The EOS AURA Tropospheric Emission Spectrometer (TES)

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The TES Science Team (* = formal co-I)

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NAME	INSTITUTION	ROLE
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Linda R. Brown	JPL	Spectroscopy
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Annmarie Eldering	JPL	Clouds & Aerosols
Brendan M. Fisher	JPL	L1A Algorithms, Calibration
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Daniel J. Jacob*	Harvard University	Tropospheric Chem. Modeling
Qinbin Li	JPL	Tropospheric Chem. Modeling
Jennifer A. Logan*	Harvard University	Tropospheric Climatology
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Frank J. Murcray*	University of Denver	Correlative Measurements, Calibration
Gregory B. Osterman	JPL	Operational Support Products
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Curtis P. Rinsland*	NASA Langley RC	Spectroscopy, Validation
Clive D. Rodgers*	Oxford University	L2 Algorithms, Validation
Stanley P. Sander*	JPL	Tropospheric Chemistry, Validation
Mark Shepherd	AER, Inc.	L2 Algorithms
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Fredric W. Taylor*	Oxford University	Strat-Trop Exchange, Non-LTE
Helen M. Worden*	JPL	Algorithm Team Leader, Calibration
John R. Worden	JPL	L2 Algorithms

The TES Experiment

Global measurements of tropospheric ozone and its precursors from TES combined with *in-situ* data and model predictions will address the following key questions:

How is the increasing ozone abundance in the troposphere affecting

- ***air quality on a global scale?***
- ***oxidizing reactions that "cleanse" the atmosphere?***
- ***climate change?***

TES Standard Products

N = Nadir, L = Limb Viewing

Product Name	Product Source		Required Sensitivity*
Level 1A Interferograms	N	L	
Level 1B Spectral Radiances	N	L	
Atmospheric Temperature Profile	N	L	0.5K
Surface Skin Temperature	N		0.5K
Land Surface Emissivity**	N		0.01
Ozone (O_3)VMR Profile	N	L	1 - 20 ppbv
Water Vapor (H_2O) VMR Profile	N	L	1 - 200 ppmv
Carbon Monoxide (CO) VMR Profile	N	L	3 - 6 ppbv
Methane (CH_4) VMR Profile	N	L	14 ppbv
Nitrogen Dioxide (NO_2) VMR Profile		L	15 - 25 pptv
Nitric Acid (HNO_3) VMR Profile		L	1 - 10 pptv
Nitrous Oxide (N_2O) VMR Profile	N	L	Control***

* Sensitivity range maps to expected concentration range

** Water emissivities are known and are therefore *input*, not output, parameters

*** Tropospheric concentration known

Simplified Chemistry of Ozone

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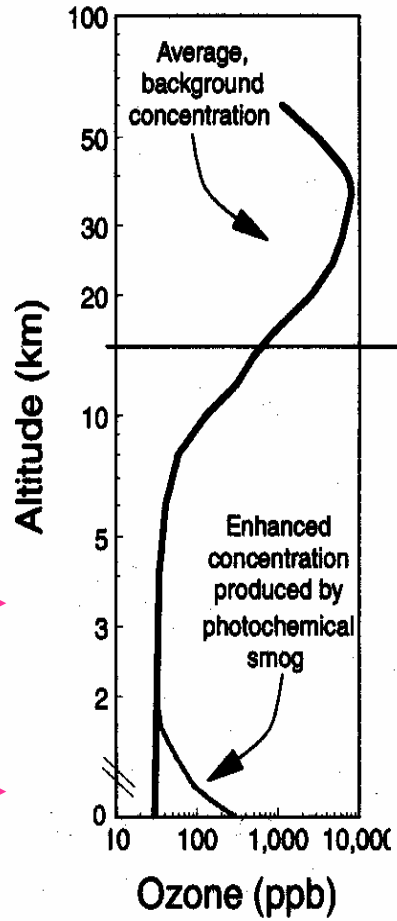
Good
(UV shield)

Bad
(greenhouse gas)

Good
(OH source)

Bad
(smog)



O_2 + UV Sunlight = O + O

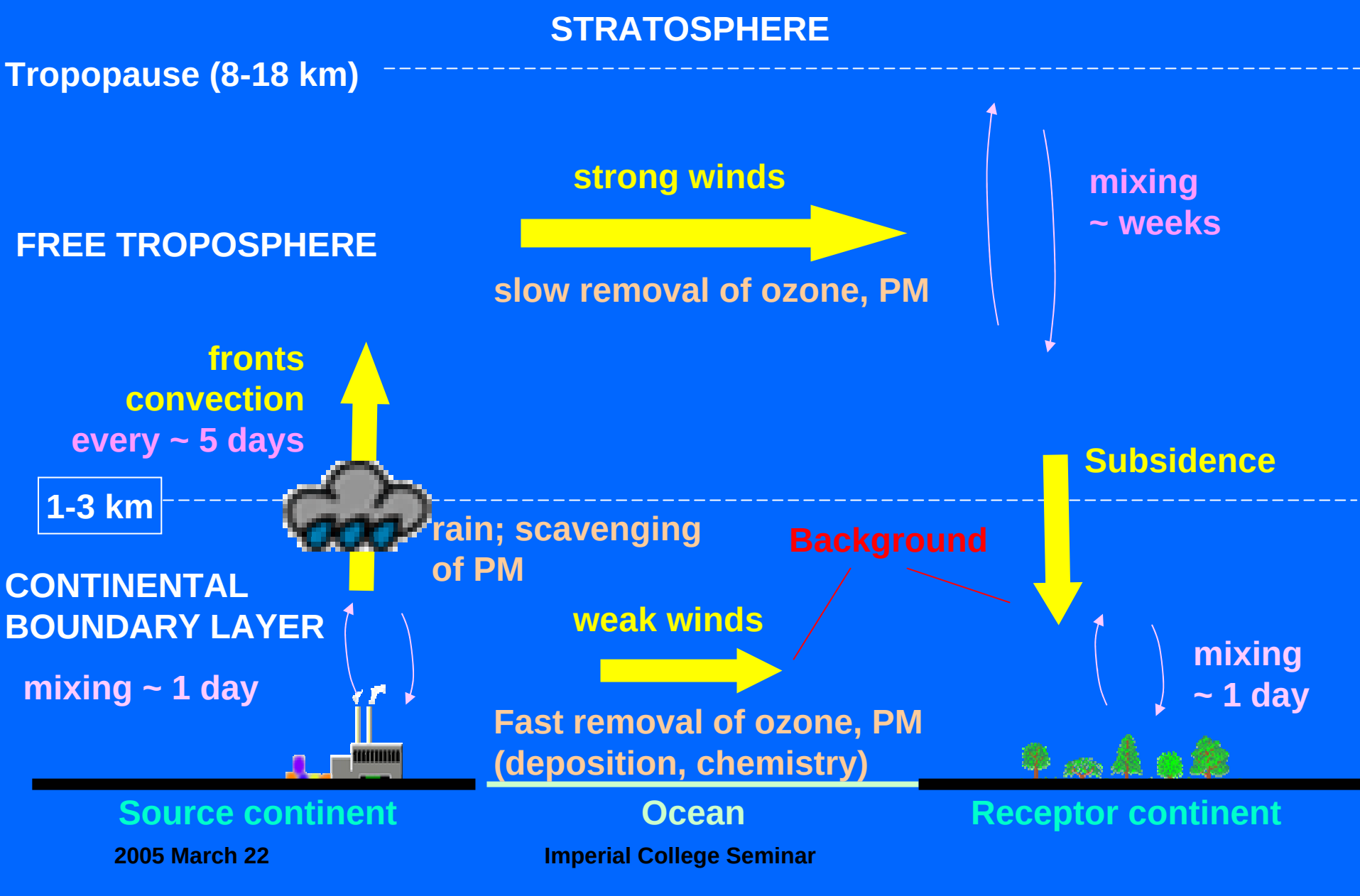
O + O_2 = O_3

Stratosphere

Troposphere

CO
VOC } + NOx + Sunlight = O_3

CONTINENTAL VENTILATION AND INTERCONTINENTAL TRANSPORT



The TES Instrument

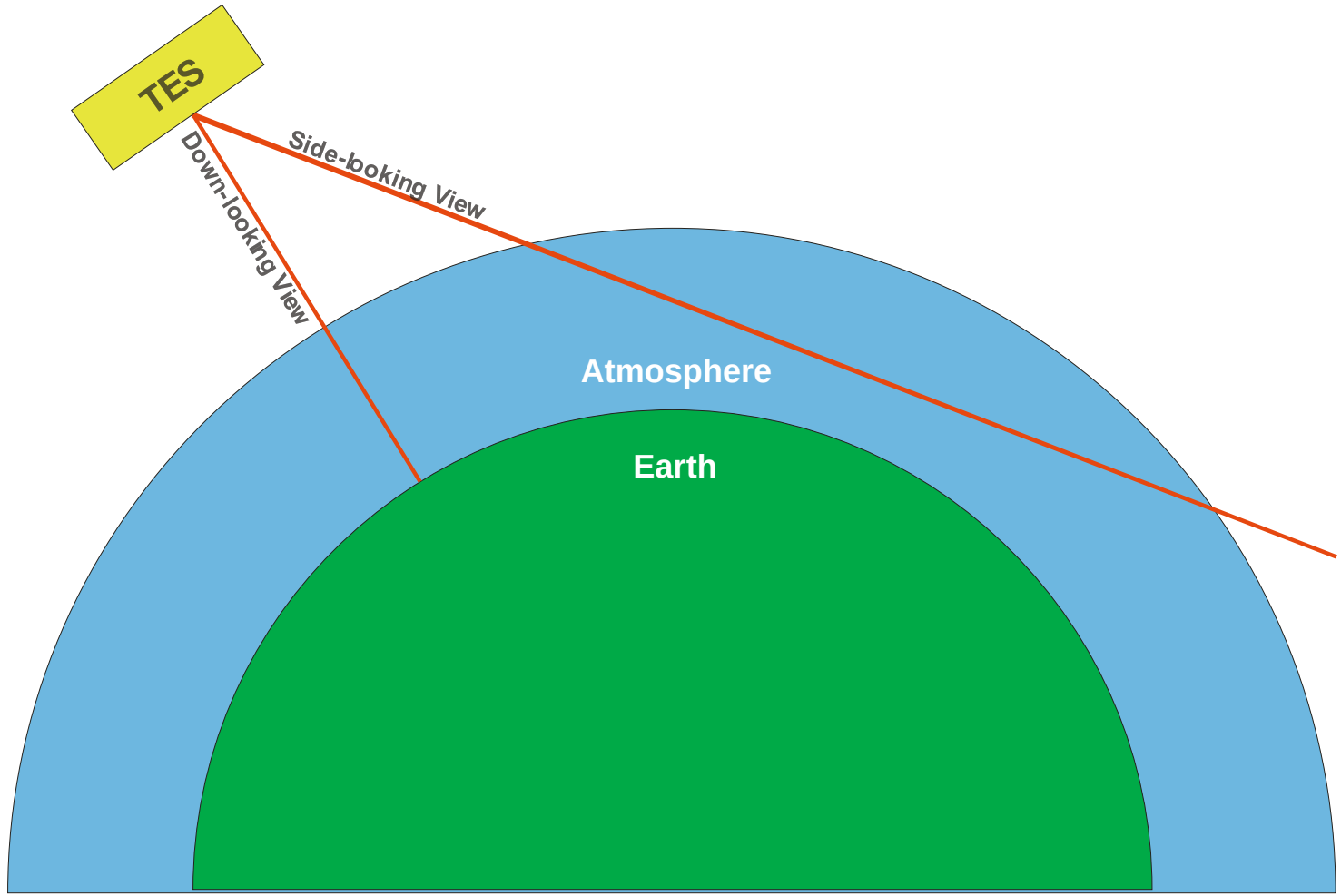
TES is an infrared imaging Fourier Transform Spectrometer (FTS) operating in the spectral range 650 – 3050 cm^{-1} (roughly 3.3 – 15.4 μm).

It features 4 1x16 element optically-conjugated focal plane arrays each optimized for a different spectral region and operating at a temperature of 63K using mechanical refrigerators. In addition, each focal plane is equipped with interchangeable cooled filters that limit the instantaneous spectral bandwidths to about 250 cm^{-1}. This provides needed control over the instrument thermal background and reduces the data rate.

Except for two external mirrors (part of the pointing system), the entire optical path is radiatively-cooled to about 165K, further to reduce the instrument background.

A particular feature of TES is that it can, unlike any other spaceborne FTS instrument, observe both downwards and sideways to the limb.

TWO WAYS OF LOOKING AT THE ATMOSPHERE



Spectrometric Units

The units most commonly used in spectrometry are the *nanometre* (1 nm = 10^{-9} metres), the *micrometre* (1 μm = 10^{-6} metres) and the *reciprocal centimetre* (cm^{-1}).

For reasons that will become clear, it is this latter unit that is most commonly used in infrared spectrometry.

CONVERSION FACTORS:

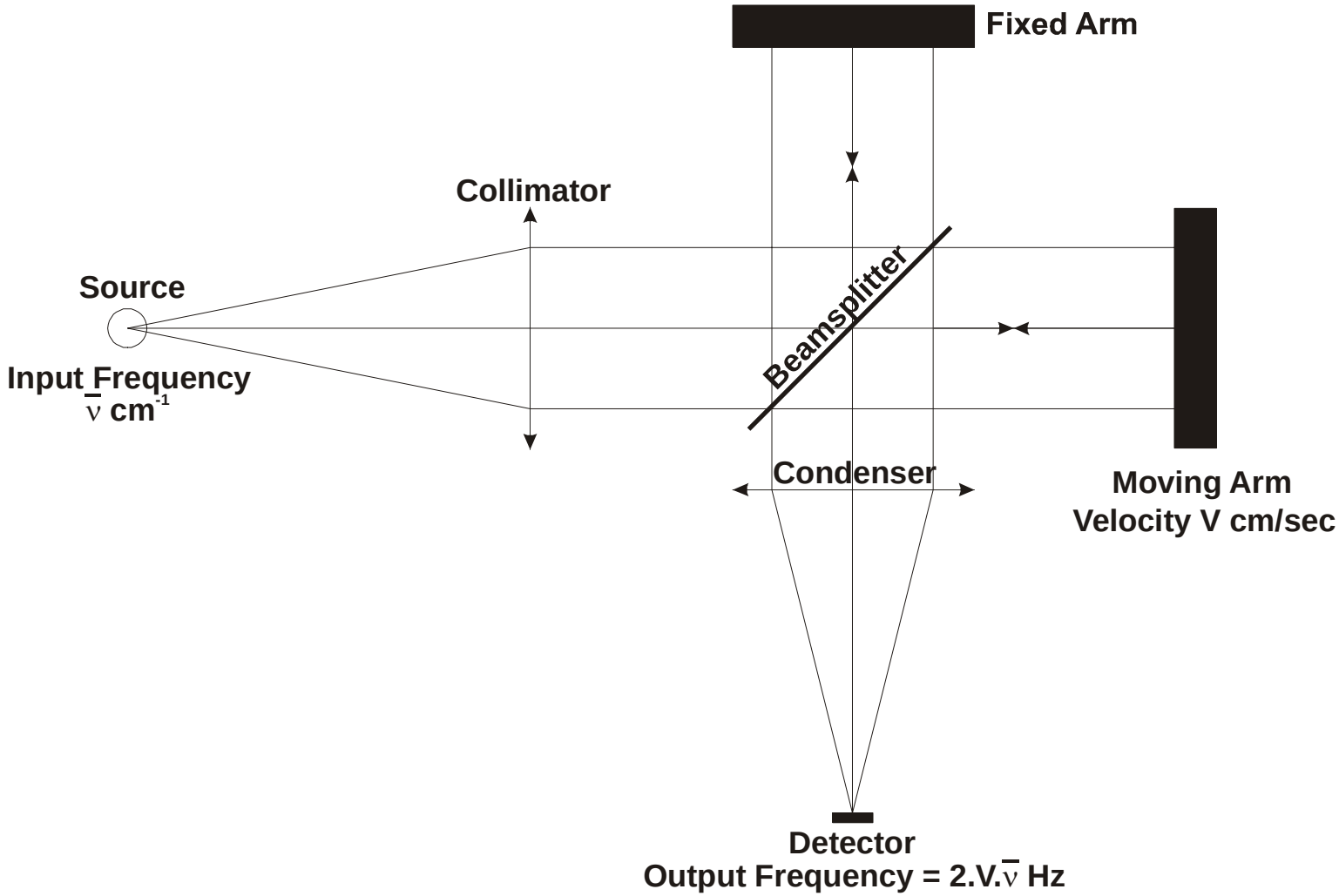
1 cm^{-1} = (Frequency in Hertz)/(Velocity of light) = 10^7/(wavelength in nanometres)

= 10^4/(wavelength in micrometres)

Occasionally, one will see the cm^{-1} referred to as the *wavenumber.*

This is a description, NOT A UNIT!

PRINCIPLE OF THE MICHELSON INTERFEROMETER

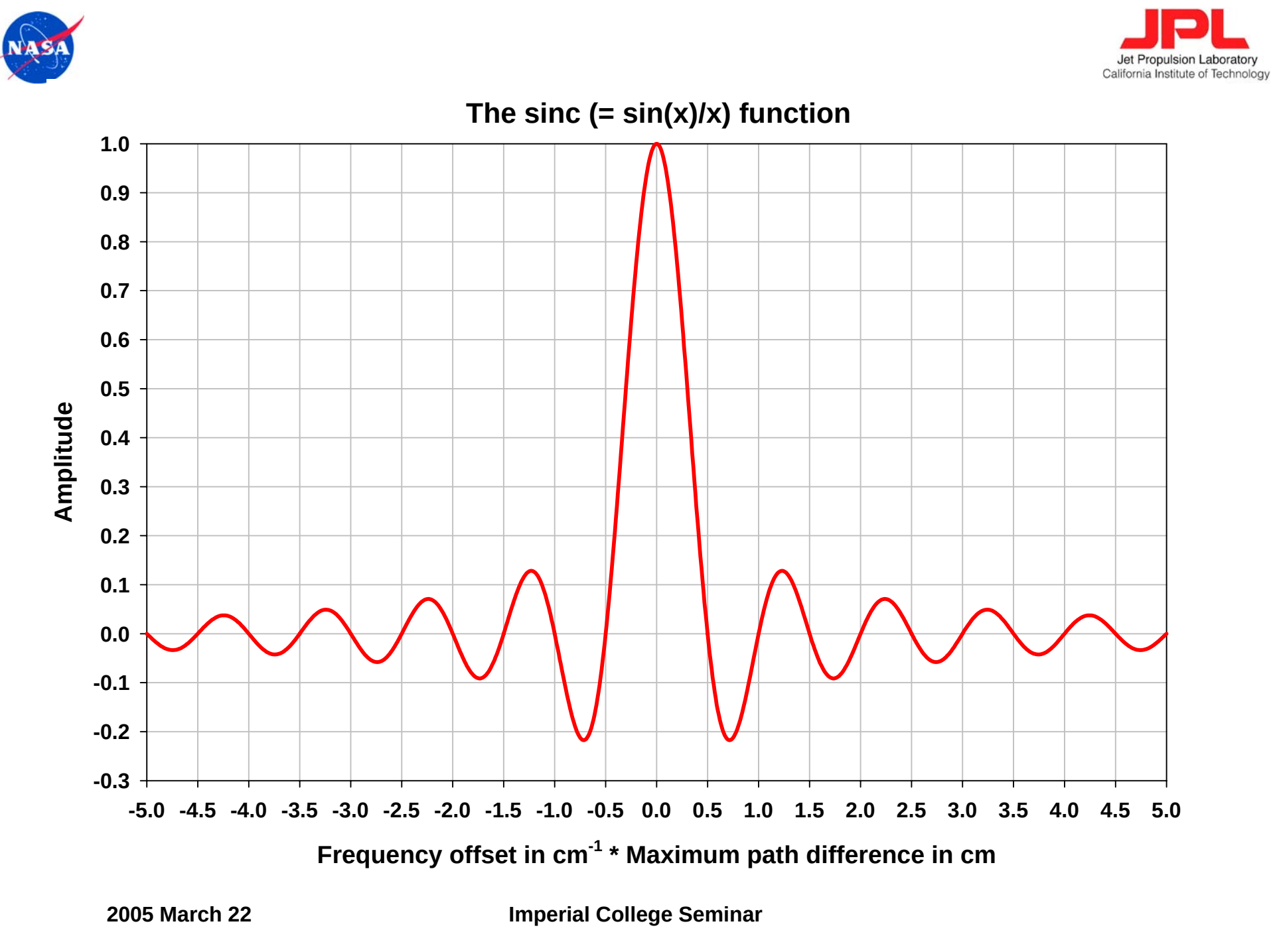


Spectral Resolution

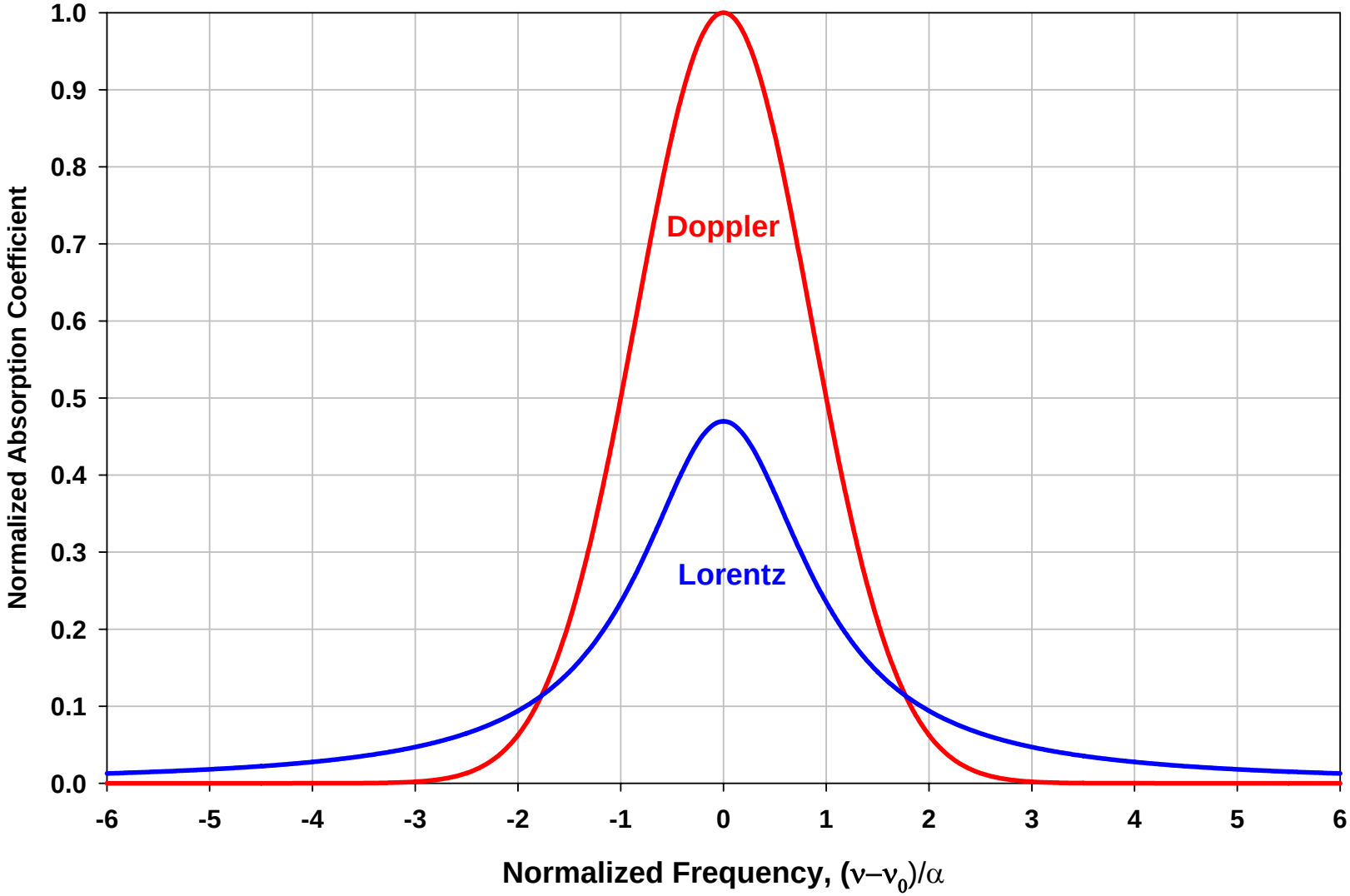
Spectral Resolution is a measure of the ability of the spectrometer to discriminate between adjacent spectral features.

As we shall see, the spectral resolution of a Fourier Transform Spectrometer (henceforth FTS) is inversely proportional to the maximum path difference employed.

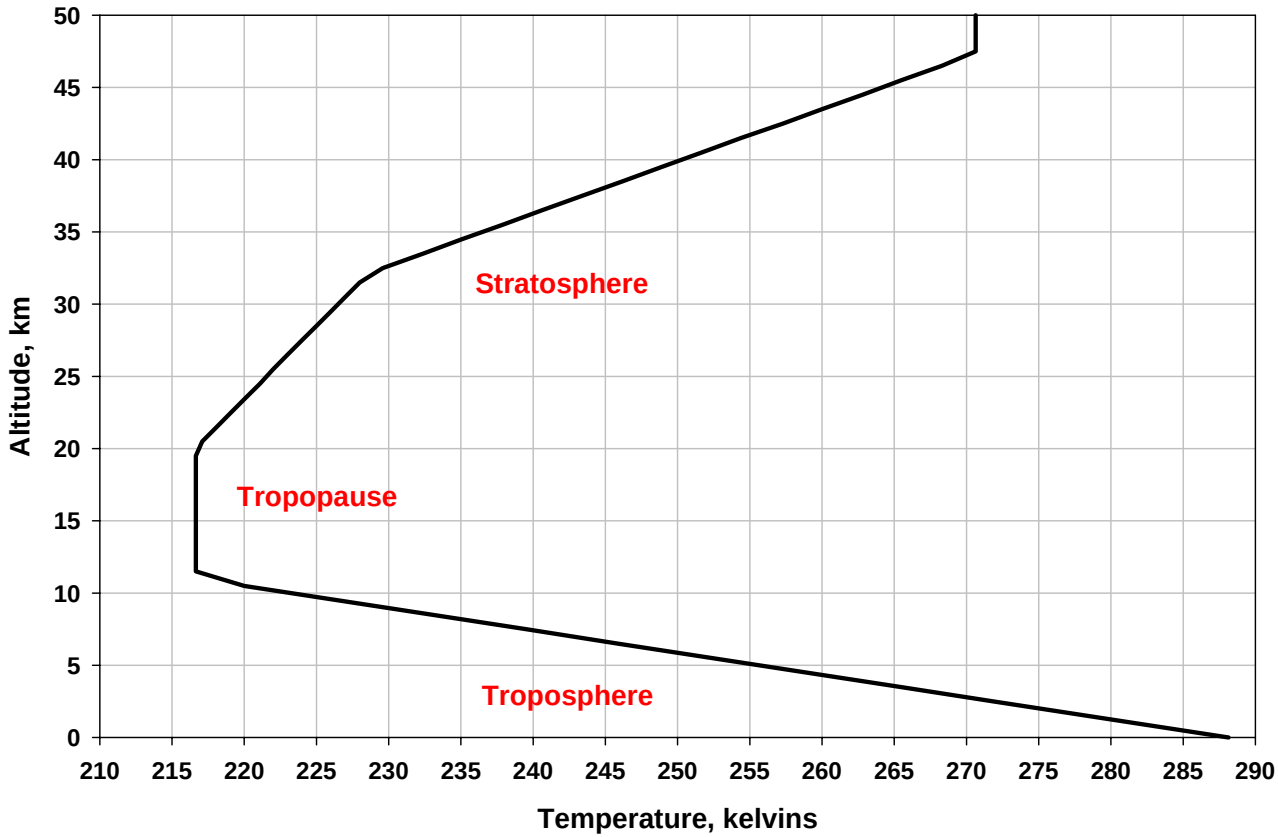
It must, however, be recognized that improved spectral resolution comes at the price of reduced signal-to-noise ratio, so the maximum path difference employed must be carefully "tuned" to the specific problem to be addressed. In short – enough but not too much!


The sinc (= sin(x)/x) function
Amplitude
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Frequency offset in cm-1 * Maximum path difference in cm

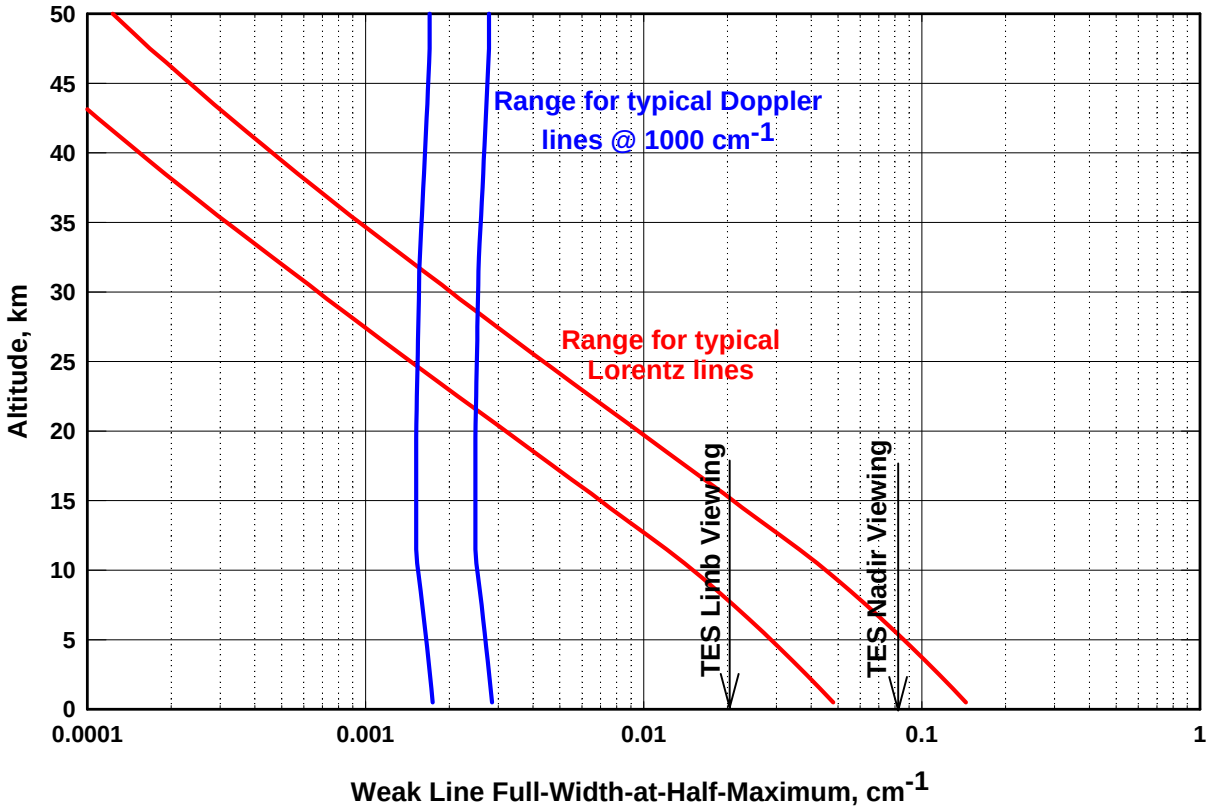
Normalized Shapes of Doppler & Lorentz Lines

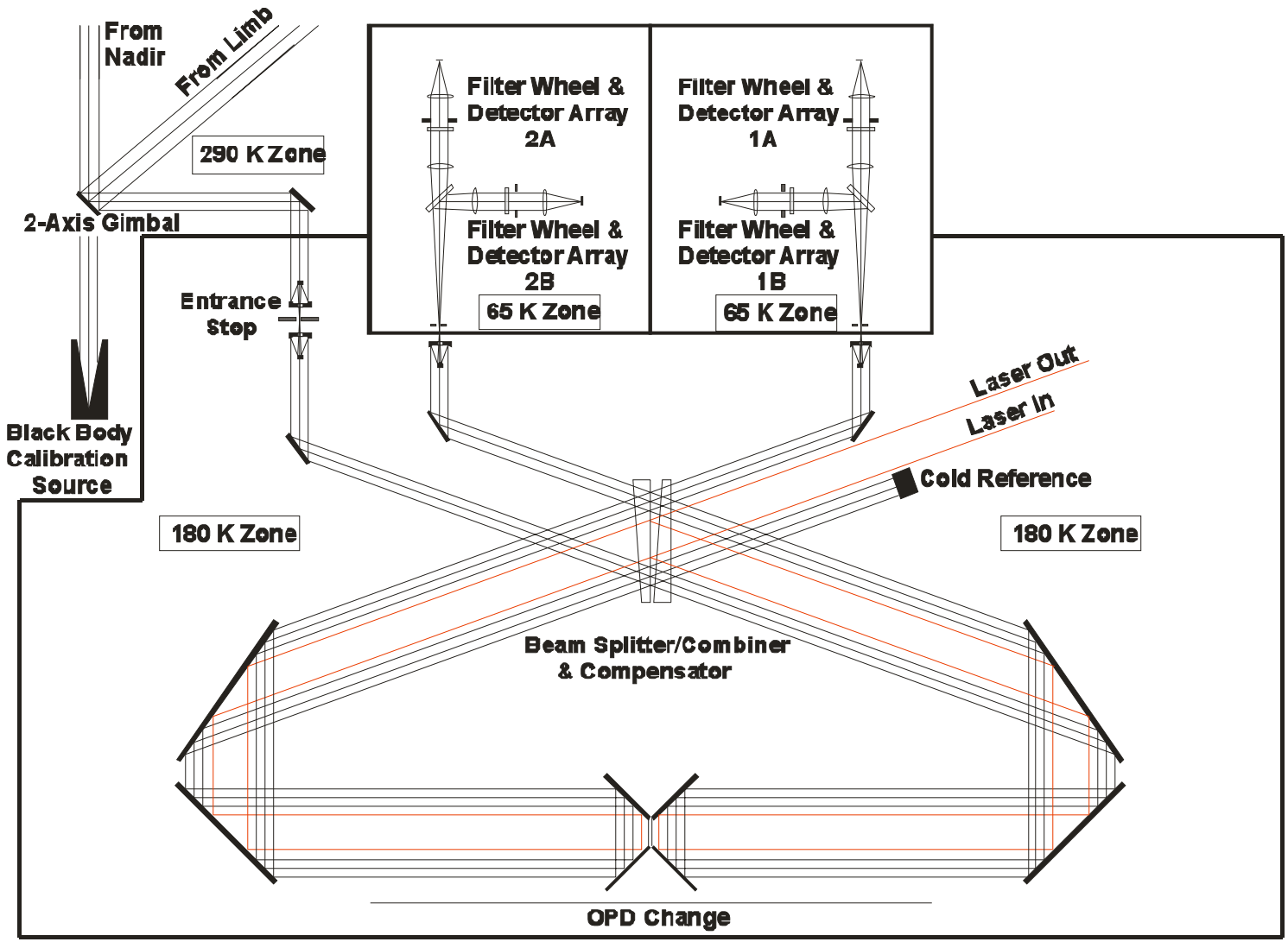


The 1976 US Standard Atmosphere Temperature Profile. Zones important to TES are indicated

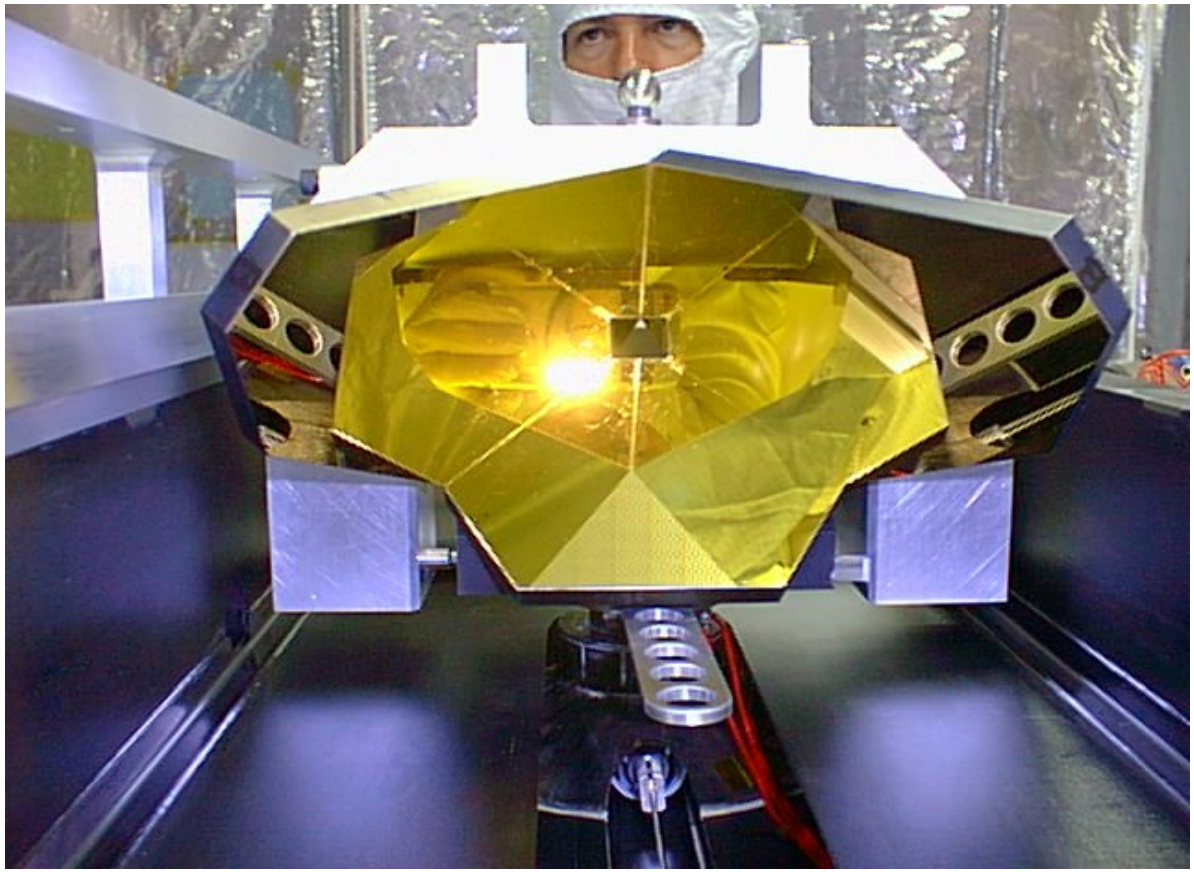


Variation of Typical Linewidths with Altitude



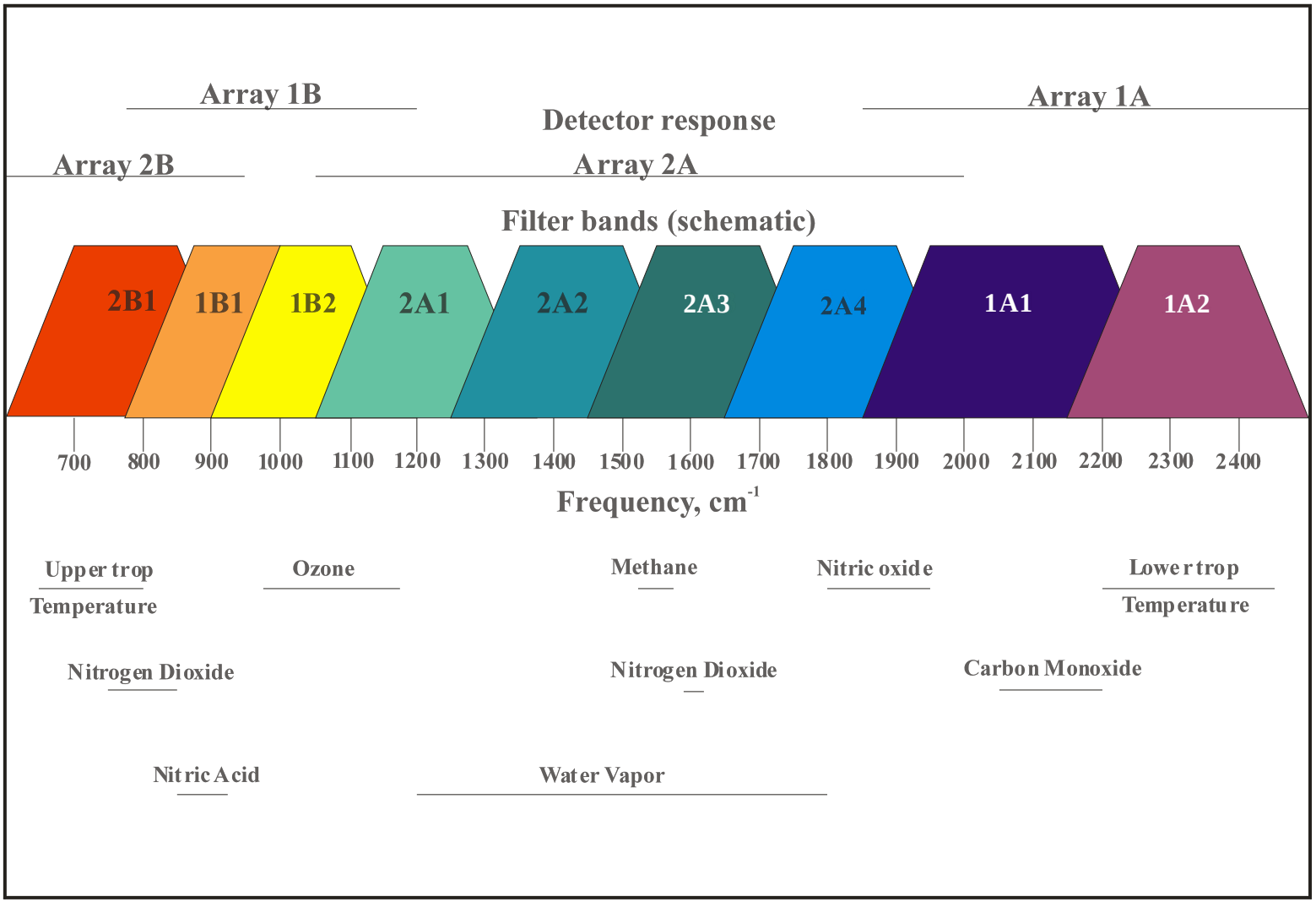


TES OPTICAL SCHEMATIC



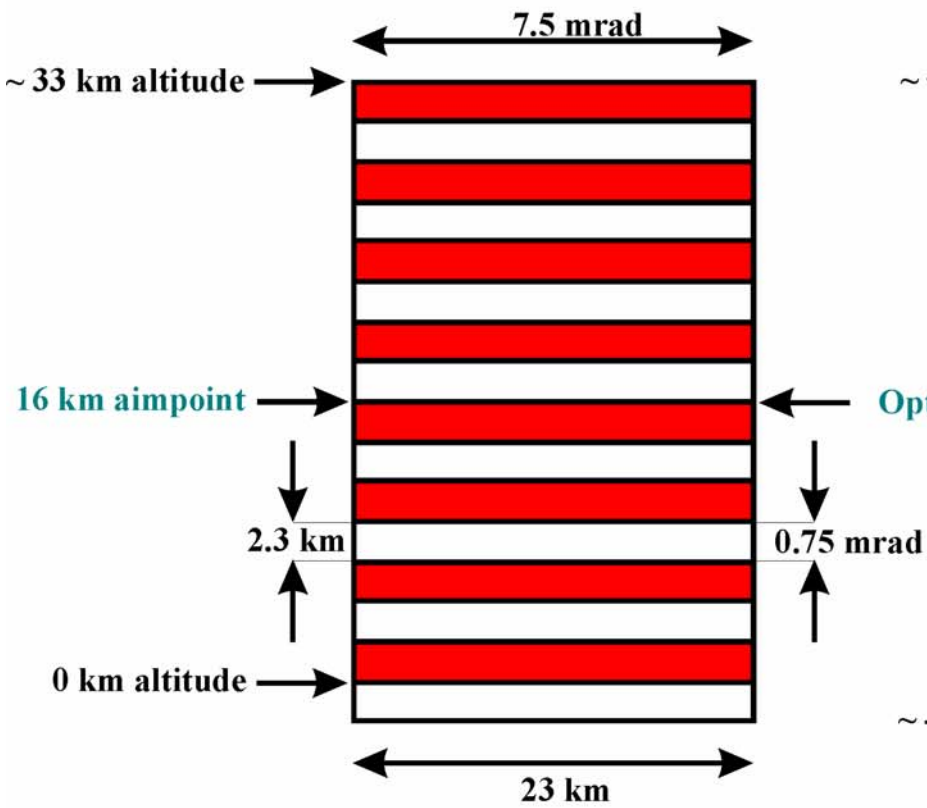
View of the TES engineering model interferometer retroreflector

SPECTRAL COVERAGE FOR OZONE & ITS PRECURSORS



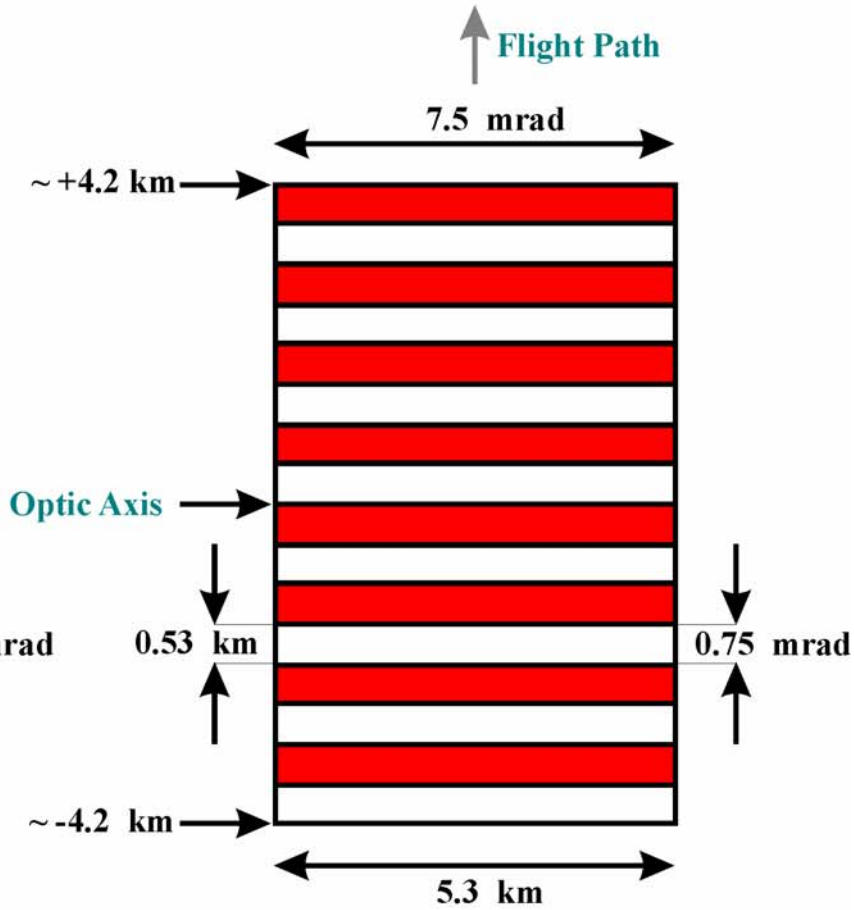
LIMB PROJECTION

Flight Path perpendicular to page



Vertical FOV ~ 13.2 mrad

NADIR PROJECTION

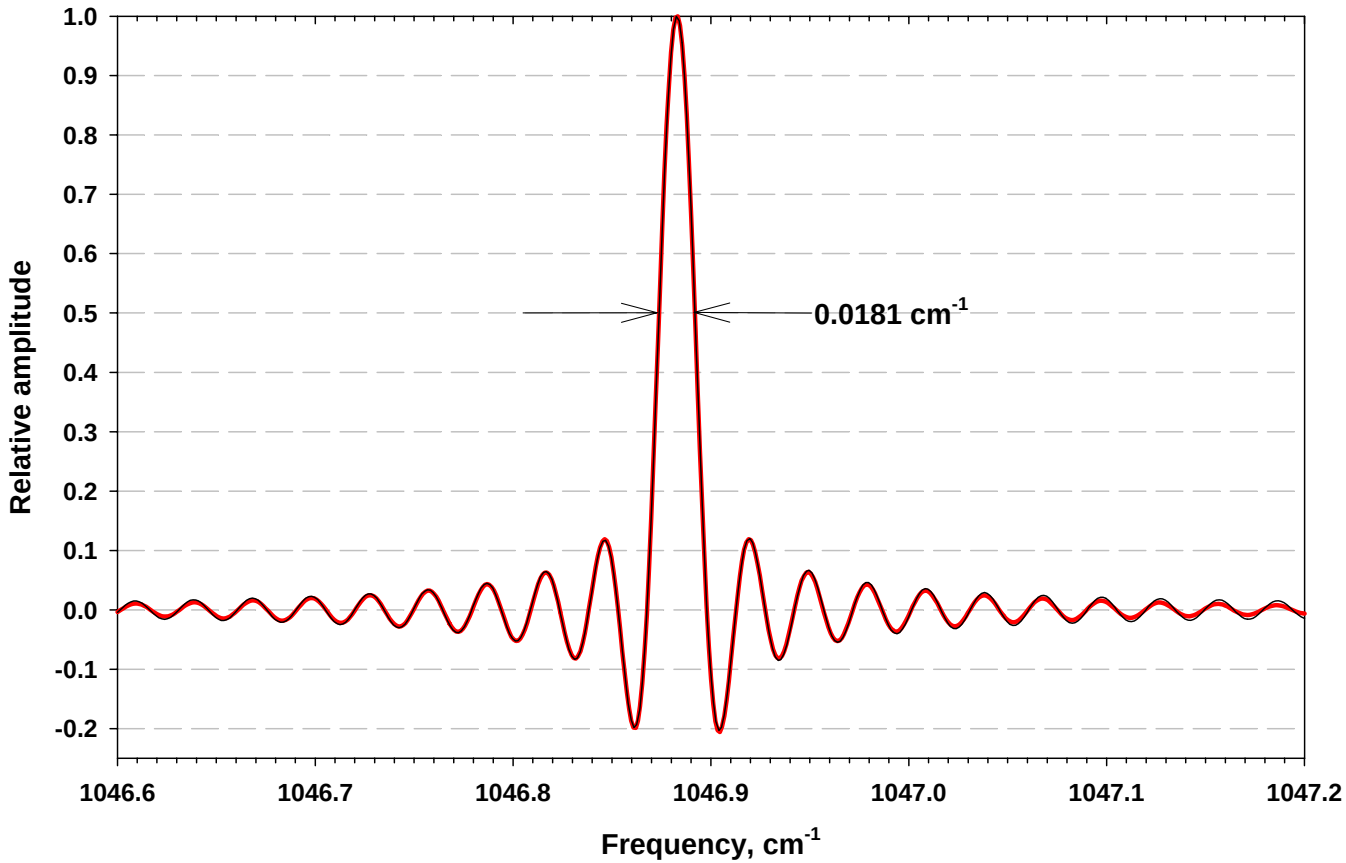


In-track swath ~ 13.2 mrad

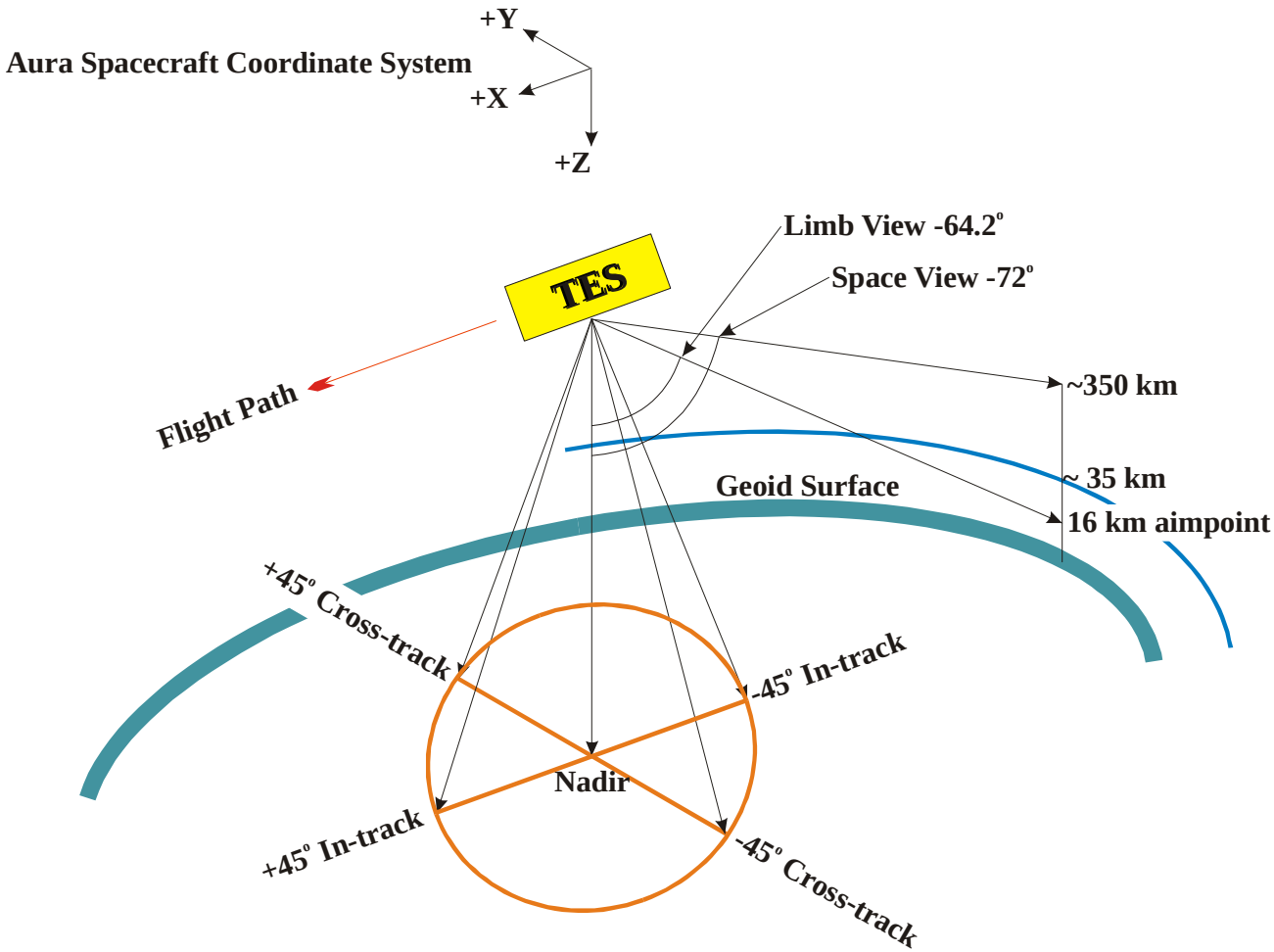
TES Instrumental Line Shape (ILS)

CO_2 Laser 00^01 - 02^00 P(20) line (nominally @ 1046.8543 cm^{-1})

Model prediction



TES Observation Geometry



TES Operating Modes

Global Survey: **16 orbits of nadir & limb observations repeated every other day. This is the source of Standard Products.**

Stare: **Point at a specific latitude & longitude for up to ~4 minutes.**

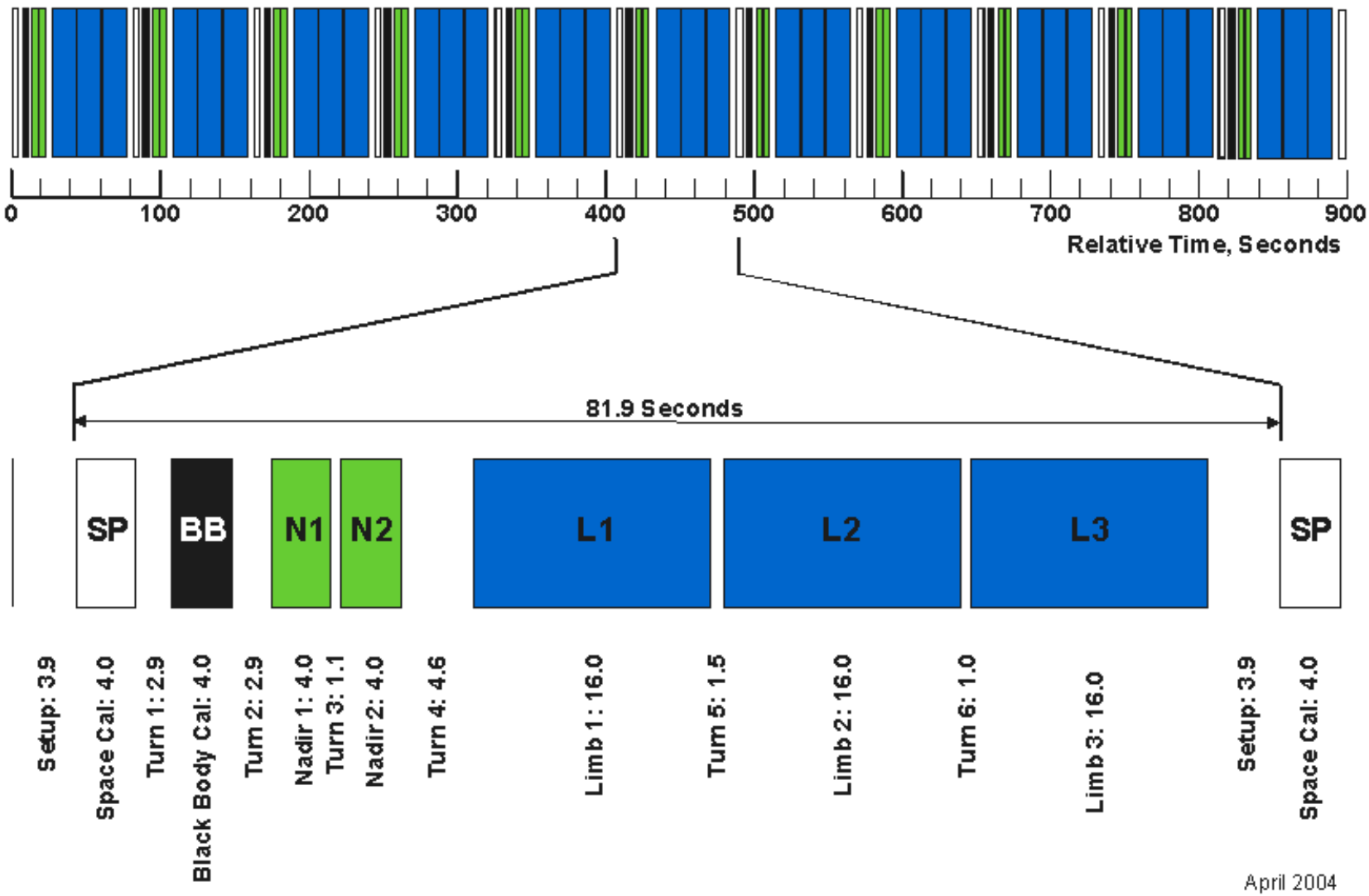
Transect: **Point at a set of contiguous latitudes & longitudes to cover ~850 km.**

Step-&-Stare: **Point at nadir for 4 seconds (5.2 seconds with necessary reset). Spacecraft has moved ~40 km. Point at nadir again. Repeat indefinitely.**

Limb Drag: **Point at the trailing limb (16 second scans). Repeat indefinitely.**

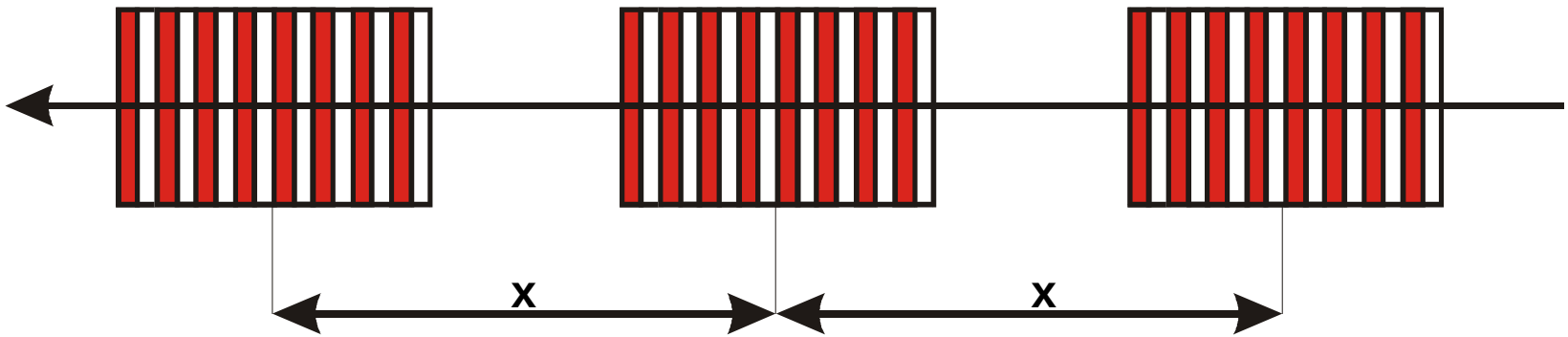
These last 4 modes constitute Special Products that are obtained *only* when no Global Survey is scheduled.

GLOBAL SURVEY OBSERVATION STRATEGY



April 2004

TES Step & Stare, Stare and Transect Modes



STEP & STARE: A set of nadir footprints spaced about 35 km apart. Can be indefinite.

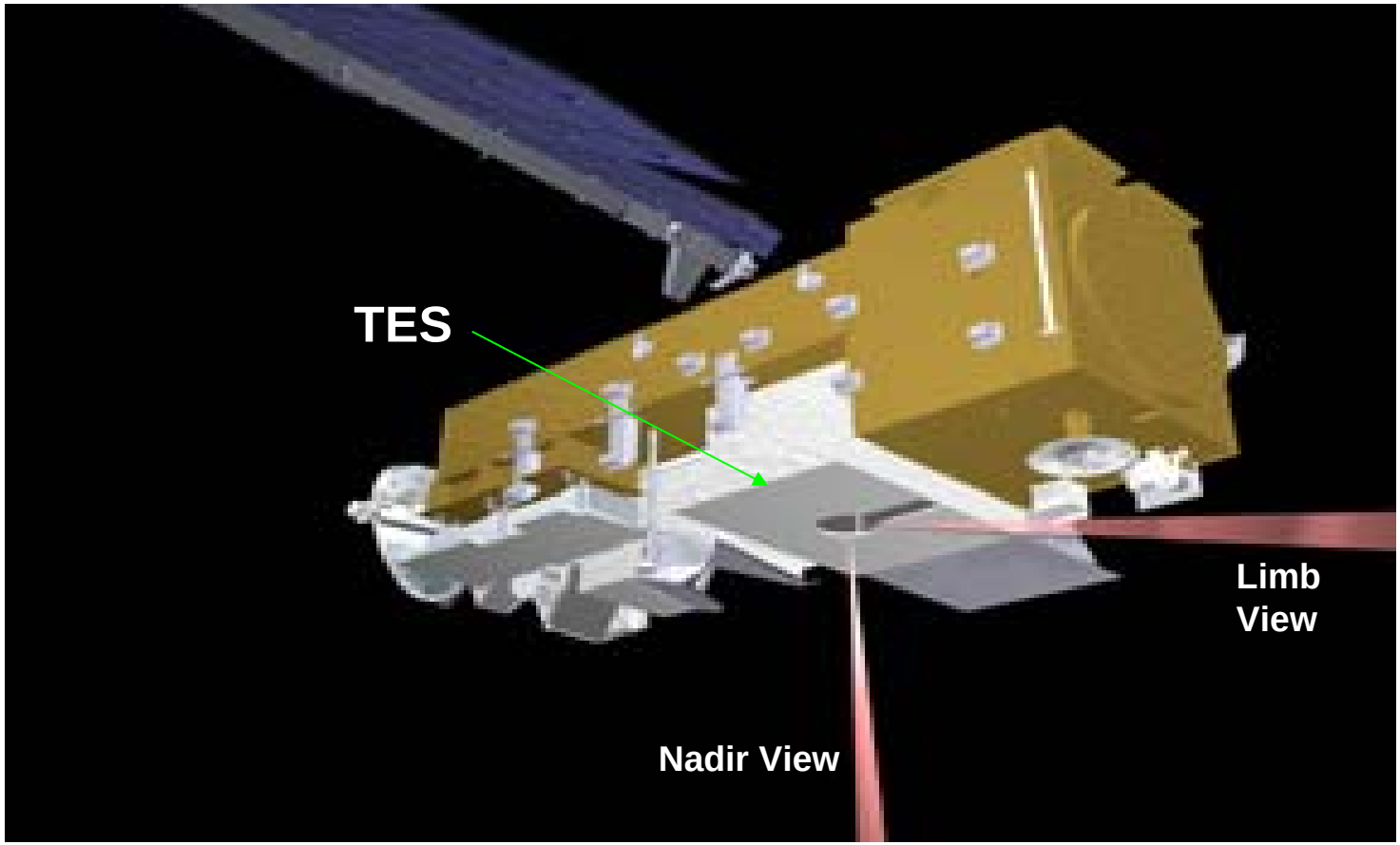
STARE: Point at a specific latitude & longitude for up to 210 seconds.

TRANSECT: A set of exactly contiguous latitudes & longitudes in a line up to 885 km long.

- Fourier transform spectrometer
- Wavelength response: 3.3 to 15.4 micron
- One scan every 4 or 16 sec. (0.1 cm^{-1} or 0.025 cm^{-1} res.)
- Four optically-conjugated 1x16 pixel detector arrays
- Spatial resolution of 5 x 8 km at nadir & 2.3 km at limb
- Passively cooled
- 2-axis gimbaled pointing mirror

TES specifications

TES on the Aura Spacecraft



Aura Launch : July 15, 2004
Vandenberg Air Force Base, CA

EOS

AURA Launch; 2004 July 15, 03:02 PDT

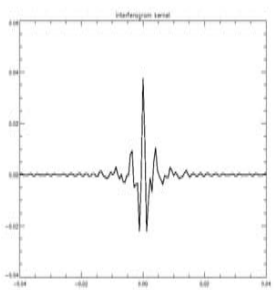
TES Algorithm Overview

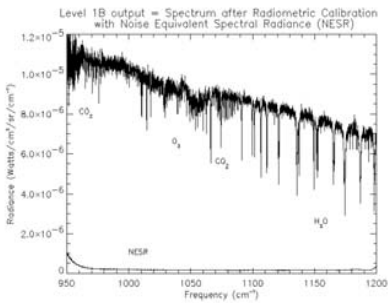
Level 1A: Produces geolocated interferograms.

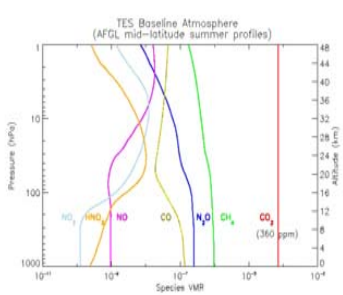
Level 1B: Produces radiometrically and frequency calibrated spectra with NESR.

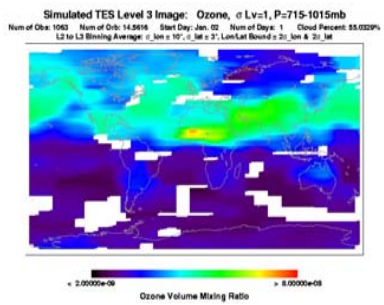
Level 2: Produces VMR and temperature profiles.

Level 3: Produces global maps.

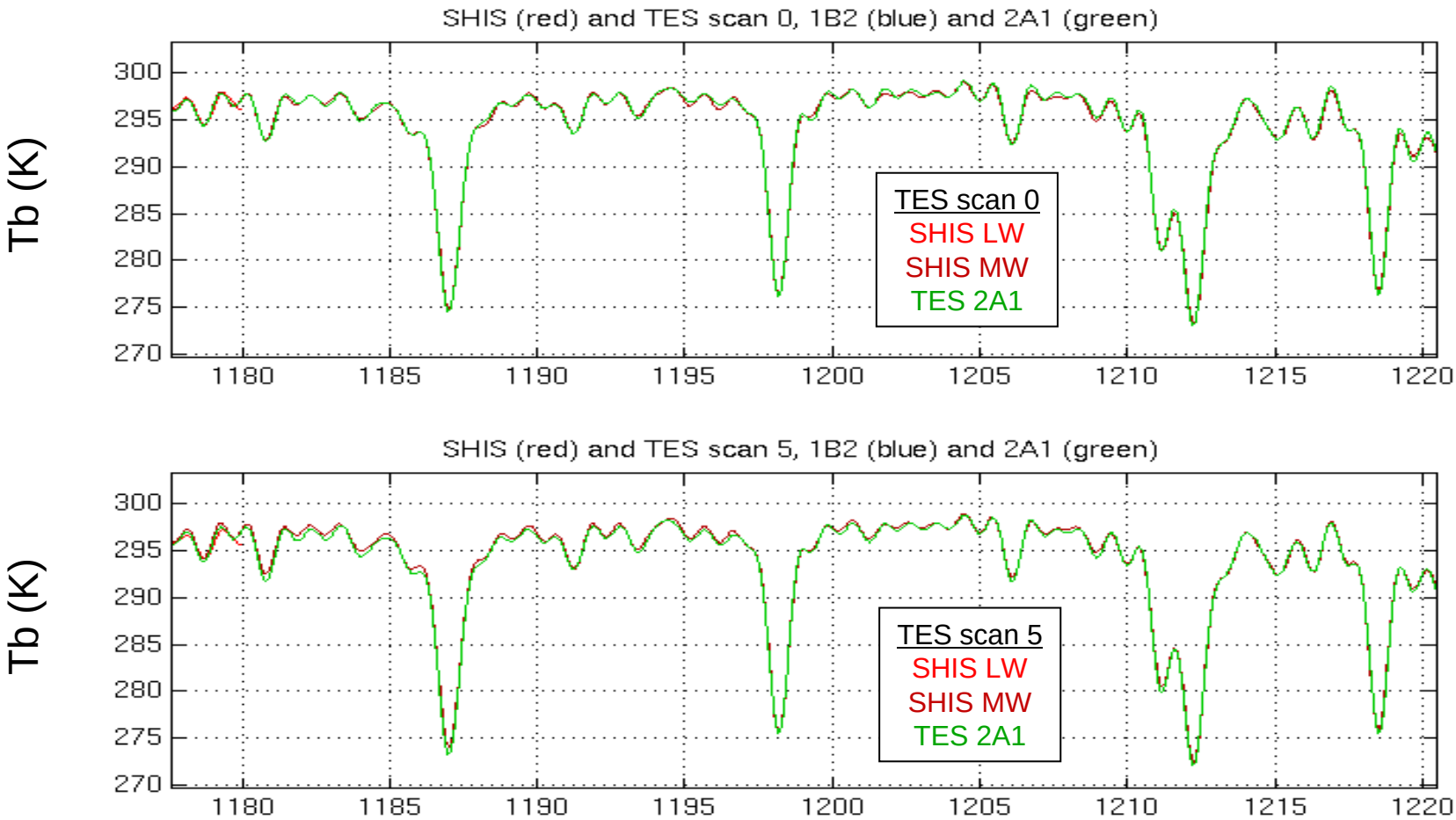




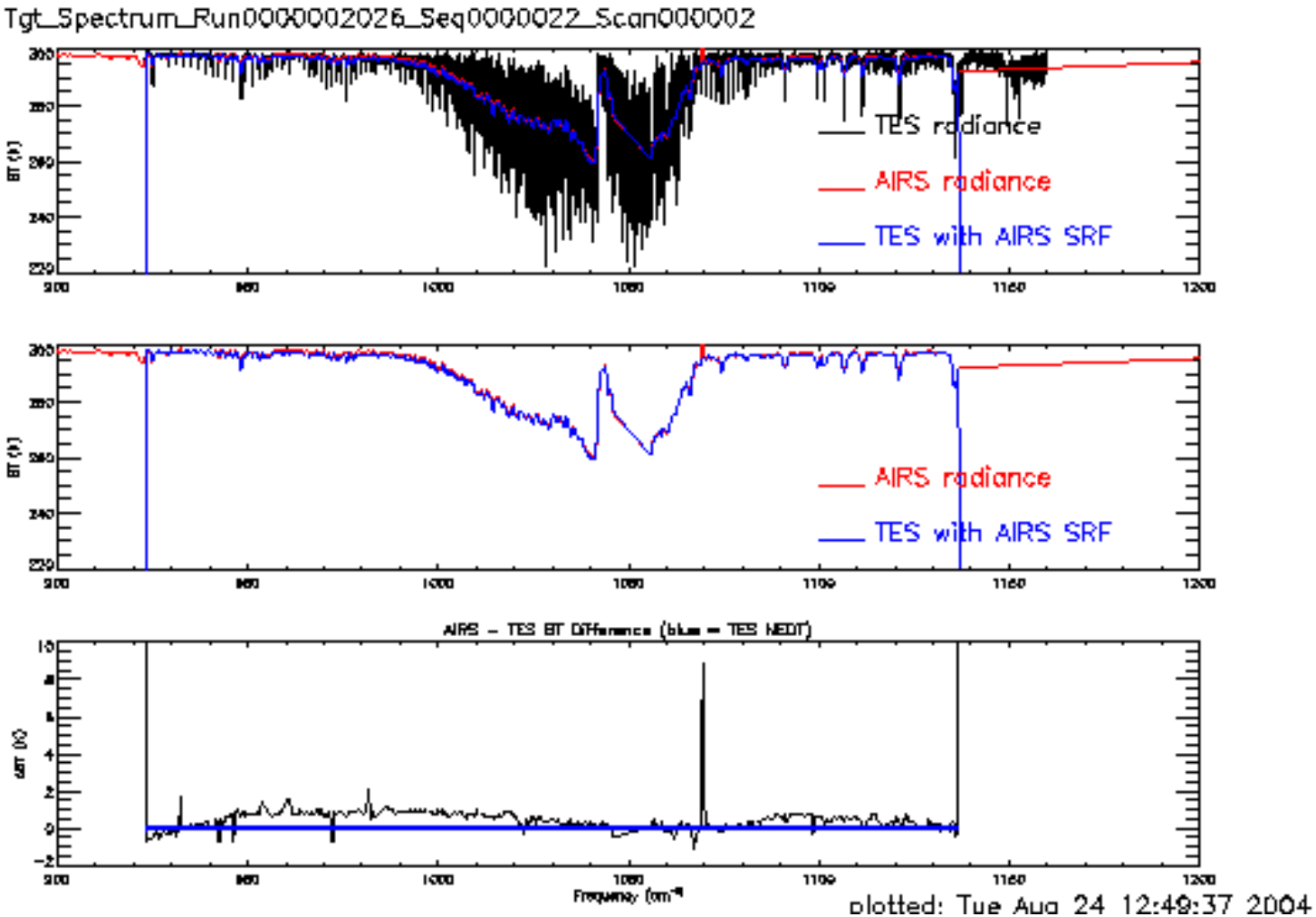




TES Radiance comparison with S-HIS (AVE campaign)



TES radiance comparison with AIRS data (same geolocation)



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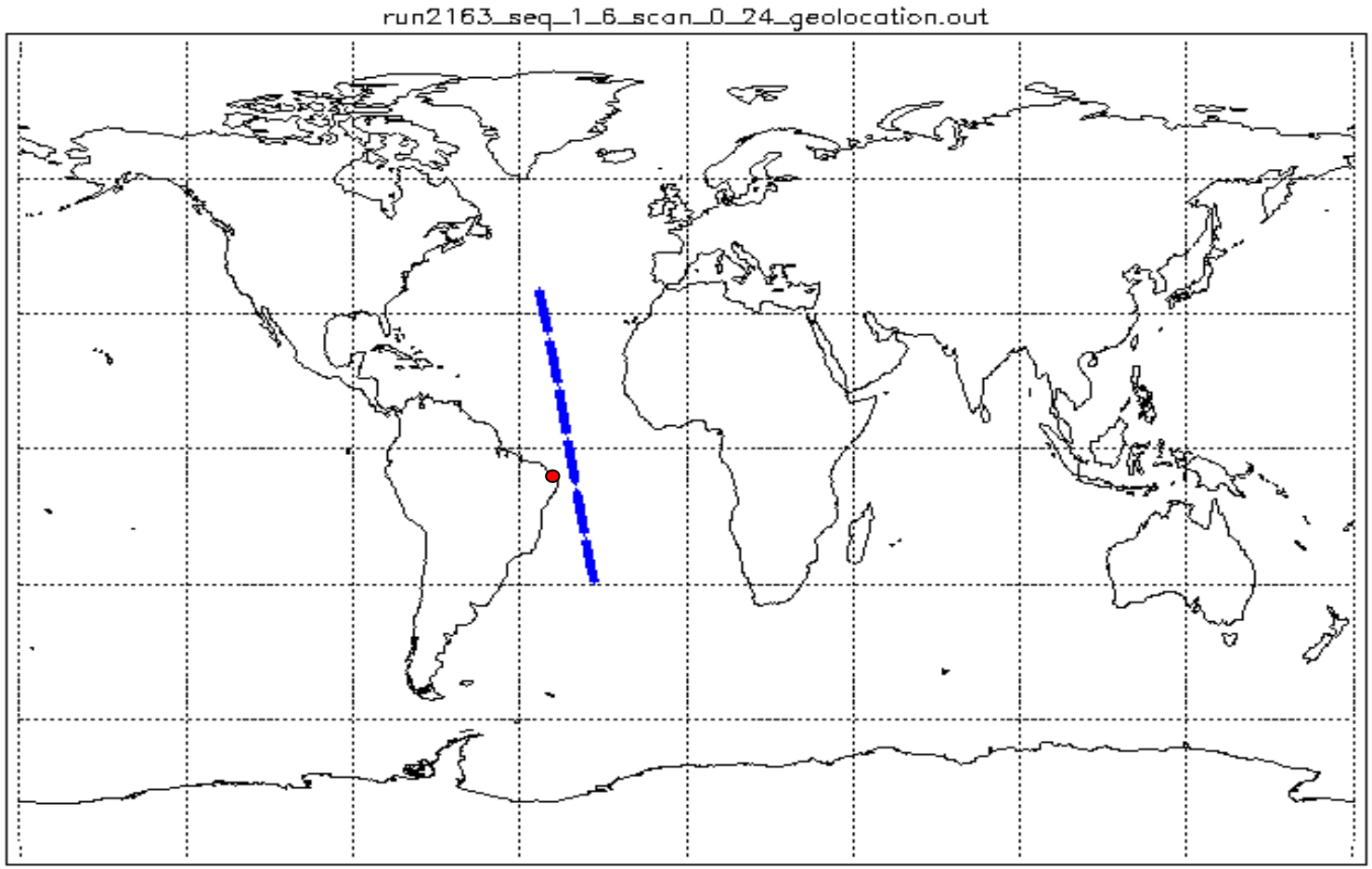
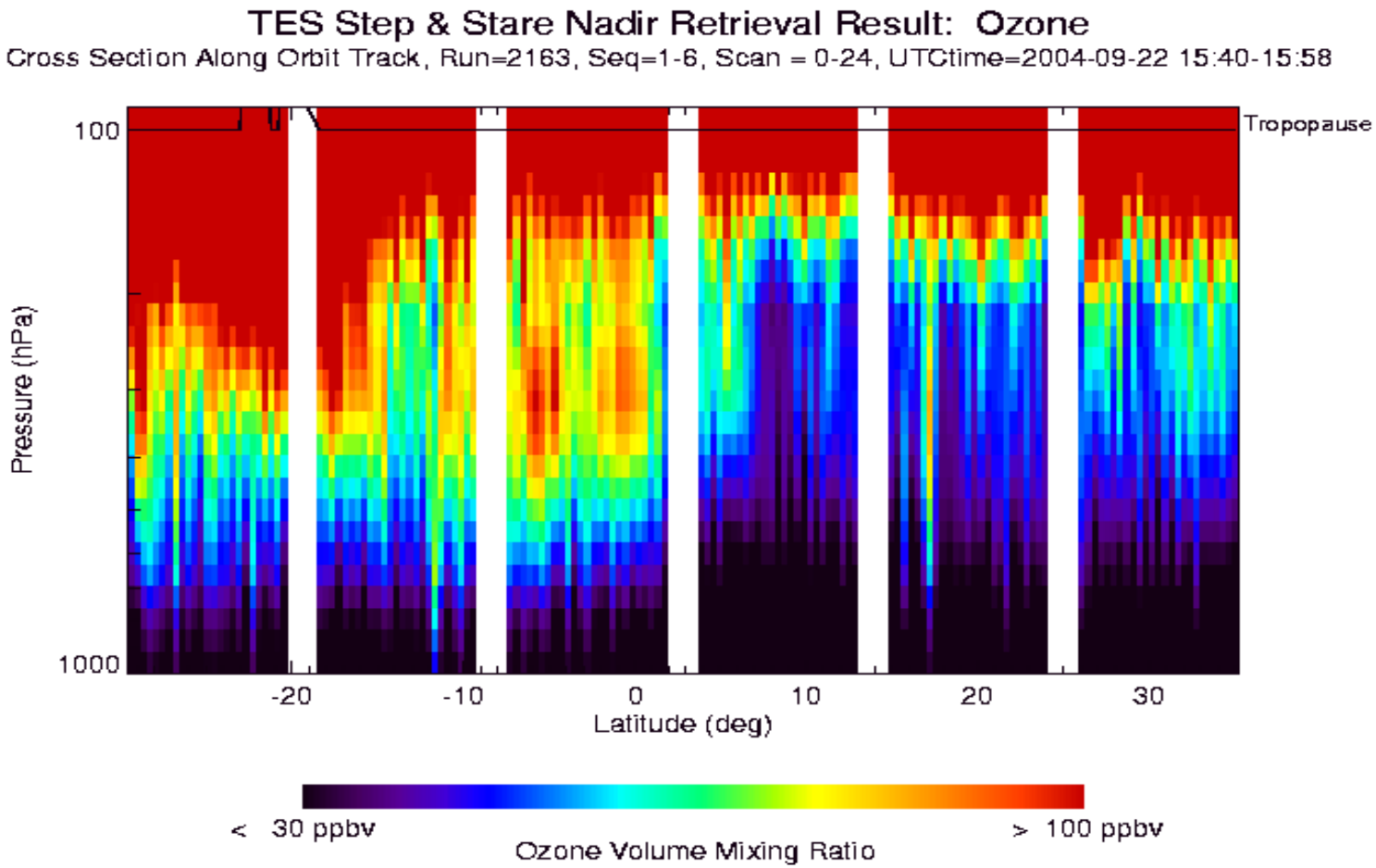
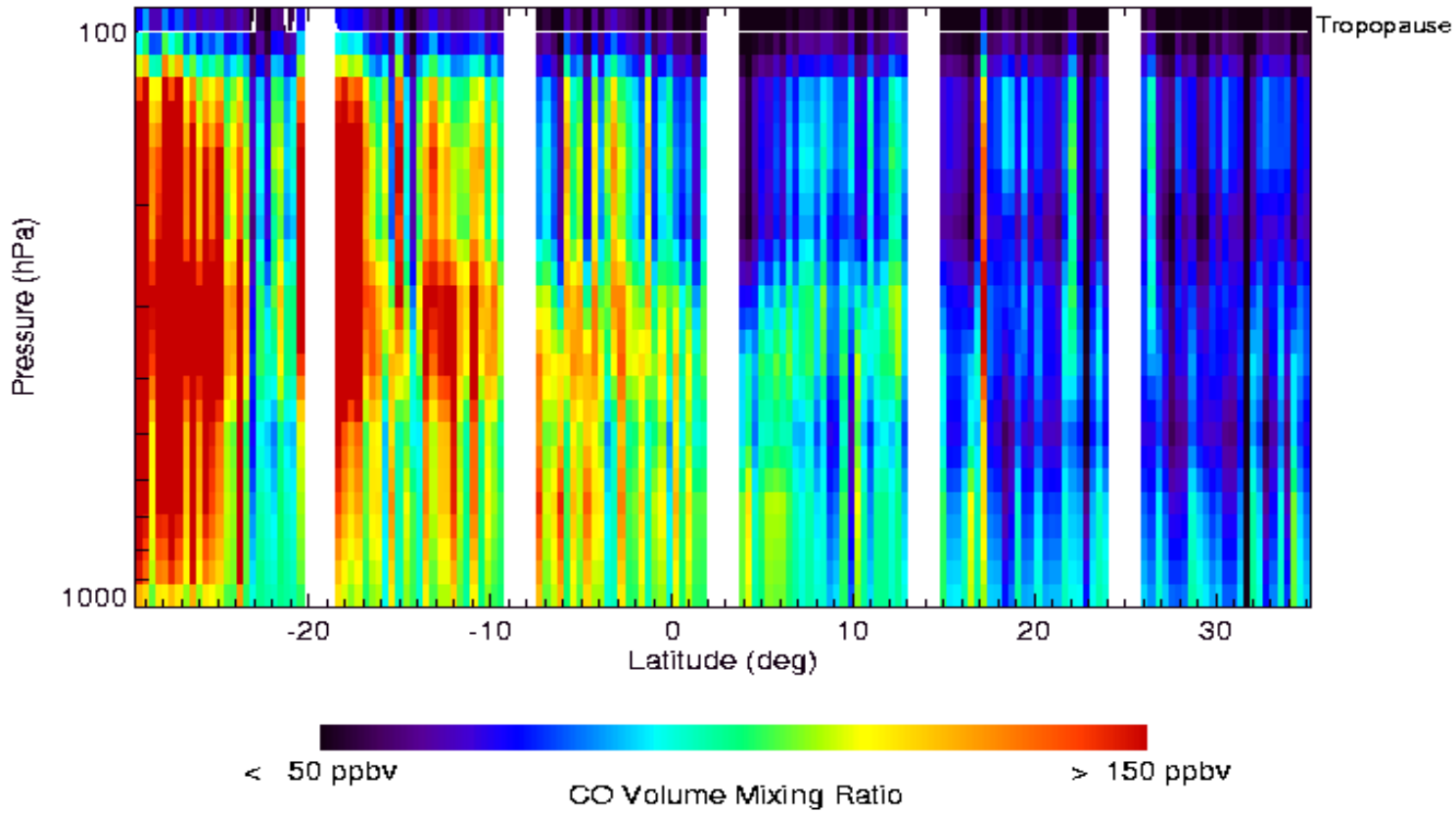
Step & Stare Mode Observation near Natal, Brazil (red dot); 2004 September 22


run2163_seq_1_6_scan_0_24_geolocation.out


TES Step & Stare Nadir Retrieval Result: Ozone
Cross Section Along Orbit Track, Run=2163, Seq=1-6, Scan = 0-24, UTCtime=2004-09-22 15:40-15:58
Tropopause
100
1000
Pressure (hPa)
-20
-10
0
10
20
30
Latitude (deg)
< 30 ppbv
> 100 ppbv
Ozone Volume Mixing Ratio

TES Step & Stare Nadir Retrieval Result: CO

Cross Section Along Orbit Track, Run=2163, Seq=1-6, Scan = 0-24, UTCtime=2004-09-22 15:40-15:58



TES Ozone retrievals & vertical resolution

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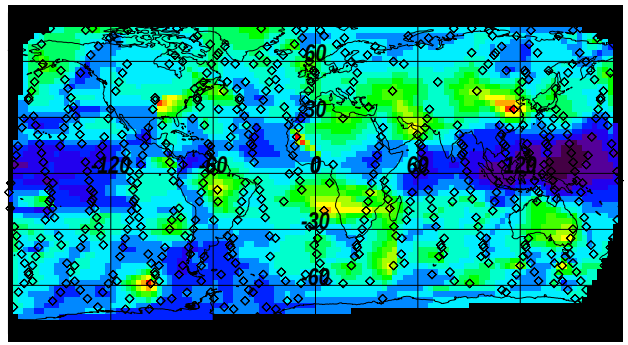
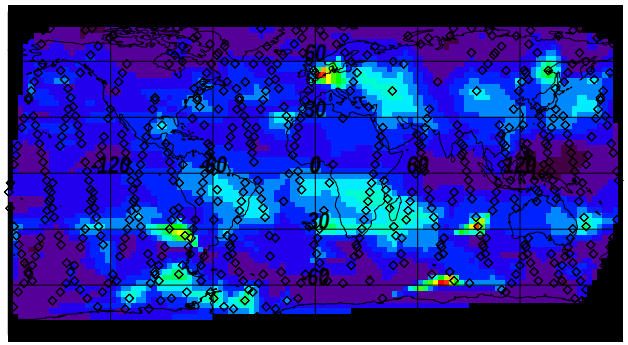
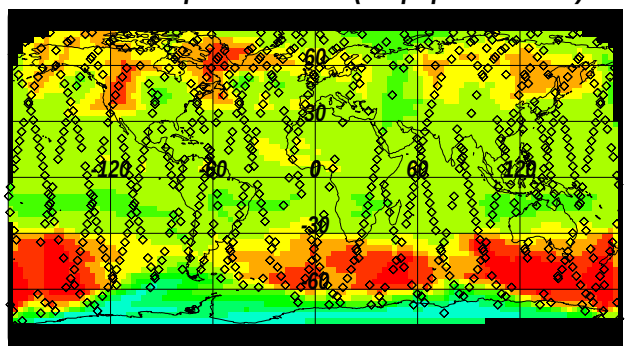
TES Lower Tropospheric Ozone (Surface - 500 hPa)



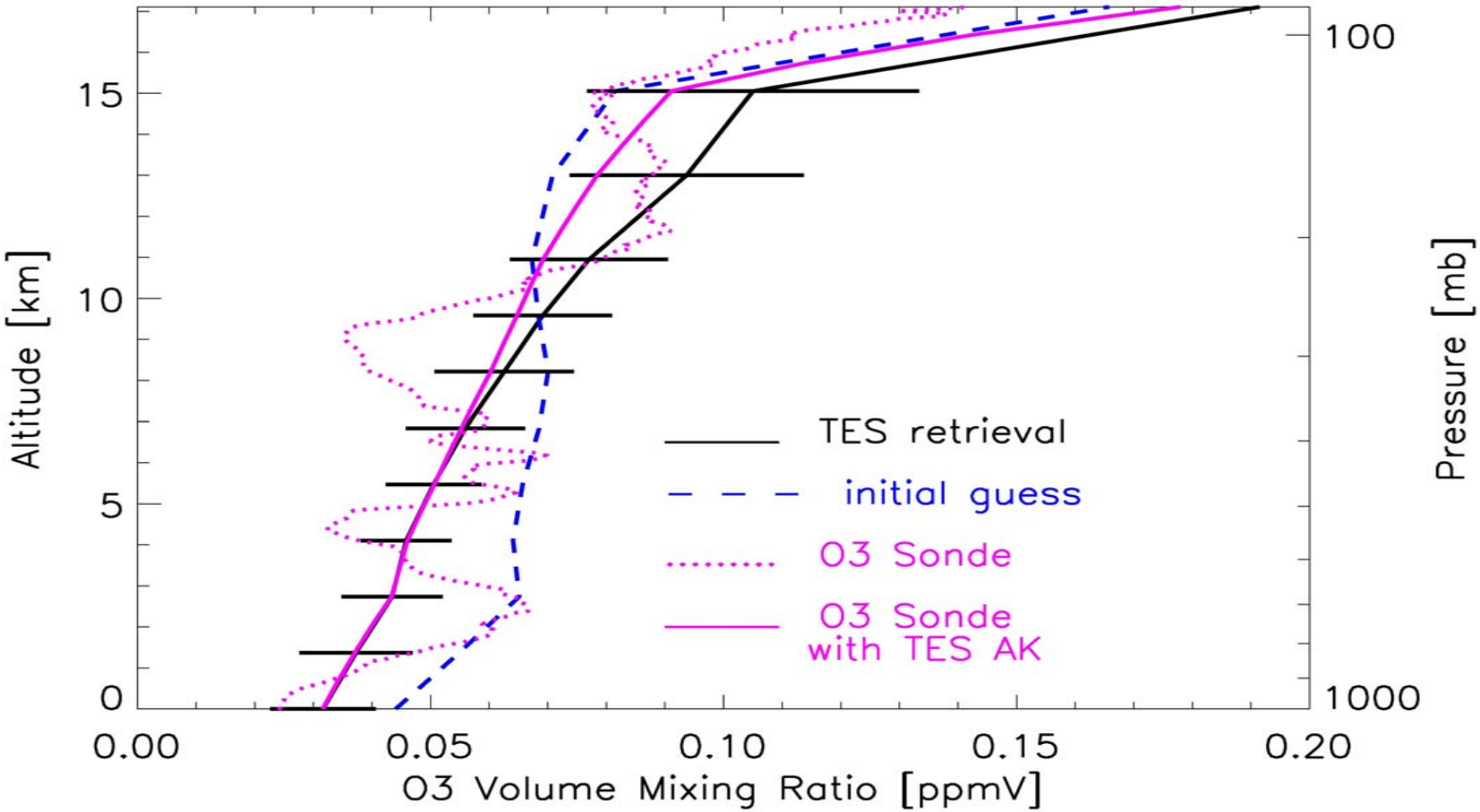
TES Upper Tropospheric Ozone (500 hPa - Tropopause)



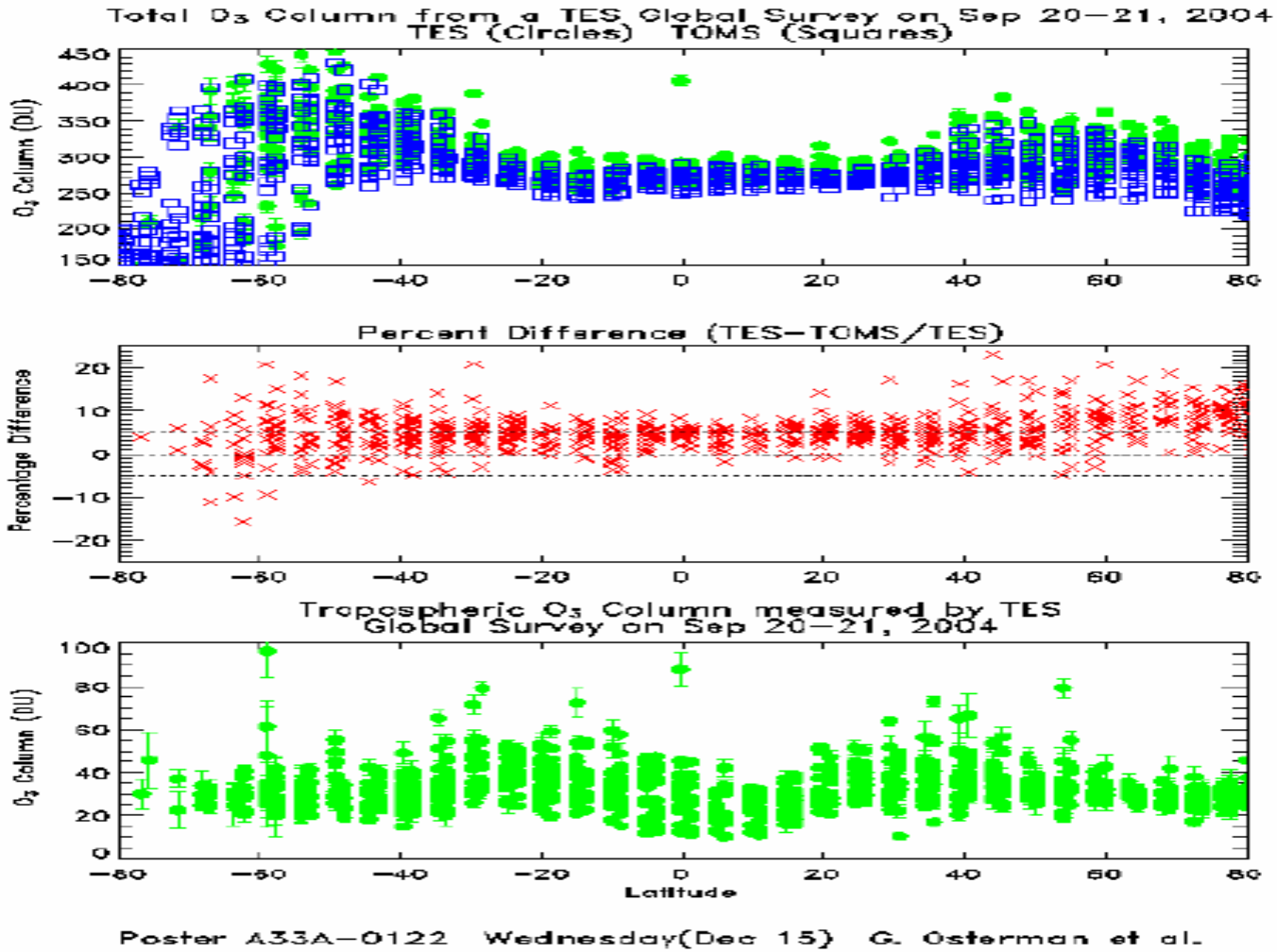
TES Stratospheric Ozone (Tropopause - TOA)



Natal, Brazil O_3 Sonde comparison to TES retrieval



TES – TOMS Intercomparison



Poster A33A–0122 Wednesday(Dec 15) G. Osterman et al.

TES Special Observation: Nadir Step & Stare for Nov 3, 2004 (150 observations from 1N to 65N)

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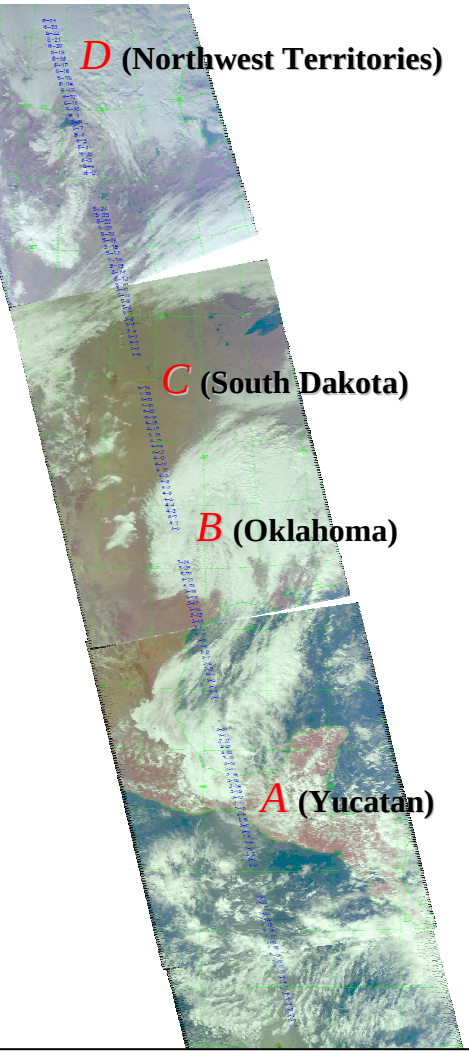
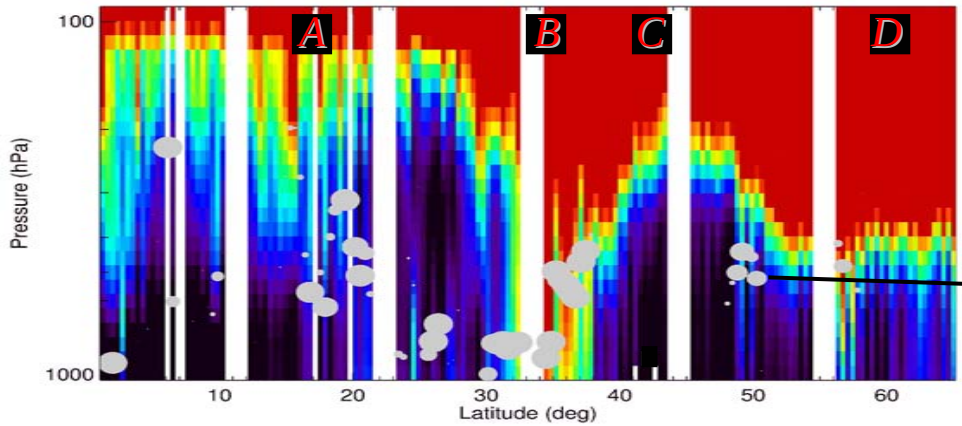
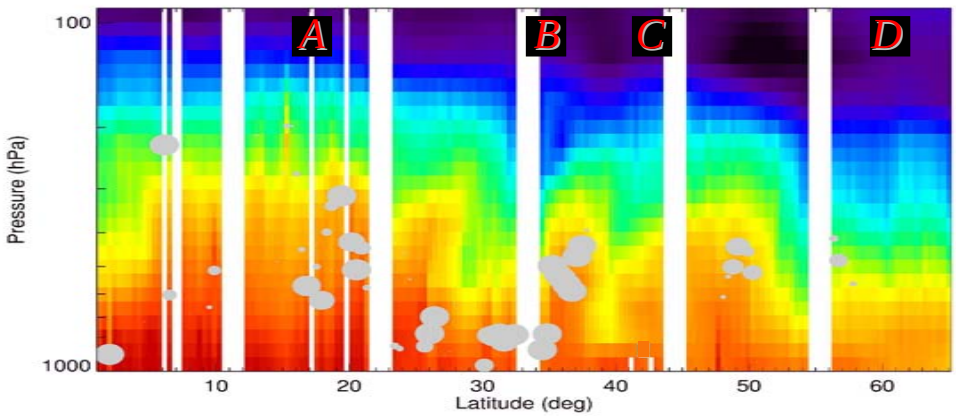




Ozone

Retrieved Clouds
Cloud effective OD = 3.0
Cloud effective OD = 0.3

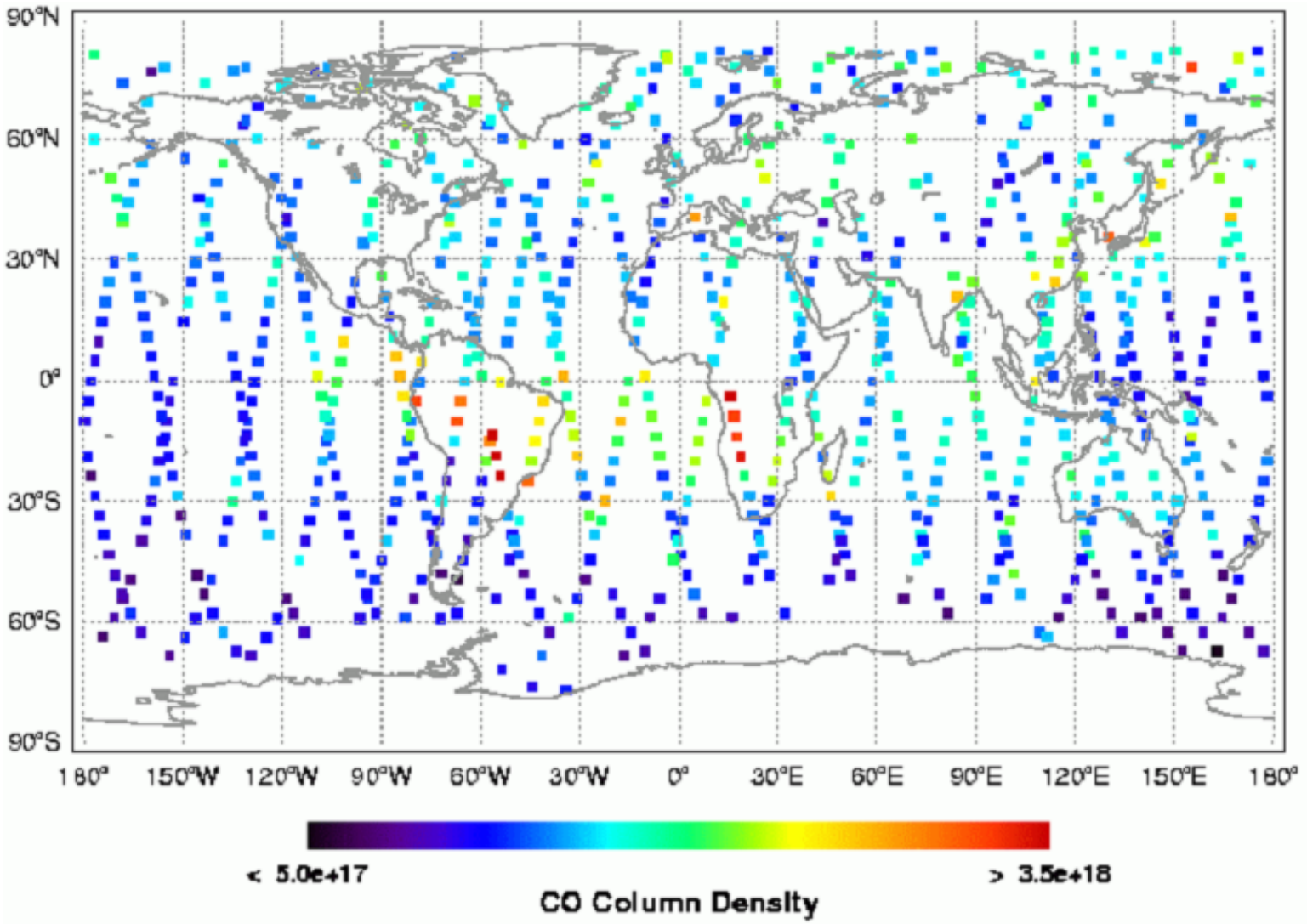


Water

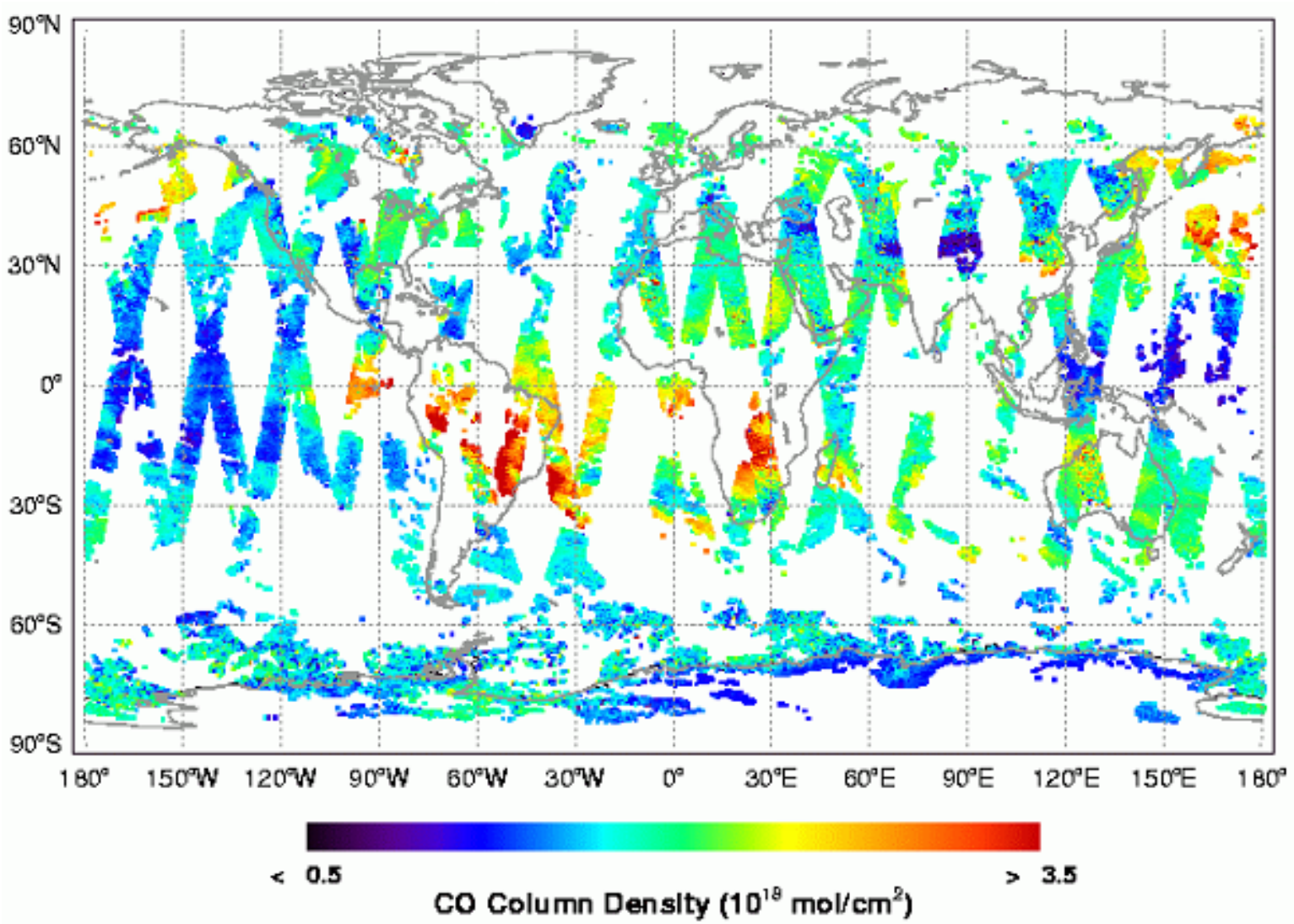
The AIRS-visible images (left) show the TES footprint locations (blue) over a variety of cloud and surface conditions.

The TES retrievals for this Step & Stare are shown for ozone and water with the TES retrieved cloud effective optical depth and height shown with gray circles.

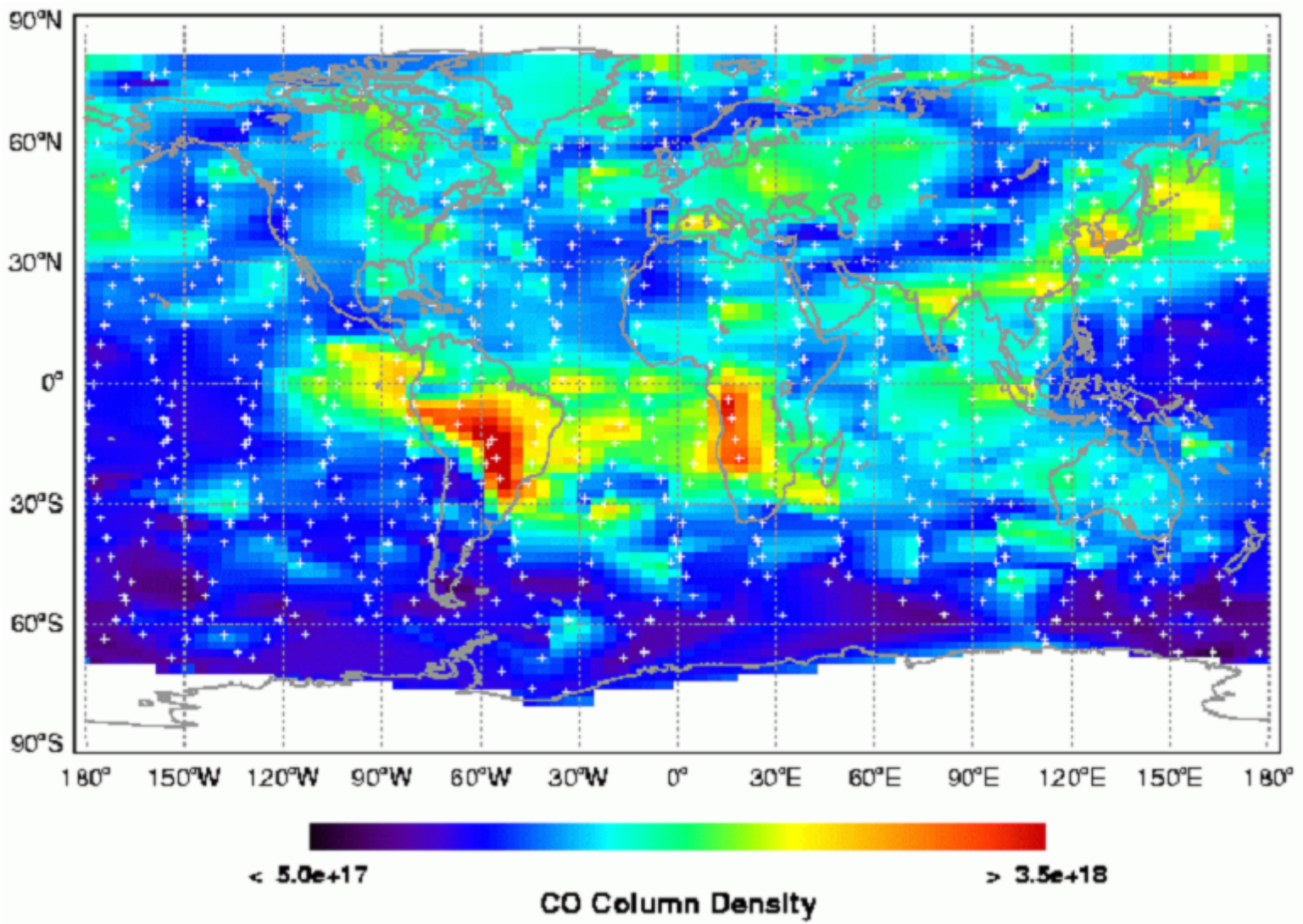
CO Column from TES, 9-20-04

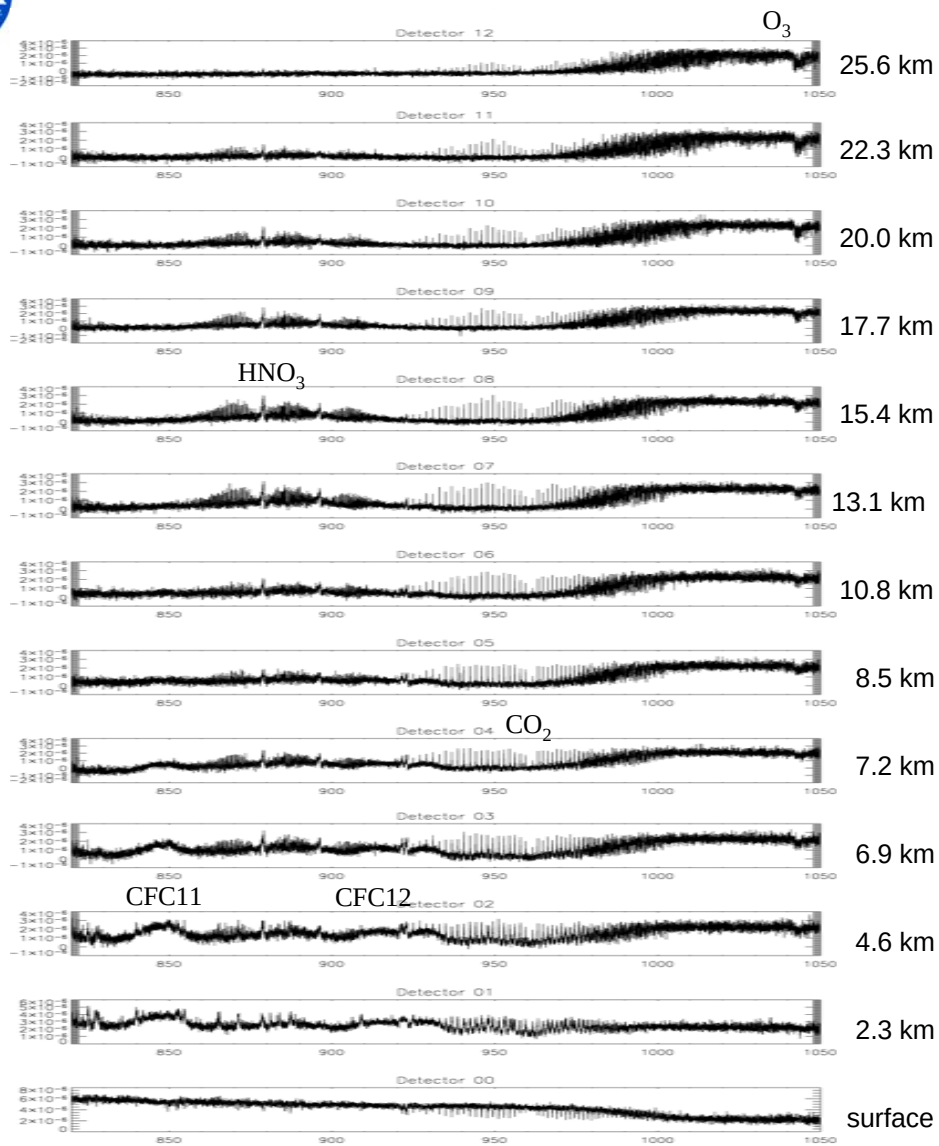


CO Column from MOPITT, 9-20-04



Interpolated CO column from TES, 9/20/04



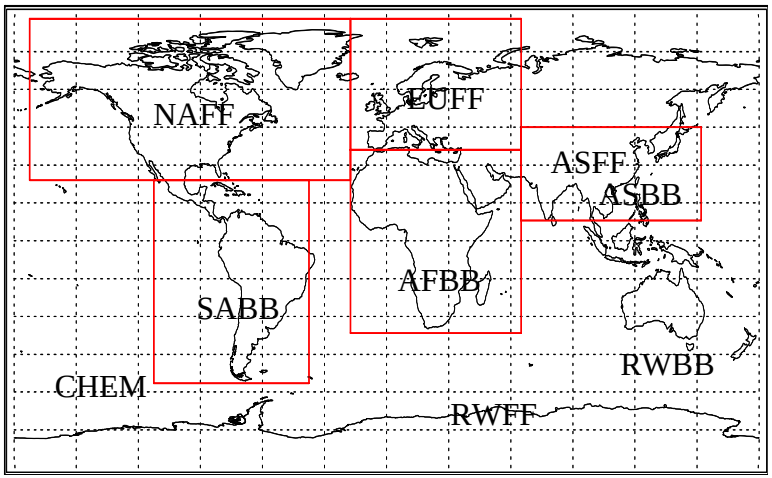


LIMB spectra for 57.6° S, 128.9° E, taken 9/20/2004. Spectra clearly show features due to Nitric Acid and CFC 11,12, with distinct altitude dependence.

O_3, CO_2 and H_2O spectral lines are also visible.

The surface is obscured by clouds.

Assimilation & Inverse Modeling of TES data



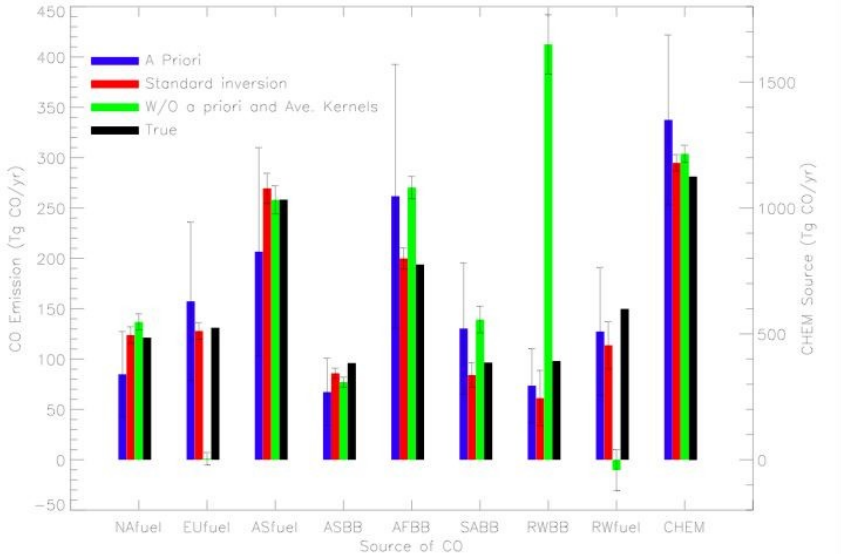


Figure 1: CO source aggregation. Taken from Jones, D. B. A., et al J. Geophys. Res.,(2003).

TES processing provides products necessary for assimilation of TES data including constraint vectors, averaging kernels, and error covariances on a fine pressure grid.

Figures show the potential of TES CO retrievals to Estimate CO sources with and without these products.

Constraint vector *Averaging kernel* *Model operator*

$$\hat{\mathbf{x}}^m = \mathbf{x}_c + \mathbf{A}(\ln \mathbf{F}(\mathbf{x}, \mathbf{u}) - \mathbf{x}_c)$$

Model TES retrieval

JPL
Jet Propulsion Laboratory
California Institute of Technology

CONCLUSIONS

TES is fulfilling its promise to provide the first-ever global overview of the key constituents of tropospheric chemistry and their inter-regional transport

For more information:

http://tes.jpl.nasa.gov

Backup

Jet Propulsion Laboratory
California Institute of Technology

Recommended Texts

TECHNIQUES

"*Remote Sensing by Fourier Transform Spectrometry*", Reinhard Beer, John Wiley & Sons Inc., New York (1992)

"*The Fast Fourier Transform*", E. Oran Brigham, Prentice-Hall Inc., New Jersey (1974)

SCIENCE

"*Inverse Methods for Atmospheric Sounding – Theory and Practice*", Clive D. Rodgers, World Scientific Publishing Co. (2000)

"*Chemistry of Atmospheres (2nd Ed)*", Richard P. Wayne, Clarendon Press, Oxford (1991)

"*Atmospheric Radiation – Theoretical Basis (2nd Ed.)*", Richard M. Goody & Yuk L. Yung, Oxford University Press (1989)

Potential Special Research Products

N = Nadir, L = Limb Viewing

Chemical Group	Common Name	Formula	Product Source	
H_xO_y	Hydrogen Peroxide	H_2O_2		L
	Mondeuterated Water Vapor	HDO	N	L
Carbon Compounds	Ethane	C_2H_6		L
	Acetylene	C_2H_2		L
	Formic Acid	HCOOH	N	L
	Methyl Alchohol	CH_3OH	N	L
	Peroxyacetyl Nitrate	$CH_3C(O)OONO_2$		L
	Acetone	$CH_3C(O)CH_3$		L
	Ethylene	C_2H_4		L
Nitrogen Compounds	Peroxynitric Acid	HO_2NO_2		L
	Ammonia	NH_3	N*	L
	Hydrogen Cyanide	HCN		L
	Dinitrogen Pentoxide	N_2O_5		L
Halogen Compounds	Hydrogen Chloride	HCl	N*	
	Chlorine Nitrate	$ClONO_2$		L
	Carbon Tetrachloride	CCl_4		L
	CFC-11	CCl_3F		L
	CFC-12	CCl_2F_2		L
	HCFC-21	$CHCl_2F$		L
	HCFC-22	$CHClF_2$		L
Sulphur Compounds	Sulphur Dioxide	SO_2	N	L
	Carbonyl Sulphide	OCS	N	L
	Hydrogen Sulphide	H_2S	N*	L
	Sulphur Hexafluoride	SF_6		L

* Volcanic/Industrial/Biomass Burning plume column densities only