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2. Authors: JB Kumer, JL mergenthaler, AE Roche and R Rairden, all with LMATC, and Robert Chatfield with ARC

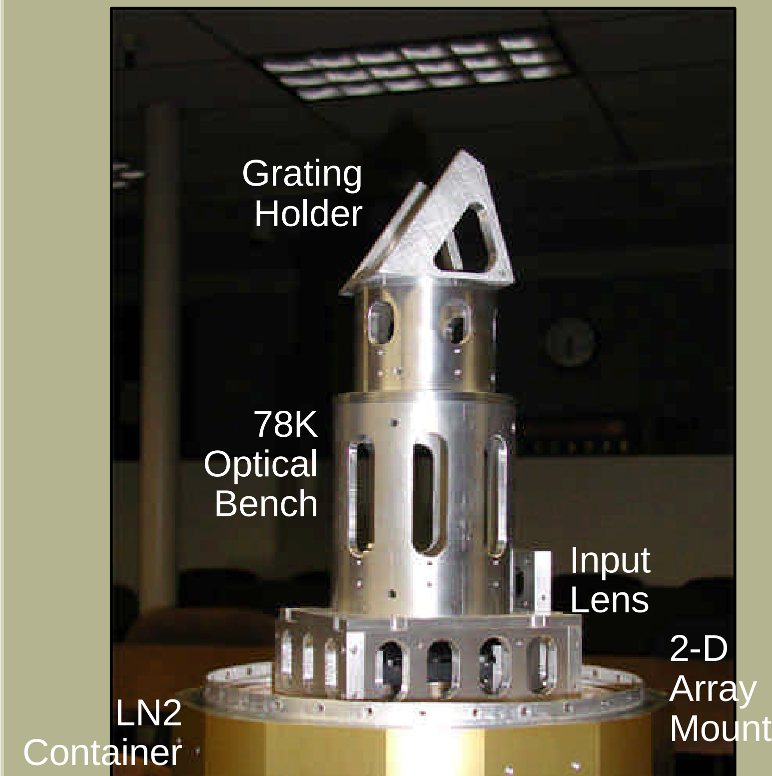
3. Tropospheric infrared mapping spectrometers (TIMS) for Air Quality measurements

4. Abstract:

We have been awarded a NASA Instrument Incubator Program (IIP) to develop grating mapping spectrometers (GMS) with very high spectral resolution, very low noise, and very wide field of view. These also would be very compact facilitating deployment in either a leo or geo application. The measurement set could be very comprehensive, addressing air quality, carbon species and climate change, or subsets of these. For this presentation we'll focus on the potential application of these GMS to provide an air quality subset of primary measurements consisting of CO partial columns, (vertical information), ozone partial columns and HCHO column. The measured spectra provide opportunity to retrieve secondary products including columns of CH4, N2O and CO2, and improved retrieval of near surface H_2O. The CH_4 and CO_2 columns ratio can be used to retrieve vertically averaged tropospheric CH_4 mixing ratio. Spectral measurements would be acquired with several spectrometers. For the species as cited above these would include solar reflected spectra near 2.33 and 2.08 μm, and emissive spectra near 4.68 μm. Additional, optimal O_3 information could be obtained by adding another emissive region near 9.52 μm. For this application we'll discuss spectral regions, spectral resolution and noise for potential geo and leo applications. For these applications we'll describe the temporal and areal coverages and footprint sizes. We'll present retrieval results predicted by a linear error analysis for these applications. We'll present results from an in house lab demonstration GMS that is a predecessor to the IIP design.

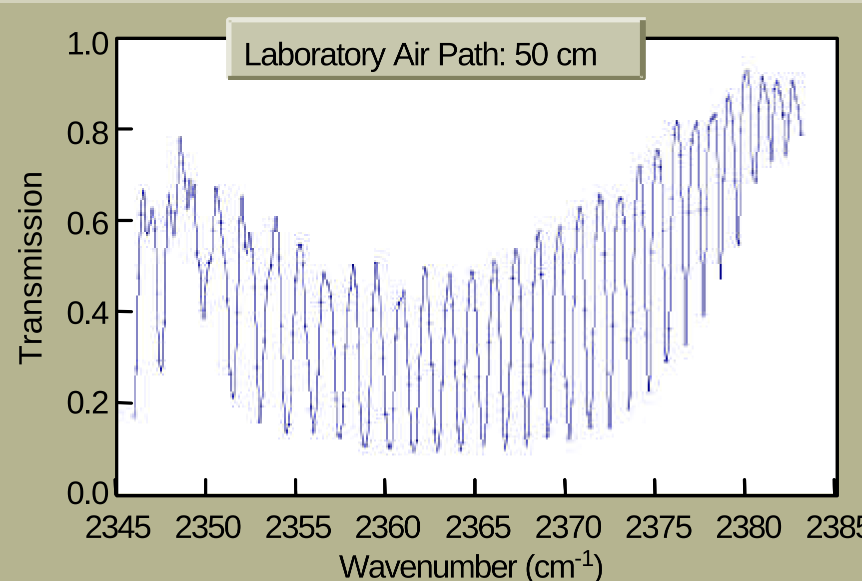
Lab demo grating mapping spectrometer (GMS)

0LN2 Cooled Demonstration Spectrometer Structure

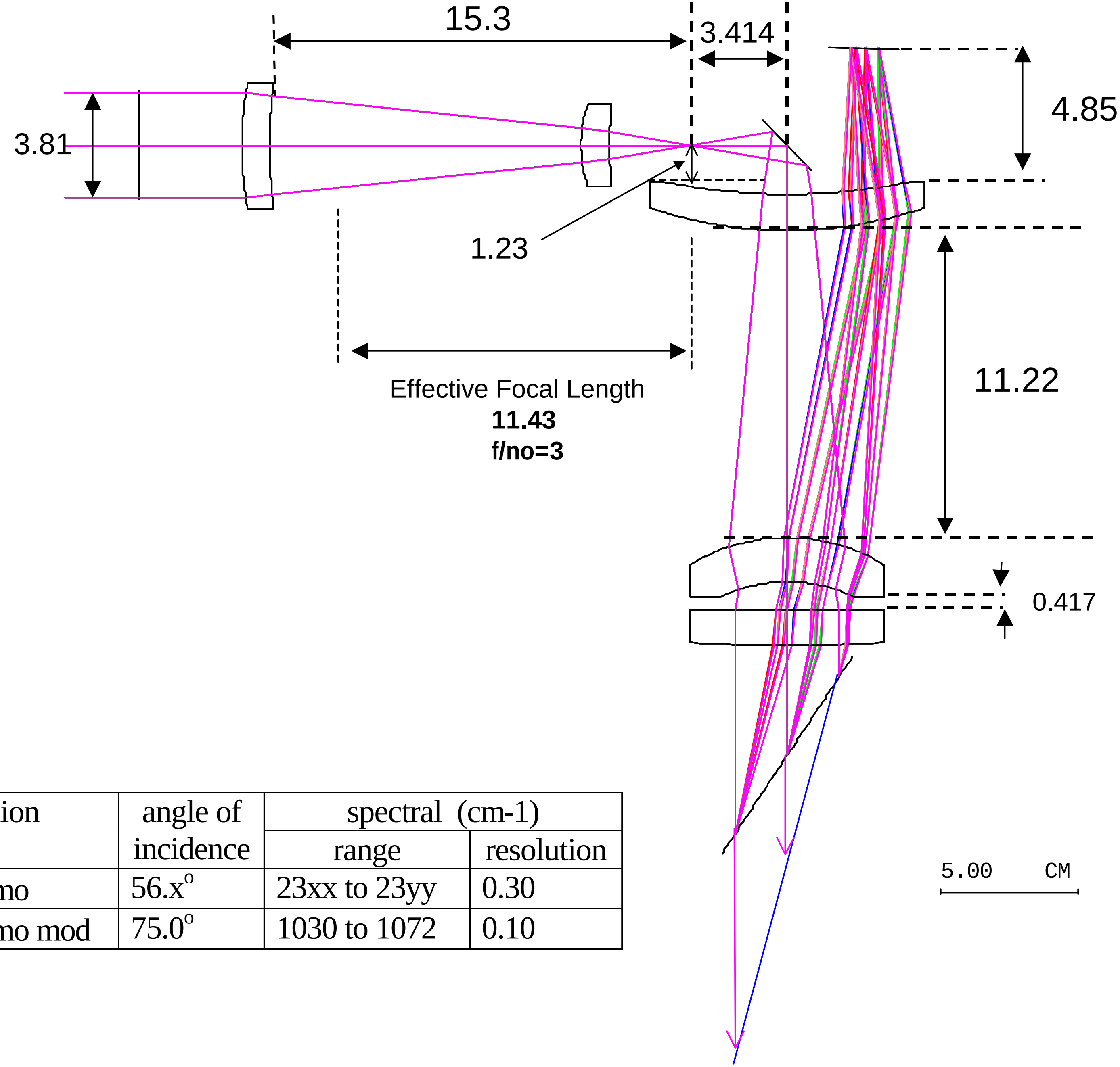


Hardware implementation of Lab demo SWIR GMS

0.3 cm^{-1} Absorption Spectra of CO_2 626 Fundamental Band Lines



Lab demo SWIR GMS absorption spectra at spectral resolution ~0.3 cm^{-1} obtained for transmission through a 50 cm path of lab air



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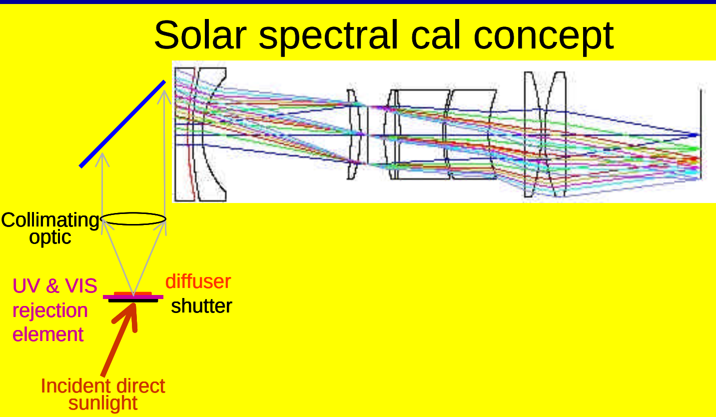
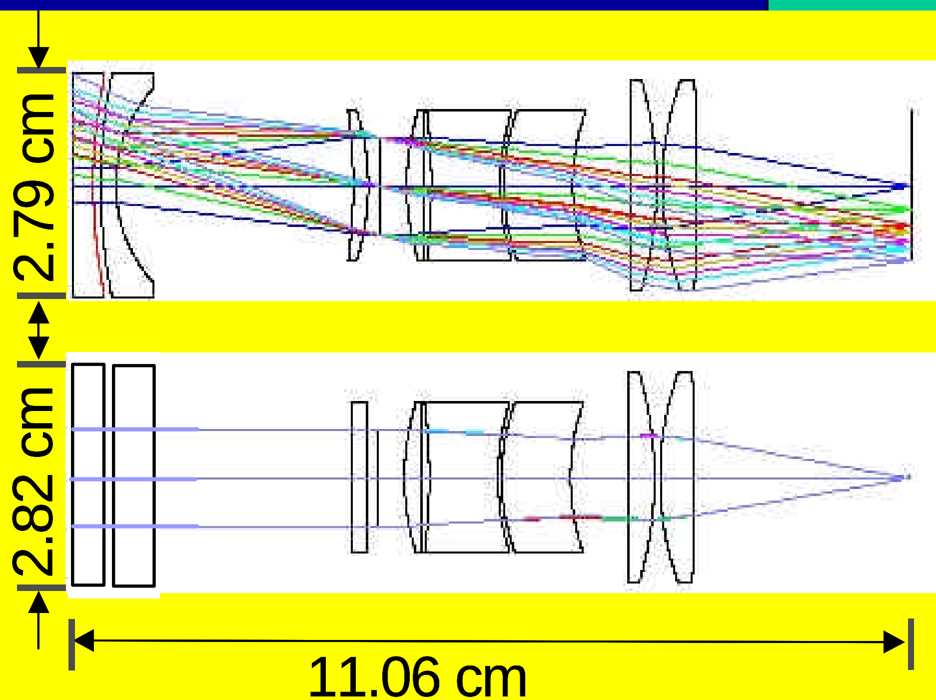
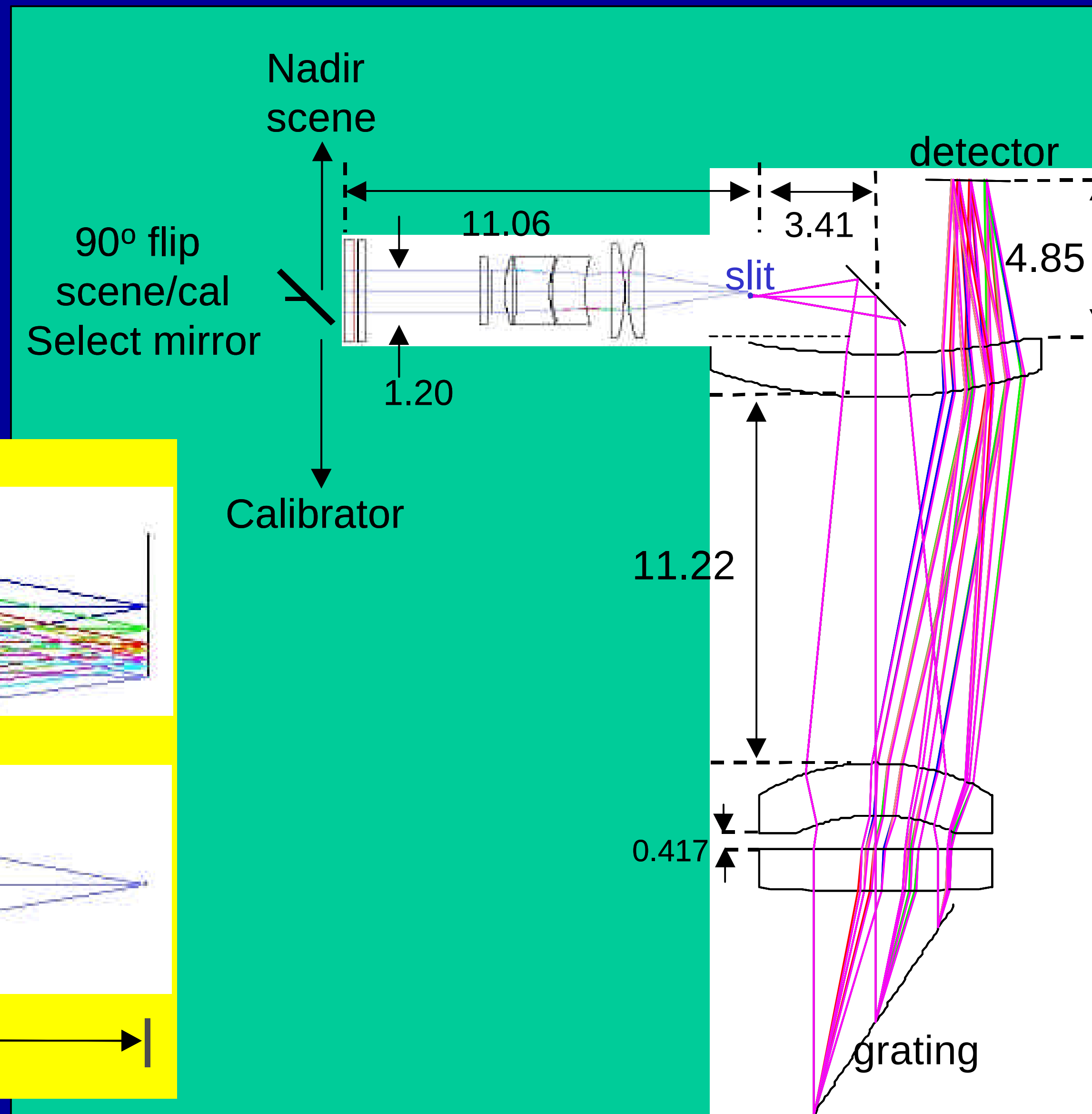
configuration	angle of incidence	spectral (cm-1)	
		range	resolution
4.2x µm lab demo	56.x°	23xx to 23yy	0.30
9.57 µm lab demo mod	75.0°	1030 to 1072	0.10

Lab demo optical design with crosstrack field widened input optics for spaceborne deployment



Two perspectives of anamorphic fore optics





The VSWIR spectrometer requiremnt for spectral resolution 0.10 cm^{-1} on the range 4281 to 4301 cm^{-1},and with a 1.84 cm slit length, is by the far the most challenging to implement

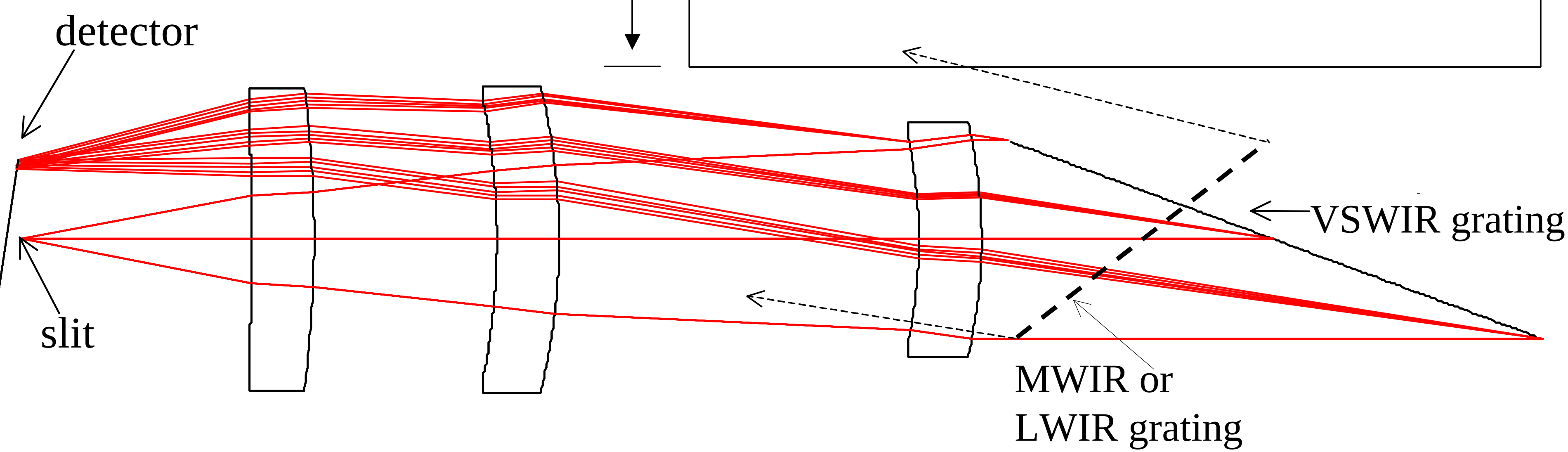
5 cm scale

9.90 in

5.76 in

The optical design below is similar to the refractive Littrow design of the lab demo, and will achieve the required VSWIR spectral resolution 0.10 cm^{-1} on the range 4281 to 4301 cm^{-1}, and with a 1.84 cm slit length, but it is rather **bulky**!

Our **IIP project** is aimed at demonstrating a much more compact design that will provide identical performance.and fit within this box.



Measurement summary table

Spectral Region and priority	Approximate wavelength	Frequency resolution	NEdN[1] goal & Threshold $mW/(m^2\ sr\ cm^{-1})$	Nadir ELF [2]	Primary Measurement (potential measurement)	Consequent Additional Benefits
VSWIR 2ndary	2.09 µm	< 0.16 cm^{-1}		1.6 km	column CO_2, clouds	ratio vs CH_4:CO_2 columns for [CH4][3]
VSWIR 2ndary	2.25 µm	< 0.16 cm^{-1}		1.6 km	column CH_4, N_2O, clouds	ratio CH4:N2O
VSWIR primary	2.33 µm	< 0.13 cm^{-1}	0.04 & 0.10	1.6 km	column CH_4, CO, H_2O, clouds	BL[3] CO, CH_4, and H_2O columns, clouds & BL
SWIR 2ndary	3.33 µm	< 0.58 cm^{-1}		3.2 km	CH_4, H_2O	good vertical info in this region
SWIR primary	3.56 µm	< 0.35 cm^{-1}	0.0016 & 0.0050	3.2 km	HCHO, CH_4, N_2O, and maybe some O_3 info	VOC's; high precision column info and some vertical info for HCHO, CH4 & N2O
MWIR primary	4.65 µm	< 0.20 cm^{-1}	0.006 & 0.012	3.2 km	CO, O_3 and H_2O	CO profile[4], tropospheric O_3 and BL H_2O
LWIR[5] primary	9.5 µm	< 0.11cm^{-1}	0.026 & 0.055	6.4 km	O_3 partial columns (PCs)	PCs @ 0-6, 6-12 & 12-22 km

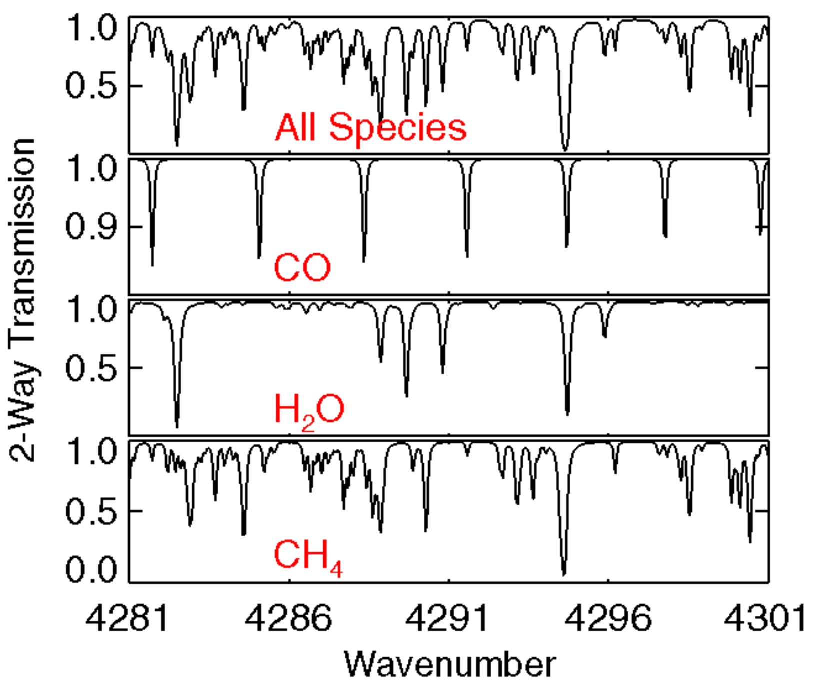
1 - @ 10% albedo for solar reflective & @ scene brightness 260 K for thermal
2 - ELF: Elemental (smallest sampled) footprint
AGF: aggregated footprint, nominally comprised of 12x12 VSWIR ELFs, co-registered with 6x6 SWIR and MWIR ELFs, and with 3x3 LWIR ELFs
3 - BL: Planetary Boundary Layer, also [CH_4] is total atmospherically averaged CH_4 mixing ratio
4 - CO profile and H2O BL require retrieval that simultaneously utilizes the VSWIR and MWIR data
5 - Active cooling required; for others, shorter wavelength operation facilitates passive (radiative) cooling

example assumes (a) 829 km polar sun-sync orbit, (b) nadir centered swath width 25.45° on the earth, (c) end point zenith LOS @ surface 67.6°, (d) average crosstrack VSWIR ELF = 2.76 km,etc

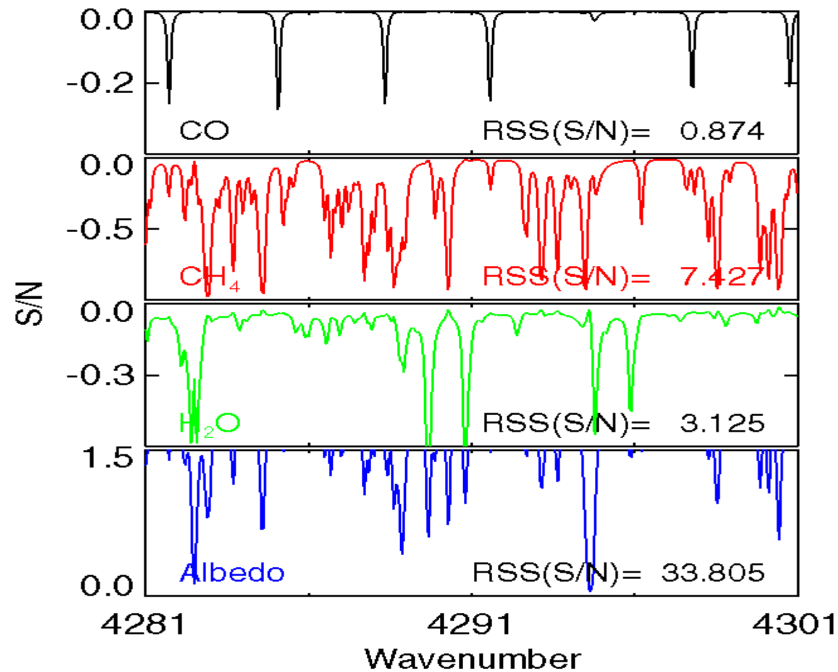
The measurements require 3 grating mapping spectrometers (GMS), one for the VSWIR, one for the SWIR and MWIR, and one for the LWIR

Solar reflective VSWIR region (~ 2330 nm) for CO

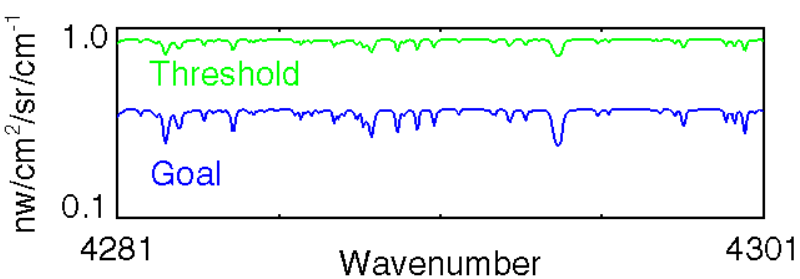
2-way transmission spectra, solar zenith angle = 45° and zenith angle for LOS to satellite = 45°



Spectral radiance changes (SRCs) in units S/N per 1% change in column, and/or albedo



Threshold & goal NEdN for aggregated footprint (AGF, xx.x km along track 7 average, yy.y km crosstrack)



linear error analysis (LEA) for columns & surface, A_{II} is the diagonal of the averaging matrix

Table of LEA results for 4281 to 4301 cm^{-1}

Geophysical parameter	Retrieval precision %	A_{II}	Rss_SNR
CO column	1.20	0.9977	0.874
CH_4 column	0.17	1.0000	7.427
H_2O column	0.40	0.9993	3.125
albedo	0.044	1.0000	33.80

MWIR region (~ 4673 nm) for CO and O_3

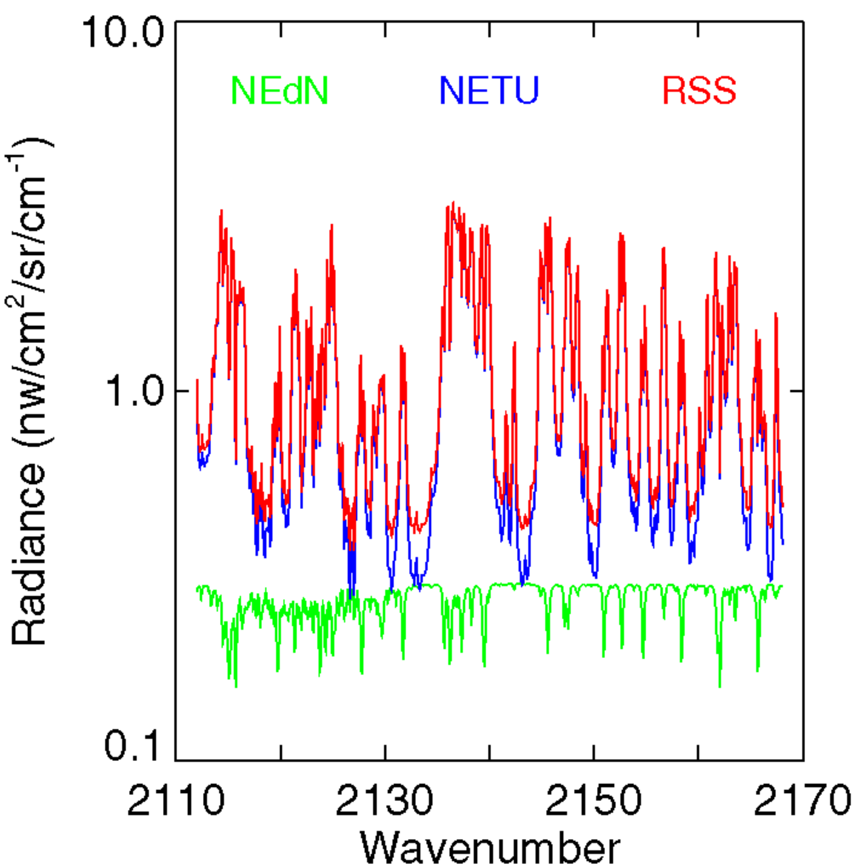
Rss_NEdN is rss of threshold instrument noise NEdN and Noise Equivalent Temperature model Uncertainty NETU for an AGF where

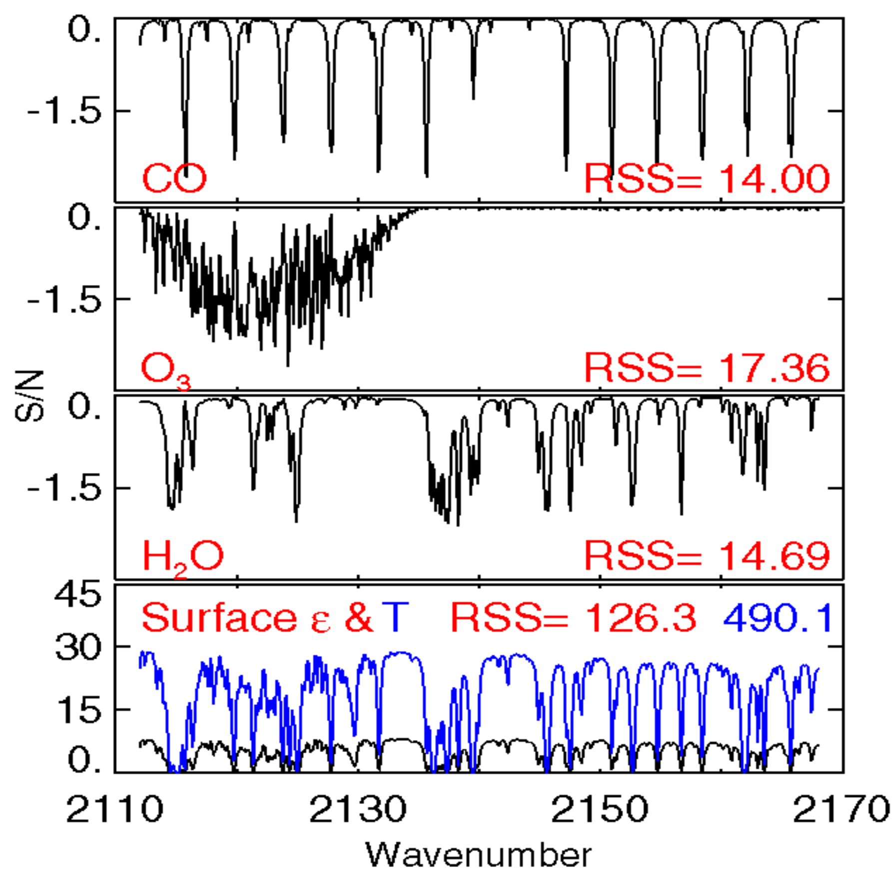
$$NETU = \Delta T(\Sigma(\partial N_{rad}/\partial T_j)^2)^{1/2}$$

For a temperature model with uncertainty ΔT=1K on 2km layers

Spectral radiance changes (SRCs) resulting from 1% changes in the columns of CO, O_3 and H_2O, and from 1% changes in surface emissivity, and 1K change in surface temperature are shown below for an AGF. (weaker CO2 & N2O contributions not shown here)

- **note the orthogonality of the species SRCs**

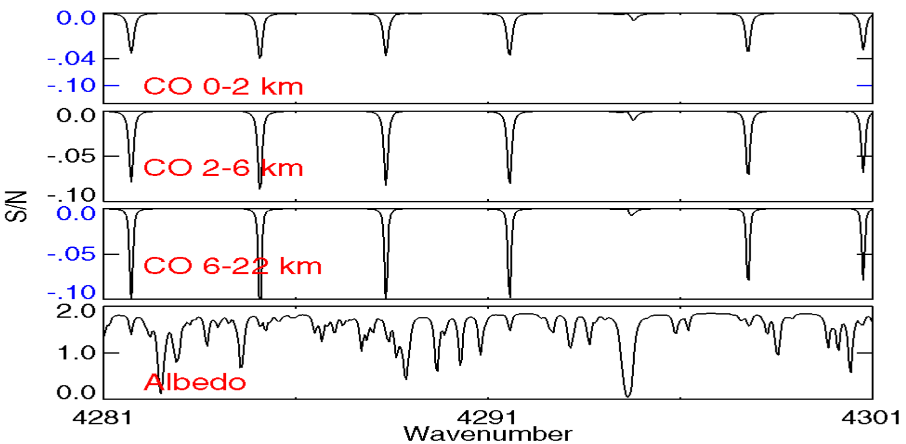


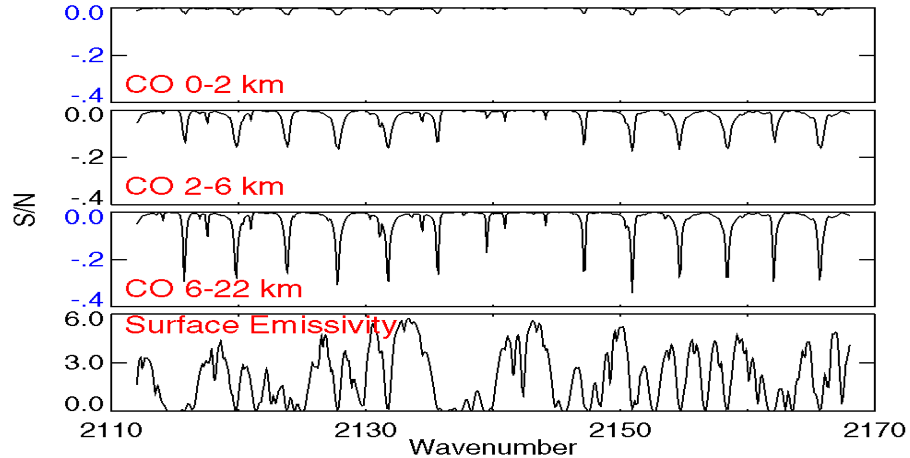


3-layer CO Retrieval

Following suggestion of our IIP co-operating scientist Robert Chatfield we executed the LEA on 3 layers that approximate independent layers for CO retrieval. the layers are selected as follows, each of the two upper layers should come as close as possible to having it's diagonal $A_{LAYER} = (DFS\text{-}A_{11})/2$ where DFS $=\Sigma A_{II}$ for a all layers of a 2km per layer model.

- On the left panel 2 figures with SRCs in the two spectral regions for 1% perturbations of CO partial columns and surface parameter perturbations of 1% emissivity & 1K temperature, and
- on the right panel tables of LEA results for day and night cases. Calculations apply for a 20km footprint.





Tables of LEA results for 3-layer CO retrieval

Daytime LEA results for layered CO retrieval			
parameter	Retrieval precision %	A_{II}	Rss_SNR
CO 0 – 2km	8.4	0.89	0.27
CO 2km – 6 km	4.3	0.97	1.13
CO 6 km –22km	2.3	0.99	1.6
Surface reflectance	.03	1.0	71.5

Nighttime LEA results for layered CO retrieval			
parameter	Retrieval precision %	A_{II}	Rss_SNR
CO 0 – 2km	24	0.11	0.20
CO 2km – 6 km	6.7	0.93	1.09
CO 6km - 22km	2.5	0.99	1.56
Surface reflectance	0.59	1.0	63.0

LWIR region (~ 9515 nm) for O_3

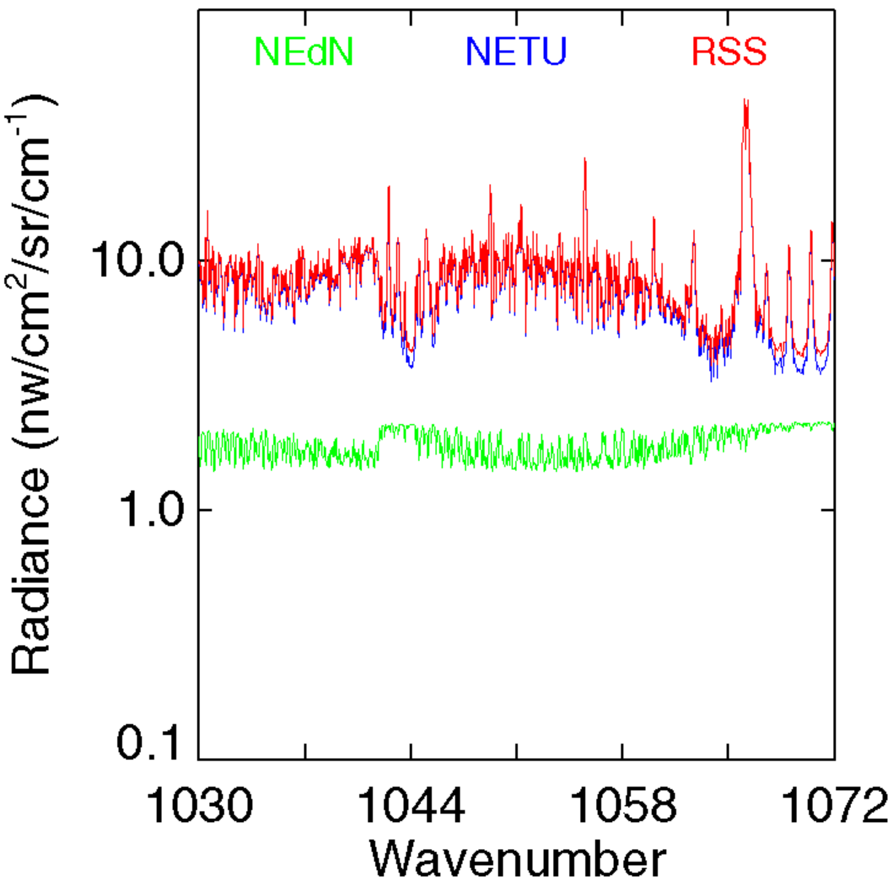
Rss_NEdN is rss of threshold instrument noise NEdN and Noise Equivalent Temperature model Uncertainty NETU for an AGF where

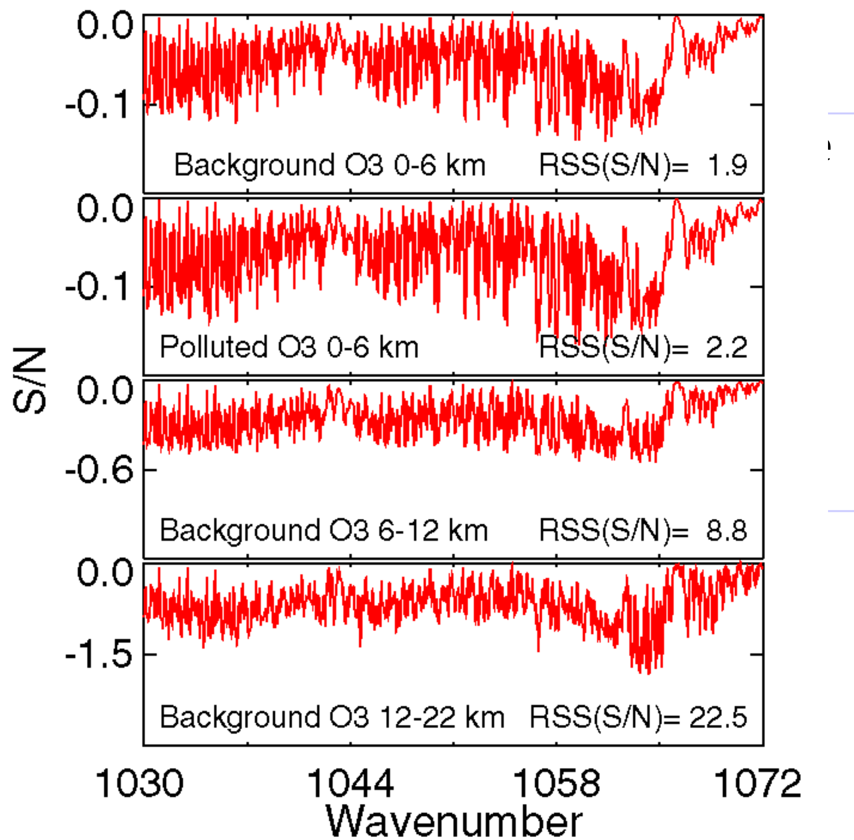
$$NETU = \Delta T(\Sigma(\partial N_{rad}/\partial T_j)^2)^{1/2}$$

For a temperature model with uncertainty ΔT=1K on 2km layers

Spectral radiance changes (SRCs) resulting from 1% changes in partial columns of O_3

- 0 – 6km background, 20 ppbv in boundary layer
- 0 – 6km, polluted, 80 ppbv in boundary layer
- 6 – 12 km background case
- 12 – 22 km background case

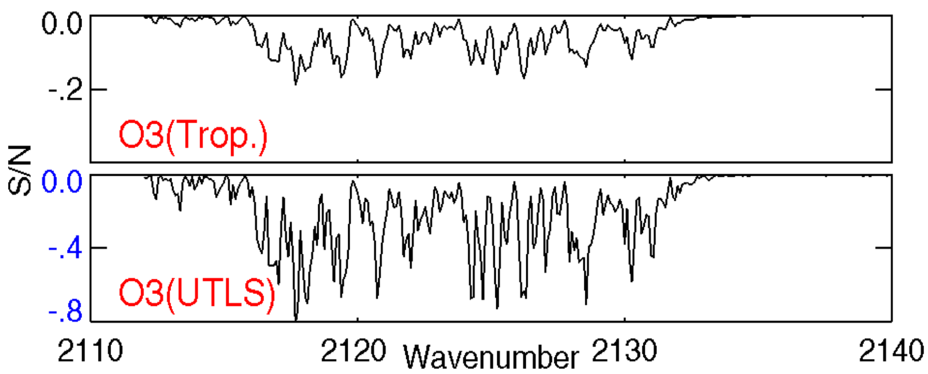




multi-layer ozone retrieval LEA on an AGF

2-layer retrieval LEA from MWIR data

- OMPS data product constraint
- On the top panel SRCs for 1% perturbations of ozone partial columns
  - 0 to 11 km and
  - 11 to 22 km
- and on the bottom panel tables of LEA results for day and night cases



MWIR LEA results for 2-layer O3 retrieval			
parameter	Retrieval precision %	A_{II}	Rss_SNR
O_3 0-11 km	6.10	0.996	1.12
O_3 11-22 km	1.44	0.979	4.66

3-layer retrieval LEA from LWIR data for background and polluted cases

LWIR LEA results for layered O3 retrieval			
parameter	Retrieval precision %	A_{II}	Rss_SNR
O_3 0-6 km, background	3.7	0.978	1.9
O_3 0-6 km, polluted	3.1	0.985	2.2
O_3 6-12 km, background	1.23	0.997	8.8
O_3 12-22 km	.269	1.0	22.5

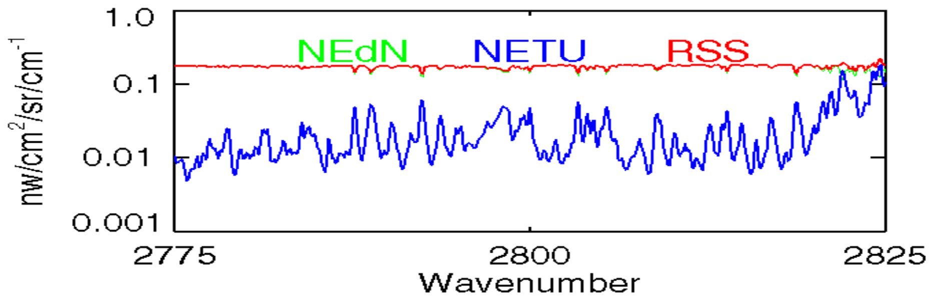
3-layer retrieval LEA from combined LWIR + MWIR data for background and polluted cases

LWIR + MWIR LEA results for layered O3 retrieval			
parameter	Retrieval precision %	A_{II}	Rss_SNR
O_3 0-6 km, background			
O_3 0-6 km, polluted			
O_3 6-12 km, background			
O_3 12-22 km			

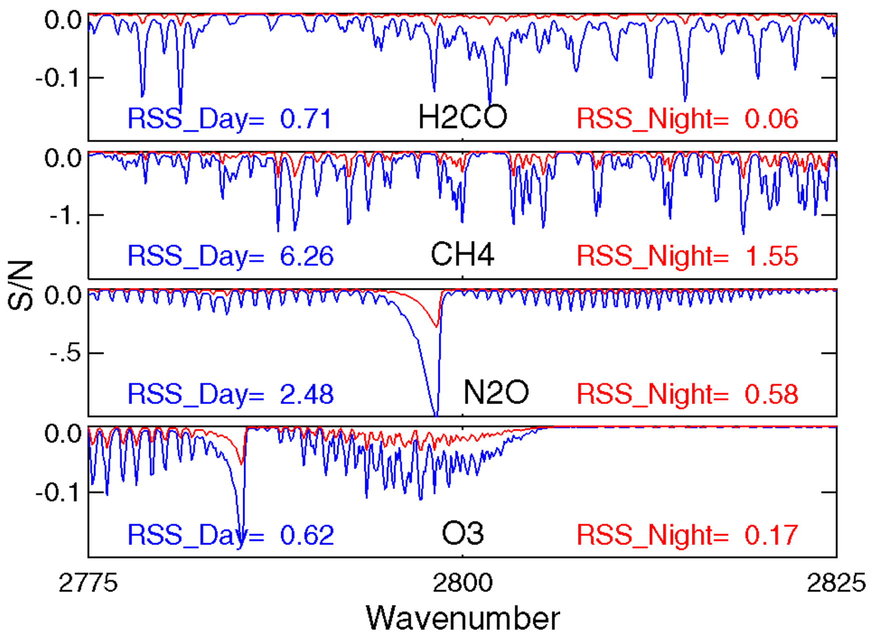
Note:Cases with no entry reflect that we were not able to finish the calculations prior to attending the 21 to 23 Feb 06 Workshop

SWIR region (~ 3571 nm) for HCHO column

Instrument NEdN, temperature uncertainty NETU and the Rss_NEdN



Day and night spectral radiance changes per 1K or 1% change in surface params or column, &/or for HCHO, CH_4, N_2O & O_3



LEA results for column for daytime case

Geophysical parameter	Retrieval precision %	A_{II}	Rss_SNR
HCHO column	1.92	0.994	0.71
CH_4 column	0.27	0.999	6.26
N_2O column	0.42	0.999	2.48
O_3 column	1.86	0.994	0.62
Surface temp	.11K	.999	91.3
albedo	0.44	0.997	19.47

LEA results for column for nighttime case

Geophysical parameter	Retrieval precision %	A_{II}	Rss_SNR
HCHO column	14.27	0.6723	0.06
CH_4 column	0.63	0.999	1.55
N_2O column	1.52	0.996	0.58
O_3 column	5.67	0.948	0.17

Summary of LEA for CO, O3, HCHO and secondary species (1 of 2)

Geophysical parameter	Retrieval precision %		A_{II}		spectral region(s)
	day	night	day	night	
CO column	1.2		0.999		VSWIR
CO partial column (PC) 0-2 km	8.4	24.0	0.89	0.11	VSWIR and MWIR
CO PC 2-6 km	4.3	6.7	0.97	0.93	VSWIR and MWIR
CO PC 6-22 km	2.3	2.5	0.99	0.99	VSWIR and MWIR
O_3 PC 0 – 11 km		6.1		0.996	MWIR
O_3 PC 11 – 22 km		1.44		0.979	MWIR
O_3 PC 0 – 6 km, background		3.7		0.978	LWIR
O_3 PC 0 – 6 km, polluted		3.1		0.985	LWIR
O_3 PC 6 – 12 km		1.23		0.997	LWIR
O_3 PC 12 – 22 km		< 1.0		1.0	LWIR
O_3 PC 0 – 6 km, background					MWIR and LWIR
O_3 PC 0 – 6 km, polluted					MWIR and LWIR
O_3 PC 6 – 12 km					MWIR and LWIR
O_3 PC 12 – 22 km					MWIR and LWIR
O3 total column	1.86	5.67	0.994	0.95	SWIR
HCHO total column	1.92	14.3	0.994	0.67	SWIR
HCHO PC 0 – x km					SWIR
HCHO PC x – 22 km					SWIR
Secondary species					
CH_4 column	< 1.0		1.0		VSWIR
H_2O column	< 1.0		0.999		VSWIR
albedo	<<1.0		1.0		VSWIR
H_2O PC 0 – 2 km					VSWIR and MWIR

Note:Cases with no entry reflect that we were not able to finish the calculations prior to attending the 21 to 23 Feb 06 Workshop

Summary of LEA for CO, O_3, HCHO and secondary species (2of 2)

Geophysical parameter	Retrieval precision %		A_{II}		spectral region(s)
	day	night	day	night	
Secondary species continued					
CH_4 column	< 1.0	< 1.0	0.999	0.999	SWIR
N_2O column	< 1.0	1.52	0.999	0.996	SWIR
CH_4 PC 0 – x km					SWIR
CH_4 PC x – 22 km					SWIR
N_2O PC 0 – x km					SWIR
N_2O PC x – 22 km					SWIR
Surface temp					SWIR
albedo					SWIR
Surface temp					MWIR
emissivity					MWIR
Surface temp					LWIR
emissivity		0.067 ?		1.00	LWIR

Models for CO, O_3, HCHO