Paper B3P3

Tropospheric Infrared Mapping Spectrometers (TIMS) for Improved Vertical Resolution Measurements of Carbon Monoxide in the Lower Troposphere

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Our IIP 2006-2008 project* involves the design, performance, and application to atmospheric CO spectroscopy, of dual infrared grating spectrometers operating near 2.33 μm (Solar Reflective) and 4.68 μm (Thermal Emissive) regions. Both use 2-D detector arrays to provide simultaneous spectral and spatial information at ~0.25 and ~0.53 cm^{-1} resolution, respectively

Outline of This Presentation

- **Motivation and Approach**
- **Spectrometer Design**
- **Radiometric/Spectral Calibration and Performance Assessment**
- **Ground-based Atmospheric Observations and Model Comparisons**
- **Concept for Space Borne Instrument to Monitor Boundary Layer and Higher-Layer Tropospheric CO, and other air quality constituents**

***Tropospheric Infrared Mapping Spectrometers (TIMS) for CO: PI J.B.Kumer, LMATC**

Motivation

Global air quality monitoring is a major theme for the next generation earth observing satellites. Two recent surveys* delineate needs and key measurement attributes:

- **Measurement of O_3, CO, NO_x, HCHO, SO_2, VOCs and Aerosols**
- **Sufficient Vertical Resolution (1- 3 km) to monitor the transport and chemical transformation of constituents from the boundary layer to the stratosphere, and identify geographical origin of pollutants and their contribution to regional air quality**
- **High Horizontal resolution (2-5 km) and coverage, to pinpoint emission sources, conduct precise regional area transport tracking, and see through small cloud-free regions**

- ** Community Workshop on Air Quality Remote Sensing from Space; Defining an Optimum Observation Strategy. NCAR, Boulder CO, 2006*

** Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond: National Research Council , 2007*

Instrumental Approach

The vertical resolution needed for boundary layer information for gases such as CO, O_3, HCHO, CH_4, with spectral features in the IR, implies high spectral resolution & high signal to noise.

These spectral/ spatial/radiometric requirements can be met by combining a large – format 2D array with a fixed grating:

- Row pixels provide spectral information, column pixels provide simultaneous spatial information; integration time is maximized
- The many small footprints along the slit and dispersive directions enable high spectral/horizontal resolution, and wide spatial swath

We focus here on tropospheric CO

As shown later, a combination of emissive spectra near 4.68 μm and reflective spectra near 2.33 μm provides good boundary layer and higher layer information

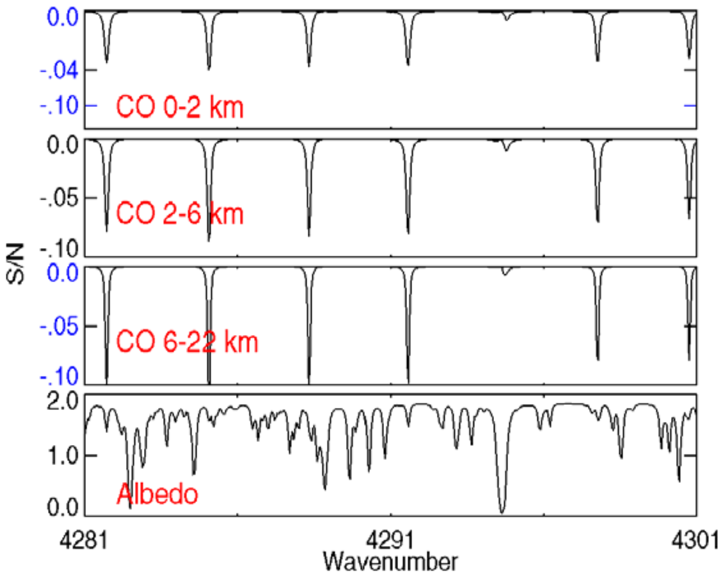
Key instrument requirements for this combination are:

$\Delta\nu \leq 0.5$ cm^{-1} at 4.68 and ≤ 0.2 cm^{-1} at 2.33 μm

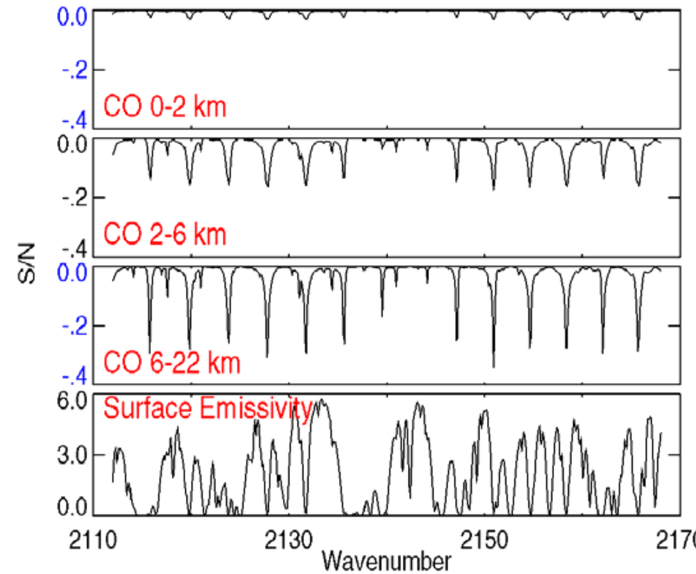
NESR $\leq 2\times10^{-10}$ w/cm2/sr/cm^{-1} at 4.6 μm, 5×10^{-10} at 2.3 μm

Potential for Near -Surface Carbon Monoxide Measurement Using Combined IR Emission and Solar Reflective Spectra

Solar Reflective Region (λ_c=2.33 μm)



Emissive Region (λ_c=4.7 μm)



Nightime (Emissive only) Precision

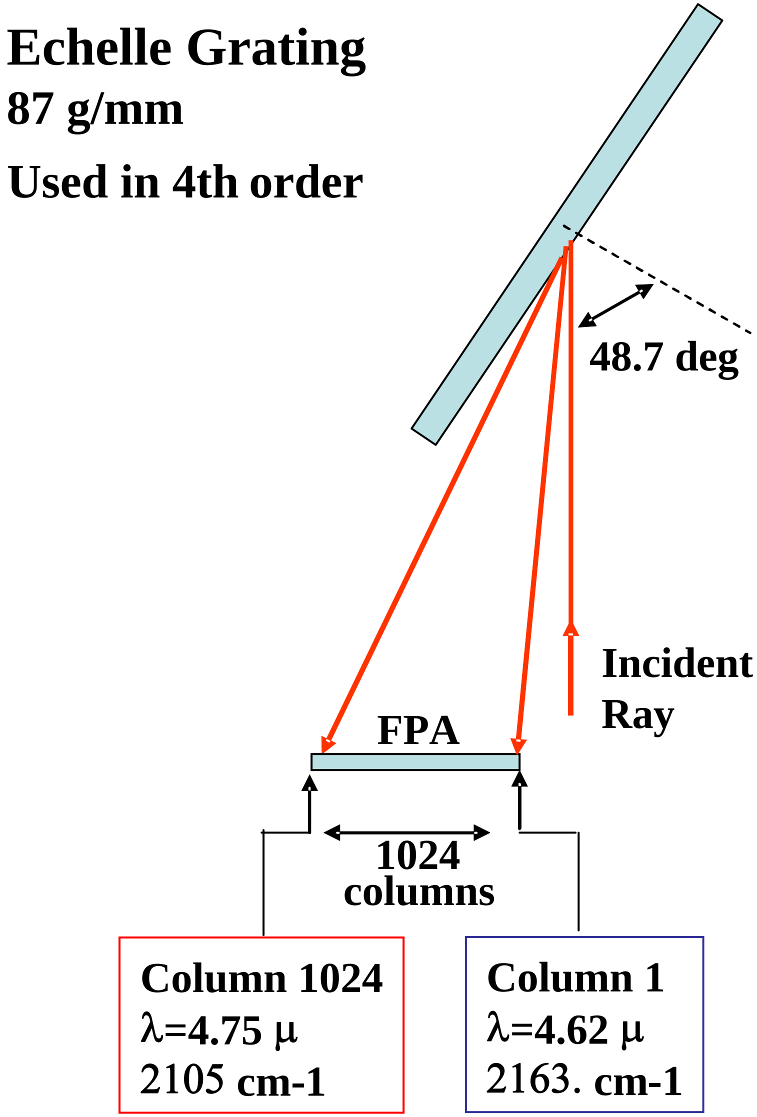
Parameter	Retrieval Precision(%)	A_{TT}
CO: 0-2 km	**24**	**0.11**
CO: 2-6 km	**6.7**	**0.93**
CO: 6-22 km	**2.5**	**0.99**

Daytime(Emissive+Reflective) Precision

Parameter	Retrieval Precision(%)	A_{TT}
CO: 0-2 km	**8.4**	**0.89**
CO: 2-6 km	**4.3**	**0.97**
CO: 6-22 km	**2.3**	**0.99**

Spectrometer Design, Calibration, and Performance

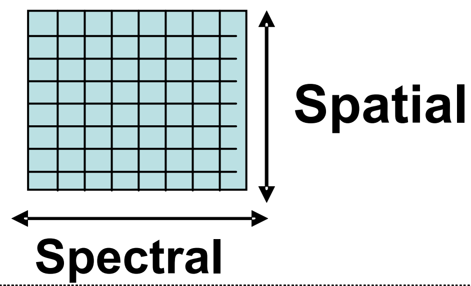
The Basic Technique: MWIR



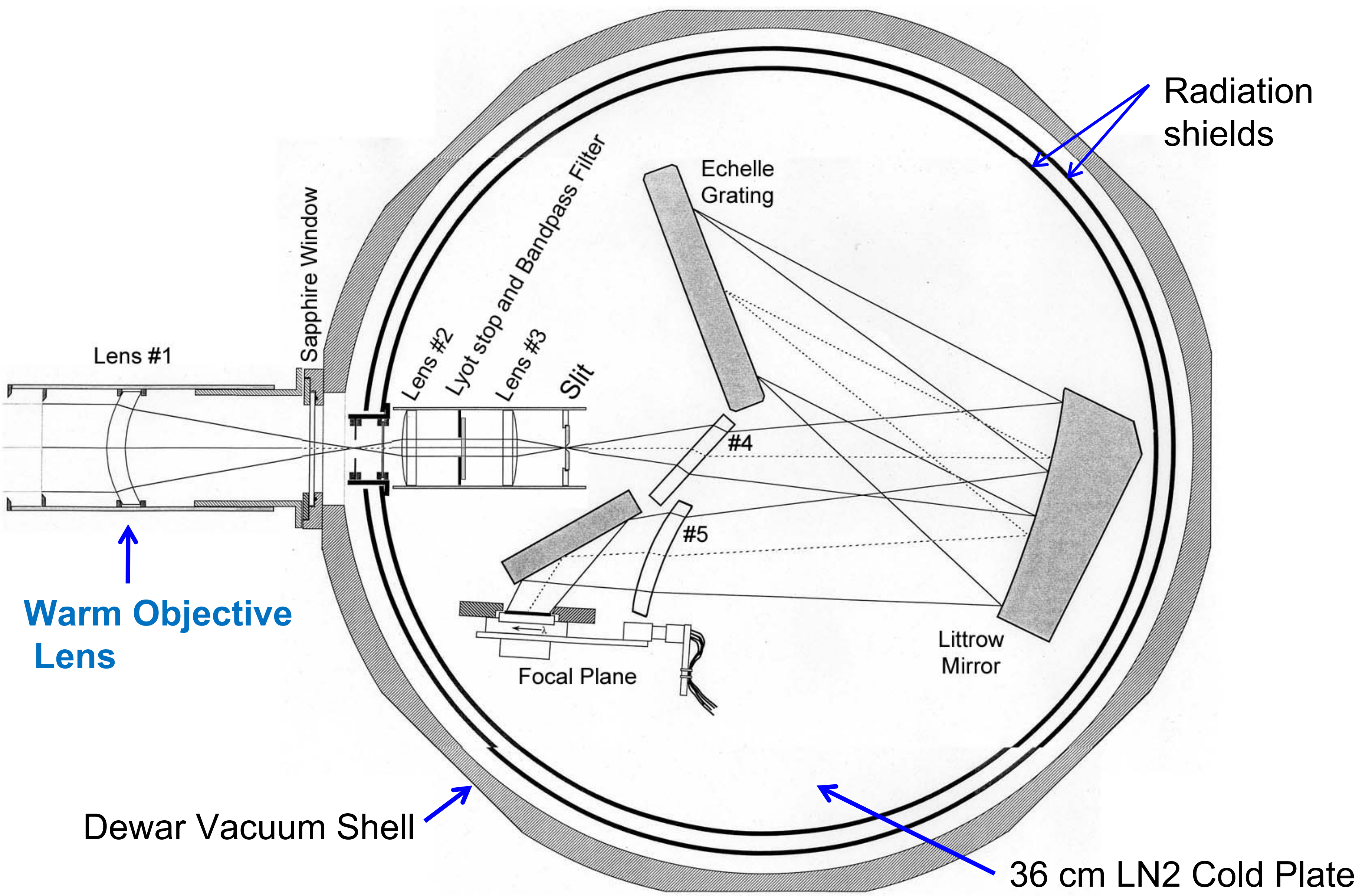
Total Array; Dispersion 58 cm-1
Dispersion per Pixel: .06 cm-1

HAWAII HgCdTe MBE Array

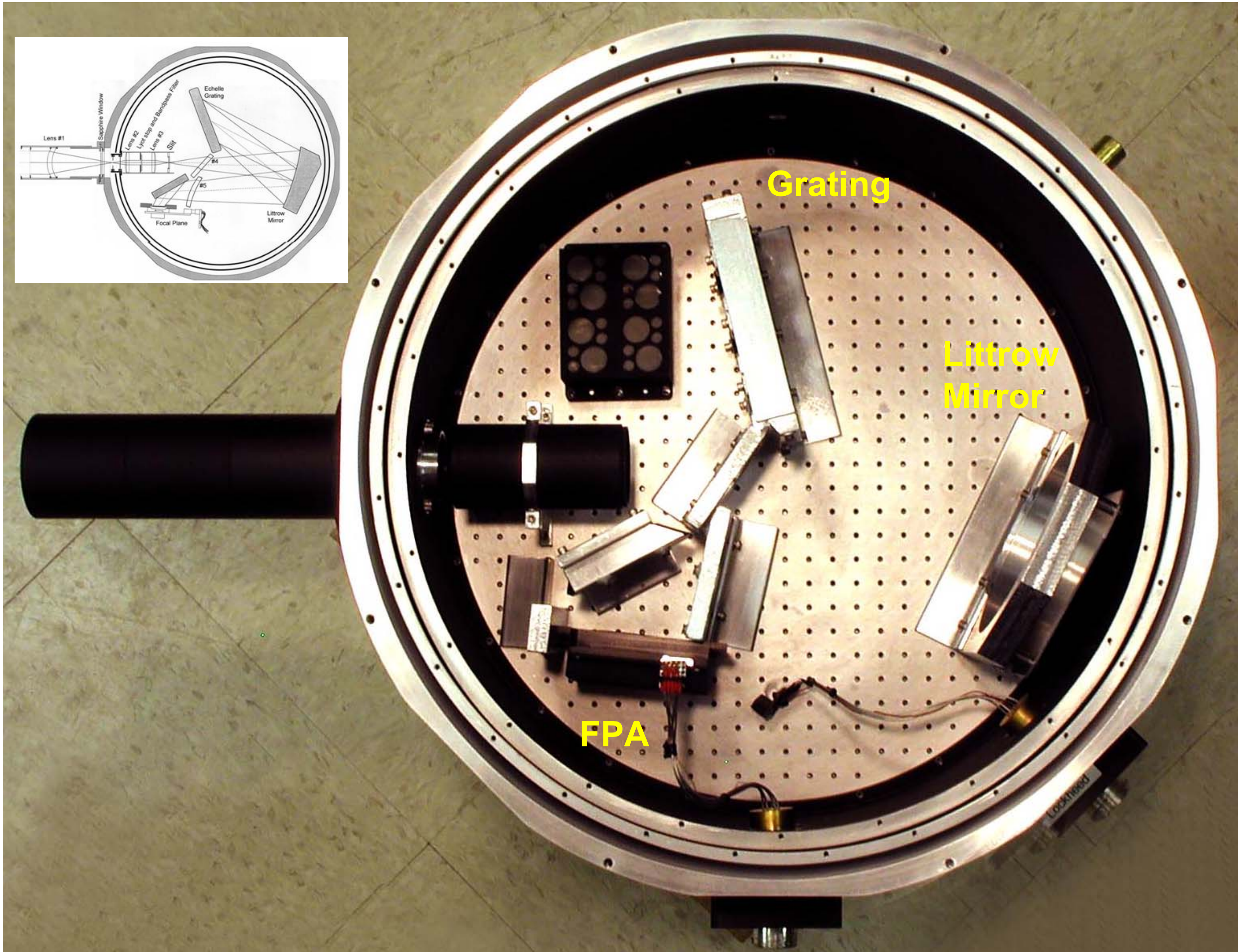
Format	1024x1024
Pixel Pitch	18.5 μ
QE (78K)	~55%
Long Wave cutoff	5.2 μ
Short Wave Cuton	0.95 μ
Read Noise (e rms)	<60 CDS
Dark Current (e/s) at 78K, 0.5V Bias	~ 50
Well Capacity (e)	10^5
Temperature	78K



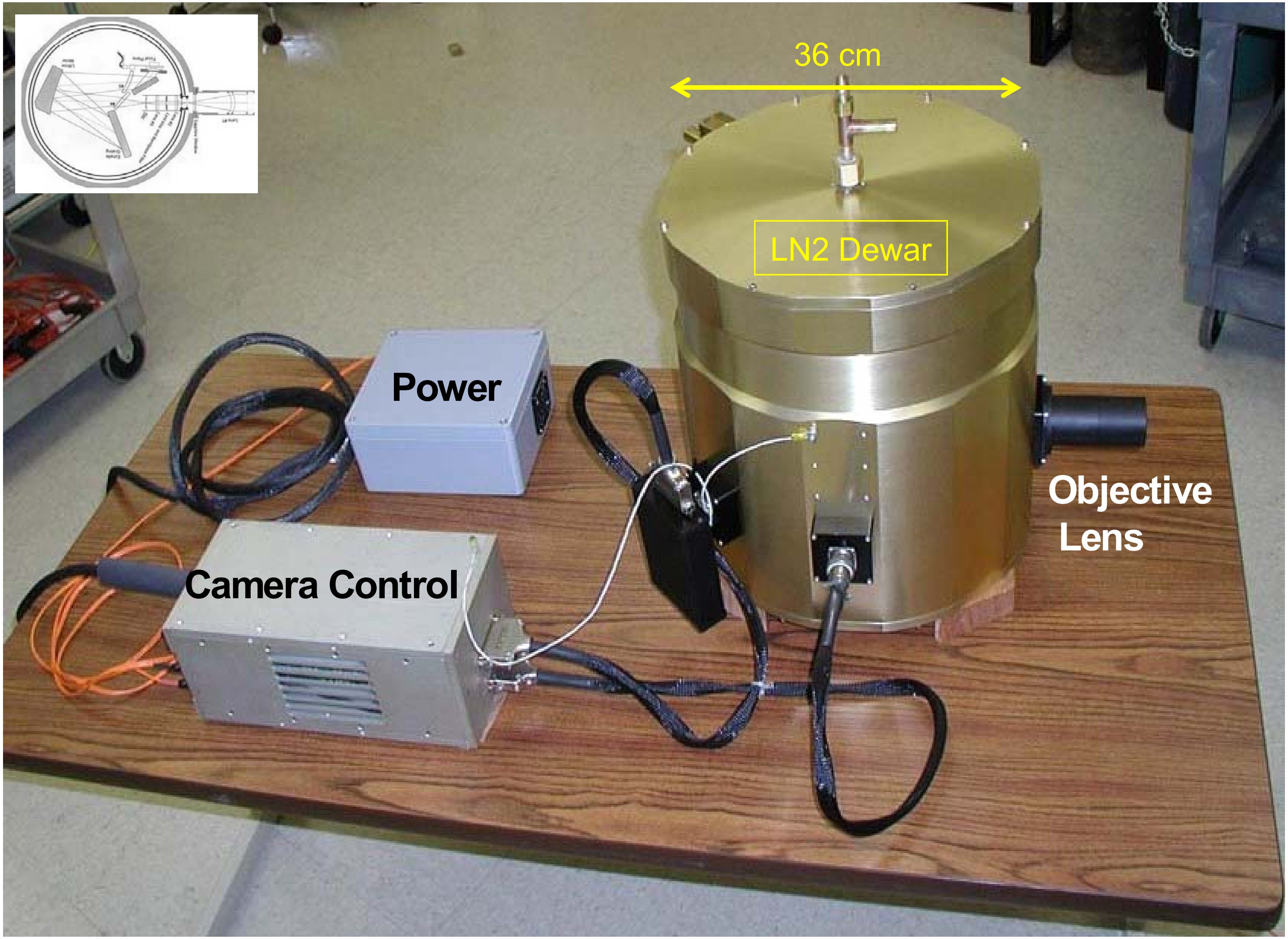
MWIR Spectrometer Optical Layout



View of MWIR Components From Above.

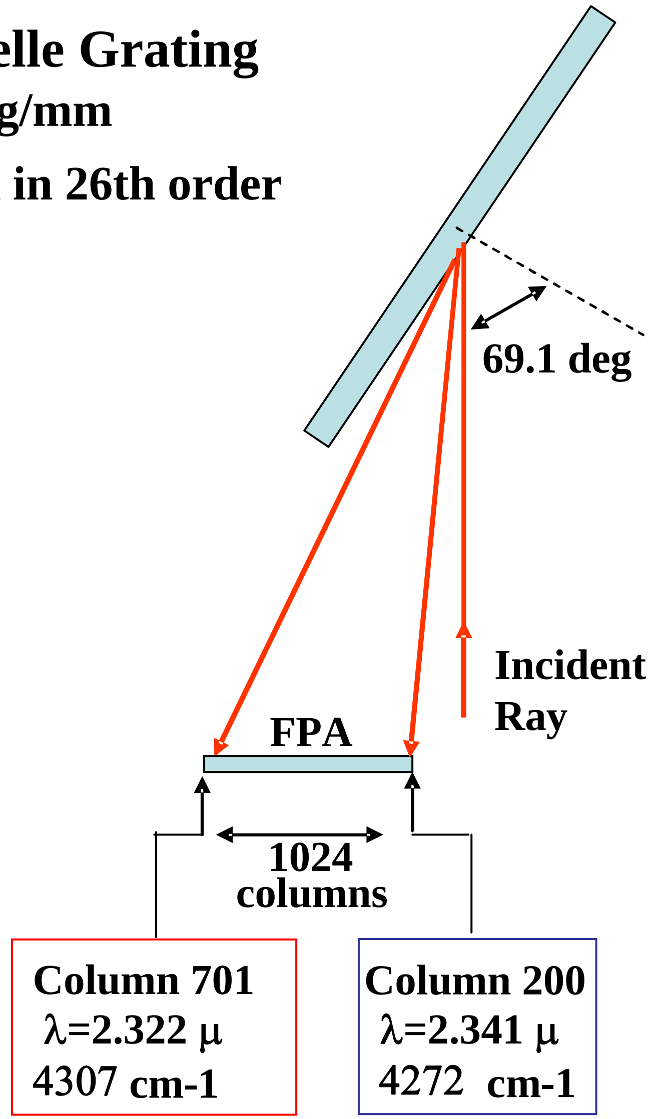


Fully assembled MWIR Spectrometer with Electronics



The Basic Technique: VSWIR

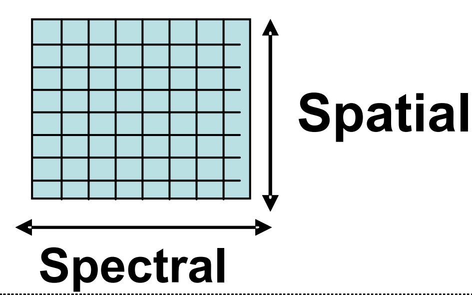
Echelle Grating
31.6 g/mm
Used in 26th order



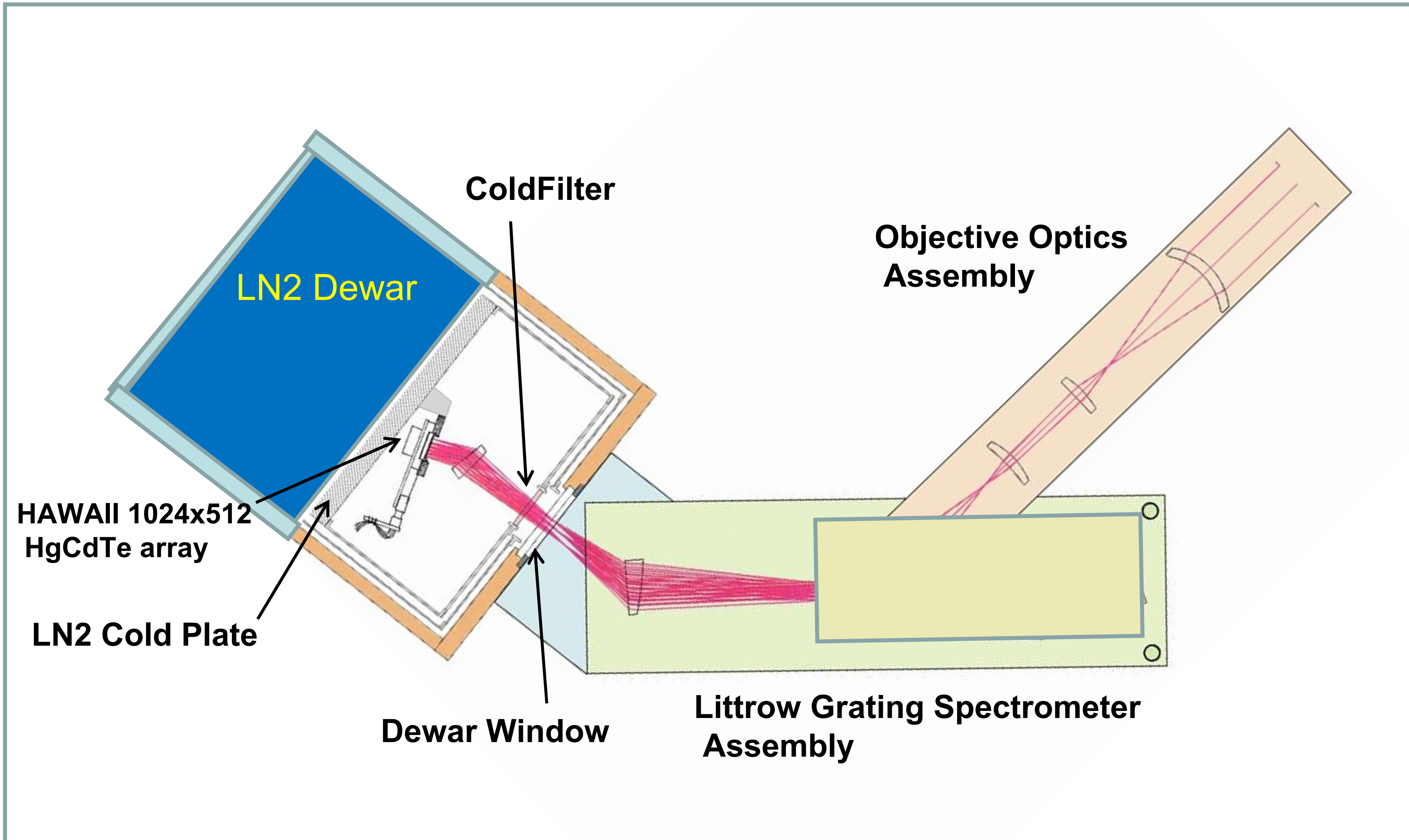
Total Array; Dispersion 35 cm-1
Dispersion per Pixel: .03 cm-1

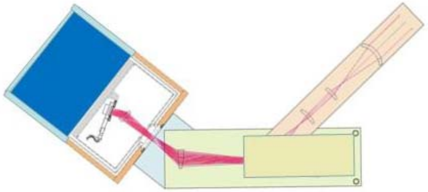
HAWAII HgCdTe PACE Array

Format	1024x512
Pixel Pitch	18.5 μ
QE (78K)	~74%
Long Wave cutoff	2.5 μ
Short Wave Cuton	0.95 μ
Read Noise (e rms)	< 25 CDS
Dark Current (e/s) at 78K, 0.5V Bias	< 1
Well Capacity (e)	10^5
Temperature	78K

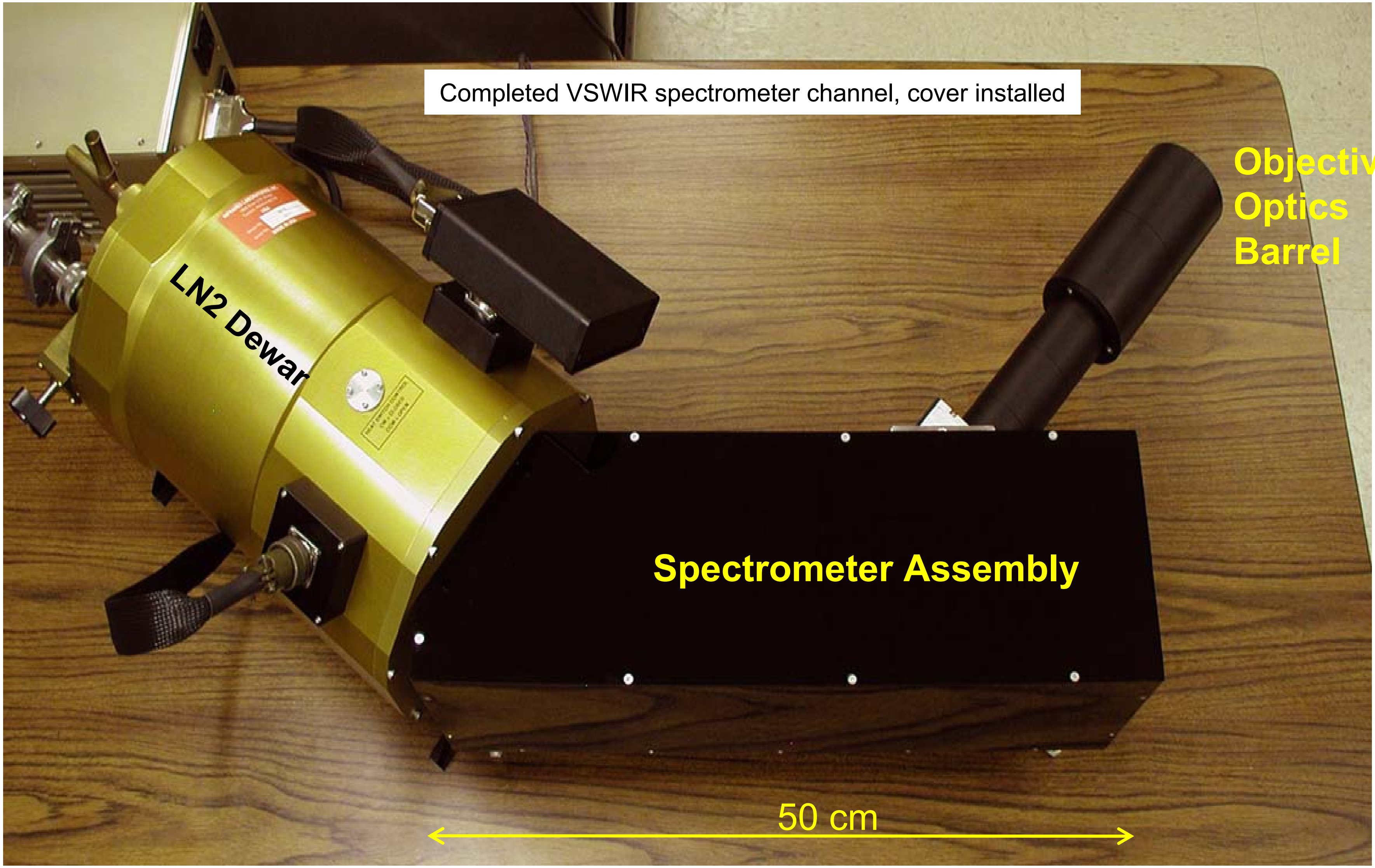


VSWIR Spectrometer Layout





Fully Assembled VSWIR Spectrometer



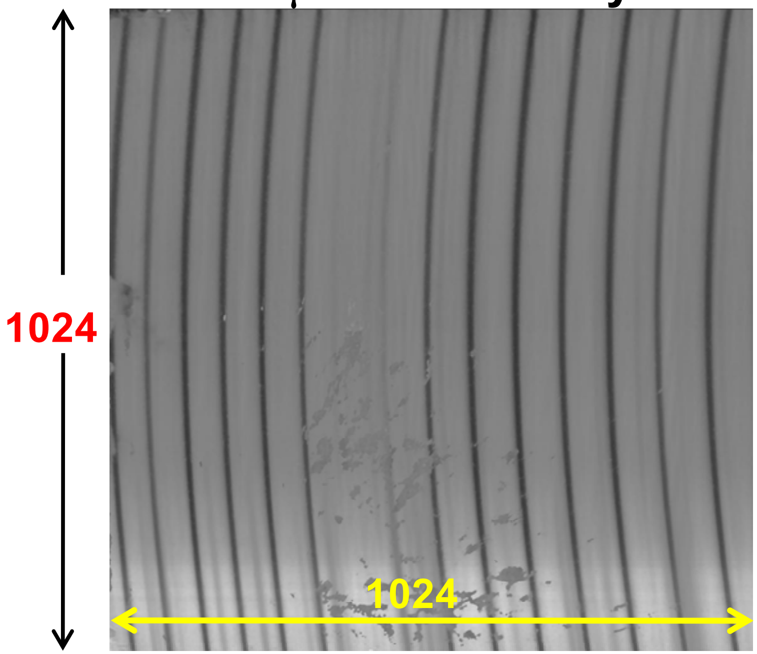
Instrument Optical Parameters and Measurement Products

TABLE 1-1 TIMS MODULE SPECTRAL PARAMETERS

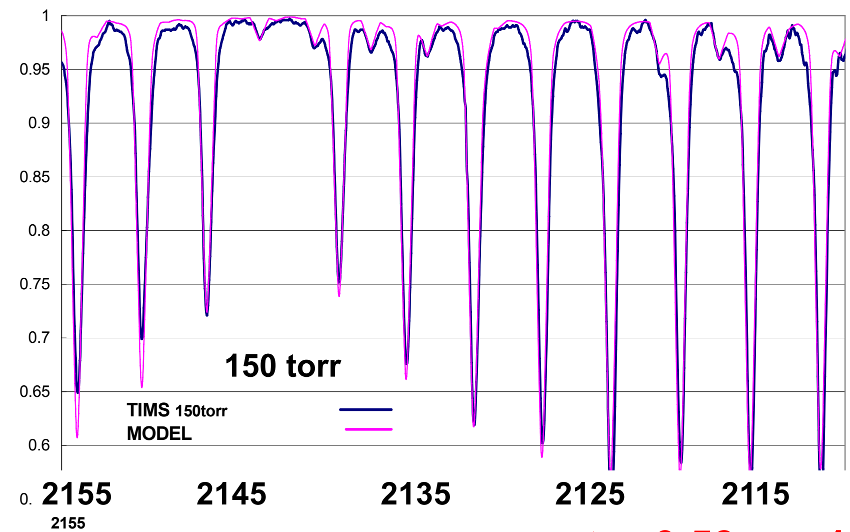
	Spectral Range	Spectral Resolution	Aperture	FOV	Measurement Products Primary Secondary
MWIR	2105–2163 cm^{-1} 4.75–4.62 μm	0.53 cm^{-1}	3.9 cm	Along Slit: 10.4 deg Pixel: 0.18 mrad	**CO,** H_2O, Clouds
VSWIR	4272–4307 cm^{-1} 2.34–2.325μm	0.25 cm^{-1}	3.9 cm	Along Slit: 4.9 deg Pixel: 0.17 mrad	**CO,** H_2O, CH4, Clouds,

Spectral Calibration Using CO Cell Absorption

4.7 μm MWIR Array

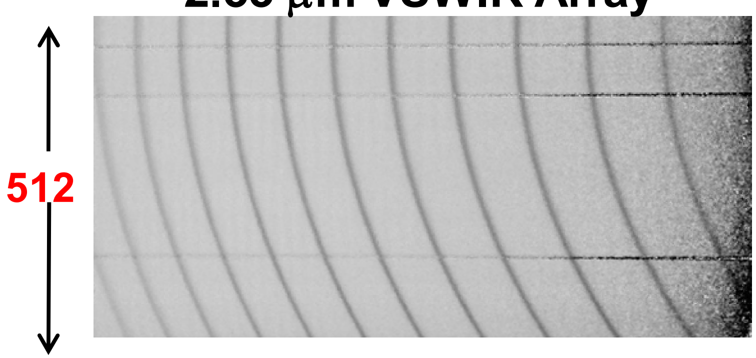


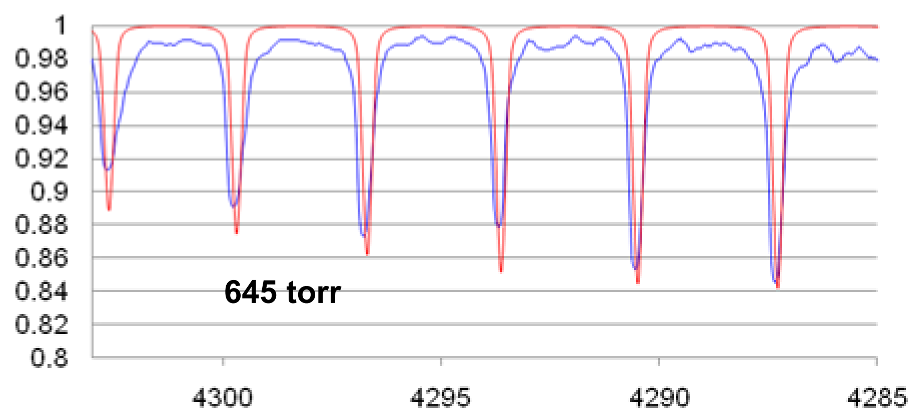
CO Cell Absorption Spectra vs Model



Δν~0.53 cm-1

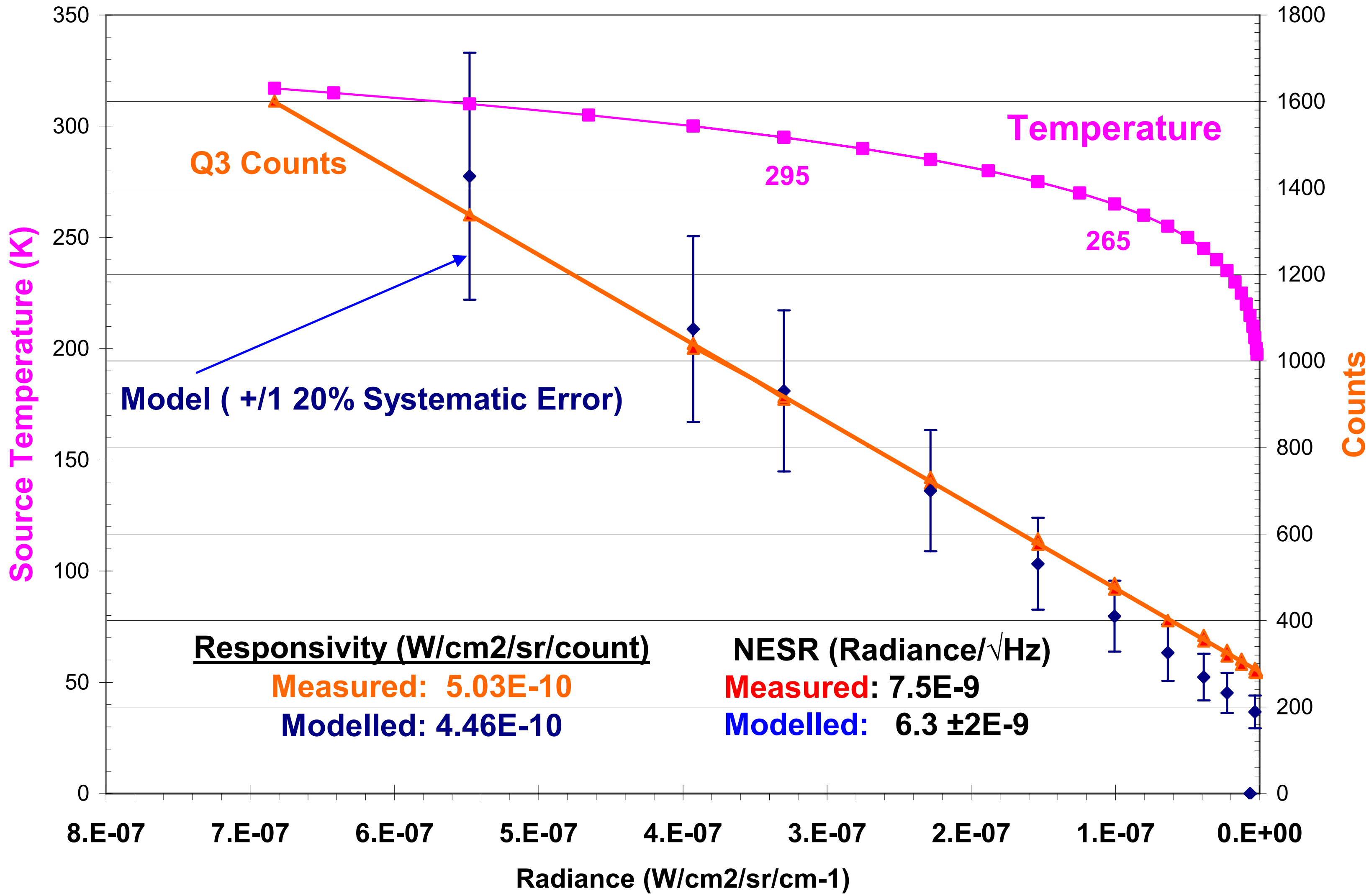
2.33 μm VSWIR Array



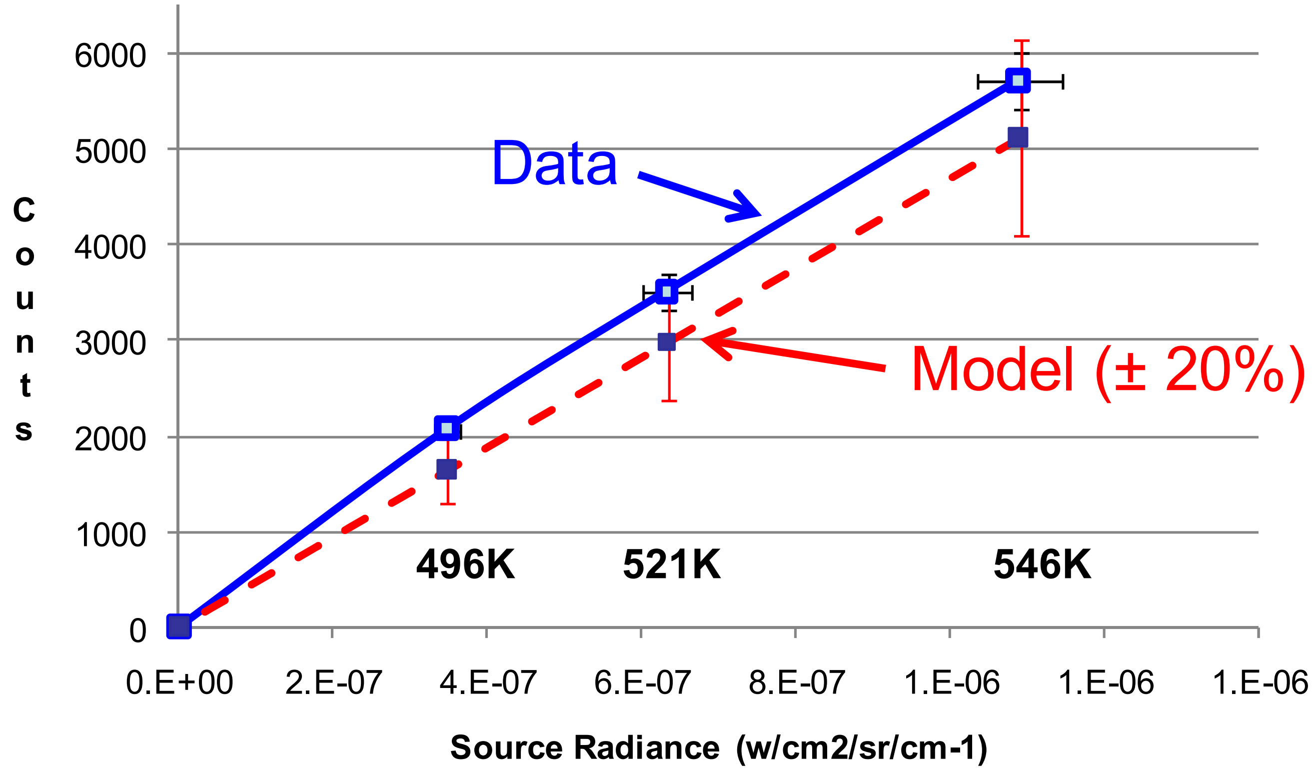


Δν~0.25 cm-1

4.68 μm VSWIR Radiometric Calibration vs Model



2.33 μm VSWIR Radiometric Calibration vs Model



	Model	Measured
Responsivity (w/cm2/sr/cm-1/count)	2.15 ±0.5 E-10	2.03 E-10
NESR (w/cm2/sr/cm-1/√Hz)	5.5±2 E-9	4.4 E-9

Ground Measurement Campaign at Denver University, May 2008

TIMS Co-Located with DU Bruker Fourier Transform Spectrometer

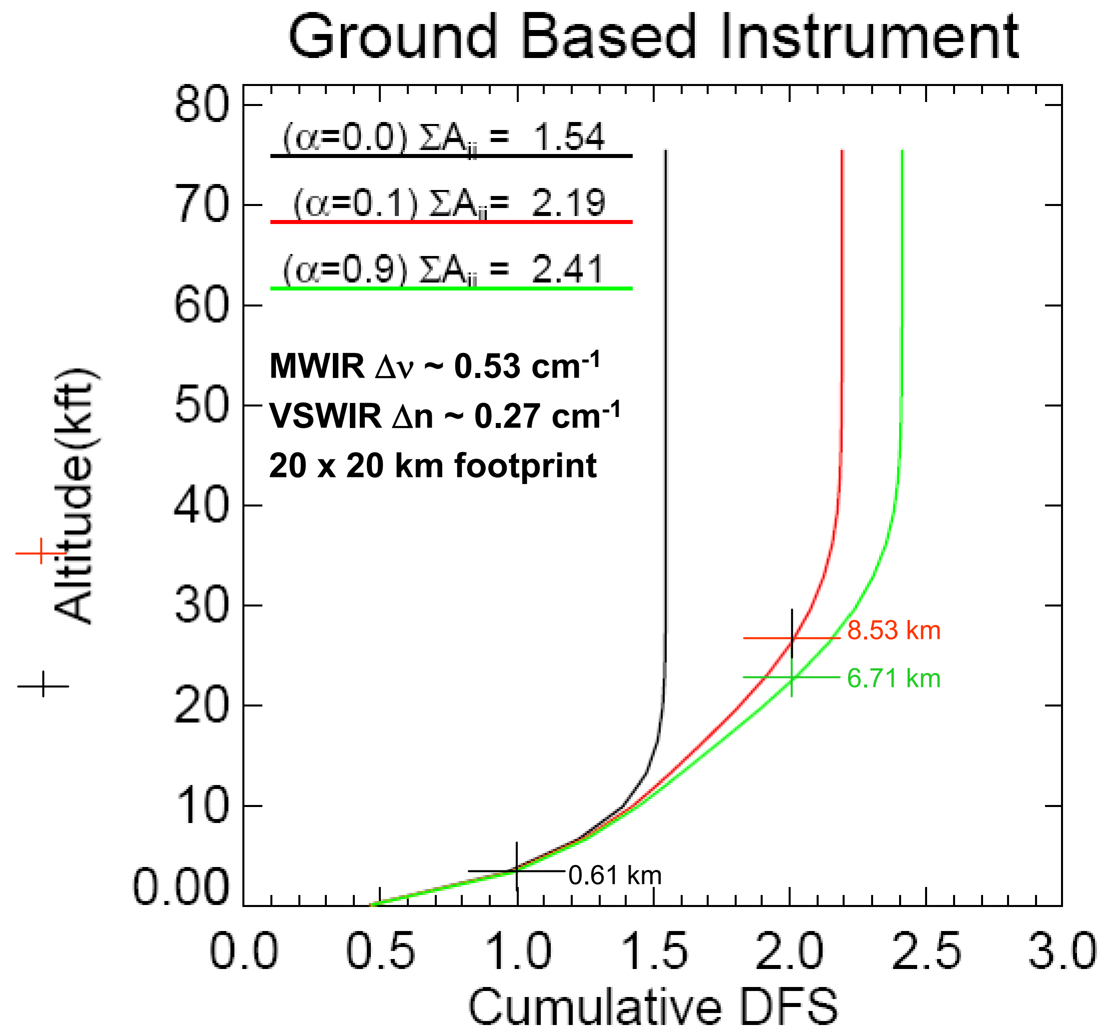
May 2008 TIMS Measurement Campaign at Denver University

Objectives

- Using TIMS 2.33 μm and 4.68 μm modules acquire radiometrically and spectrally calibrated solar absorption and sky emission spectra, fromwhich first order retrieval of atmospheric CO and other gases can be derived with a goal of DFS~ 2 (for CO)

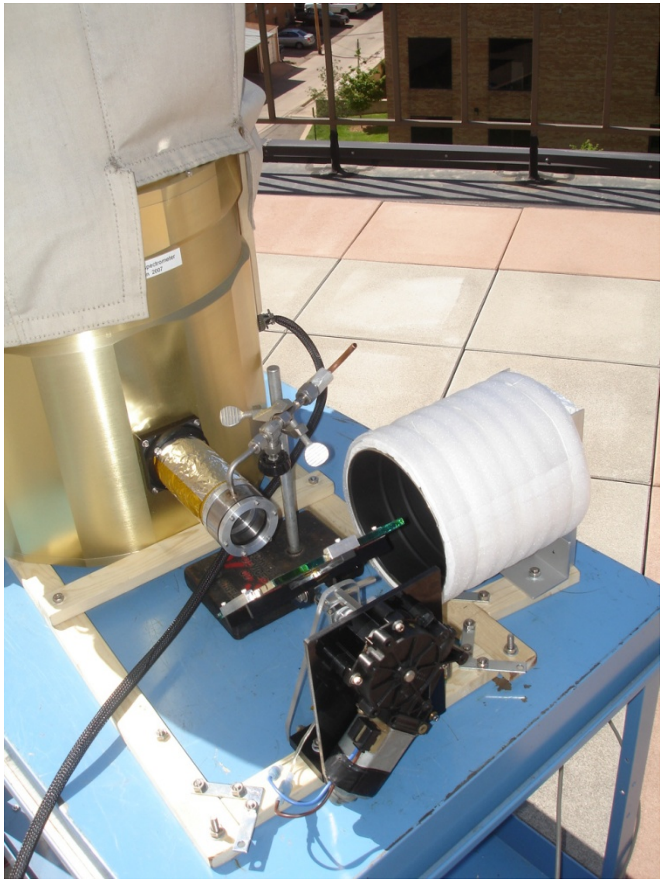
- Using TIMS 2.33 μm module, acquire spectra from terrain scattering as a simulation of nadir-looking Satellite data and to investigate effects of varying albedo on S/N

- Concurrently with the TIMS measurements acquire Bruker FTS solar absorption spectra at 2.33 and 4.68 μm, for use in TIMS spectral characterization and for correlative CO retrievals



- These represent what we'll expect to see in the joint field tests with DU
- The zero albedo case corresponds to the exclusive use of the MWIR
- The addition of the VSWIR increases the total amount of vertical information and extends it to higher altitudes

University of Denver, May 2008: MWIR 4.68 μm on deck

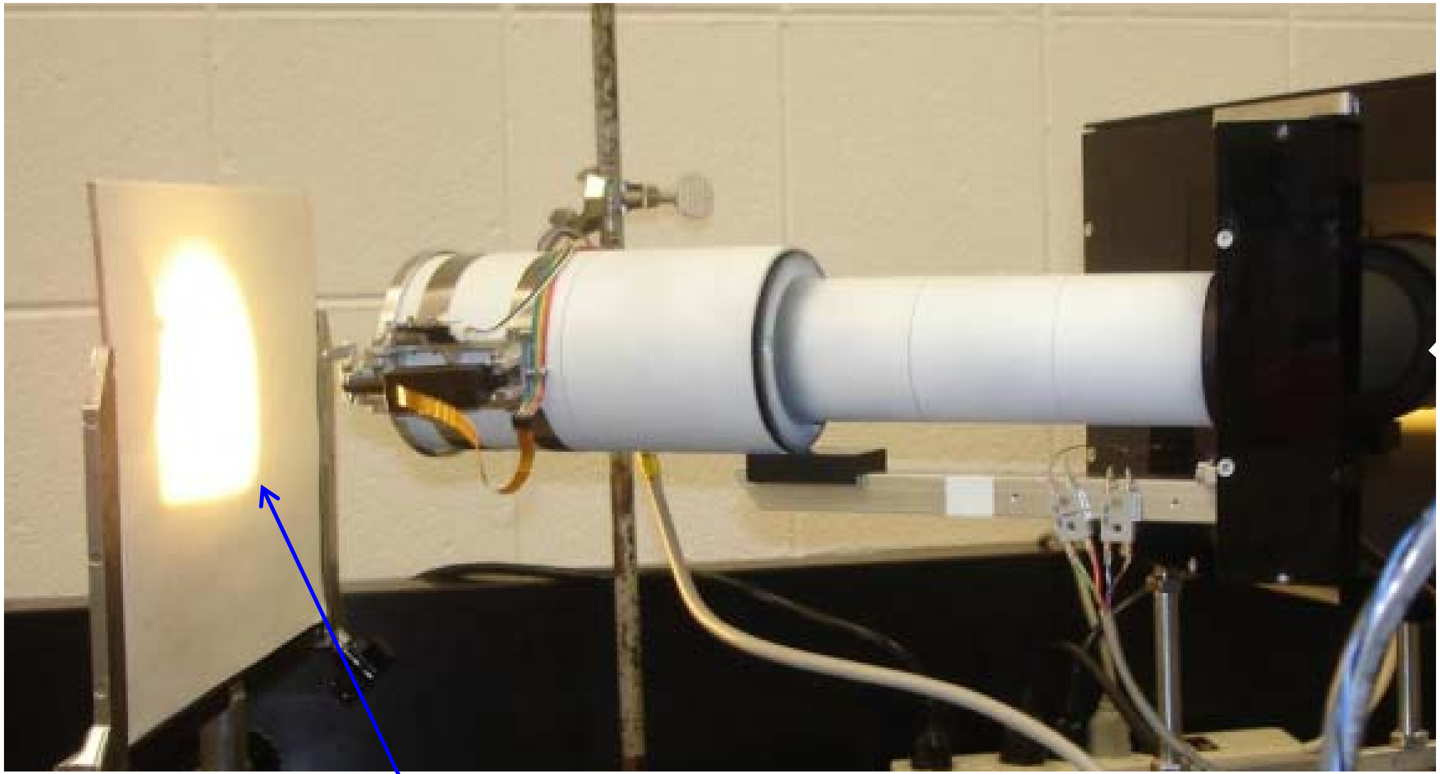


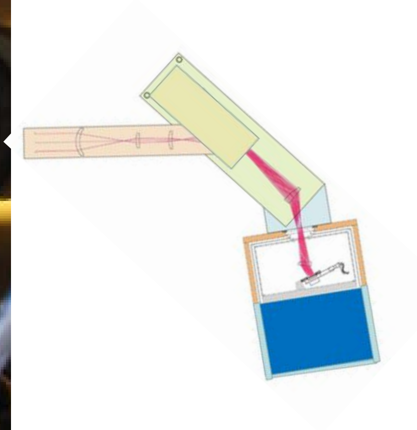
MWIR zenith mirror, shaded from direct sunlight. CO cell is in front of objective lens.

Remote control mirror rotates FOV into Black Body calibrator

MWIR dewar assembly mounted on cart. (White cloth on top is the sun shade.)

VSWIR viewing solar scattering surface in Bruker FTS laboratory

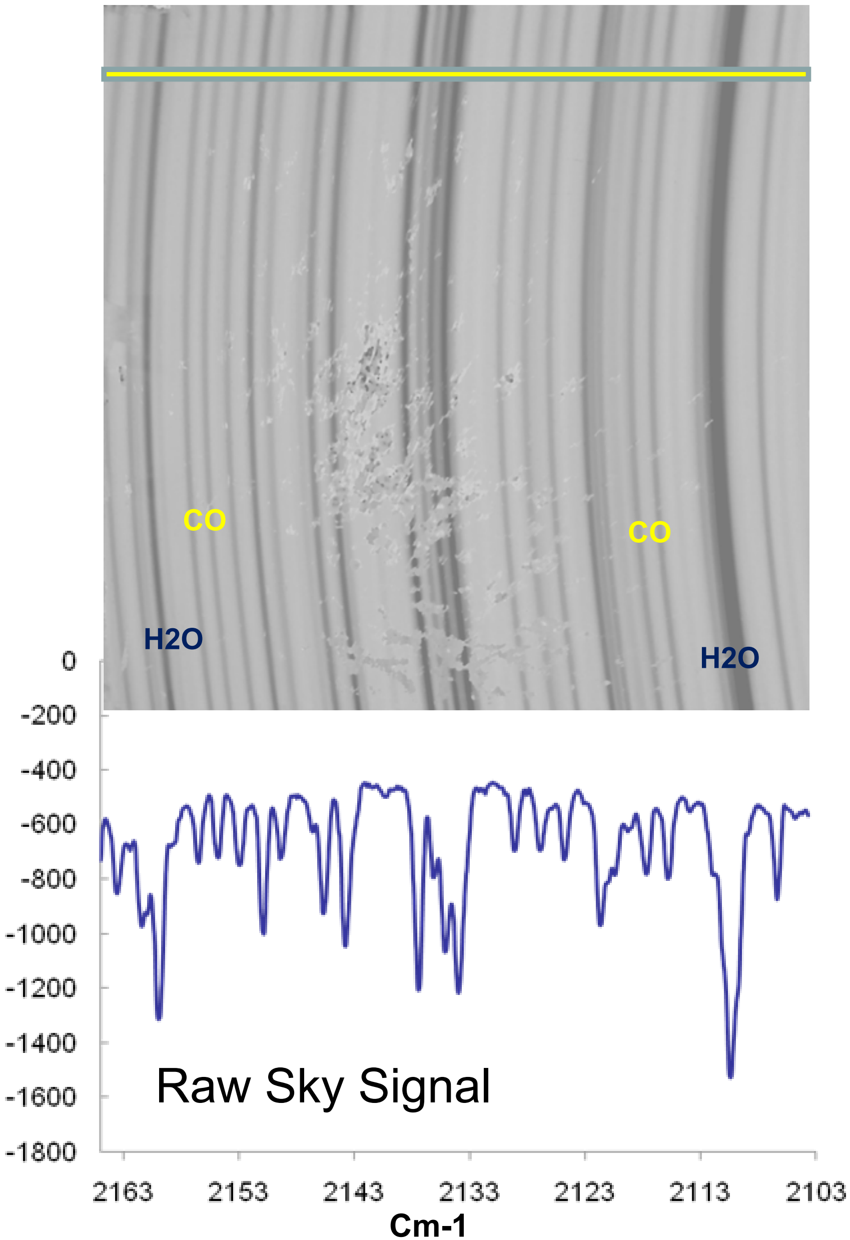




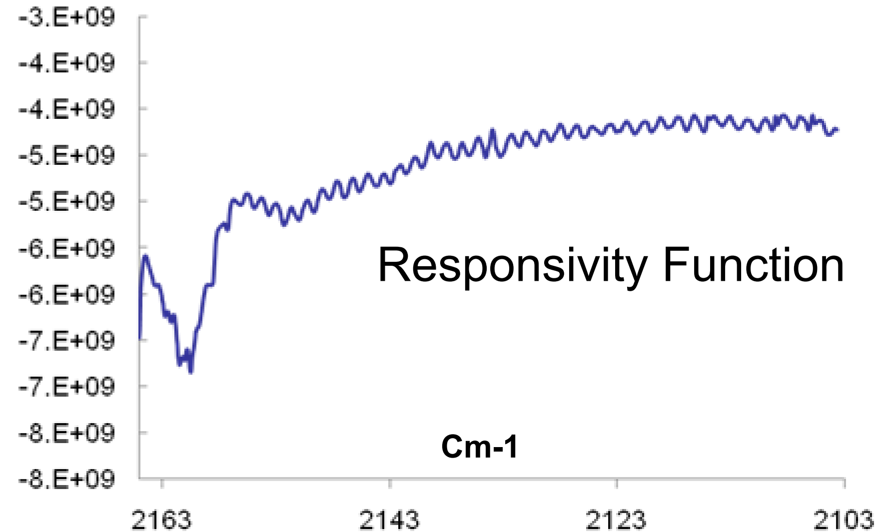
Solar Beam Relayed In to Laboratory From External Tracking Heliostat

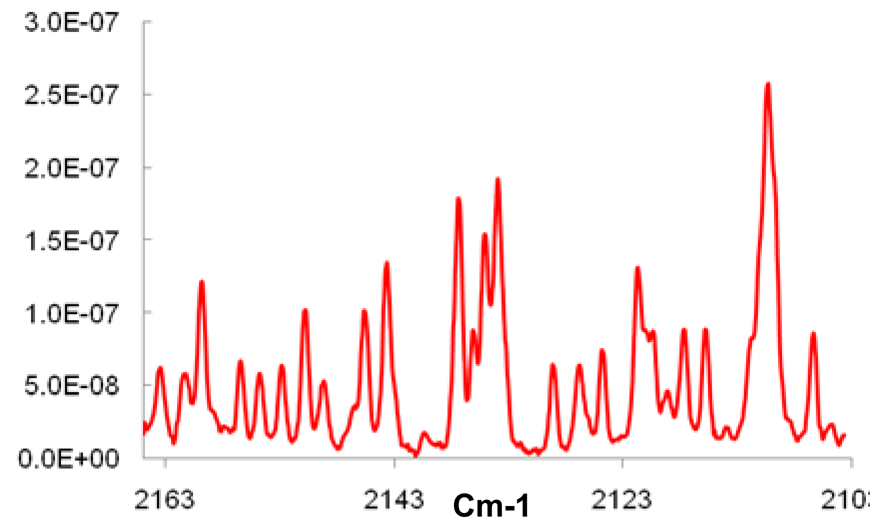
The external optics for the VSWIR are more sensitive to temperature variations than the MWIR and it was operated inside the temperature-controlled laboratory

MWIR Flat Fielding and Radiometric Calibration: May 30



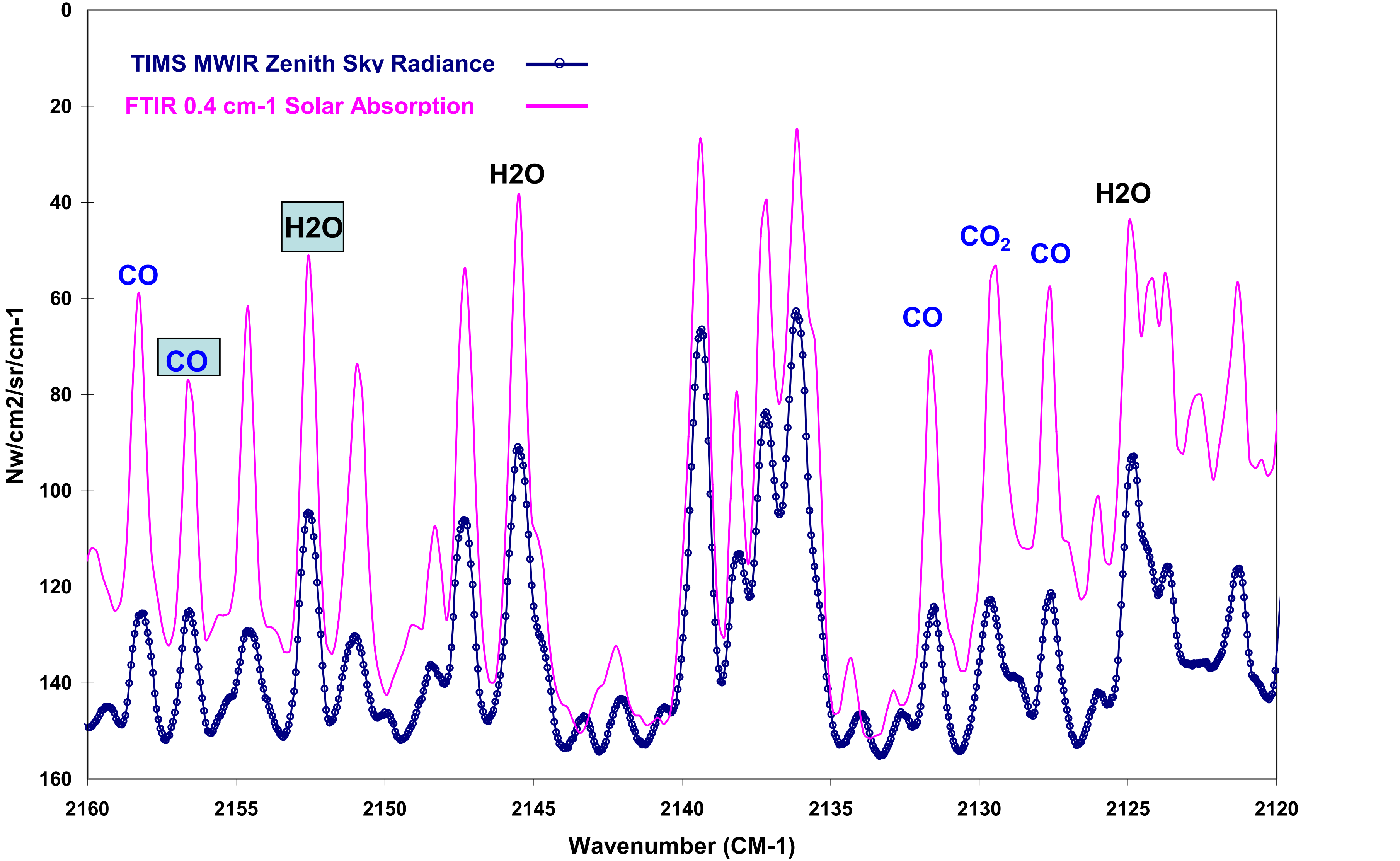
Video Image of Array Viewing the Zenith Sky



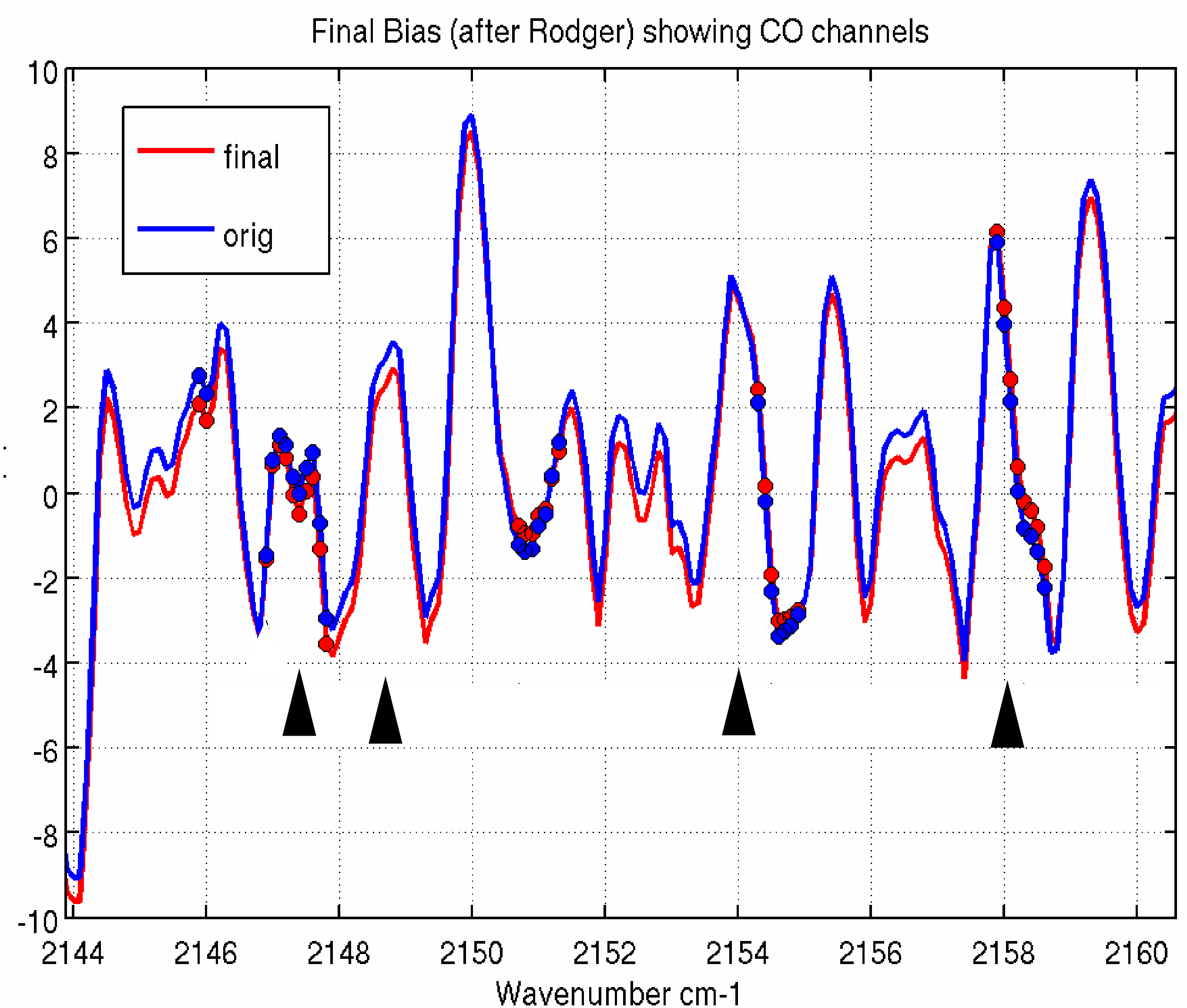


Flat Fielded/Calibrated Emission Spectrum

TIMS MWIR Emission Spectrum Overlaid with FTS Absorption Spectrum



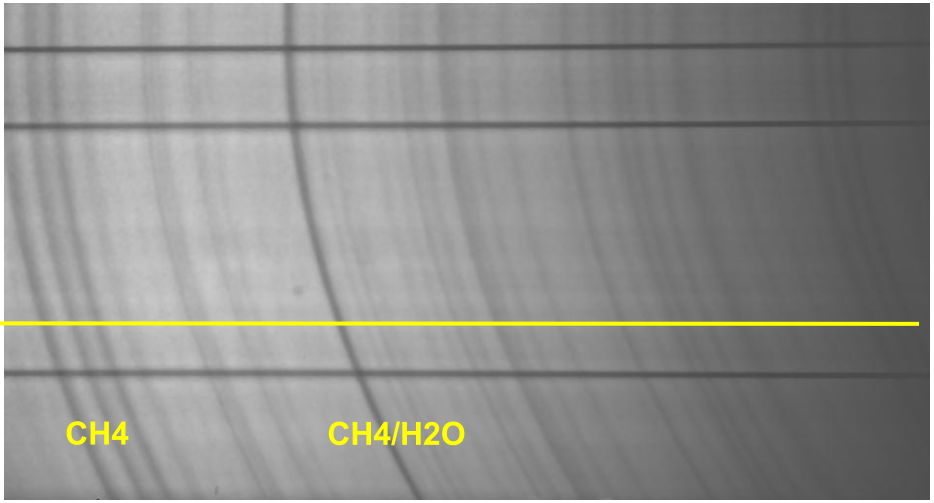
First Order Fit to MWIR Spectra*



*S. Desousa-Machado/L .Strow UMBC

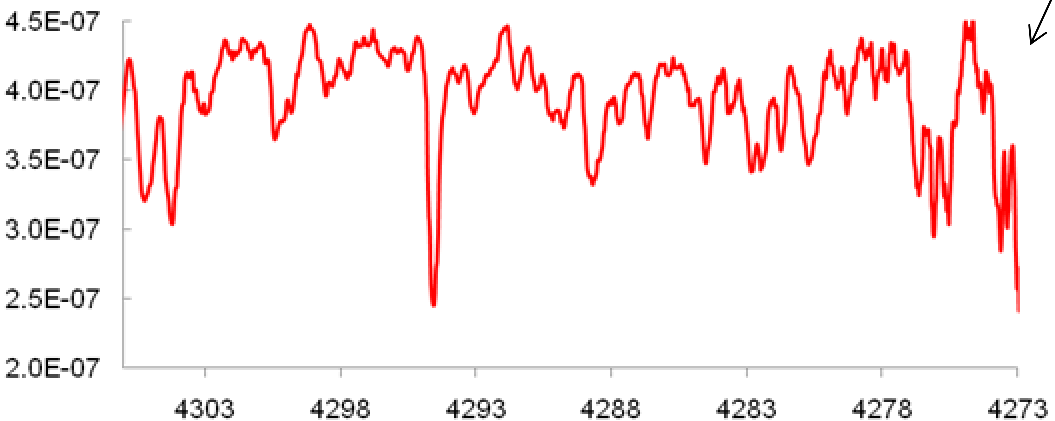
VSWIR Flat Fielding and Radiometric Calibration: May 30 Data

Wires over slit



Video Image of VSWIR array observing diffuse solar scattering surface

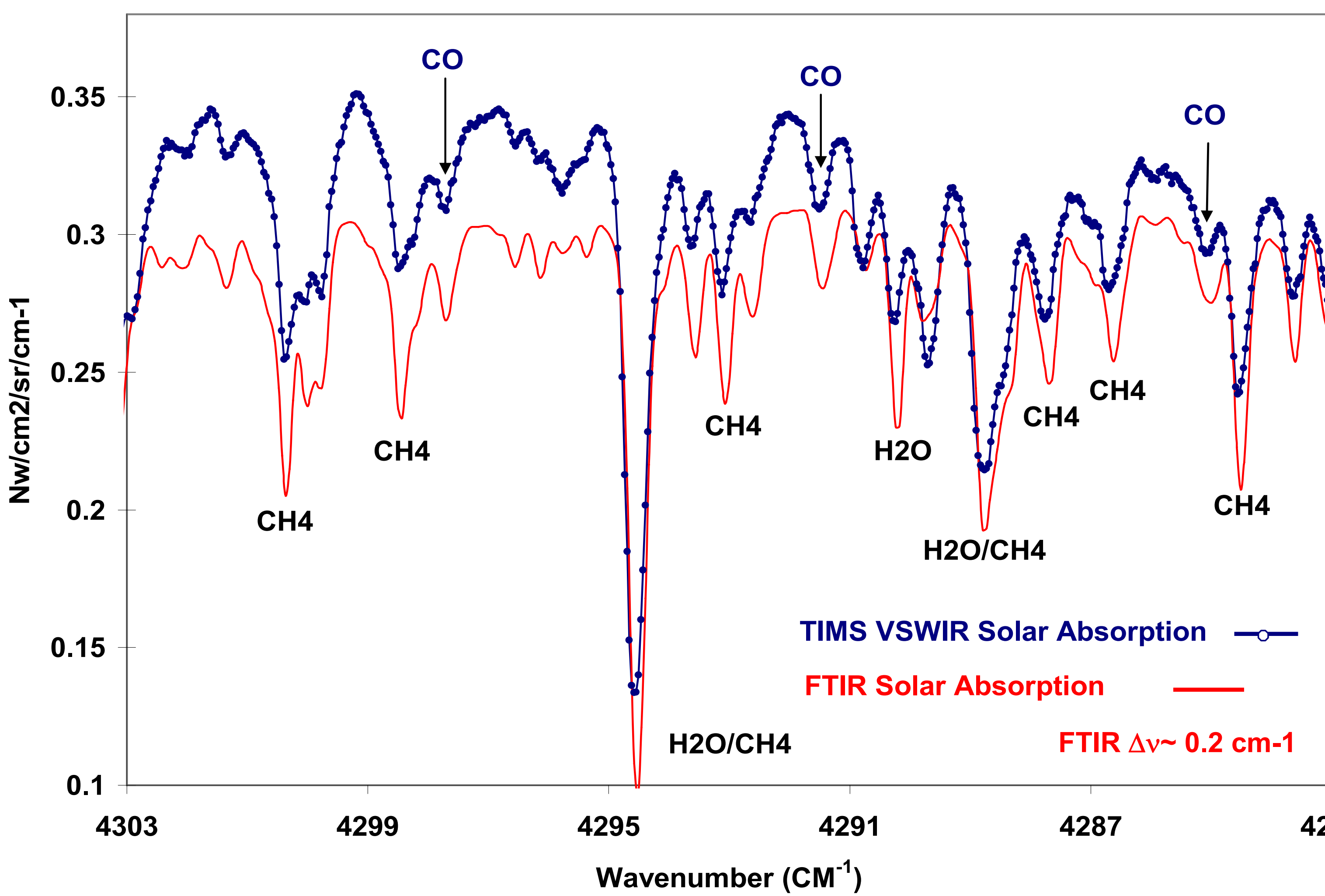
Spectrum Taken at this position



Flat fielded/calibrated absorption spectrum

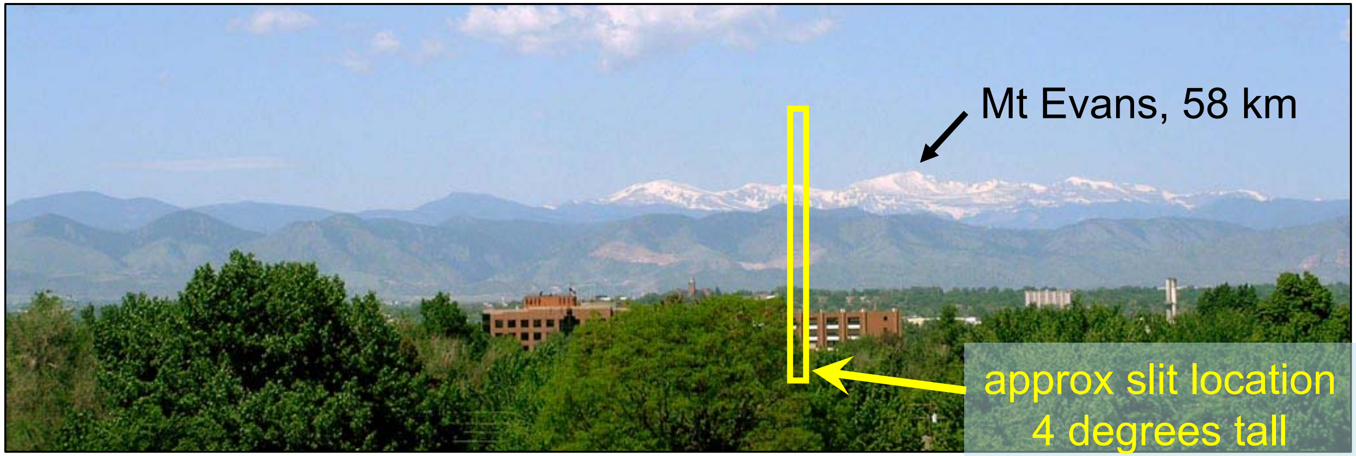
Using a similar process To that described for the MWIR for responsivity flat fielding, and using a shutter for background subtraction

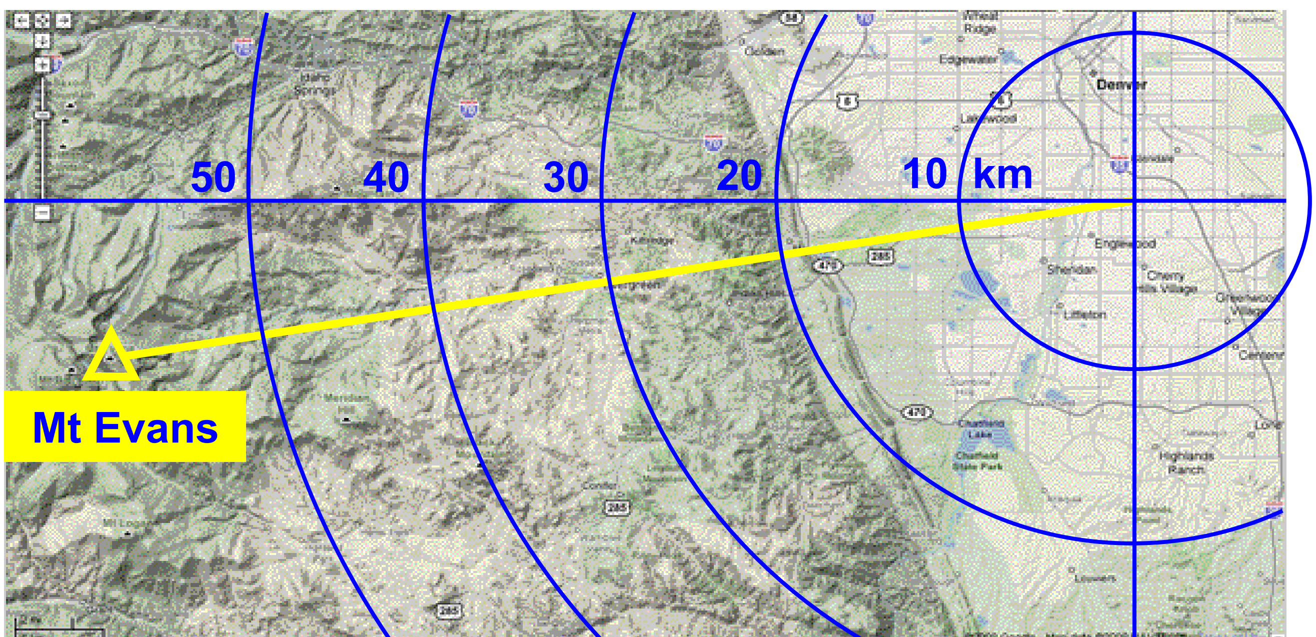
TIMS VSWIR Absorption Spectra Overlaid with FTS Spectra



VSWIR Mountain Viewing (1)

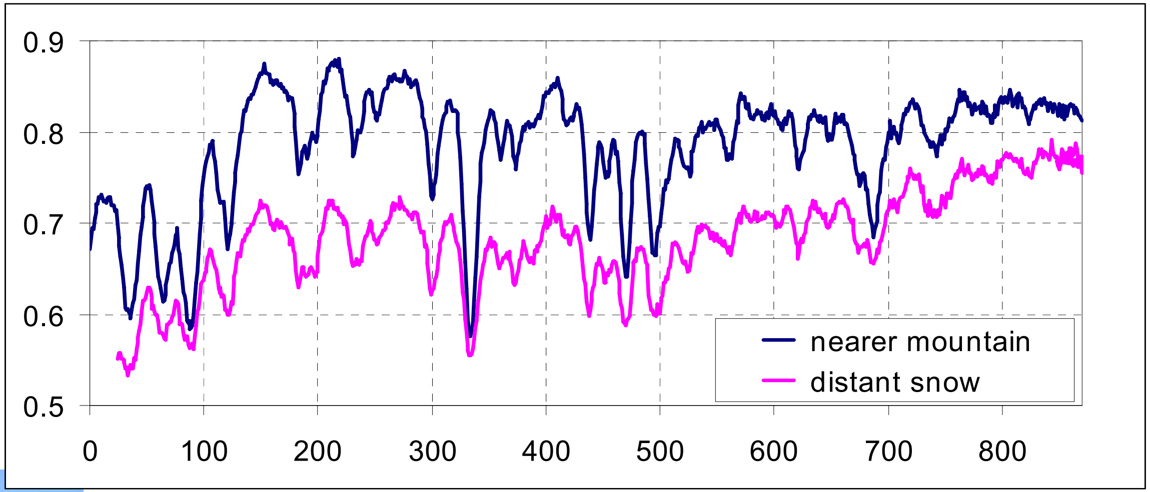
May 31 view from Denver University physics balcony

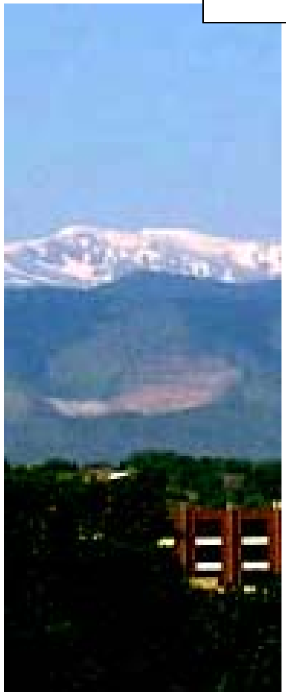


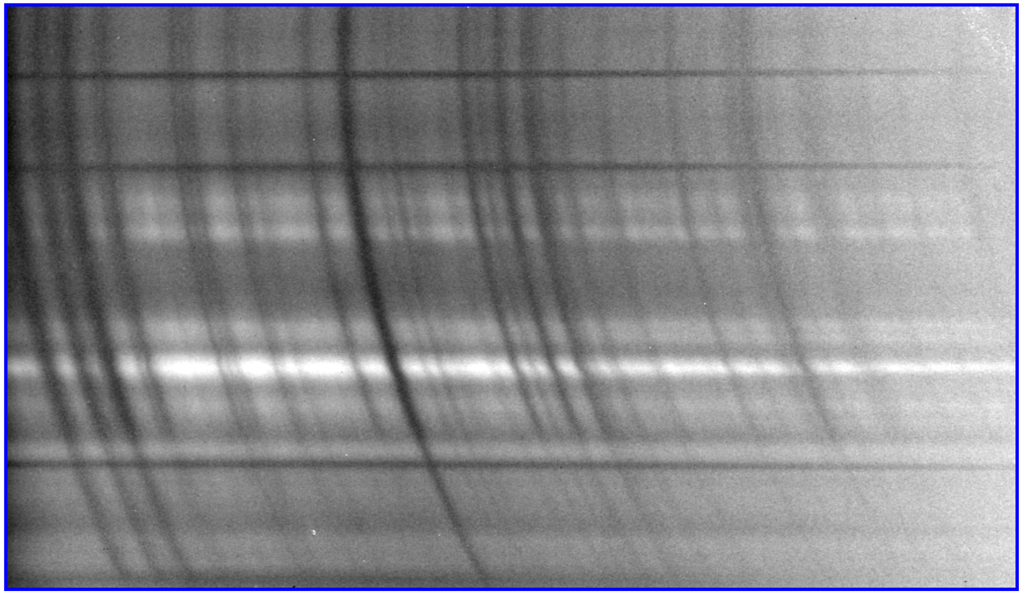


VSWIR Mountain viewing (2)

Spectral profiles viewing front range and distant snowcaps

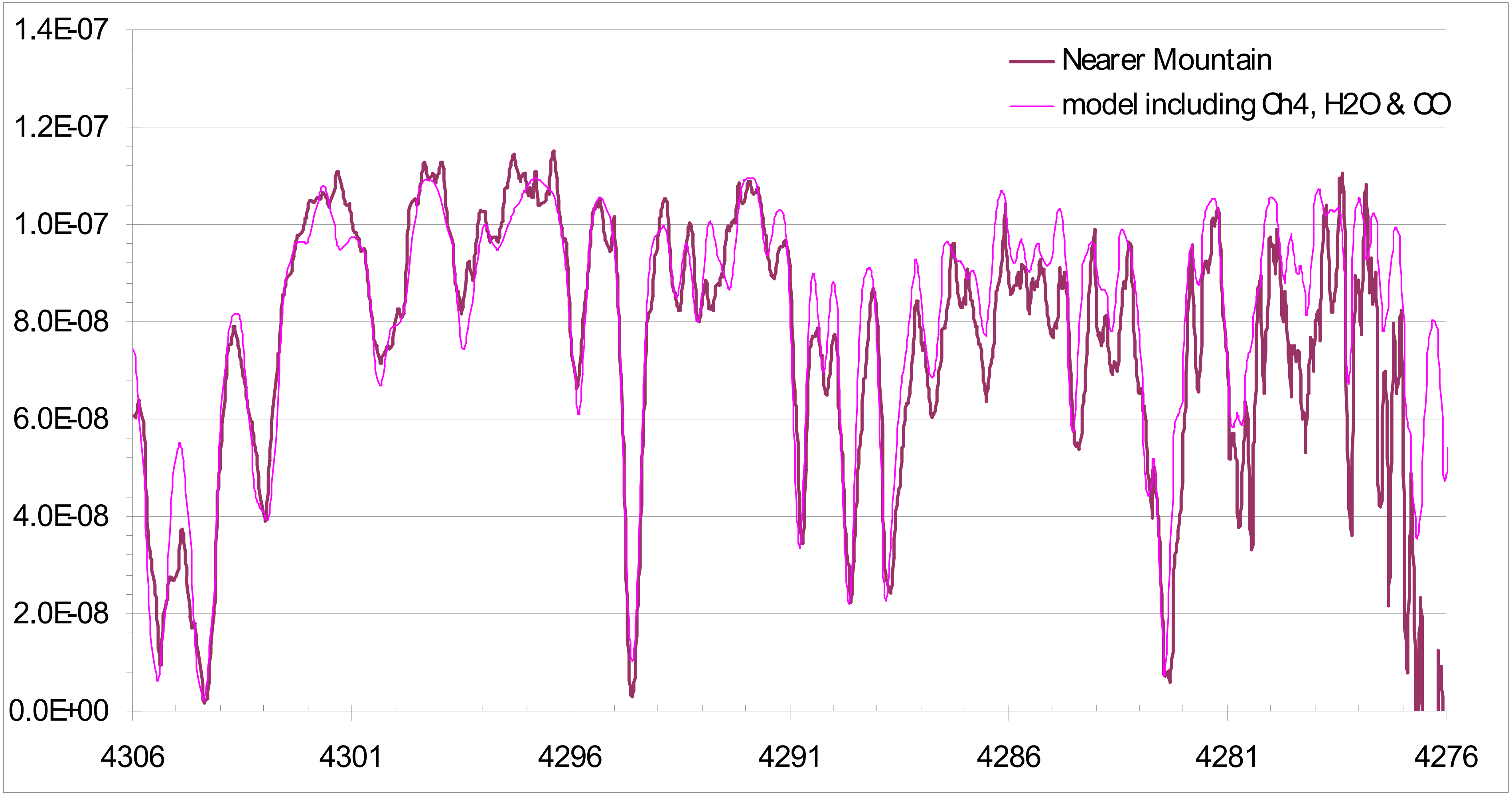






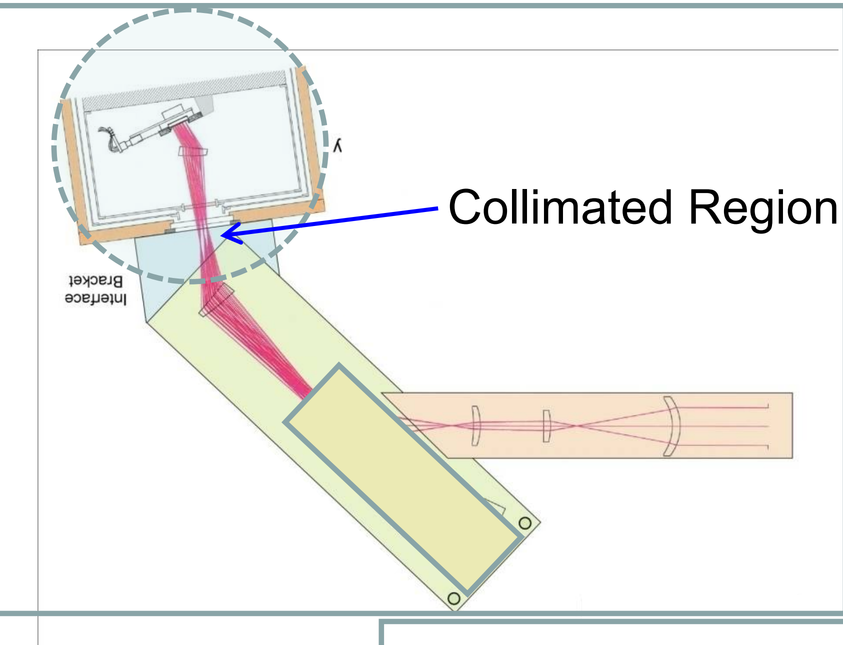
VSWIR image data, flat-field approximated

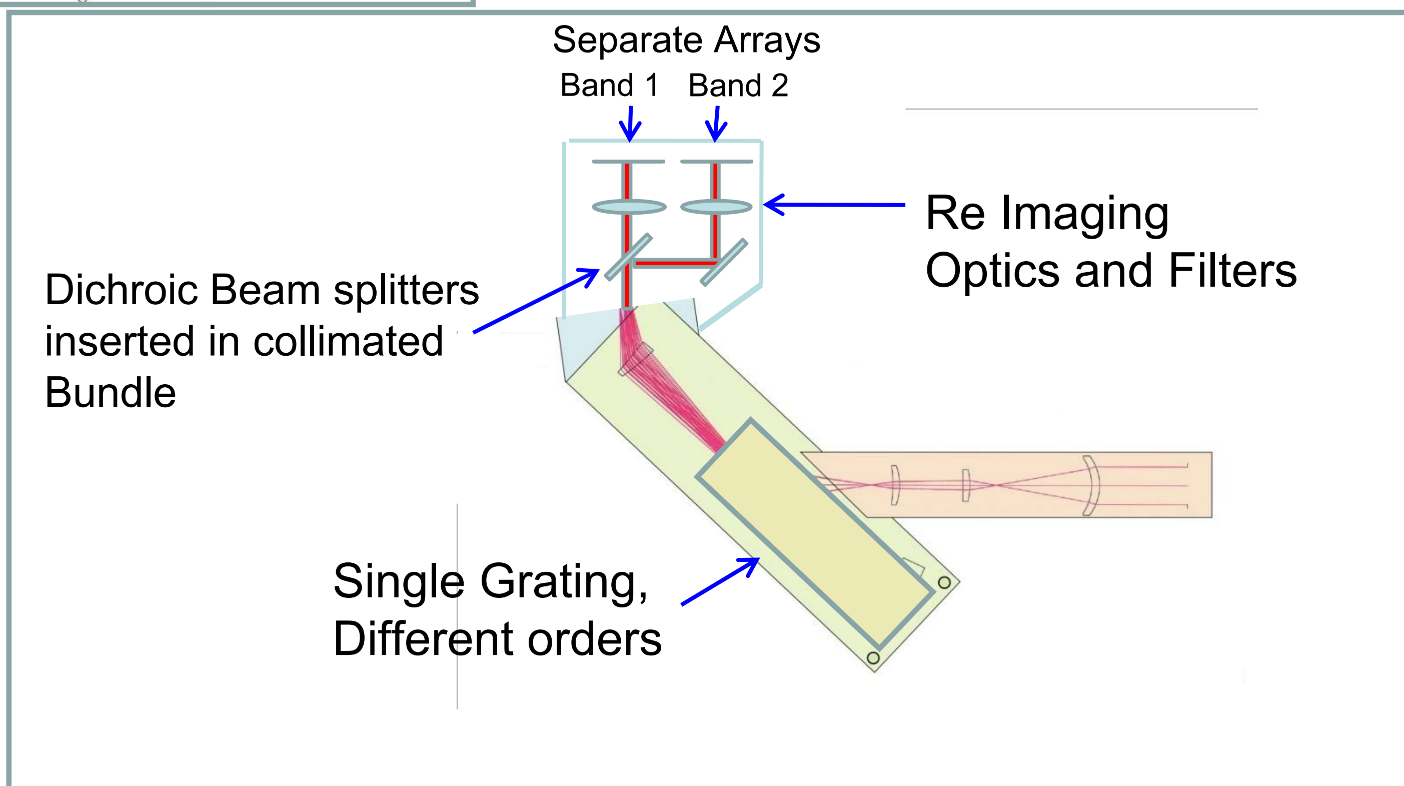
First order Modeling of VSWIR Mountain Spectra



Concept for Application of TIMS Technology to Space-Borne Air Quality Monitoring from GEO

TIMS 2.33 mm Design provides an accessible collimated bundle to facilitate beam-splitting to multiple channels



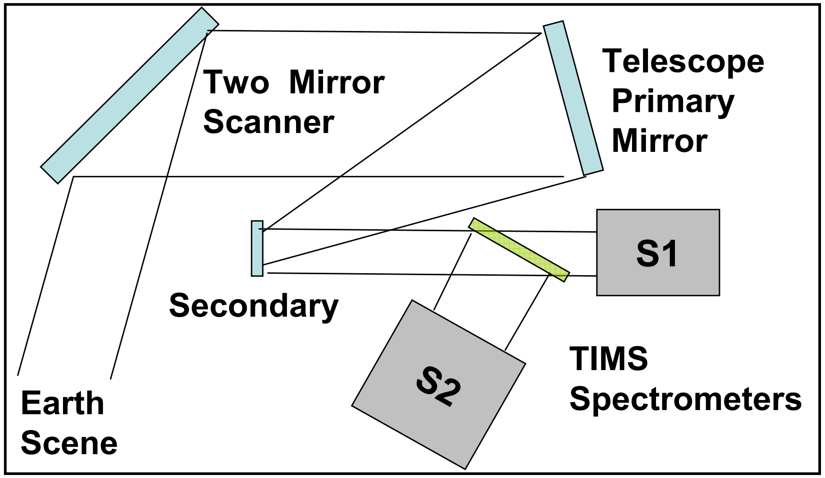


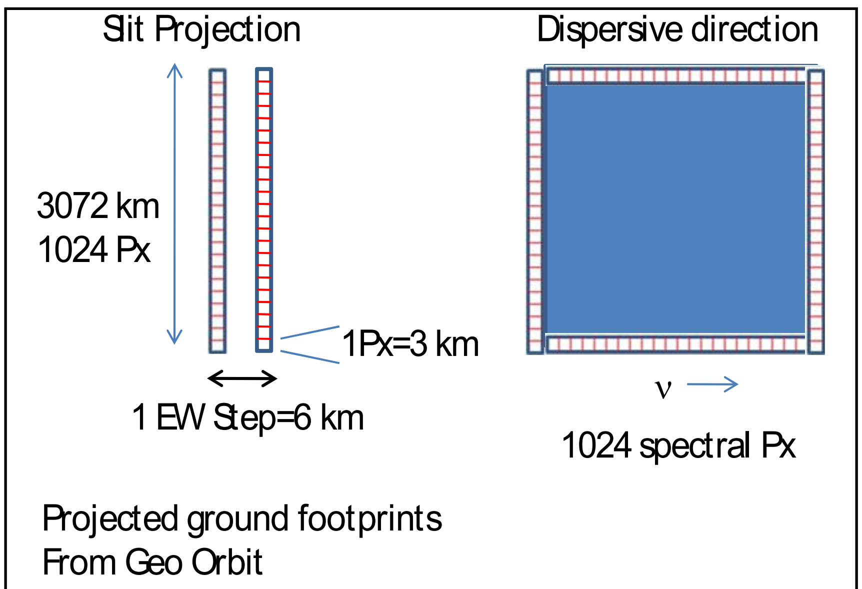
Expanded Capability TIMS for a GEO Mission

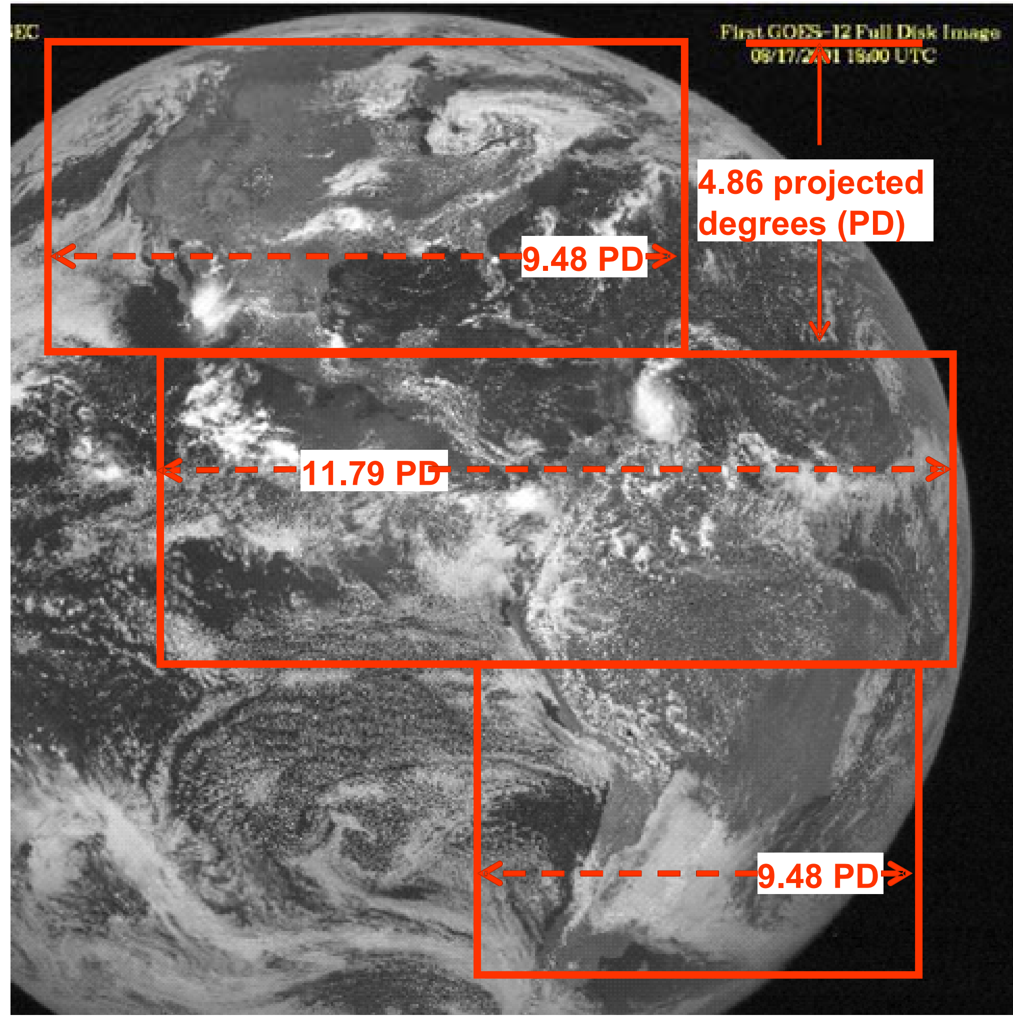
Spectrometer		Spectral region (cm^{-1})	$\lambda/\Delta\lambda$	Target Constituents
S1	a	4277 to 4313 [~2.33 μm]	19500	**CO Profile**; CH_4 & H_2O columns
	b	3036 to 3058 [~3.28 μm]	19000	**O3 Column**
S2	a	2760 to 2840 [~3.58 μm]	8500	**HCHO column**; O_3 H_2O, CH4, N2O column
	b	2112 to 2160 [4.68 μm]	8000	**CO Profile (In combination with S1-1)** Some H_2O and O_3 vertical information
	c	1035 to 1069 [9.51 μm]	7500	**O_3 Partial Columns**

Primary Tropospheric Science Products	Aggregated Footprint	Retrieved Precision
CO Profile	12x12 km 6x6km to 12x12 km	**<u>Layer</u>** **0-2 km: 10%** **2-6 km 6%** **6-22 km 4%**
HCHO Column	6x6km to 12x12 km	2.6x1015 mole/cm2
O3 Profile	6x6km to 12x12 km	**<u>Layer</u>** **0-6 km 5%** **6-12 km 3%** **12-22 km 2%**
CH4, H2O, N2O Columns		Several %

Spatial/Temporal Coverage for a GEO-TIMS Instrument Concept







3 E-W Scan Blocks Covers 50N to 45S of North And South America in 1 hr, including calibration , as required by the GEO-CAPE

Applications of TIMS-IIP Technology to Space Borne Air Quality Monitoring

TIMS Technology is included in proposed payloads for several Air-Quality mission studies:

- **Global Atmospheric Composition Mission (GACM)**
  [Team members include JPL/NASA GSFC, KNMI, LMATC]

- **Boundary-Layer Ozone Measurements from GEO**
  [Team members include NASA ARC/GSFC, LMATC]

Summary and Conclusions

- **Demonstrated High Spectral Resolution, Low-Noise Capability of Coupled Grating-Large Format 2-D Arrays in the SWIR and MWIR**

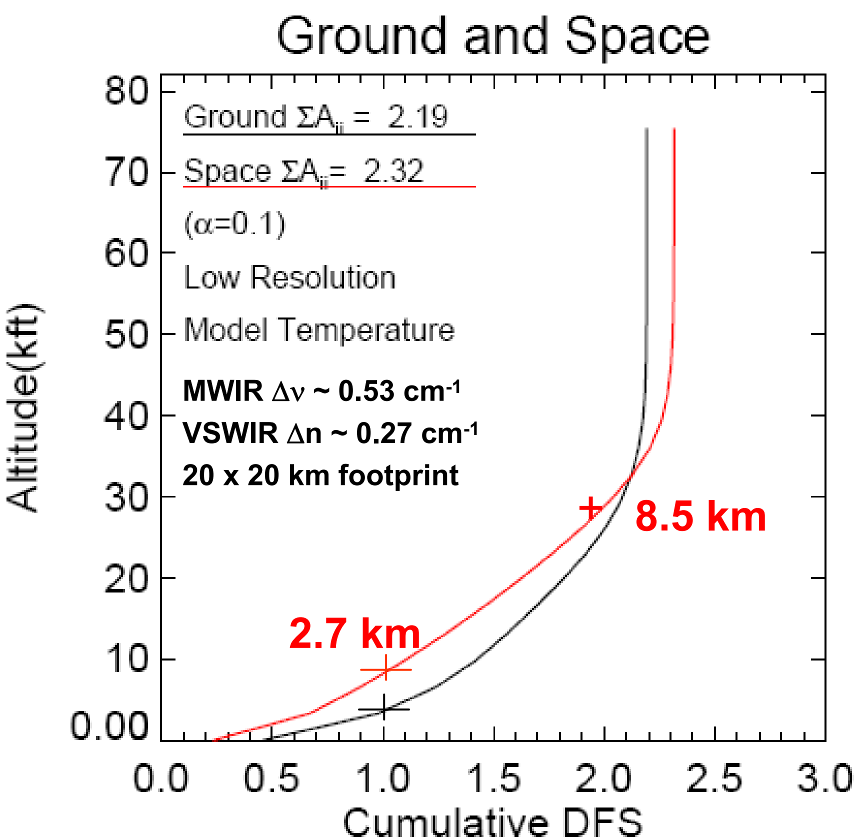
- **Ground-Based atmospheric absorption and emission spectra show well isolated lines of CO, H2O, CH4, amenable to retrieving all species**

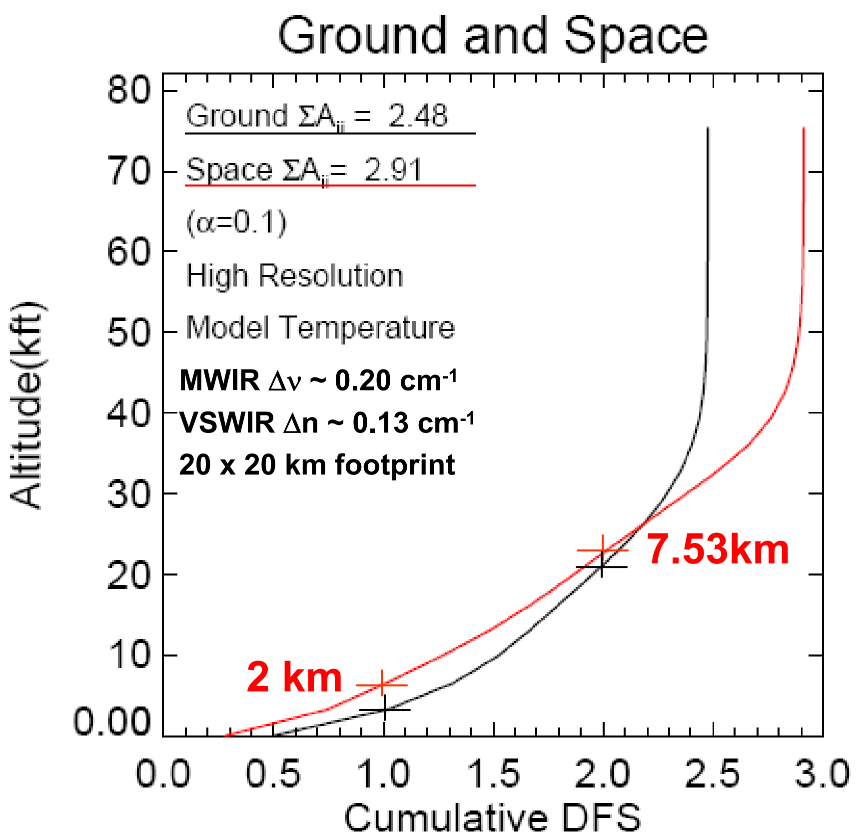
- **Analysis of May campaign data underway, expect to retrieve 2-layer CO information, showing the advantage of combined solar-reflective and thermal emission measurements for low–troposphere sounding**

- **Developing engineering concepts for space-borne application**

END

Benefit of Higher Spectral Resolution on DFS for Space View





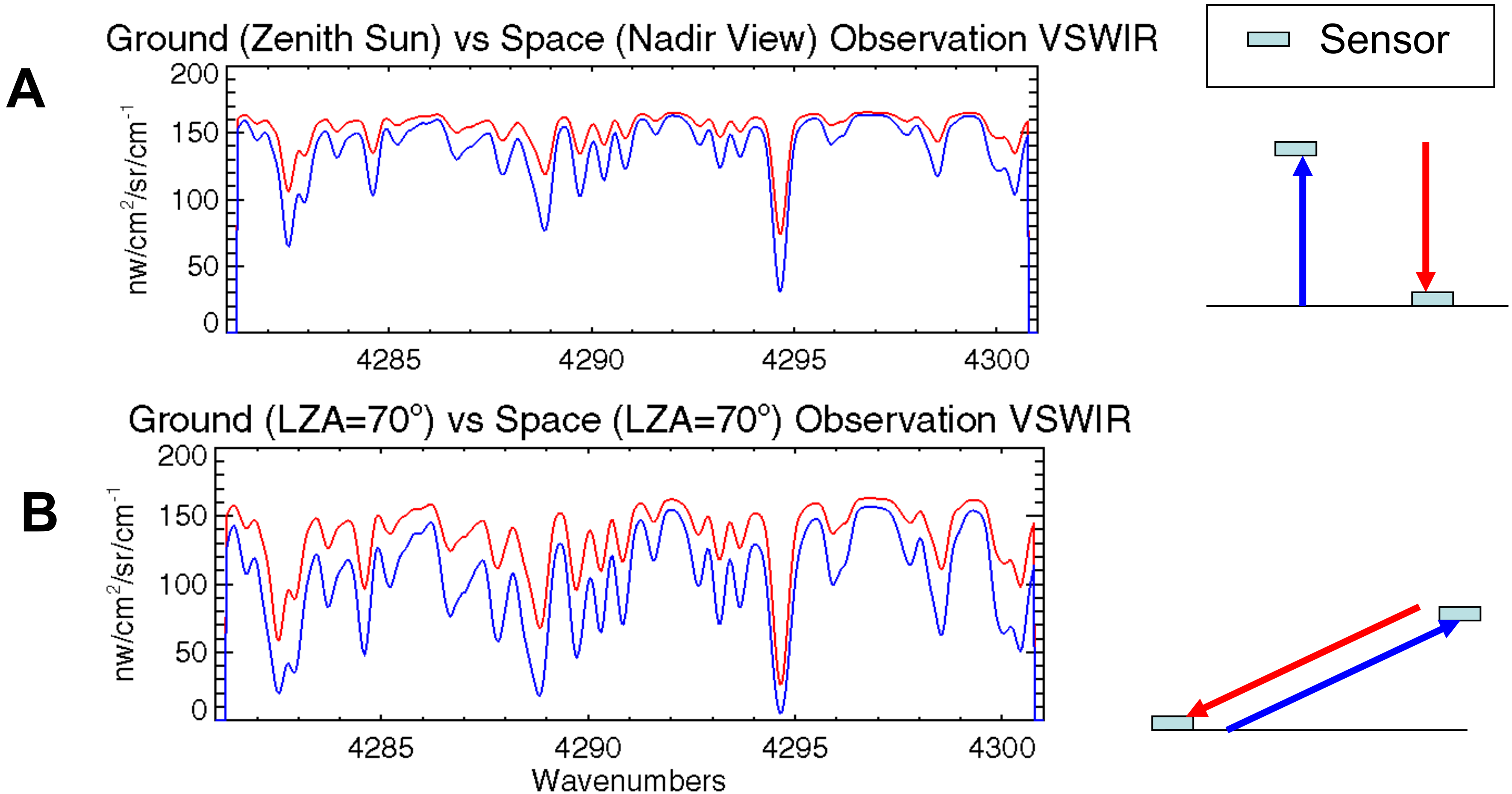
- The total vertical information is substantially improved from ~ 2.32 to 2.91 for instrument goal spectral resolutions

Backup

VSWIR comparison of nadir and upwards looking viewing

upper panel vertical shows vertical paths

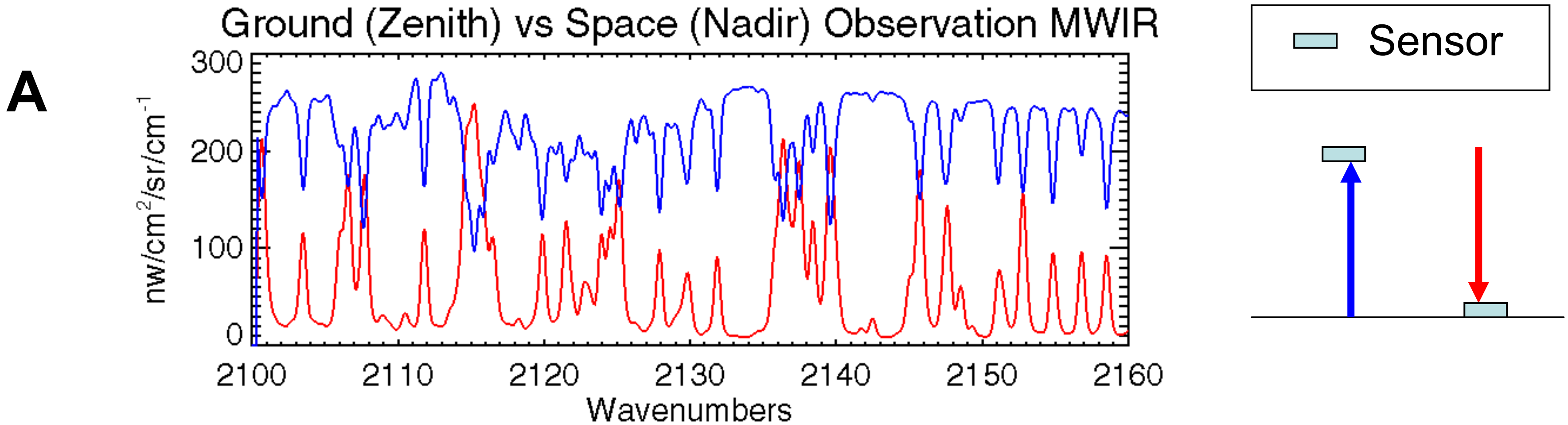
lower panel shows slant paths



MWIR comparison of nadir and upwards looking viewing

upper panel vertical shows vertical paths

lower panel shows slant paths



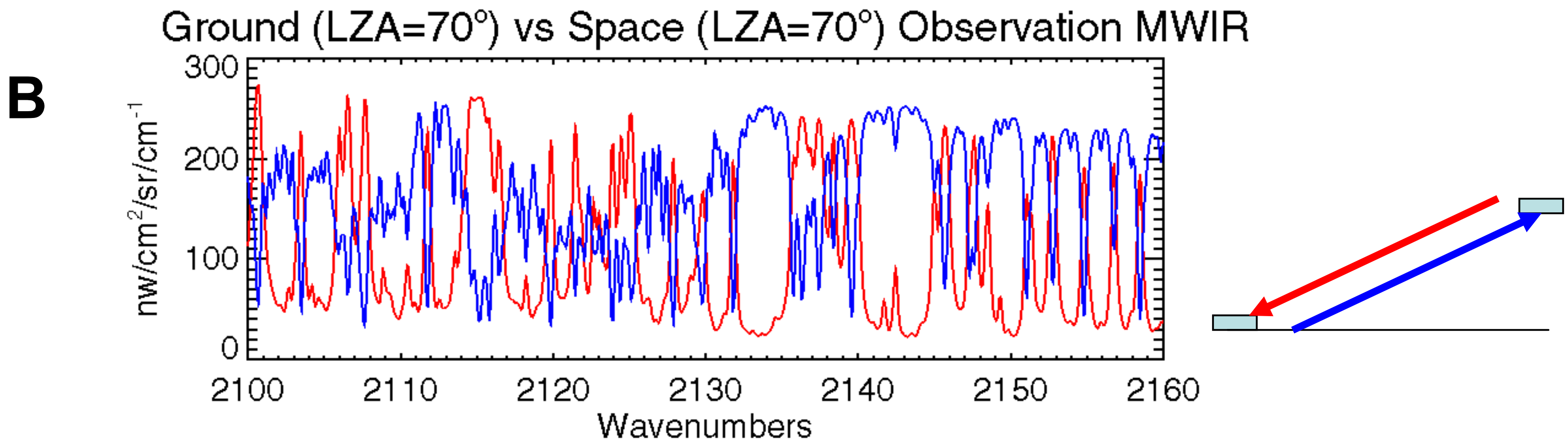
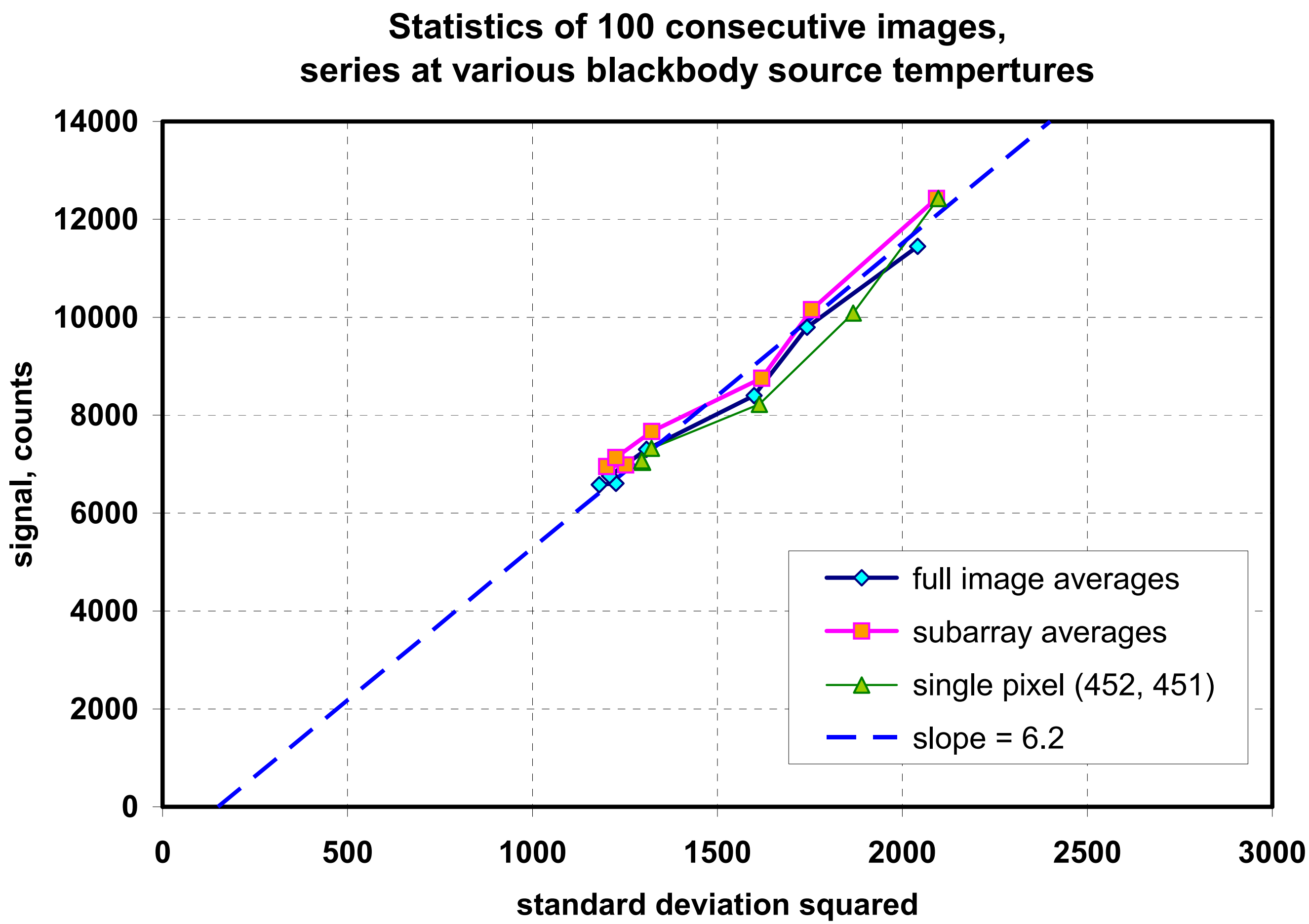
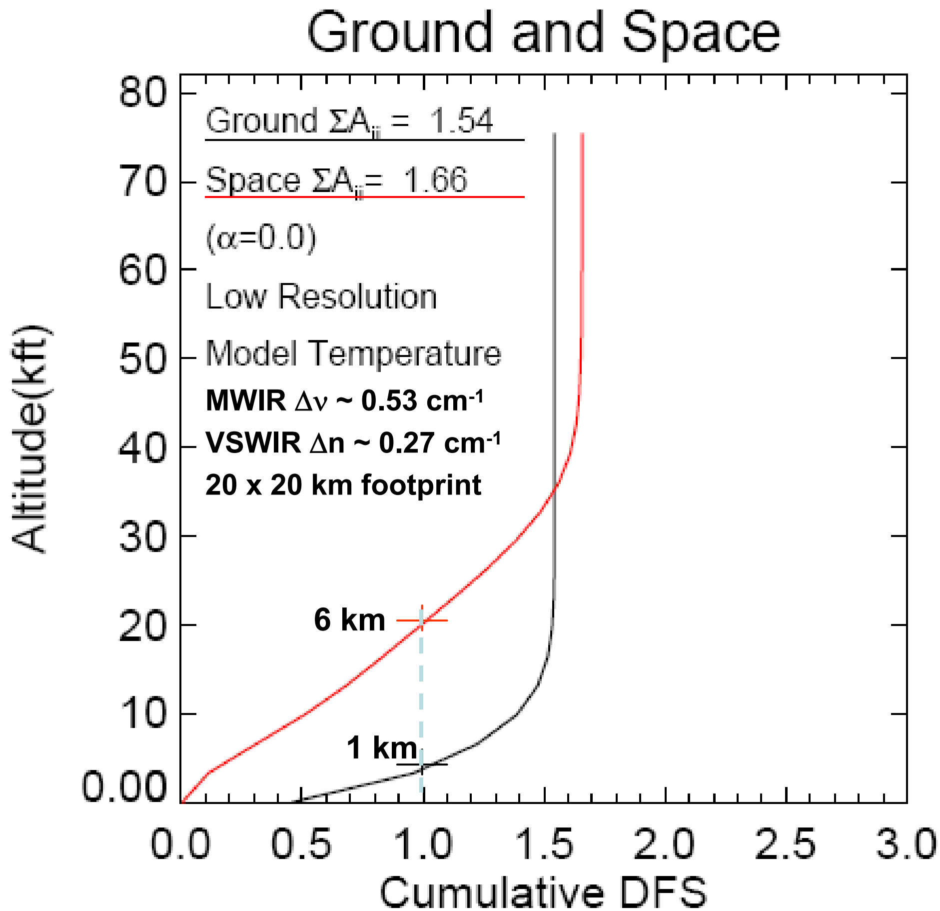


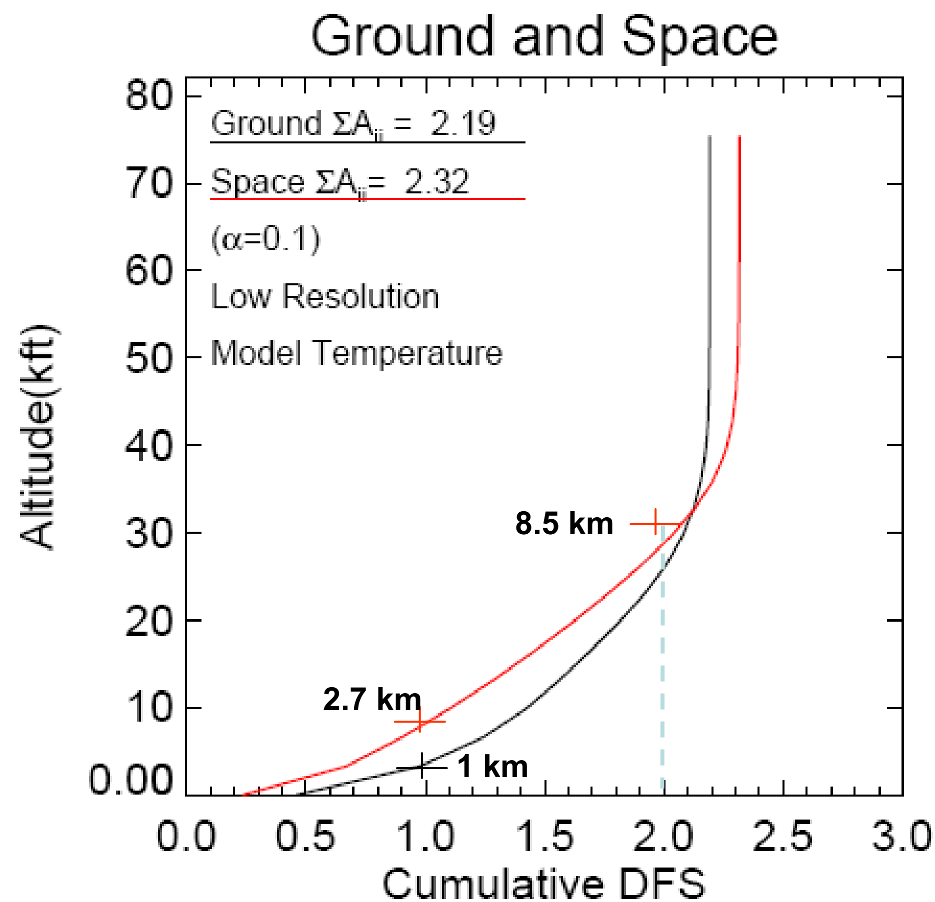
Illustration of the approach for evaluation of sensitivity and performance parameters (2 of 2)



Pixel statistics were measured across 100 consecutive images at each of seven blackbody source temperatures: 20 C, 100 C, 150 C, 200 C, 240 C, 270 C, and 300 C. Average values are plotted vs variance for a single pixel, for a 100x100 pixel subarray, and for the entire 512x1024 pixel image. The slope provides a statistical measure of detector electrons per count.



Nightime Only (4.68 μm; α=0)



Day Time (4.68/2.33 μm; α=0.1)

- Instrument noise is dominated by temperature model uncertainty
- The VSWIR (α=0.10) is necessary to get info near the surface;
- The TIMS space borne CO DFS* of ~ 2.33 compares with ~ 1.5 for MOPITT, AIRS,TES, using only the MWIR, and ~1.0 for SCIAMACHY using only VSWIR
- Even the ground-based TIMS can achieve DFS ~ 2.2

***Degrees of Freedom for Signal**

Sky Spectral Radiance Calibration.

When viewing the sky, the observed signal counts SC_i on a pixel Px_i is given by:

Sky counts $=SC_i=[SN_i]x[W_i]x[R] + [MN_i]x[W_i]x[(1\text{-}R)] + IC_i$ where:

- SN_i is the **sky spectral radiance** on Px_i, at ν_i cm^{-1} and is the quantity we wish to derive; it is in **watts/cm^2/sr/cm^{-1}**
- $\mathbf{W_i}$ is the **instrument end-end responsivity** for Px_i at ν_I cm^{-1} and is determined independently
- **R** is the known **reflectivity of the sky view mirror**, 1-R its emissivity
- $\mathbf{MN_i}$ is the **sky view mirror radiance** on Px_i at ν_I cm^{-1}; it's a function of temperature (T_{MN}) and emissivity
- $\mathbf{IC_i}$ is the **total instrument "background"counts** due to radiance from all sources other than the sky radiance, including any internal radiance leaks.

To derive SN_i , we place an extended blackbody of known temperature (T_B) and emissivity (e_B) directly in the instrument field of view and observe counts BC_i on Px_i given by:

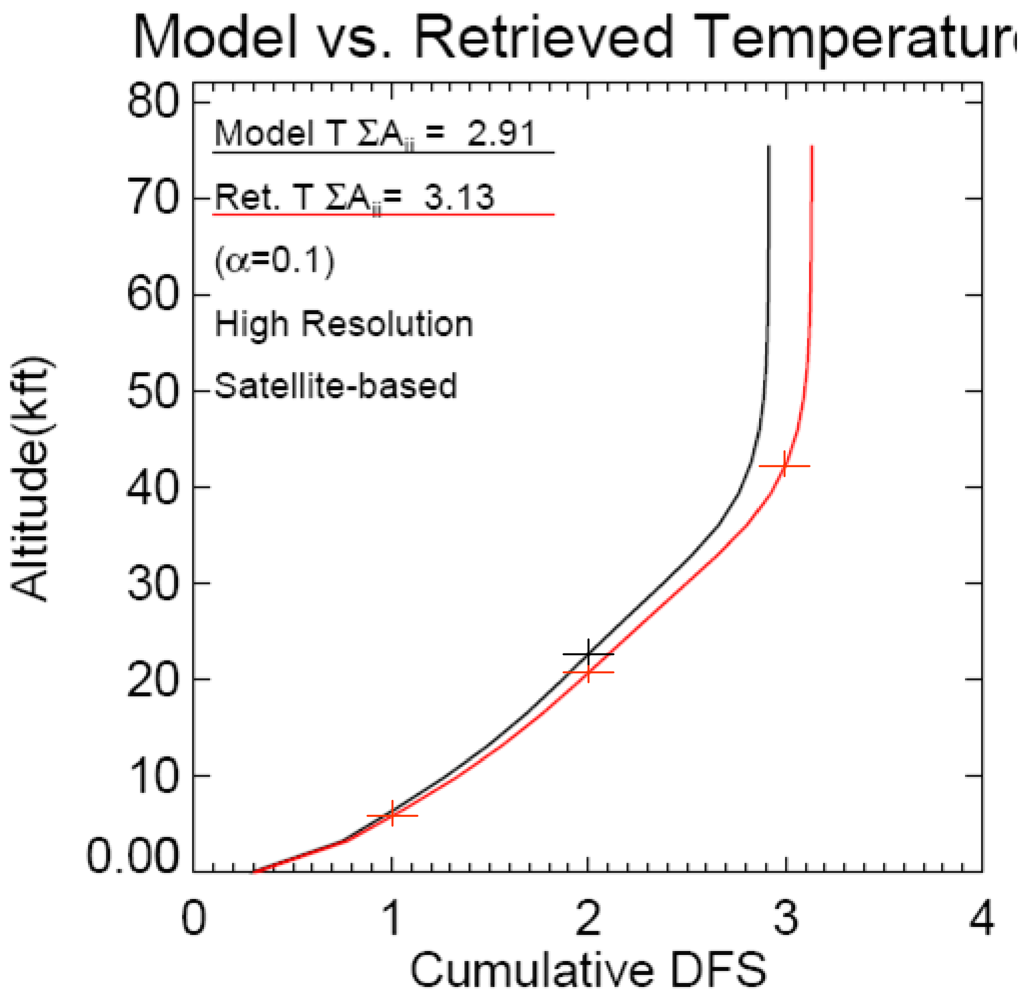
Blackbody Radiance Counts $= BC_i=[BN_i]x[(e_B)]x[W_i] + IC_i$ where:

- BN_i is the **blackbody source radiance** on Px_i at ν_i, cm^{-1} temperature T_B, emissivity e_B

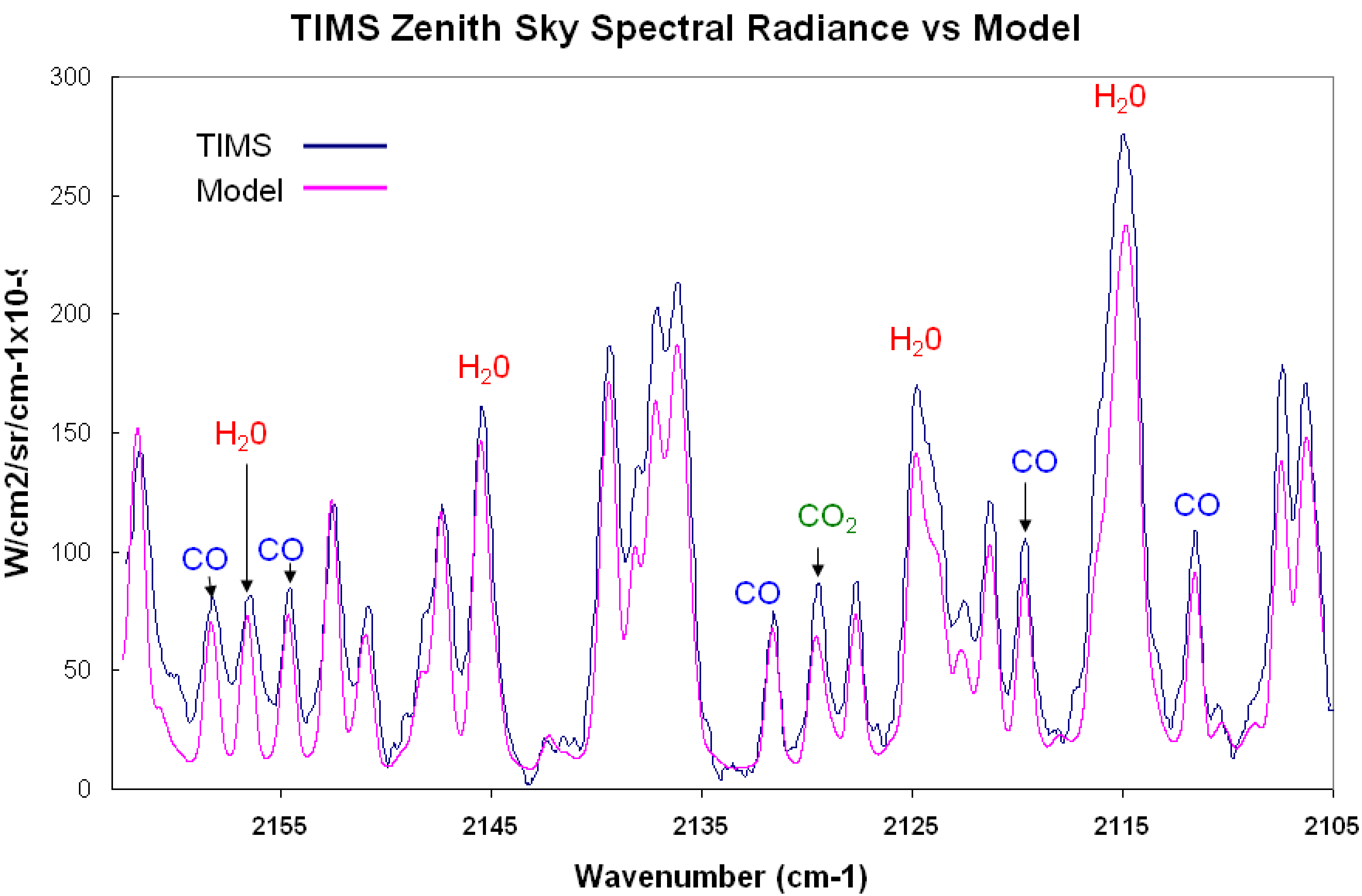
The **sky radiance is then derived** by subtracting the observed sky-view counts from the observed blackbody source counts to give:

$$SN_i =\{ [BN_i]x[(e_B)] - [MN_i]x[(1\text{-}R)] - [BC_i - SC_i]/[W_i]\}/R$$

This process subtracts the instrument background counts and flat-fields the response to sky-view radiance.

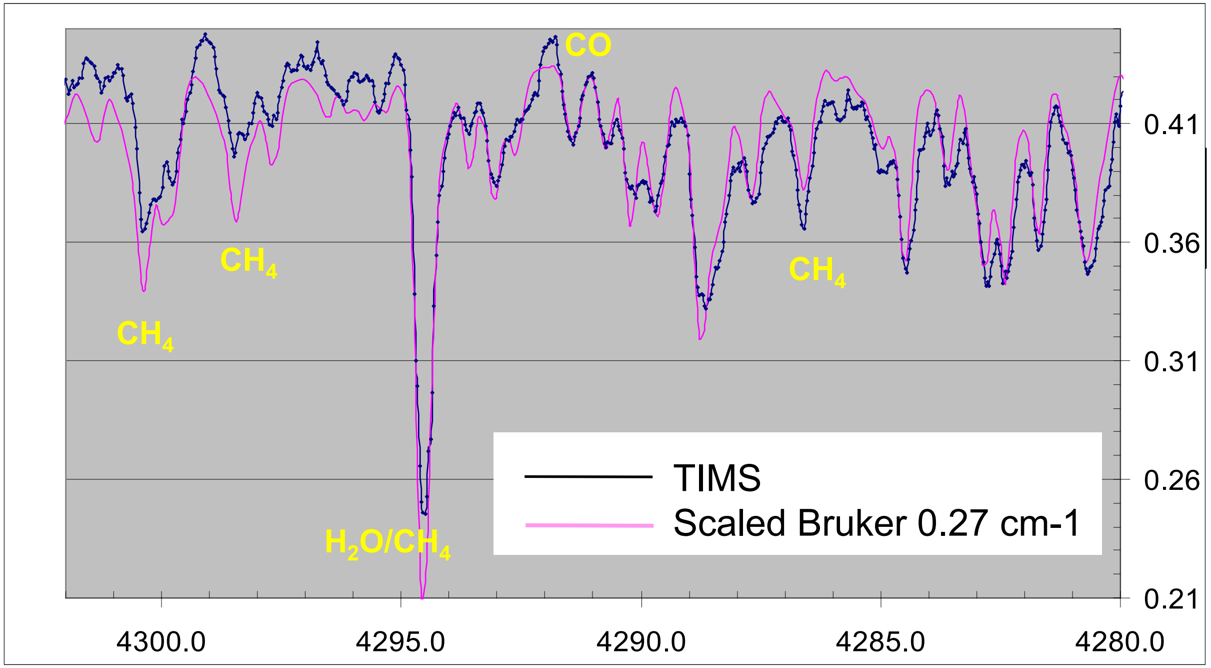


- The addition of 4.3 μm spectrometer reduces noise due to temperature uncertainty and improves the retrieval to the extent that 3 plus pieces of vertical information are obtained



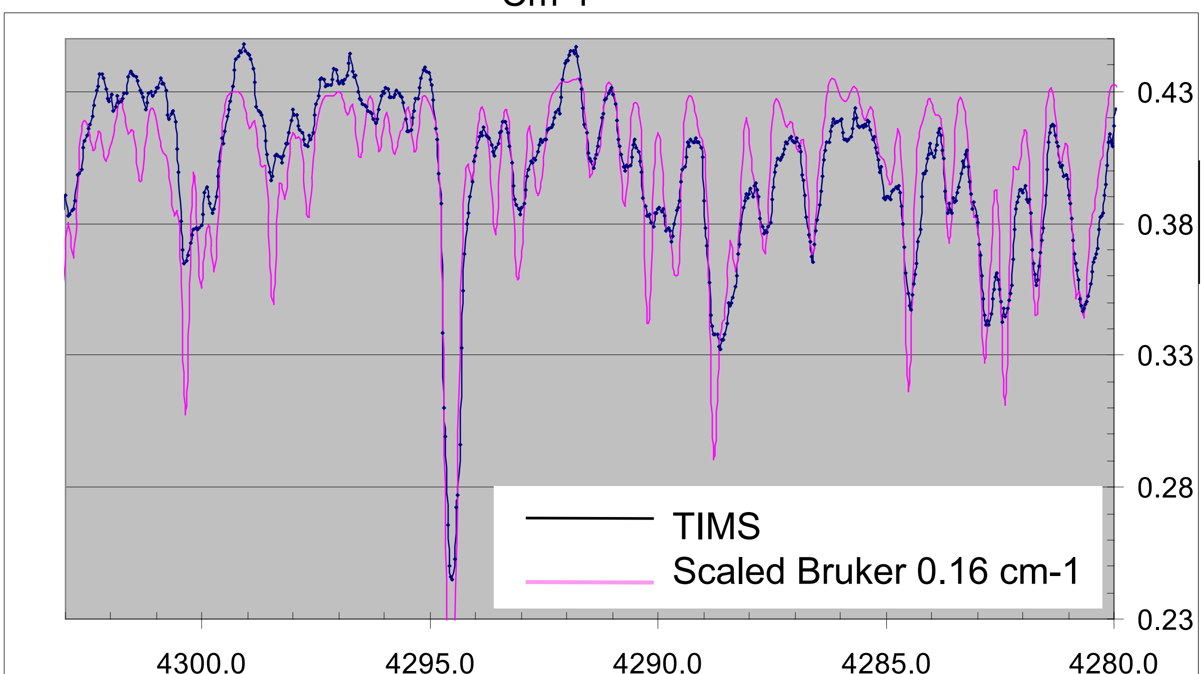
TIMS Zenith Sky Spectral Radiance vs Model
TIMS
Model
W/cm2/sr/cm-1x10-9
Wavenumber (cm-1)
300
250
200
150
100
50
0
2155
2145
2135
2125
2115
2105
CO
H2O
CO
H2O
CO
CO2
H2O
CO
H2O
CO

Preliminary Analysis of VSWIR Solar Absorption Spectra; Data acquired May 30, 2008 in Denver



Cm-1

VSWIR overlaid by Bruker running at 0.27 cm-1 FWHM



VSWIR overlaid by Bruker running at 0.16 cm-1 FWHM