Title:

Mapping methane concentrations from a controlled release experiment using the next generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG)

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Abstract:

Emissions estimates of anthropogenic methane (CH₄) sources are highly uncertain and many sources related to energy production are localized yet difficult to quantify. Airborne imaging spectrometers like the next generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) are well suited for locating CH₄ point sources due to their ability to map concentrations over large regions with the high spatial resolution necessary to resolve localized emissions. AVIRIS-NG was deployed during a field campaign to measure controlled CH₄ releases at the Rocky Mountain Oilfield Testing Center (RMOTC) in Wyoming, U.S. for multiple flux rates and flight altitudes. Two algorithms were applied to AVIRIS-NG scenes, a matched filter detection algorithm and a hybrid retrieval approach using the Iterative Maximum a Posteriori Differential Optical Absorption Spectroscopy (IMAP-DOAS) algorithm and Singular Value Decomposition. Plumes for releases as low as 14.16 m³/h (0.09 kt/year) were consistently observed by AVIRIS-NG at multiple flight altitudes and images of plumes were in agreement with wind directions measured at ground stations. In some cases plumes as low as 3.40 m³/h (0.02 kt/year) were detected, indicating that AVIRIS-NG has the capability of detecting a wide range of fugitive CH₄ source categories for natural gas fields. This controlled release experiment is the first of its kind using AVIRIS-NG and demonstrates the utility of imaging spectrometers for direct attribution of emissions to individual point source locations. This is particularly useful given the large uncertainties associated with anthropogenic CH₄ emissions, including those from industry, gas transmission lines, and the oil and gas sectors.

1. Introduction

Atmospheric methane (CH₄) is a greenhouse gas with a Global Warming Potential (GWP) 86 times that of carbon dioxide (CO₂) for a 20 year time interval (Myhre et al., 2013). The growth rate of global atmospheric CH₄ concentrations slowed between 1999 and 2006, but has increased since 2007 (Nisbet et al., 2014). The causes of these observed increases remain unclear and reflect uncertainty in the global CH₄ budget (Kirschke et al., 2013). Between 50-65% of the global CH₄ budget can be attributed to anthropogenic emissions (Ciais et al., 2013), however, there is considerable uncertainty regarding partitioning between individual anthropogenic source types and locations.

In the United States, major anthropogenic CH₄ sources ordered by magnitude include livestock (enteric fermentation and manure management), natural gas systems (production, transmission, and storage), landfills, coal mining, and petroleum systems (EPA, 2013). Numerous studies suggest bottom-up inventories for natural gas production and distribution are underestimated (Kort et al., 2008; Miller et al., 2013; Brandt et al., 2014). Multiple top-down estimates suggest fugitive CH₄ emissions from natural gas and oil production can be large, ranging between 2.3 to 7.0% of CH₄ produced annually for the Denver-Julesburg Basin, Colorado (Petron et al., 2012) and between 6.2 to 11.7% of average hourly natural gas production in the Uintah County oil and gas field (Karion et al., 2013). These estimates pertain to specific locations and times, while leak rates from different facilities should vary considerably. For example, additional studies suggest that fugitive CH₄ leakage is considerably lower (Alvarez et al., 2012; Allen et al., 2013; O'Sullivan and Paltsev, 2012).

Airborne measurements are increasingly being used to study fugitive CH₄ emissions from the oil and gas industry. So far, these mostly comprise airborne in situ measurements of CH₄ with emission estimates derived using mass balance approaches (Karion et al., 2013), ethane (C₂H₆) to CH₄ enhancement ratios (Wennberg et al., 2012), and observations of alkanes used with high-resolution atmospheric transport models (Miller et al., 2013). Airborne spectrometers like MAMAP (Methane Airborne MAPper) cannot provide the same level of accuracy and precision as in situ data but offer the potential to detect and quantify fugitive CH₄ emissions (Gerilowski et al., 2011). For example, MAMAP measurements of elevated CH₄ column abundance from coal mine ventilation shafts near Ibbenbüren, Germany permitted an inversion estimate in good agreement with reported emissions rates from mine operators (Krings et al., 2013). In addition to CH₄, MAMAP can retrieve CO₂ and water vapor due to its fine spectral resolution and high signal to noise ratio. However, MAMAP is a non-imaging spectrometer with a small field of view (FOV) limited to flying transects across gas plumes rather than quickly mapping their morphology and extent. Recently, thermal infrared imaging spectrometers such as MAKO (Tratt et al., 2014) and the Hyperspectral Thermal Emission Spectrometer (HyTES) (Glynn Hulley, personal communication, 2015) have mapped CH₄ plumes over active oil and gas fields.

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1998) and the next generation instrument (AVIRIS-NG) (Hamlin et al., 2011) were not designed for detecting CH₄ emissions. However, they have been used for high resolution mapping of natural CH₄ seeps at Coal Oil Point offshore of Goleta, California (Roberts et al., 2010) and fugitive CH₄ emissions from the Inglewood Oil Field in Los Angeles, California (Thorpe et al., 2013) and the Kern River Oil Field (Thompson et al., 2015). To

measure CH₄ enhancements, the Iterative Maximum a Posteriori Differential Optical Absorption Spectroscopy (IMAP-DOAS) algorithm (Frankenberg et al., 2005) was modified for use with AVIRIS between 2,278 and 2,358 nm (Thorpe et al., 2014). To account better for highly variable surface reflectance, a hybrid approach using IMAP-DOAS and Singular Value Decomposition (SVD) also was developed (Thorpe et al., 2014). By combining large image swaths and fine spatial resolution, imaging spectrometers like AVIRIS and AVIRIS-NG permit direct attribution of emissions to individual point source locations.

Due to an improved 5 nm spectral resolution and higher signal to noise ratio, the CH₄ sensitivity of AVIRIS-NG is greater than AVIRIS (Dennison et al., 2013; Thorpe et al., 2014). To better understand the ability of AVIRIS-NG to detect and quantify CH₄ emissions, a controlled CH₄ release experiment using variable flux rates was performed with AVIRIS-NG overflights in June 2013. For the first time, this study evaluates which flux rates can be observed using both a non-quantitative matched filter algorithm and the quantitative hybrid retrieval using IMAP-DOAS and SVD.

2. Controlled release experiment

The controlled release experiment was performed at the Rocky Mountain Oilfield Testing Center (RMOTC), a U.S. Department of Energy (DOE) facility located approximately 50 km northeast of Casper, Wyoming. The experiment was located in the northern area of RMOTC where there were fewer oil and gas wells and the influence of fugitive CH₄ emissions on our measurements could be minimized (Figure 1). Three controlled release sites were located approximately collinear, including the northernmost

site (X-N), central site (X-C), and the southern site (X-S). Each site was separated by at least 1.5 km and the ground elevation ranged between 1,510 and 1,580 m. The land cover was a mixture of grass-shrubland and was characterized by bare soil as well as green and senesced vegetation during late June when the controlled release occurred.

Figure 1. The Rocky Mountain Oilfield Testing Center is located approximately 50 km northeast of Casper, Wyoming. Outlined in red, it spans 10,000 acres of the Naval Petroleum Reserve No. 3 (NPR-3) and contains a number of oil and gas wells (black

points). Three controlled release sites were located approximately collinear (shown in green), including sites X-N ($43^{\circ} 20.100'N$, $106^{\circ} 14.148'W$), X-C ($43^{\circ} 19.365'N$, $106^{\circ} 13.653'W$), and X-S ($43^{\circ} 18.200'N$, $106^{\circ} 13.064'W$). Image data provided by RMOTC and the U.S. DOE.

A total of 5 meteorological towers were used (Figure 2d), one 15 m tower at site X-N and X-C and 3 towers at the flattest site X-S (2 at 15 m and 1 at 3 m). These towers were equipped with high frequency (20 Hz) 3-D sonic anemometers (Campbell Scientific CSAT-3) that provide wind speed and direction measurements between 8 and 9 m height for the three sites. For the analysis presented in this paper, observed plumes were evaluated for consistency with the wind speed and direction obtained from the towers.

The experiment was carried out over 7 days (20-26 June 2013) of which 6 flight days included CH_4 controlled releases at all sites. Controlled release fluxes ranged between 3.26 and 141.58 m^3/h (115 and 5,000 standard cubic feet per hour, scfh). For each of the 3 sites, a trailer tank contained the CH_4 (Figure 2b), which was passed through an expansion regulator outfitted with a heat exchanger to prevent icing due to adiabatic gas expansion and to ensure that the gas was released at approximately ambient atmospheric temperature (Figure 2b, device directly in front of trailer tank). The CH_4 release rate was controlled using a throttling regulator valve and was measured using an Onicon Inc. F-5100 thermal mass flow meter which has a measurement accuracy of $\pm 2\%$. Gas was piped away from the trailer tank using a 7.6 cm diameter flexible rubber hose to a 1 by 1 m square diffuser that was fabricated from cast iron tubing perforated every few inches (Figure 2c). The diffuser helped to ensure that the gas release was in approximately

isokinetic equilibrium with the ambient environment and to minimize buoyancy effects at the source. It also was used to prevent generating a ‘CH₄ jet,’ a more concentrated plume emitted at higher velocity that would occur using one narrow release point (i.e. using the rubber hose alone). Having the diffuser attached to a long flexible hose allowed the release point to be moved each morning in order to position it upwind of the meteorological towers. CH₄ releases began approximately 30 minutes before aircraft overflights.

Figure 2. a. Twin Otter aircraft used with AVIRIS-NG. b. Trailer tank storing CH₄ at one of controlled release sites. c. Controlled release using square diffuser. d. Meteorological tower at site X-S equipped with suite of meteorological instrumentation that includes wind speed and direction.

3. AVIRIS-NG instrument and data processing

The next generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) is a push-broom imaging spectrometer with 598 across track elements of 1 milliradian instantaneous field of view (FOV) covering a total FOV of 34° (Table 1). AVIRIS-NG measures reflected solar radiance at the nadir viewing geometry at a 100 Hz readout rate across 427 channels between 380 and 2,510 nm with a spectral sampling of 5 nm and a full width at half maximum (FWHM) of approximately 6 nm (Hamlin et al., 2011). This pushbroom instrument was developed at the Jet Propulsion Laboratory (JPL) and is similar to the visible-to-shortwave infrared (VSWIR) imaging spectrometer used in the Carnegie Airborne Observatory next generation Airborne Taxonomic Mapping Systems (AToMS) (Asner et al., 2012). In addition, similar spectrometers are being used in the Airborne Observation Platform (AOP) by the National Ecological Observatory Network (NEON) (Kampe et al., 2010). This new class of imaging spectrometers is based on the design of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), which provides 224 spectral channels at a 10 nm spectral resolution, measuring across-track with a whisk-broom scanning mechanism. In addition to a finer spectral resolution, AVIRIS-NG has both improved precision (signal to noise ratio) and accuracy compared to AVIRIS (Table 1).

During the flight campaign, a total of 55 flight lines were acquired with AVIRIS-NG at flight altitudes ranging between 0.43 and 3.80 km above ground level (AGL). While AVIRIS-NG can be flown at higher altitudes using an ER-2 aircraft, a Twin Otter aircraft was used for the controlled release experiment (Figure 2a). CH₄ detection algorithms

were applied to non-orthorectified AVIRIS-NG scenes, which are 598 pixels wide (cross track direction) and have an along track image dimension that depend on flight duration. Images were subsequently orthorectified and resulted in spatial resolutions ranging between 0.4 m per pixel (for a flight at 0.43 km AGL with image swath width ~0.28 km) to 3.6 m per pixel (3.80 km AGL with image swath of ~2.47 km).

Table 1. AVIRIS-NG and AVIRIS key measurement characteristics

	AVIRIS-NG	AVIRIS
<i>Spectral</i>		
Range	380 to 2510 nm	380 to 2500 nm
Position	5 nm	10 nm
Response	1 to 1.3 x sampling	1 to 1.2 x sampling
Calibration	+/-0.3 nm	+/-0.3 nm
<i>Radiometric</i>		
Range	0 to max Lambertian	0 to max Lambertian
Precision (SNR)	>2000 @ 600 nm, >800 @ 2200 nm	>1000 @ 600 nm >400 @ 2200 nm
Accuracy	95% (<5% uncertainty)	90% (<10% uncertainty)
<i>Spatial</i>		
Range	34 degree field of view	34 degree field of view
Sampling	1 milliradian	1 milliradian
Response	1 to 1.3 x sampling	1 to 1.3 x sampling
Sample distance	0.3 m to 20 m	4 m to 20 m
Geom. model	Full 3 axes cosines	Full 3 axes cosines
<i>Uniformity</i>		
Spectral cross track	>95% across FOV	>98% across FOV
Spectral IFOV variation	>95% Spectral direction	>98% Spectral direction

4. Hybrid IMAP/SVD CH₄ retrieval

Quantifying CH₄ concentrations present within AVIRIS-NG scenes requires radiative transfer modelling of solar radiation along the light path to the sensor in the shortwave infrared. One technique previously applied to AVIRIS for CH₄ retrievals uses the

Iterative Maximum a Posteriori Differential Optical Absorption Spectroscopy (IMAP-DOAS) algorithm (Frankenberg et al., 2005; Thorpe et al., 2014). IMAP-DOAS uses the Lambert-Beer law and optimal estimation theory to adjust the slant column densities of multiple gasses until total optical density fits the observed measurement. This permits direct comparison of simulated at sensor radiance with a known abundance of absorbers to radiance measured by the imaging spectrometer.

As shown in previous work for moderate resolution spectrometers like AVIRIS, disentangling lower frequency features such as surface reflectance from higher frequency gas absorption features can be challenging using IMAP-DOAS (Thorpe et al., 2014). To address this, an alternative hybrid approach using both IMAP-DOAS and Singular Value Decomposition (SVD) of surface reflectance properties at background CH₄ concentrations was also developed for AVIRIS (Thorpe et al., 2014). SVD is closely related to Principal Component Analysis (PCA) and has been used in a number of remote sensing applications to reduce computation time by summarizing high dimensional data (Kluser et al., 2011; Guanter et al., 2012). SVD is based on the transformation of a large number of potentially correlated vectors into a smaller set of uncorrelated (orthogonal) vectors that are denoted as singular vectors (Press et al., 2007; Rodgers, 2000).

For this study, the hybrid approach was modified for use with AVIRIS-NG. Based on a simple non-scattering radiative transfer scheme, IMAP-DOAS is used as a forward radiative transfer model at high spectral resolution using 10 atmospheric layers and the gases CH₄, H₂O, and N₂O to calculate modeled radiance at each wavelength. The high resolution modeled radiance is then convolved with the instrument lineshape function (ILS) and sampled to the center wavelengths of each AVIRIS-NG spectral band. This generates

216 a lower resolution modeled radiance at the i -th iteration of the state vector ($\mathbf{F}^{lr}(\mathbf{x}_i)$),
 217 calculated using a known reference total optical density τ^{ref} scaled by $\mathbf{x}_i$, the trace gas
 218 related state vector at the i -th iteration. Additional details on the IMAP-DOAS portion of
 219 the hybrid retrieval can be found in Thorpe et al. (2014).

220 A Jacobian Matrix is calculated for each iteration i , where each column represents the
 221 derivate vector of the sensor radiance with respect to each element of the state vector ($\mathbf{x}_i$)
 222 as follows

$$223 \quad \mathbf{K}_i = \left. \frac{\partial \mathbf{F}^{lr}(\mathbf{x})}{\partial \mathbf{x}} \right|_{\mathbf{x}_i}. \quad (1)$$

224 The Jacobian Matrix and forward model is used to optimize the state vector at the i -th
 225 iteration as described in Rodgers (2000).

226 An example of a high resolution CH_4 Jacobian is shown in Figure 3a (light red),
 227 indicating weaker absorption features between 1,600 to 1,820 nm and stronger absorptions
 228 between 2,130 and 2,450 nm. The water vapor (H_2O) Jacobian is also shown in Figure 3b
 229 (light blue) and indicates some spectral overlap with CH_4 . AVIRIS-NG was not designed
 230 for CH_4 detection and because its relatively coarse spectral resolution is far wider than
 231 individual gas absorption features it cannot fully resolve the individual CH_4 absorption
 232 lines shown by the high resolution CH_4 Jacobian. As a result, CH_4 sensitivity is reduced
 233 compared to instruments with finer spectral resolutions and there are potential interferences
 234 with lower spectral resolution surface albedo features. Convolved results using the
 235 AVIRIS-NG ILS function are also shown for CH_4 (Figure 3a, dark red) and H_2O (Figure
 236 3b, dark blue). Although CH_4 absorption features are weaker between 1,600 to 1,820 nm,

reflected radiances generally are higher at shorter wavelengths as compared to the lower radiances present for strong absorptions between 2,130 and 2,450 nm (Figure 3c).

Figure 3. a. Example of a high resolution CH_4 Jacobian (light red) and convolved results using the AVIRIS-NG ILS function (dark red). b. High resolution H_2O Jacobian (light blue) and convolved results (dark blue). c. Example AVIRIS-NG radiances for bare soil, senesced vegetation, and green vegetation.

For this study, the hybrid IMAP/SVD approach was applied individually to each spatial row (along track element) of the AVIRIS-NG detector independently prior to orthorectification. This minimizes striping effects due to small variability in detector characterization across the focal plane. Radiance first was standardized by fitting a first order polynomial to each spectrum and dividing it by the polynomial fit. For each along track element e , a mean radiance spectrum was calculated from the standardized data and

252 the IMAP-DOAS retrieval was performed on the mean spectrum to generate the CH₄
 253 Jacobian ($\mathbf{K}_{CH_4,e}$).

254 We constructed an $m \times n$ matrix $\mathbf{L}_e$ for each along track element e , where m is the
 255 number of spectral bands (for the CH₄ fit window) and n is the number of radiance spectra
 256 in each along track element as follows

$$257 \quad \mathbf{L}_e = \mathbf{U}_e \mathbf{\Lambda}_e \mathbf{V}_e^T. \quad (2)$$

258 where the $m \times m$ matrix $\mathbf{U}_e$ contains the left singular vectors, the matrix $\mathbf{V}_e$ contains the
 259 right singular vectors in their respective columns, and matrix $\mathbf{\Lambda}_e$ contains the m singular
 260 values of $\mathbf{L}_e$ on its diagonal. $\mathbf{L}_e$ can be recomposed as a linear combination of singular
 261 vectors scaled by the singular values (Murtagh & Heck, 1987).

262 $\mathbf{U}_{select}$, an $m \times c$ matrix using the first c columns of $\mathbf{U}_e$ (optimal selection of c is
 263 described below) and the CH₄ Jacobian ($\mathbf{K}_{CH_4,e}$, an $m \times 1$ matrix) are concatenated to
 264 generate a matrix $\mathbf{J}_e$ (dimensions of $m \times c+1$). Next, linear least squares can be used to find
 265 a vector $\mathbf{W}_e$ that minimizes the cost function (equation 3) for each of the measured radiance
 266 spectra $\mathbf{y}$ within each along track element e :

$$267 \quad ||\mathbf{y} - \mathbf{J}_e \mathbf{W}_e||^2. \quad (3)$$

268 where $\mathbf{W}_e$ represents the contribution of each column of $\mathbf{J}_e$ to the measured radiance.
 269 Modeled radiance $\mathbf{F}$ can be calculated as the sum of the background and CH₄ component
 270 of the radiance as follows:

$$271 \quad \mathbf{F}(\mathbf{W}_e, \mathbf{J}_e) = \sum_{k=1}^c \mathbf{J}_{e,k} \cdot \mathbf{W}_{e,k} + \mathbf{J}_{e,c+1} \cdot \mathbf{W}_{e,c+1} \quad (4)$$

The left term represents the background radiance modeled as a linear combination of the first c eigenvectors of $\mathbf{J}_e$ ($\mathbf{J}_{e,k}$) multiplied by the corresponding weights $\mathbf{W}_{e,k}$. The right term is the CH_4 component of the scene, the product of $\mathbf{J}_{e,c+1}$ (the CH_4 Jacobian, $\mathbf{K}_{\text{CH}_4,e}$) and its corresponding weight $\mathbf{W}_{e,c+1}$ (denoted as RCH_4).

RCH_4 indicates how much of the observed radiance for each spectrum can be associated with the CH_4 Jacobian (i.e. changes in absorption due to CH_4). RCH_4 is multiplied by the volume mixing ratio (VMR) for the lowest layer of the reference atmosphere to estimate the CH_4 concentration in ppm above/below background. This represents an empirical method of computing the forward model radiance, including many detector and surface albedo features that can be problematic for the IMAP-DOAS approach at coarse spectral resolutions (Thorpe et al., 2014).

The hybrid approach used a 29 band retrieval window between 2,278 and 2,423 nm, similar to a previous study using AVIRIS (Thorpe et al., 2014). To determine the optimal number of c columns of $\mathbf{U}_e$ used to generate $\mathbf{U}_{\text{select}}$, the hybrid retrieval was performed iteratively by increasing the c columns. This resulted in 29 retrievals that were assessed by minimizing the standard deviation of the RCH_4 results for the portion of the scene representing homogeneous landcover. Although the retrieval was applied to non-orthorectified data, these results were subsequently orthorectified to generate a planimetrically correct image. Additional details on the hybrid retrieval can be found in Thorpe et al. (2014).

5. Matched filter detection

In addition to the hybrid retrieval, a non-quantitative matched filter technique was also applied to AVIRIS-NG scenes. The matched filter is well suited for detecting weak signals overlaid on a cluttered background and has been used to detect simulated gas plumes in the thermal infrared (Funk et al., 2001; Theiler & Foy, 2006). It generates a linear weighting function that produces high values when an unknown spectrum matches the shape of a known gas target spectrum and uses the inverse of the scene's covariance structure to remove large-scale noise (background clutter) while isolating the gas signal.

To generate the CH₄ target for this study, one CH₄ Jacobian was generated with IMAP-DOAS using an average radiance generated from an AVIRIS-NG scene (see section 4, equation 1). The matched filter is 'matched' to both the gas signature as well as the background clutter and was calculated using the following equation applied to each along track element e of the non-orthorectified AVIRIS-NG radiance images

$$\mathbf{q}_e = \frac{\mathbf{C}_e^{-1} \mathbf{b}}{\sqrt{\mathbf{b}^T \mathbf{C}_e^{-1} \mathbf{b}}} \quad (5)$$

where $\mathbf{q}_e$ is the matched filter and represents an m -dimensional vector of optimal weights, where m is the number of spectral channels. $\mathbf{C}_e^{-1}$ is the inverted $m \times m$ covariance matrix, $\mathbf{b}$ is the m -dimensional vector containing the CH₄ target spectrum (CH₄ Jacobian), and T is the transpose operator.

All 427 AVIRIS-NG spectral channels were used for the matched filter algorithm and radiance was first standardized by subtracting the mean and dividing by the standard deviation of the scene, both scalar values. For each image pixel, a matched filter score was calculated by multiplying the transpose of the matched filter by the standardized radiance. Scores greater than one indicate significant evidence of the gas signature, which can be quantified by the 'number of sigmas' for the z distribution. A detailed description

of the matched filter algorithm is available in Funk et al. (2001) and Thorpe et al. (2013). Similar to the hybrid retrieval results, matched filter results were subsequently orthorectified to generate a planimetrically correct image.

The matched filter detection algorithm is not quantitative and in previous studies has been used to provide an image of gas anomalies (Thorpe et al., 2013; Thorpe et al., 2014). Anomalies then can be evaluated for consistency with probable emissions sources and local wind direction. In this study, segmentation based on 8-connectivity was applied to the matched filter results to isolate contiguous pixels with matched filter scores greater than 2 (equivalent to 2 standard deviations) and minimum population size of 16 pixels. Segmented matched filter results were used to generate a mask that was applied to results from the hybrid retrieval. Because the matched filter CH₄ detection sensitivity appears greater than for the hybrid retrieval (Thorpe et al., 2014), this method allows for an improved means of isolating CH₄ plumes.

6. Results:

6.1 Multiple fluxes and flight altitudes

A total of 5 of the 29 columns of $\mathbf{U}_e$ were used to generate $\mathbf{U}_{\text{select}}$ (see section 4 for selection criteria). The weights (RCH4) were multiplied by the VMR for the lowest layer of the reference atmosphere in order to estimate CH₄ concentration in ppm above/below background averaged over a 1 km subcolumn. In Figure 4 (a, e, i), true color images are provided for three AVIRIS-NG overflights acquired at location X-N for a 56.6 m³/h (2,000 scfh) flux and a flight altitude of 0.58 km AGL (0.5 m pixel resolution). The corresponding retrieval results are also shown (Figure 4b, f, j) clearly indicating that

plume shapes vary considerably during the duration of these flights (20:01:13-20:16:39 UTC, 23 June 2013). For each example, transects are indicated (start and end as red dots) and CH₄ enhancements are plotted (blue line) relative to distance along the transect (Figure 4c, g, k). The highest CH₄ enhancements are observed at the release point (near the start of transects at A, C, E) and transects cross various land cover types (Figure 4a, e, i). In Figure 4c, g, k for the transect, radiance at 2,278 nm (band 1 of the retrieval fitting window) is plotted as black points, indicating that radiance varies considerably along the transect. In Figure 4d, h, l, scatterplots of CH₄ enhancements and radiance show a greater spread in retrieval results for darker surfaces and indicate a small radiance dependency. In subsequent figures, AVIRIS-NG CH₄ retrievals will be displayed as plumes overlaid on true color images with enhancements shown in g/m² and ppm (for a 1 km layer).

Figure 4. a. AVIRIS-NG true color image for 23 June 2013 at 20:01:13 UTC. b. For the same image, CH₄ retrievals are shown. c. For transect extending from A to B (see b), CH₄ enhancements are shown (ppm, for a 1 km layer) as blue line and radiance (at band 1 of the fitting window, 2,278 nm) is plotted as black points. d. Scatterplot of radiance (2,278 nm) and CH₄ enhancements for retrieval result (see b). e. True color image at 20:05:09 UTC. f. CH₄ retrievals for 20:05:09 UTC scene. g. For transect from C to D (see f), CH₄ enhancements and radiance are shown. h. Scatterplot of radiance and CH₄ enhancements

for 20:05:09 UTC retrieval result (see f). i. True color image at 20:16:39 UTC. j. CH₄ retrievals for 20:16:39 UTC scene. k. For transect from E to F (see j), CH₄ enhancements and radiance are shown. l. Scatterplot of radiance and CH₄ enhancements for 20:16:39 UTC retrieval result (see j). All results are for 0.58 km AGL flights (pixel resolution is 0.5 m) at site X-N with a 56.6 m³/h (2,000 scfh) flux.

An assessment of the plume shapes and orientations shows consistency with the wind direction as measured by the meteorological towers at each site. Further, higher winds produce elongated plumes compared to the more compact appearance for lower wind speeds. For example, the three plumes shown in Figure 5a, d, g indicate orientations that agree well with the wind direction measured by nearby meteorological towers (Figure 5b, e, h). For the one minute period prior to the 20:05:09 UTC scene (Figure 5d), the mean speed was 6.98 m/s (standard deviation of 1.39 m/s) and the plume appears elongated (56.6 m maximum length, 5.5 m maximum width) compared to the more compact plume observed in Figure 5g for a 3.75 m/s mean wind speed (50.1 m maximum length, 10.4 m maximum width). Further, the maximum observed concentration (9.1 ppm, 5.1 g/m²) is higher for the low wind speed example compared with the high wind case (3.0 ppm, 1.7 g/m²). This is also consistent with expected longer CH₄ residence times near the sources at low wind speeds, resulting in larger column enhancements.

Using the high resolution wind data acquired at the meteorological tower, we can compute trajectories under the simplified assumption that the wind speed at the tower is representative of the small region that includes the release point at the time of measurement. In Figure 5c, f, i, trajectories were calculated for a particle originating at the release point 3 (red), 6 (green), and 9 seconds (blue) prior to the time of image

acquisition and these trajectories bound the extent of observed plumes at 20:01:13 and 20:05:09 UTC (Figure 5c, f respectively). The 20:16:39 UTC example (Figure 5i) indicates less agreement likely due to variable winds prior to image acquisition and low wind speeds (see Figure 5h).

Figure 5. At site X-N with a 56.6 m³/h (2,000 scfh) flux for 0.58 km AGL flights, AVIRIS-NG quantitative CH_4 retrievals are overlaid on true color images for plumes observed on 23 June 2013 at 20:01:13 UTC (a), 20:05:09 UTC (d), and 20:16:39 UTC (g). CH_4 enhancements are shown in g/m² and ppm (for a 1 km layer). b. Wind speed and direction were measured by nearby meteorological tower. For the one minute period prior to 20:01:13 UTC scene, mean wind direction was 241.0° (standard deviation of 13.7°) and mean speed was 4.48 m/s (standard deviation of 1.05 m/s). c. Trajectories calculated

for 3 (red), 6 (green), and 9 seconds (blue) prior to the time of image acquisition (20:01:13 UTC). e. For the period 20:04:09-20:05:09 UTC, mean wind direction was 243.5° (standard deviation of 8.2°) and mean speed was 6.98 m/s (standard deviation of 1.39 m/s). f. Trajectories calculated for 3 (red), 6 (green), and 9 seconds (blue) prior to time of image acquisition (20:05:09 UTC). h. For the period 20:15:39-20:16:39 UTC, mean wind direction was 247.0° (standard deviation of 12.2°) and mean speed was 3.75 m/s (standard deviation of 1.12 m/s). i. Trajectories calculated for 3 (red), 6 (green), and 9 seconds (blue) prior to time of image acquisition (20:16:39 UTC).

In Figure 6, 3 plumes are visible at location X-C for a flux rate of 14.2 m³/h (500 scfh). These scenes were acquired a few minutes apart at a flight altitude of 0.43 km AGL (0.4 m pixel resolution) and the plumes appear broadly consistent with the wind speed and direction (Figure 6b, d, f). For these examples, observed plume lengths are on the order of 10 to 20 m (Figure 6) and the maximum observed concentration is 2.7 ppm (1.5 g/m²). As expected, these values are lower than those for the three higher flux examples (56.6 m³/h, 2,000 scfh) shown in Figure 5. In addition, AVIRIS-NG consistently observed CH₄ plumes at multiple flight altitudes. This is important because increasing flight altitude improves ground coverage, which would be an important prerequisite for monitoring large areas. In Figure 7, plumes are shown at site X-N with a 56.6 m³/h (2,000 scfh) flux for 0.58, 1.10, and 2.00 km AGL flights.

Figure 6. At site X-C with a 14.2 m³/h (500 scfh) flux for 0.43 km AGL flights (pixel resolution is 0.4 m), AVIRIS-NG quantitative CH₄ retrievals are overlaid on true color images for plumes observed on 24 June 2013 at 17:15:25 UTC (a), 17:24:36 UTC (c), and 17:32:46 UTC (e). CH₄ enhancements are shown in g/m² as well as ppm (for a 1 km layer). b. For the one minute period prior to 17:15:25 UTC scene, mean wind direction was 169.2° (standard deviation of 12.4°) and mean speed was 3.74 m/s (standard deviation of 1.03 m/s). d. For the period 17:23:36-17:24:36 UTC, mean wind direction was 207.9° (standard deviation of 17.6°) and mean speed was 3.47 m/s (standard deviation of 0.85 m/s). f. For the period 17:31:46-17:32:46 UTC, mean wind direction was 197.0° (standard deviation of 7.9°) and mean speed was 4.88 m/s (standard deviation of 0.77 m/s).

Figure 7. At site X-N with a 56.6 m³/h (2,000 scfh) flux, AVIRIS-NG quantitative CH₄ retrievals are overlaid on true color images for plumes observed on 23 June 2013 at flight altitudes of 0.58 (a), 1.10 (c), and 2.00 km AGL (e). CH₄ enhancements are shown in g/m² and ppm (for a 1 km layer). b. For the one minute period prior to 20:16:39 UTC scene, mean wind direction was 247.0° (standard deviation of 12.2°) and mean speed was 3.75 m/s (standard deviation of 1.12 m/s). d. For the period 17:17:22-17:18:22 UTC, mean wind direction was 231.0° (standard deviation of 11.9°) and mean speed was 5.53 m/s (standard deviation of 0.66 m/s). f. For the period 18:39:06-18:40:06 UTC, mean wind direction was 182.4° (standard deviation of 18.1°) and mean speed was 3.16 m/s (standard deviation of 0.75 m/s).

6.2 Summary of all results

For the flight campaign, AVIRIS-NG was flown at 0.43, 0.58, 1.10, 2.00, and 3.80 km AGL with spatial resolutions of 0.4, 0.5, 1.0, 1.9, and 3.6 m for each image pixel, respectively. All AVIRIS-NG results are summarized in Figure 8 for a range of flux rates

and wind speeds. A segmentation approach based on 8-connectivity was used to isolate adjacent pixels of the CH₄ plume (see section 5). Segmentation used matched filter scores greater than 2 (i.e. >2 standard deviations) and a minimum of 16 adjacent pixels. This criterion permitted automatic detection by the algorithm, denoted as green circles in Figure 8. Green crosses indicate partial detections (requiring user interpretation) and non-detections are shown as red circles.

The results in Figure 8 indicate that AVIRIS-NG consistently detected CH₄ plumes for a range of flux rates and wind speeds. This trend is observed in Table 2, where detection percentages are calculated for each flux range and the majority are detections for flux ranges greater than 301 scfh (8.5 m³/h). As seen in Figure 8b, c, d, non-detections increase as fluxes decrease to around 515 scfh (14.58 m³/h), 263 scfh (7.45 m³/h) and 120 scfh (3.40 m³/h). This trend is more clearly represented in Table 2, where non-detections increased to 16%, 27%, and 71% respectively for the 700-301 scfh (19.8-8.5 m³/h), 300-151 scfh (8.4-4.3 m³/h) and 150-0 scfh (4.2-0.0 m³/h) categories. Results are also listed by flight altitude in Table 3, showing that with increasing altitude, the percentage of detection decreased while partial detections increased.

Wind speed has been shown to influence the shape of plumes (Pooler, 1965; Carpenter et al., 1971), for example lower wind speeds tend to be associated with a more compact shape with higher maximum CH₄ concentrations (see section 6.1). Therefore, lower wind speeds will favor improved detection percentages given longer residence times near the source result in larger column enhancements. To investigate this, detection percentages were calculated for a number of wind speed ranges in Table 4. However, the percentage of detection is quite similar (63.3 to 70.6%) across most wind conditions (0.00

to 7.99 m/s). For winds between 8.00 to 10.00 m/s, the detection percentage drops to 0% with a 50% partial detection rate (note small sample size of 2 examples). Given these results, it appears that flux rate has the greatest influence on percentage of detection while the influence of winds is less clear.

Figure 8. a. For all flights (multiple altitudes) for entire range of flux rates and wind speeds, detections indicated by green circles (automatic detection by algorithm), green crosses denote partial detections (requiring user interpretation), and non-detections shown as red circles. Results for lower fluxes ranges are included in b, c, and d.

Table 2. AVIRIS-NG detections by flux range

	Count	% total	Count	% total	Count	% total	Count	% total	Count	% total	Count	% total	Count	% total
	6000-3001 scfh		3000-2201 scfh		2200-1701 scfh		1700-701 scfh		700-301 scfh		300-151 scfh		150-0 scfh	
	(169.9-85.0 m3/h)		(84.9-62.3 m3/h)		(62.2-48.2 m3/h)		(48.1-19.9 m3/h)		(19.8-8.5 m3/h)		(8.4-4.3 m3/h)		(4.2-0.0 m3/h)	
Detection	4	100.0%	10	100.0%	28	93.3%	15	68.2%	30	66.7%	6	40.0%	1	5.9%
Partial	0	0.0%	0	0.0%	2	6.7%	6	27.3%	8	17.8%	5	33.3%	4	23.5%
Non-detection	0	0.0%	0	0.0%	0	0.0%	1	4.5%	7	15.6%	4	26.7%	12	70.6%
Total	4	100.0%	10	100.0%	30	100.0%	22	100.0%	45	100.0%	15	100.0%	17	100.0%

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Table 3. AVIRIS-NG detections by altitude

	Count	% total	Count	% total	Count	% total	Count	% total
	<i>0.43 and 0.58 km AGL</i>		<i>1.1 km AGL</i>		<i>2.0 km AGL</i>		<i>3.8 km AGL</i>	
Detection	37	78.7%	43	69.4%	9	56.3%	5	27.8%
Partial	5	10.6%	7	11.3%	6	37.5%	8	44.4%
Non-detection	6	12.8%	12	19.4%	1	6.3%	8	27.8%
Total	47	100.0%	62	100.0%	16	100.0%	18	100.0%

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Table 4. AVIRIS-NG detections by wind speed range

	Count	% total	Count	% total	Count	% total	Count	% total	Count	% total
	<i>0.00 to 1.99 m/s</i>		<i>2.00 to 3.99 m/s</i>		<i>4.00 to 5.99 m/s</i>		<i>6.00 to 7.99 m/s</i>		<i>8.00 to 10.00 m/s</i>	
Detection	8	66.7%	36	70.6%	38	63.3%	9	64.3%	0	0.0%
Partial	3	25.0%	5	9.8%	13	21.7%	2	14.3%	1	50.0%
Non-detection	1	8.3%	10	19.6%	9	15.0%	3	21.4%	1	50.0%
Total	12	100.0%	51	100.0%	60	100.0%	14	100.0%	2	100.0%

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483 **7. Discussion and conclusion**

484 For the first time, a controlled release experiment has demonstrated that AVIRIS-NG

485 is capable of detecting CH₄ plumes for a range of fluxes using a matched filter approach.

486 Plumes were consistently observed between 14.16 and 141.58 m³/h (500 and 5,000 scfh)

487 for wind speeds that ranged from 0.5 to 8.0 m/s (Figure 8a; Table 4). Below 14.16 m³/h,

the percentage of detections decreased, however, plumes were observed as low as 3.40 m³/h (120 scfh) (Figure 8d). Observed plume shapes and orientations were broadly consistent with wind direction and higher winds produced elongated plumes while lower wind speeds resulted in a more compact and variable appearance. In addition, AVIRIS-NG observed plumes at altitudes ranging from 0.43 to 3.80 km AGL, resulting in spatial resolutions between 0.4 and 3.6 m per pixel. Sensitivity at the higher flight altitudes is particularly important given increased ground coverage is a prerequisite for future flight campaigns focused on detecting point source emissions over large areas. The results from the RMOTC experiment indicate the potential for using imaging spectrometers like AVIRIS-NG for detection of CH₄ plumes and to directly attribute emissions to individual point source locations across a range of CH₄ flux rates and wind conditions.

AVIRIS-NG detected plumes for the entire range of fluxes used during the controlled release experiment, between 3.40 and 141.58 m³/h (120 and 5,000 scfh). For comparison, published values for CH₄ emissions from natural gas production are shown in Figure 9. Fluxes are listed in m³/h on a logarithmic scale and are shown as ranges (grey bars) or mean values (black lines). Flux rates vary considerably from 0.05 to 0.58 m³/h for pneumatic controller (Allen et al., 2015a) to between 6.66 and 1,633.65 m³/h for liquid unloadings for gas wells without plunger lifts (Allen et al., 2015b). It is important to note that for each source category there is likely significant variability and uncertainty in published results, so these examples should not be viewed as definitive or comprehensive.

The range of fluxes tested at RMOTC are shown by the blue bar and the AVIRIS-NG sensitivity is shown in cyan, including fluxes higher than those tested at RMOTC. This

indicates AVIRIS-NG can be used to detect plumes from some of the larger emission sources in existing gas fields. For example, a study by the EPA (2006) listed a 33.68 m³/h average flux rate from the top ten emitters for a number of gas processing plants, which is well within the detection capability of AVIRIS-NG. Given the reported emission rates and the observed CH₄ sensitivity of AVIRIS-NG there is a potential to observe CH₄ plumes from liquid unloadings, tanks, some vents, and gas processing plants.

Since the RMOTC experiment, a new detector array with improved quantum efficiency has been installed in AVIRIS-NG. This along with additional enhancements in spectral alignment and calibration are expected to improve the CH₄ sensitivity of AVIRIS-NG. In addition, real time detection of CH₄ plumes has been implemented using an operator interface that overlays plumes on a true color image acquired by AVIRIS-NG (Thompson et al., 2015). This has facilitated surveys over existing oil and gas fields to identify and attribute CH₄ emissions to individual point sources, including wells (Thompson et al., 2015) and well pads known to use hydraulic fracturing for natural gas extraction (Aubrey et al., 2015).

Despite these promising results, it is important to emphasize that AVIRIS-NG was not designed for CH₄ detection. An imaging spectrometer built exclusively for detection, quantification, and attribution of CH₄ plumes would have much improved sensitivity compared to AVIRIS-NG (Thorpe et al., 2014). To that end, an instrument concept is currently being developed that uses an imaging spectrometer with finer spectral resolution for improved CH₄ sensitivity that would permit detection of smaller point sources and more diffuse emissions (Thorpe et al., 2016).

Figure 9. Published values of CH₄ emissions from natural gas production in m³/h on a logarithmic scale. Multiple emission categories are listed with sources referenced by numbers in parentheses as follows: (1) (Allen et al., 2015b), (2) (EPA, 2006), (3) (EPA, 2010), (4) (EPA, 2014), (5) (Allen et al., 2015a). Values are shown as ranges (grey bars) or mean values (black lines). For each source category there is significant variability and uncertainty. Range of fluxes used for RMOTC controlled release is shown in blue. Cyan bar represents AVIRIS-NG detection capability based on results from controlled release (above 3.40 m³/h, 120 scfh). AVIRIS-NG was not designed for CH₄ detection, but offers the potential for monitoring a number of source categories. Calculated fluxes from Allen et al. (2015b) assume average 1.51 hour event for gas wells with plunger lifts and 2.34 hour event with no plunger lifts.

Recent studies have suggested that a small number of ‘super emitters’ are responsible for the majority of fugitive emissions from natural gas systems and production sites (Brandt et al., 2014; Caulton et al., 2014; Allen et al., 2015a; Allen et al., 2015b). Results from the RMOTC controlled release experiment as well as subsequent surveys over oil

and gas fields indicate that AVIRIS-NG is capable of detecting the super emitters. One benefit of imaging spectrometers is they provide the ability to rapidly image large areas with the high spatial resolution required to locate emissions and attribute emissions to individual point sources. This offers the potential to effectively mitigate the impacts of fugitive CH₄ on global climate by identifying leaks and communicating these with site operators of oil and gas fields.

Global oil and gas production is projected to rise steadily and natural gas production is expected to increase 44% between 2011 and 2040 (EIA, 2013). This projected growth will primarily result from increased development of shale gas, tight gas, and coalbed CH₄ often using enhanced recovery techniques like hydraulic fracturing and horizontal drilling (EPA, 2014). Accordingly, fugitive CH₄ emissions are expected to rise (Caulton et al., 2014) and the ability to identify these emission sources will be of even greater importance.

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List of figure captions:

Figure 1. The Rocky Mountain Oilfield Testing Center is located approximately 50 km northeast of Casper, Wyoming. Outlined in red, it spans 10,000 acres of the Naval Petroleum Reserve No. 3 (NPR-3) and contains a number of oil and gas wells (black points). Three controlled release sites were located approximately collinear (shown in green), including sites X-N ($43^{\circ} 20.100'N$, $106^{\circ} 14.148'W$), X-C ($43^{\circ} 19.365'N$, $106^{\circ} 13.653'W$), and X-S ($43^{\circ} 18.200'N$, $106^{\circ} 13.064'W$). Image data provided by RMOTC and the U.S. DOE.

Figure 2. a. Twin Otter aircraft used with AVIRIS-NG. b. Trailer tank storing CH_4 at one of controlled release sites. c. Controlled release using square diffuser. d. Meteorological tower at site X-S equipped with suite of meteorological instrumentation that includes wind speed and direction.

Figure 3. a. Example of a high resolution CH_4 Jacobian (light red) and convolved results using the AVIRIS-NG ILS function (dark red). b. High resolution H_2O Jacobian (light blue) and convolved results (dark blue). c. Example AVIRIS-NG radiances for bare soil, senesced vegetation, and green vegetation.

Figure. 4. a. AVIRIS-NG true color image for 23 June 2013 at 20:01:13 UTC. b. For the same image, CH_4 retrievals are shown. c. For transect extending from A to B (see b), CH_4 enhancements are shown (ppm, for a 1 km layer) as blue line and radiance (at band 1 of the fitting window, 2,278 nm) is plotted as black points. d. Scatterplot of radiance (2,278 nm) and CH_4 enhancements for retrieval result (see b). e. True color image at 20:05:09

UTC. f. CH₄ retrievals for 20:05:09 UTC scene. g. For transect from C to D (see f), CH₄ enhancements and radiance are shown. h. Scatterplot of radiance and CH₄ enhancements for 20:05:09 UTC retrieval result (see f). i. True color image at 20:16:39 UTC. j. CH₄ retrievals for 20:16:39 UTC scene. k. For transect from E to F (see j), CH₄ enhancements and radiance are shown. l. Scatterplot of radiance and CH₄ enhancements for 20:16:39 UTC retrieval result (see j). All results are for 0.58 km AGL flights (pixel resolution is 0.5 m) at site X-N with a 56.6 m³/h (2,000 scfh) flux.

Figure 5. At site X-N with a 56.6 m³/h (2,000 scfh) flux for 0.58 km AGL flights, AVIRIS-NG quantitative CH₄ retrievals are overlaid on true color images for plumes observed on 23 June 2013 at 20:01:13 UTC (a), 20:05:09 UTC (d), and 20:16:39 UTC (g). CH₄ enhancements are shown in g/m² and ppm (for a 1 km layer). b. Wind speed and direction were measured by nearby meteorological tower. For the one minute period prior to 20:01:13 UTC scene, mean wind direction was 241.0° (standard deviation of 13.7°) and mean speed was 4.48 m/s (standard deviation of 1.05 m/s). c. Trajectories calculated for 3 (red), 6 (green), and 9 seconds (blue) prior to the time of image acquisition (20:01:13 UTC). e. For the period 20:04:09-20:05:09 UTC, mean wind direction was 243.5° (standard deviation of 8.2°) and mean speed was 6.98 m/s (standard deviation of 1.39 m/s). f. Trajectories calculated for 3 (red), 6 (green), and 9 seconds (blue) prior to time of image acquisition (20:05:09 UTC). h. For the period 20:15:39-20:16:39 UTC, mean wind direction was 247.0° (standard deviation of 12.2°) and mean speed was 3.75 m/s (standard deviation of 1.12 m/s). i. Trajectories calculated for 3 (red), 6 (green), and 9 seconds (blue) prior to time of image acquisition (20:16:39 UTC).

846

847 Figure 6. At site X-C with a $14.2 \text{ m}^3/\text{h}$ (500 scfh) flux for 0.43 km AGL flights (pixel
848 resolution is 0.4 m), AVIRIS-NG quantitative CH_4 retrievals are overlaid on true color
849 images for plumes observed on 24 June 2013 at 17:15:25 UTC (a), 17:24:36 UTC (c),
850 and 17:32:46 UTC (e). CH_4 enhancements are shown in g/m^2 as well as ppm (for a 1 km
851 layer). b. For the one minute period prior to 17:15:25 UTC scene, mean wind direction
852 was 169.2° (standard deviation of 12.4°) and mean speed was 3.74 m/s (standard
853 deviation of 1.03 m/s). d. For the period 17:23:36-17:24:36 UTC, mean wind direction
854 was 207.9° (standard deviation of 17.6°) and mean speed was 3.47 m/s (standard
855 deviation of 0.85 m/s). f. For the period 17:31:46-17:32:46 UTC, mean wind direction
856 was 197.0° (standard deviation of 7.9°) and mean speed was 4.88 m/s (standard deviation
857 of 0.77 m/s).

858

859 Figure 7. At site X-N with a $56.6 \text{ m}^3/\text{h}$ (2,000 scfh) flux, AVIRIS-NG quantitative CH_4
860 retrievals are overlaid on true color images for plumes observed on 23 June 2013 at flight
861 altitudes of 0.58 (a), 1.10 (c), and 2.00 km AGL (e). CH_4 enhancements are shown in
862 g/m^2 and ppm (for a 1 km layer). b. For the one minute period prior to 20:16:39 UTC
863 scene, mean wind direction was 247.0° (standard deviation of 12.2°) and mean speed was
864 3.75 m/s (standard deviation of 1.12 m/s). d. For the period 17:17:22-17:18:22 UTC,
865 mean wind direction was 231.0° (standard deviation of 11.9°) and mean speed was 5.53
866 m/s (standard deviation of 0.66 m/s). f. For the period 18:39:06-18:40:06 UTC, mean
867 wind direction was 182.4° (standard deviation of 18.1°) and mean speed was 3.16 m/s
868 (standard deviation of 0.75 m/s).

869

870 Figure 8. a. For all flights (multiple altitudes) for entire range of flux rates and wind
871 speeds, detections indicated by green circles (automatic detection by algorithm), green
872 crosses denote partial detections (requiring user interpretation), and non-detections shown
873 as red circles. Results for lower fluxes ranges are included in b, c, and d.

874

875 Figure 9. Published values of CH₄ emissions from natural gas production in m³/h on a
876 logarithmic scale. Multiple emission categories are listed with sources referenced by
877 numbers in parentheses as follows: (1) (Allen et al., 2015b), (2) (EPA, 2006), (3) (EPA,
878 2010), (4) (EPA, 2014), (5) (Allen et al., 2015a). Values are shown as ranges (grey bars)
879 or mean values (black lines). For each source category there is significant variability and
880 uncertainty. Range of fluxes used for RMOTC controlled release is shown in blue. Cyan
881 bar represents AVIRIS-NG detection capability based on results from controlled release
882 (above 3.40 m³/h, 120 scfh). AVIRIS-NG was not designed for CH₄ detection, but offers
883 the potential for monitoring a number of source categories. Calculated fluxes from Allen
884 et al. (2015b) assume average 1.51 hour event for gas wells with plunger lifts and 2.34
885 hour event with no plunger lifts.