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Crosscutting Airborne Remote Sensing Technologies for Oil and Gas and Earth Science Applications

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Abstract

Airborne imaging spectroscopy has evolved dramatically since the 1980s as a robust remote sensing technique used to generate 2-dimensional maps of surface properties over large spatial areas. Traditional applications for passive airborne imaging spectroscopy include interrogation of surface composition, such as mapping of vegetation diversity and surface geological composition. Two recent applications are particularly relevant to the needs of both the oil and gas as well as government sectors: quantification of surficial hydrocarbon thickness in aquatic environments and mapping atmospheric greenhouse gas components. These techniques provide valuable capabilities for petroleum seepage in addition to detection and quantification of fugitive emissions.

New empirical data that provides insight into the source strength of anthropogenic methane will be reviewed, with particular emphasis on the evolving constraints enabled by new methane remote sensing techniques. Contemporary studies attribute high-strength point sources as significantly contributing to the national methane inventory and underscore the need for high performance remote sensing technologies that provide quantitative leak detection. Imaging sensors that map spatial distributions of methane anomalies provide effective techniques to detect, localize, and quantify fugitive leaks. Airborne remote sensing instruments provide the unique combination of high spatial resolution (<1 m) and large coverage required to directly attribute methane emissions to individual emission sources. This capability cannot currently be achieved using spaceborne sensors.

In this study, results from recent NASA remote sensing field experiments focused on point-source leak detection, will be highlighted. This includes existing quantitative capabilities for oil and methane using state-of-the-art airborne remote sensing instruments. While these capabilities are of interest to NASA for assessment of environmental impact and global climate change, industry similarly seeks to detect and localize leaks of both oil and methane across operating fields. In some cases, higher sensitivities desired for upstream and downstream applications can only be provided by new airborne remote sensing instruments tailored specifically for a given application. There exists a unique opportunity for alignment of efforts between commercial and government sectors to advance the next generation of instruments to provide more sensitive leak detection capabilities, including those for quantitative source strength determination.

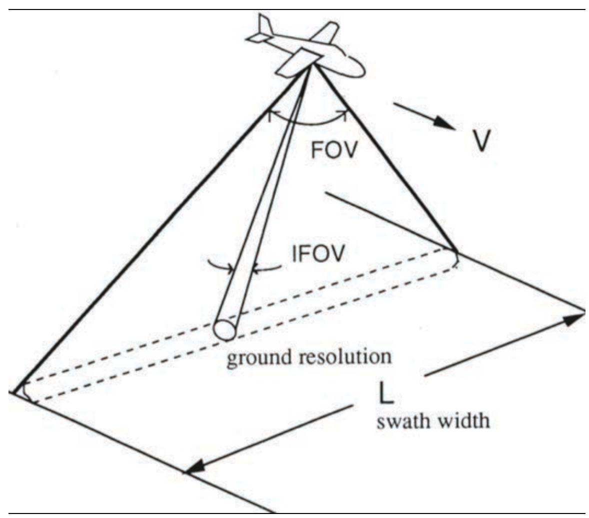

Figure 1. Concept of airborne imaging spectroscopy (Murai, 1995).

Introduction

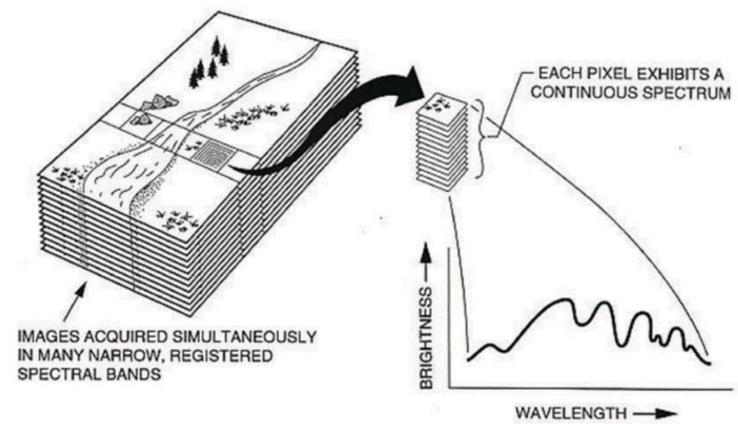

Figure 2. Imaging spectrometer data product example. For each pixel, a contiguous spectrum is generated across the spectrometer wavelength range for all optical channels. Figure credit NASA-JPL.

The Jet Propulsion Laboratory (JPL), a NASA Federally Funded Research and Development Center (FFRDC) operated by the California Institute of Technology, has been a pioneer in optical remote sensing since the 1980s. JPL capabilities include expertise across all project phases, from sensor design, construction, airborne experiment execution, and data product generation driven by science and customer needs. JPL has particular expertise in imaging spectroscopy, a passive method to interrogate objects or surfaces without physical contact. Such remote sensing has traditionally been applied to investigation of surface composition in terrestrial environments. These surface compositions are characterized using a spectral library which includes the surface reflectance or emissivity "fingerprints" of constituent materials. Airborne imaging spectrometers provide a powerful method to survey wide spatial extents and high performance surface characterization due to the wide contiguous spectral range at moderate spectral resolution. Novel quantitative methods have recently emerged for both atmospheric gases and surficial oil on water. These applications will be discussed here including contemporary airborne results.

Imaging Spectrometer Parameters

Airborne pushbroom imaging spectrometers incorporate a 2-D focal plane array to collect data over a wide swath beneath the aircraft using a nadir-mounted sensor (Figure 1). The areal coverage and spatial resolution depend on the sensor design characteristics as well as altitude. The cross track sensor characteristics include the sensor Field of View (FOV), which determines the swath coverage as a function of altitude, while an instantaneous FOV (IFOV) defines the across track resolution, or pixel size as projected on the ground. The ground resolution is also commonly referred to as ground sample distance (GSD). Based on these sensor characteristics, a simple geometric relationship links sensor characteristics to cross-track performance parameters (Equations 1 and 2).

Equation 1. $$\text{Swath Width} = 2 \cdot \text{Altitude} \cdot \text{Tan}\left[\frac{\text{FOV}}{2}\right]$$

Equation 2. $$\text{Ground Sample Distance} = \text{Altitude} \cdot \text{Tan}\left[IFOV\right]$$

Contemporary JPL pushbroom airborne imaging spectrometers include two major types: Offner and Dyson spectrometers. Offner spectrometers operate by collecting light through a narrow optical slit and using a dispersive grating and multiple mirrors, focus light onto the focal plane array (FPA) with high spectral uniformity. Thus during flight pushbroom sensors image simultaneously pixels beneath the aircraft across the entire sensor swath width. The FPA images discrete spectral channels across the entire contiguous spectral range (axis-1) while cross track spatial information is captured across the second axis (Figure 2). The original AVIRIS sensor was built as a whiskbroom sensor which imaged using a linear detector array – a scan mirror was used to provide spatial coverage in the cross-track direction. Pushbroom approaches eliminate any moving optical subsystems by implementing a fixed optical train. In order to optimize sensor performance with respect to the signal to noise ratio, it is helps to fly slowly with these systems (80-100 kts) to enhance oversampling. The second type of spectrometer that JPL specializes in are Dyson spectrometers. The main difference in Dyson spectrometer designs compared to Offner types is that the dispersion is accomplished using an arsenic-doped silicon block. These Dyson designs often result in a smaller form factor, particularly in the thermal infrared region of the spectrum, while still maintaining excellent spectral uniformity.

Imaging Spectrometer Science Application Areas

Improvements in the technical performance of imaging spectrometers and science data analysis strategies (including software) has led to rapid expansion of science and technology focus areas using imaging spectrometers. This can be summarized generally in terms of moving from "…*basic landscape classification to full spectral quantification and analysis* (Ben-Dor et al., 2013)." The breadth of these advanced airborne scientific applications are summarized below (Table 1).

Table 1. Subset of imaging spectroscopy applications at advanced maturity with cross-cutting commercial and government applications. Table based on Ben-Dor et al. (2013) and Staenz (2009). Many applications require spectral mixture analysis.

Category	Application	Science	Application
Surface feature investigation	Surveillance and target identification	Safety Monitoring	National Security
	Urban/ocean mapping, Environmental; Monitoring	Environmental disturbances, slope instability	National Security, Disaster management, fisheries investigations
	Infrastructure monitoring	Asphalt condition	Disaster preparedness and forecasting
Surface Composition Investigation	Geology (Lithosphere, Cryosphere)	Mapping of specific minerals	Mining industry to identify specific minerals and map natural resources
	Terrestrial Ecology (Biosphere)	Ecosystem monitoring	Change detection through persistent analysis (regulatory / environmental)
		Precision agriculture	Vegetation species detection
		Vegetation Health (chlorophyll-a detection)	Precision Agriculture
		Citrus tree detection	MESMA approach
	Cryosphere (Hydrosphere)	Snow parameters (dust)	Snow melt prediction (albedo)
	Soil Properties (Pedosphere)	Detection of contaminants, salts, or ammonium in soil	Forecasting of natural hazards – mapping variability of soil properties (landslide events)
		Compaction assessment	Natural Hazard Forecasting
Ocean Monitoring	Water quality (Hydrospherer)	CDOM, Turbidity	Environmental impacts of coastal runoff (anthropogenic and natural)
	Minor constituents	**Oil surface slicks**, dissolved organics	**Contaminant release**
	Particulates	Turbidity	Storm assessment
	Biogeochemistry	Coral maps / health	Change detection through persistent analysis (regulatory / environmental
	Microorganism discrimination (e.g. phytoplankton)	Biodiversity	Researchers
Atmospheric Investigation	Dominant atmospheric constituents	Water Vapor Content	NOAA interest
		Aerosol Load	Identifying / quantifying anthropogenic greenhouse gas emissions
		Oxygen	Atmospheric science
		CO_2	Global Climate Change (verification of treaty requirements)
		Forest fire and smoke monitoring	U.S. Forest Service
	Trace Gas Detection	**Methane**	**Global Climate Change**
		Asbestos (airborne)	Disaster management

APPLICATION #1: Imaging Spectrometer Applications for Investigation of Oil on Water

The Deepwater Horizon Oil spill began on 20-April-2010. One of the NASA remote sensing instruments was deployed less than a month later: the Airborne Visible Infrared Imaging Spectrometer (AVIRIS). Due to the desire to image large areas of the oil spill, the sensor was deployed on the NASA ER-2 platform on 17-May-2010. The ER-2 surveys at high altitudes (~20km) in order to maximize spatial coverage (i.e. 12.2 km swath width). While this option for high altitude deployment maximizes achievable spatial coverage, it is not suitable for all science applications (e.g. 20 meters per pixel GSD).

The results from these experiments revealed the suitability of optical remote sensing for oil slick assessment in the visible (0.4-0.7 μm), near infrared regions (1.2, 1.7 μm), and shortwave infrared regions (2.3 μm). Figure 3 demonstrates results from these optical remote sensing observations, including oil on water using the sensor's visible channels (Figure 3a) and near infrared channels (Figure 3b). It was demonstrated through correlation with laboratory measurements that the depth of the 1.2 micron hydrocarbon absorption feature (Figure 2c) provides quantitative oil thickness information (Clark et al., 2010).

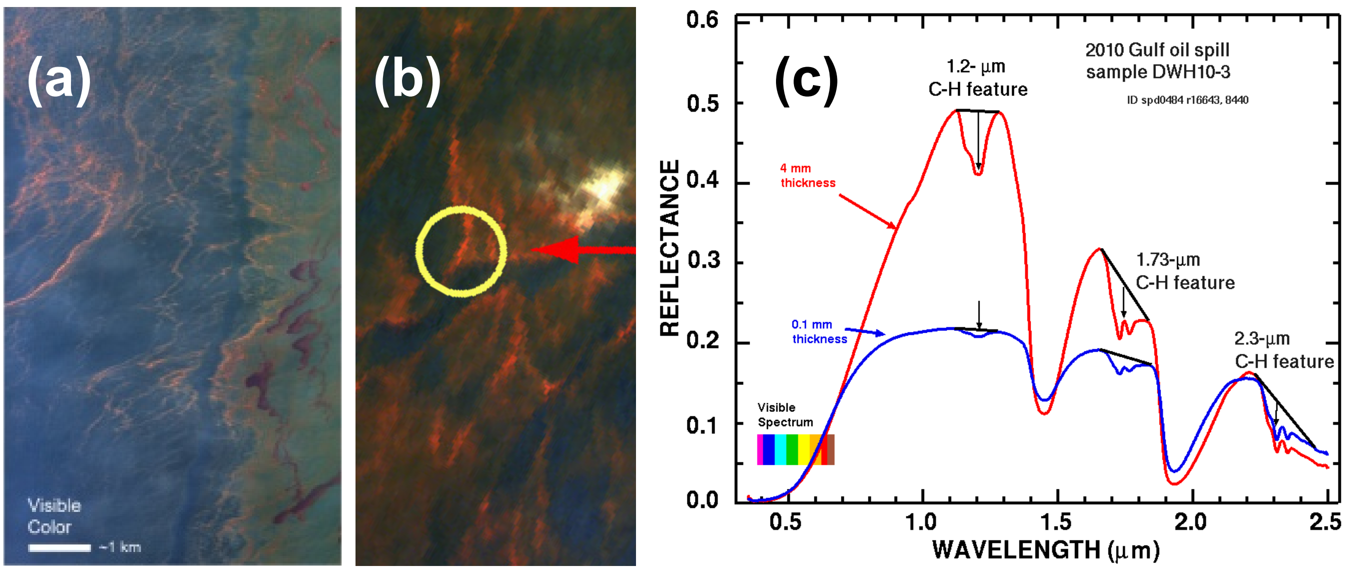

Figure 3. Imaging spectrometer data products from flights using AVIRIS classic, collected on 17-May-2010. For each pixel, a contiguous spectrum is generated across the spectrometer wavelength range (visible through infrared) for all optical channels (Clark et al., 2010). (a) Utility of visible data shows the spatial extent of oil slicks on water, (b) near infrared signatures reveal an intensity map showing the areas with higher oil thicknesses, (c) representation of the reflectance values typical of oil emulsions on water show distinct signatures of for a thick oil slick (red) and a thin slick (blue). The 1.2, 1.7 micron features are particularly diagnostic of oil thickness, the former wavelength which provides accurate thickness estimates. The follow-on sensor to AVIRIS classic is the pushbroom imager AVIRIS-ng, which offers increased spectral resolution across the same wavelength range.

These Deepwater Horizon data was the first time that optical imaging spectrometry demonstrated quantitative capability for oil slick thickness determination. Thus the community has come to recognize the suitability of this technique for disaster response and estimates of net surface oil. This sensing approach should be considered by oil producers/operators and environmental agencies as an excellent tool for monitoring oil/water emulsions in oceanic environments if case any future needs arise.

APPLICATION #2: Imaging Spectrometer Applications for Remote Sensing of Atmospheric Methane

Contemporary demonstrations of advanced NASA airborne imaging spectrometers for detection of fugitive methane emissions yield impressive results. These imaging techniques utilize sensors with wide spectral range in the visible to shortwave infrared (VIS-SWIR, VSWIR) or long wave infrared (LWIR) spectral regions. The NASA sensors offer much greater signal to noise ratio and greater spectral resolution than the few imaging spectrometers available commercially. Thus these JPL applications reap the benefits of the most advanced imaging spectrometers in the VSWIR and LWIR that have been built. JPL and colleagues have begun flights over conventional oilfields and unconventional production areas in order to help constrain natural and anthropogenic methane emissions, including quantification of fugitive emissions sources using highly mature algorithms. These airborne spectrometers have demonstrated sensitivities at flux rates as low as <250 standard cubic feet per hour (scfh) when flown at low altitudes (~1000m) using VSWIR or LWIR sensors. **These results were demonstrated with existing NASA spectrometers that were not designed specifically for methane detection.** We share below some contemporary results over operational oilfields and outline our strategy for further data collections for oilfield surveying. We also introduce a concept for development of a dedicated sensor that will meet the needs of government agencies that are focused on strategies for widescale detection of fugitive emissions (e.g. DOE) at high sensitivity (e.g. 6 scfh). This technology thrust trends towards specialized imaging systems suited for purpose – a strategy that is discussed here for an application of national significance, methane detection. Given JPL's previous methane detection work using existing NASA sensors, the solution of a dedicated imaging spectrometer for field scale imaging of methane plumes is uniquely low risk and should accomplish the fugitive emissions monitoring goals common to regulatory, environmental, and energy industries.

Imaging spectrometers provide a unique solution for non-invasive investigation of large areas. The feasible spatial coverage for a daily survey at low altitude is on the order of hundreds of square kilometers (flight plan dependent) while flying at relatively low altitudes (1-3 km). Determination of atmospheric trace gas constituents for widescale mapping with imaging systems demands advanced technologies with extremely high signal to noise (S/N). We currently apply our most advanced imaging spectrometers for this purpose: HyTES (LWIR) and AVIRIS-NG in the SWIR (AV-NG specifications, Table 2).

Table 2. Characteristics of NASA imaging spectrometer AVIRIS-NG, which is effective for methane detection / mapping. [FPA = Focal Plane Array; FOV = Field of View; IFOV = Instantaneous FOV].

		AVIRIS-NG
Spectrometer Type (passive sensors)		Visible to shortwave Infrared (VSWIR)
Spectral Range		0.38 – 2.51 μm
Spectral Resolution		5 nm
Detector Technology		HgCdTe (MCT)
Instrument Analytical Strategy		Reflectance spectroscopy
Dispersion Technique		Offner
Across Track	*Field of View (FOV)*	34°
	Swath width at 1 km	611 m
	Swath width at 3 km	1834 m
	Instantaneous FOV (IFOV)	1 milliradian
	Pixel Size at 1km	1 m
	Pixel Size at 2km	3 m
FPA	*Across Track Pixels*	598
	Spectral Channels	427

NOTE-1: Detection of fugitive emissions from point sources is enhanced by flying at low altitudes (e.g. 1-3 km) due to the reduction of ambient atmosphere "dilution".
NOTE-2: AVIRIS-NG currently includes real-time methane detection as part of its onboard data system, allowing for identification of point source fugitive emissions in real time.

Figure 4. Deployment configuration.

One need which has resulted in widescale adoption of imaging spectroscopy is that production of data products is typically labor intensive, resulting in significant delay in results due to the vast amount of data generated by these imaging spectrometers. Given this, one solution is to implement real-time algorithms as part of an on-board flight data system. A realtime detection system for methane point-source visualization currently exists as part of the AVIRIS-NG onboard data system (Figure 4). This successful implementation results in real time data analysis during collection and allows for an adaptive flight planning approach using the heads-up display, as stipulated by the mission goals.

Imaging Spectroscopy in the Short Wave Infrared (SWIR) using AVIRIS-NG

The JPL next generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) is a passive imaging spectrometer which operates by collecting the upwelling (reflected) solar radiation in discrete bands across the visible (0.4 µm) through shortwave infrared (2.5 µm). Using this technique, characteristics of surface features can be diagnosed using the detected spectral signatures or fingerprints. AVIRIS-NG provides high spectral resolution for a visible/infrared imaging spectrometer (5 nm bandwidth), exceeding those of other flight systems by at least a factor of 2. Increased spectral resolution allows for more detailed discrimination between surface features. An example data product is shown below, overlaid atop a visible composite image produced using the RGB channels of AVIRIS-NG. The SWIR spectral region for AVIRIS-NG is shown in Figure 6, where utilization of methane absorption features between 2.2-2.4 µm yield optimal results.

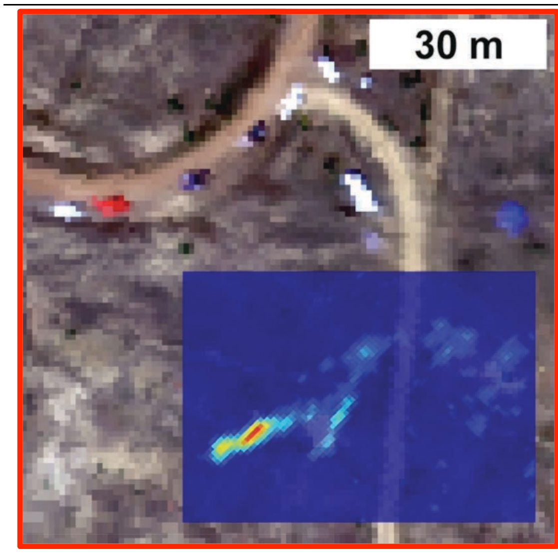

Figure 5. Example methane retrieval overlaid on visible map of the surface compiled from three AVIRIS-NG spectral channels (RGB). (http://scienceandtechnology.jpl.nasa.gov/newsandevents/newsdetails/?NewsID=2420).

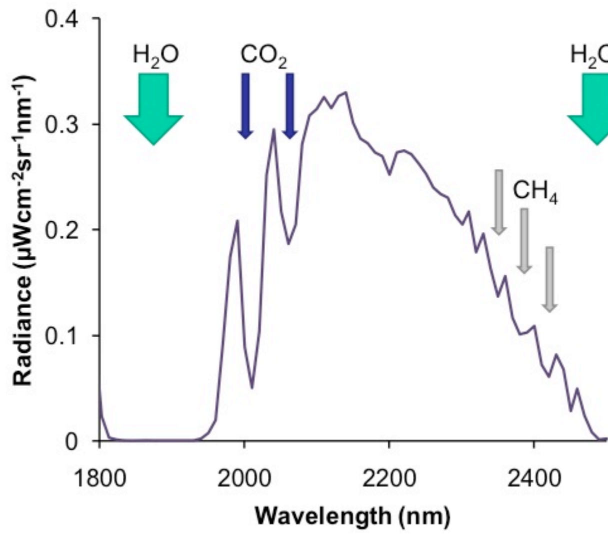

Figure 6. Relevant spectral features for SWIR methane retrievals using AVIRIS-NG. The 2.2-2.4 µm infrared features, the strongest absorption features in the SWIR, provide the most suitable region for methane detection.

In September 2014, six AVIRIS-NG scenes were acquired over Garfield County, a region with considerable gas and oil gas extraction. Flights were acquired around 1.4 km above ground level (AGL), which resulted in images around 0.8 km wide and 8 km in length, with a ground resolution of 1.3 m per pixel. Using similar techniques described in Thorpe et al. (2014; in prep), quantitative methane retrievals were performed on all images and a number of plumes were clearly visible emanating from multiple well pads. In this study, two examples are presented to illustrate the ability of AVIRIS-NG to directly attribute methane emissions to individual point sources and provide methane concentrations on a per pixel basis.

Figure 6 shows an AVIRIS-NG true color image subset with superimposed methane enhancements indicates a plume extending over 600 m downwind of the emission source. Obtained by a nearby meteorological station, wind speed and direction (Figure 6, white arrow) are broadly consistent with the observed plume geometry. Google Earth imagery with finer spatial resolution is also included from June 2014 (Figure 7, red box), however, the high density of infrastructure makes the primary emissions source unclear.

According to the Colorado Oil and Gas Conservation Commission facility database, there are eighteen wells on the well pad shown in Figure 7, of which four are abandoned, six in the drilling stages, and eight in production (COGCC, 2015). Horizontal drilling is used at each well and the majority of production is gas with a small proportion of oil. A number of these wells use hydraulic fracturing as indicated by disclosure forms available online through the national hydraulic fracturing chemical registry FracFocus (FracFocus, 2015).

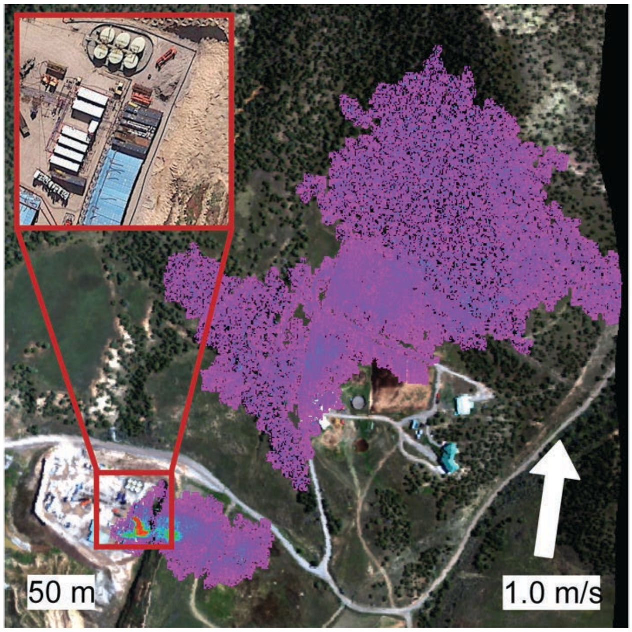

Figure 7. AVIRIS-NG true color image subset with superimposed methane plume from Sept. 2014 flight in Garfield County, Colorado. Plume extends over 600 m downwind of the emission source. Google Earth imagery with finer spatial resolution is also included from June 2014 (red box), however, the high density of infrastructure makes the primary emission source unclear.

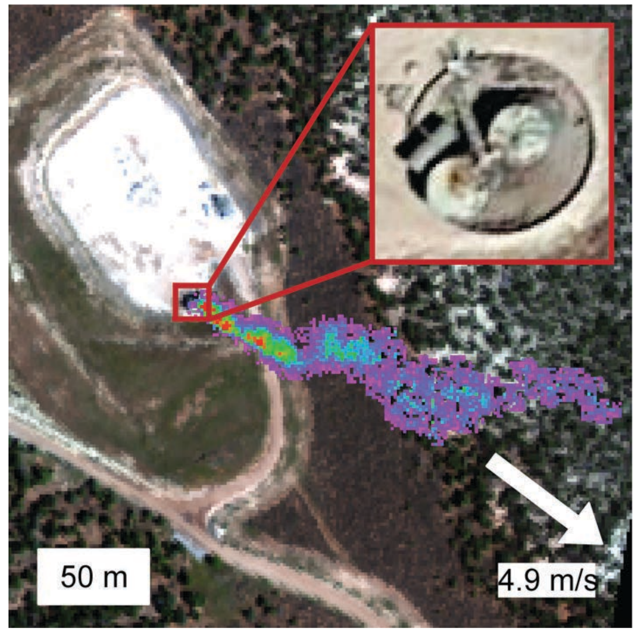

Figure 8. AVIRIS-NG true color image subset with superimposed methane plume from Sept. 2014 flight in Garfield County, Colorado. Plume extends 200 m downwind of the emission source. Google Earth imagery with finer spatial resolution is also included from June 2014 (red box), indicating that tanks in the inset scene are a potential source of the fugitive methane.

A second example shown in Figure 8 clearly indicates a plume consistent with the local wind direction (white arrow) that extends 200 m downwind of the emission source Google Earth imagery obtained from June 2014 indicates the likely source is tanks located on the edge of the well pad. Five wells are located at the center of this well pad and all use horizontal drilling to produce mostly gas (COGCC, 2015).

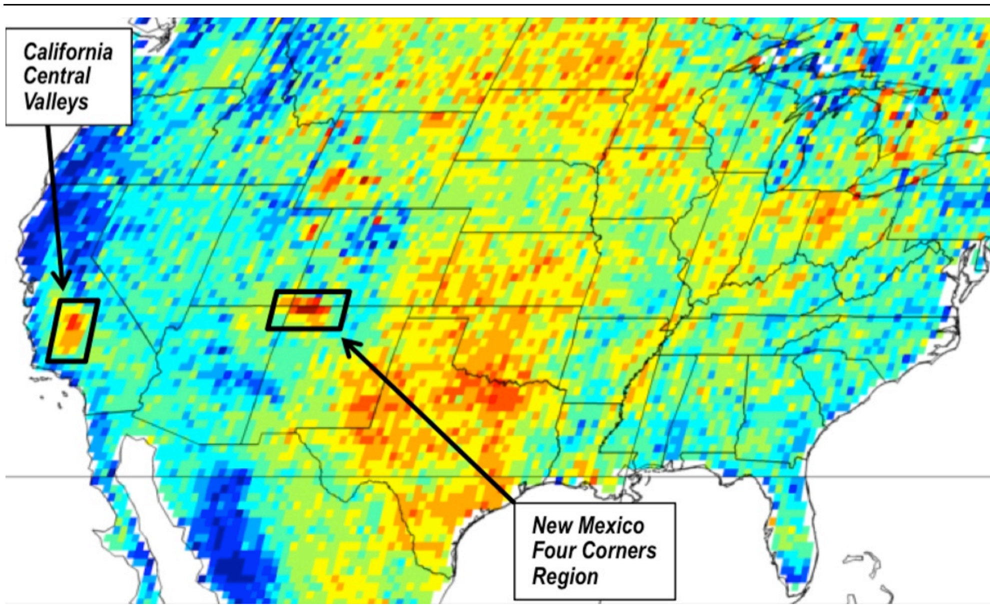

Figure 9. Total atmospheric column CH_4 enhancements expressed in parts-per-million (xCH_4) compiled for the continental United States using data from the SCIAMACHY sensor (2003-2009 average). The Four Corners region and California's central valleys are the top priority for future JPL airborne surveys. Data was corrected for elevation and latitudinal gradients. Figure courtesy Dr. Christian Frankenberg (JPL); dataset identical to that used in a previous publication (Kort, Frankenberg et al., 2014).

Conclusions and Path Forward

The results shown above demonstrate the utility of existing advanced NASA imaging spectrometers for detection of oil on water and quantitative mapping of methane plumes. While existing datasets for both applications is currently quite small, future opportunities to further demonstrate these capabilities are a high priority for our program. For instance, JPL is currently analyzing archived data collected as part of previous flight campaigns to find more examples of imagery that includes potential natural and anthropogenic methane sources. JPL NASA is also pursuing opportunities for dedicated campaigns to target regions that will investigate methane point source strengths using AVIRIS-NG and HyTES. The overall strategy for these future campaigns is to focus these high-resolution airborne investigations over the largest methane anomalies detected in the United States, as detected via satellite (Figure 9). Thus the Four Corners region and California Central Valleys are candidates for near term NASA flight campaign opportunities. We are optimistic that multiple campaign opportunities will materialize in the near term under NASA and non-NASA sponsorship given the common goal of industry, regulatory, and environmental agencies to minimize uncontrolled fugitive methane sources.

The optimal solution for wide-scale methane monitoring remains to build an imaging spectrometer sensor fit for purpose. As mentioned above, neither AVIRIS-NG nor HyTES were designed specifically for quantitative methane detection – however sensitivities in the range of 250 scfh remain impressive. A new sensor would improve the achievable sensitivity (<10 scfh) and increase specificity for small point-source emissions sources. This is the optimal solution from a science perspective to help understand the spatiotemporal variability of natural and anthropogenic methane emissions. The major improvements of this "game-changing" spectrometer design includes a narrower spectral range with enhanced spectral resolution – these factors will increase the sensitivity, specificity, and spatial resolution, while virtually eliminating any false positives. This sensor has been designed to be accommodated on a fixed wing aircraft or helicopter for more flexible flight implementation. While current imaging spectrometer technologies provide an effective solution to quantitatively detect fugitive methane emissions, AMS would provide a dedicated sensor to satisfy most government and industry goals to significantly reduce emissions.

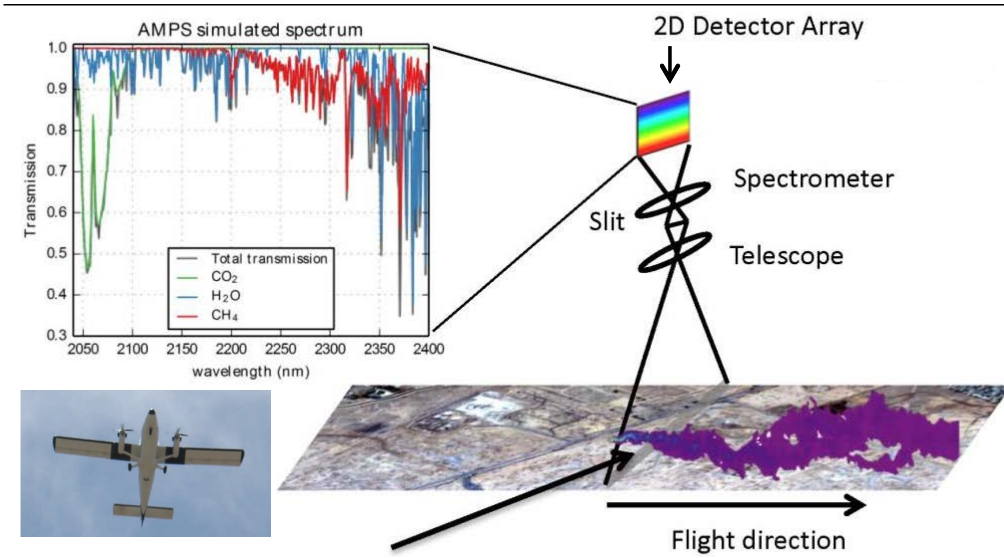

Figure 10. Airborne Methane Plume Spectrometer (AMPS) instrument concept. This is a dedicated imaging spectrometer customized for methane detection. Enhanced spectral resolution compared to current sensors covers the strong absorption region for methane in the SWIR. Image courtesy C. Frankenberg (JPL). A similar instrument can also be designed for methane detection using LWIR.

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