

Mapping methane and carbon dioxide point source emissions with SBG type observables



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### CH<sub>4</sub> and CO<sub>2</sub> absorption features





# AVIRIS-NG (CH<sub>4</sub>)

Coal mine ventilation shaft emissions



(b) CH<sub>4</sub>: 20 April 2015, 18:06:24 UTC





# AVIRIS-NG (CH<sub>4</sub>)

Coal mine ventilation shaft emissions

(a) 20 April 2015, 18:06:24 UTC



(c) 20 April 2015, 18:06:24 UTC



(d) Google Earth: 15 March 2015



(b) CH<sub>4</sub>: 20 April 2015, 18:06:24 UTC



Thorpe et al., 2017



# AVIRIS-NG $(CH_4)$

Coal mine ventilation shaft emissions



(c) 20 April 2015, 18:06:24 UTC



(d) Google Earth: 15 March 2015





(e) H<sub>2</sub>O: 20 April 2015, 18:06:24 UTC



Thorpe et al., 2017

H<sub>2</sub>O ppm •m enhance.



# AVIRIS-NG (CH<sub>4</sub>)

• CH<sub>4</sub> retrieval radiance fits



Thorpe et al., 2017



# AVIRIS-NG (CO<sub>2</sub>)

Power plant



(b) CO<sub>2</sub>: 12 Sept. 2014, 19:23:59 UTC





# AVIRIS-NG (CO<sub>2</sub>)

Power plant

(a) 12 Sept. 2014, 19:23:59 UTC



(c) 12 Sept. 2014, 19:23:59 UTC



(b) CO<sub>2</sub>: 12 Sept. 2014, 19:23:59 UTC



Thorpe et al., 2017



AVIRIS-NG (CO<sub>2</sub>)

• CO<sub>2</sub> retrieval radiance fits



Thorpe et al., 2017



# AVIRIS-NG (CH<sub>4</sub>)

 AVIRIS-NG CH<sub>4</sub> sensitivity study led by Alana Ayasse (University of California, Santa Barbara)

### a) Modelled land covers

oil coated vegetation	white painted roof 3	grass golf course	dead grass	concrete bridge	red tile roof	
white painted roof 1	CEME- ceanothus	palm tree	evergreen bark	concrete parking structure 1	soil 1 Cathedral Oaks	
calcite	MARSH- Wetland vegetation	lake	bark	concrete parking structure 2	soil 2 Modoc	
plastic covered crops	BAPI- coyote- brush	ocean glint	needle litter	tennis court	soil 3	
white painted roof 2	SASP- willow	rock	airport asphalt	asphalt & gravel roof	soil 4	



 AVIRIS-NG CH<sub>4</sub> sensitivity study led by Alana Ayasse (University of California, Santa Barbara)

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### b) Modelled CH<sub>4</sub>





 AVIRIS-NG CH<sub>4</sub> sensitivity study led by Alana Ayasse (University of California, Santa Barbara)

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### b) Modelled CH<sub>4</sub>



### c) Retrieved CH<sub>4</sub>





 AVIRIS-NG CH<sub>4</sub> sensitivity study led by Alana Ayasse (University of California, Santa Barbara)

### a) Modelled land covers concrete red tile oil coated white grass golf dead egetation grass painted course bridge roof roof 3 concrete white CEMEevergreen soil 1 palm tree parking painted Cathedral ceanothus bark structure roof 1 Oaks 1 concrete MARSH calcite lake bark parking soil 2 Wetland structure Modoc vegetation 2 plastic BAPIocean needle tennis soil 3 covered litter coyote glint court crops brush white rock airport asphalt & soil 4 SASPpainted asphalt gravel willow roof 2 roof

# b) Modelled CH<sub>4</sub>



### c) Retrieved CH<sub>4</sub>



d) Characterized uncertainties in retrieved CH<sub>4</sub>



### Ayasse et al., 2018





2016 Ahmedabad India plumes (8.1 m spatial resolution)



Dennison et al., in prep



### SBG-like observables (CH<sub>4</sub>)

Simulated 30 m data using SBG-like point spread function and noise

10 nm spectral resolution



Concentration-Path Length (ppm-m)





### SBG-like observables (CH<sub>4</sub>)

Simulated 30 m data using SBG-like point spread function and noise

10 nm spectral resolution



5 nm spectral resolution



Concentration-Path Length (ppm-m)







Duren et al., in prep





Duren et al., in prep



### AVIRIS-NG CH<sub>4</sub> plumes

9/28/17, 20:00:57 UTC



Natural Gas Compressor 9/18/17, 20:15:42 UTC



Oil well 8/30/17, 20:42:11 UTC



Leaking LNG tank (airport)



Dairy (manure lagoon)

6/18/17, 19:39:55 UTC



Waste Water Treatment 3/9/17, 19:18:57 UTC



Landfill



100 m

# California Baseline Methane Survey

### AVIRIS-NG CH<sub>4</sub> plumes Wind speed (HRRR reanalysis) 9/28/17, 20:00:57 UTC 9/22/16, 18:42:15 UTC 00 m Instantaneous emission flux (kg/hr) **Natural Gas Compressor** Dairy (manure lagoon) Annual emission flux 9/18/17, 20:15:42 UTC 6/18/17, 19:39:55 UTC (kg/hr) Source apportionment Waste Water Treatment Oil well By IPCC sector 3/9/17, 19:18:57 UTC 8/30/17, 20:42:11 UTC (Duren et al., in prep) 38% 25% 26% Landfill





Leaking LNG tank (airport)

20



- Phase 1

   report:
   <u>http://bit.l</u>
   <u>y/Baselin</u>
   <u>eMethane</u>
   <u>Survey</u>
- Phase 2 analysis ongoing

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C.Gov R	AIR RESOURCES BOARD About Our Work Resources Business Assistance Rulemaking News				
Monday, November 27, 2017	AB 1496 Research Program				
UP LINKS	This page last was reviewed on October 30, 2017				
<ul> <li>Reducing Air Pollution - ARB Programs</li> <li>Research Activities</li> <li>Methane Research Program</li> </ul>	Assembly Bill No. 1496, Chapter 604, Section 39731 (Thurmond, 2015) In 2015, the Governor approved Assembly Bill 1496 (AB 1496) which requires ARB to do the following:				
<ul> <li>PROGRAM LINKS</li> <li>AB 1496 Methane Research</li> <li>Statewide GHG Monitoring Network</li> <li>Statewide Natural Gas Storage Facility Survey</li> </ul>	<ul> <li>Undertake monitoring and measurements of high emission methane "not spots"</li> <li>Life-cycle greenhouse gas emissions analysis of natural gas produced and imported into California</li> <li>Review and assess the atmospheric reactivity of methane as a precursor to the formation of photochemical oxidant</li> <li>Update relevant policies and programs to incorporate new information</li> </ul>				
RELATED LINKS   Megacities Carbon Project (NASA)  California Greenhouse Gas Emissions Measurement Project (LBNL)  RESOURCES  Contact Us  Join Any Research Email List(s)  Library Catalog  RSS / Newsfeed	<ul> <li>Statewide Methane Survey</li> <li>A key component of ARB's research effort is a large-scale statewide aerial methane survey being conducted by NASA Jet Propulsion Laboratory (JPL), through funding from ARB and CEC. The project focuses on identifying and mitigating methane "super emitters", and utilized minaging camera capable of seeing methane to visually identify large methane plumes throughout the State. The first comprehensive survey was conducted during the Fall of 2017. The survey will capture sources in all important methane source sectors, including:</li> <li>Oil and Gas - production/processing, storage, transmission, distribution</li> <li>Agriculture - dairies, manure, rice fields</li> <li>Waste - landfills, waste water</li> </ul>				
	Resources:				

- California Methane Survey Phase I Interim Report NEW!
  - Phase I Report Source List NEW!
- Staff Presentation to the Board on California Statewide Methane Survey (September 2017)



PBS NewsHour story: <u>http://bit.ly/PBSMethaneSurvey</u>





Transcript Audio

By – Miles O'Brien

Science correspondent Miles O'Brien joins us from the atmosphere above Southern California, where NASA engineers leverage state-of-the-art



### Methane Source Finder

 NASA funded web based data portal including methane data at different spatial/temporal resolution (gridded emissions data, plumes from imaging spectrometers, infrastructure layers)



LA Basin regional analysis



### Methane Source Finder

 NASA funded web based data portal including methane data at different spatial/temporal resolution (gridded emissions data, plumes from imaging spectrometers, infrastructure layers)



Exploring local CH<sub>4</sub> hotspots



### Methane Source Finder

NASA funded web based data portal including methane data at different spatial/temporal resolution (gridded emissions data, plumes from imaging spectrometers, infrastructure layers)



Landfill

source



Remote Sessing of Environment 114 (2010) 592-606



### Mapping methane emissions from a marine geological seep source using imaging spectrometry

Dar A. Roberts <sup>a,a</sup>, Eliza S. Bradley <sup>a</sup>, Ross Cheung <sup>b</sup>, Ira Leifer <sup>c</sup>, Philip E. Dennison <sup>d</sup>, Jack S. Margolis <sup>e</sup>

<sup>1</sup> Dipartmere of Coopraphy, Detremity of California Sexta Rochen, CJ, 52166, USA.
<sup>2</sup> Reportenent of Attemptietic Strinus, Detremity of California Las Augúis, CJ 20000, USA.
<sup>3</sup> Reportenent of Coopraphy, and Coarse for National and Federadore, Distribution, California, Sexta Hennes, CA, 1994, USA.
<sup>4</sup> Reportenent of Coopraphy and Coarse for National and Federadore Historica, University of Outa, Sait Laine, CAJ, 2004. ABSTRACT

ARTICLE INFO Ankie Natory Received 25 May 2000 Received in revised form 23 October 2009 Accepted 31 October 2009

Keywords: Pypesspectral data AVM85 CH<sub>6</sub> Michane Madre sreps Coal OI Point wep field Rendual

A BIT TAKE T The Data of Tables and the second sec

ent with Ol<sub>4</sub> and estimated radiance spectra that matched measurements. All storag anomali-in close vicinity to and downwind from known Ol<sub>4</sub> sources. However, contrary to simulate overly sensitive to albedo, restricting high confidence anomalies only to the brightest s





Mapping methane concentrations from a controlled release experiment () Countra using the next generation airborne visible/infrared imaging spectrometer (AVIRIS-NG)

AK, Thorpe <sup>A,h,a</sup>, C. Frankenberg<sup>1,2</sup>, AD, Aubrey<sup>1,3</sup>, DA, Roberts<sup>1,3</sup>, AA, Nottrott<sup>1,4</sup>, TA, Rahn<sup>+</sup>, JA, Sauer<sup>2</sup>, MK, Dubey<sup>4</sup>, K.R. Cordigan<sup>1,5</sup>, C. Arata<sup>1</sup>, AM, Steffler<sup>4</sup>, S. Hills<sup>1</sup>, C. Haselwimmer<sup>4</sup>, D. Charlesworth<sup>1</sup>, C.C. Funk<sup>1,3</sup>, R.G. Green<sup>1,5</sup>, S.R. Lindeen<sup>2,4</sup>, J.W., Boardman<sup>1</sup>, M.L. Eastwood<sup>1</sup>, C.M. Sarture<sup>2,5</sup>, S.H. Nolte<sup>3</sup>, I.B. Mccubbin<sup>3</sup>, D.R. Thompson<sup>-1</sup>, J.P. McFadden<sup>1</sup>

And Mitterground J. J. P. Handberg, H. Handler, K. M. Handberg, K. Handberg, K.

### ARTICLE INFO ABSTRACT

Antile Italiany Received 15 Naty 2015 Received in envised form 22 March 2016 Accepted 24 March 2016 Ausliche ontinent April 2016	Emissions estimates of antheopopatic methone (CR), i scores are highly uncertain and many energy production are localized petr difficult to quantify. Althouse imaging spectrumeters like Antheore Visible-Infrared fraging Spectrumeter (ANRE NC) are well used for locating CRs, their a killing to map concentrations over large regions with the high spatial resolution network and the states of the spectrum and the production of the spectrum of spectrum of
Rigmonda: Mechane	Mountain Oilfield Testing Center (BMOTC) in Wyoming, U.S. for multiple flux rates and flight gorithms were applied to AVIIIS-NG scenes, a matched filter detection algorithm and a hybrid
CIH	using the herative Maximum a Posteriori Differential Optical Absorption Spectroscopy (IMAF
Meeting	and Singular Value Decomposition, Plumes for releases as low as 14, 16 m <sup>2</sup> /th (0.09 kt/year) we
Concertations	served by AMRIS-NG at multiple flight abitudes and images of plumes were in agreement wi
Controlled	measured at ground stations. In some cases plumes as low as 3.40 m <sup>2</sup> /h (0.02 kt/wear) were d
Release	that AVIRE-NG has the capability of detecting a wide range of fugitive CH <sub>4</sub> source categories fo

### **@AGU** PUBLICATIONS

### Geophysical Research Letters

RESEARCH LETTER

### Space-based remote imaging spectroscopy of the Aliso Canyon CH<sub>4</sub> superemitter

D.R. Thompson<sup>1</sup>, A.K. Thorpe<sup>1</sup>, C. Frankenberg<sup>1,2</sup>, R. O. Green<sup>1</sup>, R. Duren<sup>1</sup>, L. Guanter<sup>3</sup>, A. Hollstein<sup>1</sup>, E. Middleton<sup>4</sup>, L. Ong<sup>4</sup>, and S. Ungar<sup>4</sup>

sy Points: The ICO 1 logation spectrometer measured Oly, free the Allos Cary ordenzion, of a Oly, superventiter phase Multiple advocume to spectromisms by the ANRS C-reaging spectrometer comborate the plarme morpholog and magnitude Implical precision agrees with <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadera, California, USA, <sup>2</sup>Division of Goological and Palentary Sciences, California Institute of Technology, Pasadera, California, USA, <sup>3</sup>Division of Content Potsdam, GZ Con-Benarch, Centre for Consciences, Palsdam, Canarray, MAAA Coddad Sugare Tight Centre, Cheneble, Rayland, USA, <sup>2</sup>Elo 1 Scientifi Termitha, NISA Colland Space Flight Centre, Cenerlibeth, Manyland, USA, Sensor Research Scientist, Universitie Space Research. Association

Abstract: The Also Caryon pay torsays fuelty near Prine Ranch, California, produced a large account of the mittain that that the State 2115 for Barry 2115. The Hyperice manying spectrometer and the state of the state o

### 1. Introduction

On 23 October 2015, a well blowout was reported at the Aliso Canyon underground natural gas storage facility near Porter Ranch, California. A sustained release of CH, into the atmosphere continued until opera-tors successfully capped the leak in February 2016 (Conky et al., 2016). The event was an extreme example of

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this Successful pages to fear in Relative 2016 (2014) view (d. 2014). The exist was an extense subject of 2014 (2014) view (d. 2014) view (d

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L10702, doi:10.1029/2011GL046729, 2011

### Detection of marine methane emissions with AVIRIS band ratios Eliza S. Bradlev,1 Ira Leifer,2 Dar A. Roberts,1,3 Philip E. Dennison,4

and Libe Washburn1, Received 31 January 2011; revised 2 April 2011; accepted 5 April 2011; published 20 May 2011

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### The Airborne Methane Plume Spectrometer (AMPS): **Quantitative Imaging of Methane Plumes in Real Time**

Andrew K. Thorpe, Christian Frankenberg, Robert O. Green, David R. Thompson, Andrew D. Aubrey, Pantza's Monroulis, Michael L. Eastwood, Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grow Dr. Pasadena, CA 91109

818-354-8094 Andrew K. Thorpe@ipl.nava.gov

methane | Four Corners | remote sensing | heavy tail

PNAS

Andrew.K. ThorpegypLassa.gov				
Abstract—The Airborne Methane Plante Spectrometer (AMPS) is a mattere instrument concept that is ready for development at the Jet Propulsion Laboratory (JPL). At its core is a novel high- resolution imaging spectrometer that records solar reflected light horizont 150 and 243 and 24 and solar reflected	these emissions is of interest given the large uncertainties associated with anthropogenic emissions, including industrial point source emissions and fugitive $\rm CH_4$ from oil and gas infrastructure.			
strong methane (CH4) bands in the short-wave infrared. The	TABLE OF CONTENTS			
push-broom spectrometer will leverage recent advancements in grating design and large-format 2D focal plane arrays to	1. INTRODUCTION			
enable-for the first time-the high spectral resolution	2. MEASUREMENT TECHNIQUE			
necessary for trace gas retrievats combined with high-	3. AMPS DESIGN			
sensing. AMPS features a 36° field of view with 600 resolved	4. REAL TIME CH4 PLUME MAPPING			
spatial elements across track (1 mRad) and 431 pixels in the	5. POTENTIAL APPLICATION			
spectral dimension. All other aspects of the instrument, such as the telescone cross-coder image stabiliter CPS are identical to	6. CONCLUSIONS			
available airborne JPL spectrometers in operation.	APPENDICES			
	A. RETRIEVAL PRECISION			
The AMPS design is based on the next generation Airborne Vidble Infrared Imaging Spectrometer (AVIRIS.NC), which	B. SPATIAL RESOLUTION REQUIREMENTS9			
has been used for high resolution mapping of CH4	C. DETECTION LIMIT ANALYSIS			
concentrations from a controlled release experiment [1] and	D. SIGNAL TO NOISE REQUIREMENTS			
over existing milural gas fields [2]. A real time CH4 plume detection canability originally developed for AVIRIS/NC and	E. AMPS RADIOMETRY 10			
successfully demonstrated over oil fields [3] will also be	F. DECOUPLING SURFACE AND THE			
implemented with AMPS. This will facilitate surveys over	ATMOSPHERE			
existing oil and gas fields to identify and attribute CH4 emissions	ACKNOWLEDGEMENTS			
with repeat imaging of supported sources, and allow real time	REFERENCES			
communication to site operators or ground crews equipped with	BIOGRAPHY13			

### ..13 CrossMark

### Airborne methane remote measurements reveal heavytail flux distribution in Four Corners region

Christian Frankenberg<sup>ub.5.</sup>, Andrew K. Thorpe<sup>5</sup>, David R. Thonpson<sup>8</sup>, Glynn Hulley<sup>9</sup>, Eric Adam Kort<sup>4</sup>, Nick Vance<sup>1</sup>, Jakob Borchardt<sup>4</sup>, Thomas Kringo<sup>5</sup>, Konstantin Gerilowski<sup>7</sup>, Colm Sweeney<sup>54</sup>, Stephen Conley<sup>46</sup>, Brian D. Bue<sup>5</sup>, Andrew D. Auderg<sup>15</sup>, Simon Flock<sup>1</sup>, and Robert O. Green<sup>9</sup>

Tabilities of declarge and Revenues, California California Fondaça, Paralaman, C.A. 1923, "Un Proprietar Lakenceurs, California Viente and California Viente Andrea Viente Viene Viente V Edited by Gregory P. Anner, Carnegie Institution for Science, Starford, CA, and approved June 17, 2016 (received for review April 10, 2016)

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Setting 2.12 sequept 1 have charged benchmark to be setting 1 by black to be

methane | Four Corners | remote sensing | heavy tail Fugitive methane emissions are thought to often exhibit a heavy-tail distribution (more high-emissions sources than expected in a normal distribution), and thus efficient missions are exhibit a heavy-tail distribution (more high-emissions sources) and and normal distribution (more high-emissions sources) and normal distribution (more high-emissions) are efficient missions are efficient missions).



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High resolution mapping of methane emissions from marine and terrestrial sources using a Cluster-Tuned Matched Filter technique and imaging spectrometry

Andrew K. Thorpe \*\*, Dar A. Roberts \*, Eliza S. Bradley \*, Christopher C. Funk \*, Philip E. Dennison <sup>6</sup>, Ira Leifer <sup>4</sup>

Department of Geography, Unbernity of California, Sami Berben, GA, Henda States Eli Golaphia Marcella and Christer Machael, Geogn Department of Calegorgies, University of Calegories, Sami Barbani, GA, United States Department of Geography and Corner for Nitrand and Instrudygical Montplex University of Cale. Soli Lake Cap, UI, United States Market Science Todami, Ulivinities of Calegories, Sami Barbane, CO, United States

### ARTICLE INFO ABSTRACT

Received 7 September 2 Received in mixed from Accepted 19 March 2013 Available online xxxx

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In this study, a Cluster-Tuned Matched Filter (CTMF) technique was applied to data acquired by the Airborn In this study, a Court Tend Matchell Tiller (CMP) (rehinique ani appent in data agures up on one Vishell hardness disagness productions of the study of the study of the study of the study of the CMP, a Mot Call Of Num tentre are printly protonent (CM), and the Call Of Num tentre are printly of the study of the printly of the study of t March 2013 tations of results identified 16 distinct locations of contiguous poors with high CTMF-cores and segments were classified into probable CT4, according and the segment and the second property of the second probable CT4 over the full spectral range measured by AVIRS. This technique is particularly well sained for application over the full spectral frage measured by AVIRS. This technique is particularly well sained for application over the full spectral frage measured by AVIRS. This technique is particularly well sained for application over the full spectral frage measured by AVIRS. arge arms to detect CH emission from concentrated point sources and should permit detection of additional trace gasses with distinct absorption features, including cachen disoxide (CG) and nitrous oxide (No.O) flux, imaging spectrometry by an AVBE-Bae sensor has the potential to improve high resolution greenhouse one womande house convention before hour assess. © 2013 Elsevier Inc. All rights reserved

> Atmospheric § Atmospheric Measurement

Techniques

Atmos. Meas. Tech., 8, 4383-4397, 2015 wave atmos-meas-tech net/8/4383/2015/ doi:10.5194/amt.8.4383.2015 D Author(s) 2015. CC Attribution 3.0 License. 00

### Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane

### D. R. Thompson<sup>1</sup>, I. Leifer<sup>2</sup>, H. Bovensmann<sup>3</sup>, M. Eastwood<sup>1</sup>, M. Fladeland<sup>4</sup>, C. Frankenberg<sup>1</sup>, K. Gerilowski<sup>2</sup>, R. O. Green<sup>1</sup>, S. Kratwurst<sup>3</sup>, T. Krings<sup>3</sup>, B. Luns<sup>4</sup>, and A. K. Thorpe<sup>1</sup>

1 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA Bubbleology Research International Solvang, CA, USA University of Bremen, Institute of Envi ntal Physics, P.O. Box 330440, 28334 Bremen, Germany, <sup>4</sup>NASA Ames Research Center, Moffett Field, CA, USA

Correspondence to: D. R. Thompson (david.r.thompson@jpl.nasa.gov)

Received: 15 March 2015 – Published in Atmos. Meas. Tech. Discuss : 22 June 2015 Revised: 10 September 2015 – Accepted: 10 September 2015 – Published: 19 October 2015

Abstract. Localized anthropogenic sources of atmospheric CI4 are highly uncertain and temporally variable. Airborne imaging quantify these emissions. In a campaign context, the science yield can be damatically increased by real-time retrieves. Tradit Airborne imaging spectrometers have been deployed for a wide range of scientific, regulatory, and disaster response objectives. Takikanally these campings with of fourchell environmental conditions and then fly pre-arranged survey pathility radiometric calibration and geolocation. Signif-cant time can puss beford data are analyed fully, and mattin of the arrive too last for mil-course corrections during the campaint. Buttory: instructional to correlation starting the campaign. However, improvements in computing power, communication, and telemetry are changing this situation.

> Atmospheric 💡 Atmospheric Measurement

Techniques



### Andrew K. Thorpe<sup>1</sup>, Christian Frankenberg<sup>1,1</sup>, David R. Thompson<sup>1</sup>, Riley M. Duren<sup>1</sup>, Andrew D. Aubrey<sup>1</sup>, Brian D. Bue<sup>1</sup>, Robert O. Green<sup>1</sup>, Konstantin Gerliowski<sup>1</sup>, Thomas Krings<sup>2</sup>, Jakob Borchardt<sup>1</sup>, Eric A. Kort<sup>4</sup>, Colm Sweene<sup>3</sup>, Stephen Conley<sup>6,5</sup>, Dar A. Bolert<sup>2</sup>, and Philip E. Denniso<sup>9</sup>

1 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA <sup>1</sup>el repuisso i lacearoy, claitorna insuitue oi cennologi, rasaetta, claitorna, USA Division of Genologia alu Paneary Sciences, California Intitute of Technology, Paadena, California, USA <sup>1</sup>Institute of Environmental Physics (UPA, University of Brennen, Brennen, Gennary <sup>4</sup>Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan, USA <sup>4</sup>Cooperative Institute for Research in Environmental Sciences, University of Clicada, Bouldar, Colonda, USA "Cooperative Institute for Research in Environmental Sciences, University of Colorado, Bouider, Cole "Global Menticine) Division, NOAA Earth System Research Laboratory, Boulder, Colorado, USA "Scientific Aviation, 3335 Alport Road, Boulder, Colorado, USA "Department of Geography, University of California, Santa Barbara, Santa Barbara, California, USA "Department of Geography, University of Utah, Salt Lake City, Utah, USA

Correspondence to: Andrew K. Thorpe (andrew.k.thorpe@ipl.nasa.gov)

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Abstract. At local scales, emissions of methane and carbon mapped from the flue-gas stacks of two coal-fired power

Another Articles was a characteristic and another failed sources of the deformation of the analysis of the deformation of the analysis of the deformation of the analysis of the deformation of the deforma sion sources verified by the true color AVIRIS-NG scenes t high gratial resolution. In a requires study, more than 250.



Atmos. Meas. Tech., 7, 491-506, 2014 s-tech.net/7/491/2014/ © Author(a) 2014 CC Attribution 3.0 License

Atmospheric & Measurement \$ Techniques

### Retrieval techniques for airborne imaging of methane concentrations using high spatial and moderate spectral resolution: application to AVIRIS

### A. K. Thorpe<sup>1,2</sup>, C. Frankenberg<sup>2</sup>, and D. A. Roberts<sup>1</sup>

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Abstract. Two quantitative retrieval techniques were eval-uated to estimate methane (CH<sub>4</sub>) enhancement in concern-source emissions and fugitive CH<sub>4</sub> from the oil and gas insance or constanting theorem (Crist) emanatements in concern-trated plumes using high spatial and moderate spectral reso-lution data from the Airborne Vsaible/Infrared Imaging Spec-trometer (AVIRIS). An iterative maximum a posteriori differdustry. ential optical absorption spectroscopy (IMAP-DOAS) algo rithm performed well for an ocean scene containing natura CH4 emissions from the Coal Oil Point (COP) seep field near 1 Introduction C14, emissions from the Co10 G13/W01 (C07) seep field near starting and the Co10 G13/W01 (C07) seep field near with an instantance of mathematic forcing 21 less games from correst are expected to aqual between 213 to 0.01 pero C14, with an instantance on adultic forcing 21 less games from corresponding to above 25 to 0.0000 error for a 1000 to 1000, 211 mer that plants. Haveen, MAPEGOA results for a stres-tion of the stress of the corresponding to above 25 to 0.0000 error for the stress of the corresponding to above 25 to 0.0000 error for a 1000 to 1000, 211 mer that plants. Haveen, MAPEGOA results for a stres-tion of the stress of the corresponding to above 25 to 0.0000 to 1000, 211 mer to 0.0000 to 0.0000, 211 mer to 0.0000 to



### OTC-25984-MS

### Crosscutting Airborne Remote Sensing Technologies for Oil and Gas and

Earth Science Applications A.D. Aubrey, C. Frankenberg, R.O. Green, M.L. Eastwood, D.R. Thompson - NASA Jet Propulsion Laboratory, California Institute of Technology, A.K. Thorpe, University of California, Santa Bartera

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### Abstract

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Aldrons imaging spectroscopy has evolved dematically since the 1980s as a volver result acousting tochargon and to general: 2-dimensional maps of underse properties over large appendia error. Traditional applications for games authous mining aspectroscopy. The occurs applications are particularly relevant to the mode of both the cil and gam as well as generated sector and the strengthment of relative error both and applications are particularly relevant to the mode of both the cil and gam as well as generated sector and and the strengthment of photoenton ficharum suggest environment and mapping strongbates generated sector gam components. There backing are provide valuable capabilities for performance regregate an addition to detection and paraficiation of relative sectors.

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### Evaluating the effects of surface properties on methane retrievals using a (Register of spatial synthetic airborne visible/infrared imaging spectrometer next generation (AVIRIS-NG) image

Alana K. Ayasse<sup>3,-</sup>, Andrew K. Thorpe<sup>3,</sup>, Dar A. Roberts<sup>1</sup>, Christopher C. Funk<sup>c</sup>, Philip E. Dennison<sup>4</sup>, Christian Frankenberg<sup>4,3</sup>, Andrea Steffke<sup>6</sup>, Andrew D. Aubrey<sup>4,3</sup> Franzy and evaluations of point-strain strainstances, Bar Training or Assessing of Jammer of Header (1999). Franzy Review of Groups, Strain Strain, S

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that allow operators to coordinate multiple measurements of the most active areas. This can improve science outcomes for both single- and multiple-platform missions. We describe a case study of the NASA/ESA CO2 and MEthane eXperiment (COMEX) campaign in California during June and Au-gust/September 2014. COMEX was a multi-platform camssign to measure CH4 plumes released from anthropogenic



EARTH SCIENCE AND APPLICATIONS FROM SPACE

RFI#2 15 MAY 2016

# Understanding anthropogenic methane and carbon dioxide point source emissions

Riley M. Duren<sup>1</sup>, Andrew K. Thorpe<sup>1</sup>, Robert O. Green<sup>1</sup>, Christian Frankenberg<sup>2</sup>, David R. Thompson<sup>1</sup>, Andrew D. Aubrey<sup>1</sup>, Charles E. Miller<sup>1</sup>, Kevin R. Gurney<sup>3</sup>, Luis Guanter<sup>4</sup>, Heinrich Bovensman<sup>5</sup>, Konstantin Gerilowski<sup>5</sup>, Ilse Aben<sup>6</sup>, Andre Butz<sup>7</sup>, Colm Sweeney<sup>8</sup>, Eric A. Kort<sup>9</sup>

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 Imaging spectrometer for gas mapping provides unique capabilities that compliment existing measurements



Duren et al., 2016



- Imaging spectrometer design for gas mapping reflect balance between
  - Detection threshold (spectral resolution, spatial resolution)
  - Coverage (swath)

Observing System	Imaging spectrometer specifications	Source population	Fraction of population sampled	Fraction of total emissions from sampled population (for the given detection threshold)	Detection threshold (kg/hr)	Spatial resolution (m)*	Sample interval** (days)
Tier A	Platform: single satellite Spatial resolution: 30 m Swath width: 180 km Spectral resolution: <b>5 nm</b> Wavelength: 1.9 - 2.5 micron	CH4: 10,000,000 facilities <sup>1b</sup> (global) CO2: tens of thousands of facilities (global) <sup>1a</sup>	99%	30% >80%	1,000	30 30	30
Tier B	Platform: Smallsat constellation Spatial resolution: 10 m Spectral resolution: 10 m Daily sampling: 250,000 km <sup>2</sup> (target mode) FWHM: <b>1 nm</b> Wavelength: 1.9 - 2.5 micron	CH4: 10,000,000 facilities (global) <sup>2</sup> CO2: tens of thousands of facilities <sup>1a</sup> (global)	>50%	50-90% <sup>3</sup> >90%	20,000	10	15

<sup>1a</sup> Of 21,000 large power plants in the CARMA database, 30% (~7000 plants) are responsible for 99% of CO2 emissions from that sector; there are also thousands of other industrial facilities that are large CO2 emitters

<sup>1b</sup> An estimated 10,000,000 facilities globally; only ~100,000 facilities contribute 30% of methane point source emissions (scaled from US GHGRP)

<sup>2</sup> Assume super-emitter distribution (scaled from US EIA data and Zavala-Araiza et al, 2015; Lyon et al, 2015; Frankenberg et al, 2016)

<sup>3</sup> Predict 50-90% completeness with the cited detection threshold (varies by sector)

\*Native resolution of the instrument (pixel size) - not necessarily flux estimate resolution (which is often larger for area source sounders) \*\*Rough estimate of sample interval based on orbit/campaign driven revisit interval and the impact of clouds, northern hemisphere summer

### Duren et al., 2016



Orbital Hyperion instrument and AVIRIS also observed CH<sub>4</sub> plume

### Hyperion (10 nm): 1/1/16, 16:39 UTC Low Earth orbit





Orbital Hyperion instrument and AVIRIS also observed CH<sub>4</sub> plume

x 10<sup>5</sup>

2

1.8

1.6

1.4

1.2

0.8

0.6

0.4

0.2

### Hyperion (10 nm): 1/1/16, 16:39 UTC Low Earth orbit









### 2017 Decadal Survey

- Earth System Explorer-Targeted Observable: Greenhouse Gases
  - "Low Earth Orbit observation of [CH4 and CO2] plumes from point sources using SWIR spectrometers with very high spatial resolution (less than 50 m) over limited viewing domains." (NRC, 2018)





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- California Energy Commission (CEC)