MOPITT Validation Summary

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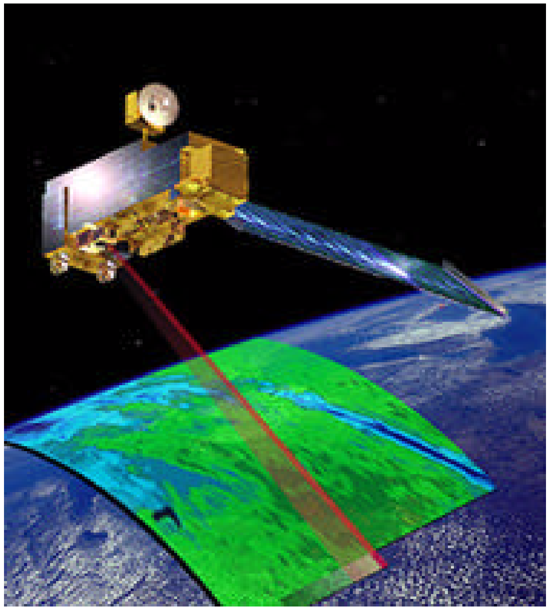
and

the MOPITT Correlative Team



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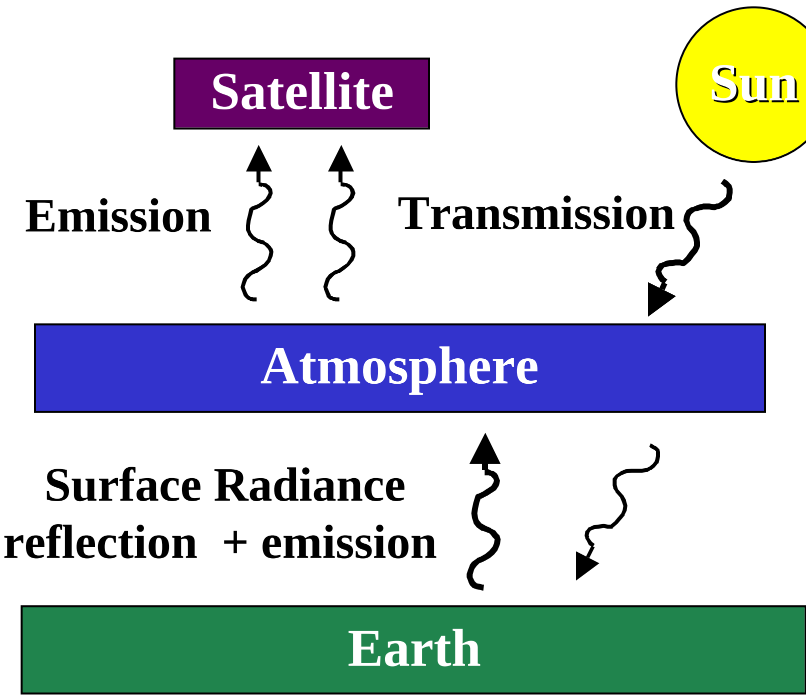
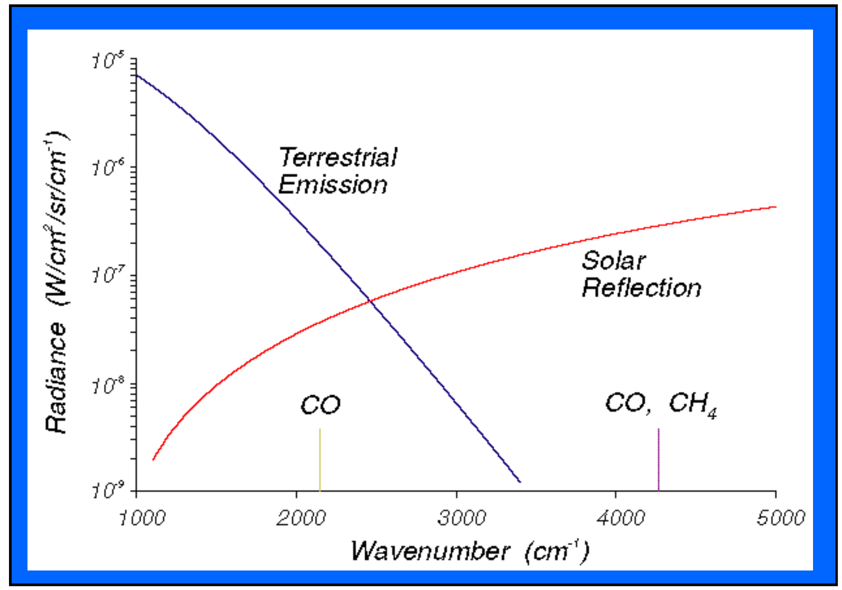
MOPITT Standard Scientific Products

- **Level 1 data products**
  - Calibrated and geo-located radiances
- **Level 2 data products**
  - Tropospheric CO profiles with a 22 km horizontal resolution
  - Mixing ratios at 4 km vertical resolution and 10% precision (at 850, 700, 500, 350, 250, 150 mbar)
  - CO total column with 10% precision
  - CH_4 total column with 1% precision
- **Level 3 data products**
  - Gridded global CO distribution (global maps via assimilation)
  - Gridded global CH_4 distribution (global maps via assimilation)

MOPITT Spectral Bands

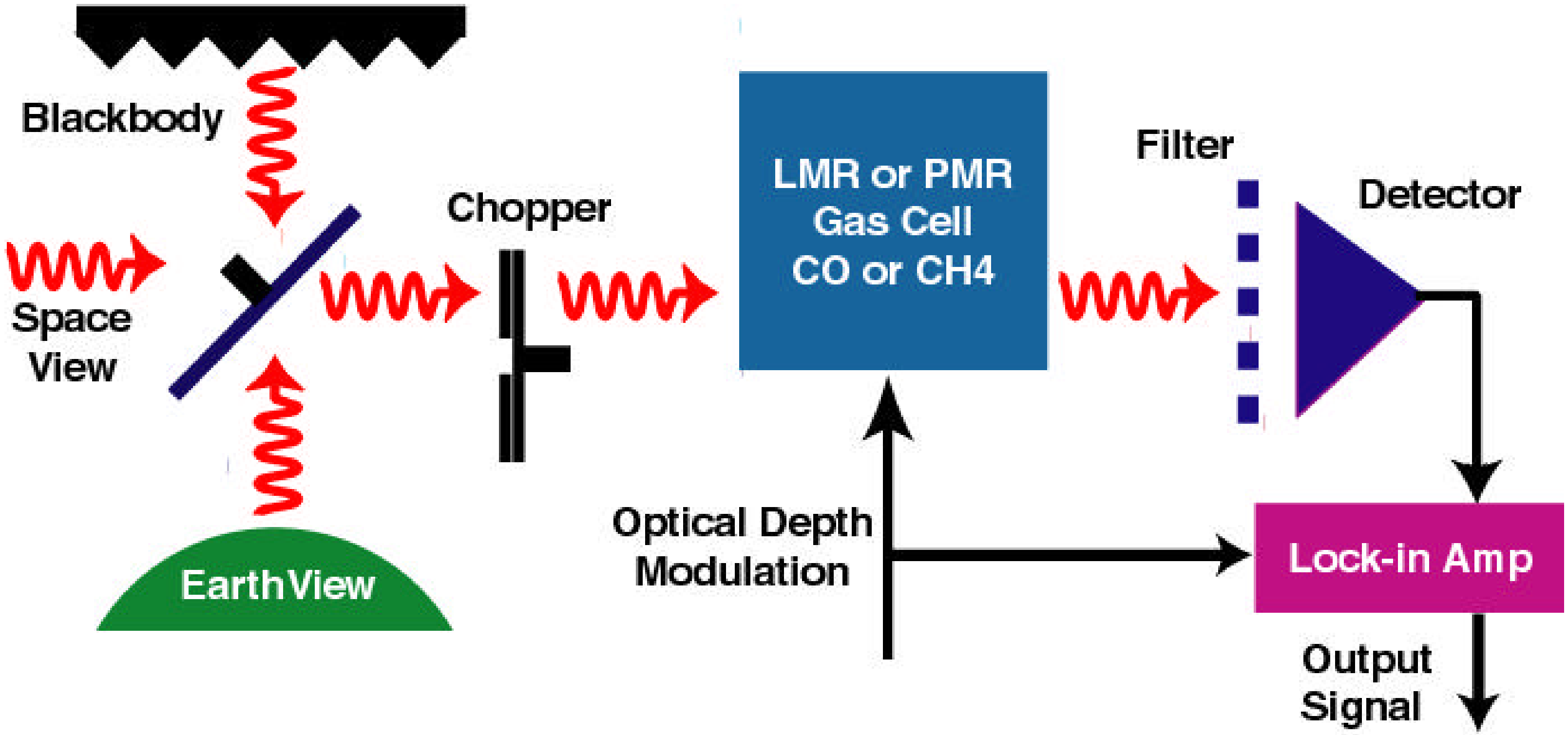




- **MOPITT operates by sensing infra-red radiation from either:**
  - **The thermal emission/absorption at 4.7 μm for CO profiles.**
  - **Reflected sunlight at about 2.2-2.4μm for CO and CH_4 column measurements in daylight. The use of solar channels enhances the instrument sensitivity to the atmosphere boundary layer.**

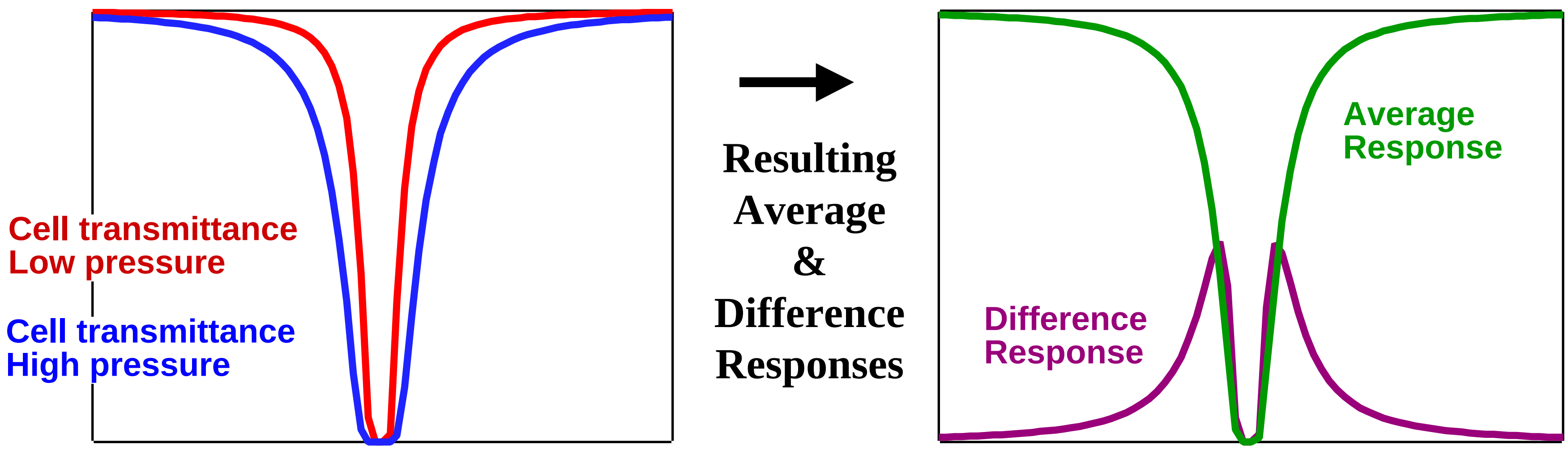
- **The radiation is modified by absorption/emission processes in the atmosphere and these changes are detected in the MOPITT instrument using Correlation Radiometry**

Correlation Radiometry



- **Signals pass through a cell containing the target gas, CO or CH4**
- **The cell pressure (PMR) or length (LMR) is varied**
- **This produces a modulation in cell opacity within the lines of the target gas**
- **The cell opacity at other frequencies remains constant**

MOPITT Measurements by Correlation Radiometry: Average and Difference Signals



- Two MOPITT signals are possible:
  Average Signal: Mean of the low and high opacity signals
  Difference Signal: Difference of low and high opacity signals
- Average response is low at target gas line positions
  → Information about background radiance (surface temperature)
- Difference response is only significant at target gas line positions
  → Effective high-resolution spectral filter to information about target gas

MOPITT Validation Strategy

- **Radiances (L1):**
  - Validate passbands of optical filters by analysis of Average Signal radiances over ocean scenes
  - Validate Difference Signal radiances against Forward Model using ***in situ*** aircraft profiles
  - Compare MOPITT-A observations to MOPITT radiances
- **Mixing ratios and column densities (L2):**
  - Compare ***in situ*** aircraft vertical profiles to MOPITT mixing ratios, after applying averaging kernels to the ***in situ*** profiles
  - Calculate column amounts from ***in situ*** aircraft data, using averaging kernels, and compare to retrieved column amounts
  - Compare ground-based spectroscopic retrievals to MOPITT column amounts
  - Compare MATR observations with MOPITT retrievals
- **Scientific Validation**
  - Compare MOPITT with results from global chemical transport model MOZART for qualitative validation of seasonal and geographical variations
  - Use assimilated data (L3) for further science studies

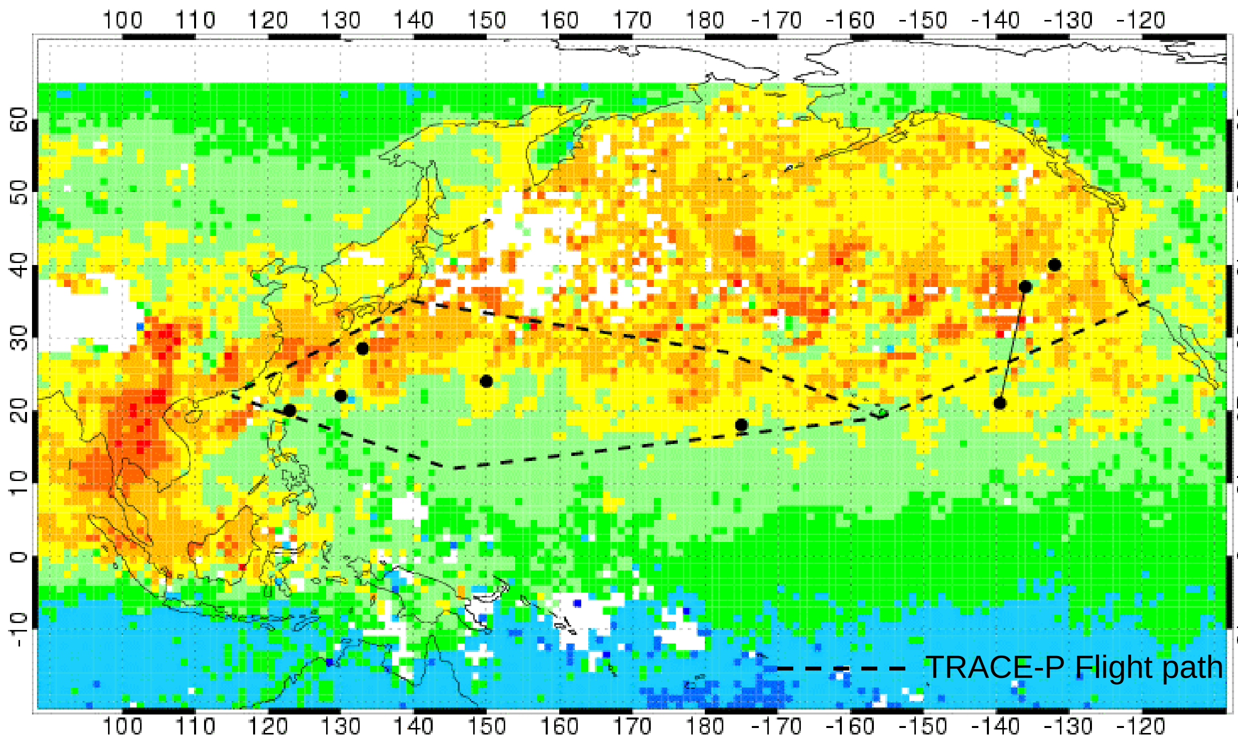
MOPITT Validation Field Campaigns

- **MOVE (MOPITT Validation Experiment) in May 2000**
  - Flights over Oklahoma ARM/CART site scuttled by Los Alamos fires
  - Spectroscopic stations collected intensive data set anyway
- **SAFARI in Africa during August and September 2000**
  - First data collection flights by MOPITT-A on ER-2
  - Additional ***in situ*** profiles collected by NOAA/CMDL
  - Very good coordination with MOPITT overpasses
  - Some simultaneous data from MOPITT, MOPITT-A, ***in situ***
- **MATR flights over Colorado and California in Oct. 2000**
  - Combined MATR remote sensing and ***in situ*** samples from Citation
  - Collected data for MOPITT overpasses: day/night, land/ocean
  - Collected data for: CO/CH_4, clear/cloudy conditions
- **MOVE over ARM/CART site in March/April 2001**
  - Bad weather and MOPITT anomaly prevented useful data collection

Participation in TRACE-P

- TRACE-P, a NASA/GTE aircraft campaign, was conducted over the western Pacific during Feb-Apr, 2001 to study the outflow of Asian pollution
- NASA's DC-8 and P-3B, were used to make observations throughout the troposphere to 12 km altitude
- Daily MOPITT data over the western Pacific were provided to TRACE-P in near-real-time for use in flight planning
- TRACE-P aircraft made 7 profiles (·) coincident with Terra for MOPITT validation

MOPITT at 700 hPa Feb 16-Mar 1, 2001 for TRACE-P



Aircraft *in situ* Validation Data: NOAA/CMDL

CMDL "Anchor" Sites (P. Novelli)	# Profiles received through Mar 2001
Carr, Colorado	32
Poker Flats, Alaska	12
Harvard Forest, Mass.	9
Molokai, Hawaii	16
Raratonga, Cook I.	10

- Regular program of flask sampling from aircraft (on-going)
- Consistent data analysis and calibration performed at NOAA/CMDL
- Profiles generally only to 400 hPa
- More frequent profiles would be desirable
- Close coordination with MOPITT overpasses is important

Aircraft *in situ* Validation Data: Campaigns

Campaigns	Dates
SAFARI-2000 (S. Africa); ***CMDL***	Aug 14 – Sep 7, 2000
PICO3 (Cape Verde); ***CMDL***	Oct 2000
MOVE (Colorado, Nevada); ***CMDL***	Oct 14 - 26, 2000
TOPSE (N. America); ***NCAR, UC-Irvine***	Feb 4 - May 23, 2000
COBRA (N. America); ***Harvard***	Aug 1 - 24, 2000
BIBLE-C (Japan-Australia); ***U. Nagoya***	Nov 24 - Dec 15, 2000
TRACE-P (W. Pacific); ***NASA Langley***	Feb 24 – Apr 10, 2001

- Shorter time periods, but greater geographical coverage than anchor sites
- Profiles frequently to higher altitudes (12 km)
- SAFARI, MOVE, TRACE-P coordinated profiles with MOPITT overpasses

FTIR Validation Data

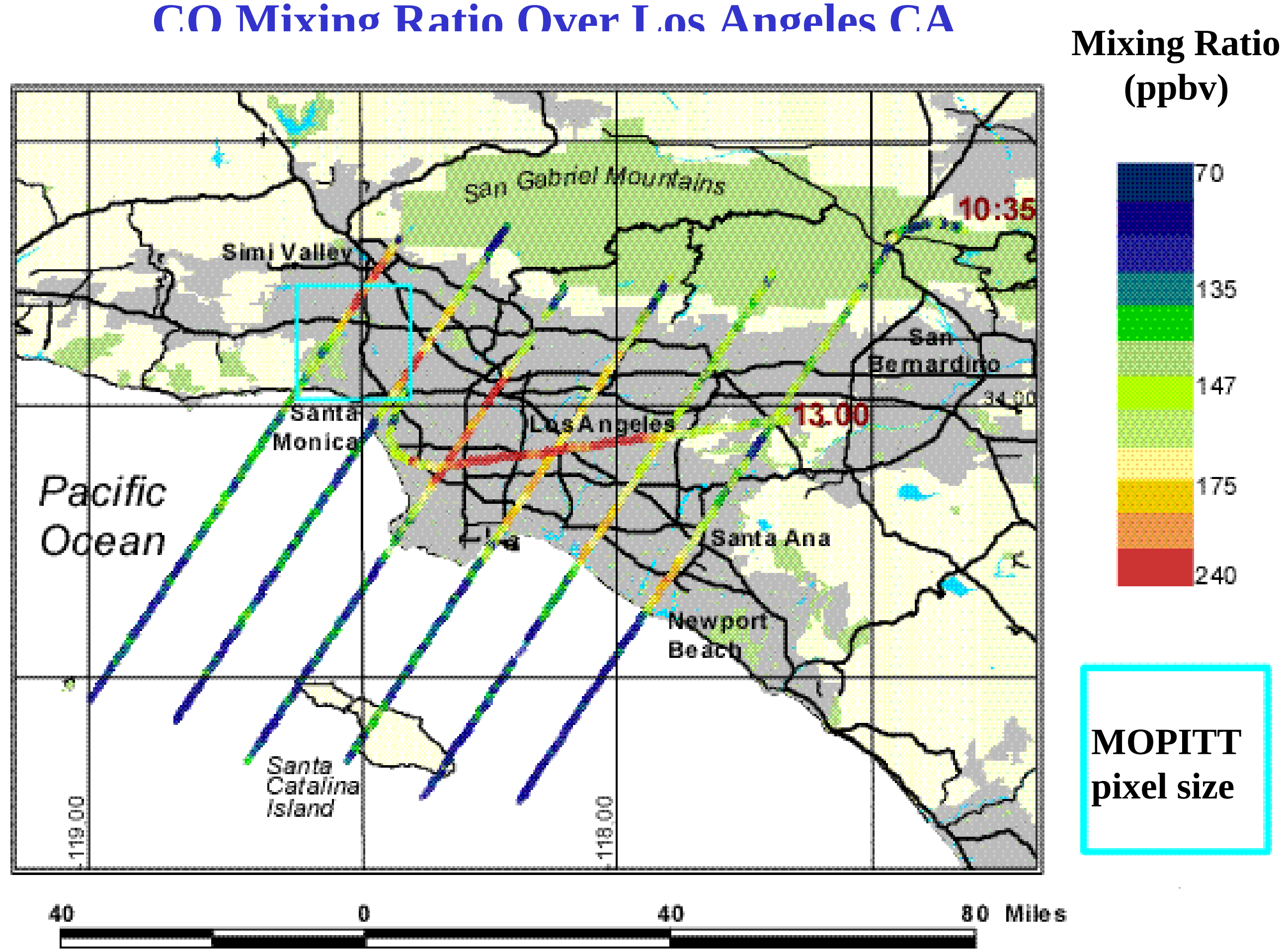
Ground-based column observations

STATION	Dates (# Retrievals)	INVESTIGATORS
Lauder, NZ	Jan 4 - Dec 30, 2000 (**339**)	NIWA; N.Pougatchev
Valdes, Argentina	Aug 28, 2000 - Feb 18, 2001 (**23**)	L. Yurganov
Wollongong, Australia	May 26 - Sep 13, 2000 (**274**)	D.Griffith, Univ. Wollongong
Mauna Loa, Hawaii	Jan 4 - Apr 11, 2000 Apr 14 - Jun 6, 2001 (**60**)	F.Murcray, Univ. Denver
Rikubetsu, Japan	Jan 6 - Oct 1, 2000 (**205**)	Univ. Nagoya; N.Pougatchev
Moshiri, Japan	Jan 1 - Nov 1, 2000 (**366**)	Univ. Nagoya; N.Pougatchev
Zvenigorod, Russia	Mar 6 - Oct 2, 2000 (**49**)	Inst. Atm. Physics; L.Yurganov
Peterhoff, Russia	May 13 - Aug 29, 2000 (**15**)	SPBU; L.Yurganov
Poker Flats, Alaska	Mar 10 - Sep 20, 2000 Mar 22 - May 18, 2001 (**105**)	F.Murcray, Univ. Denver
Spitsbergen, Norway	Mar 22 - Aug 3, 2000 (**28**)	J.Notholt, AWI, Potsdam

MOPITT Airborne Test Radiometer (MATR)

- Three-channel gas filter correlation radiometer for measuring CO or CH_4 using one length- and one pressure-modulated cell
- Uses same spectral passbands and correlation techniques as MOPITT
- Used for MOPITT data validation to investigate radiometrically complicated scenes in detail

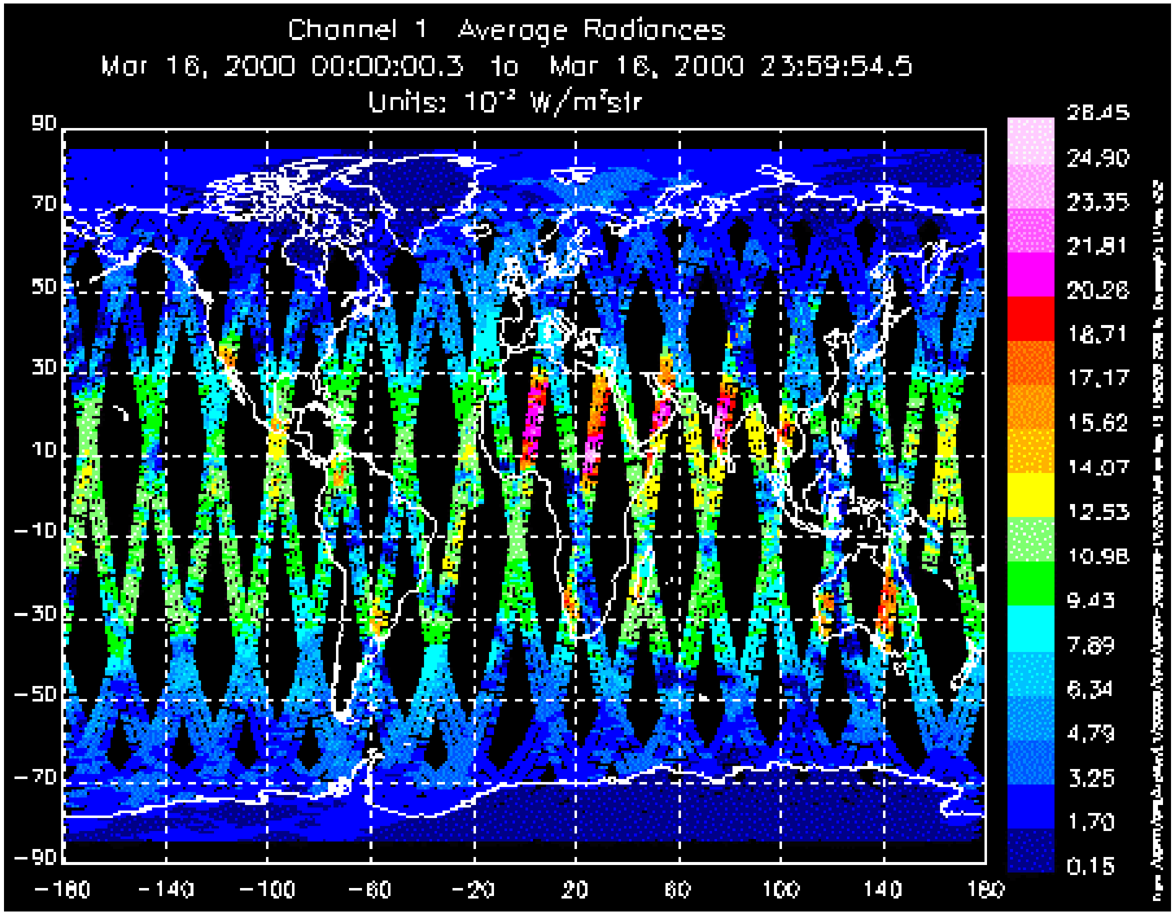
CO Mixing Ratio Over Los Angeles CA



MOPITT Level 1b Data Calibrated Radiance Product

MOPITT Level 1b calibrated signal data shows:

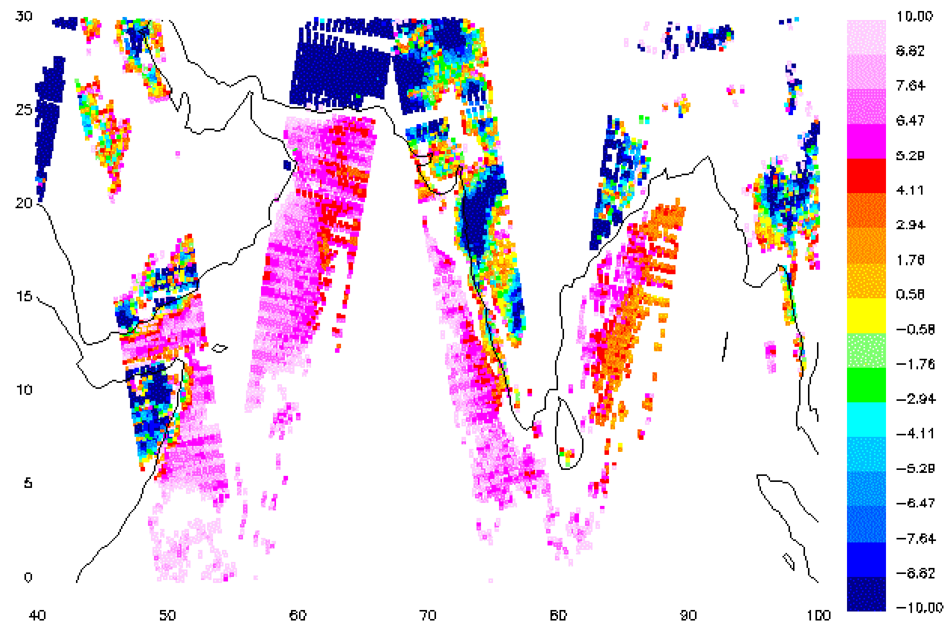
- Geolocated radiances for each MOPITT channel Average and Difference Signal
- Strong dependence on surface temperature which dominates the signal variation
- Clouds appearing cold
- Diurnally varying signal
- Not particularly suited to research applications without further processing to Level 2



MOPITT L1 Validation: Average Signals

- **Quality of MOPITT cloud detection & retrievals depends on accuracy of radiances**
- **Average Signal radiance calibration and Forward Model both require accurate specification of optical filter profiles**
- **Use of nominal ‘pre-launch’ optical filter profiles produces radiance biases (relative to Forward Model) when processing actual MOPITT data**

- **For quantifying radiance biases, clear-sky ocean scenes were identified where filter-related radiance biases dominate all other potential sources of bias**
- **Nominal filter profiles adjusted by ‘filter shift’ values derived from observed Average Signal radiance biases over these scenes**



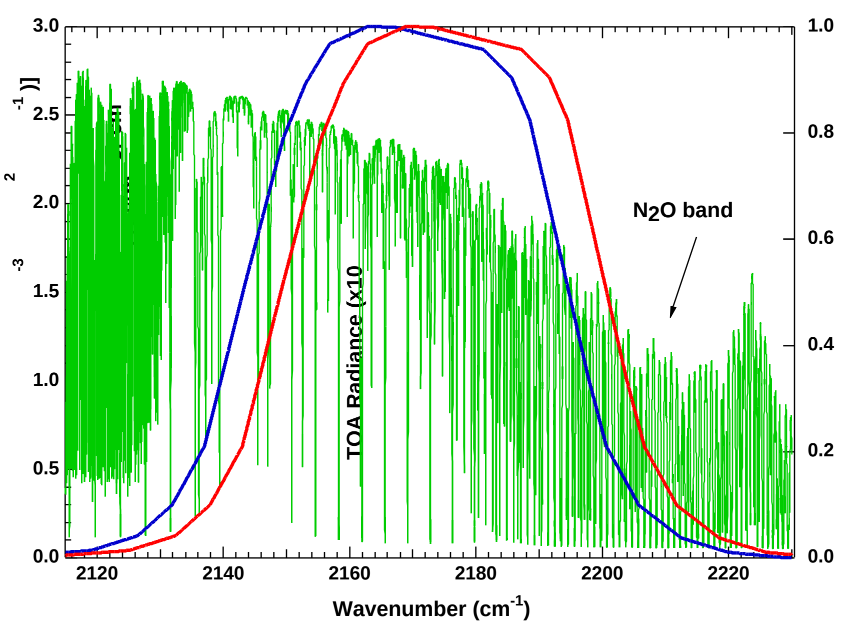
Preliminary Average Signal Radiance Bias (%)

MOPITT L1 Validation
Filter shift determination

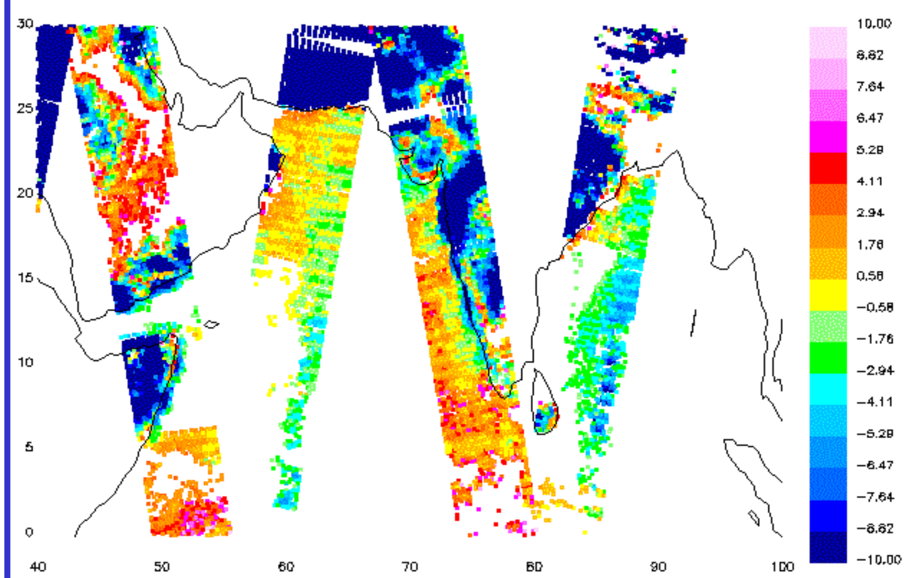
A set of MOPITT nighttime radiances was formed for scenes over the Indian Ocean where biases relative to modeled radiances were observed to be most consistent

Bias statistics were used to determine the ‘filter shift’ values

L1 & L2 processors were revised to incorporate filter shifts, and radiances were rechecked against Forward Model



Final Average Signal Radiance Bias (%)

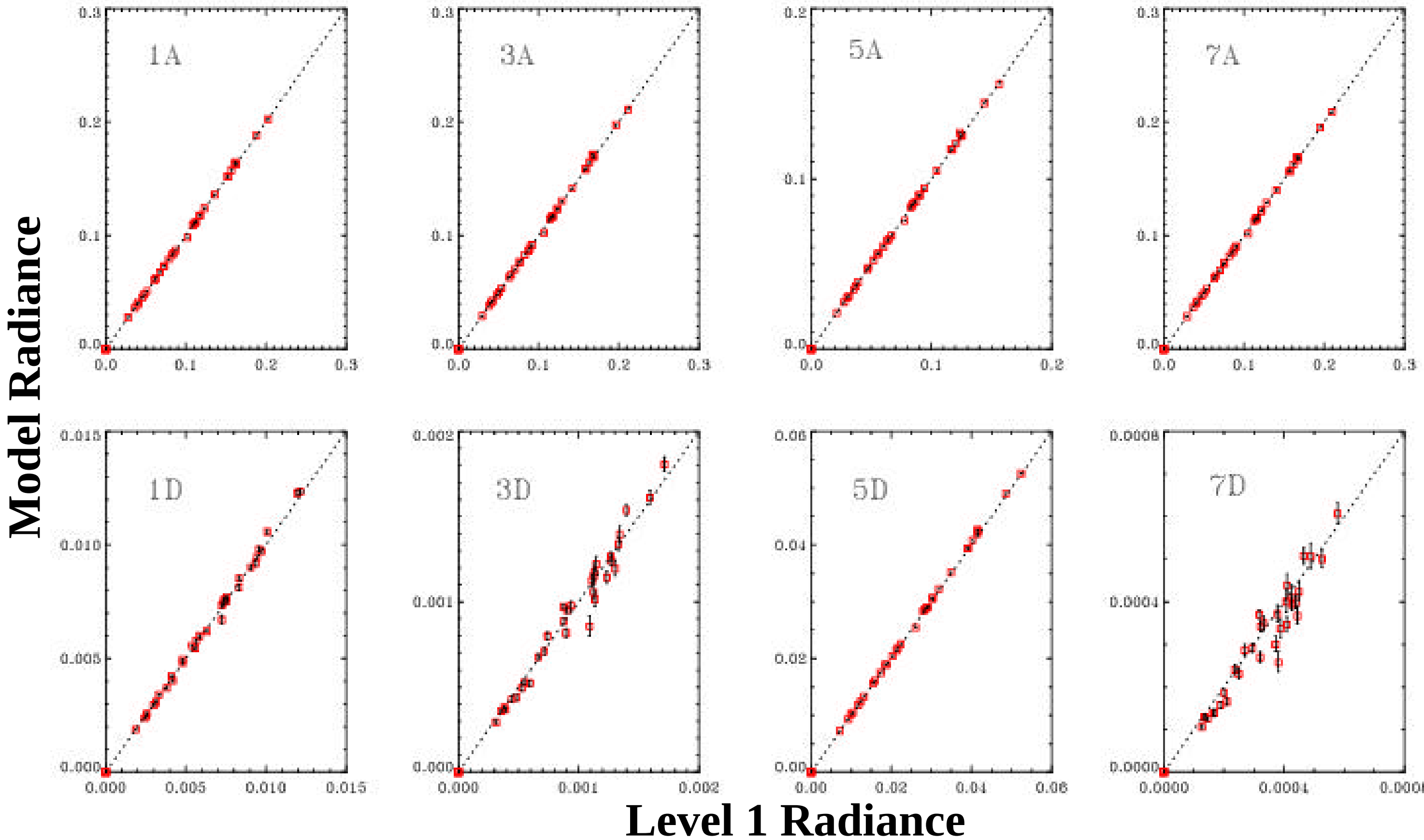


MOPITT L1 Validation: Difference Signals

<u>Goal:</u> Verify agreement of MOPITT satellite radiances and operational Forward Model in situations where all relevant inputs (including trace-gas profiles) to Forward Model are well-characterized

- Agreement between measured and modeled Difference Signal radiances is essential to producing reliable trace-gas retrievals
- NCEP met data is temporally and spatially interpolated to the MOPITT pixels and used in forward model
- MOPITT thermal-channel signals are very sensitive to surface temperature which exhibits large space/time variability. This is retrieved from the MOPITT radiances
- In situ CO profiles used in Forward Model coordinated with MOPITT overpasses
- Model-measurement differences may also arise from temporal and spatial displacements between the MOPITT pixels and CO ***in situ*** data, and from the lack of ***in situ*** data for the upper troposphere / lower stratosphere region

MOPITT L1 Validation Examples

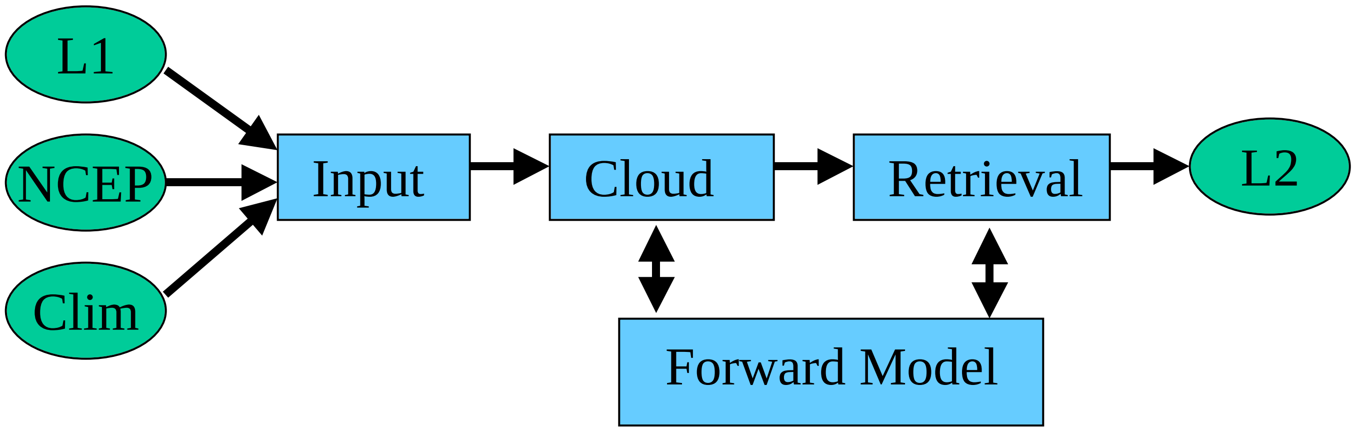


Forward model calculations using CMDL CO profiles compared to MOPITT L1 for all anchor sites and SAFARI 2000 3/4/00-10/13/00

The agreement between the satellite radiances and model-calculated radiances based on in-situ profile data shows first order agreement.

The MOPITT Level 1-2 Processor

After the Level 0-1 Processor has converted instrument counts into calibrated channel radiances, the Level 1-2 Processor retrieves the final geophysical CO and CH_4 data

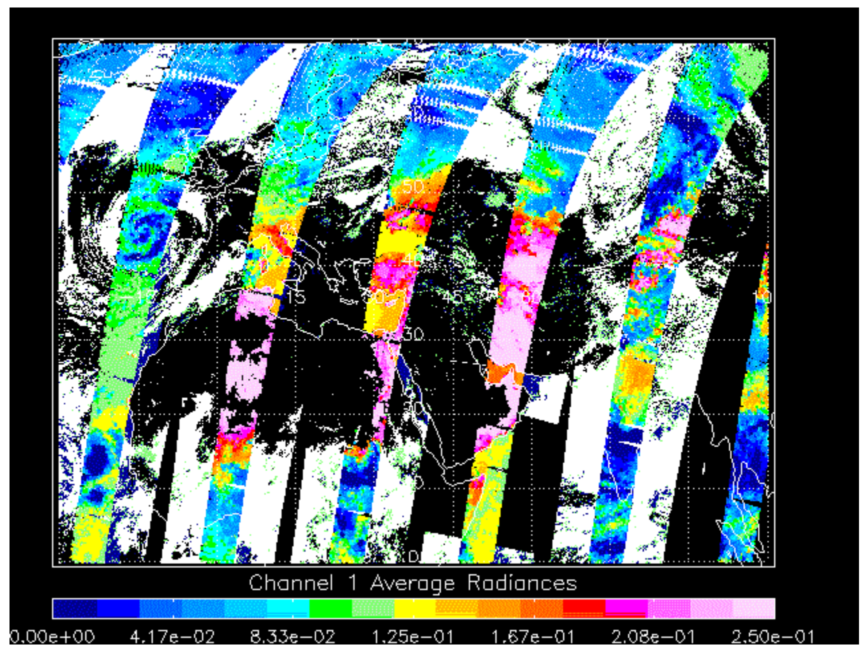


- Met data & climatology are interpolated in time & space to match L1 observation
- The L1 data and the ancillary data are passed to the cloud detection module
- Only the clear pixels are passed to the retrieval module
- The retrieval module calculates the abundance of carbon monoxide and methane

MOPITT Cloud Detection

- Clouds are detected using threshold tests which check thermal and solar radiance differences between observations and model calculations
- An equivalent cloud top pressure can be estimated using reflected solar radiation from the CH_4 channels
- Detection compares well with the MODIS cloud mask
- Overcast and partially cloudy situations are characterized to allow CO profiles to be retrieved above cloud tops and in the presence of broken clouds

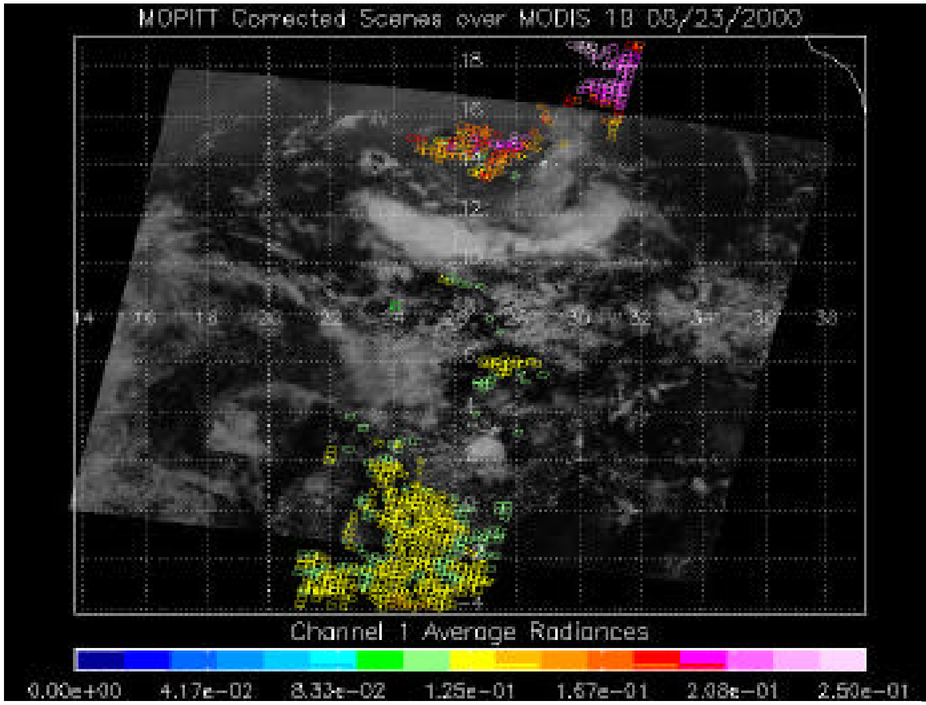
MOPITT Ch-1 thermal radiance overlapping the MODIS cloud mask. Cold radiances usually signify cloud and match well with the MODIS white mask.

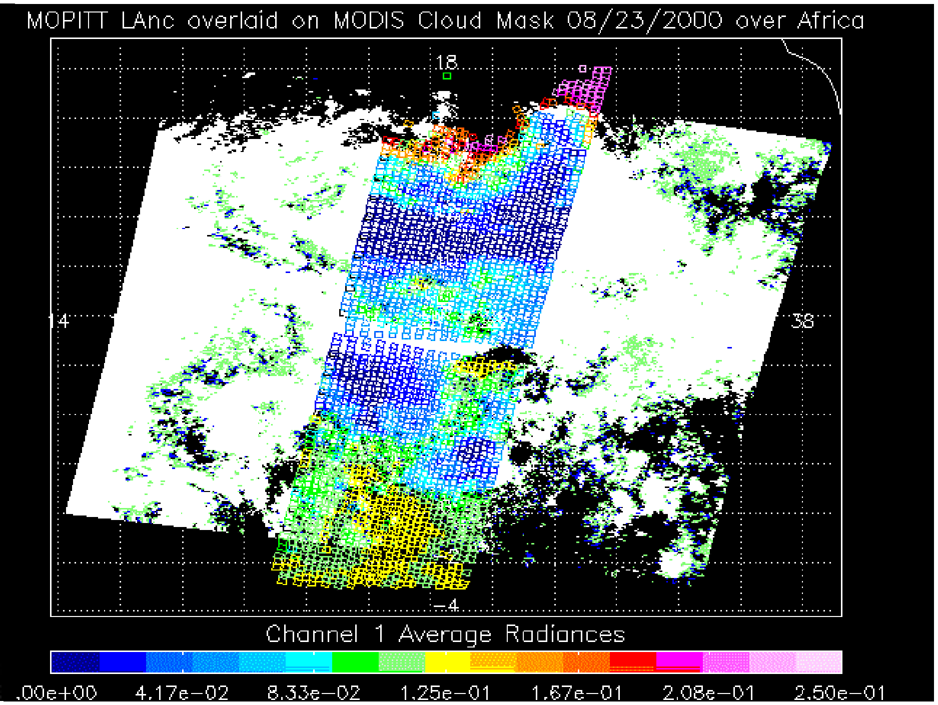


MOPITT Cloud Validation

Clear scenes detected by MOPITT cloud algorithm overlaid on a MODIS visible image. Colors shows the MOPITT thermal radiance.

MOPITT and MODIS co-location. The image is a MODIS cloud mask and the plot the MOPITT footprints. Color shows the MOPITT thermal radiance.





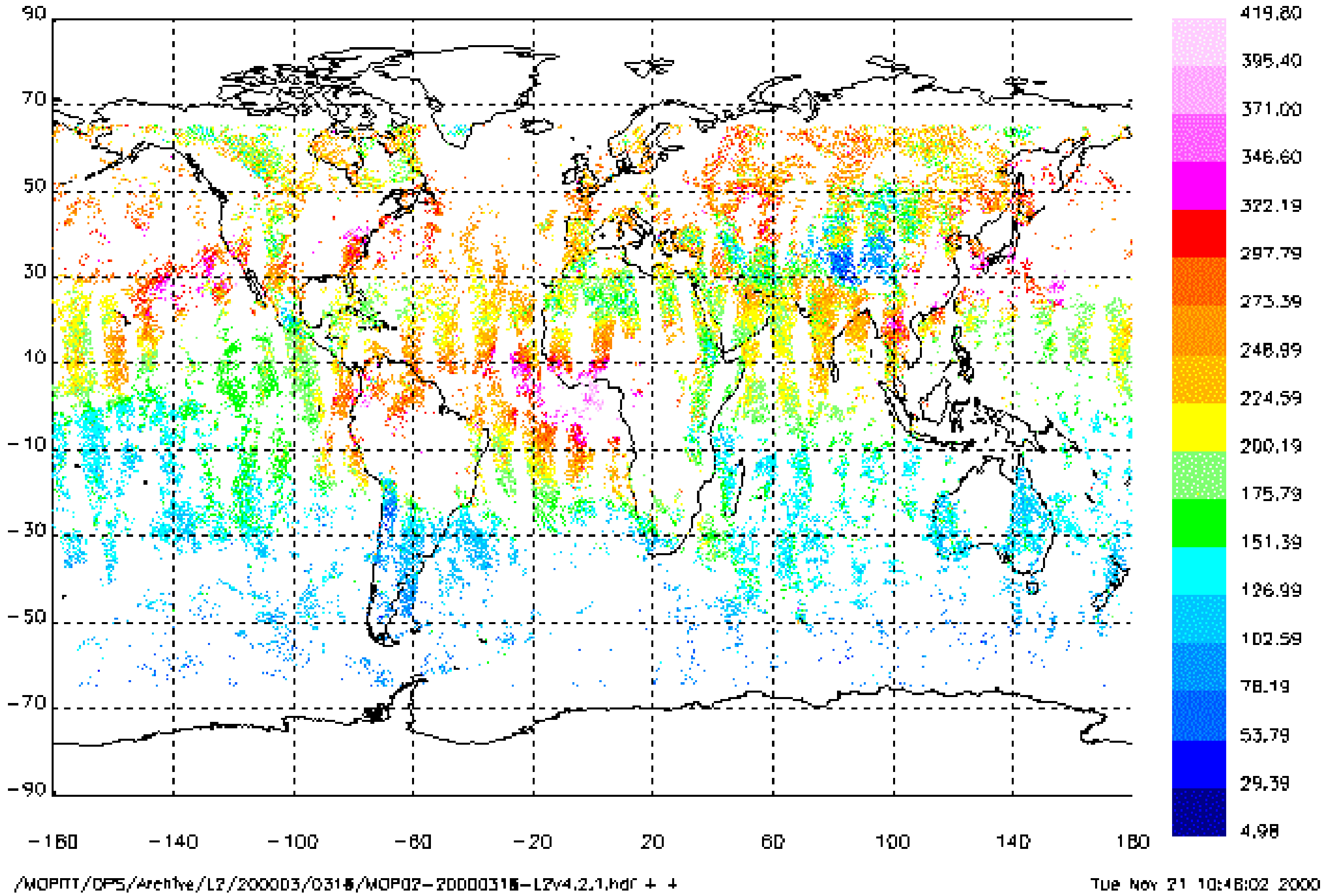
MOPITT cloud detection algorithm agrees with MODIS cloud mask 83% globally

MOPITT Level 2 Data
CO Total Column Product

MOPITT Level 2 CO Column data shows:

- Clouds filtered
- High CO amounts correlate with areas of industrial pollution and biomass burning
- Influence of topography evident
- Regions lat. > 65° not processed due to cloud problems

CO Total Column x10^{16} (mol/cm^2)
Mar. 16-18, 2000



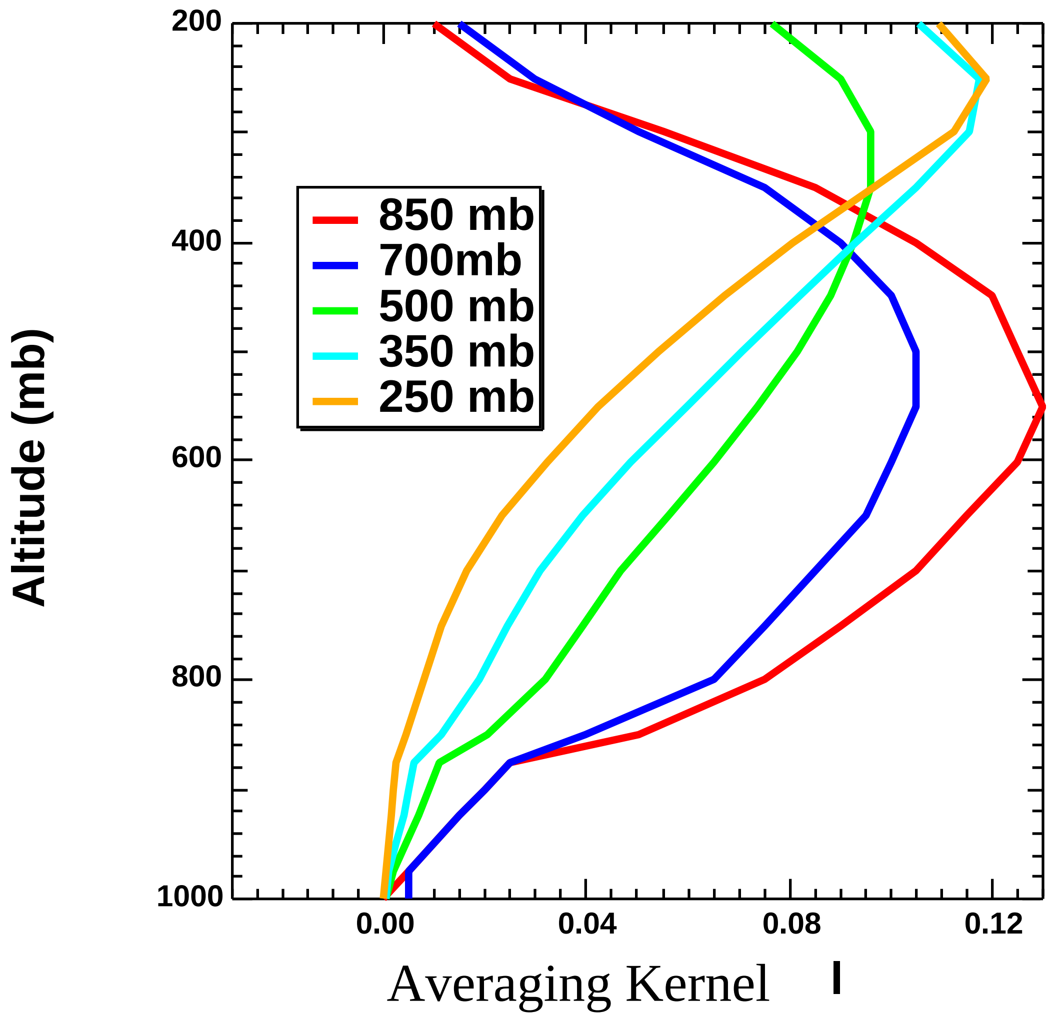
MOPITT Retrieval Technique

- Satellite measurements do not by themselves contain sufficient information to unambiguously determine the trace gas concentration
- We use our prior knowledge of the physical and statistical variability of the trace gas distribution in the atmosphere to choose the solution that has the maximum likelihood
- The retrieval algorithm incorporates statistical properties of the trace gas variability in the form of the a priori vertical profile and covariance matrix
- The retrieved profile $\boldsymbol{x}_{ret}$ can then be expressed as a linear combination of the 'true' profile $\boldsymbol{x}$ and the a priori profile $\boldsymbol{x}_a$

$$\mathbf{x}_{ret} \approx \mathbf{Ax} + (\mathbf{I} - \mathbf{A})\mathbf{x}_a$$

- The Averaging Kernel $\boldsymbol{A}$ represents the measurement sensitivity to the true profile and depends on those factors affecting the radiative transfer of the measured signal through the atmosphere

CO Retrieval Level Averaging Kernels



MOPITT averaging kernels from information contained in the 4.7 μm thermal channels

Greater sensitivity at lower altitudes will be added when information from the 2.2 μm reflected solar channels is included in the retrieval

The MOPITT L2 profile product $\boldsymbol{x}_{ret}$ will be accompanied by ***A*** and $\boldsymbol{x}_a$ and a prescription for comparing with model and in-situ measurements

MOPITT L2 Validation

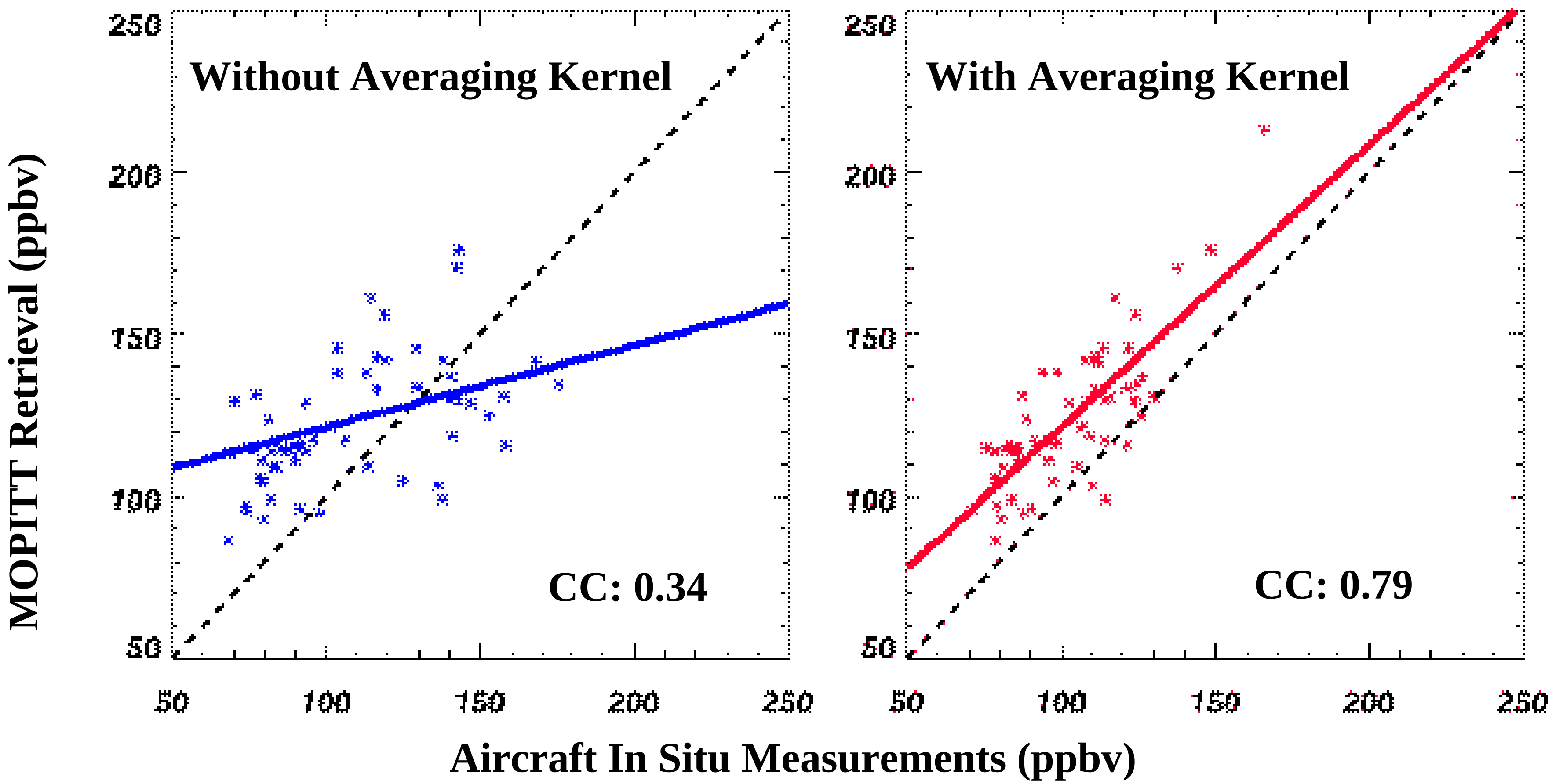
- When comparing mixing ratios or column densities from MOPITT to other measurements or models, the sensitivity of the MOPITT retrieval to the true observed profile must be considered

- An ***in situ*** comparison profile (x_{comp}) must be transformed using the averaging kernels (A) and ***a priori*** profile (x_a) before being compared to MOPITT retrieved values:

$$x_{comp}' = x_a + A(x_{comp} - x_a)$$

Cannot simply make DIRECT comparisons between retrievals and other measurements or models

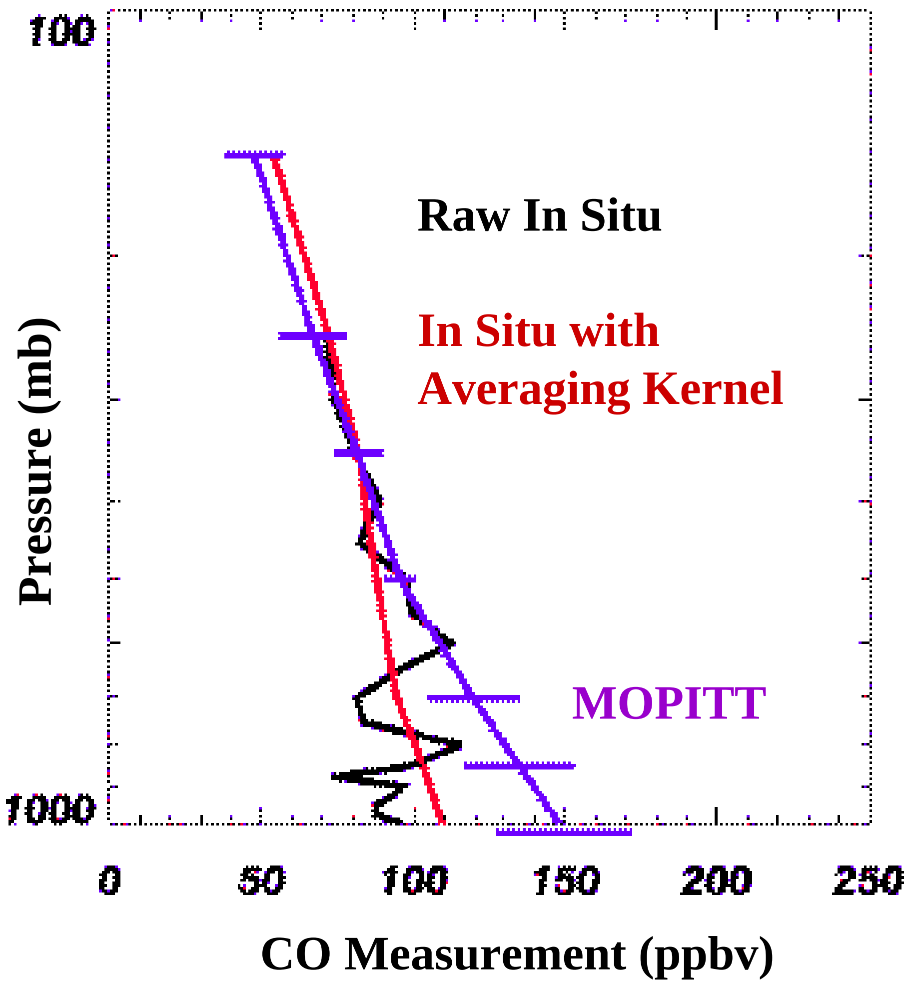
Comparison with in situ aircraft data at 500 mb



Validation sites worldwide. Mainly CMDL flask data

Apparent MOPITT bias of about + 20 ppbv is still being investigated….

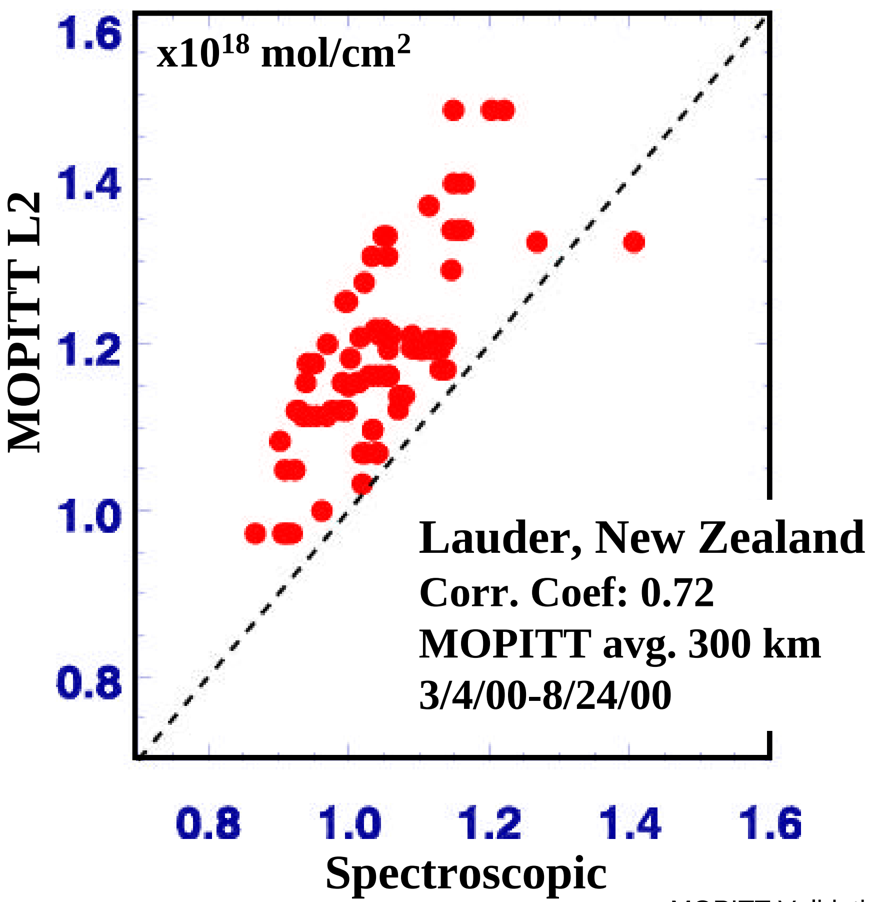
Effect of averaging kernels on vertical resolution

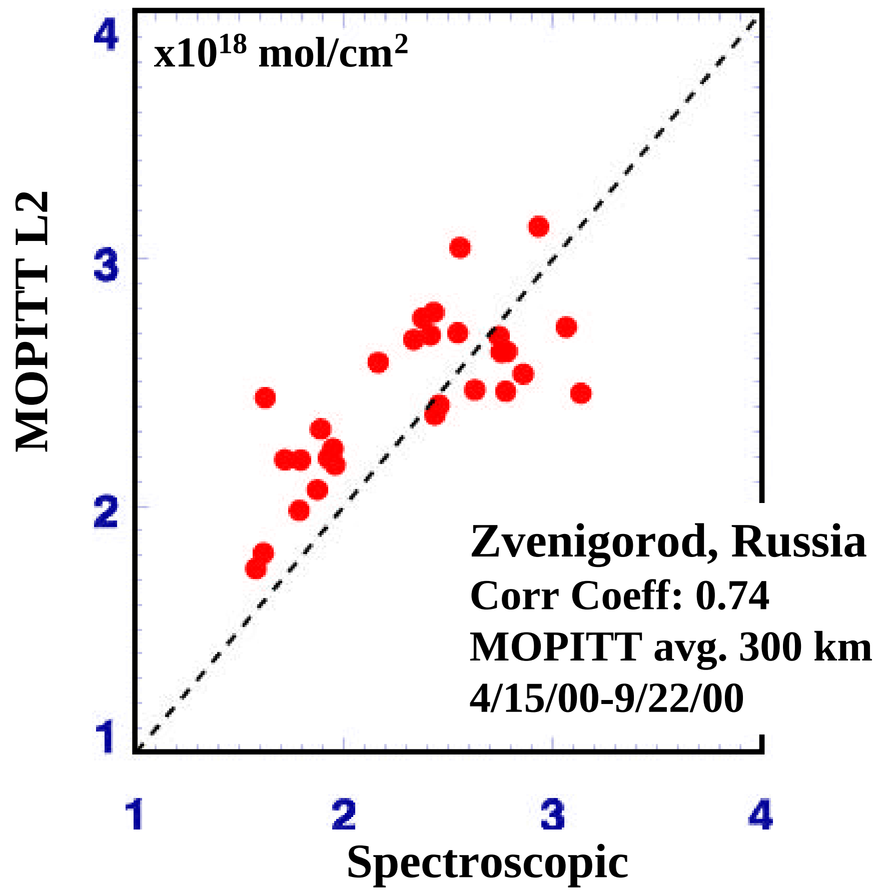


- Comparison of retrieved MOPITT profile with aircraft ***in situ*** measurement taken during the PICO3 campaign
- Applying the MOPITT averaging kernel removes fine scale vertical structure
- Apparent MOPITT retrieval bias of +20 ppbv at low altitude is still being investigated
- Calibration issues are being investigated for source of bias

MOPITT L2 Validation
Comparison with spectroscopy

Goal: Verify agreement of retrieved CO total column amounts from MOPITT L2 and ground-based solar spectroscopy measurements at sites worldwide

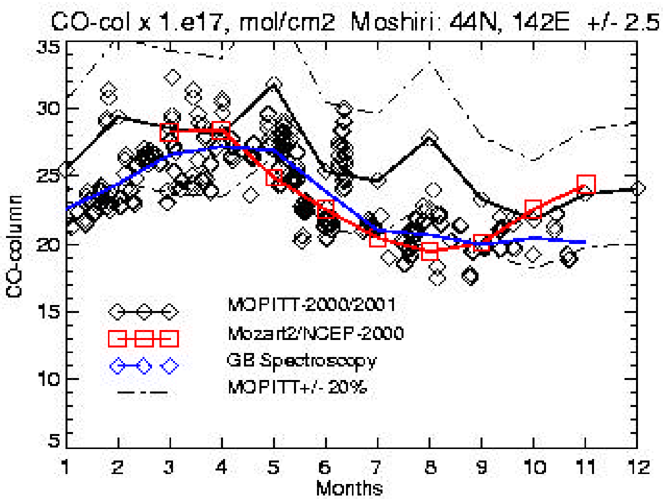


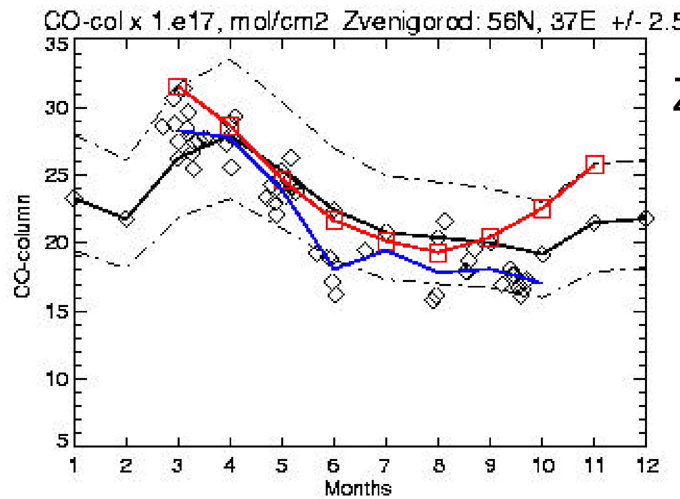


MOPITT and Ground-based FTIR

Monthly averaged MOPITT CO columns compared with spectroscopic column data

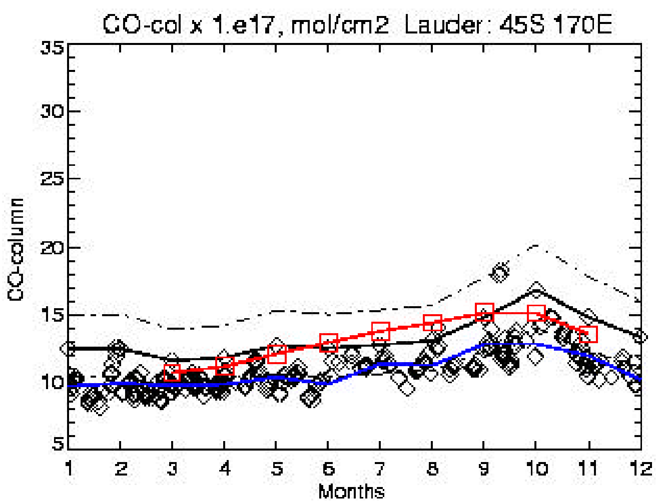
Moshiri
Japan

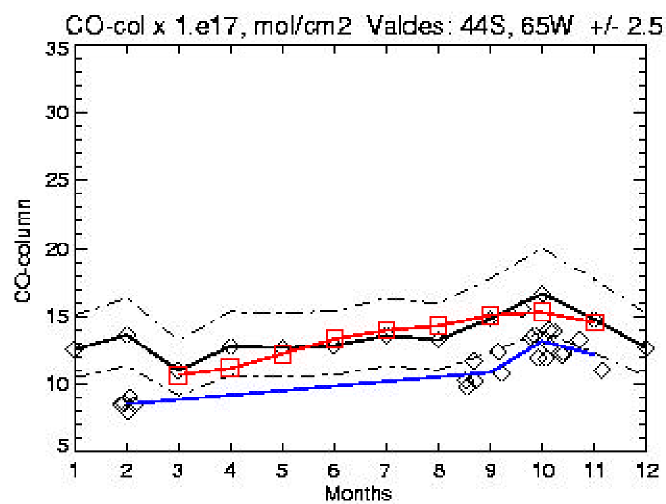




Zvenigorod
Russia

Lauder
NZ





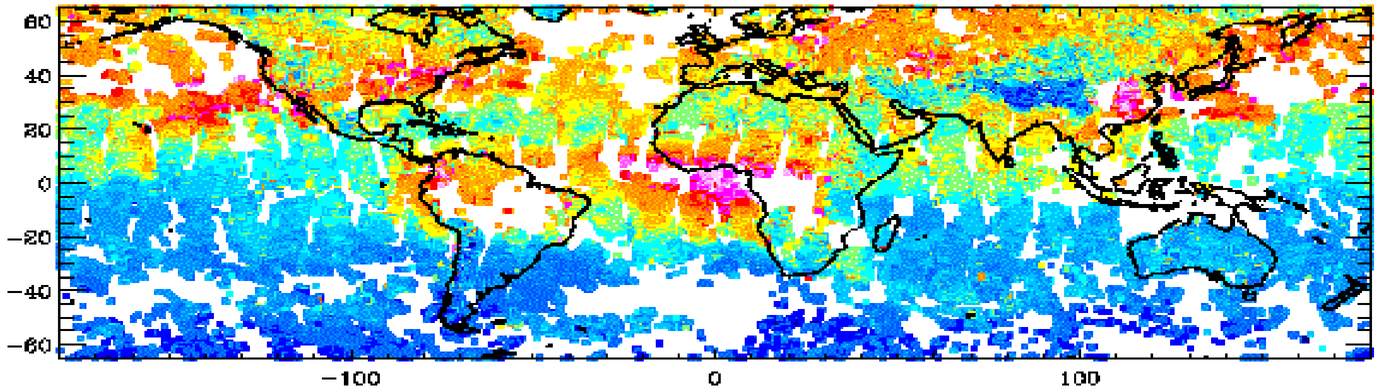
Valdes
Argentina

MOPITT L2 Validation
Model Comparison

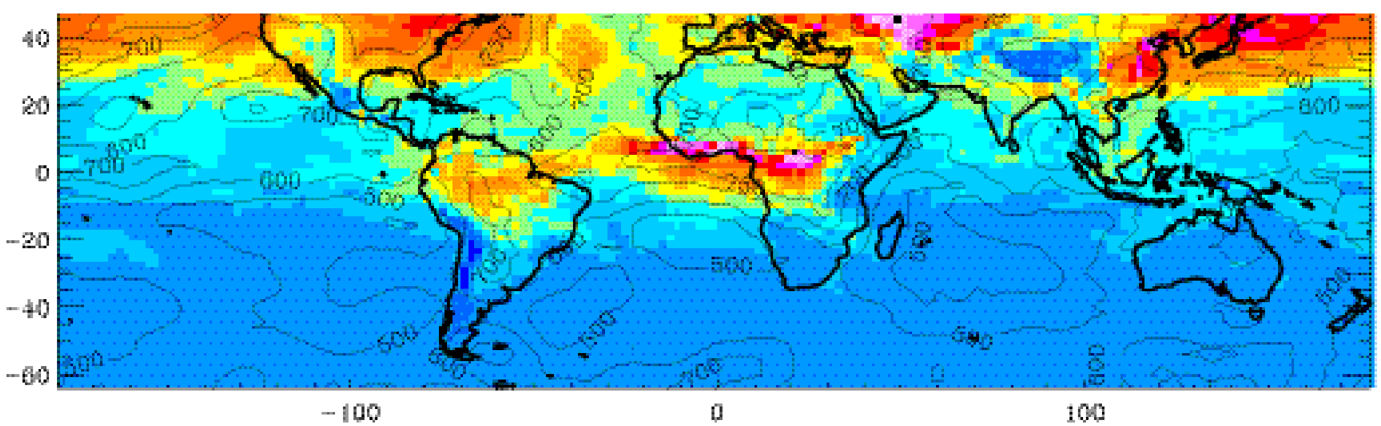
- Comparisons with a 3-D global CTM such as MOZART-2 can be insightful
- MOPITT and MOZART show similar high values over S. America and Africa from biomass burning, and industrial pollution through the Northern Hemisphere

03/15-17/2000

MOPITT



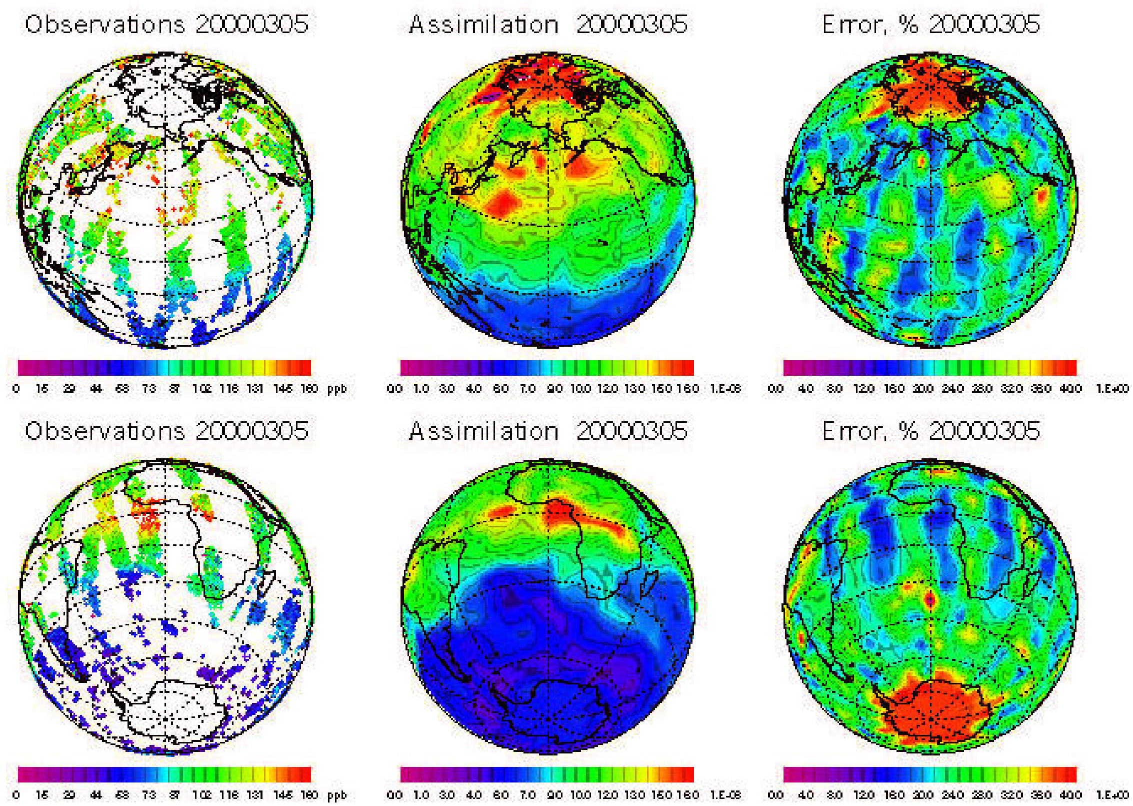
MOZART



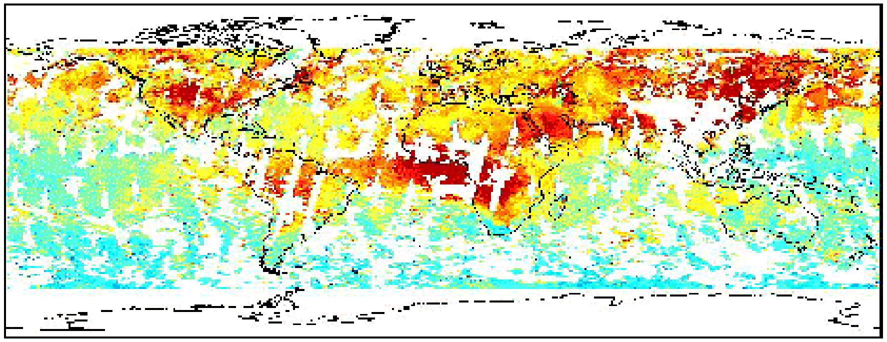
MOPITT L3 CO Assimilation

L3 CO will be produced via assimilation of L2 data into MOZART-2 CTM

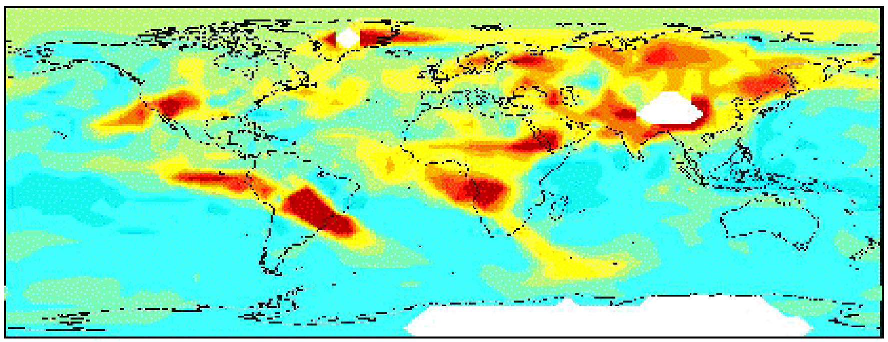
- MOPITT is assimilated into MOZART-2 at 5.6° longitude by 5.6° latitude (T21) (or higher: T42, T63), with 28-60 levels, full tropospheric chemistry, ECMWF or NCEP dynamics
- Error fields are advected along with the CO
- The high spatial and temporal density of the measurements results in the assimilation being strongly constrained by MOPITT data



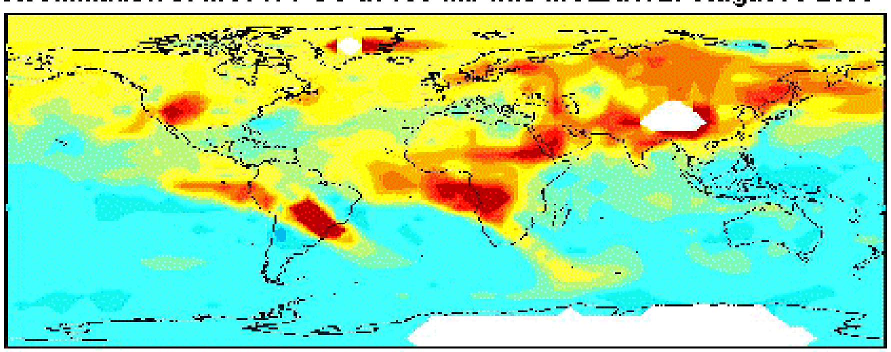
MOPITT CO at 700 mb: Combined data for August 1-3 2000

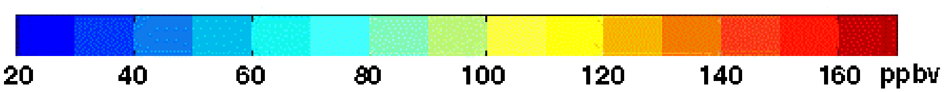


MOZART2 CO at 700 mb: August 3 2000



Assimilation of MOPITT CO at 700 mb into MOZART2: August 3 2000





Assimilation of MOPITT CO profile into the MOZART-2 chemical transport model using NCEP dynamical fields

TOP: MOPITT 700 mb, Aug. 1-3 2000

- Elevated CO associated with industrial pollution is evident over US & China, with significant Asian outflow into the Pacific Ocean
- Biomass burning is an important source of CO in Africa, South America, and India at this time

CENTER: MOZART-2 prediction

- The general pattern of the CO source regions is well represented

BOTTOM: Sequential assimilation

- High measurement density constrains assimilation, such that the strength and locations of the CO emissions follow closely the MOPITT data

Validation Status

MOPITT L1:

Validation against calculated clear sky radiances over uniform regions in the Indian Ocean led to finalization of filter shifts

Validation through comparison with model calculations for characterized scenes leads to confidence in Forward Model

MOPITT L2:

Validation of cloud detection using MODIS continuing

CO profiles are being validated against ***in situ*** measurements

CO total column amounts are being validated against ground-based spectroscopic observations

Comparisons with MATR retrievals to 200 hPa are planned

MOPITT L3:

Assimilation in MOZART: Validation science activities

Validation Issues

- Limited ***in situ*** data above 400 hPa is impeding validation
- Instrument anomaly may require new mode of MOPITT operation using channels 5-8 only. This will require validation issues at Levels 1 and 2 to be revisited
- Continuous independent monitoring (***e.g***., ground-based FTIR) is needed for long-term validation
- Measurements made by the MOPITT-A aircraft instrument will be used in future
- Comparison with future satellite instruments (***e.g.***, SCHIAMACHY on ENVISAT, TES on EOS-Aura) will be valuable
- After instrument problems are resolved, CH_4 retrievals will be validated using similar techniques and same data sources as used for CO
- Use non-coincident data to validate L3