



Airborne DOAS retrievals of methane, carbon dioxide, and water vapor concentrations at high spatial resolution: application to AVIRIS-NG

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Abstract. At local scales, emissions of methane and carbon dioxide are highly uncertain. Localized sources of both trace gases can create strong local gradients in its columnar abundance, which can be discerned using absorption spectroscopy at high spatial resolution. In a previous study, more than 250 methane plumes were observed in the San Juan Basin near Four Corners during April 2015 using the next-generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) and a linearized matched filter. For the first time, we apply the iterative maximum a posteriori differential optical absorption spectroscopy (IMAP-DOAS) method to AVIRIS-NG data and generate gas concentration maps for methane, carbon dioxide, and water vapor plumes. This demonstrates a comprehensive greenhouse gas monitoring capability that targets methane and carbon dioxide, the two dominant anthropogenic climate-forcing agents. Water vapor results indicate the ability of these retrievals to distinguish between methane and water vapor despite spectral interference in the shortwave infrared. We focus on selected cases from anthropogenic and natural sources, including emissions from mine ventilation shafts, a gas processing plant, tank, pipeline leak, and natural seep. In addition, carbon dioxide emissions were

mapped from the flue-gas stacks of two coal-fired power plants and a water vapor plume was observed from the combined sources of cooling towers and cooling ponds. Observed plumes were consistent with known and suspected emission sources verified by the true color AVIRIS-NG scenes and higher-resolution Google Earth imagery. Real-time detection and geolocation of methane plumes by AVIRIS-NG provided unambiguous identification of individual emission source locations and communication to a ground team for rapid follow-up. This permitted verification of a number of methane emission sources using a thermal camera, including a tank and buried natural gas pipeline.

1 Introduction

It is important to better understand the processes controlling changes in atmospheric methane (CH₄) and carbon dioxide (CO₂), the two dominant anthropogenic climate-forcing agents. CH₄ and CO₂ contribute approximately 17 and 64 % of the total radiative forcing attributed to anthropogenic

greenhouse gases and halocarbons (Myhre et al., 2013). The atmospheric growth rates are strongly influenced by anthropogenic emissions of CH₄ and dominated by fossil fuel CO₂ emissions. Anthropogenic CH₄ sources were estimated to contribute 10.6 % of the total 2014 anthropogenic emissions of the United States, with major sources including natural gas systems (2.6 %), enteric fermentation (2.4 %), landfills (2.2 %), petroleum systems (1.0 %), and coal mining (1.0 %) (EPA, 2016a). CH₄ is a precursor for tropospheric ozone and is strongly linked with co-emitted reactive trace gases that are the focus of air quality mitigation policies. US anthropogenic CO₂ sources make up 81 % of the total anthropogenic emissions and are dominated by fossil fuel combustion, including electricity generation (30 %), transportation (25 %), and industrial emissions (12 %) (EPA, 2016a). US emissions of both gases are projected to increase (EIA, 2013) and a number of studies have suggested that EPA bottom-up emission inventories are underestimated for CH₄ (Miller et al., 2013; Wecht et al., 2014; Turner et al., 2015). US fossil fuel CO₂ emissions are better constrained through existing inventories of fossil fuel sales and combustion, but global uncertainties are growing with the rise of a number of large developing countries where emissions information is not readily available (NRC, 2010; Ballantyne et al., 2015; Ciais et al., 2015).

There remains uncertainty regarding the sources and sinks of atmospheric CH₄, as reflected by the ongoing scientific discussion on both the hiatus in the atmospheric growth rate in the early 21st century and the unexpected rise starting in 2007 (Nisbet et al., 2014). Further, regional top-down emissions estimates cannot discriminate source categories and thereby attribute fluxes to specific processes or sources. Uncertainty in anthropogenic CH₄ emissions is large at multiple scales and process attribution remains challenging because emissions originate from biological processes, venting, and leaks (Kirschke et al., 2013; Schwietzke et al., 2016; Schaefer et al., 2016).

Recent studies suggest that the majority of CH₄ emissions from oil and gas supply chains are caused by a number of super-emitters, which could explain underestimates in bottom-up inventories (Zavala-Araiza et al., 2015; Lyon et al., 2015; Brandt et al., 2014, 2016). The ability to identify emission sources offers the potential to constrain regional greenhouse gas budgets and improve partitioning between anthropogenic and natural emission sources. Although CH₄ has a short atmospheric lifetime (about 9 years), it has a very high global warming potential (GWP) that is 86 times greater than CO₂ on a 20 year timescale (Myhre et al., 2013). This means that even small amounts of emissions reduction will result in large reductions in the overall atmospheric radiative forcing.

Driving surveys using in situ instruments have been used to identify CH₄ emission sources in major US metropolitan areas like the Los Angeles basin (Hopkins et al., 2016), Boston (Phillips et al., 2013), and Washington, D.C. (Jackson et al., 2014), as well as to measure fluxes (Rella et al., 2015).

Recently, ground-based thermal imaging systems have also been used to identify CH₄ emissions (Johnson et al., 2015; Galfalk et al., 2016). However, these methods require comprehensive sampling techniques, are time consuming, and can be limited to regions with sufficient road access. In situ airborne measurements offer the potential for increased coverage and have been used for US regional CH₄ flux estimates using mass balance approaches for the Uintah Basin in northeastern Utah (Karion et al., 2013), the Marcellus formation in southwestern Pennsylvania (Caulton et al., 2014), and the Barnett Shale formation in Texas (Smith et al., 2015; Lavoie et al., 2015). These measurements reflect gas concentrations at the flight altitude and these studies are designed to estimate aggregate emissions for large regions rather than identifying individual emissions sources.

More recently, in situ airborne measurements using a chemically instrumented Mooney aircraft have been used to estimate fluxes from known sources like the Aliso Canyon leak (Conley et al., 2016) and for a number of sources identified by imaging spectrometers in the Four Corners region (Frankenberg et al., 2016). This method samples the atmosphere directly at the flight path altitude and can measure multiple gas species. The Methane Airborne MAPper (MAMAP) spectrometer (Gerilowski et al., 2011) has also been used to measure elevated CH₄ and CO₂ column abundances to quantify emissions from a coal mine ventilation shaft (Krings et al., 2013), power plants (Krings et al., 2011), and a landfill (Krautwurst et al., 2017). MAMAP is a non-imaging spectrometer with a small field of view limited to flying transects across gas plumes rather than quickly mapping their morphology and extent on small scales. Both instruments are better suited for either investigating known emission sources or identifying larger regional emissions as opposed to individual sources.

2 Airborne imaging spectrometers

Airborne imaging spectrometers like the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1998) and the next-generation instrument AVIRIS-NG (Hamlin et al., 2011) can map large regions while providing the spatial resolution required to identify individual emissions within scenes. While not originally designed for mapping emissions, these instruments measure the 0.38 to 2.5 μm range, which includes many gas absorption features (Fig. 1). This has permitted quantitative retrievals of CH₄ using AVIRIS (approximately 10 nm spectral resolution and sampling) for marine seeps (Roberts et al., 2010; Thorpe et al., 2014). Water vapor retrievals have been demonstrated with AVIRIS (Gao and Goetz, 1990; Thompson et al., 2015a) mainly for atmospheric correction and reflectance retrievals. However, AVIRIS water vapor retrievals have also been used to measure plant transpiration, demonstrating potential appli-

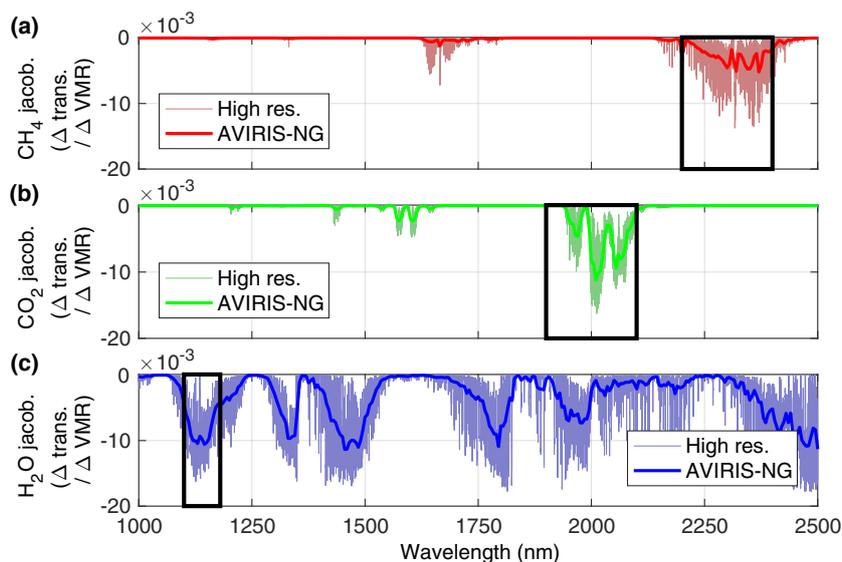


Figure 1. High-resolution gas Jacobians plotted in lighter colors and for AVIRIS-NG (5 nm spectral resolution and sampling) for (a) CH₄ (red), (b) CO₂ (green), and (c) H₂O (blue). These examples were calculated for a 5% change in CH₄ (red), (b) CO₂ (green), and (c) H₂O over the total column. AVIRIS-NG retrieval windows are indicated by the black outlines.

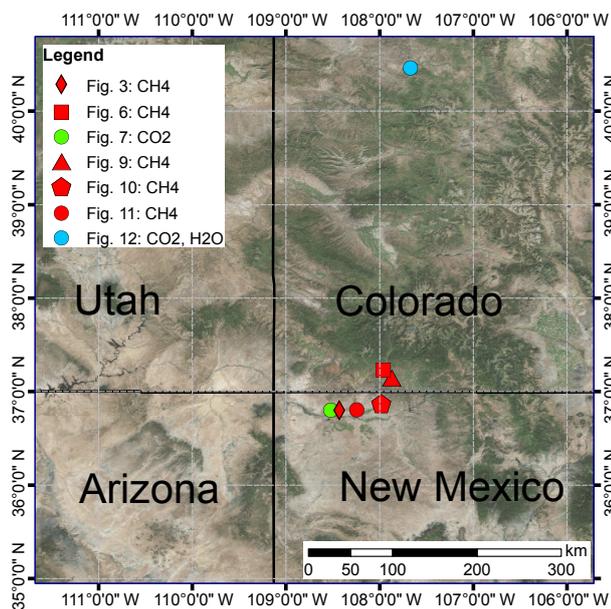


Figure 2. Locations of gas plumes presented in this study.

cation to the fields of ecology and meteorology (Ogunjemiyo et al., 2002).

AVIRIS has been used for high-resolution mapping of CO₂ plumes from industrial sources (Dennison et al., 2013) and wildfires (Marion et al., 2004; Deschamps et al., 2011). More recently, AVIRIS-NG (approximately 5 nm spectral resolution and sampling) has surveyed large regions to identify CH₄ emissions associated with oil production (Thompson et al., 2015b), gas extraction (Frankenberg et al., 2016),

hydraulic fracturing (Aubrey et al., 2015), and a landfill (Krautwurst et al., 2017). This is possible due to a 34° field of view, which results in an image swath of 1.8 km when flying at 3 km a.g.l. (above ground level).

Airborne imaging spectrometers that operate in the thermal infrared, such as the Mako and HyTES instruments (Tratt et al., 2014; Hulley et al., 2016), have also been used for mapping CH₄ plumes. However, the altitude of maximum sensitivity varies with environmental conditions like thermal contrast (Kuai et al., 2016), which can make plumes difficult to detect and quantify, and sensitivity to near-surface emissions decreases with flight altitude, which can limit ground coverage. Because AVIRIS and AVIRIS-NG measure reflected solar radiation in the shortwave infrared, CH₄ retrieval sensitivity is impacted only slightly by flight altitude due to additional gas attenuation along the optical path. However, at higher flight altitude and coarser spatial resolution a gas enhancement is diluted over a larger image pixel, thereby decreasing instrument sensitivity. The ability to fly high results in more efficient flight campaigns due to improved ground coverage. For example, AVIRIS-NG consistently observed plumes for a CH₄ controlled release experiment for all altitudes flown (up to 3.8 km a.g.l.) and AVIRIS has observed CH₄ plumes flying at 8.9 km a.g.l. (Thorpe et al., 2014). AVIRIS has also mapped CH₄ plumes over multiple days from the Aliso Canyon leak by flying 6.6 km a.g.l., resulting in an image swath approximately 4.0 km wide (Thompson et al., 2016). This also offers the potential for space-based detection of emission sources, like the observed CH₄ plume from Aliso Canyon using the orbital Hyperion imaging spectrometer (Thompson et al., 2016).

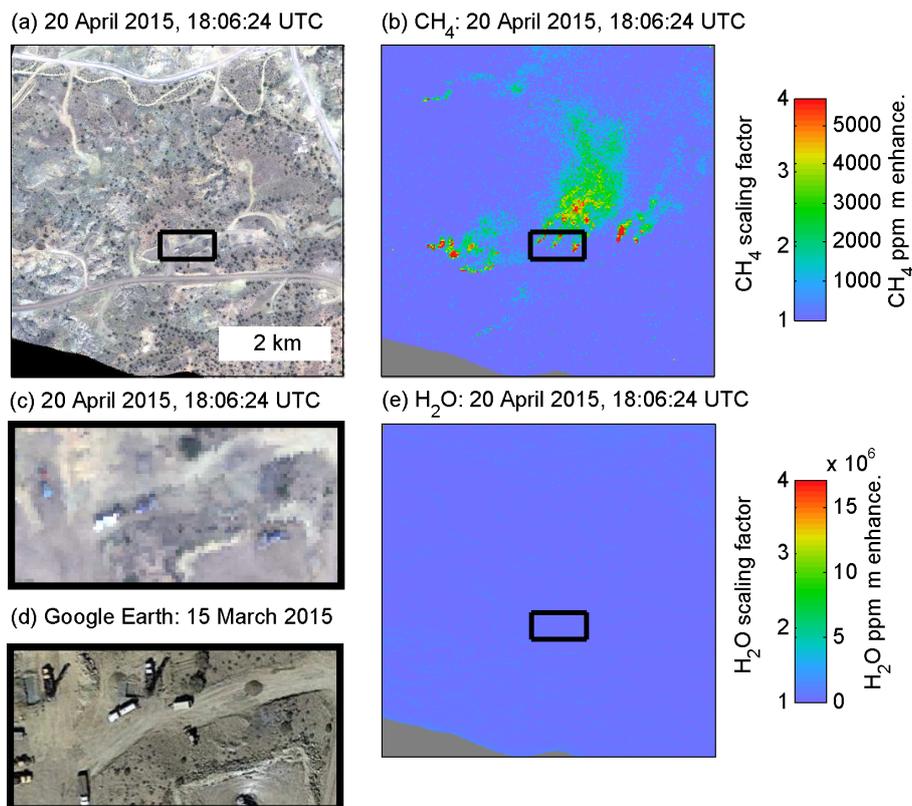


Figure 3. (a) AVIRIS-NG true color image subset. (b) A number of CH₄ plumes are clearly visible with maximum enhancements in excess of 5000 ppm · m. (c) Close-up of AVIRIS-NG true color image shown by black outline in (a). (d) Higher-resolution Google Earth imagery for same area reveals drilling rigs at an active underground coal mine, suggesting that the origin of these plumes is mine workings ventilation shafts. (e) H₂O retrieval does not indicate enhancements. For all images, north is up.

In a previous study (Thorpe et al., 2014), the iterative maximum a posteriori differential optical absorption spectroscopy (IMAP-DOAS) retrieval was applied to AVIRIS for quantitative mapping of CH₄ from natural and anthropogenic sources. In this study, the application of IMAP-DOAS has been expanded for use with AVIRIS-NG for multiple gas species, including CH₄, CO₂, and H₂O. We present results from AVIRIS-NG data acquired in New Mexico and Colorado, including from a flight campaign in the San Juan Basin near Four Corners. We will present results for a number of sources, including CH₄ from mine ventilation shafts, a gas processing plant, tank, pipeline leak, and natural seep, as well as CO₂ and H₂O plumes associated with power plants (Fig. 2).

3 Study sites and AVIRIS-NG data

Space-based observations collected by the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartography (SCIAMACHY) instrument (Bovensmann et al., 1999) showed CH₄ enhancements in the Four Corners region (Kort et al., 2014). This made for an ideal location for follow-up

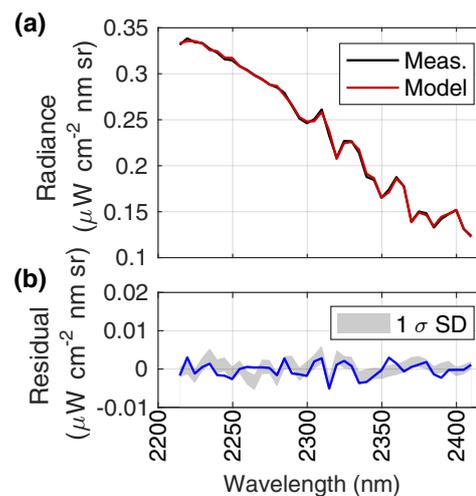


Figure 4. (a) AVIRIS-NG measured and modeled radiance for one image pixel within the CH₄ plume used for the CH₄ retrieval (see Fig. 3b). (b) The residual is plotted with 1σ SD boundary calculated from residuals for the entire scene.

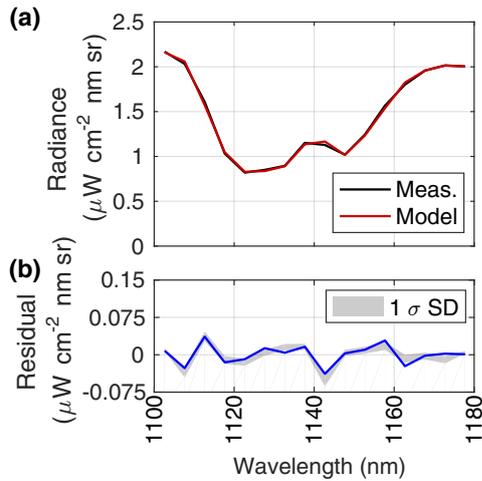


Figure 5. (a) AVIRIS-NG measured and modeled radiance for one image pixel within the CH₄ plume used for the H₂O retrieval (see Fig. 3e). (b) The residual is plotted with 1 σ SD boundary calculated from residuals for the entire scene.

surveys using AVIRIS-NG to identify individual emission sources. During the flight campaign, the AVIRIS-NG instrument was equipped with a real-time CH₄ mapping capability using a waterfall display monitored by the instrument operator. Observed CH₄ plumes were overlaid on a true color image displaying location information and the maximum CH₄ enhancement (Thompson et al., 2015b). This permitted adaptive survey strategies to investigate observed plumes and the ability to send images of the plume with accurate locations to a ground crew for subsequent follow-up. A Xenics Onca-VLWIR-MCT-384 thermal imaging camera with a Spectrogon optical filter centered at 7.746 μm was used by the ground crew to verify a number of plumes observed in real time by AVIRIS-NG.

Located in New Mexico and Colorado, the San Juan Basin produces natural gas from sandstone, coal bed CH₄, and shale formations and is the fourth largest US gas field when it comes to total production (EIA, 2015). During a 5-day campaign in April 2015, AVIRIS-NG targeted an area corresponding to the highest CH₄ enhancements observed with SCIAMACHY (Frankenberg et al., 2016). A 2500 km² area was covered in approximately 2 days (9.2 flight hours) flying at 3 km a.g.l., resulting in scenes with an image swath of around 1.8 km and a ground resolution of 3 m. The remaining flight days were used for additional follow-up flights and some repeat observations, sometimes at lower flight altitudes. During the campaign, a number of potential CH₄ emission sources were targeted, including infrastructure associated with natural gas production like well pads, tanks, gas processing plants, a coal mine, and natural coal bed CH₄ seeps. While the flight campaign focused on CH₄ sources, the coal-fired San Juan power-generating station was also flown as a potential CO₂ emission source.

4 IMAP-DOAS retrievals

A detailed description of the IMAP-DOAS retrieval for AVIRIS can be found in Thorpe et al. (2014). Gas retrievals were performed on orthorectified radiance data. Atmospheric profiles were generated by updating prior gas profiles from the US standard atmosphere obtained from the radiative transfer models LOWTRAN/MODTRAN (Kneizys et al., 1996) using volume mixing ratios (VMRs) from the NOAA Mauna Loa station, United States (NOAA, 2015). Temperature, pressure, and water vapor VMR profiles representative of the time period of the flight campaign were acquired from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project (Kalnay et al., 1996). Spectral parameters for CH₄, CO₂, H₂O, and N₂O were used from the HITRAN 2008 database (Rothman et al., 2009) and a classical Voigt spectral line shape was used to calculate vertical optical densities for 14 atmospheric layers that spanned sea level to the top of the atmosphere.

Above the aircraft, vertical optical densities were combined and an air mass factor (AMF) was calculated to account for one-way transmission. Vertical optical densities below the aircraft were also combined with an AMF reflecting two-way transmission. This resulted in a two-layer atmospheric model that speeds up the retrieval and incorporates the ground elevation and flight altitude for each AVIRIS-NG scene. The two-layer model was used to model reflected solar radiation perturbed by the absorbing species CH₄, CO₂, H₂O, and N₂O. Three retrieval windows were used, each targeting the primary gas of interest. CH₄ retrievals were performed between 2215 and 2410 nm (Fig. 1) and included fits for H₂O and N₂O. Gas Jacobians that reflect changes in absorption due to the absorbing species CH₄, CO₂, and H₂O are shown in Fig. 1. Because N₂O has weak absorption features, these Jacobians are not shown. Between 1904 and 2099 nm, CO₂ retrievals included H₂O and N₂O as additional unknown variables of the retrieval, while H₂O retrievals between 1103 and 1178 nm also included CO₂ and N₂O. Therefore, the state vector (\mathbf{x}_n) for each retrieval window has six entries (three gases for two atmospheric layers). Modeled radiance at high spectral resolution was calculated for each wavelength with a forward radiative transfer model using the following equation:

$$\mathbf{F}^{\text{hr}}(\mathbf{x}_i) = \mathbf{I}_0^{\text{hr}} \cdot \exp\left(-\sum_{n=1}^6 A_n \cdot \boldsymbol{\tau}_n^{\text{ref}} \cdot \mathbf{x}_{n,i}\right) \cdot \sum_{i=0}^k a_k \lambda^k, \quad (1)$$

where $\mathbf{F}^{\text{hr}}(\mathbf{x}_i)$ is the forward modeled radiance at the i th iteration of the state vector; \mathbf{I}_0^{hr} is the incident intensity, a solar transmission spectrum (G. Toon, personal communication, 2013); A_n is the AMF for each n number of atmospheric state vector elements; $\boldsymbol{\tau}_n^{\text{ref}}$ is the reference vertical optical density for each n number of atmospheric state vector elements (including optical densities of the three absorbing species); $\mathbf{x}_{n,i}$

is the trace-gas-related state vector at the i th iteration, which scales the prior optical densities of each of the absorbing species in each n layer (six rows, three gases for two atmospheric layers); and a_k are polynomial coefficients to account for low-frequency spectral variations.

The state vector contains the spectral shift (not shown here) and a low-order polynomial function (a_k) to account for the broadband variability in surface albedo (see Frankenberg et al., 2005). The high-resolution modeled radiance is convolved using the instrument line shape function and sampled to the center wavelengths for each AVIRIS-NG spectral band, resulting in a lower-resolution modeled radiance at the i th iteration of the state vector $F^{\text{lr}}(\mathbf{x}_i)$, calculated using a known τ_n^{ref} scaled by $x_{n,i}$.

A Jacobian matrix is calculated for each iteration i , where each column represents the derivative vector of the sensor radiance with respect to each element of the state vector (\mathbf{x}_i).

$$\mathbf{K}_i = \left. \frac{\partial F^{\text{lr}}(\mathbf{x})}{\partial \mathbf{x}} \right|_{\mathbf{x}_i} \quad (2)$$

The state vector at the i th iteration can be optimized as follows (Rodgers, 2000):

$$\mathbf{x}_{i+1} = \mathbf{x}_a + \left(\mathbf{K}_i^T \mathbf{S}_e^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1} \right)^{-1} \mathbf{K}_i^T \mathbf{S}_e^{-1} \cdot \left[\mathbf{y} - F^{\text{lr}}(\mathbf{x}_i) + \mathbf{K}_i(\mathbf{x}_i - \mathbf{x}_a) \right], \quad (3)$$

where \mathbf{x}_a is the a priori state vector (six rows), \mathbf{x}_i is the state vector at the i th iteration (six rows), \mathbf{S}_e is the error covariance matrix, \mathbf{S}_a is the a priori covariance matrix, \mathbf{y} is the measured AVIRIS-NG radiance, $F^{\text{lr}}(\mathbf{x}_i)$ is the forward model evaluated at \mathbf{x}_i , and \mathbf{K}_i is the Jacobian of the forward model at \mathbf{x}_i .

The retrieval optimizes a scaling factor relative to the a priori profile. The a priori scaling factor is set to one as an initial guess for each gas in the two layers, while the a priori covariance matrix was set to constrain the fit to the atmospheric layer beneath the aircraft where high variance is expected. To do so, very small prior covariances were set for the uppermost layer (above the aircraft). Because the observed plumes are not expected to extend above the AVIRIS-NG flight altitude, this assumption is reasonable. Gas concentrations were calculated in ppm · m by multiplying the gas state vector at the last iteration (gas scaling factor) by the VMR for the lowest layer of the reference atmosphere and the distance between the aircraft and the ground. In subsequent figures, color bars will indicate the scaling factors and gas enhancements relative to background, which were calculated by subtracting the retrieved gas concentration from the background concentration for the lowest layer of the reference atmosphere.

The covariance $\hat{\mathbf{S}}$ was calculated to estimate expected IMAP-DOAS retrieval errors as follows:

$$\hat{\mathbf{S}} = \left(\mathbf{K}^T \mathbf{S}_e^{-1} \mathbf{K} + \mathbf{S}_a^{-1} \right)^{-1}, \quad (4)$$

where the diagonal of $\hat{\mathbf{S}}$ corresponds to the covariance at each atmospheric layer associated with the gases used for each fitting window. \mathbf{S}_e , the error covariance matrix, is a diagonal matrix representing expected errors for the retrieval algorithm. For each gas retrieval, the square root of the corresponding diagonal entry of $\hat{\mathbf{S}}$ is multiplied by the VMR in the lowest layer of the atmospheric model for each retrieved gas (CH₄: 1.86 ppm; CO₂: 399 ppm; H₂O: 7745 ppm). Using scene parameters for a 1 km flight altitude a.g.l. with 25.6° solar zenith and variable signal-to-noise ratio, this corresponds to an error of between 0.14 and 0.55 ppm CH₄ beneath the aircraft. For CO₂, the error ranges between 6.6 and 26.4 ppm and for H₂O between 9.4 and 37.5 ppm.

5 Results

5.1 CH₄ emissions from natural gas sector

AVIRIS-NG identified over 250 CH₄ plumes during the Four Corners flight campaign (Frankenberg et al., 2016) using a linearized matched filter (Thompson et al., 2015b). The linearized matched filter models the background of radiance spectra as a multivariate Gaussian and provides a scalar value that represents the fraction of the gas target signature that perturbs the background. Because the target signature is defined as the change in radiance of the background caused by adding a unit mixing ratio length of CH₄, detected quantities are reported in mixing ratio lengths (ppm · m). This method is computationally efficient and accounts for the full covariance of background (atmosphere and surface) and instrument noise using in-scene data, providing high sensitivity to local enhancements.

The current speed of the IMAP-DOAS retrieval algorithm precludes it from being applied to all 250 examples presented in the previous study (Frankenberg et al., 2016). Instead, IMAP-DOAS retrievals for only a few examples will be presented here, reflecting CH₄, CO₂, and H₂O plumes from a variety of emission sources. The first example from a 20 April 2015 flight at 1.1 km a.g.l. (Fig. 3b) is made up of at least 10 plumes with maximum enhancements in excess of 5000 ppm m, which is equivalent to a concentration of 0.5 % in a 1 m thick layer or roughly an XCH₄ (dry air column-averaged mole fraction) enhancement of around 500 ppb that is almost 25 % of a total background column. Results from the H₂O retrieval (Fig. 3e) do not indicate enhancements collocated with CH₄ plumes. The true color image subset in Fig. 3a reveals a few dirt roads, but the close-up of the AVIRIS-NG scene indicated by the black boxes in Fig. 3a and b indicates some visible infrastructure that is difficult to interpret at the 1 m AVIRIS-NG pixel resolution (Fig. 3c).

In Fig. 3d, Google Earth imagery for the same area provides improved spatial resolution and reveals what appears to be drilling rigs at an active underground coal mine on 15 March 2015, suggesting the origin of these plumes are mine

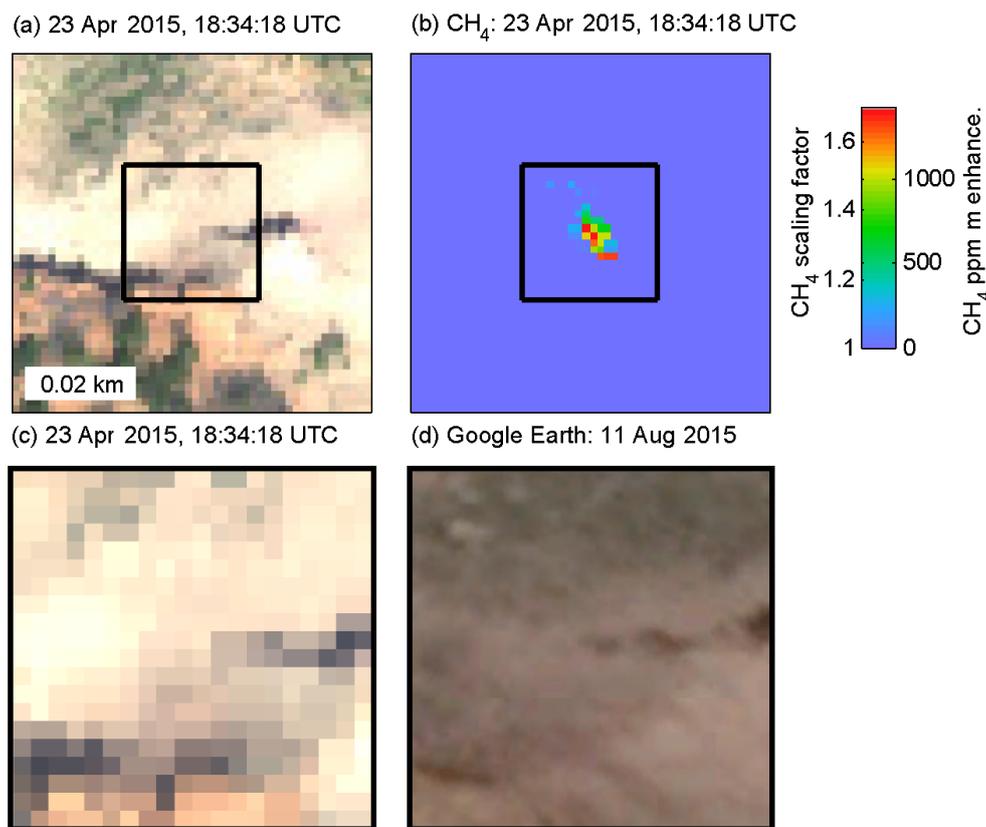


Figure 6. (a) AVIRIS-NG true color image subset. (b) A small CH₄ plume is visible from a confirmed geological source at Moving Mountain near Durango, Colorado. (c) Close-up of AVIRIS-NG true color image. (d) Higher-resolution Google Earth imagery provides additional spatial context. For all images, north is up.

workings ventilation shafts. Frankenberg et al. (2016) estimated an aggregate flux of 2236 kg h^{-1} for these plumes. Measured and modeled radiance is shown for one image pixel within the CH₄ plume for the CH₄ retrieval fitting window (Fig. 4a) and for the H₂O retrieval (Fig. 5a). For both examples, the residuals are also plotted (Fig. 4b, Fig. 5b) in addition to the 1σ SD boundary calculated from residuals for the entire scene.

Additional examples are presented in Appendix A, including from another 20 April 2015 flight at 1.4 km a.g.l. that results in a 1.2 m resolution (Fig. A1b). Multiple CH₄ plumes are visible from this gas processing facility, one emanating from a source beyond the east edge of the AVIRIS-NG scene. This example was associated with a planned maintenance operation, which resulted in a large temporary CH₄ plume that was recorded and reported through the normal Greenhouse Gas Reporting Program (Williams, 2016). A second plume is visible at a location shown by the black box in Fig. A1a, indicating white pipes associated with an interstate pipeline as the likely emission source (Fig. A1c and d).

An H₂O retrieval was also performed for this scene and did not reveal enhancements collocated with the CH₄ plumes. For all subsequent examples, H₂O retrievals were

performed but will be shown only in cases where H₂O plumes were observed (see Sect. 5.3). As shown in Fig. A1a, the CH₄ plumes cross over many land cover types with variable brightness and very dark surfaces resulted in anomalously high retrievals. CH₄ results from radiances less than $0.01 \mu\text{W cm}^{-2} \text{sr}^{-1} \text{nm}^{-1}$ for any band of the CH₄ fitting window, corresponding to shadows and water, were removed from the results shown in Fig. A1b.

In Fig. A2b and e, CH₄ emissions from a tank were observed on 19 and 21 April 2015 at 2.8 and 3.2 km a.g.l. (pixel resolutions of 2.6 and 3.0 m respectively). The Google Earth close-up shown in Fig. A2d indicates a tank as the likely emission source, which was confirmed by the ground crew using a thermal imaging camera on multiple days. Video A1 (see Supplement) was acquired on 21 April 2015 at around 18:00 UTC and clearly shows a CH₄ plume originating at the top of the tank that is consistent with the AVIRIS-NG CH₄ plume observed the same day.

In Frankenberg et al. (2016), CH₄ emissions from a pipeline leak were presented (see Fig. 4 and Movie S2; Frankenberg et al., 2016) and subsequent to publication another suspected pipeline leak (Fig. S6; Frankenberg et al., 2016) was confirmed (K. Spray, Department of Energy, per-

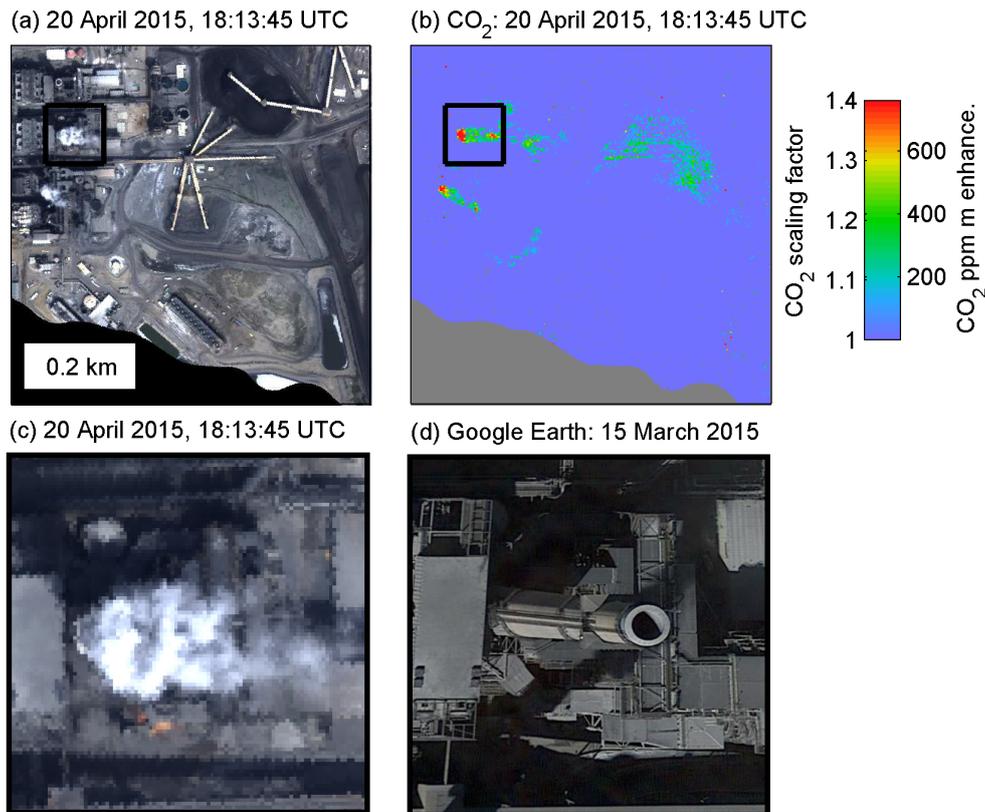


Figure 7. (a) AVIRIS-NG true color image subset. (b) CO₂ plume is visible. (c) Close-up of AVIRIS-NG true color image. (d) Higher-resolution Google Earth imagery provides additional spatial context. For all images, north is up.

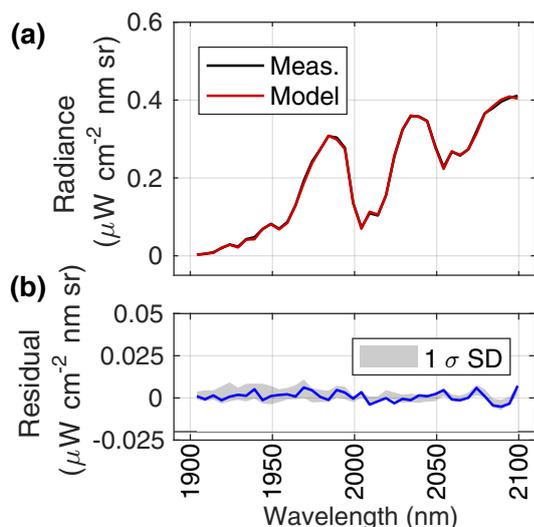


Figure 8. (a) AVIRIS-NG measured and modeled radiance for one image pixel within the CO₂ plume for the CO₂ retrieval (see Fig. 7b). (b) The residual is plotted with 1 σ SD boundary calculated from residuals for the entire scene.

sonal communication, 2016). That leak was independently identified and repaired by the operator as a part of their normal operations prior to publication. In Fig. A3b, the CH₄ plume from the 19 April 2015 flight at 3.0 km a.g.l. (2.7 m pixel resolution) does not appear associated with visible infrastructure and subsequent investigation by the ground crews identified the plume origin on 24 April 2015 using the thermal camera (Video A2, see Supplement). This location was along a marked, buried natural gas pipeline and was subsequently confirmed as a pipeline leak and ultimately shut down for repairs by the local pipeline operators. The estimated flux for this example is 28 kg h⁻¹ (Frankenberg et al., 2016), which would result in an estimated annual loss of 13.2 million cubic feet, equivalent to USD 100 000 (assuming constant annual flux and average cost of USD 7.40 per thousand cubic feet).

5.2 Geological CH₄ emissions

AVIRIS has been used for quantitative retrievals of CH₄ for marine seeps (Roberts et al., 2010; Thorpe et al., 2014) and more recently a plume observed with AVIRIS-NG was verified as a geological source (see Fig. S6 in Frankenberg et al., 2016). Subsequent analysis of the Four Corners data set revealed another CH₄ plume from a confirmed geological

source at Moving Mountain near Durango, Colorado (LTE, 2015). This AVIRIS-NG scene was acquired at 1.3 km a.g.l. (1 m pixel resolution) and shows a 10 m long plume (Fig. 6b).

5.3 CO₂ and H₂O emissions from power plants

While Dennison et al. (2013) demonstrated the ability of AVIRIS for high-resolution mapping of CO₂ plumes, in this study we present two examples using quantitative retrievals. The first example is from the coal-fired San Juan Generating Station near Farmington, New Mexico, that was flown on 20 April 2015 at 1.2 km a.g.l. Two CO₂ plumes are clearly visible in Fig. 7b and correspond to two flue-gas stacks that appear active given visible emissions in the true color image (Fig. 7a, c). A third flue-gas stack appears inactive (Fig. 7a) with no visible CO₂ plume (Fig. 7b). The San Juan Generating Station reported 2015 emissions of 9843 kt of CO₂, equivalent to a flux of 1 123 666 kg CO₂ h⁻¹ (EPA, 2016b). An example of a CO₂ retrieval fit and the residual is shown in (Fig. 8).

The second example is from a 12 September 2014 flight that included the coal-fired Craig Station near Craig, Colorado. CO₂ plumes are visible from flue-gas stacks (Fig. A4b) and extend more than 1 km downwind. This power plant reported 2014 emissions of 9300 kt of CO₂, equivalent to a flux of 1 061 644 kg CO₂ h⁻¹ (EPA, 2016b). Within the same scene, an H₂O plume is also visible (Fig. A4d) emanating from a region that contains a number of cooling towers adjacent to two large cooling ponds (Fig. A5a). CH₄ retrieval results are also shown in Fig. A5c, indicating that CH₄ plumes are not visible in the scene and emphasizing the ability of these retrievals to distinguish between CH₄ and H₂O despite spectral interference (see Fig. 1). Results for dark surfaces like the cooling ponds were removed from Fig. A4b by excluding radiances less than 0.10 μW cm⁻² sr⁻¹ nm⁻¹ for any band of the CO₂ fitting window, for radiances less than 0.002 μW cm⁻² sr⁻¹ nm⁻¹ for any band of the H₂O fitting window (Fig. A4d), and for radiances less than 0.01 μW cm⁻² sr⁻¹ nm⁻¹ for any band of the CH₄ fitting window (Fig. A4c).

In Fig. A5a, the AVIRIS-NG true color image is shown for the close-up indicated by the black box in Fig. A4. The flue-gas stacks are visible in the lower left as CO₂ sources and cooling towers in the upper right as possible H₂O sources. Ellipses delineate the shapes of plumes visible in the true color images for the flue-gas stacks (red) and cooling towers (blue). The arrows indicate winds to the southeast for the flue-gas stacks (consistent with CO₂ plumes in Fig. A4b) and to the east for the cooling towers (consistent with H₂O plumes in Fig. A4d). In A5b, the higher-resolution Google Earth imagery clearly indicates the flue-gas stacks are much taller (182 m) than the cooling tower (TRI, 2016) based on assessment of shadows, which could explain variable wind directions at the flue-gas stacks and in the vicinity of the cooling towers. Given the presence of the cooling

ponds immediately adjacent to the cooling towers, it is unclear whether the observed H₂O plume shown in Fig. A4d is caused solely by the cooling towers or reflects the combined influence of the towers and evaporation from the cooling ponds.

6 Conclusions

In this study, we use the airborne imaging spectrometer AVIRIS-NG and the IMAP-DOAS retrieval to generate gas concentration maps for observed CH₄, CO₂, and H₂O plumes. While more than 250 CH₄ plumes were observed in the San Juan Basin near Four Corners (Frankenberg et al., 2016), this study focused on a few results from anthropogenic and natural sources, including emissions from mine ventilation shafts, a gas processing plant, tank, pipeline leak, and natural seep. In addition, CO₂ emissions were observed from the flue stacks of two coal-fired power plants and an H₂O plume was mapped for the cooling towers for one power plant. Observed plumes were consistent with known and suspected emission sources verified by true color AVIRIS-NG imagery and higher-resolution Google Earth imagery.

AVIRIS-NG has the high spatial resolution necessary to resolve small-scale emissions and can map large regions quickly, covering the 2500 km² Four Corners study in approximately 2 days (9.2 flight hours). This capability is aided by real-time detection and geolocation of gas plumes, permitting unambiguous identification of individual emission source locations and communication to ground teams for rapid follow-up. This permitted verification of a number of emission sources presented in this study using a thermal camera, including a tank and buried natural gas pipeline. The AVIRIS and AVIRIS-NG instruments have demonstrated CH₄ plume mapping capabilities at multiple flight altitudes, ranging from as low as 0.4 to 3.8 km a.g.l. (0.4 to 3.8 m pixels) for a controlled release experiment (Thorpe et al., 2016a) to 9 km a.g.l. for the Coal Oil Point marine seeps (Thorpe et al., 2014). AVIRIS observed the Aliso Canyon leak on multiple flight days at 6.6 km a.g.l. (6.6 m pixels) while the Hyperion imaging spectrometer, also 10 nm spectral resolution but 30 m pixels, mapped the plume and demonstrated the potential for a space-based application (Thompson et al., 2016).

This study demonstrates a comprehensive greenhouse gas monitoring capability that targets CH₄ and CO₂, the two dominant anthropogenic climate-forcing agents. The ability to identify individual point source locations of CH₄ and CO₂ emissions has relevance to the research community and the private sector. Understanding the spatial and temporal distribution and the magnitude of these emissions is of interest given the large uncertainties associated with anthropogenic emissions. This includes industrial point source emissions of CH₄ and CO₂, CH₄ from oil and gas operations as well as natural gas distribution and storage, CH₄ from agricul-

tural sources, and CH₄ and CO₂ from landfills. Site operators could identify and mitigate CH₄ emissions, which reflect both a potential safety hazard and lost revenue. Water vapor results demonstrate the ability of these retrievals to distinguish between CH₄ and H₂O despite spectral interference in the shortwave infrared while offering the potential to improve atmospheric correction and reflectance retrievals with application to the fields of ecology and meteorology.

Despite these promising results, an imaging spectrometer built exclusively for quantitative mapping of gas plumes would have improved sensitivity compared to AVIRIS-NG (Thorpe et al., 2014). For example, an instrument providing a 1 nm spectral resolution and sampling (2000–2400 nm) would permit mapping CH₄, CO₂, H₂O, CO, and N₂O from more diffuse sources using both airborne and orbital platforms (Thorpe et al., 2016b). The ability to identify emission sources offers the potential to constrain regional greenhouse gas budgets and improve partitioning between anthropogenic and natural emission sources. Because the CH₄ lifetime is only about 9 years and CH₄ has a high GWP, targeting reductions in anthropogenic CH₄ emissions offers an effective approach to decrease overall atmospheric radiative forcing.

Data availability. The AVIRIS-NG data used in this study are available upon request at <http://avirisng.jpl.nasa.gov/> or <http://aviris.jpl.nasa.gov/>. Videos showing methane plumes observed using a thermal imaging camera are available at <https://doi.org/10.5446/30884> and <https://doi.org/10.5446/30883> (Thorpe and Krohn, 2017a, b).

Appendix A

This appendix contains additional figures referenced in Sect. 5.

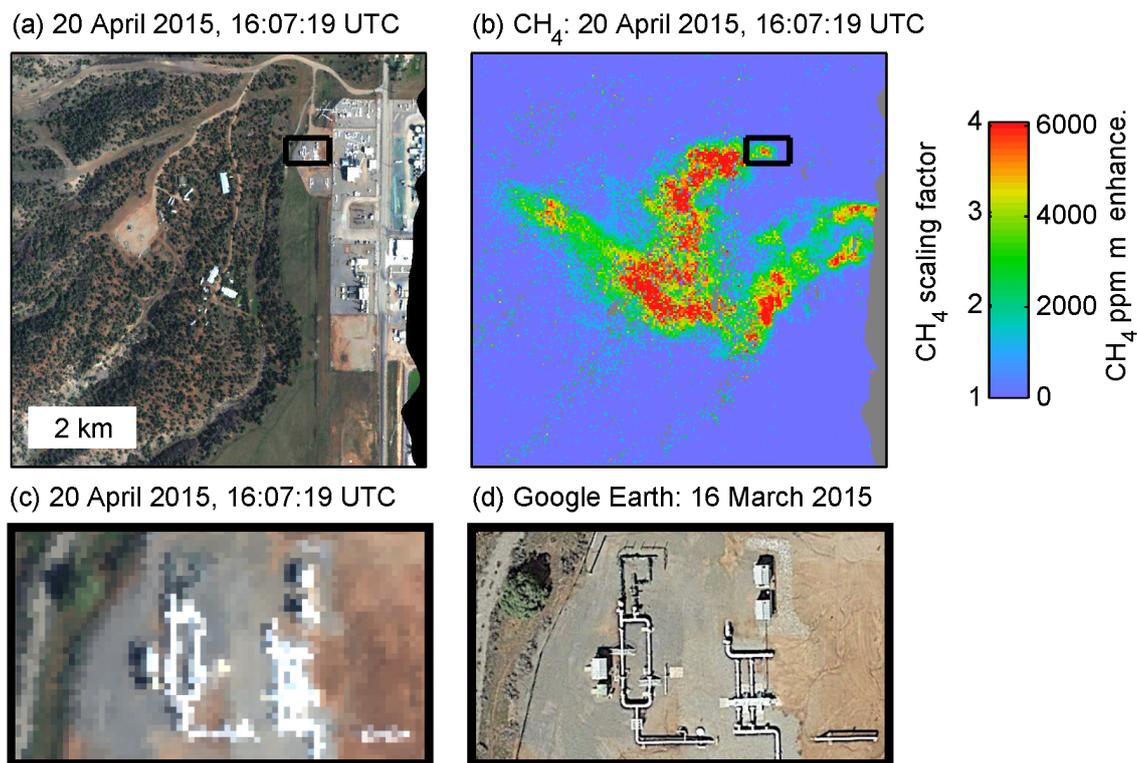
A1 CH₄ emissions from gas processing facility

Figure A1. (a) AVIRIS-NG true color image subset. (b) Multiple CH₄ plumes are visible from this gas processing facility, one emanating from a source beyond the east edge of the AVIRIS-NG scene. A second plume is visible at a location shown by the black box. (c) Close-up of AVIRIS-NG true color image indicates white pipes associated with an interstate pipeline as the likely emission source. (d) Higher-resolution Google Earth imagery provides additional spatial context. For all images, north is up.

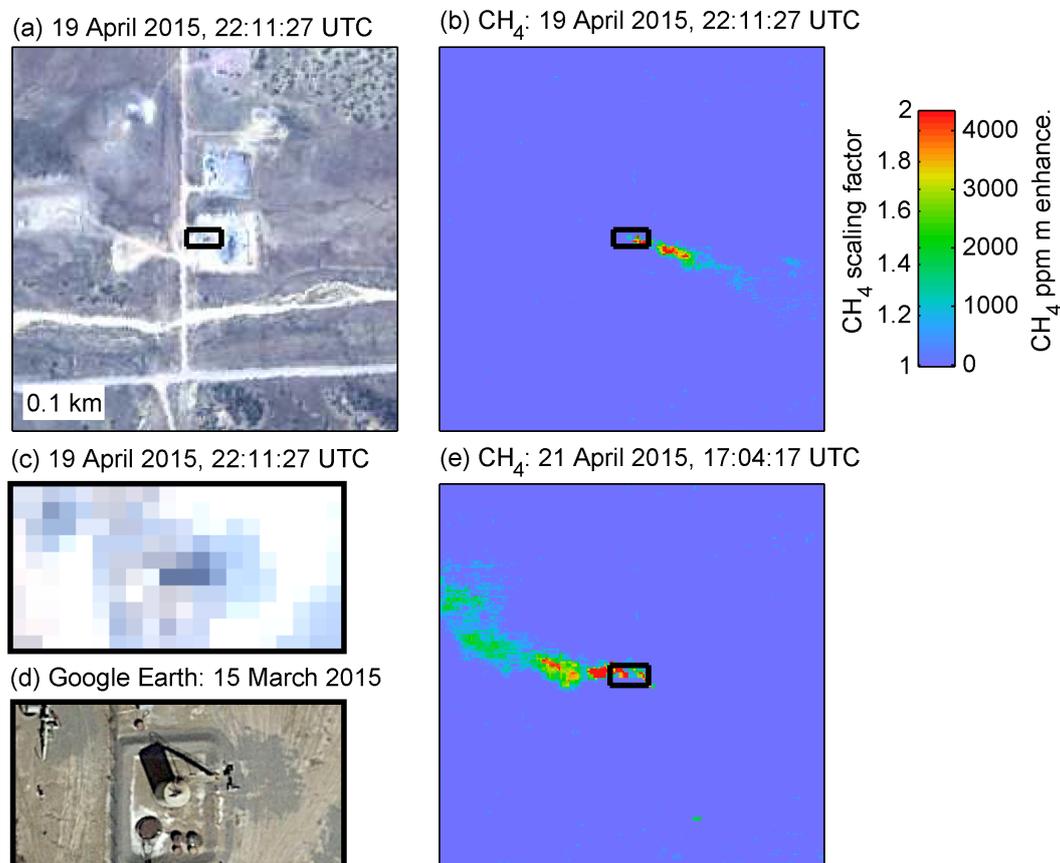
A2 CH₄ emissions from tank

Figure A2. (a) AVIRIS-NG true color image subset from 19 April 2015. (b) Prominent CH₄ plume visible from location indicated by the black box. (c) Close-up of 19 April 2015 AVIRIS-NG true color image. (d) Higher-resolution Google Earth imagery indicates the emission source is a tank. (e) Scene from 21 April 2015 indicates a CH₄ plume from the same source with an different orientation due to changes in wind direction. For all images, north is up. A thermal camera video for this source is shown in Video A1.

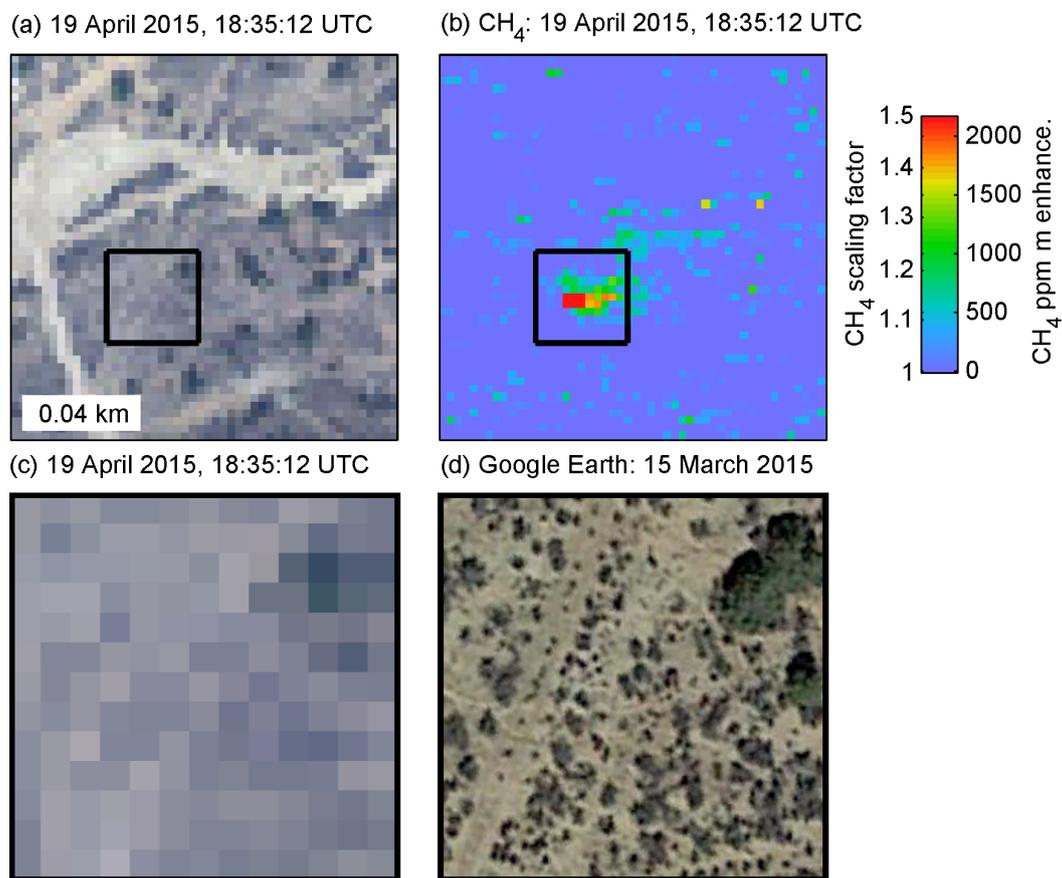
A3 CH₄ emissions from pipeline leak

Figure A3. (a) AVIRIS-NG true color image subset. (b) A CH₄ plume is visible for a confirmed leak from a buried natural gas pipeline. (c) Close-up of AVIRIS-NG true color image. (d) Higher-resolution Google Earth imagery does not indicate visible infrastructure. For all images, north is up. A thermal camera video for this source is shown in Video A2.

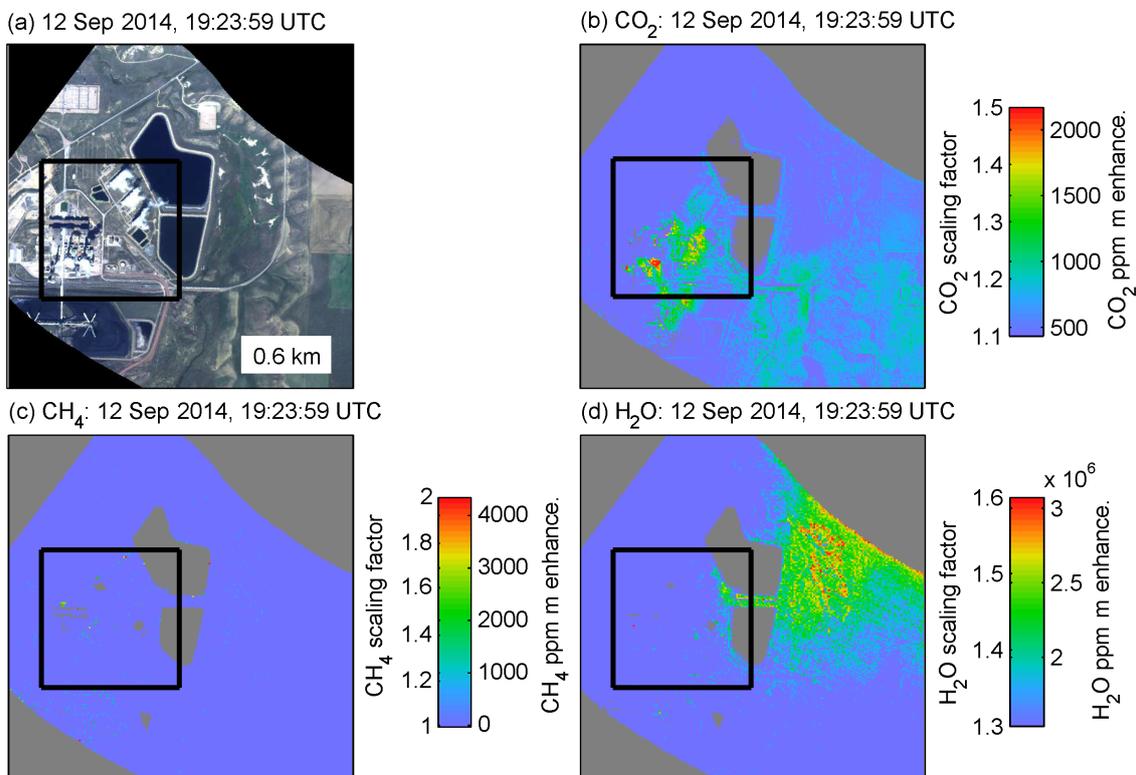
A4 CO₂ and H₂O emissions from power plant

Figure A4. (a) AVIRIS-NG true color image subset. (b) CO₂ plumes are visible emanating from flue-gas stacks. (c) CH₄ retrieval results. (d) H₂O plume visible from cooling towers (see Fig. A5). For all images, north is up.

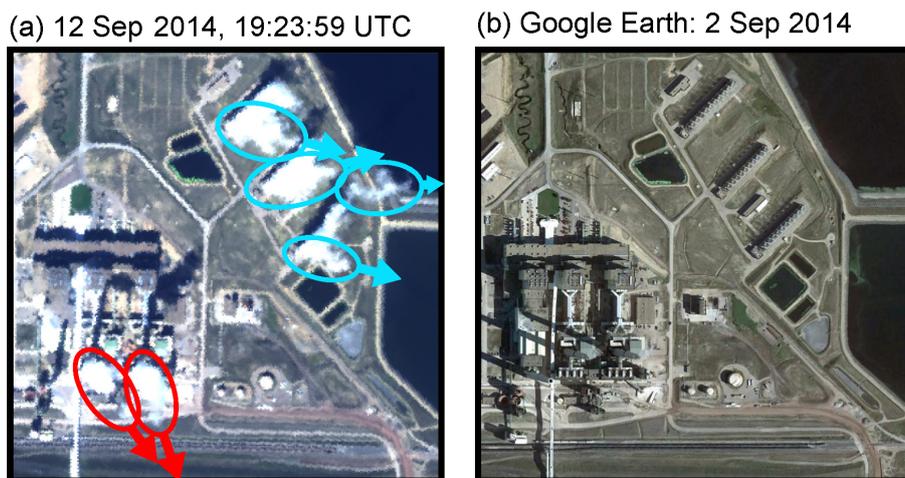


Figure A5. (a) AVIRIS-NG true color image for close-up indicated by black box in Fig. A4. Flue-gas stacks visible in lower left as CO₂ sources and cooling towers in upper right as H₂O sources. Ellipses delineate shapes of plumes visible in true color images for the flue-gas stacks (red) and cooling towers (blue). The arrows indicate winds to the southeast for the flue-gas stacks (consistent with CO₂ plumes in Fig. A4b) and to the east for the cooling towers (consistent with H₂O plumes in Fig. A4d). (b) Higher-resolution Google Earth imagery clearly indicates the flue-gas stacks are much taller than the cooling towers based on assessment of shadows. For both images, north is up.

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