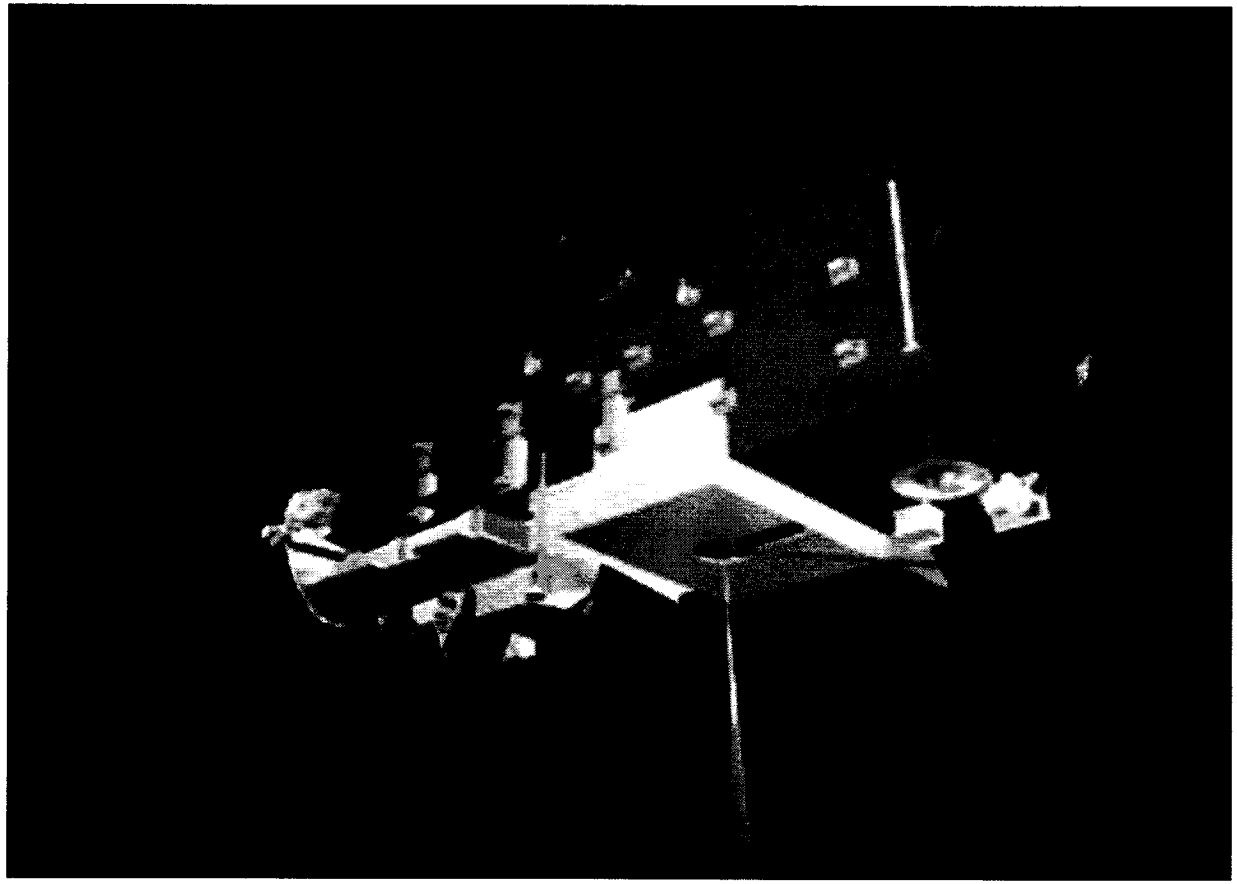
Characterization of Aura-TES (Tropospheric Emission Spectrometer) Nadir and Limb Retrievals

Helen Worden

TES Science Team

Jet Propulstion Laboratory, CalTech

The Tropospheric Emission Spectrometer (TES) on the Aura Platform



Nadir View

Advantages
Lower probability of cloud interference, good horizontal spatial resolution.

Disadvantages
Limited vertical resolution.

Primary Species
T_{atm}, H_2O, O_3, CH_4, CO

Limb View

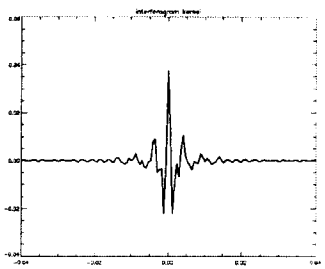
Advantages
Good vertical resolution. Enhanced sensitivity for trace constituents.

Disadvantages
Higher probability of cloud interference. Poorer line-of-sight spatial resolution.

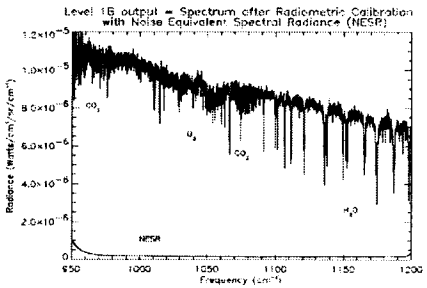
Primary Species
Nadir Species + HNO_3,NO,NO_2

TES Data Processing Steps

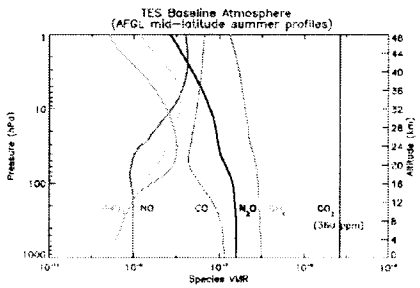
- Level 1A: Produces geolocated interferograms
- Level 1B: Produces [illegible] radiance spectra and estimated [illegible] spectral [illegible]
- Level 2: Produces [illegible] abundance [illegible] Pot Fourier [illegible] [illegible]
- Level 3: Produces global maps for each [illegible]



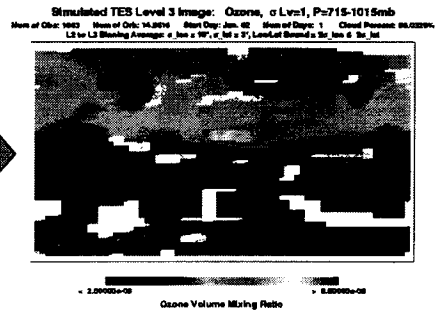
L1A



L1B



L2



L3

Level 2 Algorithms

- Binning and Ordering
  - Determines how measurements in a Global Survey are grouped for optimal processing.
- Retrieval
  - Algorithms for a single "target", either limb or nadir where nadir is the average of 2 scans (same ground location) in the Global Survey.
  - Following slides will describe:
    - Retrieval Strategy & Suppliers
    - ELANOR (Earth Limb and Nadir Operational Retrieval)
    - Error Analysis
- Product Generation
  - L2 standard products for each Global Survey
  - Temporal & spatial averaging

Level 2
Retrieval Strategy & Suppliers

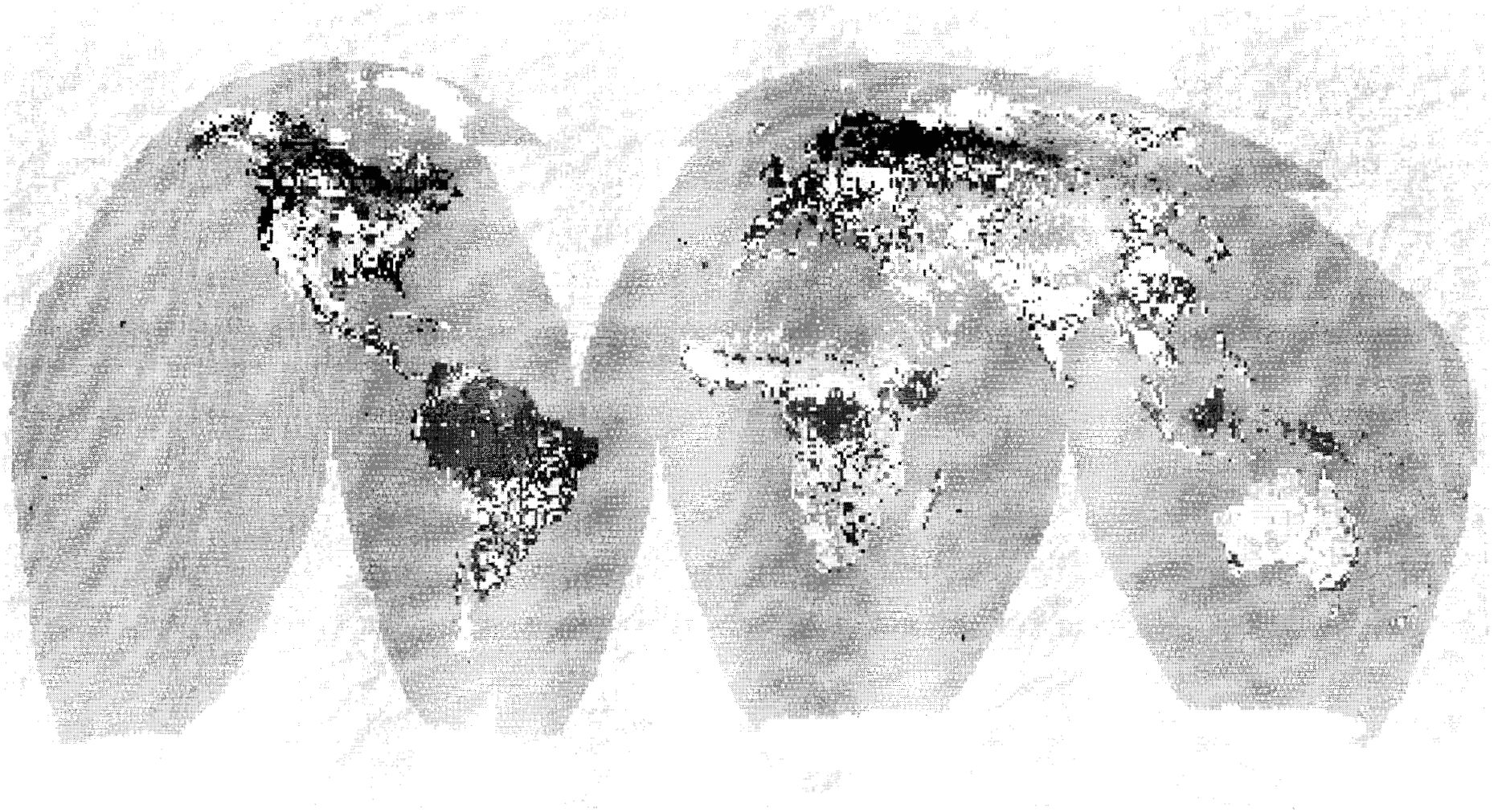
- Retrieval Suppliers
(Inputs for a single target scene)
    - Appropriate pressure grid including surface for nadir targets
    - Atmospheric & surface Full State Vector (FSV) initial guess
        - T, H_2O from meteorological data
        - Other trace gases from climatology data
        - land surface emissivity derived from surface type data
    - Microwindows (small spectral frequency ranges used for retrieval)
    - Mapping of FSV to retrieval parameters (and back to FSV)
    - *A priori* vectors and covariance matrices or other constraint types
    - L1B spectral averaging, apodization & microwindow extraction

Level 2
Retrieval Strategy & Suppliers

- Retrieval Strategy
(determine appropriate retrieval steps)
    - FSV input for cloud free target
    - Cloud determination step
    - Revision of input if cloud detected

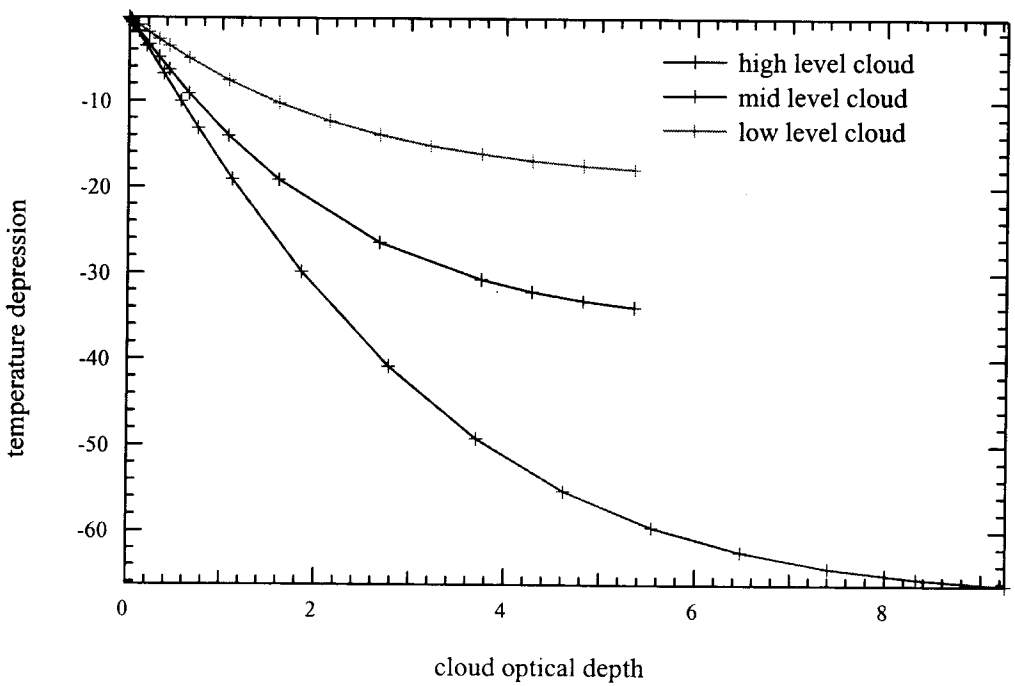
Global Land Use Database

Operational Support Product (OSP)
used by surface emissivity supplier



Level 2
Nadir Cloud Detection

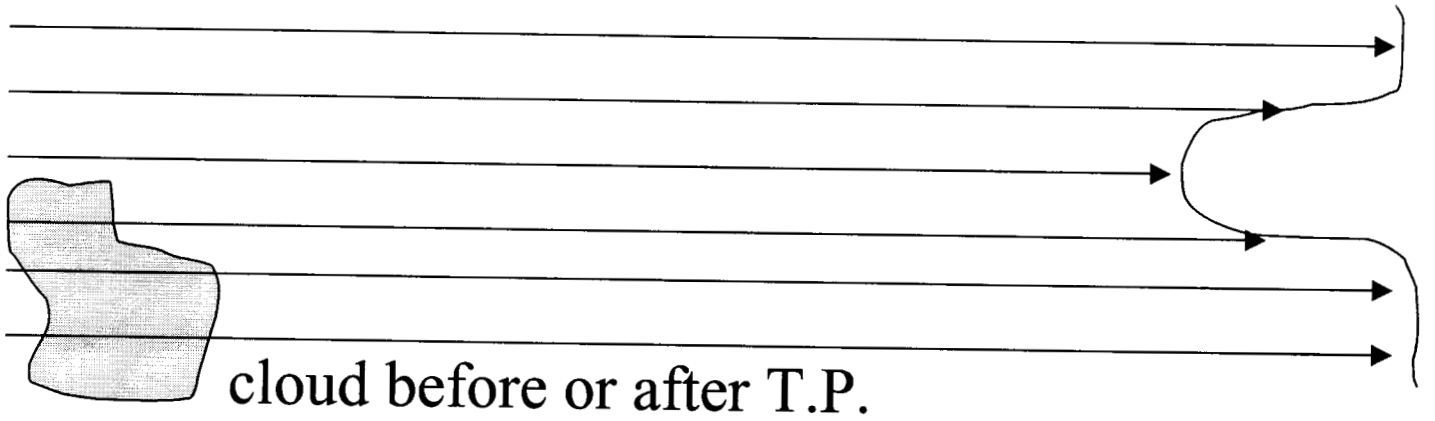
- Cloud detection will use tests of the radiances in the "window" region (11μm)
- L1B will flag large variability of this radiance across detectors so that nadir scenes with broken clouds or variable surface are rejected for L2.
- Retrieval strategy must make an initial estimate of the clear-sky radiance to identify uniform cloudy scenes (*i.e.*, cloud-filled footprint) vs. clear.



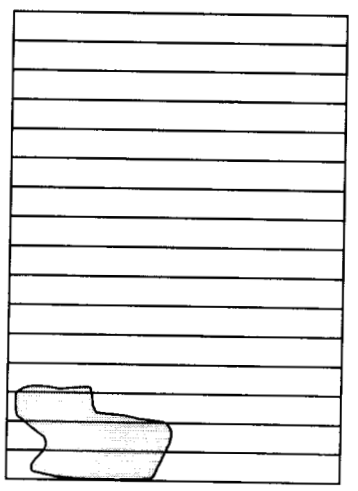
Cloudy-clear brightness temperature differences vs. optical depth for various cloud altitudes.

Limb Cloud Scenarios

1)

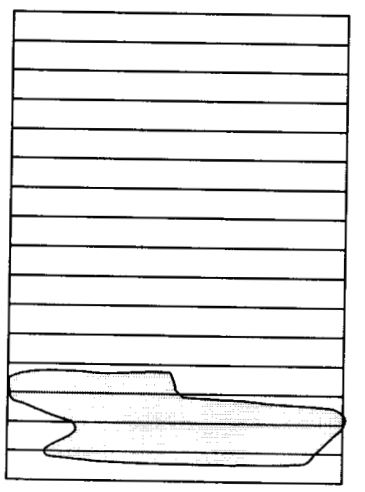


2)



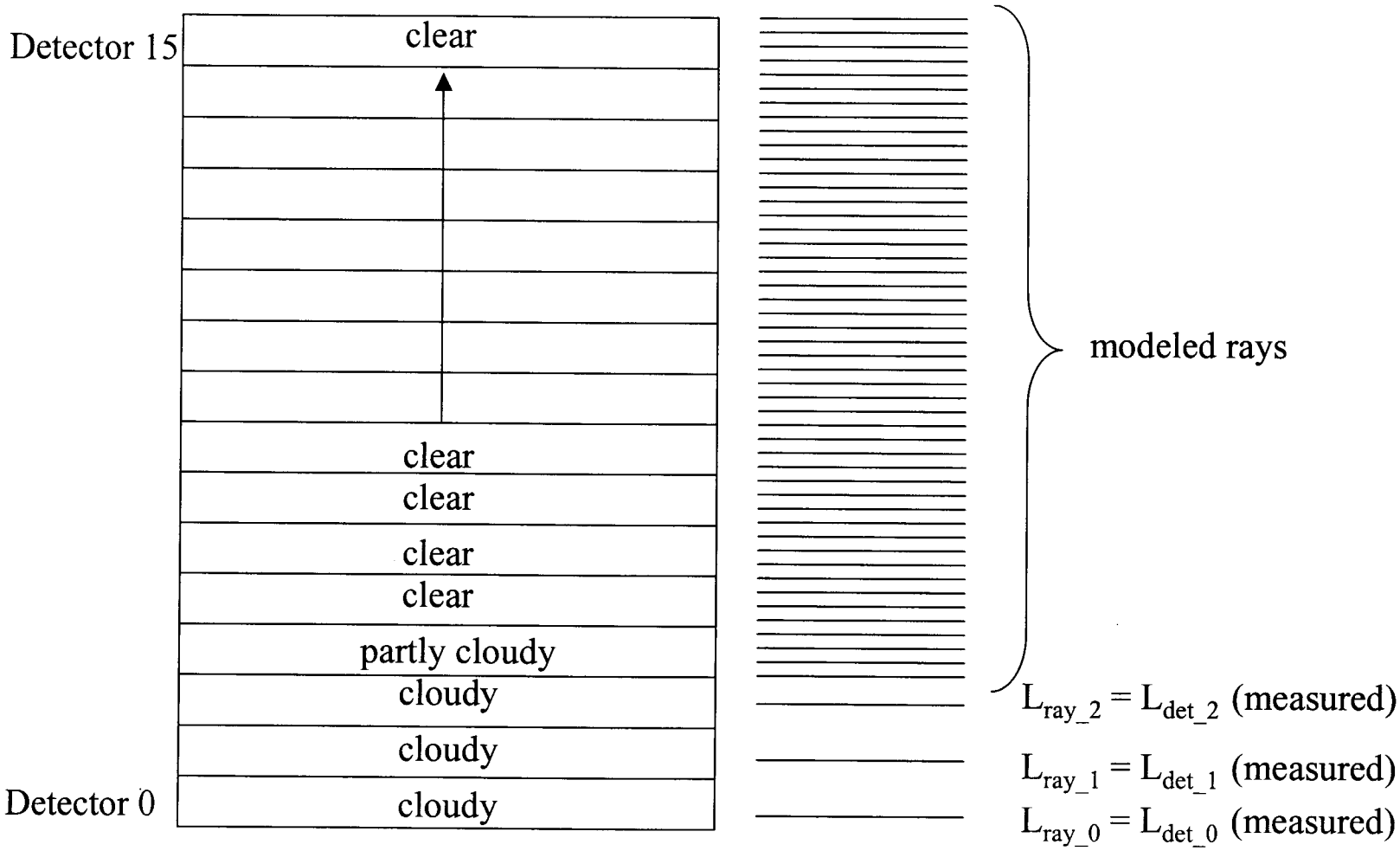
cloud filling
half of pixel

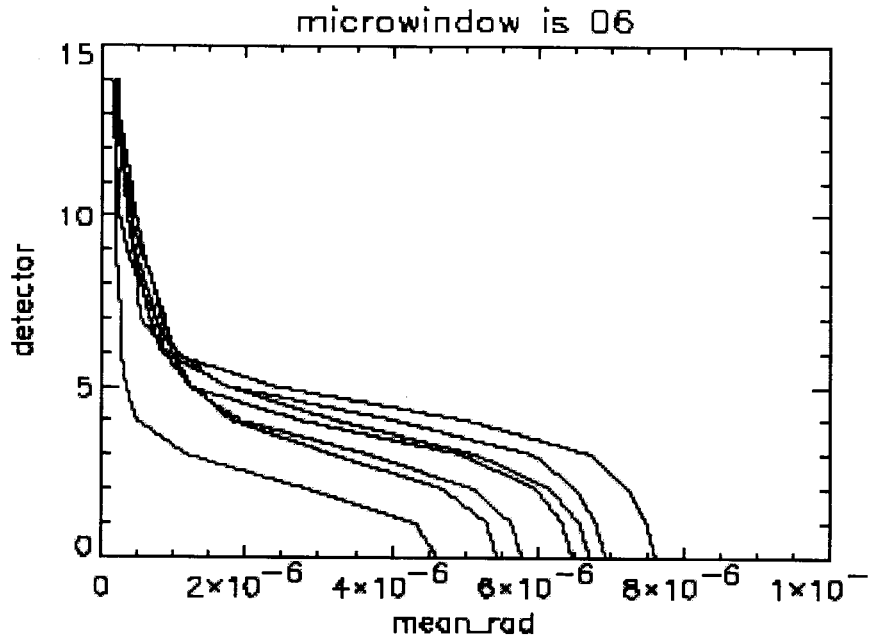
3)

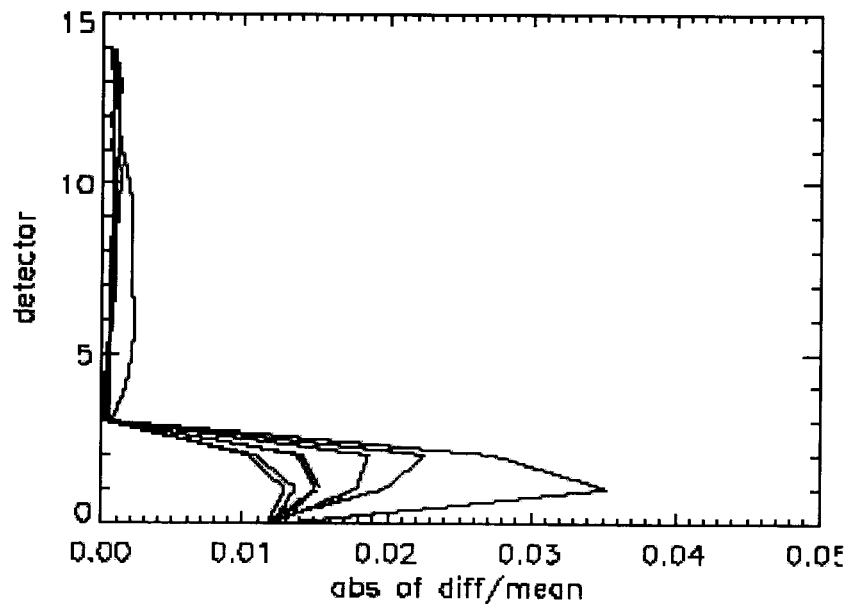


cloud filling
most of pixel

Approach for Including Cloud Radiances in FOV Integration







Test of 7 different latitude cases to estimate effect of substituting measured detector radiances for modeled limb rays.

Microwindow 6 is an optically thin case. Other optically thick cases have smaller radiance errors.

Level 2 Algorithms

ELANOR

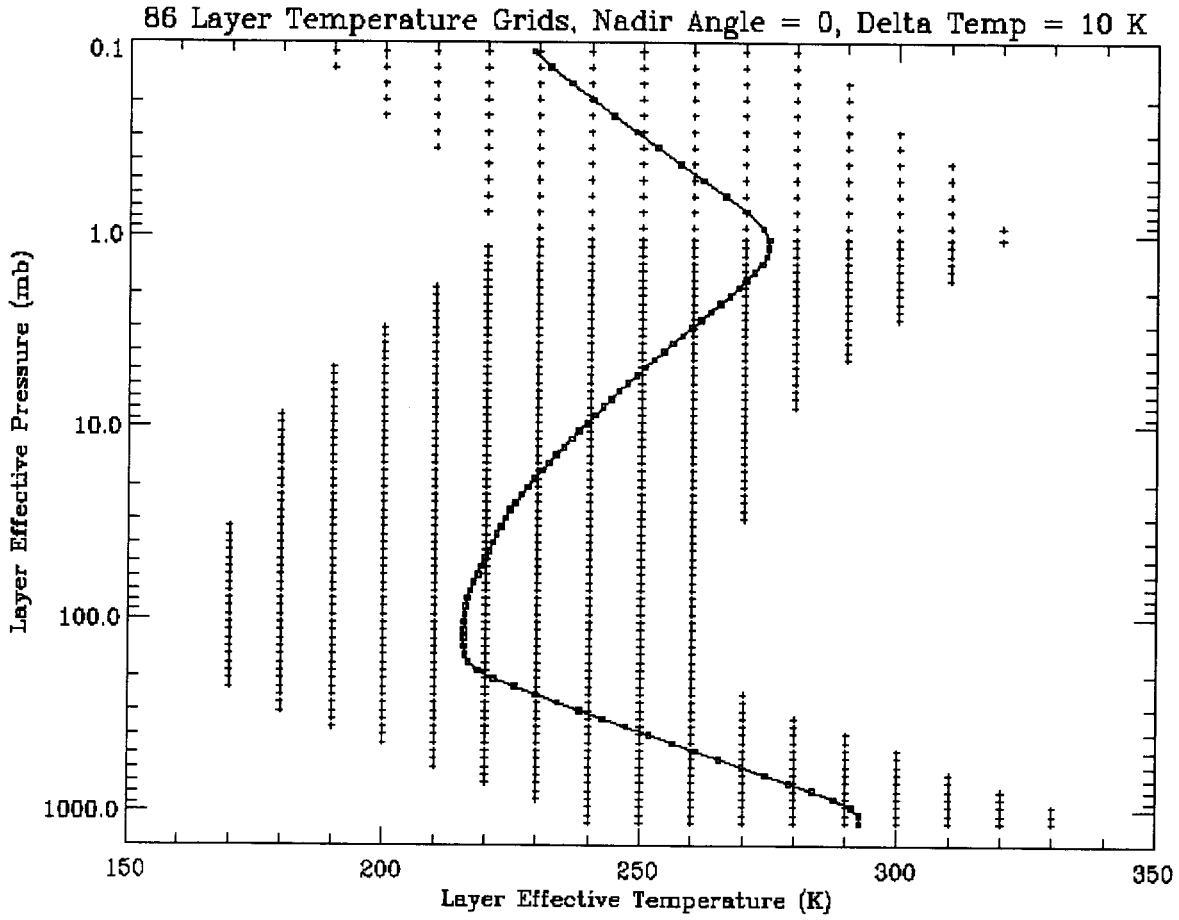
(Earth Limb And Nadir Operational Retrieval)

ELANOR is the algorithm for a single retrieval step

- Retrieval step is for a subset of retrieved species using spectral "microwindows" of the L1B data.
- Performs non-linear least squares fit with iterations of:
  - Forward model (FM) spectrum & Jacobian generation for estimate of atmospheric and surface FSV (full state vector)
    - Ray Tracing
    - Optical depth calculation (tables or line-by-line)
    - Radiative Transfer
    - ILS (Instrument Line Shape) convolution
    - Limb only: FOV (Field of View) integration
  - Inversion (FM compared to L1B data) for retrieval parameters and update of FSV.
    - Levenberg-Marquardt algorithm
- Algorithm inheritance from LBLRTM (AER) and SEASCRAPE (JPL).

Level 2
Absorption Coefficient Tables

Pressures and Temperatures for Stored Absorption Coefficients



- "ABSCO" tables allow better performance with only slightly worse accuracy (compared to line-by-line calculation)

- Must be read efficiently and storage becomes an architecture design issue.

Level 2

Error Analysis & Post-retrieval Processing

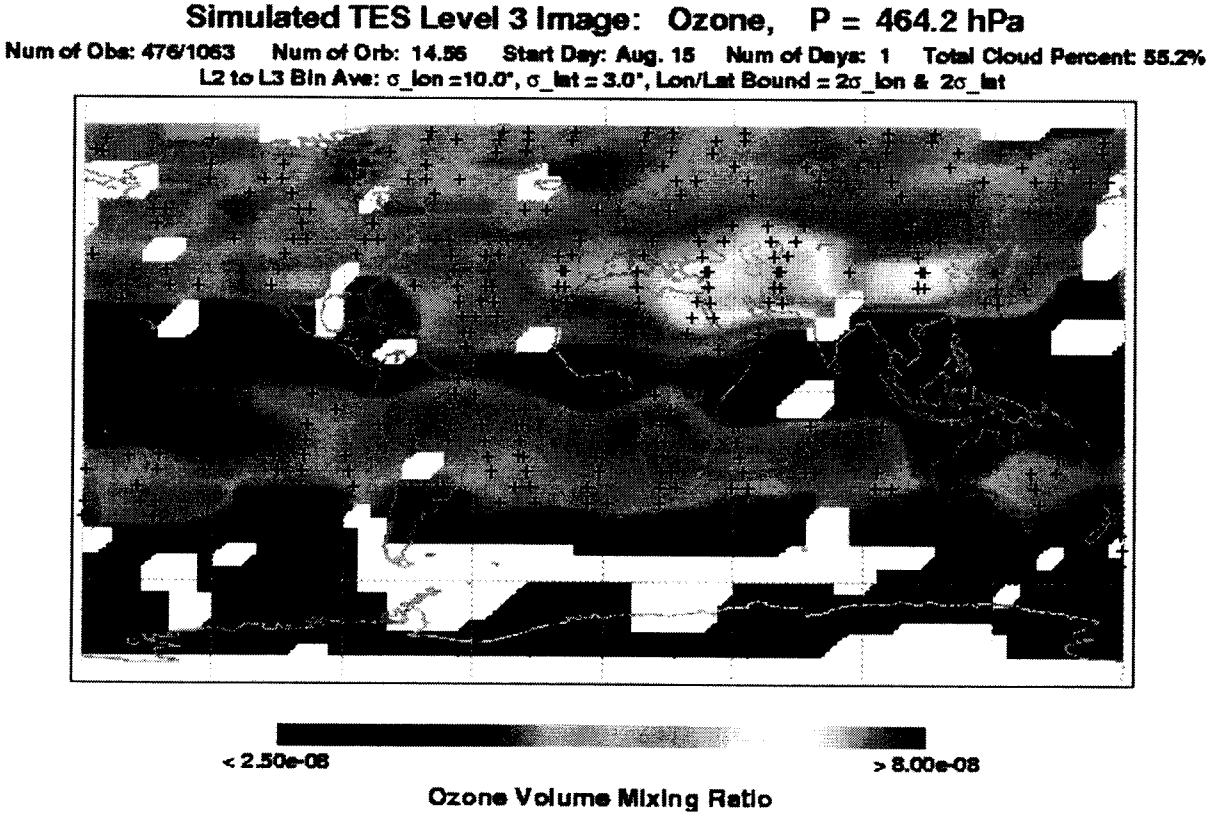
For each retrieved parameter in a target scene, we estimate covariances for:

- Retrieval noise (using measurement NESR)
- Smoothing error (accuracy due to vertical smoothing)
- Systematic errors from instrument and model

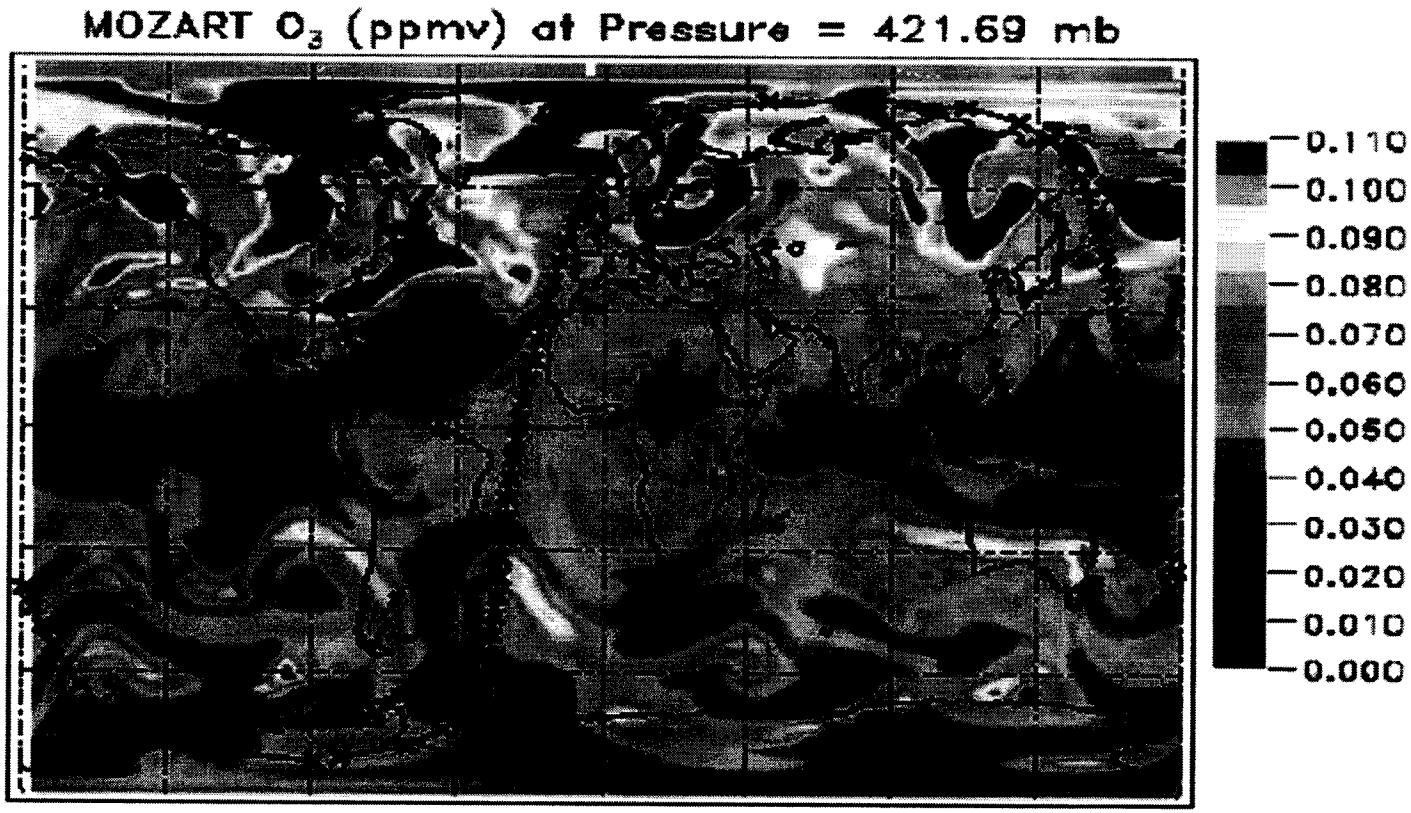
For weekly, monthly and spatially averaged products we plan to use a Kalman filter approach with the single target retrievals in order to minimize the impact of *a priori.* This is still in the planning stages (no prototype yet).

Level 3 Algorithms

Level 3 will mainly produce browse products with gridded, interpolated map images.



Single Orbit Test



Mozart model for O_3 at 422 mb with TES targets for a single orbit overplotted (**X**)

Input and Assumptions

- Simulated TES spectra were created using profiles sampled from MOZART3 (NCAR) model data. MOZART resolution is 2.8°x2.8° with 66 vertical levels (0-140 km).

- MOZART3 was driven by WACCM met. fields; data are for the Oct. 2 day of an arbitrary year. (WACCM = Whole Atmosphere Community Climate Model, from NCAR)

- Same profiles used for both limb and nadir retrievals (simple vertical profiles based on lat/lon sampling of the model data).

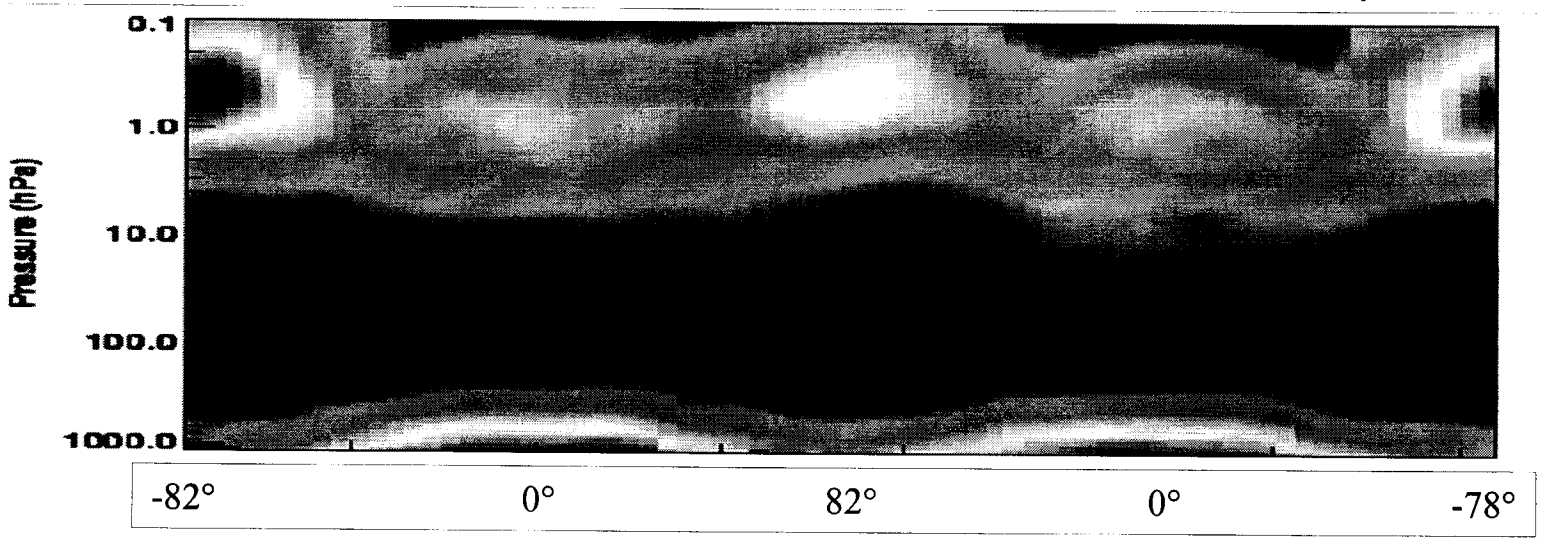
- No clouds or aerosols. Results from this 1st test will be a baseline for later tests.

- Retrieved surface T, but not surface emissivity.

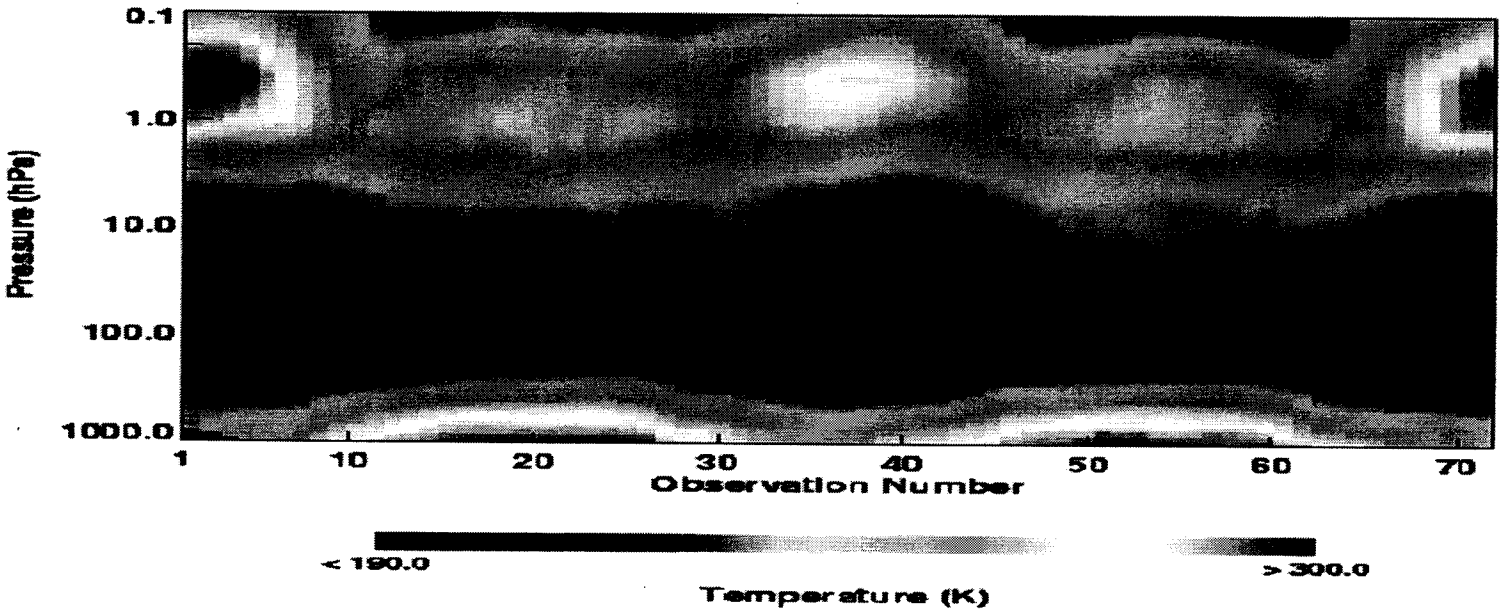
- Noise added to simulations is from current estimates with delivered detectors.

TES Filter ID	2B1	1B1	1B2	2A1	2A4	1A1
Frequency Range (cm^{-1})	650 – 900	820 – 1050	950 – 1150	1100 – 1325	1700 – 1950	1900 – 2250
Nadir NESR (nW) 16 pixel avg.	11		8.3	8.0		3.8
Limb NESR (nW)	59	51	36	33	12	9.7

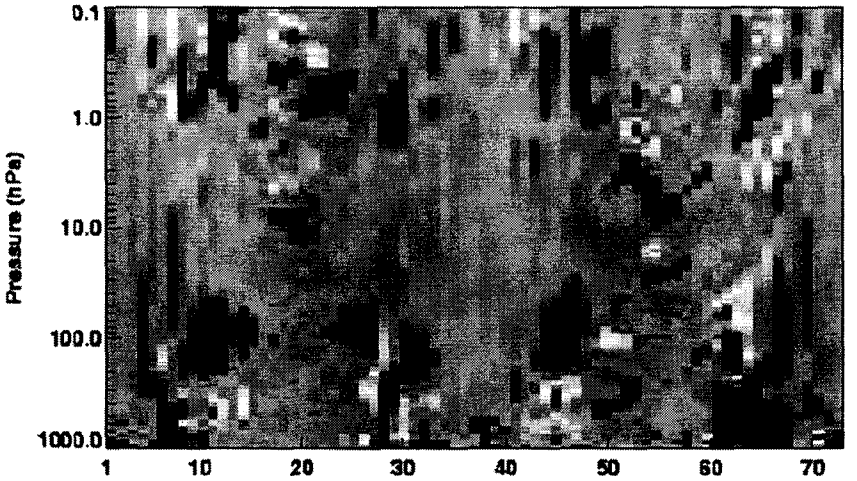
MOZART model cross-section along TES orbit track: Temperature



TES Nadir Retrieval: Temperature

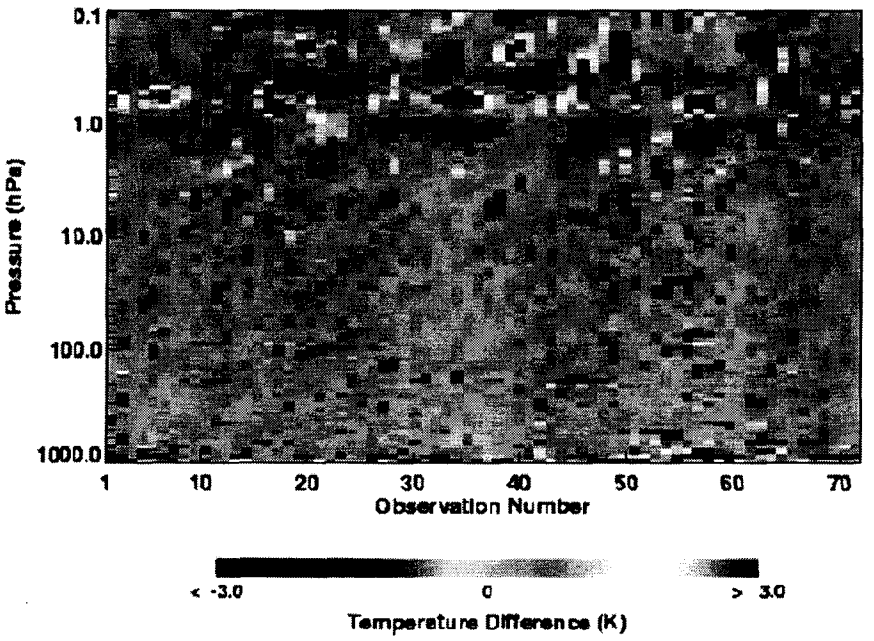


True vs. Initial Guess Along TES Orbit Track: Temperature



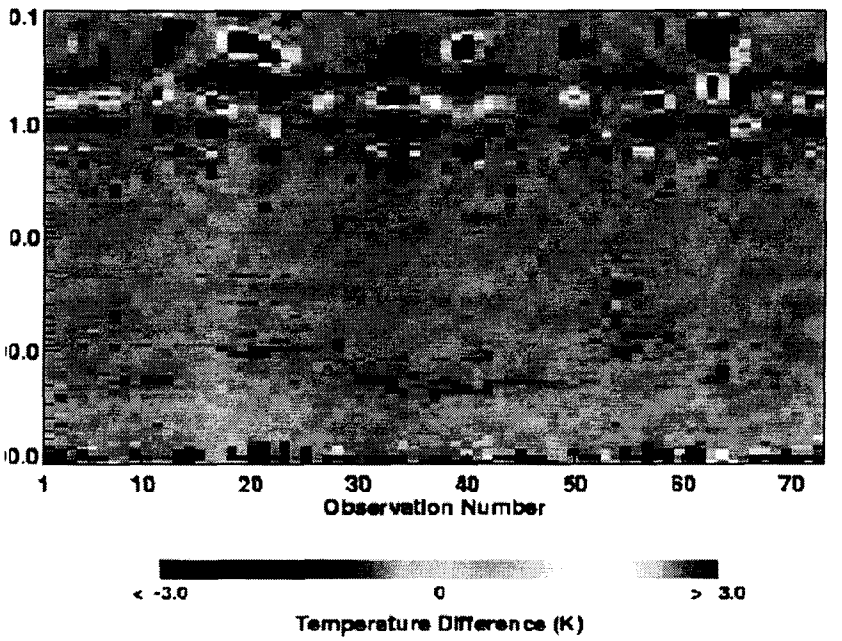
True vs. Retrieval Along TES Orbit Track: Temperature

Nadir

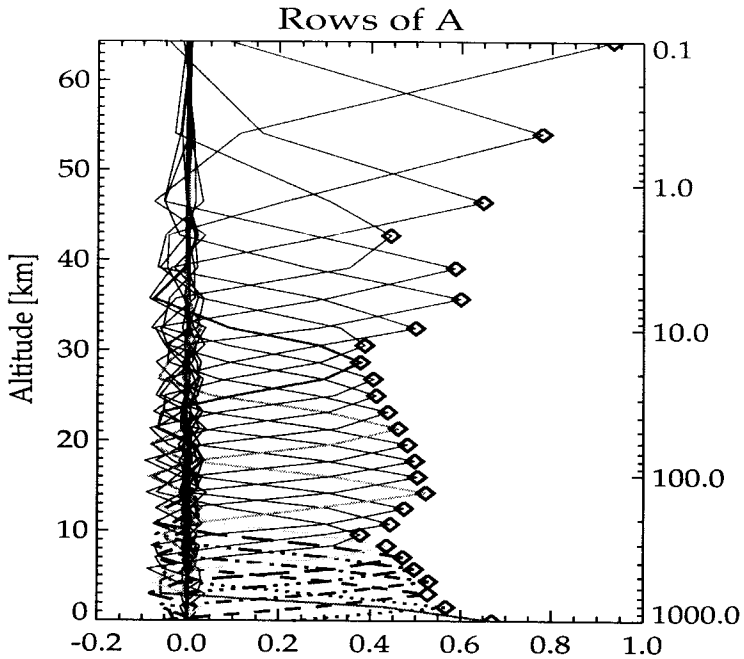


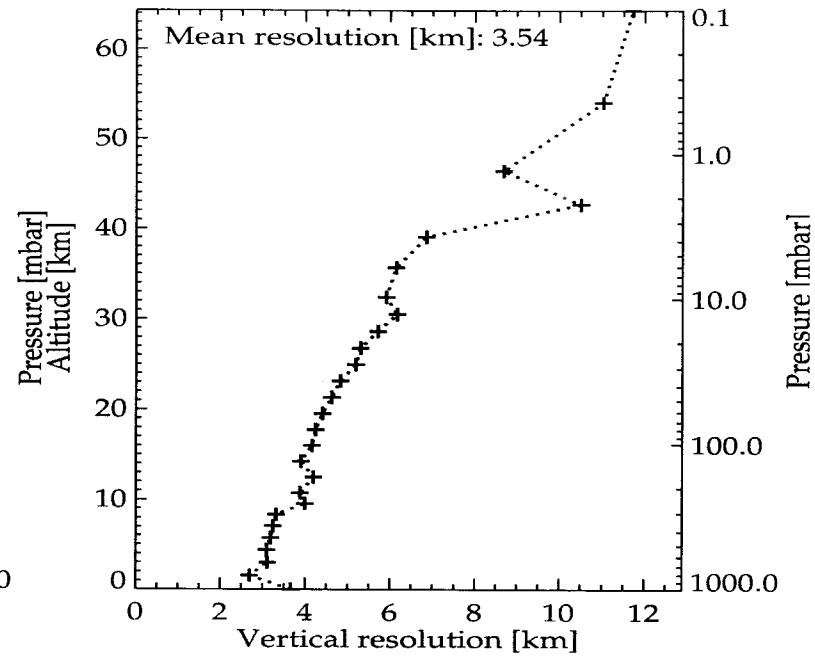
True vs. Retrieval Along TES Orbit Track: Temperature, Limb

Limb



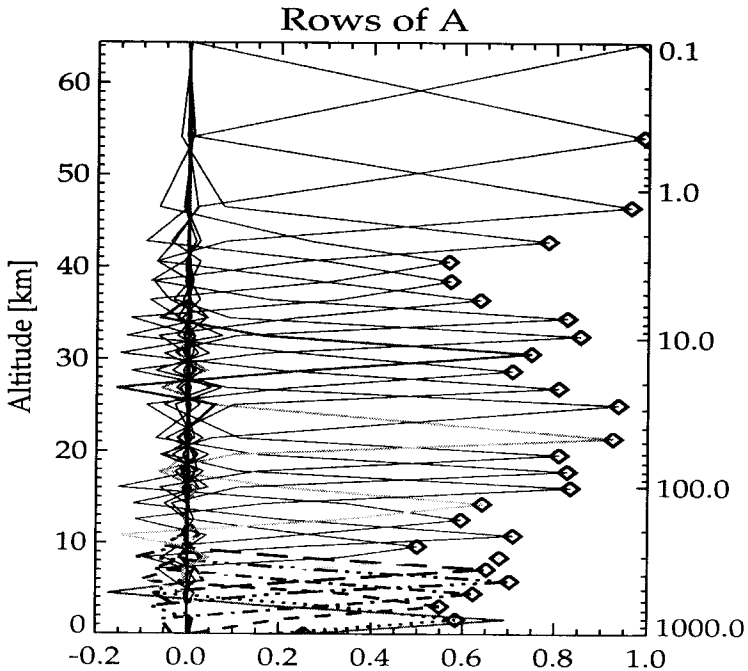
Nadir T_{atm} Averaging Kernel

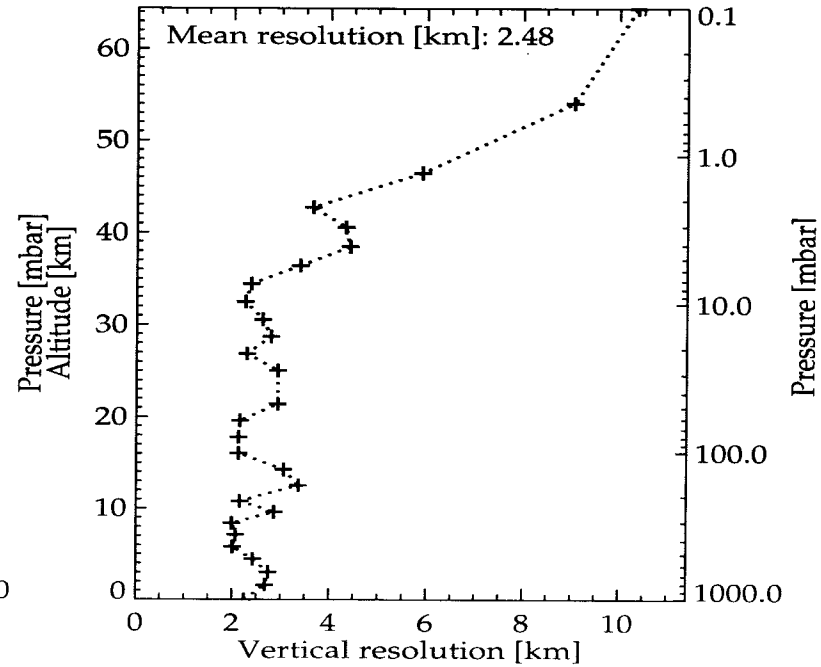




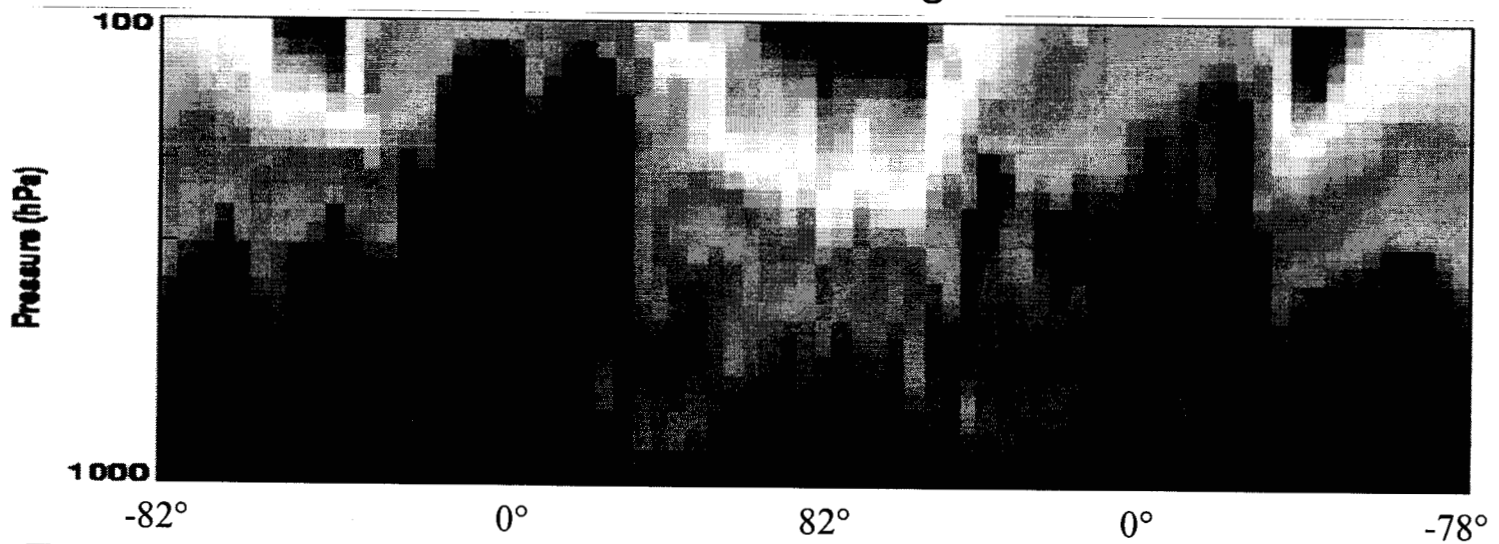
$$A = (K^T S_m^{-1} K + S_a^{-1})^{-1} K^T S_m^{-1} K$$

Limb T_{atm} Averaging Kernel

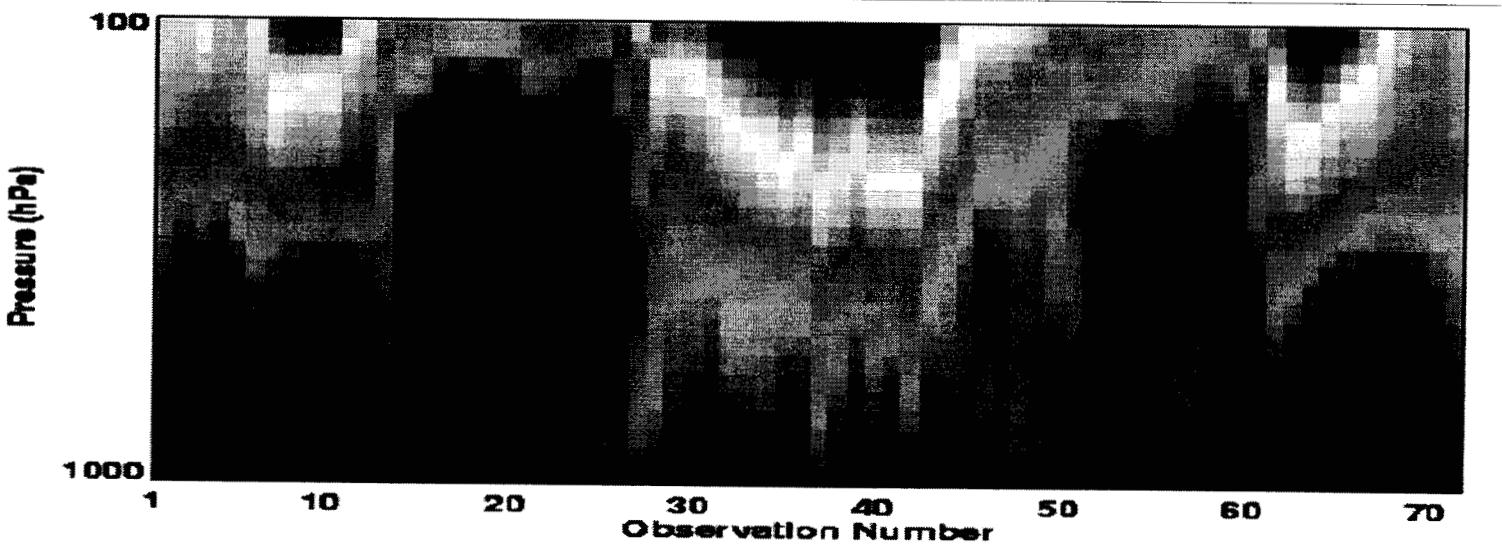


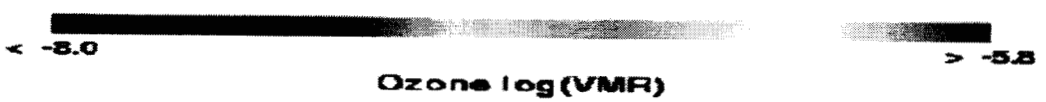


MOZART model cross-section along TES orbit track: Ozone



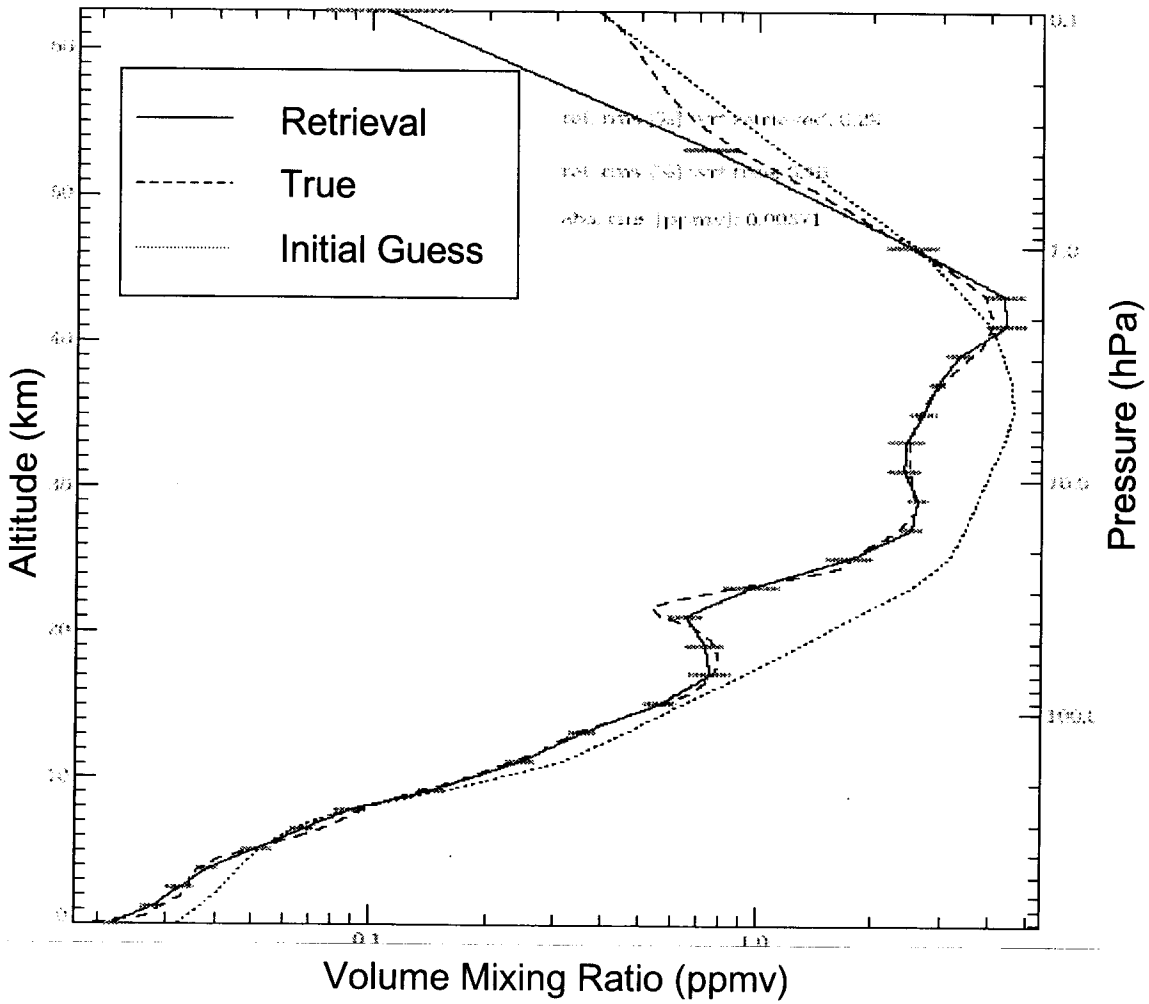
TES Nadir Retrieval: Ozone



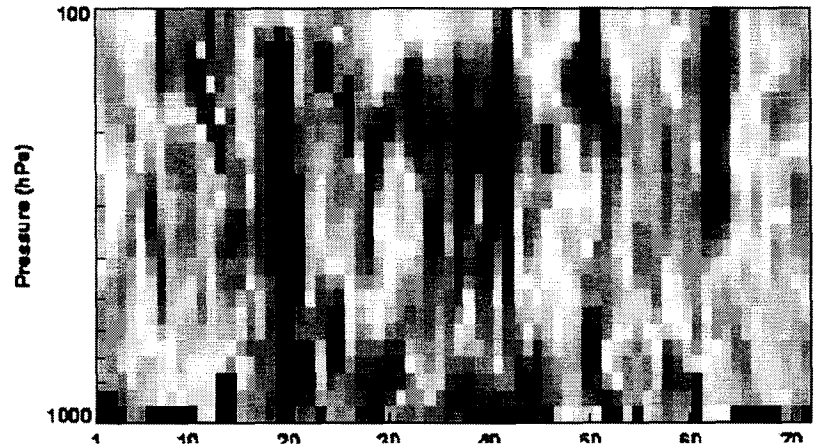


Single Orbit Test

Antarctic Limb Ozone Retrieval Example

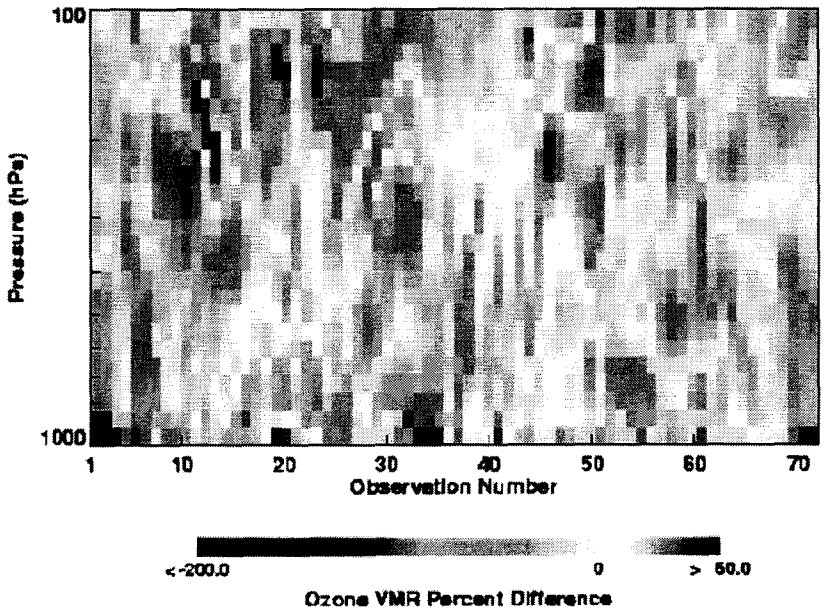


True vs. Initial Guess Along TES Orbit Track: Ozone



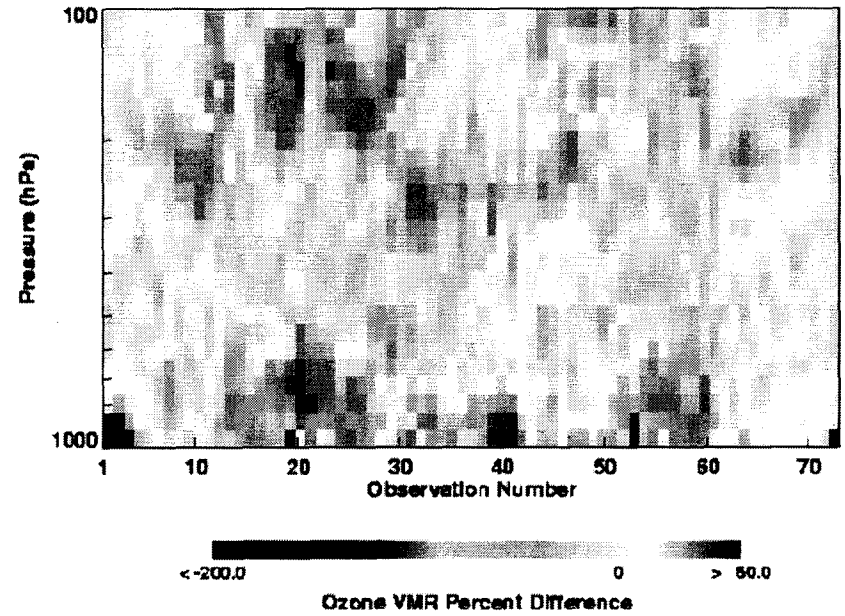
True vs. Retrieval Along TES Orbit Track: Ozone

Nadir

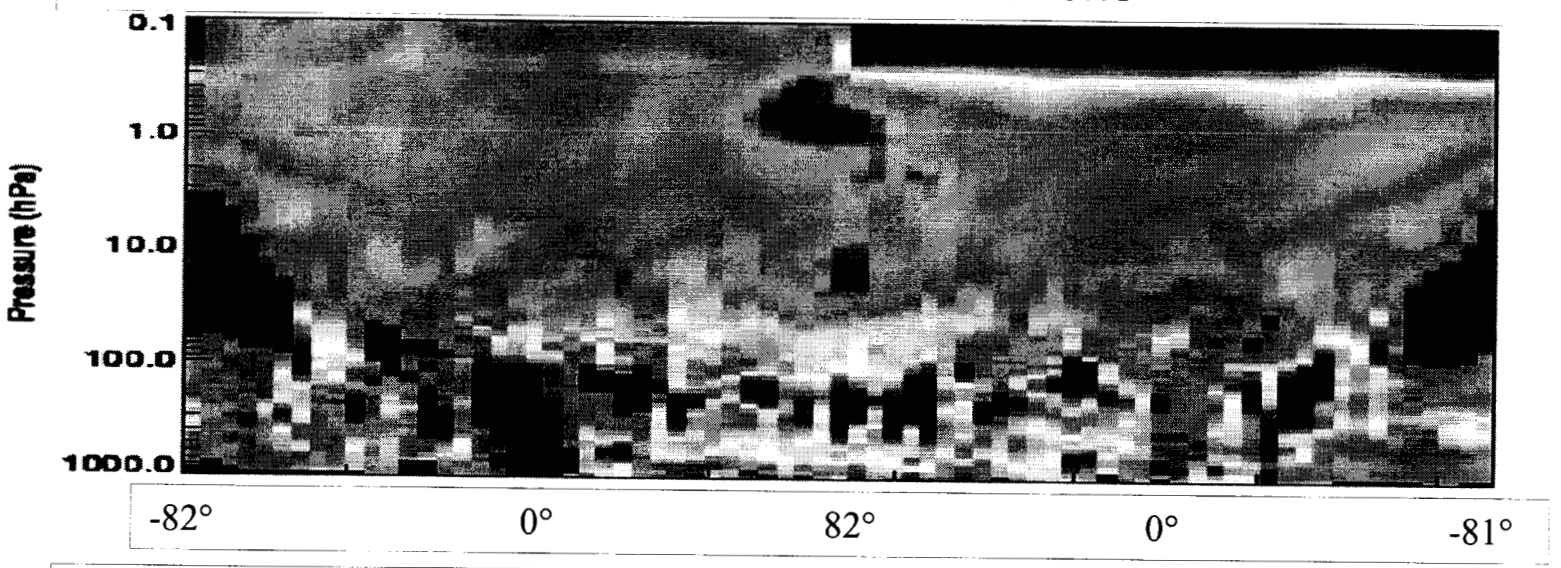


True vs. Retrieval Along TES Orbit Track: Ozone, Limb

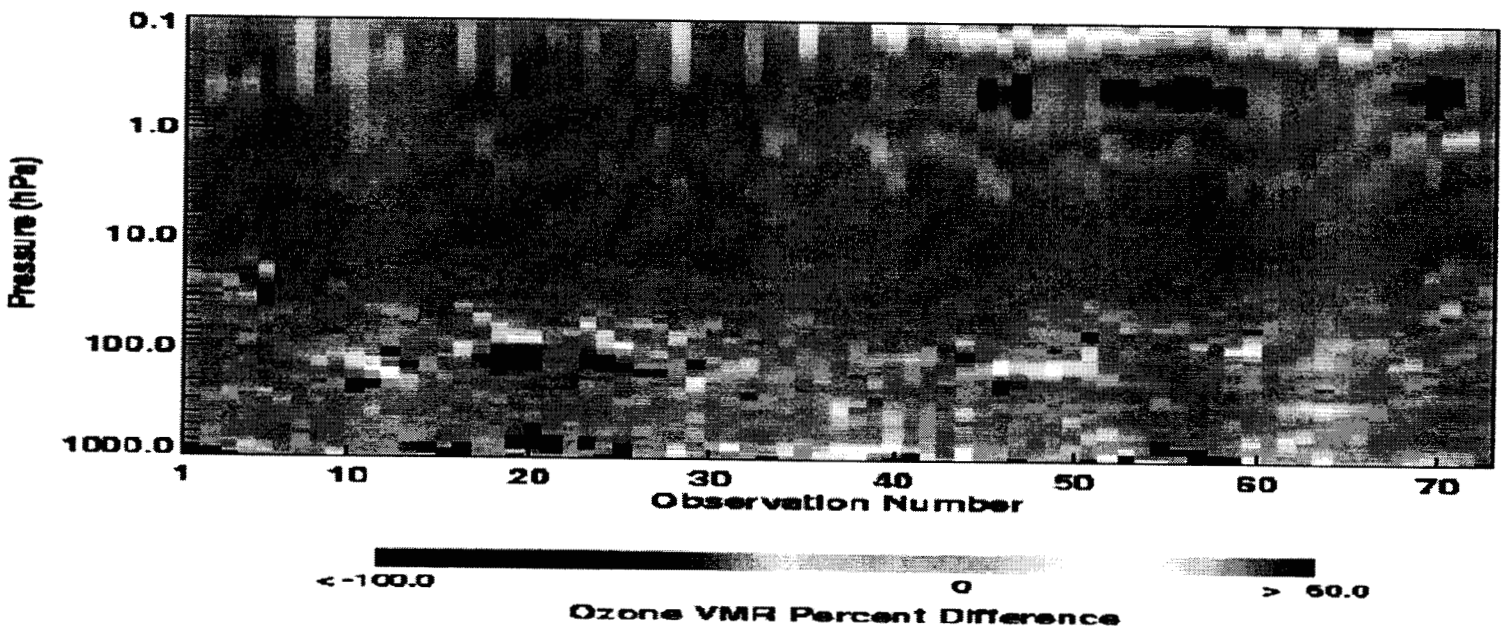
Limb



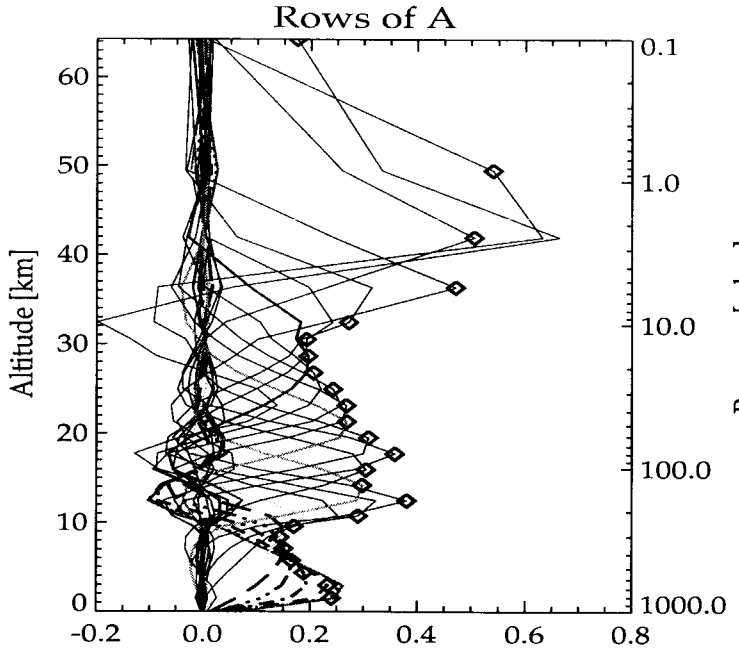
True vs. Initial Guess: Ozone

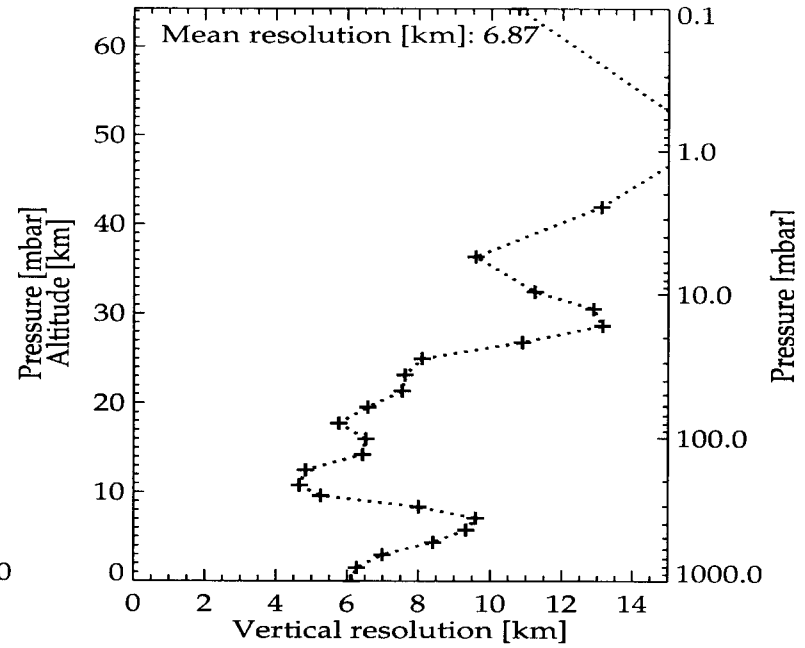


True vs. TES Limb Retrieval: Ozone

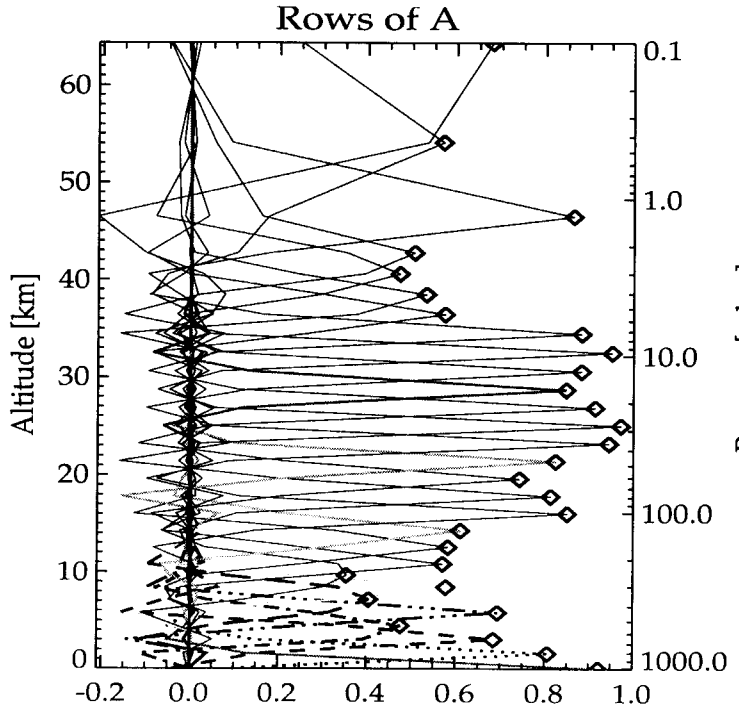


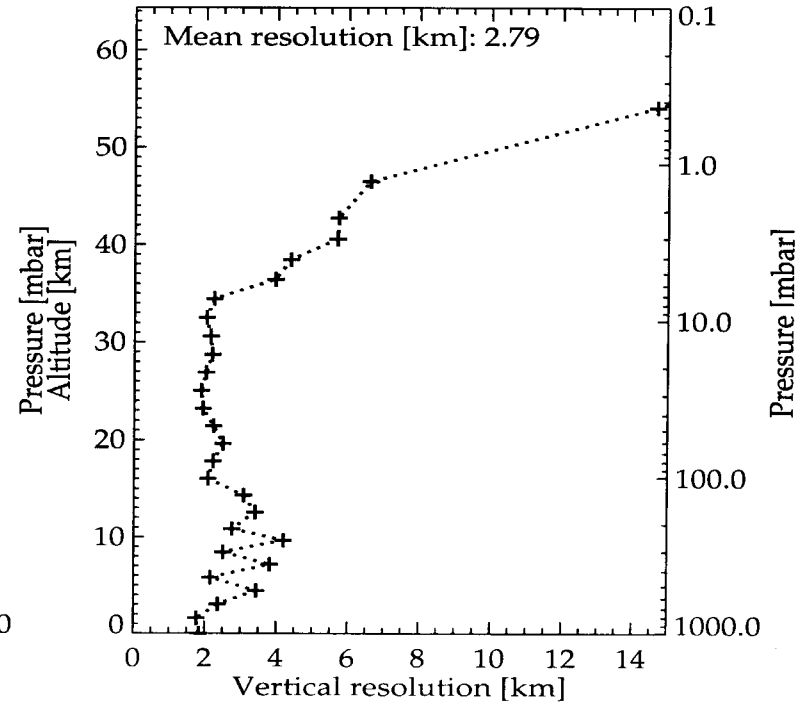
Nadir O_3 Averaging Kernel

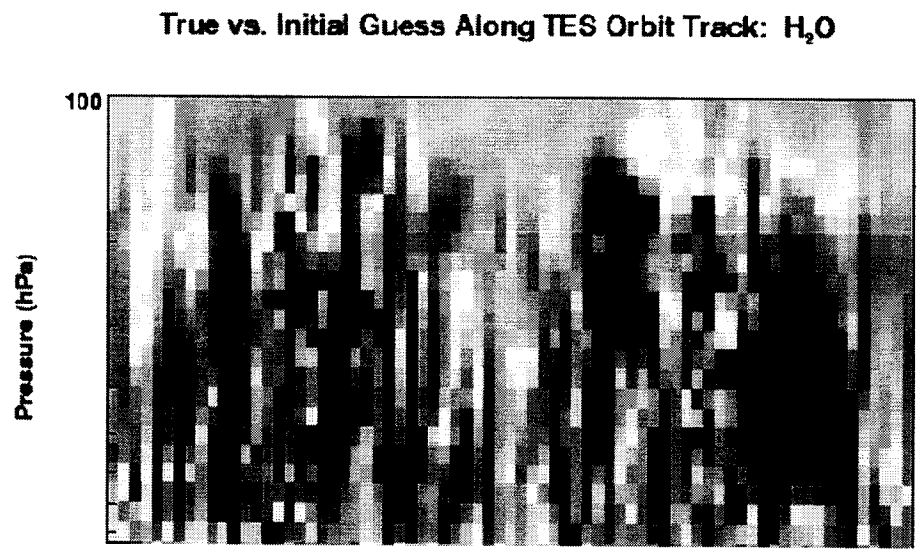


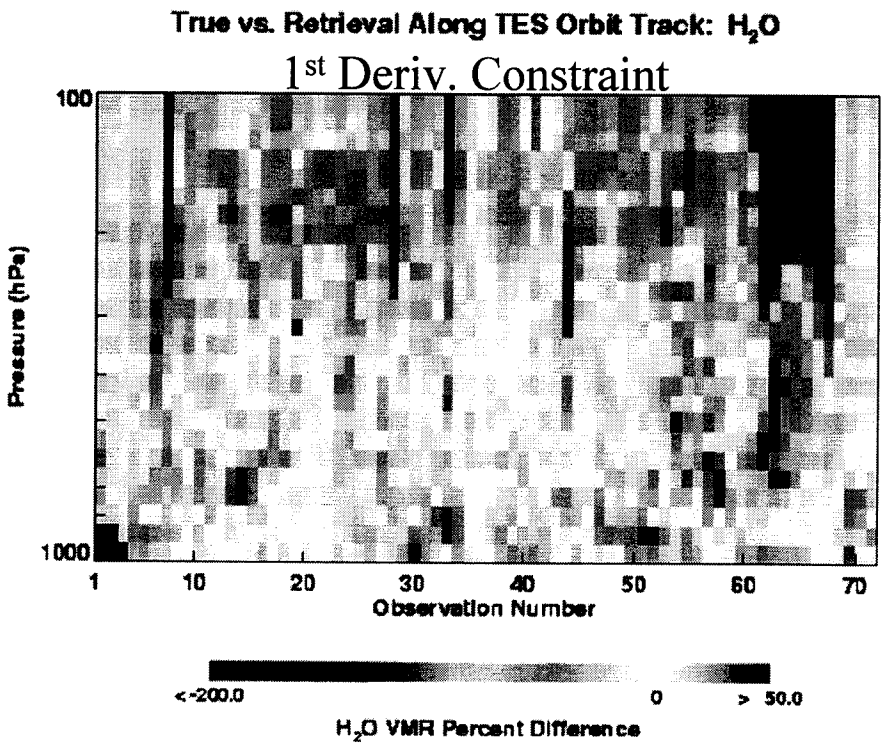


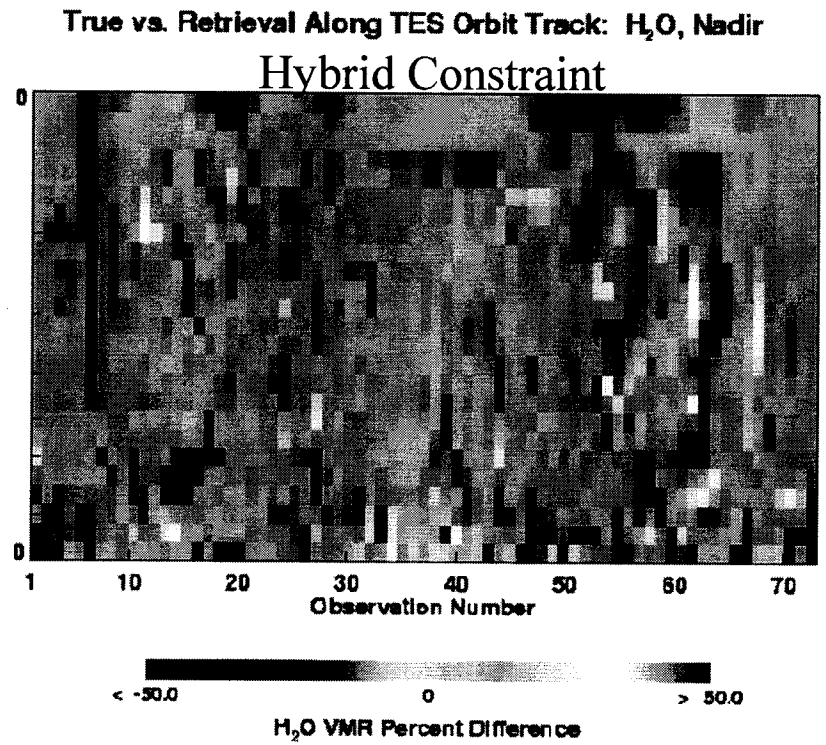
Limb O_3 Averaging Kernel

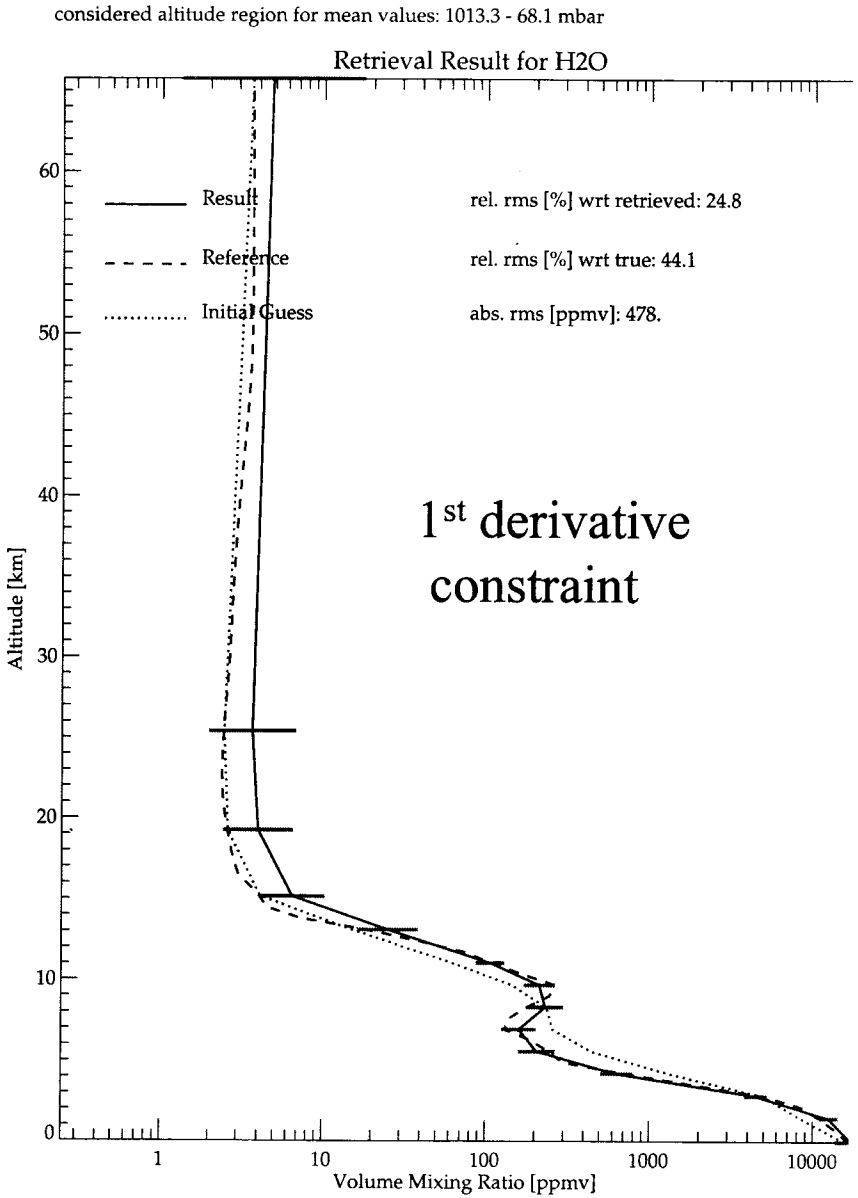


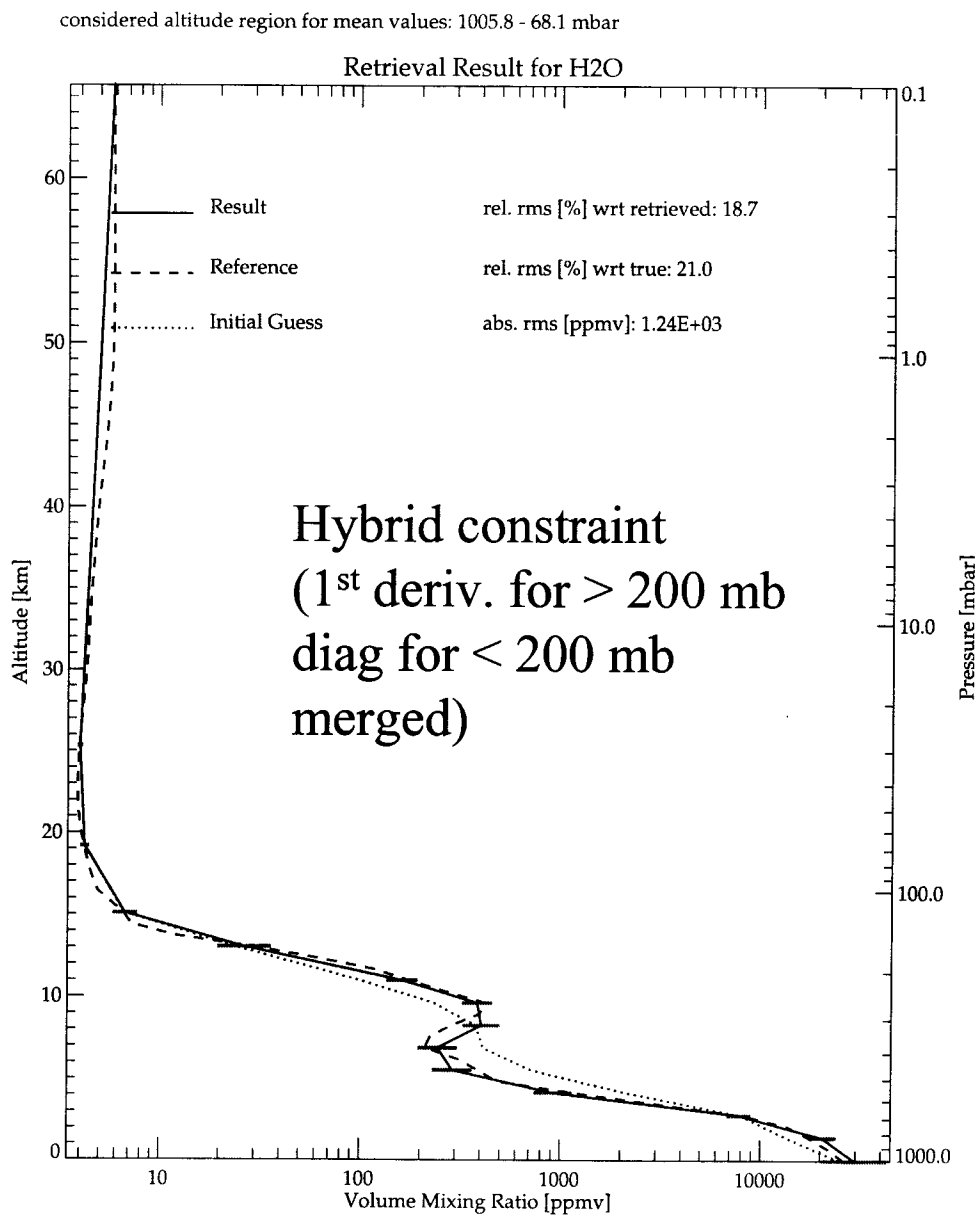



True vs. Initial Guess Along TES Orbit Track: H_2O
100
Pressure (hPa)


True vs. Retrieval Along TES Orbit Track: H_2O
1st Deriv. Constraint
100
1000
Pressure (hPa)
1
10
20
30
40
50
60
70
Observation Number
< -200.0
0
> 50.0
H_2O VMR Percent Difference


True vs. Retrieval Along TES Orbit Track: H_2O, Nadir
Hybrid Constraint
0
0
1
10
20
30
40
50
60
70
Observation Number
< -50.0
0
> 50.0
H_2O VMR Percent Difference


considered altitude region for mean values: 1013.3 - 68.1 mbar
Retrieval Result for H2O
Result
Reference
Initial Guess
rel. rms [%] wrt retrieved: 24.8
rel. rms [%] wrt true: 44.1
abs. rms [ppmv]: 478.
1st derivative constraint
Altitude [km]
Volume Mixing Ratio [ppmv]
/project/SOT/nadir/TWPR_output/t10/OBS_11369_t10/4_result_plot.ps
Fri Feb 22 12:10:46 PST 2002, target = H2O


considered altitude region for mean values: 1005.8 - 68.1 mbar
Retrieval Result for H2O
Result
Reference
Initial Guess
rel. rms [%] wrt retrieved: 18.7
rel. rms [%] wrt true: 21.0
abs. rms [ppmv]: 1.24E+03
Hybrid constraint (1st deriv. for > 200 mb diag for < 200 mb merged)
Altitude [km]
Pressure [mbar]
Volume Mixing Ratio [ppmv]
/project/SOT/nadir/TWPR_output/t11/OBS_11369_t11/4_result_plot.ps
Sun Mar 3 13:51:59 PST 2002, target = H2O

Statistics for Nadir Cases

Temperature Retrievals

Region 17-19 observations each	Trop os. Vertical Resolution (km)	Degrees of Freedom Signal	Trop os. RMS Error (K)
Arctic & Antarctic	**3.4**	**13.8**	**0.72**
Southern Mid-Lat.	**3.3**	**14.8**	**0.81**
Tropics	**3.0**	**16.3**	**0.76**
Northern Mid-Lat.	**3.3**	**15.3**	**0.82**

H_2O Retrievals

Region 17-19 observations each	Trop os. Vertical Resolution (km)	Degrees of Freedom Signal	Total Column Error (%)
Arctic & Antarctic	**5.1**	**4.8**	**10.4**
Southern Mid-Lat.	**3.8**	**3.0**	**2.6**
Tropics	**3.8**	**4.6**	**3.5**
Northern Mid-Lat.	**3.8**	**3.9**	**6.1**

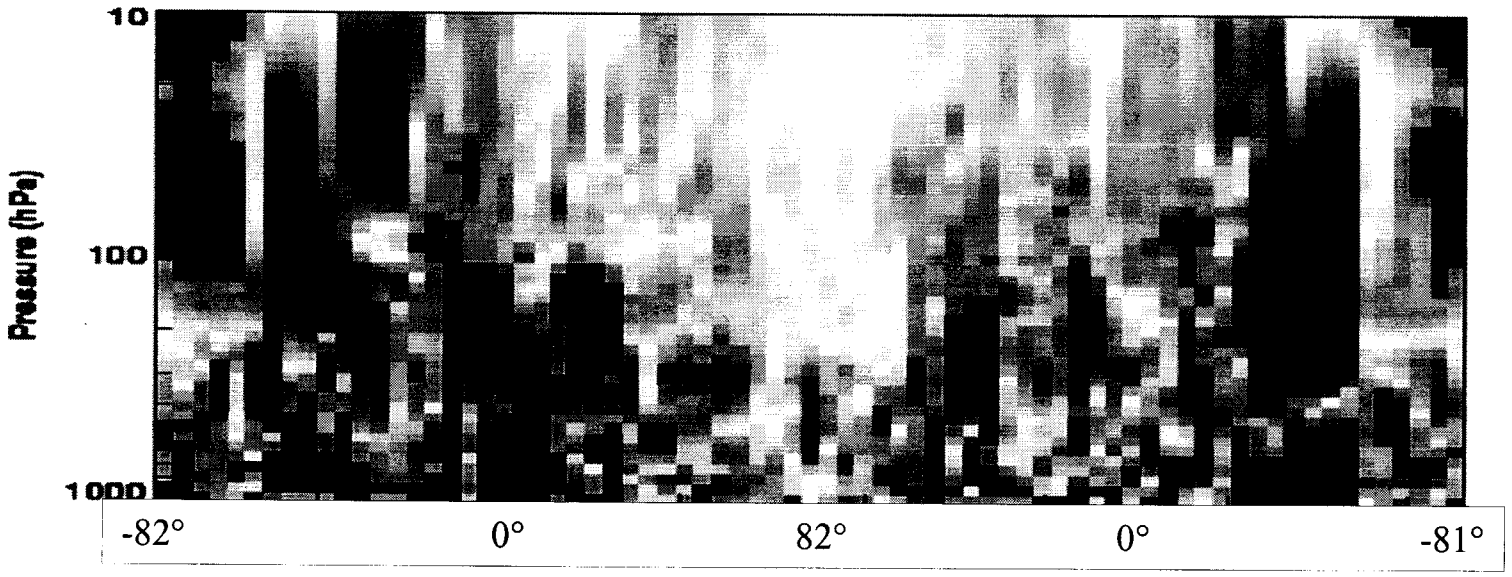
O_3 Retrievals

Region 17-19 observations each	Trop os. Vertical Resolution (km)	Degrees of Freedom Signal	Total Column Error (%)
Arctic & Antarctic	**6.0**	**6.4**	**1.3**
Southern Mid-Lat.	**6.7**	**7.1**	**0.78**
Tropics	**7.2**	**7.8**	**0.53**
Northern Mid-Lat.	**6.7**	**7.4**	**0.45**

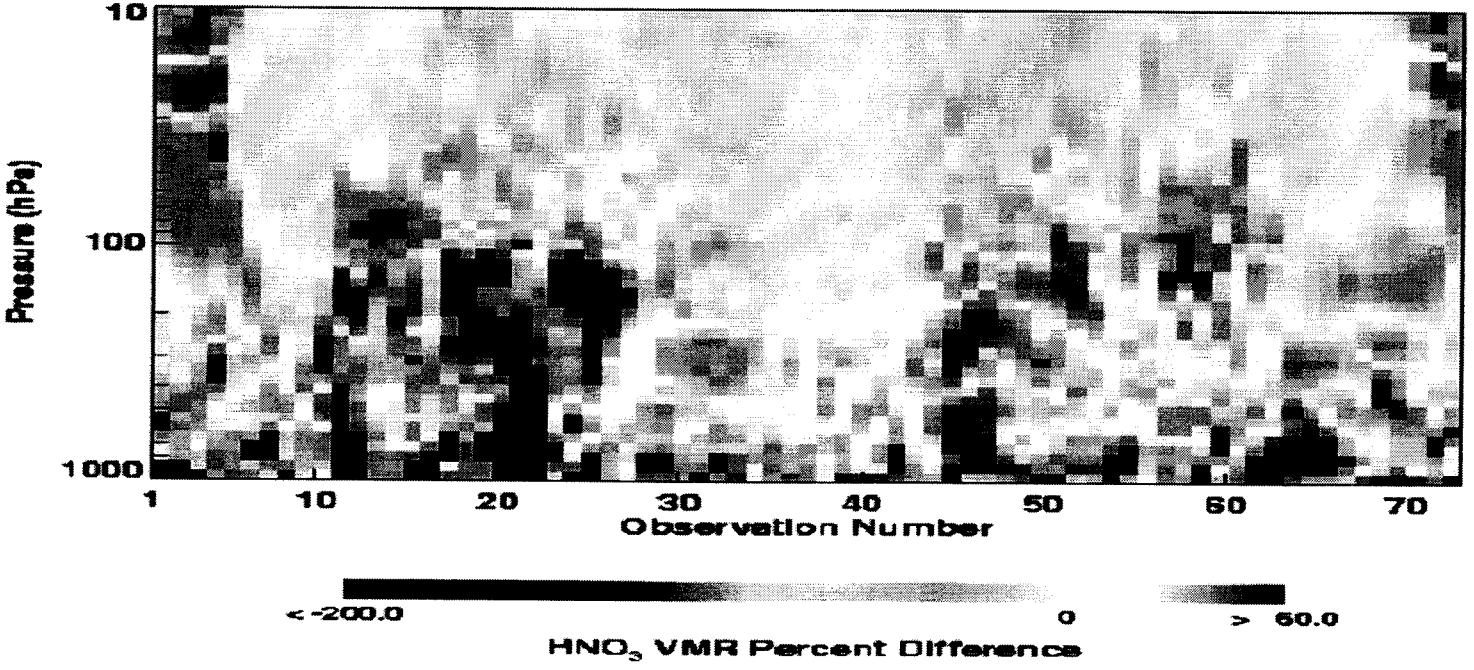
CH_4 Retrievals

Region 17-19 observations each	Trop os. Vertical Resolution (km)	Degrees of Freedom Signal	Total Column Error (%)
Arctic & Antarctic	**6.5**	**4.5**	**1.0**
Southern Mid-Lat.	**6.7**	**4.9**	**0.7**
Tropics	**6.3**	**5.9**	**1.7**
Northern Mid-Lat.	**6.3**	**5.3**	**1.1**

True vs. Initial Guess: HNO_3



True vs. TES Limb Retrieval: HNO_3



Average Values for 73 Limb Cases

Retrieved Species	Errors (True-Retrieved)	Degrees of Freedom For Signal	Vertical Resolution (km) (0-33 km)
T_atm	0.56 K (0-33 km)	20.2	2.50
O_3	1.0 % (column)	20.2	2.72
HNO_3	8.6 % (column)	12.1	3.28

TES Error Characterization

For the single orbit test, in order to compare with the "true" profile, we have:

$$S_{tot} = \left(A - I\right) S_a^{true} \left(A - I\right)^T \ (smoothing)$$

$$+ G S_e G^T \ (retrieval\ noise)$$

Where $$G = \left(K^T S_e^{-1} K + \Lambda\right)^{-1} K^T S_e^{-1}$$

$$A = GK$$

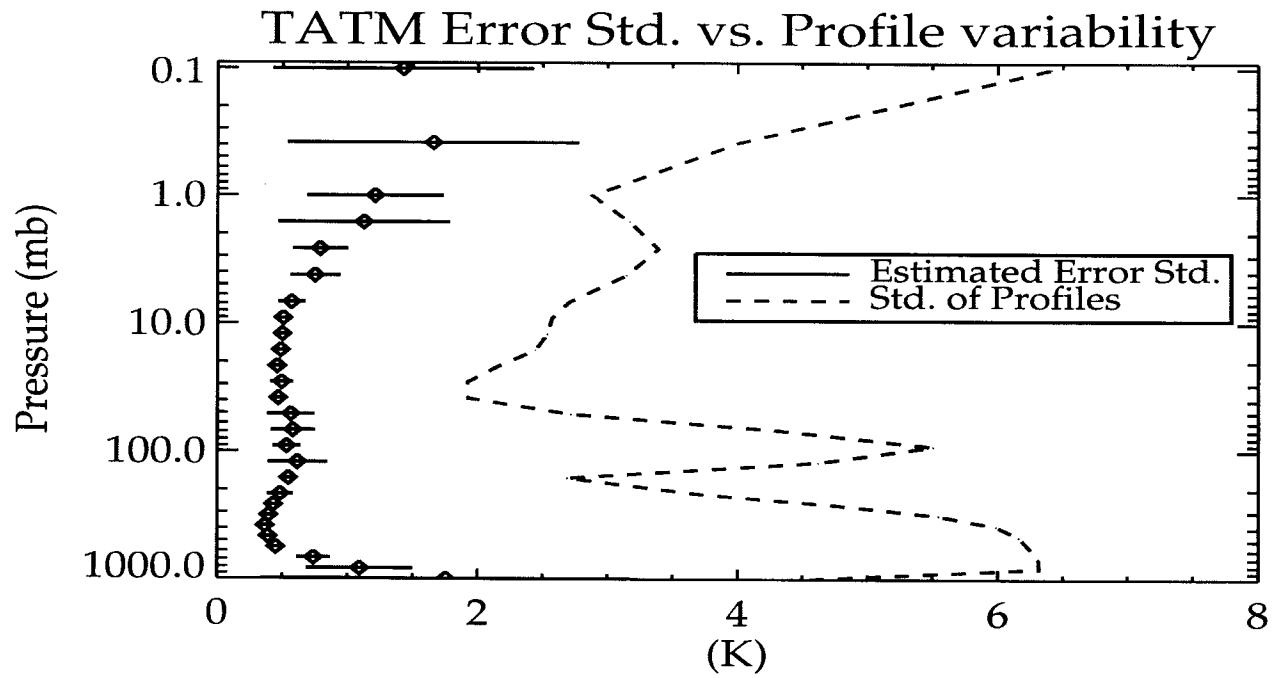
$$\Lambda = \text{Constraint matrix}$$

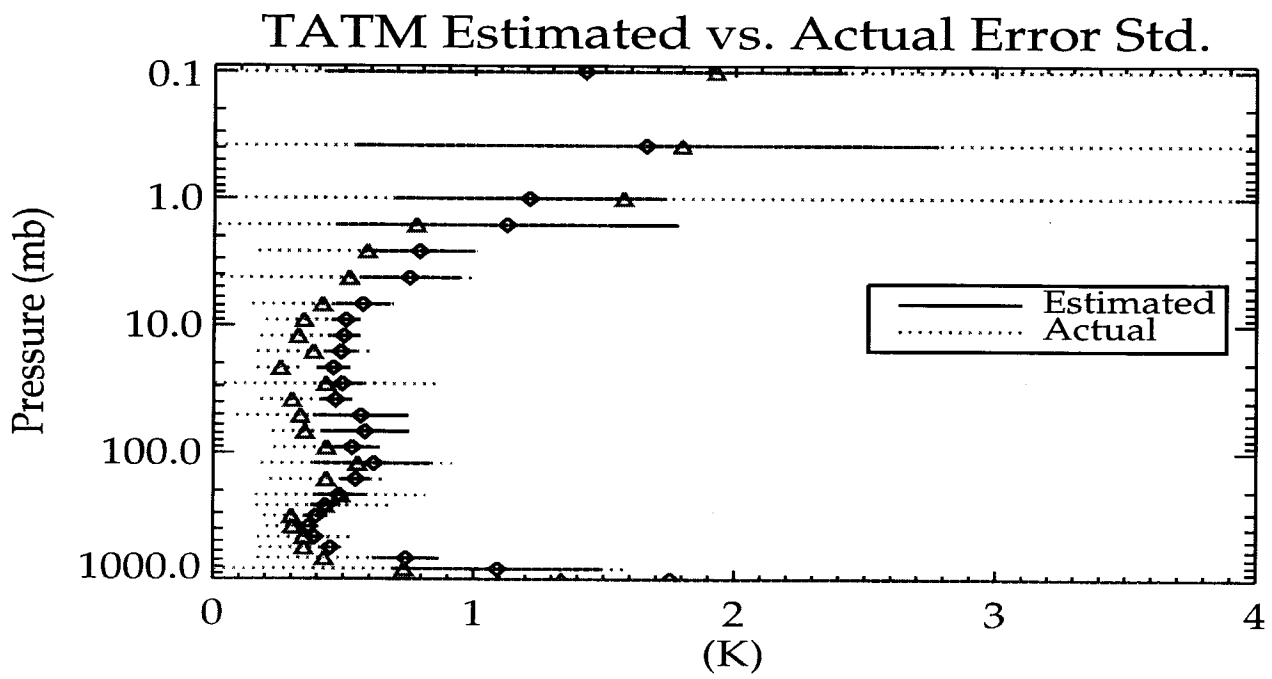
Our smoothing error is underestimated:

- Doesn't include representation error
  (need to use full K)
- S_a^{true} has artificially small variance
  (computed from a single model day).

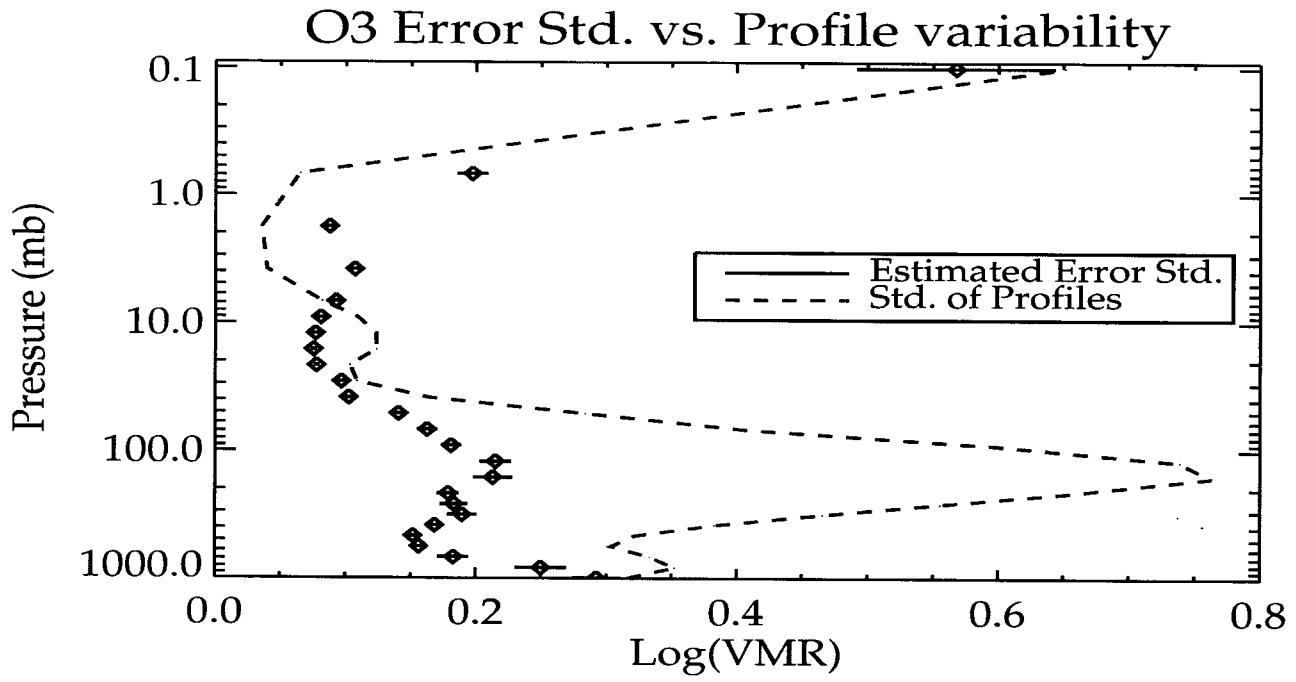
Still need to characterize:

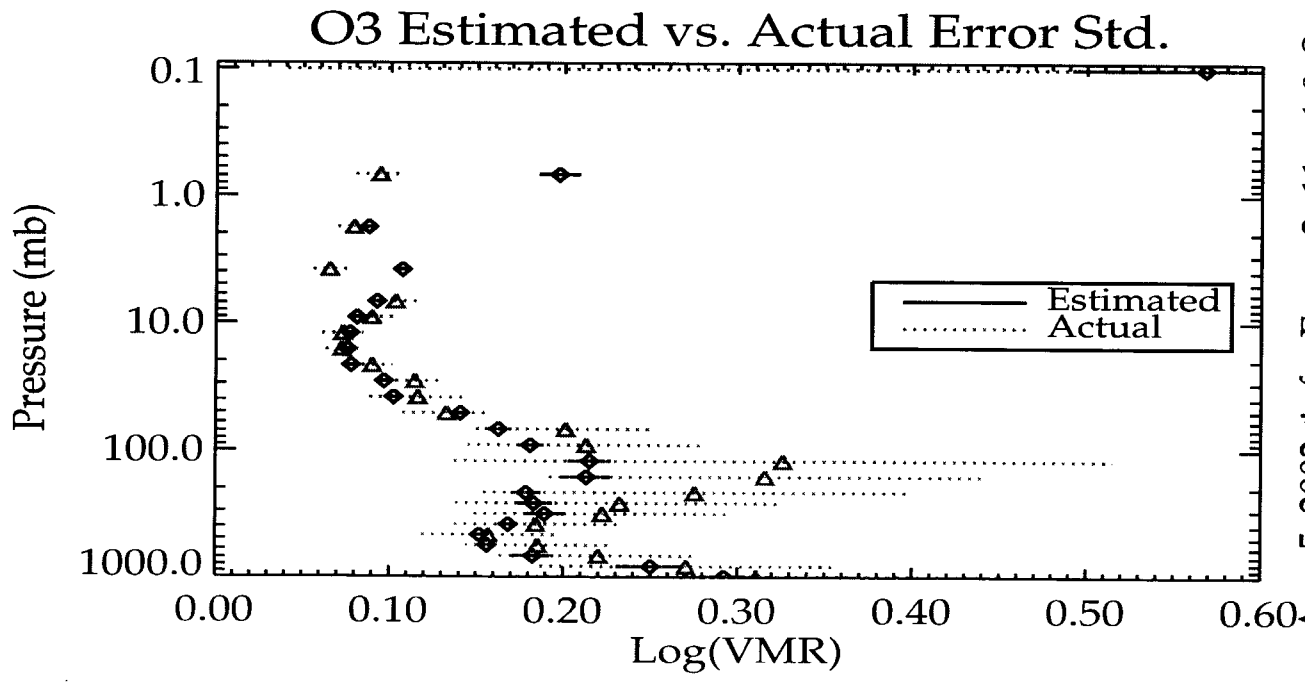
- Forward model parameter error
  i.e., errors from non-retrieved parameters:
  $S_f = GK_bS_bK_b^TG$
- Model error
  i.e., errors from model approximations





Apr 5, 2002 info_Errors2 t11 v1.0 Susan Sund

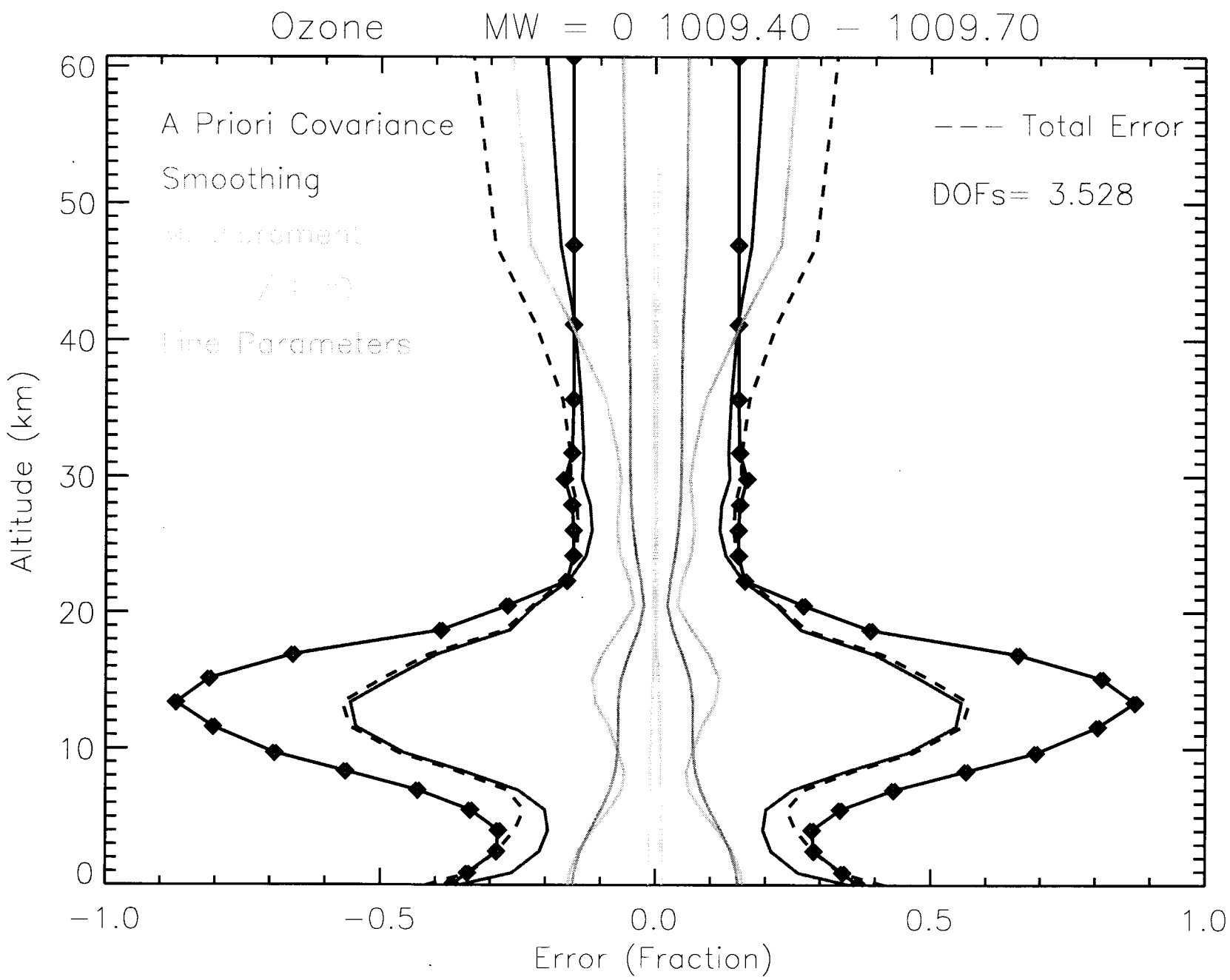


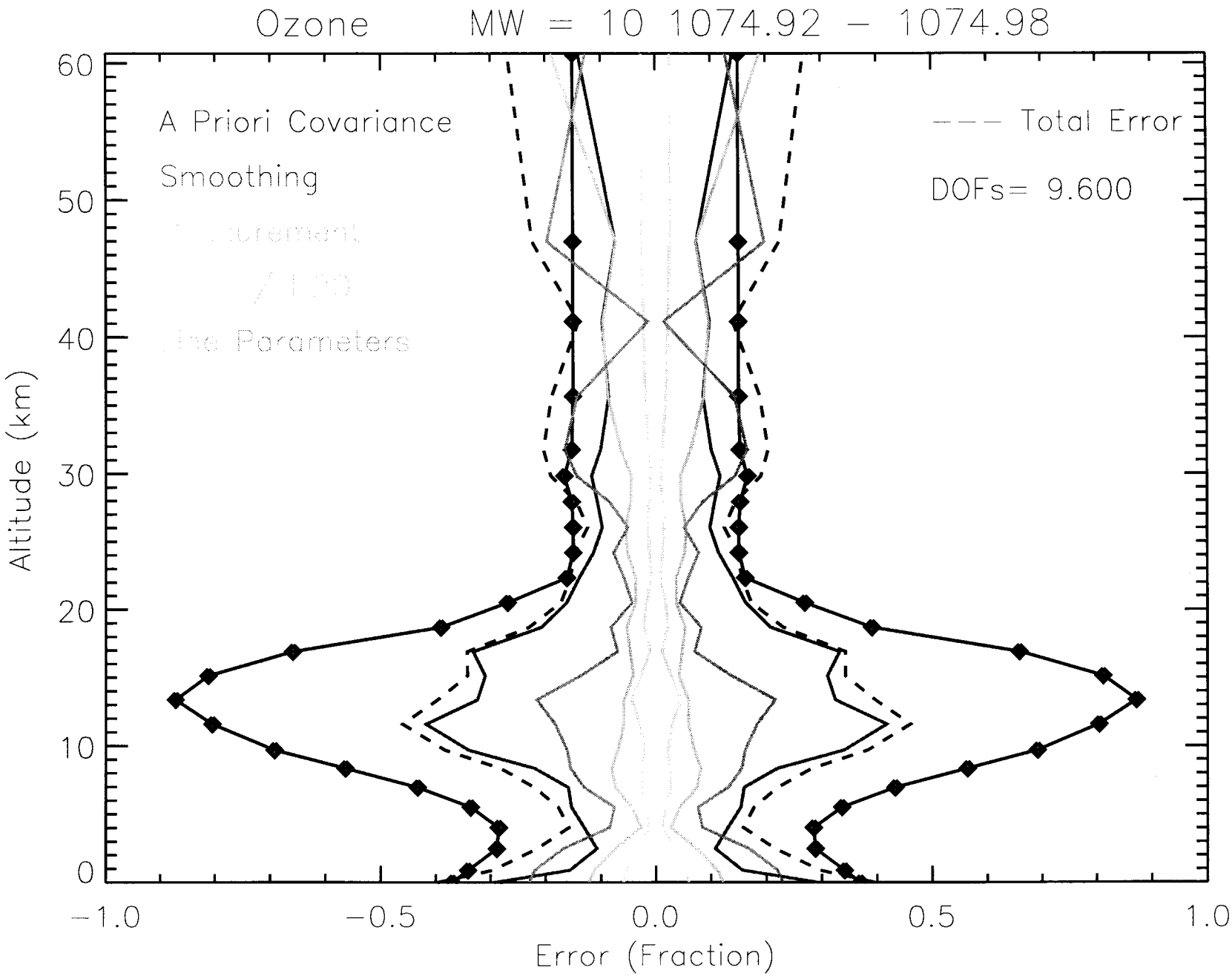


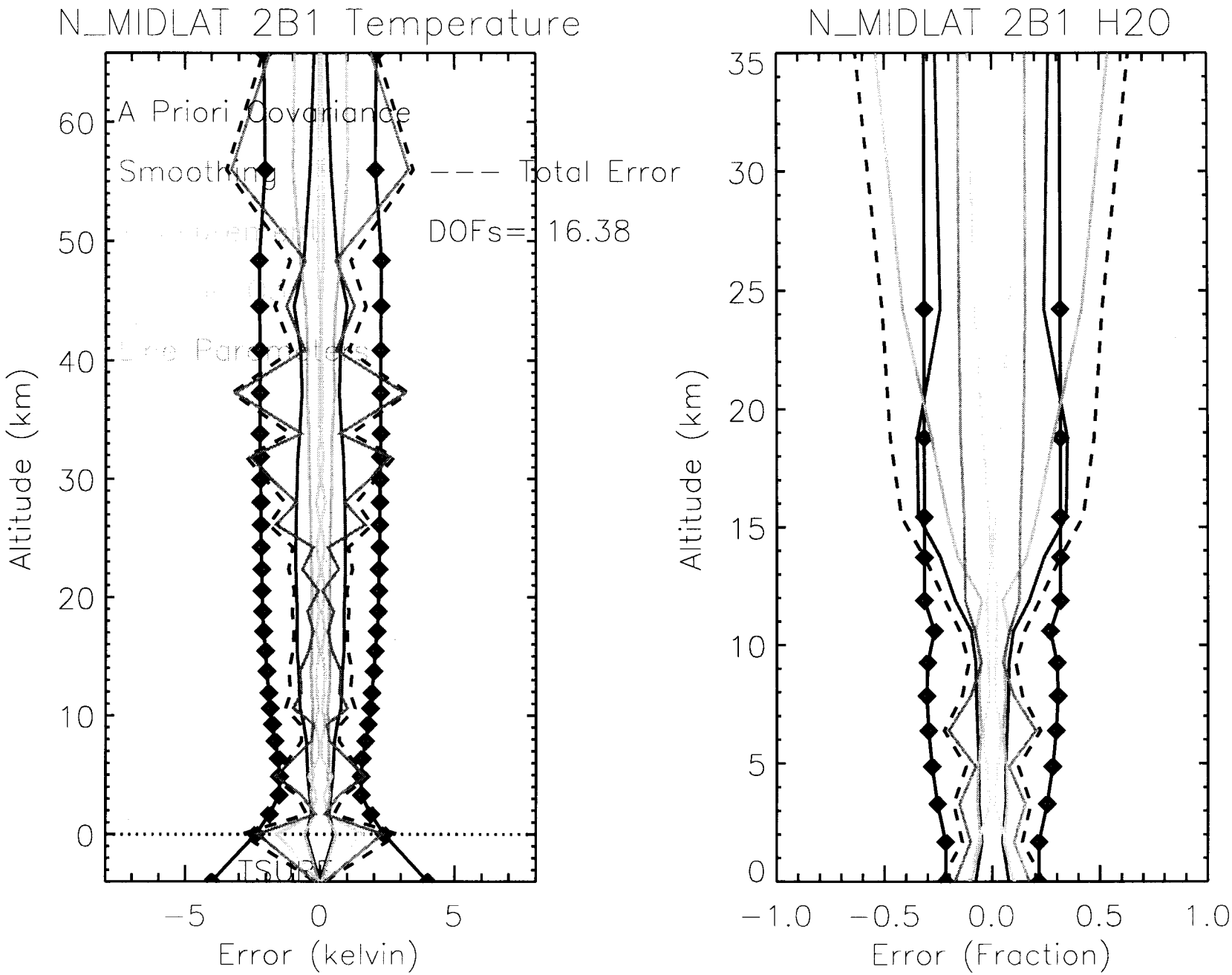
Apr 5, 2002 info_Errors2 t11 v1.0 Susan Sund

Current/Future Work

- Updating the ATBD (now at V1.2, V2.0 by 5/2003)
- Limb "tomographic" retrieval
  - uses 3 limb measurements to retrieve 4 profiles over 6° latitude.
- Cloud top pressure determination step
- Retrievals with transmissive clouds/aerosols using proxy gray-body layers.
- Preparation for "One-Day Test" with launch ready support data (*e.g.*, microwindow, constraints, strategy tables).


Ozone MW = 0 1009.40 – 1009.70
A Priori Covariance
Smoothing
Line Parameters
--- Total Error
DOFs= 3.528
Altitude (km)
Error (Fraction)
60
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0


Ozone MW = 10 1074.92 – 1074.98
A Priori Covariance
Smoothing
Total Error
DOFs= 9.600
Altitude (km)
Error (Fraction)
60
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0


N_MIDLAT 2B1 Temperature
A Priori Covariance
Smoothing
Line Parameters
TSURF
--- Total Error
DOFs= 16.38
Altitude (km)
Error (kelvin)
N_MIDLAT 2B1 H2O
Altitude (km)
Error (Fraction)