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A GEO-CAPE Measurement Concept that is Based on the ESTO Instrument Incubator Project (IIP) Tropospheric Infrared Mapping Spectrometers (TIMS)

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TIMS applications: GEO-CAPE [and other]

- GEO-CAPE calls for
  - Wide-area CO mapping (7 km nadir pixel) of North and South America from 45 ^{o}S to 50 ^{o}N at approximately hourly intervals
    - With vertical profiling capability provided by measurements of solar reflective in the weak CO band at 2.3 μm AND in the strong band at 4.6 μm
- Below we describe a TIMS GEO-CAPE operational approach that
  - Maps vertically resolved CO on 6 km nadir footprints on North and South America from 45 ^{o}S to 50 ^{o}N on one hour intervals
- Next we present TIMS atmospheric CO measurements
  - That simulate & demonstrate TIMS vertically resolved CO retrieval on the smallest 6 km footprints, and on larger ganged 30 km footprints
    - Demonstrate secondary retrieval of CH_4 and vertically resolved H_2O
    - The measurements are compared with validation data from Denver University (DU), AIRS, and ECMWF
- Finally we point out TIMS broad versatility for
  - An expanded GEO-CAPE roll with primary species set CO plus O_3 and HCHO
  - Aircraft deployed applications (a) OCO validation or (b) demonstrate ASCENDS CO measurements
  - HAA deployment for CO or other

- Space applications
  - Ancillary CO measurements for decadal survey mission ASCENDS
  - Geo carbon trade monitoring ?
    - Facilitates extended dwell times in regions of suspected violation
    - Would use all or some of the OCO regions & maybe a mechanized polarizer
  - GACM, for example we were involved in the GSFC led LeoMAC study

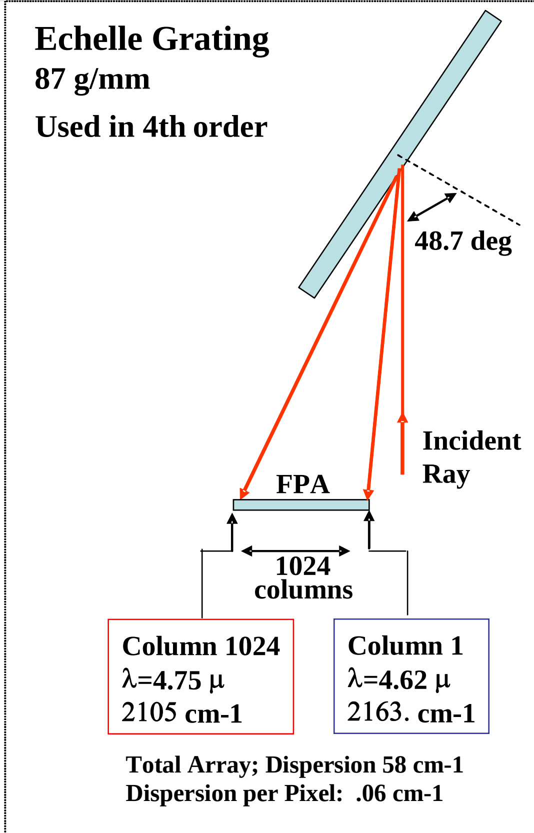
Presentation outline

- TIMS objectives, approach design and hardware
- GEO-CAPE TIMS operational scenario
- TIMS joint atmospheric measurements at/with Denver University (DU)
    - Setup and operations, calibrated radiance data and its validation
    - CO retrieval and validation
  - These measurements directly simulate CO retrieval performance to be expected in the TIMS GEO-CAPE application
- Approach to an “expanded TIMS GEO-CAPE” application
- Approach
- Aircraft and HAA (or UAV)
- Leo applications
    - Ancillary CO for ASCENDS, narrow FOV
    - GACM, wide FOV and expanded species set

TIMS objectives

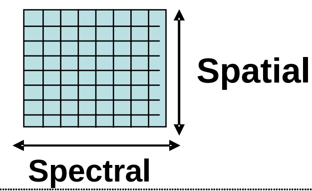
- Wide area measurements of vertically resolved CO on small footprints, for example
  - –From geo with scan pattern and footprints as per the GEO-CAPE measurement requirements
    - “6 km nadir footprints on North and South America from 45 oS to 50 on one hour intervals”
  - –In leo polar orbit, with horizon to horizon pushbroom scan for twice daily global coverage & with < 6 km footprints @ nadir
  - –Measurements in both the CO 2.3 & 4.6 μm bands with high spectral resolution and low signal to noise in order to precisely retrieve vertical amounts

TIMS approach, 4.6 μm (MWIR) example



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



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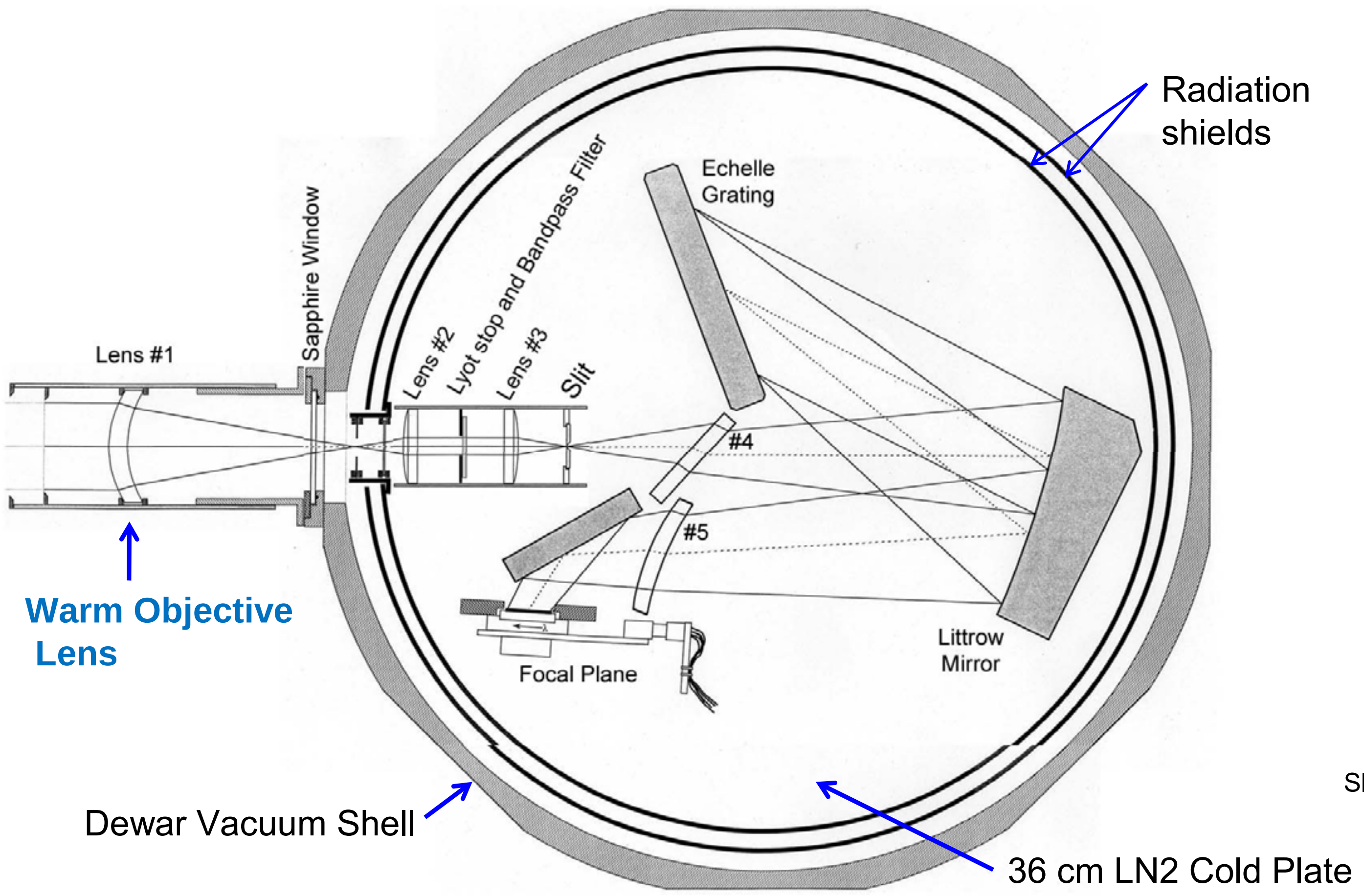
- Image the scene on to a slit feeding the grating spectrometer & then reimaging on to a low noise 2D focal plane array
  - The slit is projected to the nadir, e.g., for GEO-CAPE application along a strip of length ~3072km
  - for each point on the slit, a spectrum is laid out across the array as shown above
  - A swath of contiguous footprints is acquired by pushbrooming the slit across the earth in a direction perpendicular to the slit orientation
  - High spectral resolution is achieved by using a Littrow arrangement with a large angle of incidence
  - Noise is minimized by cooling instrument components to the extent that noise is dominated by the statistics of signal photons within the narrow band (e.g., here 0.06 cm-1) of the dispersion/pixel

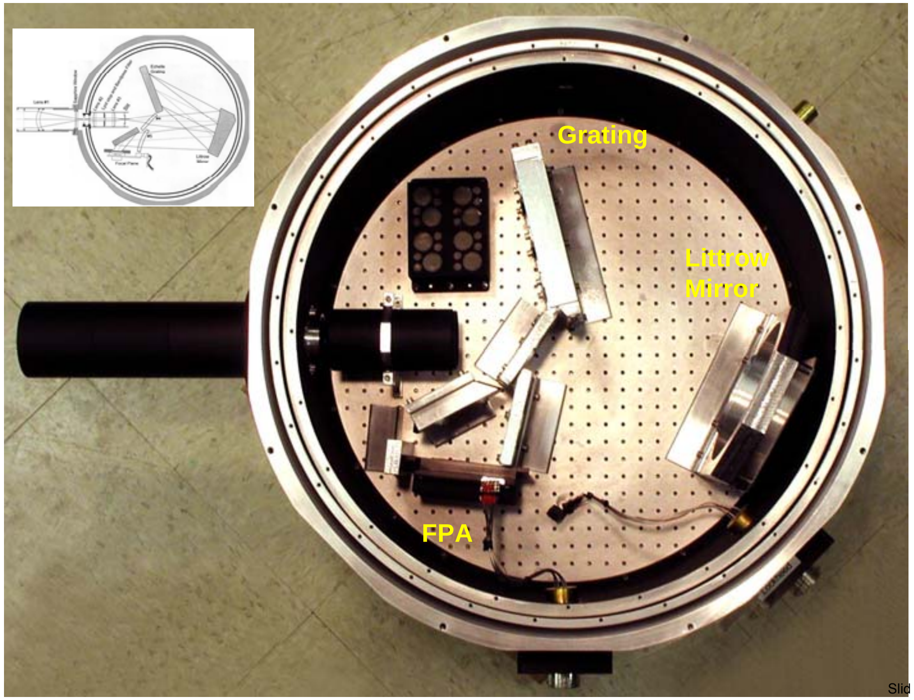
TIMS demonstration designs and hardware

- In order to minimize cost the demonstration designs utilize LN2 for cooling
  - –This would also minimize cost for aircraft deployment
  - –However for long duration missions (e.g., space, UAV, HAA) where mass is an issue, cooling would be supplied by a mix of passive radiative cooling and active (mech. Refrigerator, TE)

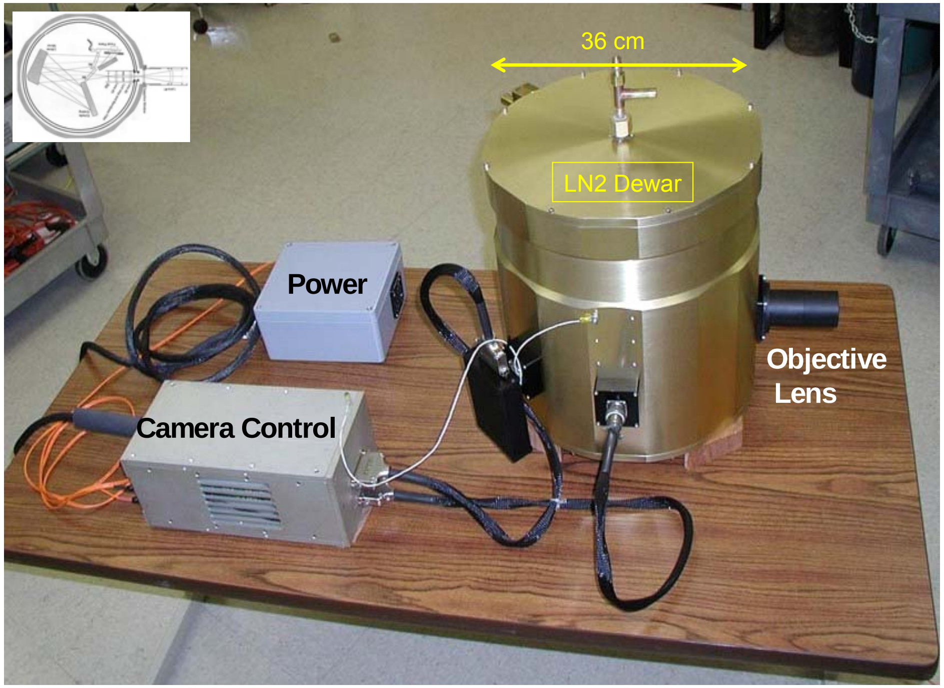
MWIR Spectrometer Optical Layout



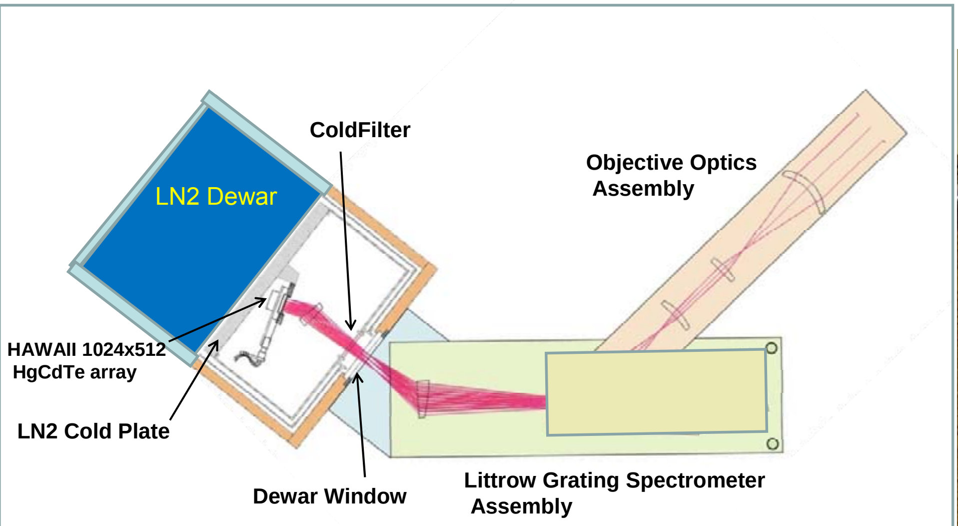
View of MWIR Components From Above.



Fully assembled MWIR Spectrometer with Electronics

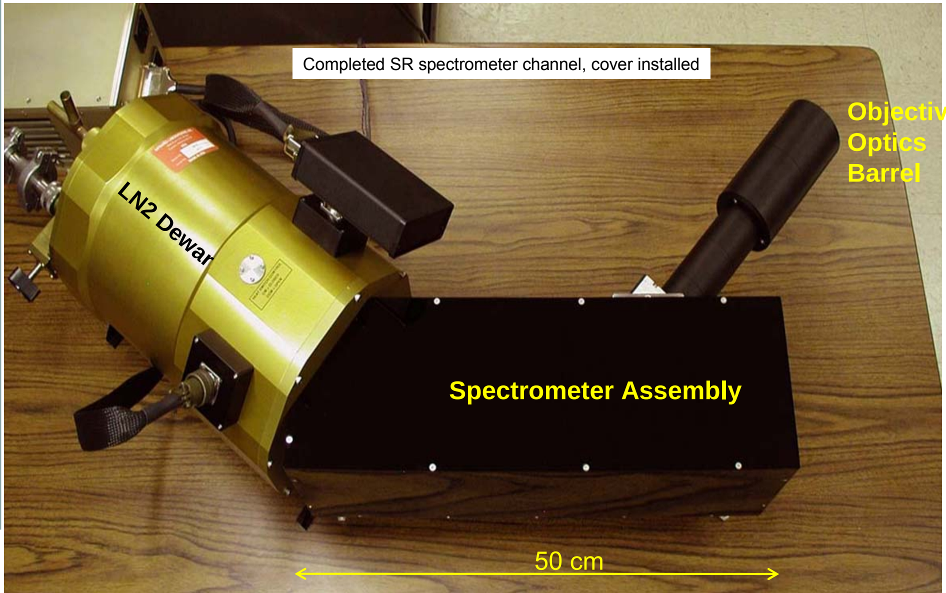


2.3 μm (VSWIR) Spectrometer Layout

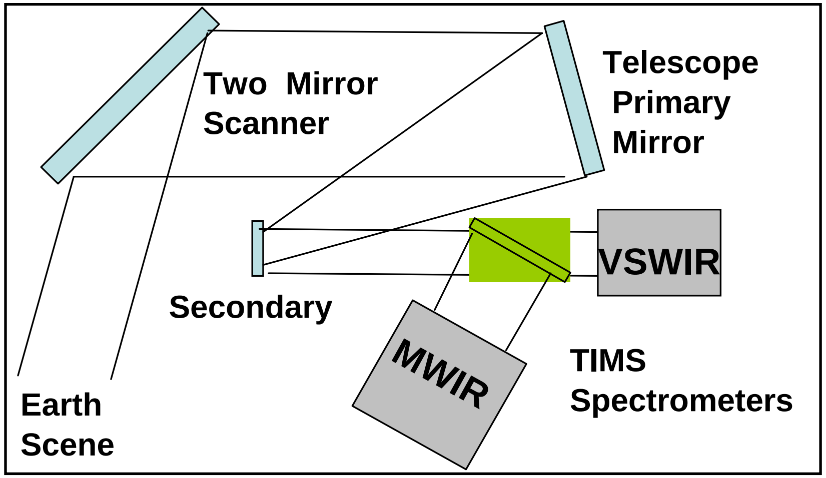


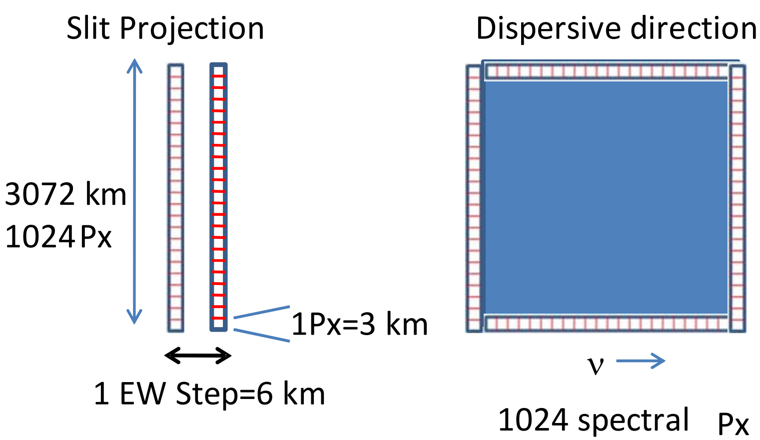
the re-imaging arm offers the possibility for multi-channel measurements

Fully Assembled VSWIR Spectrometer



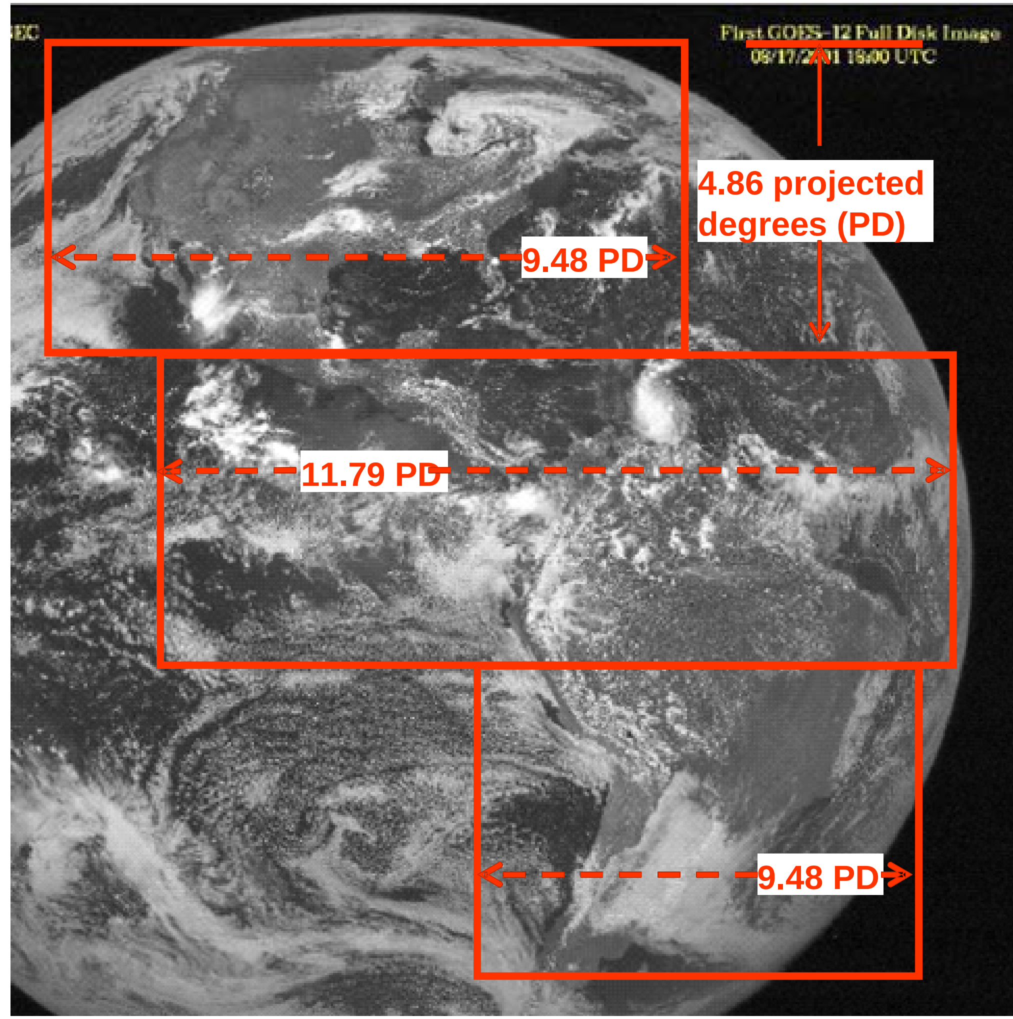
Spatial/Temporal Coverage example for a GEO-TIMS Instrument Concept





Projected ground footprints require a 7.25 cm aperture

Total length of the 3 scans = 30.75°, ie., ~ 19437 km.
Thus it takes 3240 steps to execute the 3 scans & at 1 step/sec it takes about one hour for complete coverage

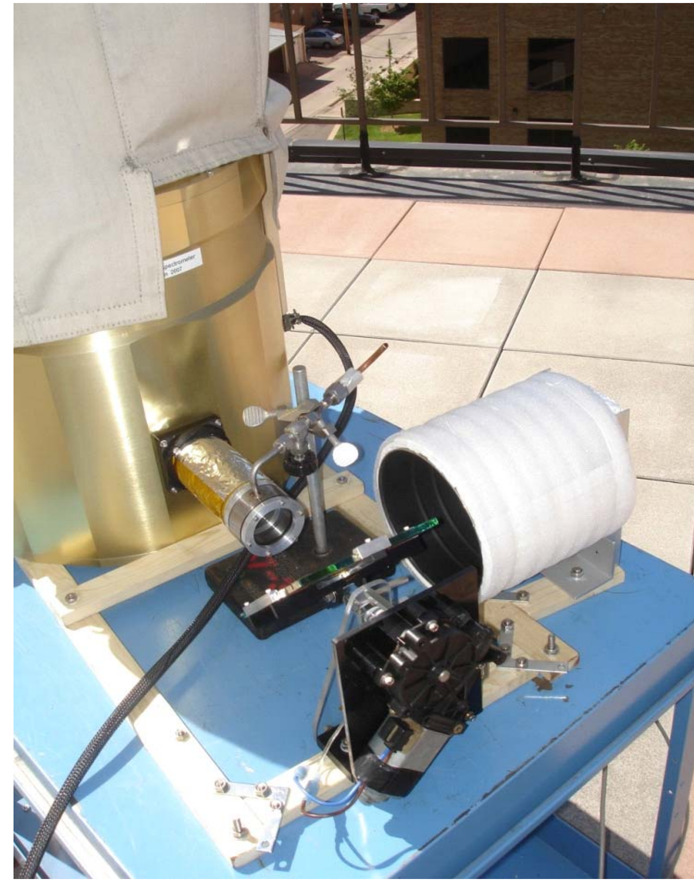


3 E-W Scan Blocks Covers 50N to 45S of North And South America in 1 hour, including calibration , as required by the GEO-CAPE

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

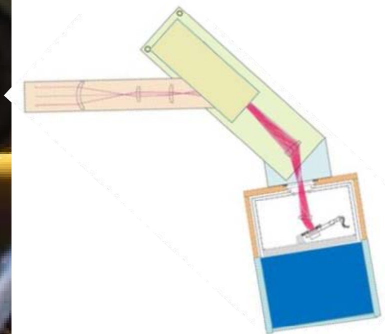
SR
Heliostat

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



- MWIR zenith mirror, shaded from direct sunlight. CO cell is in front of objective lens .
- Remote control mirror rotates FOV into BlackBody calibrator

VSWIR unit viewing solar scattering surface in Denver University laboratory



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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 therefore it needed to be operated inside the temperature-controlled laboratory

Runs to simulate GEO-CAPE operations

- Acquire a sequence of 25 data frames with 1-s integration times
  - For a single frame a 2-pixel wide spectral row simulates the measurement a 6 km x 6 km GEO-CAPE minimum footprint
  - And for 25 averaged frames this simulates a 30 km x 30 km ganged GEO-CAPE footprint

  –Acquire calibration data including multiple temperature black body (BB), MWIR reference BB, VSWIR zero levels, BB and sky viewing through cell with&without CO
- For validation, DU FTS atmospheric data are taken simultaneously in the same bands at highest spectral resolution, and at resolution degraded that of TIMS
- At this time we have evaluated one 25 observation sequence, and we'll present
  - Examples from the calibration process
  - Validation of the calibrated radiance data
  - CO retrieval results and validation

Note in proof: analysis below does not account for geocape doubled path to sun and therefore S/N for geocape 6 km footprint should be 40, not 20

VSWIR radiance signal/noise S/N in the GEO-CAPE operational concept data acquired on a 6 km x 6 km footprint by a 1-s integration time is simulated by the DU 1-s 2-pixel observation, and we'll be showing results for this case in subsequent slides

	DU field campaign	GEO_CAPE concept operations
Zero level counts (cts)	9200	< 100
Signal (cts) for albdedo (α)	2000 for retrieved α = 0.4	500 for expected median albedo =0.1
Total cts (TC)	TC = 11200 =9200+2000	TC = 600 = 100 + 500
Noise (N) $\rightarrow \sqrt{(TC)}$	$N \rightarrow \sqrt{(11200)} = 106$	$N \rightarrow \sqrt{(600)} = 25$
Signal/noise (S/N)	S/N = 2000/106 = 20	S/N = 500/25 = 20 QED

Calibration, example of image processing & extraction of spectra

Flat fielded VSWIR image =
([sky image] – [dark image])/([BB image]-[dark image])

Spectral registration is established by comparison with modeled spectra for either sky data [this example], or for CO cell data

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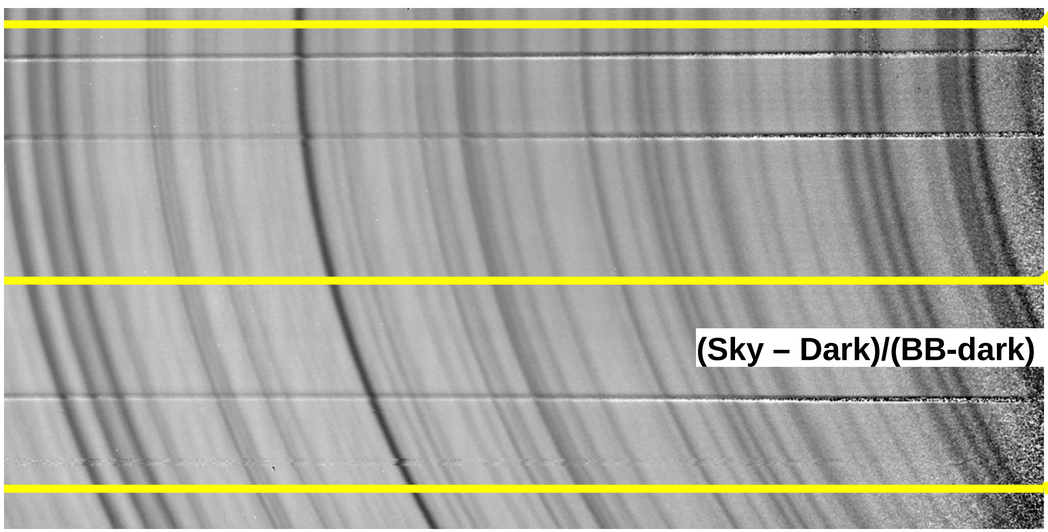
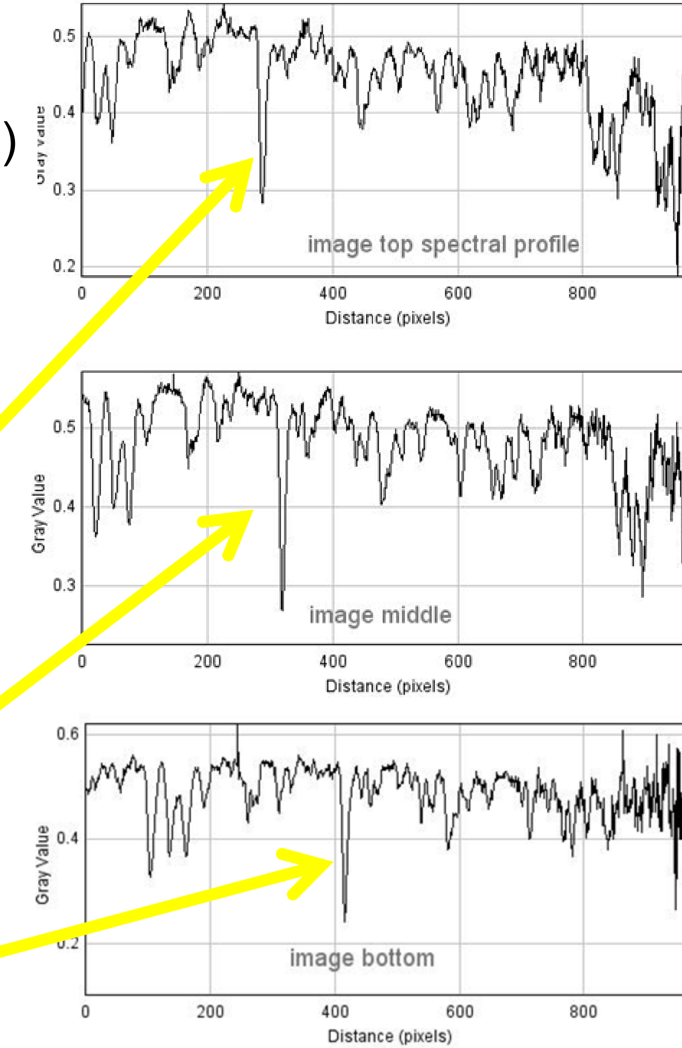
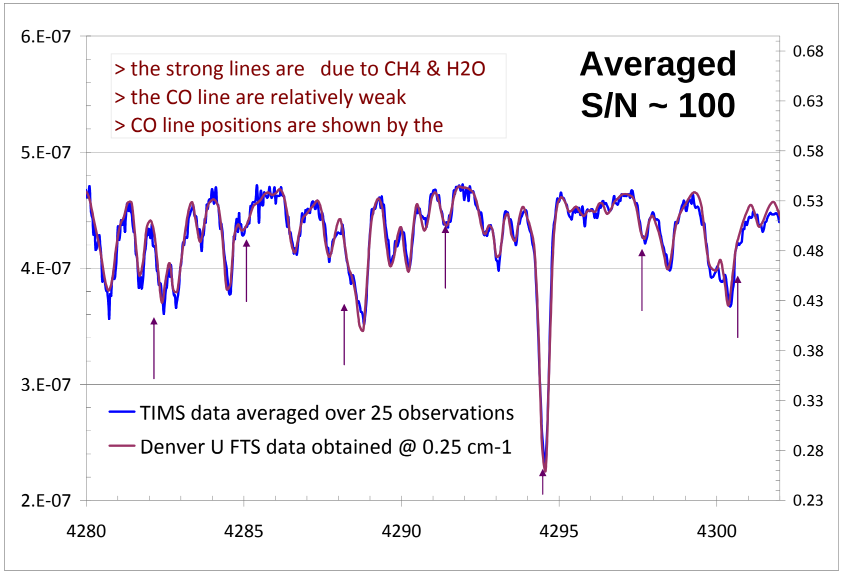


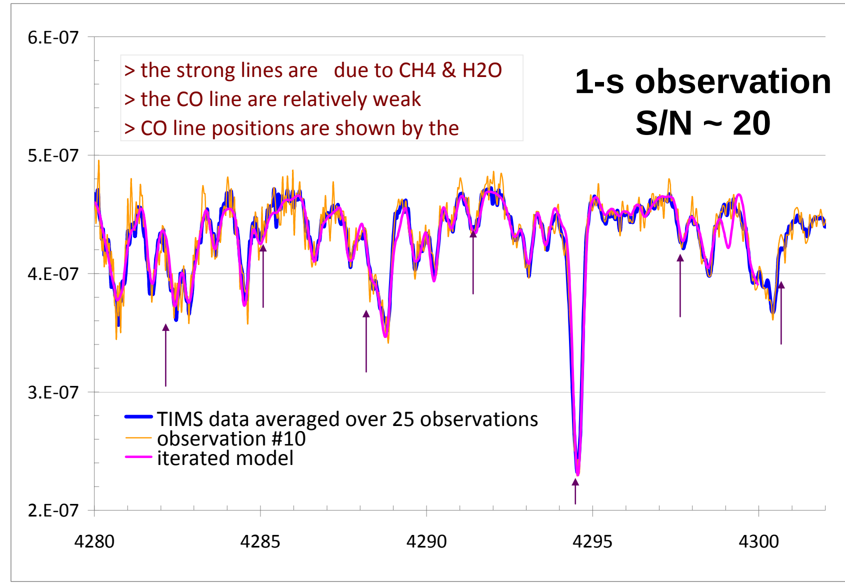


TIMS radiance; validation vs DU FTS data & comparison with models

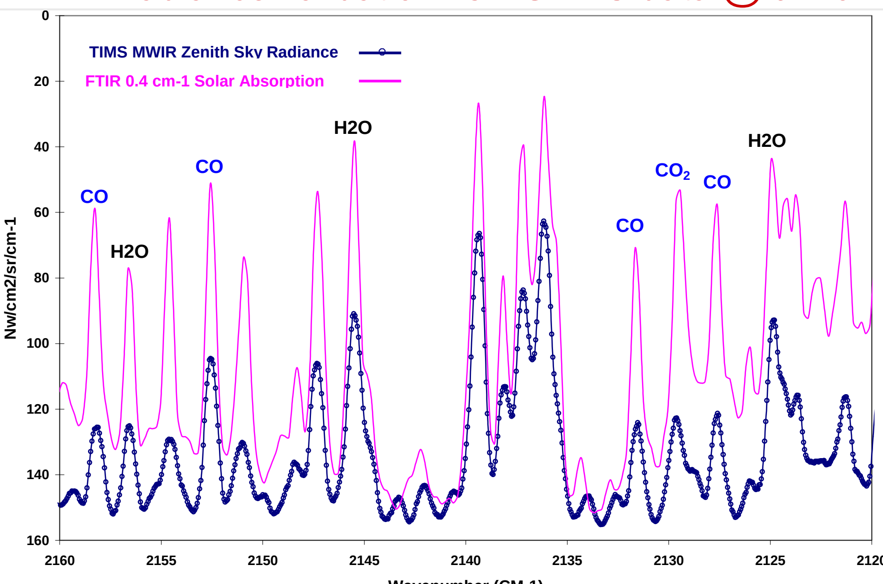
VSWIR radiance validation vs DU FTS data @ 0.25 cm^{-1}



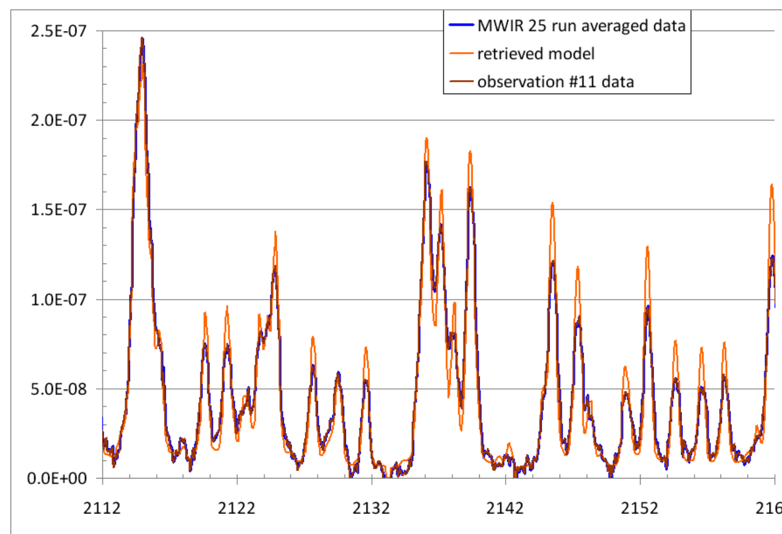
and comparison vs the retrieved model



MWIR radiance validation vs DU FTS data @ 0.4 cm^{-1}



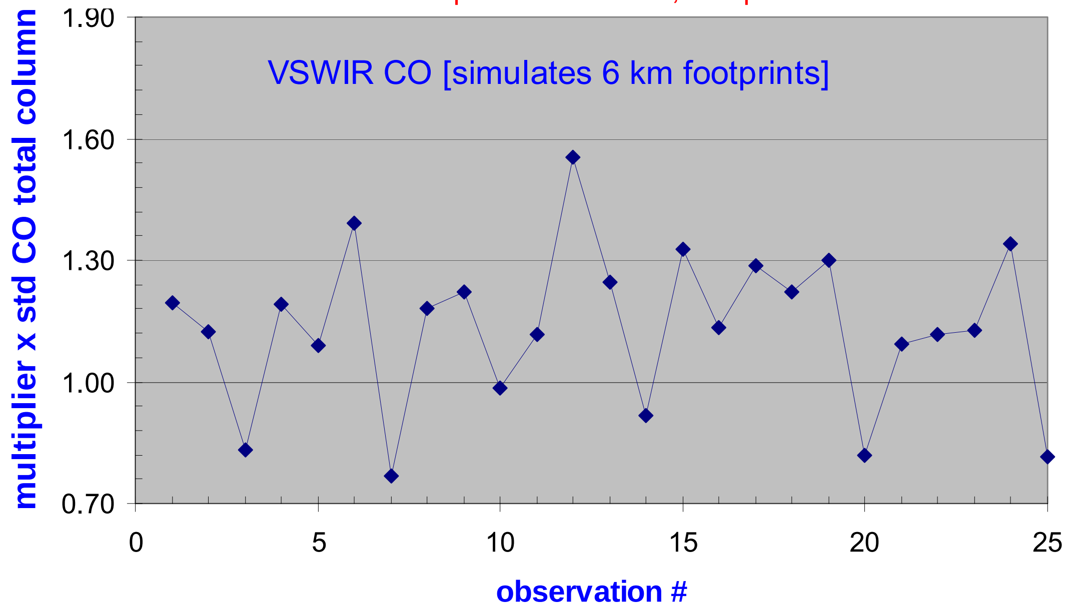
and comparison vs the retrieved model



Note S/N much larger for MWIR than VSWIR

TIMS VSWIR column retrieval & validation

shows 25 1-s observations, each with radance noise simulating retrieval on a
6 x 6 km TIMS GEO-CAPE minimum footprint, but with just 1/2 the CO path
results: mean multiplier = 1.14; multiplier STDV =0.20; and precision is 17.2 %
therefore, for ganged 30 km x 30 km footprints: mean multiplier = 1.14;
and multiplier STDV =0.05; and precision is 3.4 %



Validation of TIMS VSWIR column multipliers vs those retrieved from the DU FTS data obtained at 0.25 cm^{-1} spectral resolution

Parameter	DU vswir	average tims vswir	bias
Co	1.31	1.14 ± 0.05	1.15
H2O	0.73	0.62 ± 0.01	1.18
CH4	1.01	0.89 ± 0.003	1.14

VSWIR column retrievals expressed as multipliers of standard or modeled products

Multiplier x US standard for CO & CH4
Multiplier x ECMWF for H2O
US_std CO_col =1.88e+18 molecules/cm^2,
ECMWF_ H2O_col =3.72e+22 molecules/cm^2,

TIMS results for a 6 km x 6 km footprint

Species	multiplier	precision (%)
CO	1.14	8.6
CH4	0.89	0.93
H2O	0.61	3.72
Albedo	0.407†	0.23

results for a 12 km x 12 km footprint

CO	1.14	4.3
H2O	0.61	1.66

results for a 30 km x 30 km footprint

CO	1.14	1.72

some more CO column info/validation

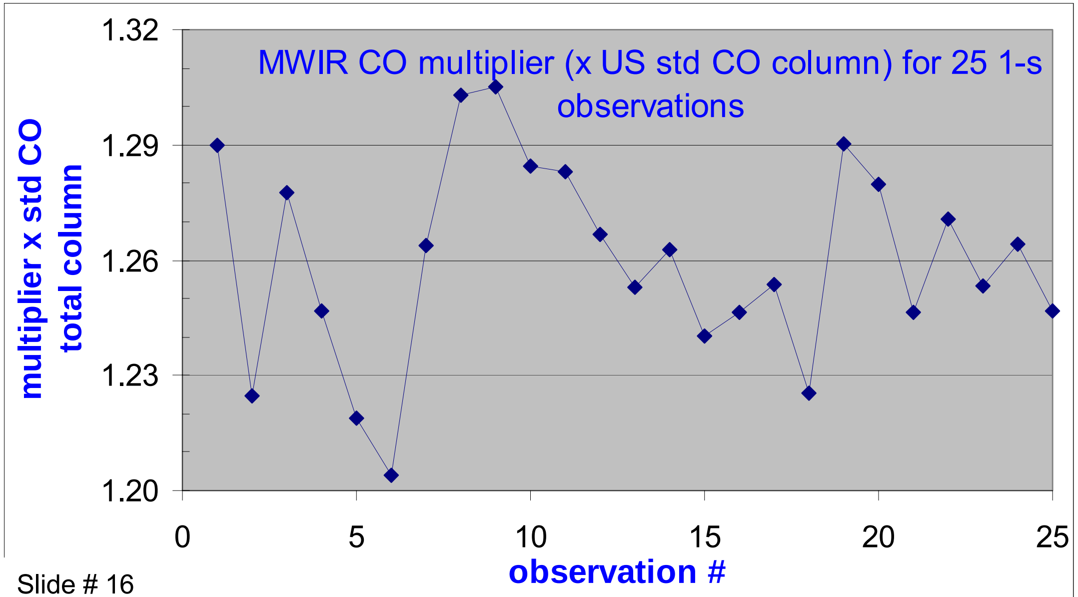
AIRS CO_col =1.81e+18, M=0.96
DU_MWIR_HIRES_col =1.85e+18, M=0.98
DU_VSWIR_LORES_col =2.37e+18, M=1.31
TIMS_VSWIR_col =2.05e+18, M=1.14

some H2O column info/validation

AIRS CO_col =2.50e+22, M=0.67
DU_MWIR_HIRES_col =2.35e+22, M=0.63
DU_VSWIR_LORES_col =2.71e+22, M=0.73
TIMS_VSWIR_col =2.27e+22, M=0.61

† note, albedo is the retrieval result, not a multiplier

TIMS MWIR column retrieval & validation



Species	multiplier	precision (%)
CO	1.26	2.36
H_2O	0.91	1.57

some more CO column info/validation

AIRS CO_col =1.81e+18, M=0.96
DU_MWIR_HIRES_col =1.85e+18, M=0.98
DU_VSWIR_LORES_col =2.37e+18, M=1.31
TIMS_VSWIR_col =2.05e+18, M=1.14
TIMS_MWIR_col =2.40e+18, M=1.26

some H_2O column info/validation

AIRS CO_col =2.50e+22, M=0.67
DU_MWIR_HIRES_col =2.35e+22, M=0.63
DU_VSWIR_LORES_col =2.71e+22, M=0.73
TIMS_VSWIR_col =2.27e+22, M=0.61
TIMS_MWIR_col =3.39e+22, M=0.91

Preliminary TIMS 2-layer CO retrieval

expressed in multipliers of the US std partial columns in the lower layer from 810 to 720 mb, and in the layer above 720 mb from

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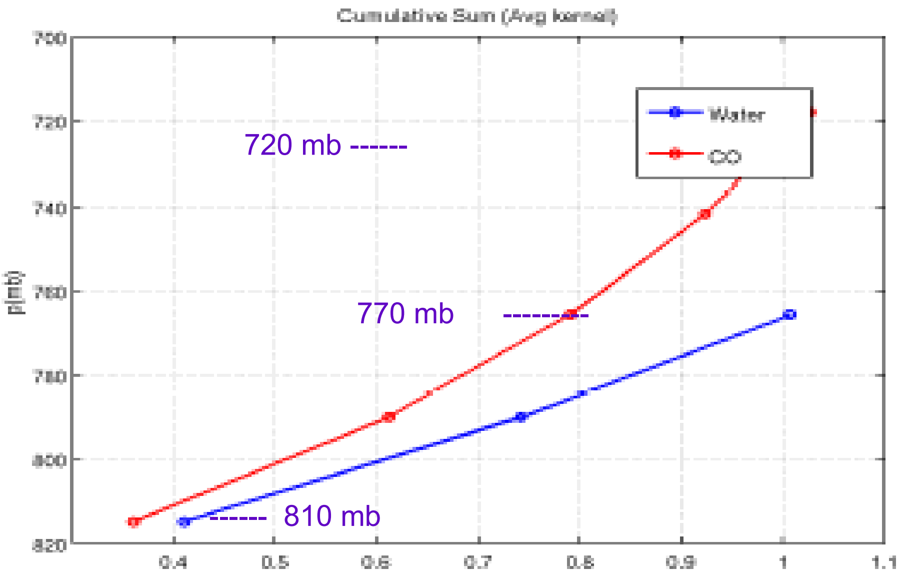


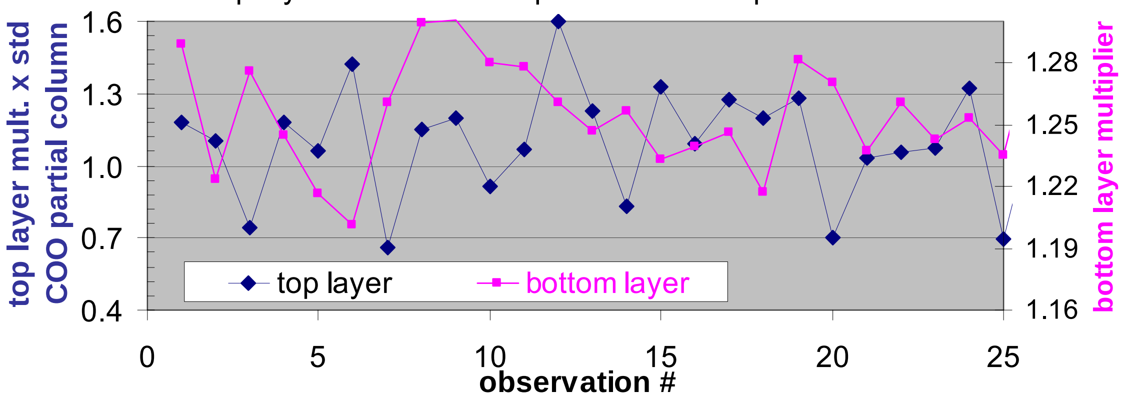
To the left, plotting cumulative dfs (sum on averaging kernel matrix diagonal elements from ground pressure level to altitude pressure level).

Note the uplooking TIMS MWIR is insensitive to the upper troposphere for both CO and H2O.

For CO dfs =1 at about 720 mb, and goes to < 1.4 as pressure goes to zero.

For our preliminary 2-layer retrieval we assign the MWIR multiplier x the US std to the partial column in the lower layer, and the multiplier in the upper is selected so that the total column multiplier is the same as retrieved from the VSWIR.

for the DU campaign 2-row 1-s observations
bottom layer: mean multiplier = 1.26 with precision 2.40 %
top layer: mean multiplier = 1.10 with precision 21.5 %

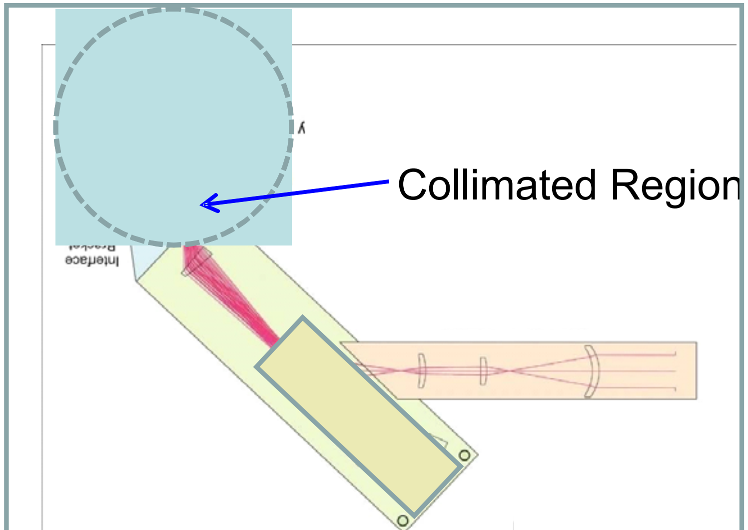


We expect to obtain at least 2-layer (TBD) retrieval in the GEO-CAPE case too. In the nadir perspective the noisier VSWIR will provide the information for the lower layer.

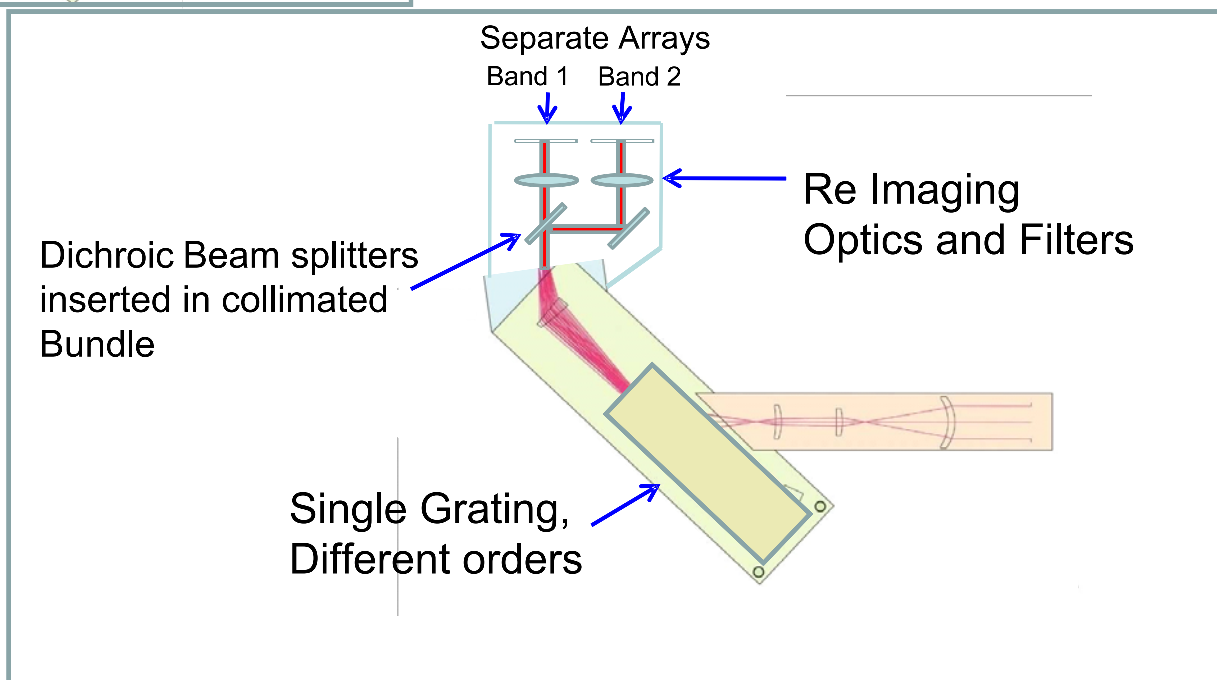
In the lower layer there will be sensitivity to:

- Gross CO pollution localized to the smallest 6 km x 6 km footprints.
- the order < 10 % of the background CO in larger ganged footprints, e.g., 30 km x 30 km.

Expanded Capability TIMS for GEO-CAPE



TIMS VSWIRDesign provides an accessible collimated bundle to facilitate beam-splitting to multiple channels



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**