Detecting Enhanced Levels of Atmospheric Methane Using Thermal Infrared Imagery

Cody Webber
John Kerekes
Rolando Raqueno

Digital Imaging and Remote Sensing Laboratory
Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology
Rochester, New York

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Outline

- Introduction and Inspiration
- Investigation Objectives
- Examination of an Existing Airborne System
- Description of Brightness Temperature Data Set Creation
- Description of Model System (MURI) Noise Modeling
- Results and Future Work

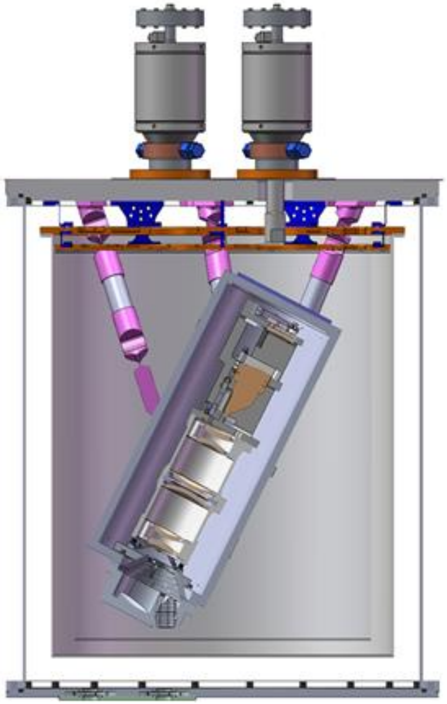
Purpose of Investigation

- Methane mapping for environmental monitoring
  - Methane is a contributor to atmospheric heat trapping
  - California law requires methane monitoring from likely sources
- Airborne Imaging Systems already exist to detect methane:
  - AVIRIS (Visible-SWIR)
  - HyTES (Thermal Infrared)
- Investigate application of new technology
  - Utilize MODTRAN produced sensor reaching radiances to predict performance requirements

HyTES Description

http://hytes.jpl.nasa.gov

- NASA JPL Hyperspectral Thermal Emission Spectrometer
- Airborne imaging spectrometer
- High efficiency, low scatter concave blazed grating



Instrument Characteristic	HyTES
Mass (Scanhead)	12kg
Power	400W
Volume	1m x 0.5m (cylinder)
Number of pixels x track	512
Number of bands	256
Spectral Range	7.5 - 12 µm
Spectral Sampling Interval	4.5µm/256, i.e. 17 nm
Frame speed	35 or 22 fps
Integration time (1 scanline)	28 or 45 ms
Total Field of View	50 degrees
Calibration (preflight)	Full Aperature Blackbody
Detector Temperature	40K
Spectrometer Temperature	100K
Slit Length and Width	20 mm x 39 µm
IFOV	1.7066
Pixel Size/Swath at 2,000 m flight altitude	3.41m/1868.33m
Pixel Size/Swath at 20,000 m flight altitude	34.13m/18683.31m
Saturation Temperatures	see Figure below

Region of Methane Absorption Feature

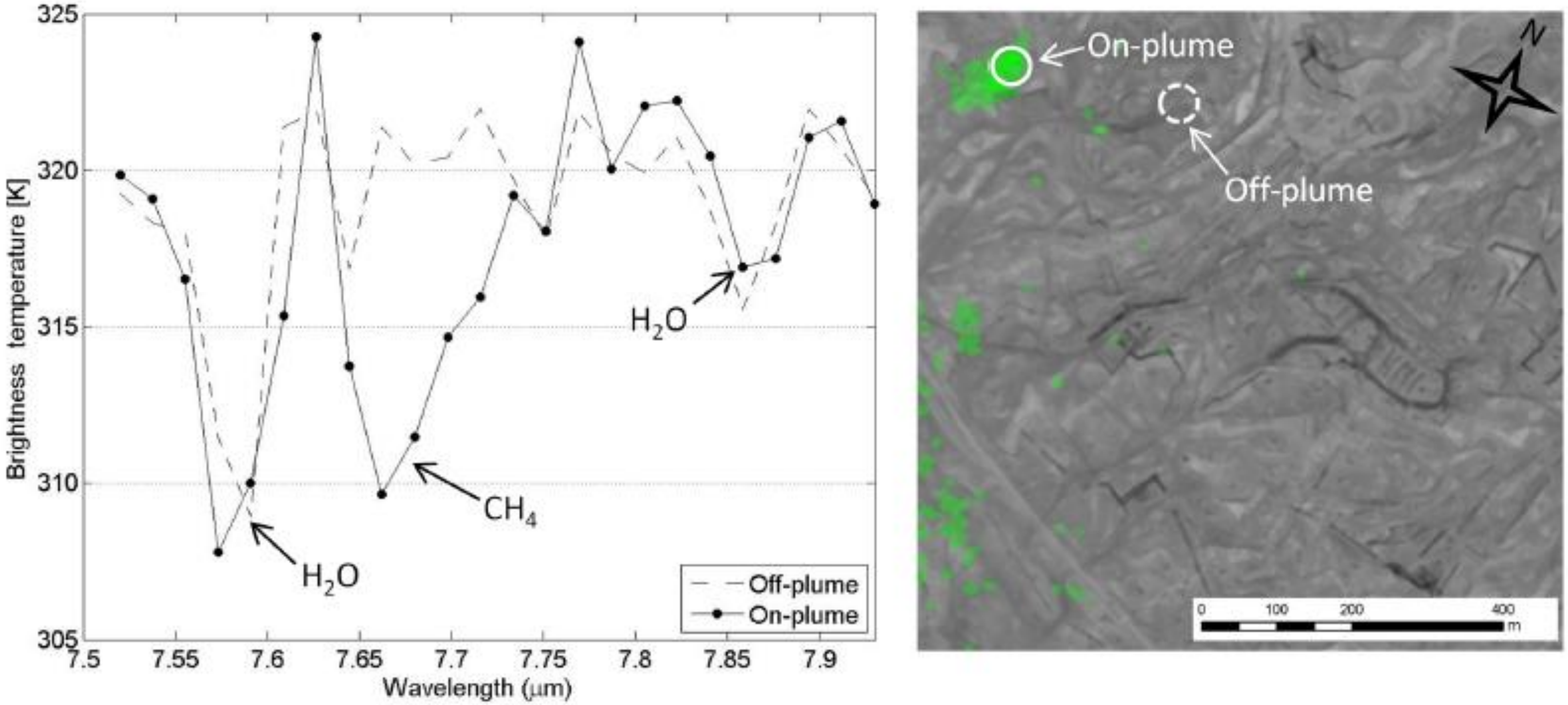


Figure taken from :

Hulley et. al., "High spatial resolution imaging of methane and other trace gases with the airborne Hyperspectral Thermal Emission Spectrometer (HyTES)," *Atmospheric Measurement Techniques,* vol. 9, no. 5, pp. 2393-2408, 2016.

Thermal Imagery Potential Improvement

- Airborne thermal imagers, such as HyTES, require potentially heavy and expensive cooling systems
- Microbolometers are thermal detectors which can be used to create an FPA that does not require cooling
- DRS Technologies proposed microbolometer based system: Multi-Band Uncooled Radiometer Imager (MURI)
- MURI airborne prototype selected for funding under NASA Earth Science Technology Office (ESTO) Instrument Incubation Program (IIP) for 2017 - 2020

MURI Description

- Multi-band Uncooled Radiometer Imager
  - DRS Technologies proposed system for NASA ESTO’s Instrument Incubation Program
  - Two designs: satellite mounted and an airborne demo system
  - Multispectral 6 band instrument
  - Includes coverage of Landsat 8’s 2 thermal bands (TIRS)
  - Main goal to prove low cost microbolometer FPA are useable in the following applications:
- Potential Science Applications
  - Soil Moisture Content
  - Land Surface Climatology
  - Ecosystem Dynamics
  - Volcano Monitoring
  - Hazard Monitoring
  - Methane Detection

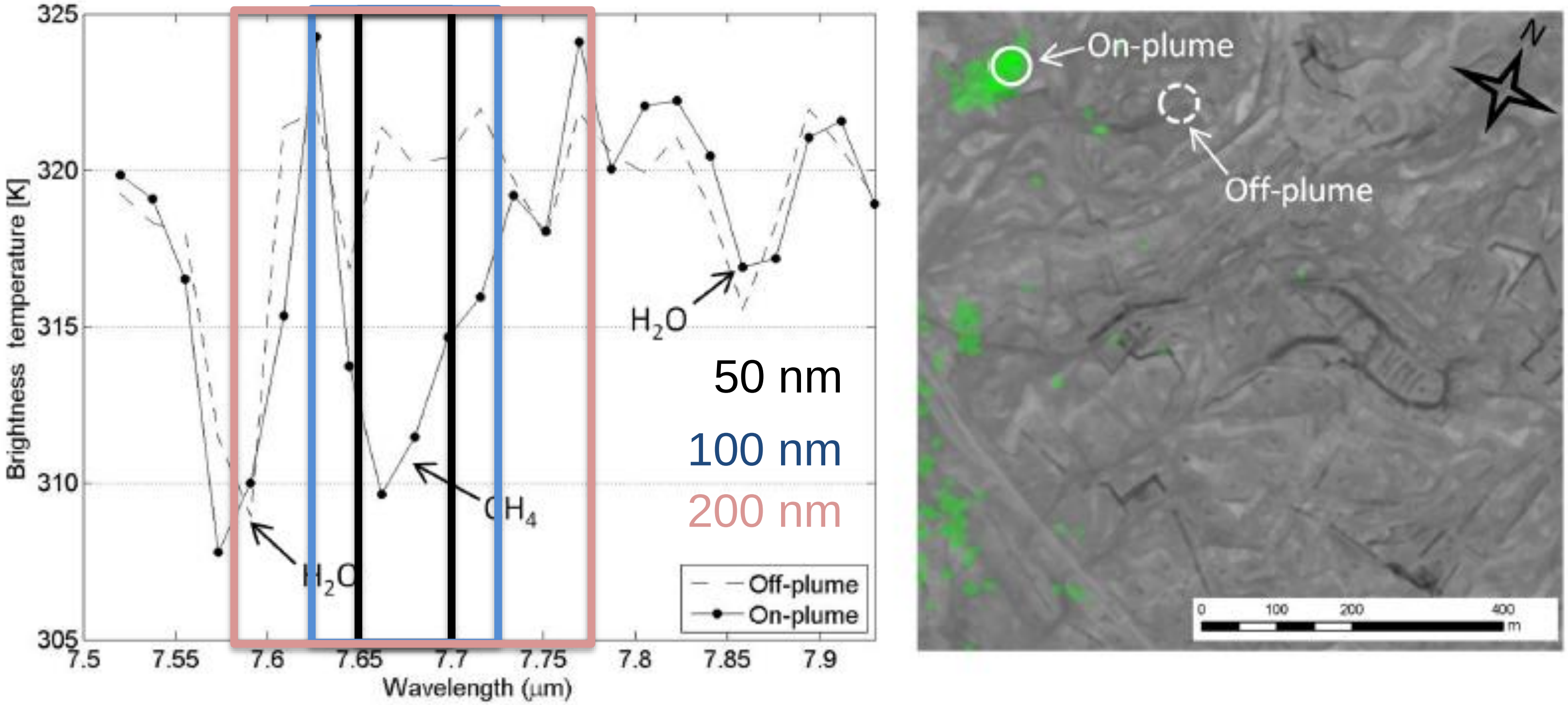
MURI Development

- Schedule
  - Completed 1st Year: Design and performance modeling
  - 2nd Year: Construction of airborne demonstration instrument
  - 3rd Year: Validation flights

Investigation Objectives

- Explore bandwidth sensitivity for spectral band allocated for methane detection in thermal
- Compile a brightness temperature difference dataset:
  - Examine a system that successfully detects methane: NASA/JPL HyTES
  - Perform radiative transfer simulations using MODTRAN 6
- Develop a radiometric model based on MURI:
  - In-house capability to predict noise as a function of scene radiance
  - Noise floor calculations based on initial DRS 300 k Noise Equivalent delta Temperature (NEdT) prediction

Region of Methane Absorption Feature



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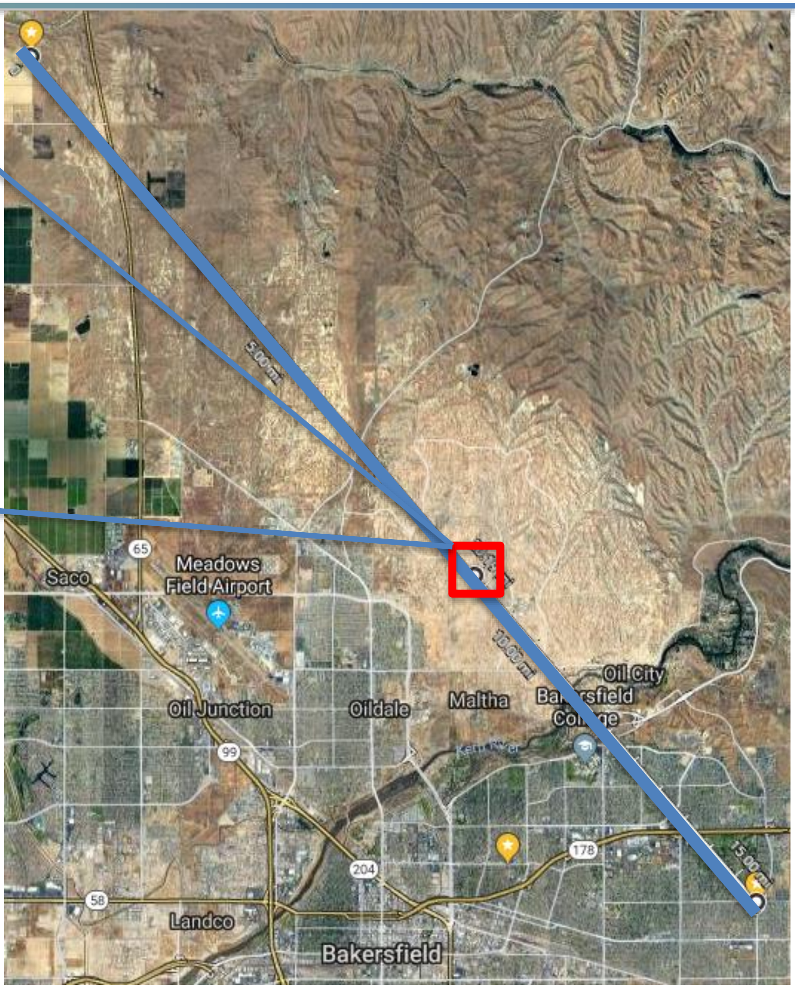
Exploring HyTES Data

- Obtained data from 2016 paper
  - Hulley et. al., "High spatial resolution imaging of methane and other trace gases with the airborne Hyperspectral Thermal Emission Spectrometer (HyTES)," *Atmospheric Measurement Techniques,* vol. 9, no. 5, pp. 2393-2408, 2016.
- L3 data acquired, includes flagged images indicating NH3, CH4 presence
- Chosen July 8th 2014 @Kern River Oil Line 3 Run 1
  - 2014-07-08.185512.KernRiverOil.Line3-Run1-Segment01-110000-level_1a
- Explored as empirical example of airborne LWIR methane detection

Selected Flightline at Kern River Oil Fields

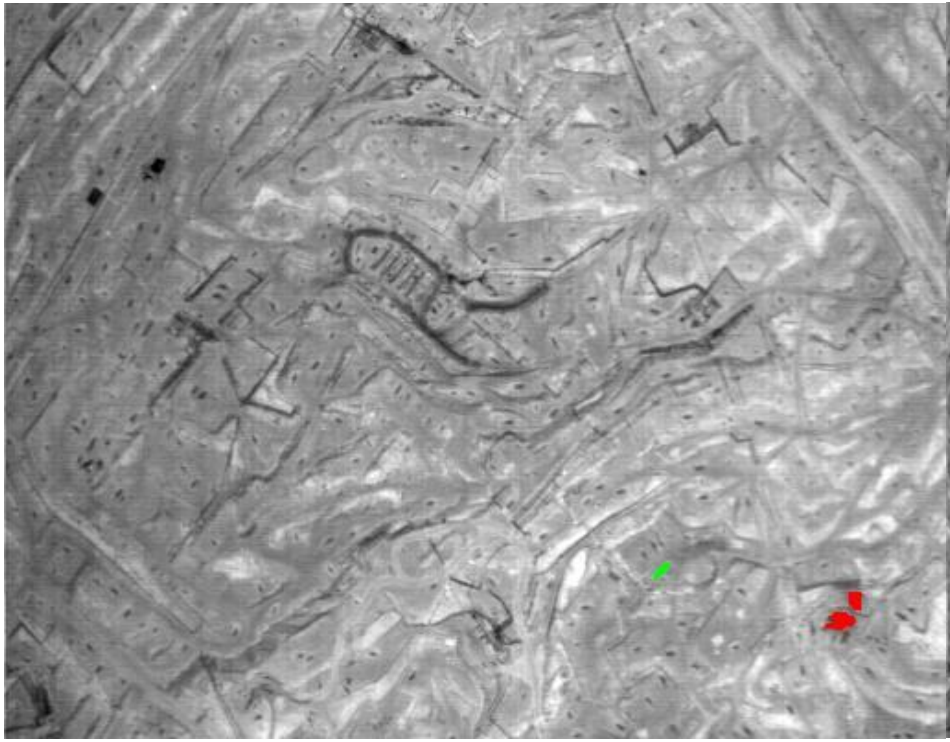
Zoom image rotated to HyTES orientation (35.445282 N 118.996964 W)



Google Maps image of flight line for HyTES near Bakersfield, CA

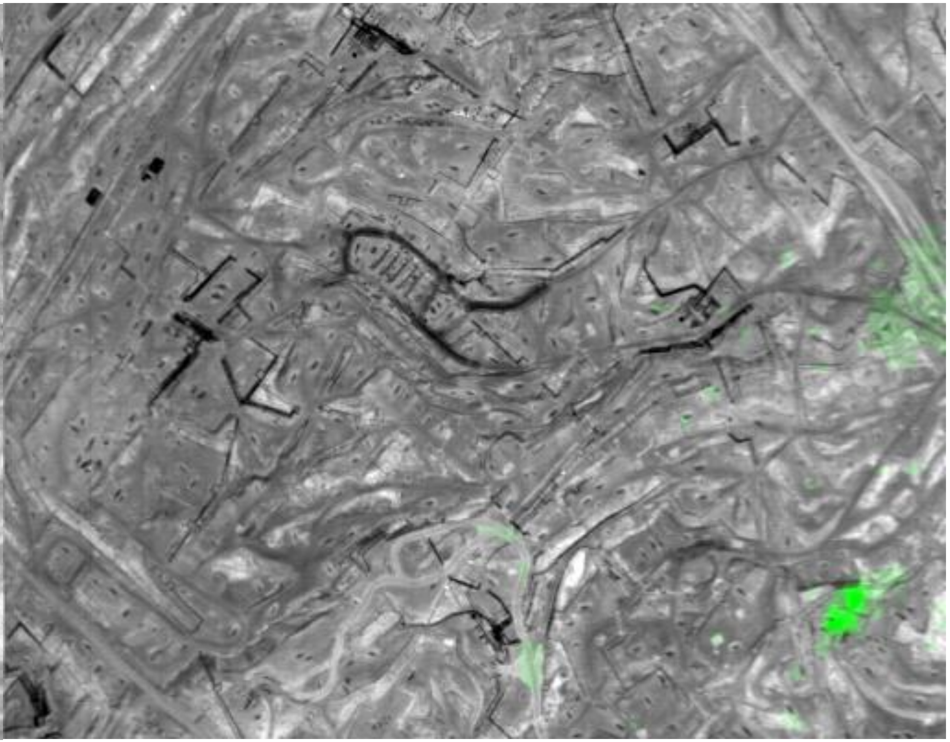
Background and Plume Present Regions of Interest

HyTES Band 10 (7.68 µm)



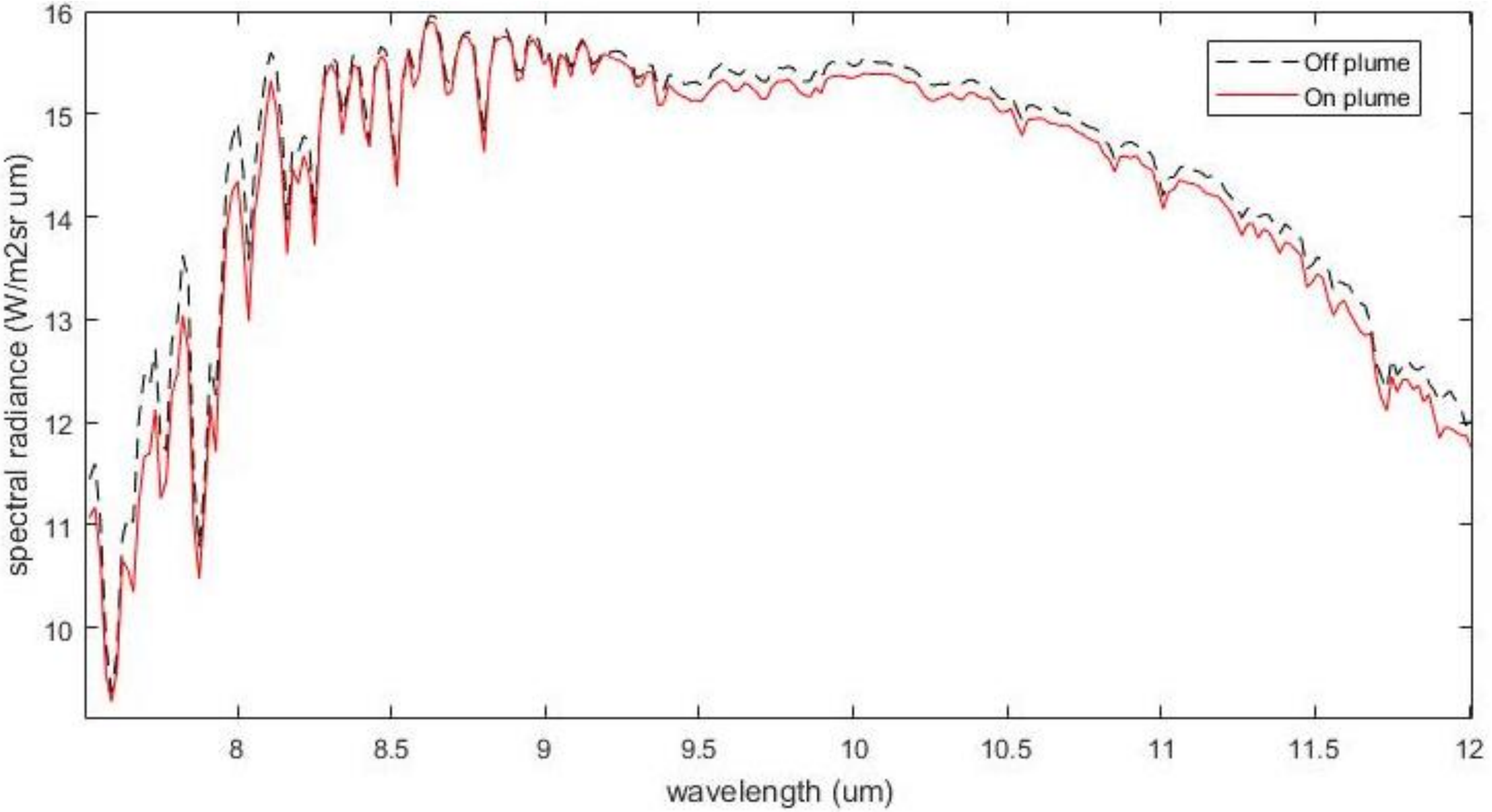
Red: methane plume
Green: Background

HyTES Grayscale Image w/Methane Detection

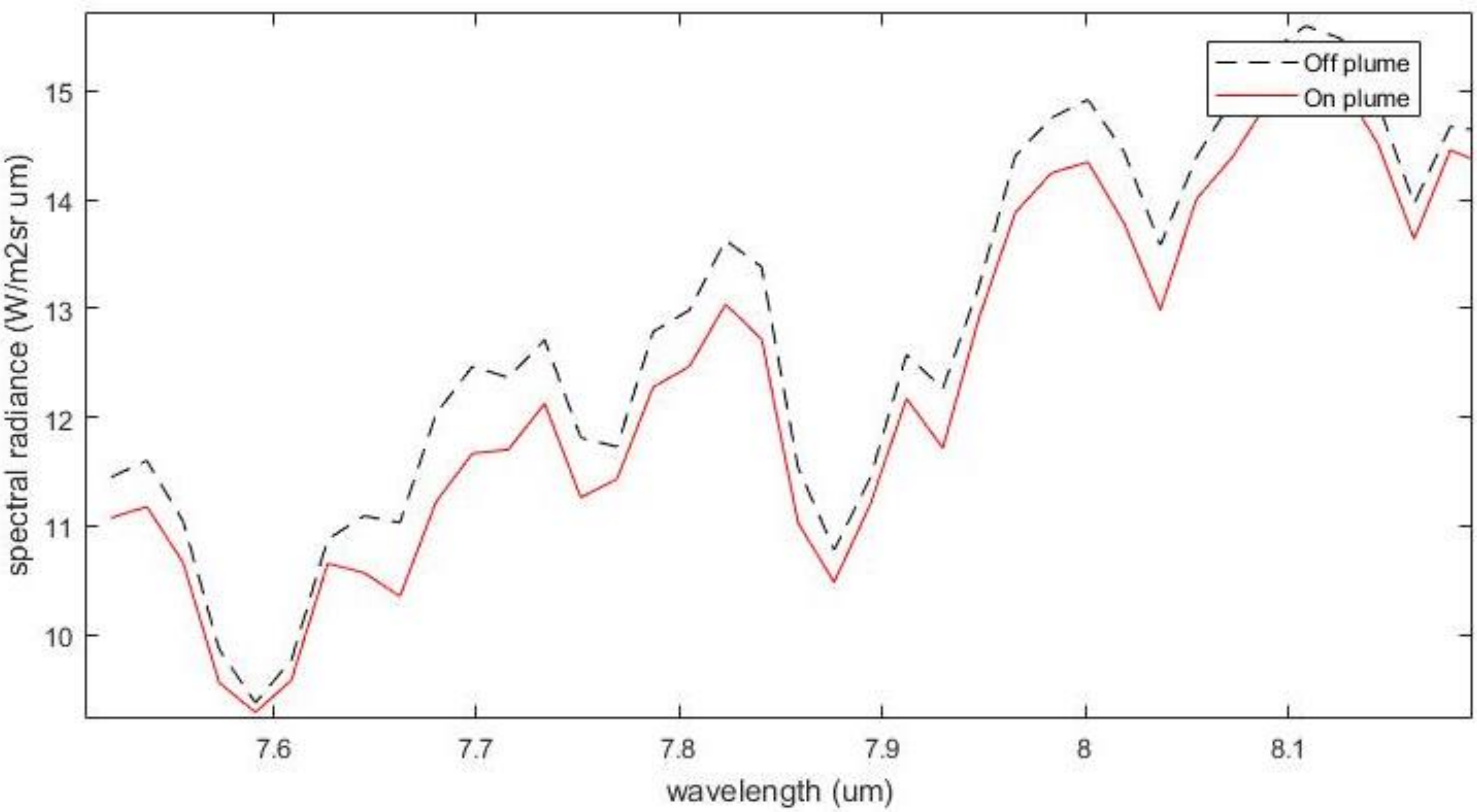


Methane detection map provided by JPL HyTES Team

HyTES Average Spectra of ROIs Comparison

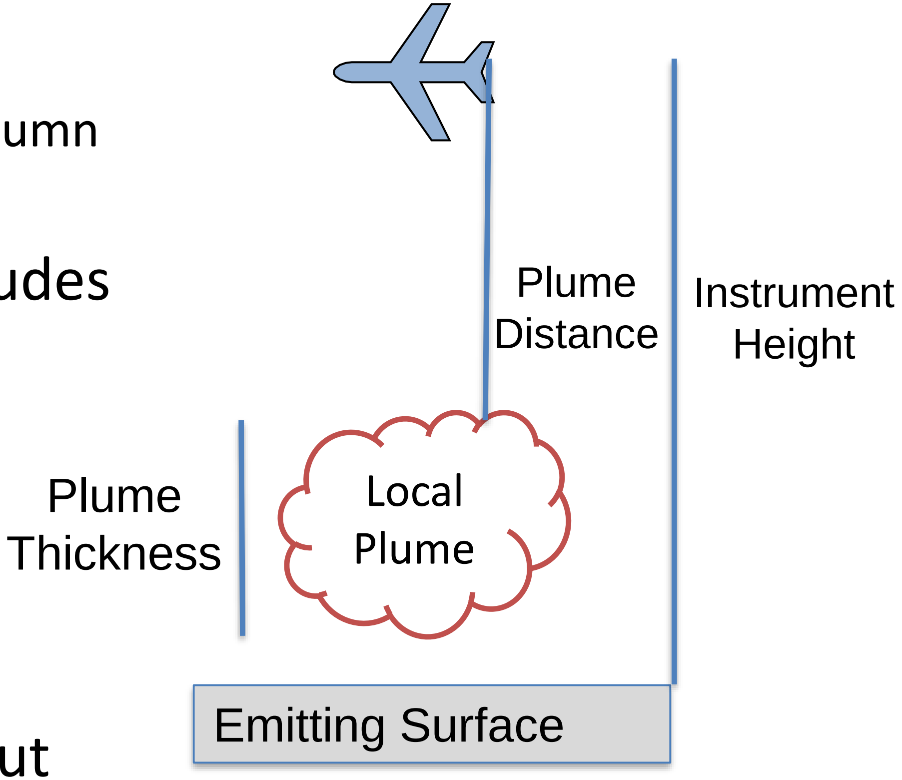


HyTES Average Spectra of ROIs in Methane Absorption Band



MODTRAN6 Modeling Study Using Localized Plume Model

- Baseline atmospheric model
  - Greybody emitting surface
  - Midlatitude Summer with water column scaled by 50%
- Local chemical plume model includes
  - Plume distance from detector
  - Thickness of plume
  - **Concentration of gas**
  - **Temperature of plume**
- Single MODTRAN run generates spectral radiance with and without plume



Parameters

- Constants:
  - Instrument height (15000 feet or 4.572 km)
  - Background emitting surface temperature (305 K)
  - Surface emission (0.95)
  - Plume thickness (20 m)
  - Plume height (570 m)
- Variables:
  - Methane concentration within plume
  - Temperature of methane plume
- Simulation Results:
  - Brightness Temperature Differences

Determining Methane Concentrations for Plume Models

- Methane concentrations chosen at:
  - 100 ppm, 500 ppm, 1000 -10000 ppm at 1000 ppm intervals

Concentrations (ppm)	Description
1-2	Background Atmospheric
1000	Threshold for safe exposure daily for 8 hours
50,000	Lower Explosive Limit
150,000	Upper Explosive Limit
500,000	Asphyxiation

-Government of Canada (2004). Agri-facts. Methane (CH4) safety factsheet Agdex 729-2.

-T. J. Blasing. US Department of Energy (2016). CDIAC. Recent Greenhouse Gas Concentrations.

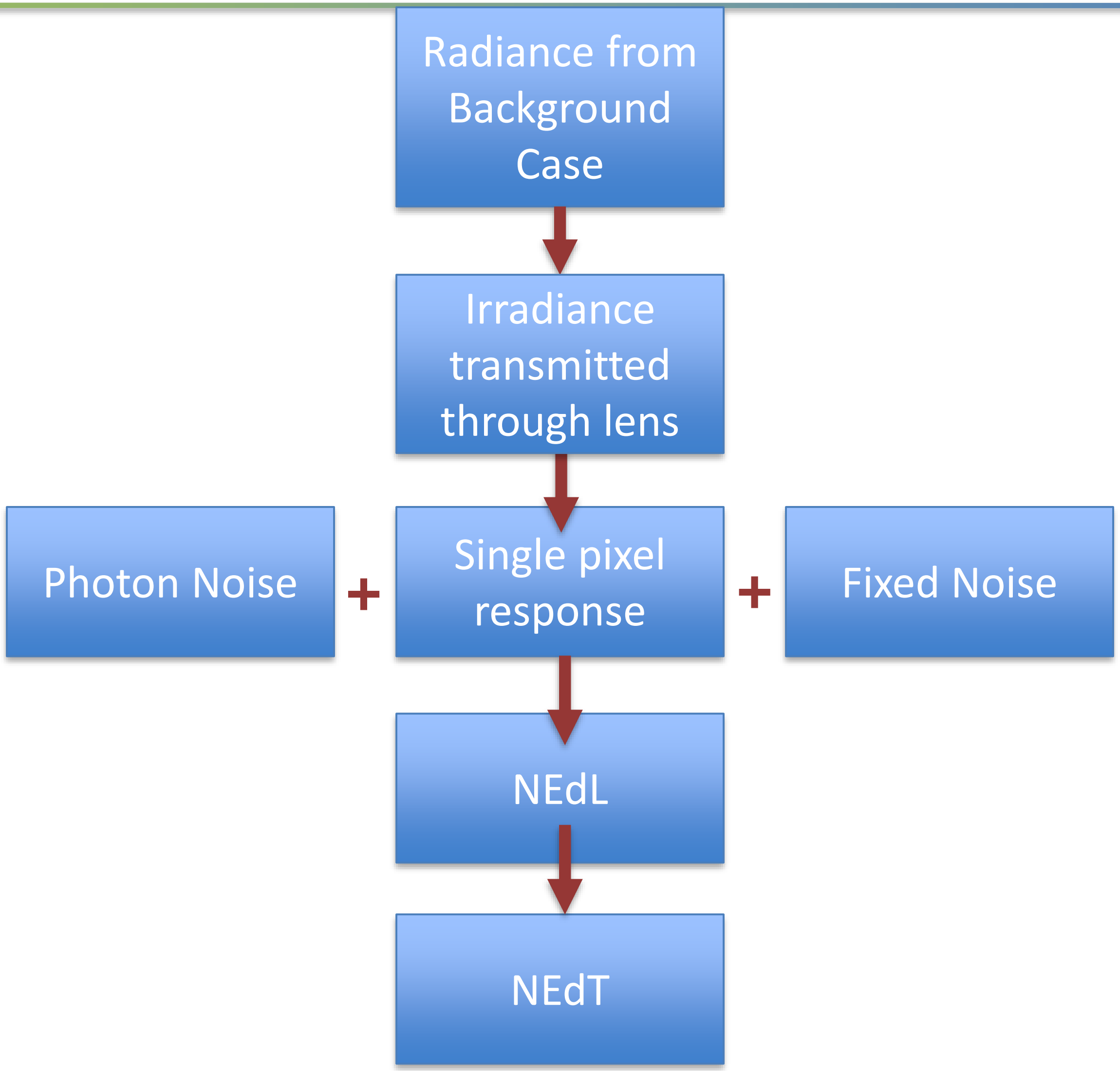
Assessing Methane Detection

- Calculate band-averaged effective spectral radiance for single band from MODTRAN 6 simulation
- Calculate apparent temperature or brightness temperature from effective radiance
- Calculate temperature difference between ambient (no plume) and plume present cases
- Compare to Noise Equivalent delta Temperature (NEdT)

$$L_{eff} = \frac{\int L_{MOD} R d\lambda}{\int R d\lambda}$$

$$T_{app} = \frac{hc}{\lambda k_b log \frac{hc}{\lambda^5 L_{eff}}}$$

MURI Noise Modeling Summary



Radiance from Background Case

Irradiance transmitted through lens

Photon Noise + Single pixel response + Fixed Noise

NEdL

NEdT

Preliminary MURI Noise Modeling

$$L_{eff} = \frac{\int BR d\lambda}{\int R d\lambda}$$

$$NEdL = \frac{L_{eff} N_{tot}}{S_{photons} QE}$$

$$\Phi = \frac{L_{eff} \tau \pi A}{1 + 4(f\#^2)}$$

$$NEdT = \frac{NEdL}{\frac{dB}{dT}}$$

$$S_{photons} = \Phi t \lambda / hc$$

$$Ns = \sqrt{S_{photons}\, QE}$$

$$N_{tot} = \sqrt{N_{floor}^2 + N_s^2}$$

Variable	Meaning
B	spectral radiance provided by MODTRAN
R	responsivity
λ	wavelength
Leff	effective radiance
Φ	detector flux
A	area of detector
τ	optical transmission coefficient
f#	f-number of optics
Sphotons	photon single
t	integration time
h	Planck constant
c	speed of light
Ns	photon noise
QE	quantum efficiency
Ntot	total noise
Nfloor	system noise
NEdL	noise equivalent delta radiance
NEdT	noise equivalent delta temperature

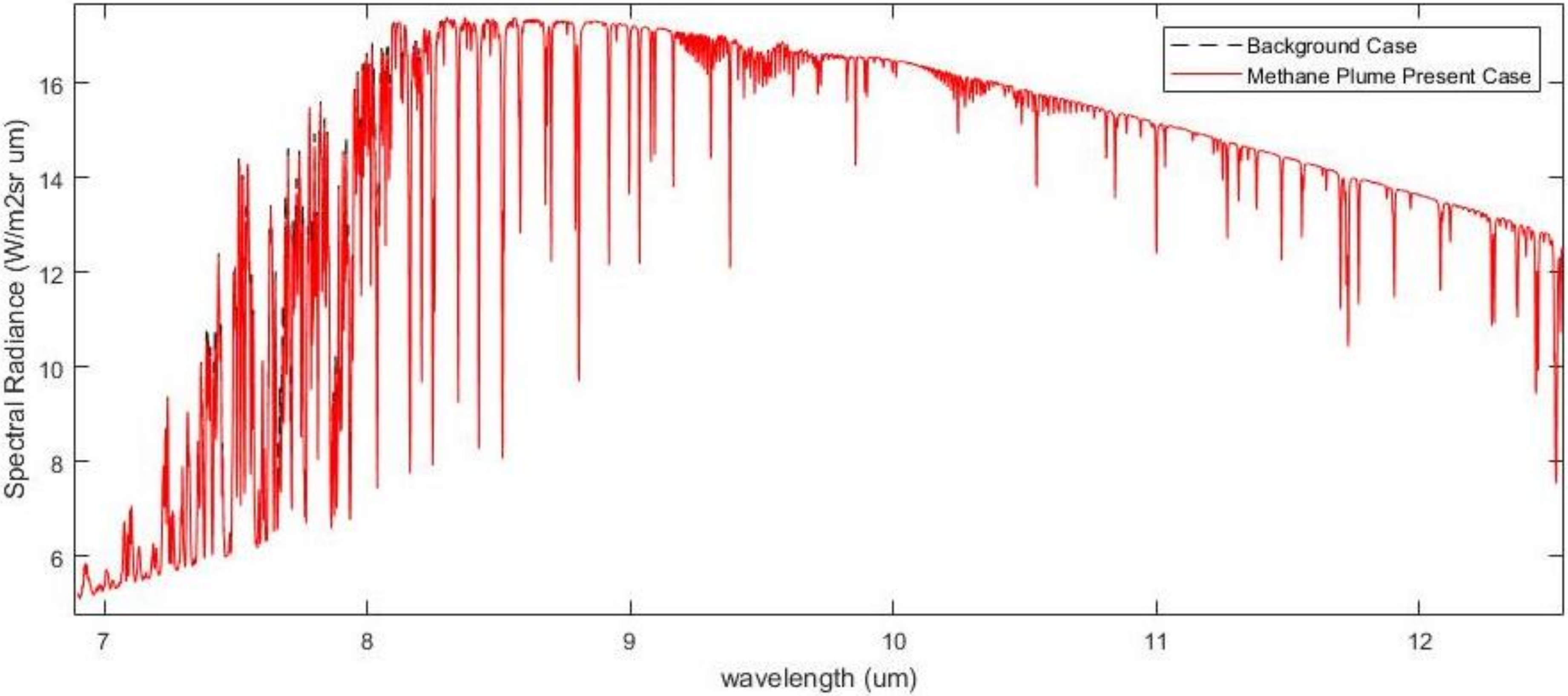
Methane Band NEdT Calculations

- Calculated using MODTRAN6 background case results as input radiance
- Parameters:
  - Band center at 7.68 um
  - Instrument height (15000 feet or 4.572 km)
  - Background Temperature (305 K)
  - Surface Emission (0.95)
  - Midlatitude summer
  - 50% water column concentration

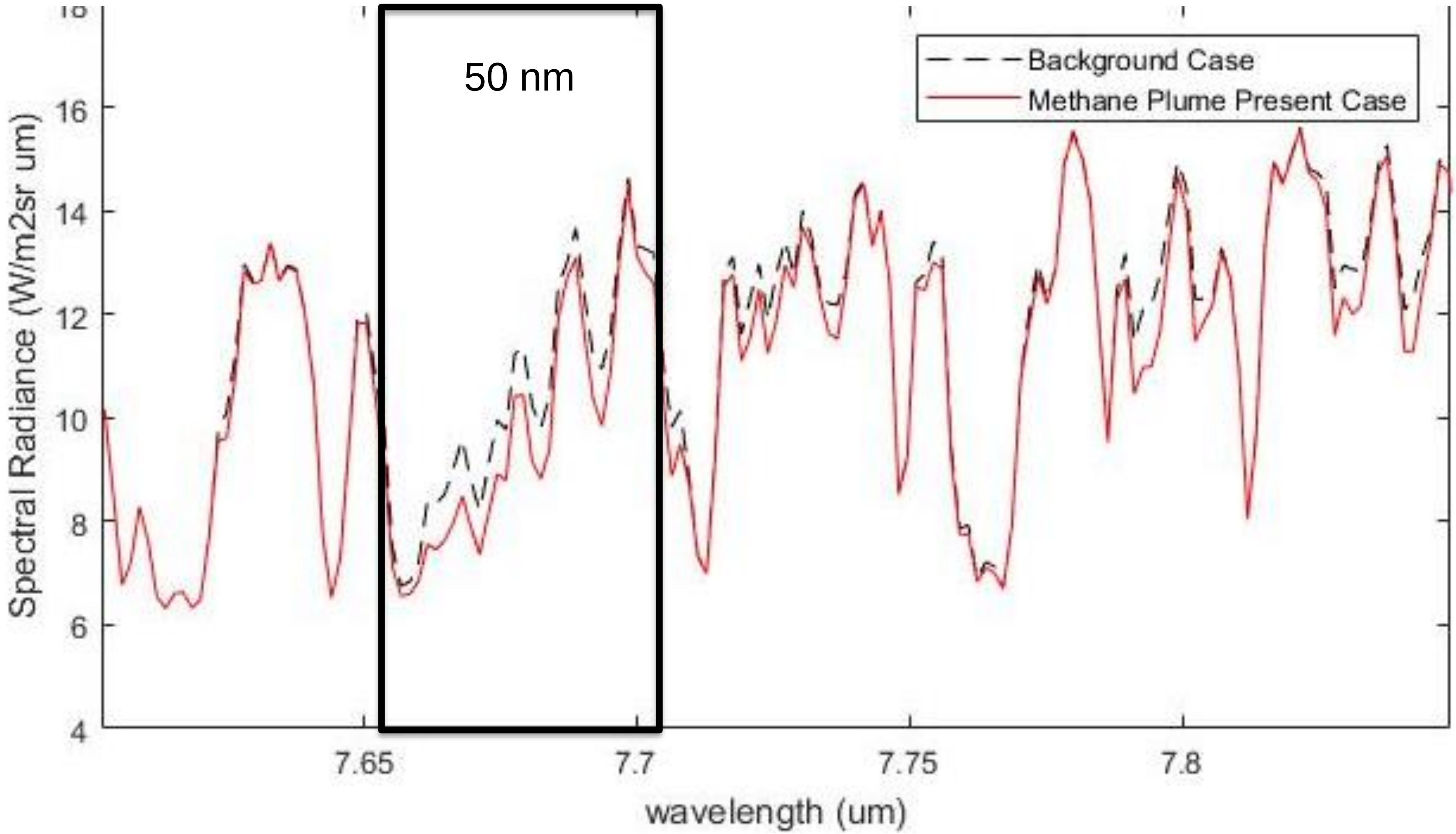
.05 um	.1 um	.2 um
0.70	0.70	0.71

Preliminary NEdT for MURI Methane Band in K

High Resolution MODTRAN6 output

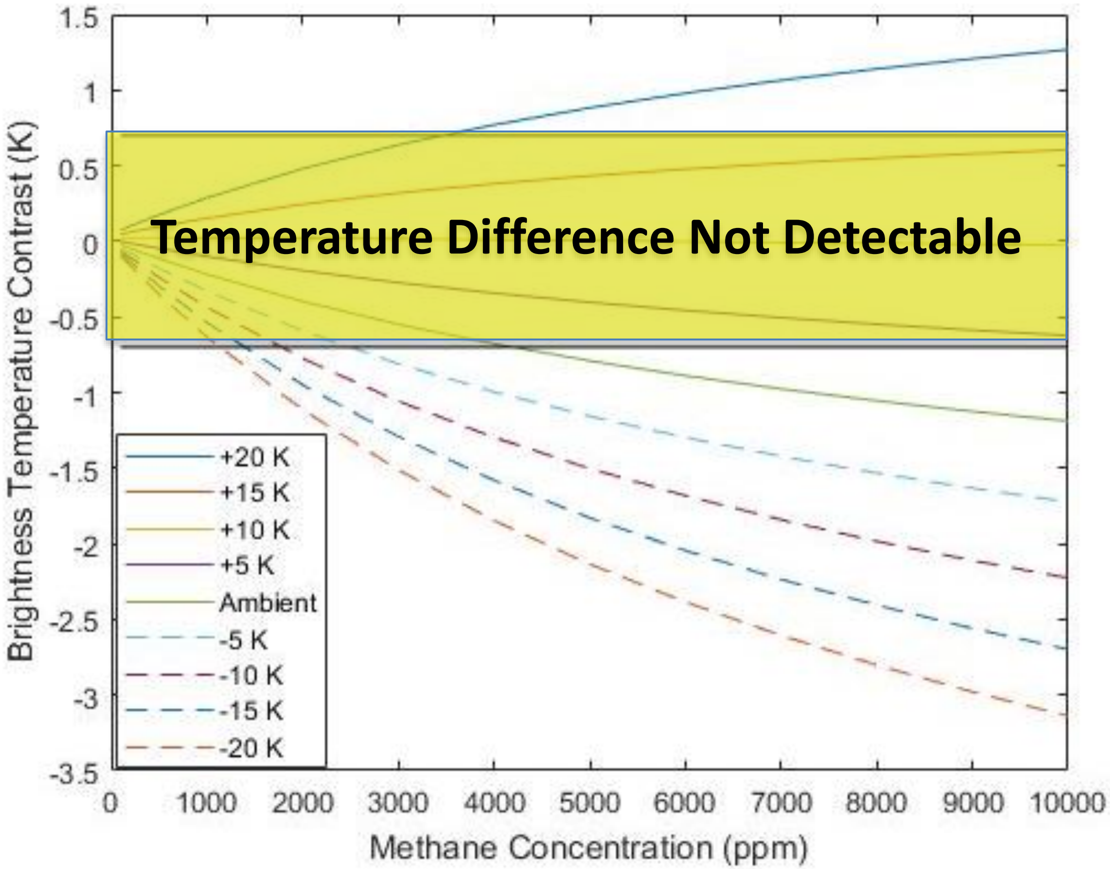


High Spectral Resolution Methane Absorption Region



Brightness Temperature as a Function of Methane Concentration

- Displaying Brightness Temperature difference for a single temperature difference
- 50 nm band pass
- Parameters
  - Instrument height (15000 feet or 4.572 km)
  - Background emitting surface temperature (305 K)
  - Surface emission (0.95)
  - Plume thickness (20 m)
  - Plume height (570 m)



Brightness Temperature as a Function of Plume Temperature

- Displaying Brightness Temperature difference for a single methane concentration
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- Parameters:
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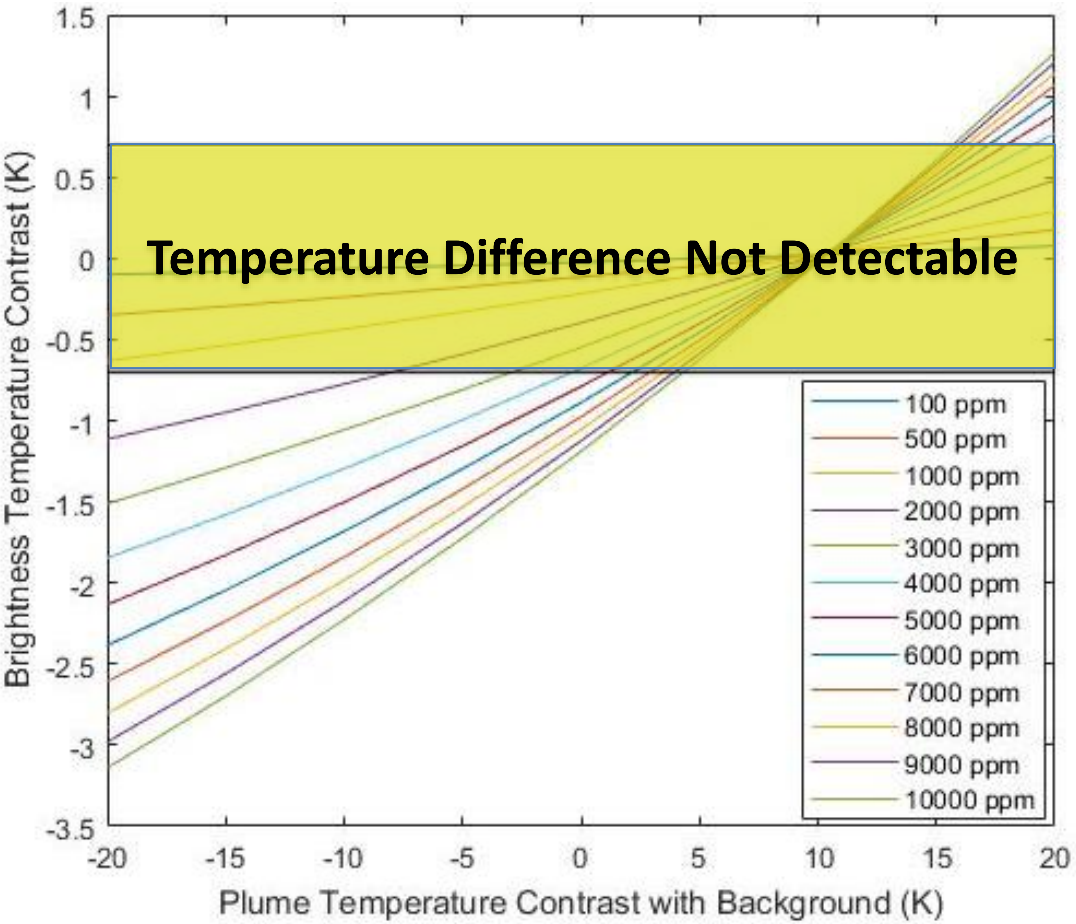
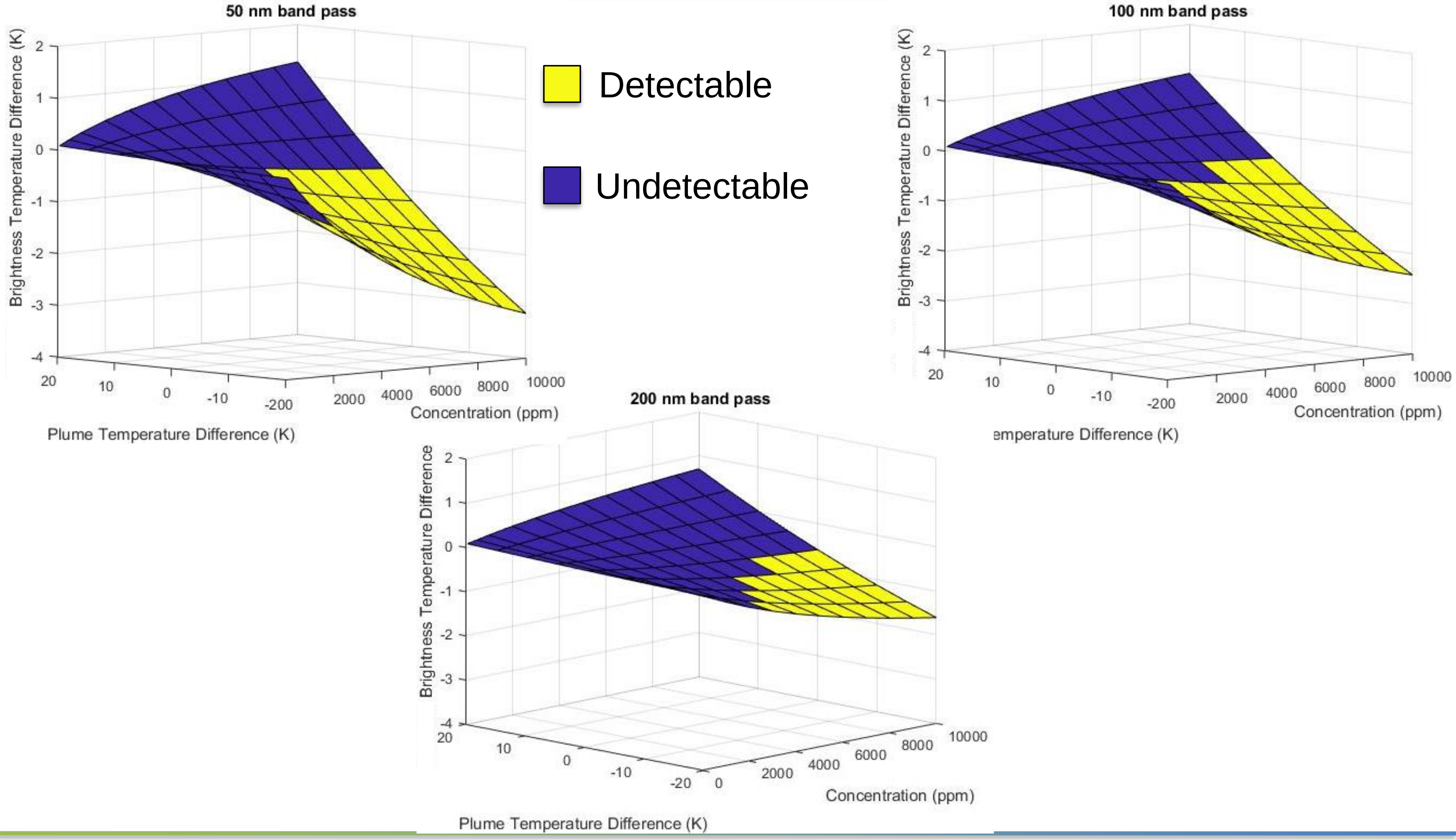


Results and Trends

- As concentration increases, the temperature difference increases
- At the current background and atmospheric temperature, absorbing plumes (negative plume temperature difference) tend to shows higher contrast
- Visualization of both trends shown via surface plots

Detectable and Nondetectable Scenarios: Surface Plot Comparisons



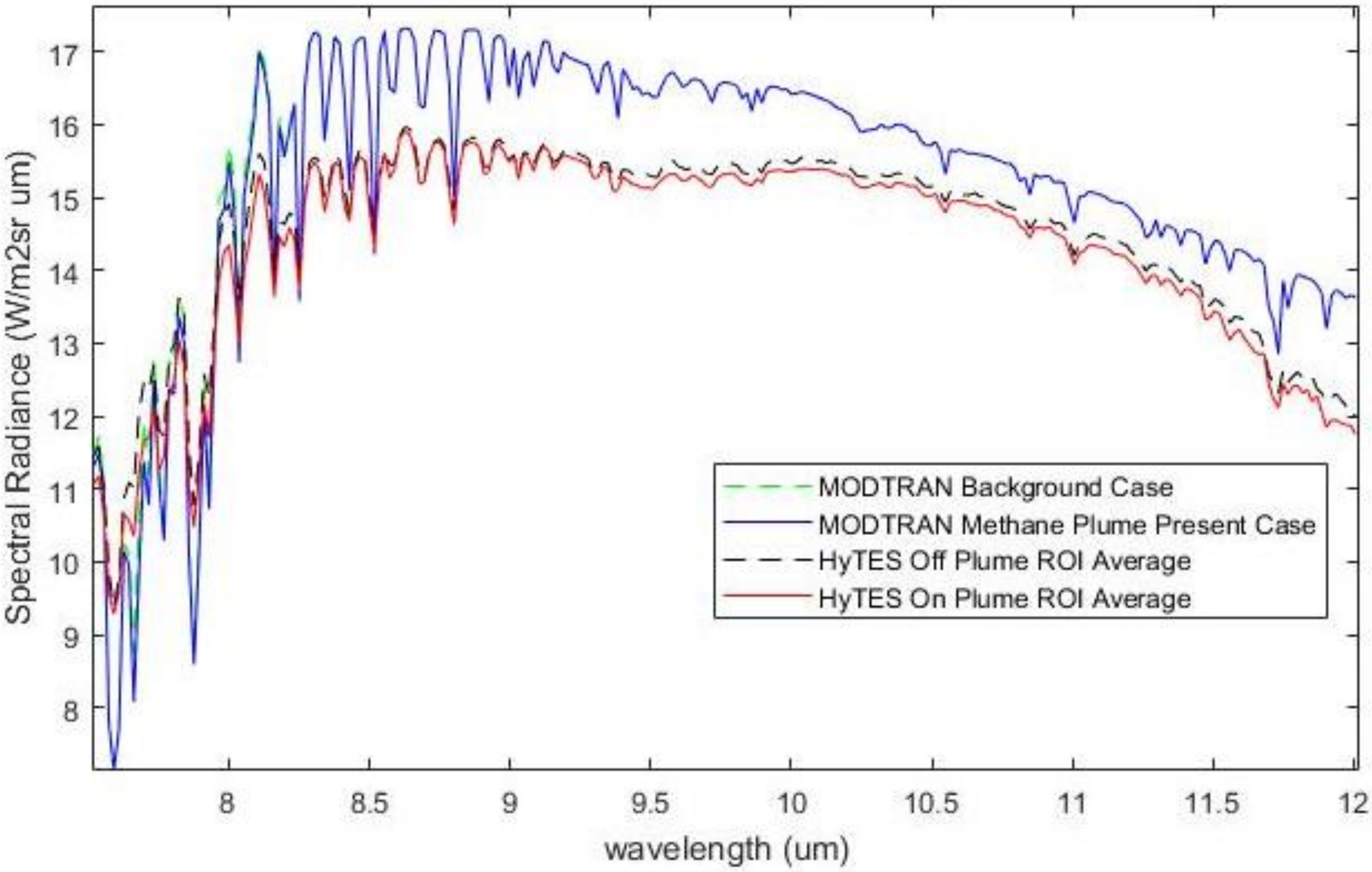
Conclusions

- For this arrangement we see the lowest concentration and temperature difference currently visible is:
  - 2000 ppm and -5 K with a 50 nm bandpass
- For an emitting plume the lowest plume temperature difference and concentration is:
  - 4000 ppm and +20 K with a 50 nm bandpass
- Of the 3 band passes examined, the 50 nm bandpass successfully detects in the highest number of scenarios

Future Work

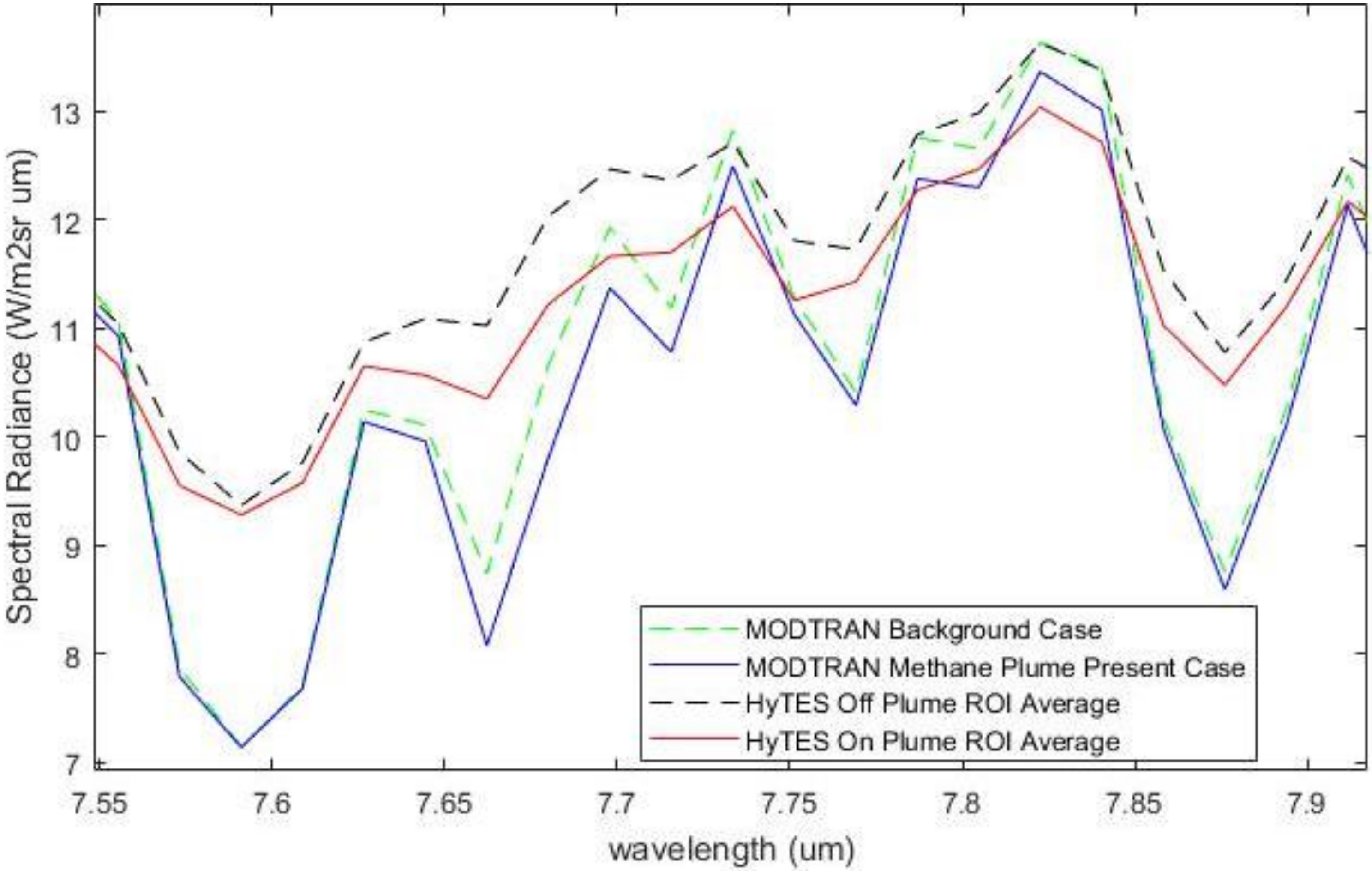
- Explore additional situations:
  - Adjust baseline atmospheric model
  - Adjust total water concentration in column
  - Adjust column temperature profile
- Validate approach by producing results that estimate empirical data (HyTES)

Preliminary Empirical Data and Model Comparison



Preliminary Empirical Data and Model Comparison Methane Absorption Region

- Further exploration needed



Review

- Study motivated by thermal imaging system that does require cooling
- Examined HyTES: a system currently used to detect methane in the thermal infrared
- Detailed the creation of a brightness temperature dataset
- Compared temperature difference to modeled NEdT of MURI system
- Displayed results for band pass sensitivity study indicating a 50 nm bandpass detects methane in the highest number of scenarios