievals have been developed
Absorption spectroscopy (Thorpe et al., 2014)
- Best fit simulated radiances with known gas abundance to observed radiance with unknown gas abundance
- Permits estimate of gas abundances below the aircraft
CH$_4$ Mapping with AVIRIS and AVIRIS-NG

- Garfield County, CO
  (natural gas extraction using hydraulic fracturing)

- Four Corners, CO NM
  (coal bed CH$_4$)
Garfield County, CO
- Gas wells using hydraulic fracturing
- AVIRIS-NG flight 1.4 km AGL (above ground level)

(Aubrey et al., 2015)
CH$_4$ Mapping with AVIRIS and AVIRIS-NG

- Four Corners, CO & NM
  - Coal ventilation shaft
  - AVIRIS-NG flight 1.4 km AGL
CH$_4$ Mapping with AVIRIS and AVIRIS-NG

- Four Corners, CO & NM
  - Coal ventilation shaft
  - AVIRIS-NG flight 1.4 km AGL
AMPS measurement technique

- AMPS will allow quantitative retrievals of CH$_4$, CO$_2$, CO, H$_2$O, and N$_2$O
- AMPS designed to detect CH$_4$ emissions as low as 0.17 m$^3$/h (6 standard cubic feet per hour, scfh)
  - Order of magnitude smaller than what current airborne systems can detect

![Large Eddy Simulation (LES) for 6 scfh CH$_4$ emission](image)
- Spectrometer requirements derived from plume model
  - 10 cm spatial resolution
  - Continuum level signal-to-noise ratio (SNR) > 175
  - Optimal spectral resolution of 1 nm (1 nm FWHM)
AMPS imaging spectrometer design has been identified that provides:
- High spectral resolution
- Fine spatial sampling
- Wide field-of-view
- High SNR

**AMPS key measurement characteristics**

<table>
<thead>
<tr>
<th>Spectral</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>1900 to 2420 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>1 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response</td>
<td>1 to 1.5 x sampling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>+0.05 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Radiometric | | | | | | | | | | |
| Range | 0 to max Lambertian | | | | | | | | | | |
| Precision (SNR) | ≥300 @ 2300 nm, | | | | | | | | | | |
| Accuracy | ≥90% (<5% uncertainty) | | | | | | | | | | |
| Accuracy | ≥99% characterization | | | | | | | | | | |

| Spatial | | | | | | | | | | |
| Range | 36 degree field of view | | | | | | | | | | |
| Sampling | 1 milliradian to 1.5 x sampling | | | | | | | | | | |
| Sample distance | 0.3 m to 20 m | | | | | | | | | | |
| Geom. model | Full 3 axes cosines | | | | | | | | | | |
Flight platforms and observing strategies

- For low flux rates (0.17 m³/h, 6 scfh)
  - Fly high and fast
  - Traditional fixed wing aircraft (e.g., ER-2, Proteus, Twin Otter, WB-57, B-200)

- For larger flux rates
  - Fly low and slow
  - Helicopter
Real time CH$_4$ plume mapping

- Currently operational with AVIRIS-NG
- CH$_4$ plumes overlain on true color images with accurate latitude and longitudes for suspected emission sources
Real time CH\(_4\) plume mapping

- Permits:
  - Sharing plume characteristics and location information with ground crews
  - Verification of plumes using ground based sensors like thermal cameras and in situ gas samplers

![FLIR Gas Finder thermal camera](image1)

![Picarro in situ CH\(_4\) sensor](image2)
Real time CH$_4$ plume mapping

- Plume observed in real time at Four Corners
  - Location information provided to ground crew
  - Thermal camera used to verify plume from tanks
• AVIRIS-NG has observed CH$_4$ plumes for:
  • Oil fields (conventional and enhanced recovery)
  • Gas fields (conventional and unconventional)
  • Multiple leaks from gas pipelines

Potential application: CH$_4$ from oil/gas operations
AVIRIS-NG sensitivity shown below (cyan)
- Based on CH$_4$ controlled release experiment
- AMPS sensitivity (green) will permit detection of smaller emission sources

Potential application: CH$_4$ from oil/gas operations
Potential application: CH$_4$ from oil/gas operations

- Identifying CH$_4$ emission sources has potential value for:
  - Site operators
    - Identify and mitigate CH$_4$ emissions (safety hazard, lost revenue)
    - Opportunity to reduce environmental footprint
  - Regulatory agencies and scientific community
    - Understanding the size and distribution (spatial, temporal) of emissions

AVIRIS-NG real time CH$_4$ plume detection at Four Corners
Potential application: CH$_4$ from other sources

- Wastewater treatment facilities and agricultural emissions
  - Considerable sources of the global CH$_4$ budget

- Quantify emissions from natural sources like terrestrial and marine seeps
Potential application: CO$_2$, CO, H$_2$O, N$_2$O

- Stationary combustion and wildfires (CO$_2$, CO, N$_2$O)
- Cattle feedlots and wastewater treatment (N$_2$O)
- Leak detection from CO$_2$ capture and storage facilities
**Conclusions**

- Airborne Methane Plume Spectrometer (AMPS) is an advanced imaging spectrometer
  - Enable quantitative imaging of CH$_4$, CO$_2$, CO, H$_2$O, and N$_2$O plumes
  - Unprecedented spatial resolution and precision
  - Real time detection and geolocation of gas plumes
Acknowledgements

- JPL:
  - AVIRIS-NG team
  - Brian Bue (real time CH$_4$ mapping)
  - Simon Hook and Bill Johnson (thermal camera)

- Chevron Energy Technology Company:
  - Andrea Steffke, Christian Haselwimmer, et al. (controlled release)

- United States Geological Society:
  - Raymond Kokaly, Gregg Swayze (surface spectroscopy)
  - Roger Clark (retired)

- University of California, Santa Barbara:
  - Dar Roberts (surface spectroscopy)


