22-24 September 09 GEO-CAPE Workshop

A GEO-CAPE instrument concept, operations and some performance estimates developed by the ESTO IIP project IIP-04-0081 Tropospheric Infrared Mapping Spectrometers (TIMS)

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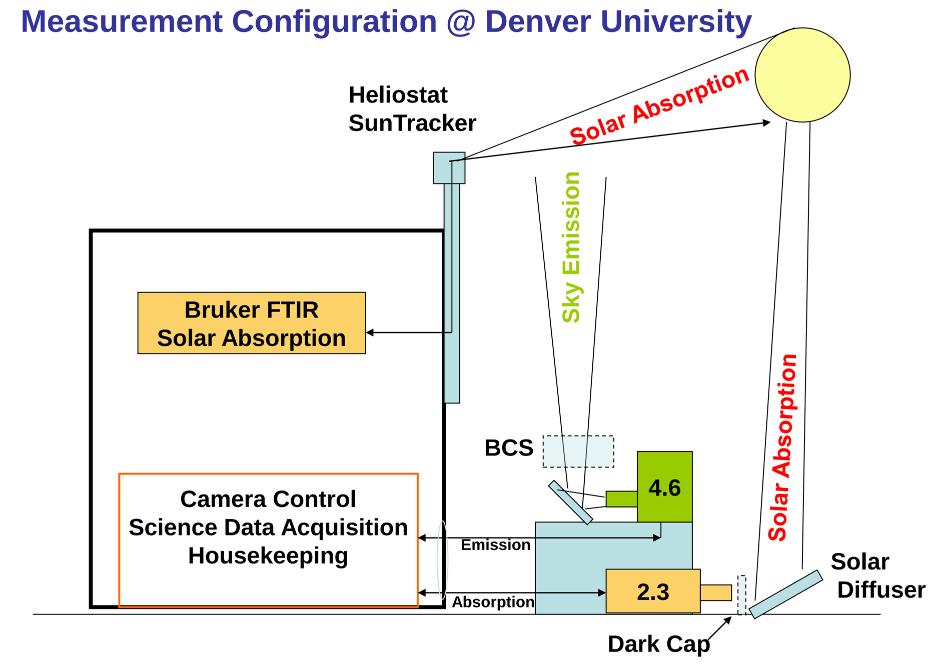
slide # 1

Summary: IIP TIMS completed Dec. 2008

- Developed mapping spectrometers @ 2.33 & 4.67 µm for vertical tropospheric CO retrieval
- Demonstrated
  - multi-layer vertical CO retrieval from measurements of atmospheric radiance that simulate GEO-CAPE operations that
  - satisfy the Decadal Survey areal coverage rate & footprint requirements,also demonstrated
  - H_2O retrieval with potential for unprecedented vertical resolution in the boundary layer (BL)
  - 1% precision for total column CH_4 retrieval
- Developed an instrument concept using TRL 6 or better supporting components to implement the GEO-CAPE operation
- Expanded the concept to include ozone bands @ 9.6, 3.3 & 3.6 µm and extrapolation of the performance data showed these provide tropospheric ozone capability:
- Expanded GEO-CAPE TIMS provides vertical information including
  - BL CO, tropospheric ozone and BL H_2O and
  - Total CH_4 column 1% precision and does this
  - With Decadal Survey Report specified
    Areal coverage rate and — footprint

slide # 2

Measurement Configuration @ Denver University



slide # 3

Set up at DU (1of 2)

University of Denver, May 2008
MWIR (4.69 µm) unit on the balcony


- MWIR zenith mirror directs sky atmospheric emission into the entrance aperture of the MWIR unit, shaded from direct sunlight.
- In this picture the CO cell is positioned in front of objective lens
  - The CO cell is removed for acquisition of sky data
  - Ratio of with & without cell data monitor spectral cal
- Remote control mirror alternately selects between sky scene and temperature monitored black calibrator can

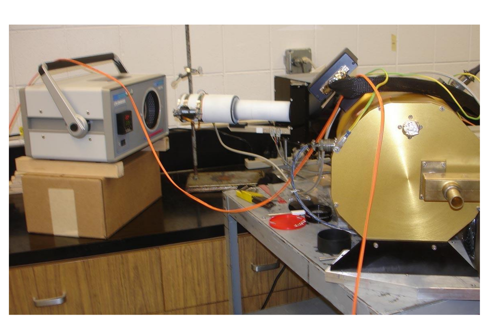
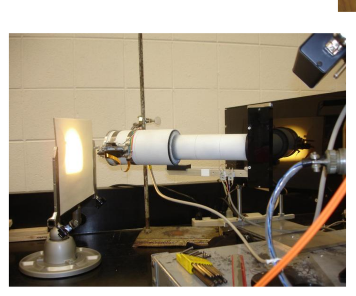
MWIR dewar assembly mounted on cart. (White cloth on top is the sun shade.) Control and power cables pass through wall into lab. Omega blackbody calibration source is on separate cart at right, under white sheet.

slide # 4

Set up at DU (2of2)

University of Denver, May 2008

VSWIR (2.33 µm) unit inside air-conditioned lab

Above, VSWIR channel views into Omega blackbody calibration source.

At left, heliostat directed sunlight is viewed on a white diffuser. Atmospheric absorption spectrum in sunlight

The CO cell was mounted in front of the objective lens on selected data sets. (see discussion above re the MWIR operations)

slide # 5

May 2008 Measurement Campaign

Overall Approach

- Acquire TIMS data for several consecutive days in order to
  - debug the approach
  - obtain data for diverse conditions
  - search for day to day CO variation
- Conduct TIMS radiometric calibration at the beginning and end of each day's observations to ensure accurate radiance products
- For each TIMS atmospheric and calibration operation include observations through a cell containing a known pressure of CO to aid in spectral characterization and retrieval
- Acquire Bruker solar absorption data at both TIMS wavelengths, alternating between Spectral Survey Mode (SSM) - running FTS in 3 selected resolutions bracketing the TIMS resolution- and Retrieval Mode (RM)-running the FTS at resolution best suited for retrieval

May 29	Test runs for VSWIR, &MWIR Calibration and Atmospheric Observations

May 30	Calibration 1	Science Frame 1	Science Frame 2	Science Frame 3	Calibration 2
TIMS FTS	8 Am -9:45 am Black Body Cal	9:45- 10:30am Sun Scatter/Sky SSM-RM-SSM	11:45-12:15 pm Sun Scatter/Sky SSM-RM-SSM	2 pm -2:30 pm Sun Scatter/Sky SSM-RM-SSM	3 pm to 3:30 pm Black Body Cal

May 31	Calibration	Science Frame 4	Science Frame 5
TIMS FTS	9 Am -9:35 AM	10:00- 11:30 Sun Scatter/Sky SSM-RM-SSM	12:30 pm-1 pm VSWIR View of Sunlit Mountains SSM-RM-SSM

slide # 6

Operational Calibration Approach

VSWIR

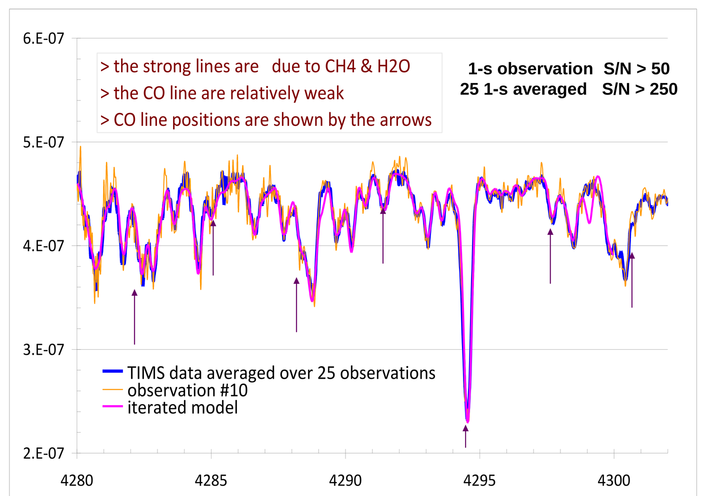
- As noted, The VSWIR Instrument background is dominated by the broadband emission from the ambient temperature spectrometer cavity ("downstream" of the grating), and changes in this background can occur during a calibration sequence due to temperature variations
- This background is tracked by periodically closing a shutter over the objective lens, and in addition spectrometer temperatures are continuously recorded during each measurement
- Operating the VSWIR outside in sunlight causes significant background increase, increasing noise and radiometric drift, so it was always operated inside in a controlled environment
- In this environment, during calibration and science data acquisition, spectrometer temperatures were typically found to vary by < 0.06 K during a given measurement, resulting in an insignificant background change

MWIR

- For the MWIR module, the grating spectrometer operates at 77K inside a dewar; its background therefore is that due to narrowband emission from the external objective lens and is much less susceptible to ambient temperature changes
- The MWIR was routinely operated in sunlight, and was calibrated in position outside

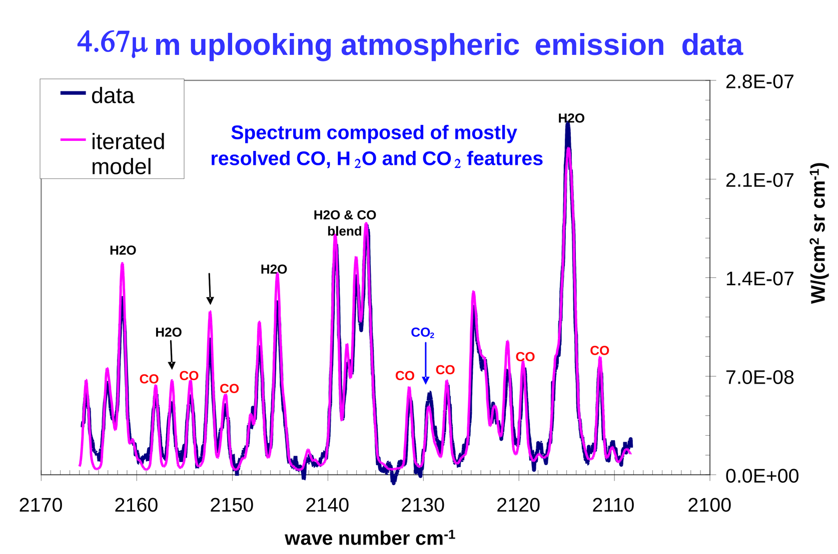
slide # 7

Comparison of the retrieved model radiance with the VSWIR data



slide # 8

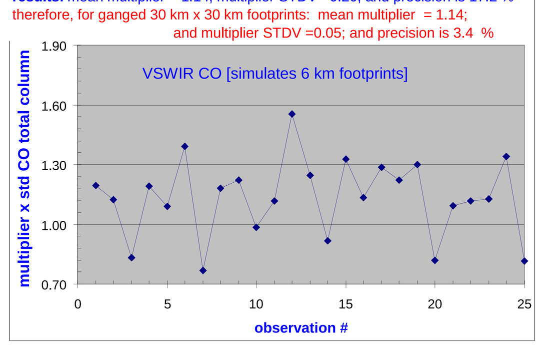
Comparison of the retrieved model radiance with the MWIR data



slide # 9

TIMS VSWIR column retrieval & validation

shows 25 1-s observations, each with radiance 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 %



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 GEO-CAPE footprint
[attend our presentation IN24A-03 this afternoon]

Species	multiplier	precision (%)
CO	1.14	8.60
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

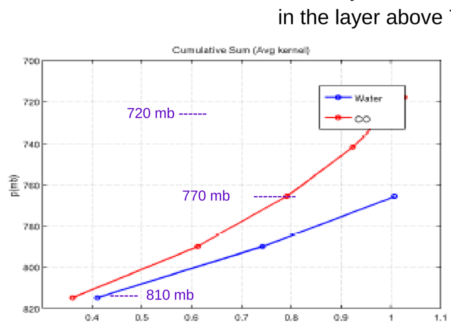
CO	1.14	1.72

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

slide # 10

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

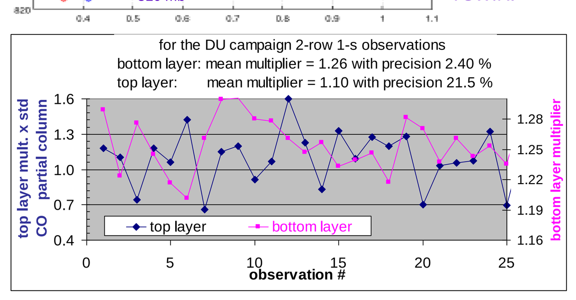


To the left, plotting cumulative dfs (sum on averaging kernel matrix diagonal elements from ground pressure level to altitude pressure level).

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.



slide # 11

Independent vertical pieces of information, otherwise referred to as Degrees of Freedom for Signal (DFS) within the retrieval community (1 of 2)

- The DFS is a measure of the number of layers of the atmosphere in which a retrieval of the species partial column that is independent of the a-priori can be implemented
- By independent is meant, if the DFS for the layer = 1, then the retrieval is entirely the result of the measured radiance data, independent of any a-priori amount. The latter is a best estimate based on the existing measurement data base and modeling (e.g., climatology).
- The vertical information content is a function of the
  - atmospheric model
  - instrument characteristics such as the spectral range, spectral resolution, spectral sample width and noise per spectral sample
  - Uncertainty and or expected variability in the a-priori best expectation for the retrieval
- These ingredients are used to calculate a so-called **averaging matrix A** that contains the vertical information.
- The a-priori model atmosphere is parceled into a relatively large number = I_{MAX} (97 in the examples we'll show below) of narrow Atmospheric Modeling Layers (AML)
- The uncertainty in the a-priori information is expressed in terms of a **solution covariance matrix Ca** with I_{MAX} rows & columns
  - in the simplest formulation Ca is simply diagonal with elements = square of the uncertainty for the amount in the corresponding AML
- The averaging matrix A is square with I_{MAX} rows & columns
- The total DFS is the sum over all the diagonal elements of A, ie., DFS = ΣA_{ii} over i=1 to I_{MAX}.
  - As above, DFS is the total # of aggregate [ie., larger] layers in the atmosphere in which the retrieval CO partial columns are independent of the a-priori best expectation for the retrieval

slide # 12

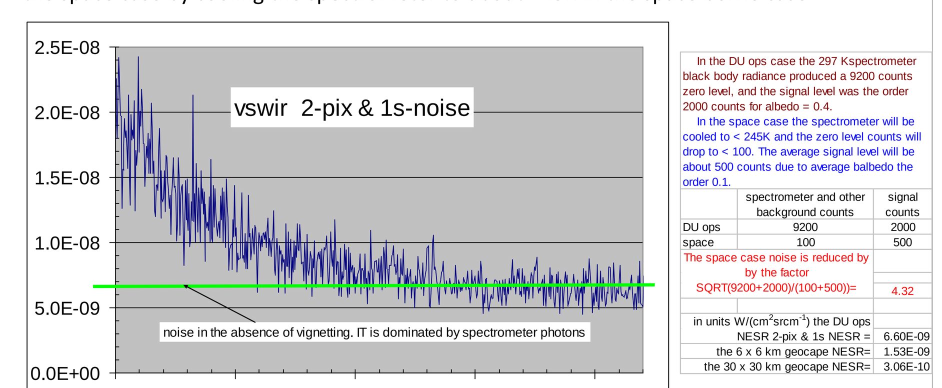
Independent vertical pieces of information, otherwise referred to as Degrees of Freedom for Signal (DFS) within the retrieval community (2 of 2)

- Below we'll show calculations of $DFS_Z = \Sigma A_{ii}$ from the ground, ie., the bottom of lowest AML designated by i=1, up to the top (at altitude z) of the AML designated by i=Z
  - As altitude increases, every time DFS_Z increases by unity , another independent aggregate layer, consisting of a contiguous group of AML, is identified.
  - As would be expected a tight constraint [as specified for the solution covariance matrix Ca] results in less independence of the retrieval.
    - for example if for all AML the diagonal elements of the solution covariance matrix are set to Ca_{ii} = 0.1², this constitutes a tight constraint that in effect means that the knowledge of the quantities to be retrieved is only uncertain by 10%, therefore in first order the information the retrieved quantities are expected to be at most about 10% different than the a-priori. So the measurement needs to be relatively powerful to provide added vertical information
      - However, that same measurement would provide relatively more vertical information if the a-priori expectation for the retrieval quantities is not as well known, ie., Ca_{ii} > 0.1²
    - In any case, if the retrieval is applied for the aggregate layers with a ΔDFS_Z value across them = 1, then that retrieval is independent of the value of the a-priori and is as precise, or more so, than SQRT(Ca_{ii})
      - However, there is 2nd order dependence on the profile shapes through the independent layers so that in practice first the retrieval for column is executed to retrieve partial column for all the independent layers then the profile is adjusted to be continuous at the layer boundaries while maintaining the retrieved column values then the process is repeated to convergence

slide # 13

VSWIR 1-s noise used for the GEO-CAPE DFS_Z calculation

- NESR per sample is calculated from the standard deviation of the radiance value at each of the samples for 25 1-s data frames
- NESR for each spectral sample is plotted vs ν the wave# along the horizontal axis.
- NESR is dominantly due spectrometer noise therefore should be constant vs ν
- Increasing NESR from 4290 to 4280 cm-1 is due to vignetting by the warm spectrometer lens that will not be present in the space application
- Therefore the noise value = 6.6E-9 W/(cm² sr cm⁻¹) for the DU diffuser viewing case
- As explained in the worksheet to the lower right this is reduced by a further factor of 4.3 for the space case by cooling the spectrometer to about 245K in the space borne case



In the DU ops case the 297 K spectrometer black body radiance produced a 5000 counts zero level, and the signal level was the order 2000 counts for albedo = 0.4
In the space case the spectrometer will be cooled to ~ 245K and the zero level counts will drop to ~ 100. The average signal level will be about 500 counts due to average radiance for order 0.1

	spectrometer and other background counts	signal counts
DU ops	5000	2000
space	100	500

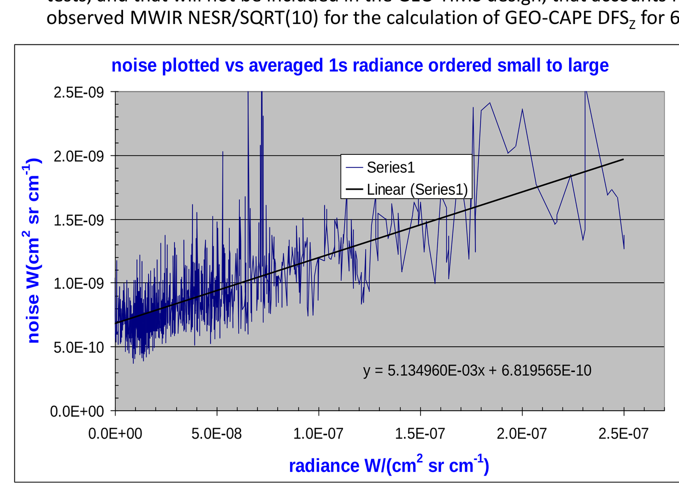
The space case noise is reduced by the factor
SQRT(5000+2000)/(100+500) = 4.32

In units W/(cm² sr cm⁻¹) the DU ops NESR 2-pix & 1s NESR = 6.60E-09
the 6 x 6 km geocape NESR = 1.53E-09
the 30 x 30 km geocape NESR = 3.06E-10

slide # 14

MWIR 1-s 2-pix noise used for the DFS_Z calculations

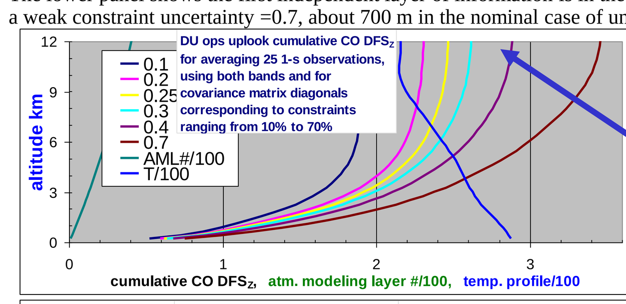
- DU operations observed NESR is plotted vs observed radiance
- An analytic linear fit of the NESR vs the ordered radiance is shown below
- For a nadir radiance as seen from GEO the calculated NESR is the value from the linear fit divided by SQRT(10) as explained in next bullet statement
  - The TIMS utilized at DU has a 10% transmission neutral density filter in it for use in hot black body tests, and that will not be included in the GEO TIMS design, that accounts for the use of the DU observed MWIR NESR/SQRT(10) for the calculation of GEO-CAPE DFS_Z for 6x6 km footprints and reduced by another factor x 5 for 30x30 km footprints

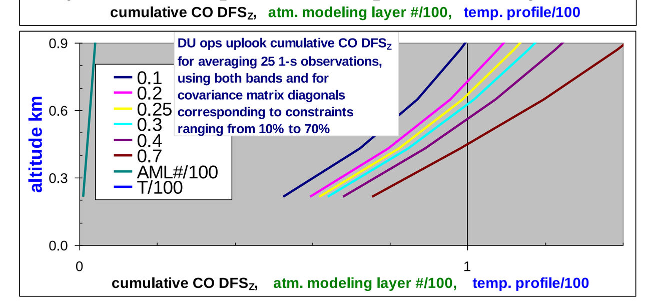


slide # 15

DFS_Z for the TIMS DU up looking operations for the case of 25 averaged 1-s observations

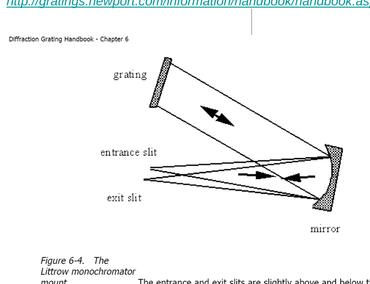
- The combined VSWIR and MWIR data sets are used for this calculation
- The upper panel shows there are at least 2 layers of independent information, even for a strong constraint, and more than 3 for a weak constraint
- The lower panel shows the first independent layer of information is in the first 250 m above the ground for a weak constraint uncertainty =0.7, about 700 m in the nominal case of uncertainty = 0.25, and 900m for the strong constraint uncertainty 0.10





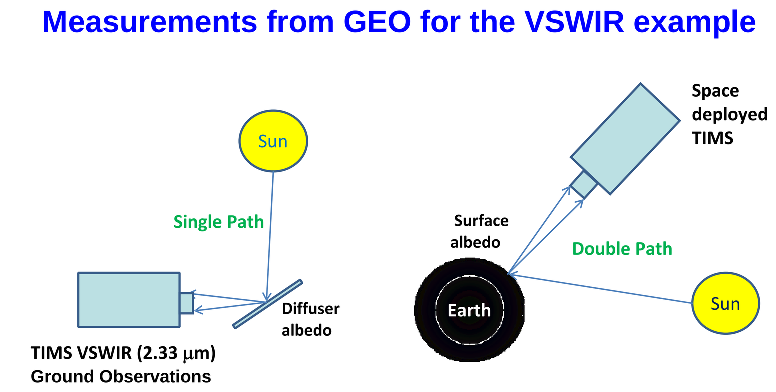
Note that we are working a 3 DFS approach that is independent of a-priori for CO retrieval from our data set

TIMS spectrometer is reflective Littrow as per Figure 6-4 at the Newport grating website (shown below)
http://gratings.newport.com/information/handbook/handbook.asp



slide # 16

Cartoon shows relation Of DU measurements to Measurements from GEO for the VSWIR example

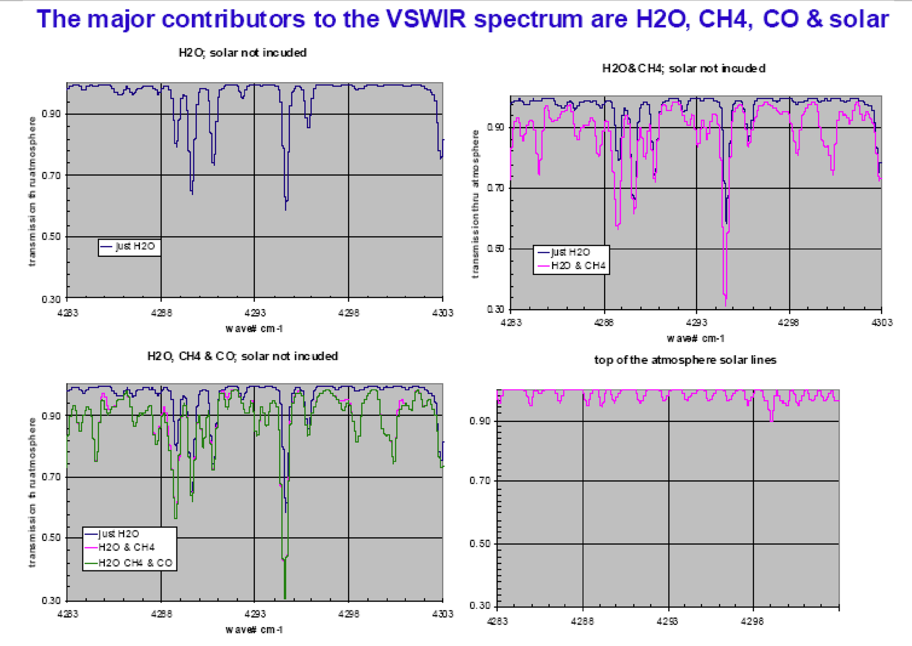


In the VSWIR case, the cartoon shows the similarity of observing the sunlight reflected from a diffuser at the earths surface with the case of observing the sunlight reflected from the earths surface from space. However, there are differences

- The sunlight makes a single pass through the atmosphere before observation by TIMS at the ground , and a double pass before observation by TIMS in space, therefore the CO absorption signal is twice as strong in the space case
- The reflectance of the earth is on the average about 4 times less than that of the diffuser as deployed at DU, therefore the light level is about 4 times less in the case of a 1s integration time
- As discussed in the text, the noise equivalent radiance NESR in the space case is decreased by more than a factor of 4 by moderate cooling of the spectrometer from room temperature on the ground to ≤ 245K in space

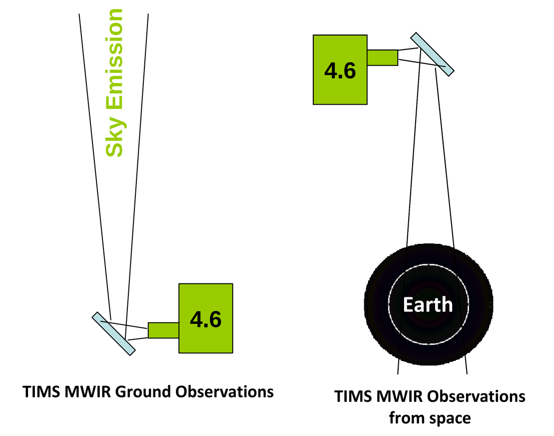
slide # 17

The major contributors to the VSWIR spectrum are H2O, CH4, CO & solar



Illustrates contributions to the VSWIR spectrum from CO, H_2O, CH_4 and the solar contribution.

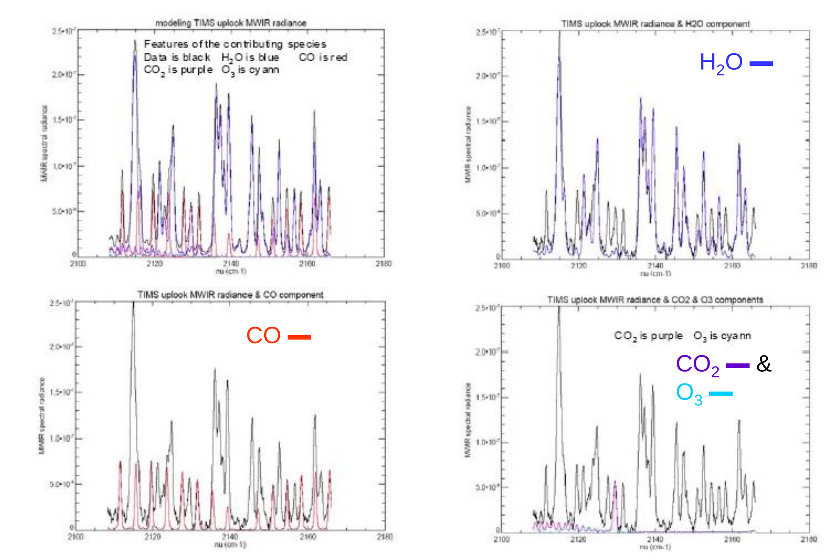
slide # 18



In the MWIR case, the cartoon shows the similarity of observing sky emission from the earths surface with the case of observing earth emission from space. The difference would be that, in the space based case a neutral density filter that reduces signal by a factor of 10 that is installed in the as built TIMS MWIR unit that was utilized in the operations at DU , would not be there. Therefore the TIMS MWIR NESR would be improved by a factor of SQRT(10) relative to the as built TIMS

slide # 19

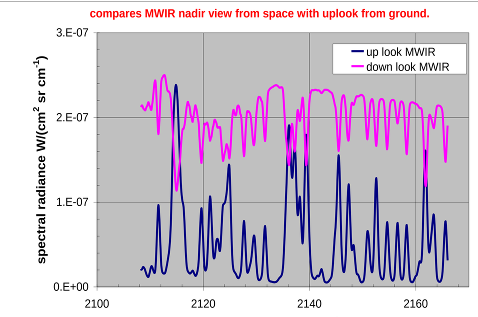
MWIR uplooking, major contributing species are H_2O, CO, CO_2 & O_3



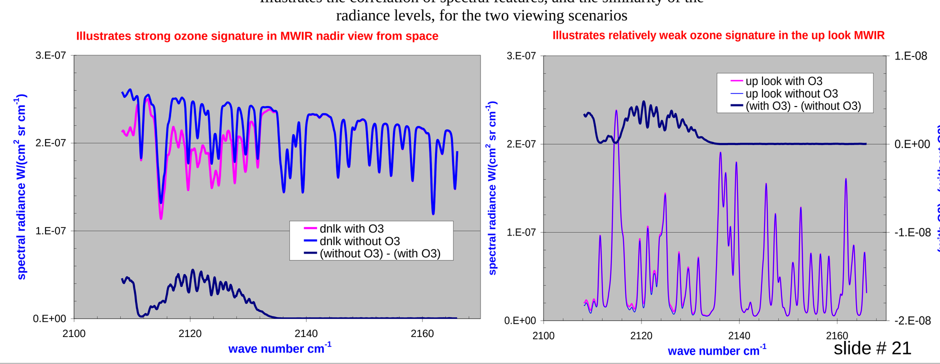
The DU TIMS MWIR uplook data [— black trace] and model components of H_2O —, CO —, CO_2 — and O_3 — are shown here to illustrate contributions of the major species

slide # 20

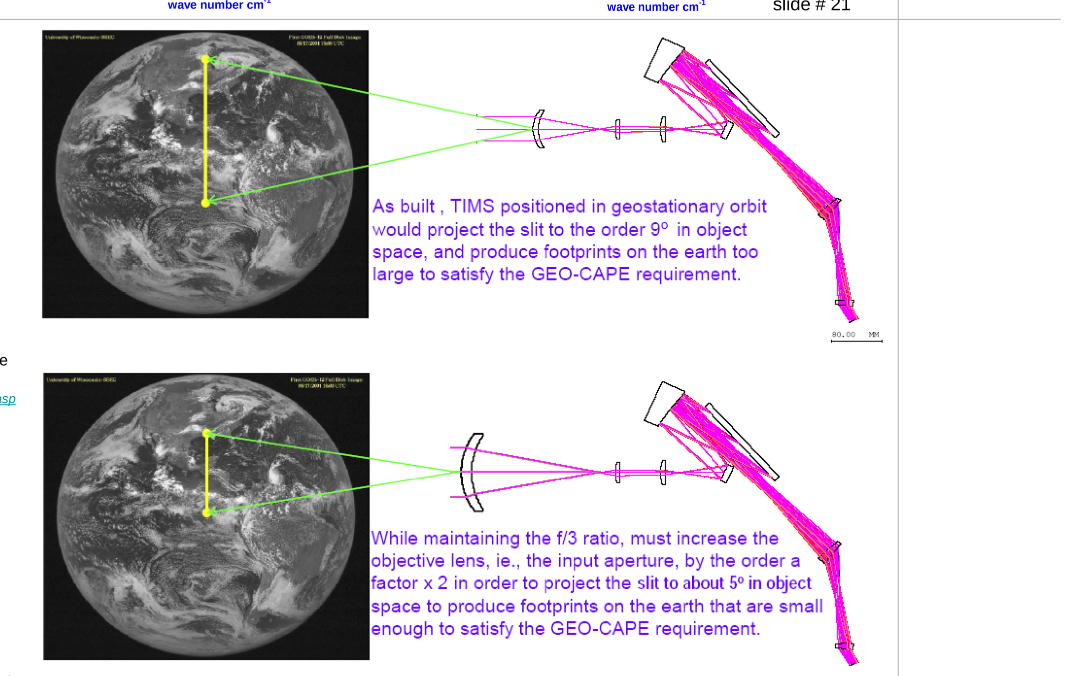
compares MWIR nadir view from space with uplook from ground.



Illustrates the correlation of spectral features, and the similarity of the radiance levels, for the two viewing scenarios



slide # 21



As built , TIMS positioned in geostationary orbit would project the slit to the order 9° in object space, and produce footprints on the earth too large to satisfy the GEO-CAPE requirement.

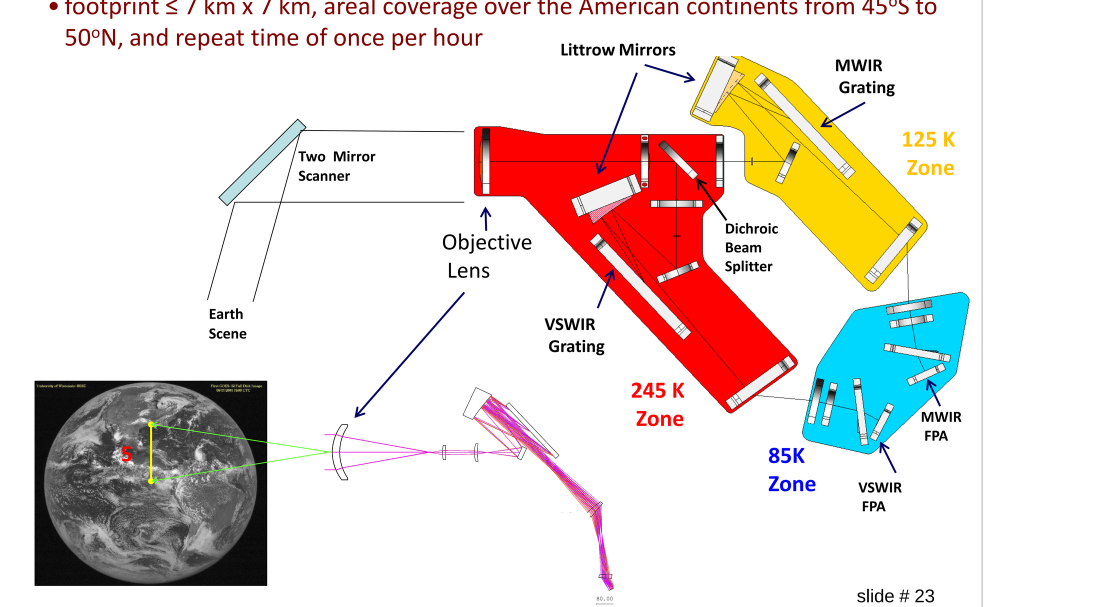
While maintaining the f/3 ratio, must increase the objective lens, ie., the input aperture, by the order a factor x 2 in order to project the slit to about 5° in object space to produce footprints on the earth that are small enough to satisfy the GEO-CAPE requirement.

Illustrates that increasing the input aperture (in this case the input lens of the f/3 objective) reduces the footprint on the earth to the GEO-CAPE requirement.

slide # 22

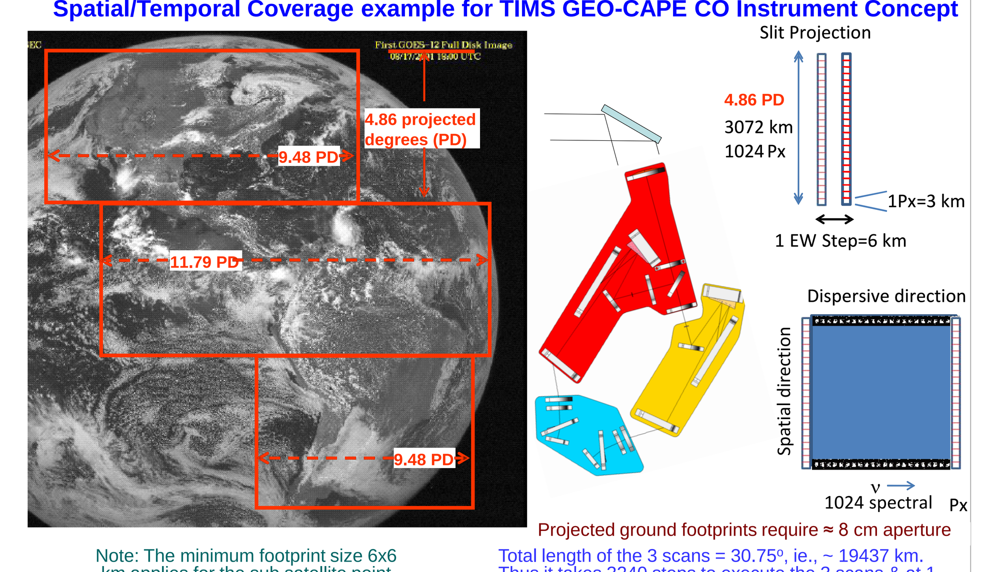
GEO-CAPE instrument concept; GEO-cape CO measurement requirements are:

- achieve the order 2 to 3 layer vertical profile capability within the troposphere
- footprint ≤ 7 km x 7 km, areal coverage over the American continents from 45°S to 50°N, and repeat time of once per hour



slide # 23

Spatial/Temporal Coverage example for TIMS GEO-CAPE CO Instrument Concept



Projected ground footprints require ≈ 8 cm aperture

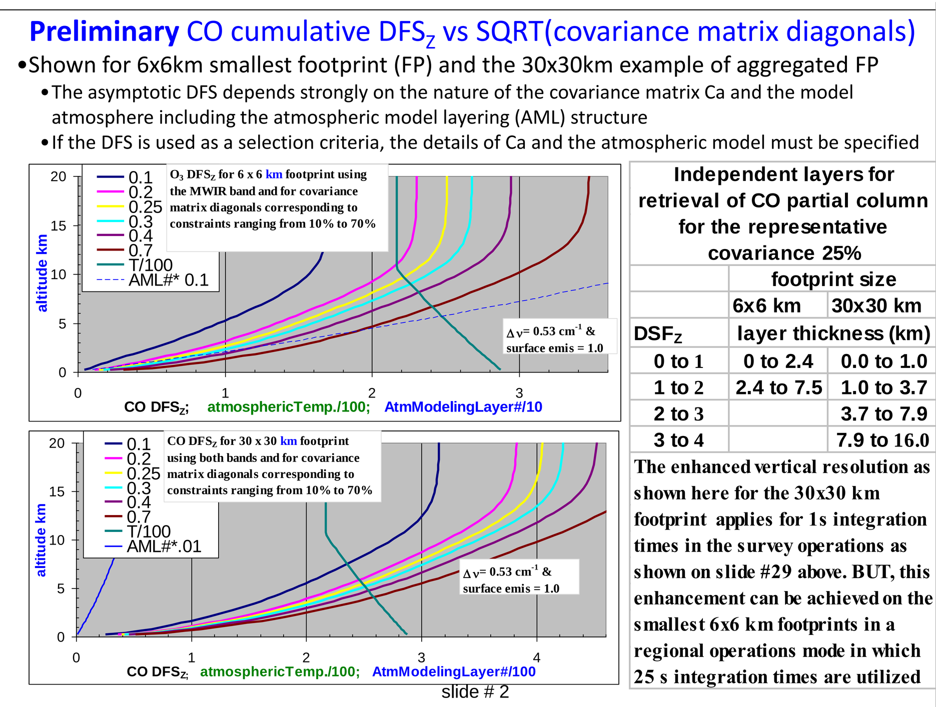
Note: The minimum footprint size 6x6 km applies for the sub satellite point

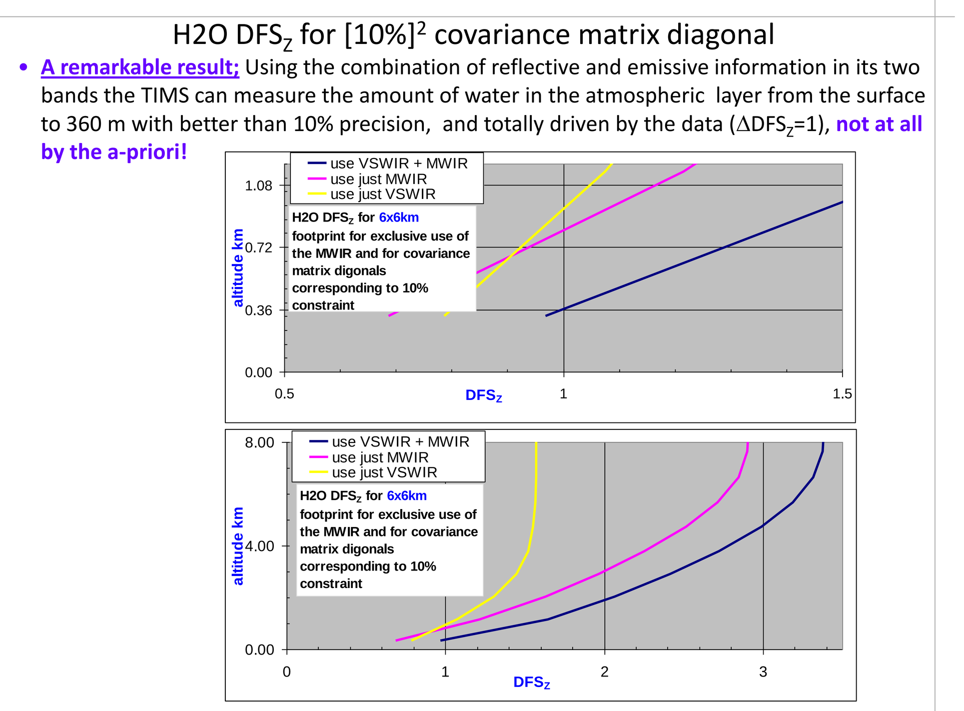
Total length of the 3 scans = 30.75°, ie., ~ 19437 km. Thus it takes 3240 steps to execute the 3 scans & at 1 step/sec it takes about one hour for complete coverage

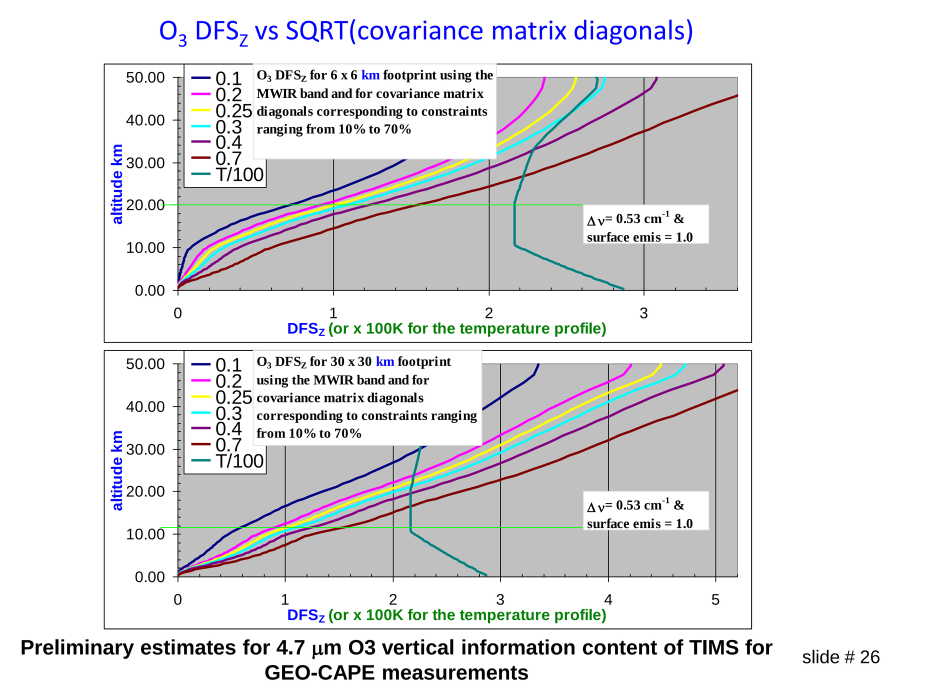
3 E-W Scan Blocks Covers 50N to 45S of North And South America in 1 hour, including calibration , as required by the GEO-CAPE

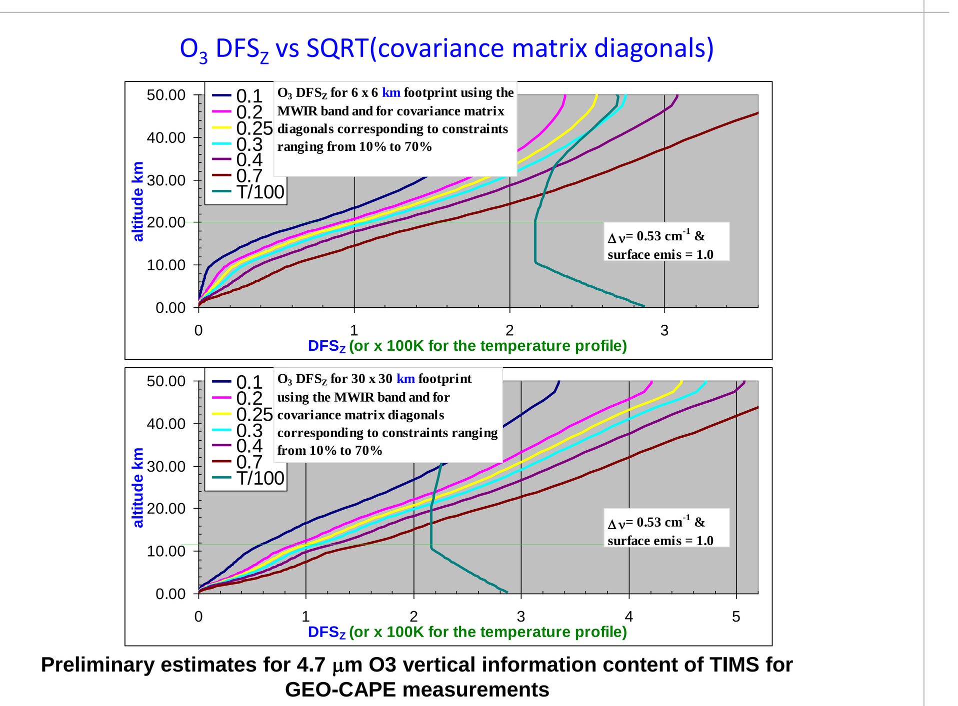
Slide # 24

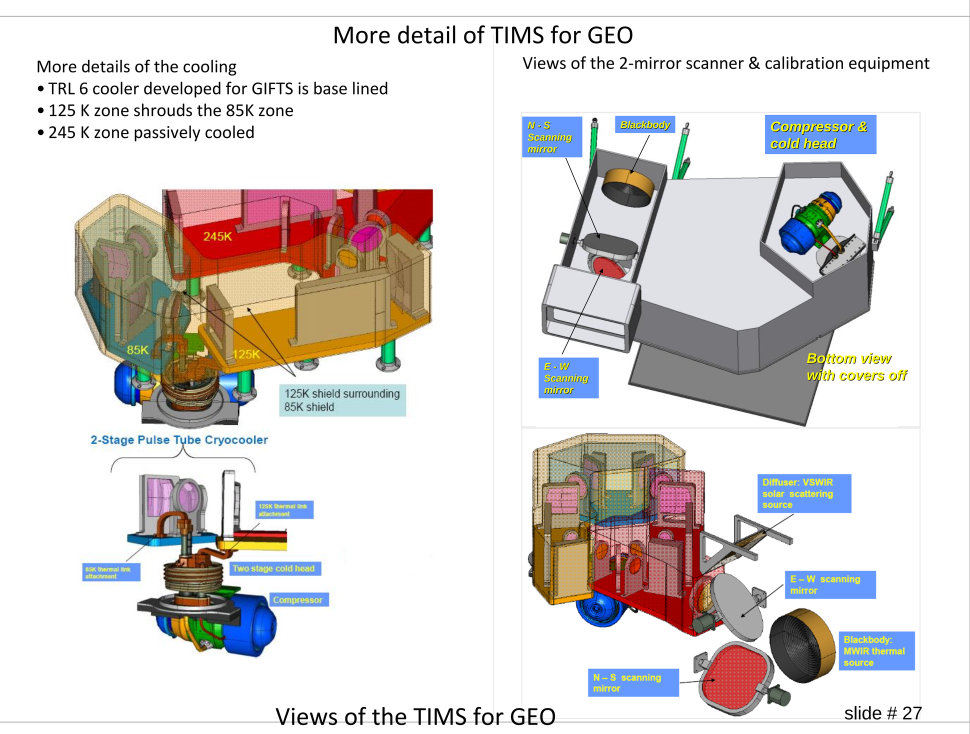
Slides ordered from top to bottom

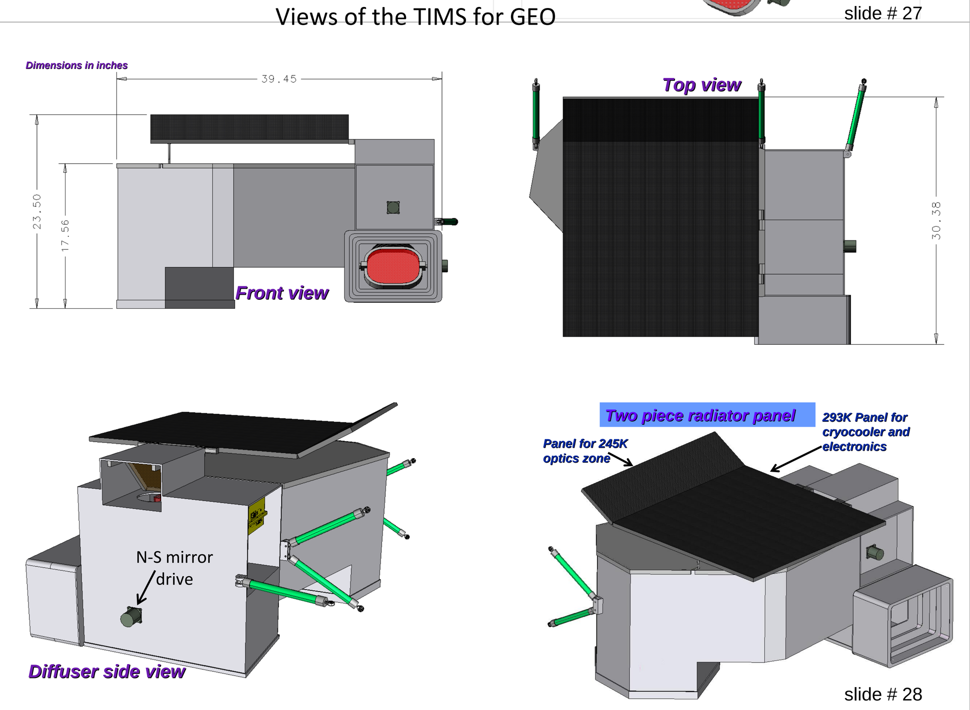






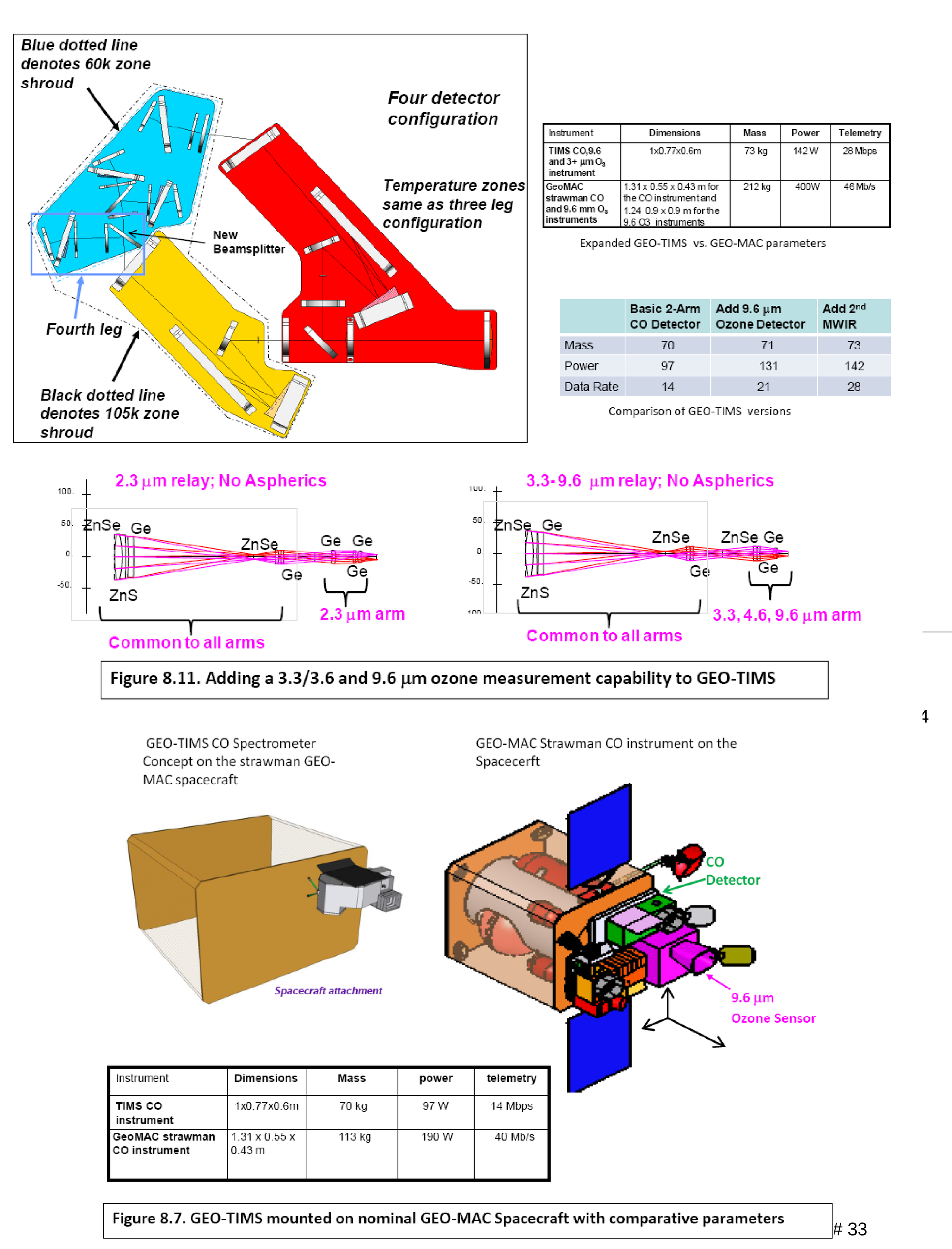


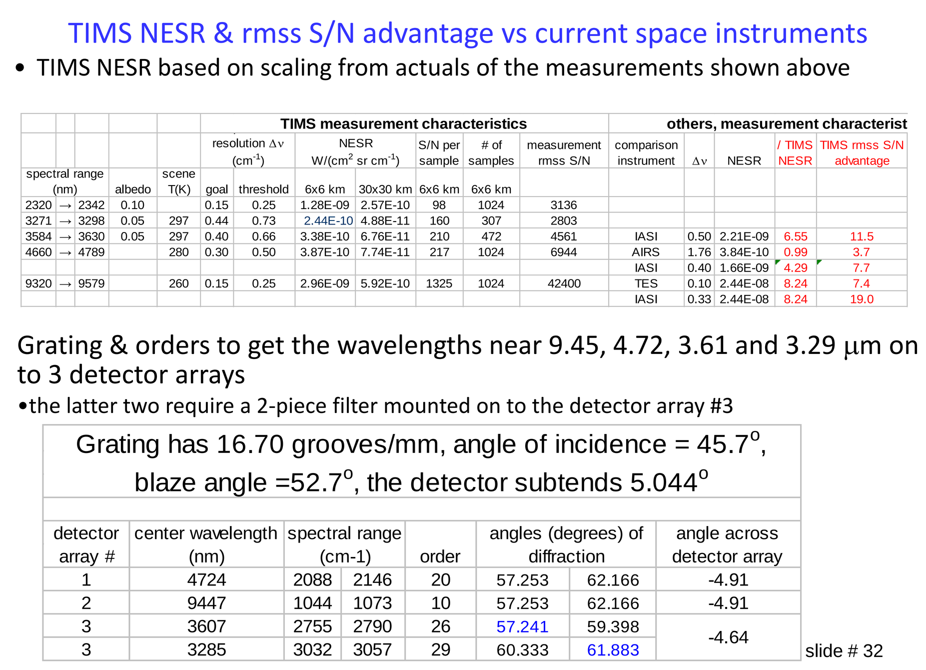


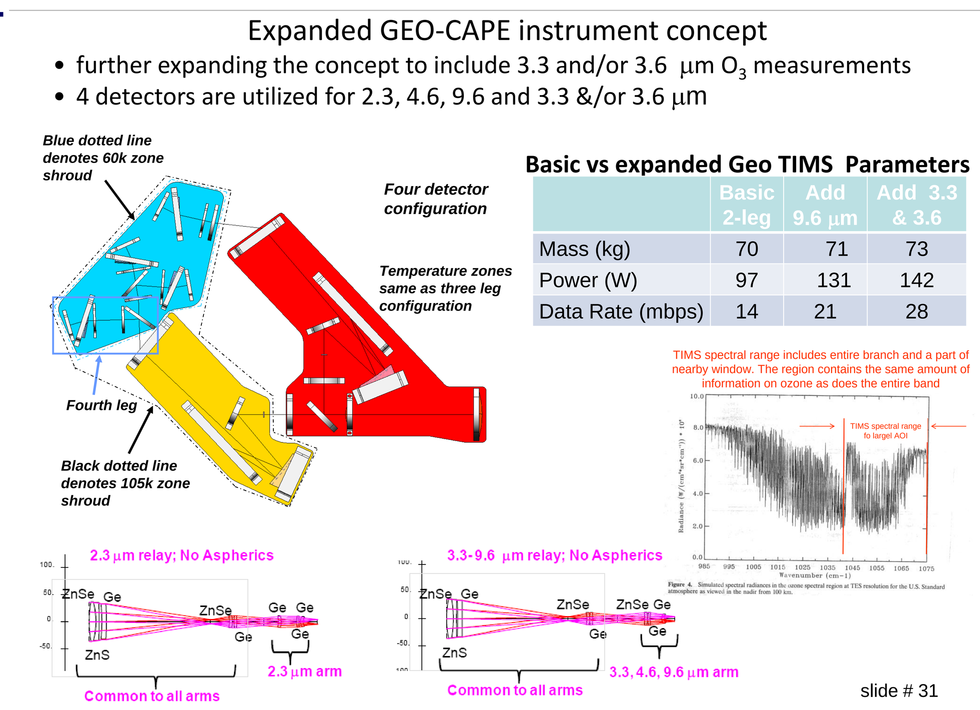


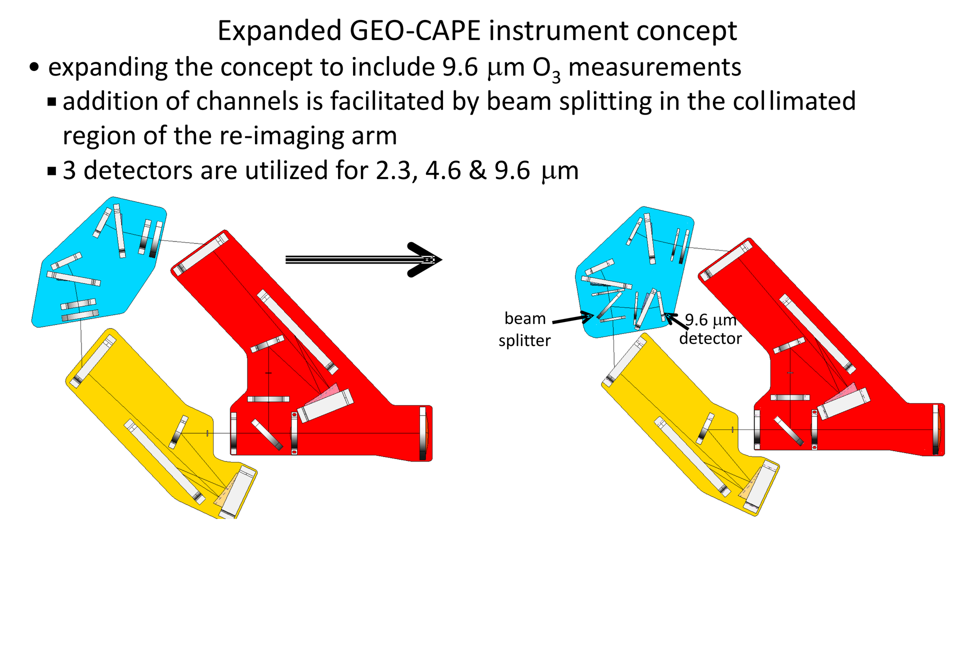
Slides ordered from top to bottom

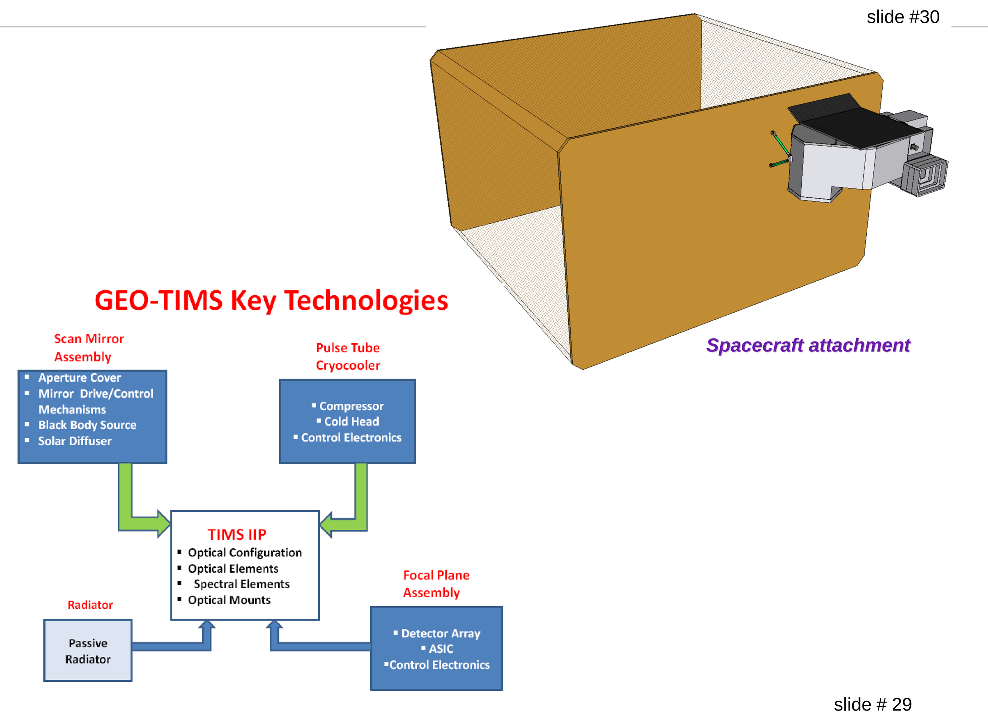
Slides ordered from bottom to top











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Conclusions

- We have successfully completed our objective to demonstrate high quality CO retrieval from the TIMS measurements of atmospheric spectra
  - We have demonstrated that VSWIR CO column retrieval precision scales to better than the requirement of 10% for the minimum GEO-CAPE footprint
  - Our CO retrievals are consistent with validation data
  - We have demonstrated unprecedented two-layer CO retrieval
    - Only recently has the MOPITT begun to achieve this capability
  - We have demonstrated high precision for retrieval of ancillary, but important, CH_4 (<1%), H_2O (<4%) and albedo (<0.3%)
- We have shown how these results scale to the GEO-CAPE scenario
  - The GEO deployed TIMS will be able to meet all the GEO-CAPE CO measurement requirements for foot print size, areal coverage rate, and vertical resolution
- We have presented an instrument concept for the GEO-CAPE application
- We have shown how the instrument can be upgraded with very little extra effort to also make measurements in the ozone regions 9.45, 3.61 and 3.29 µm
- We have shown that these measurements should provide vertical information on ozone in the troposphere that is enhanced compared to previous measurements (e.g., TES & IASI) due to the
  1. Use of the additional solar reflective spectral regions
  2. The GEO TIMS NESR and rmss signal to noise is enhanced relative to the TES & IASI