Atmospheric Composition Sounding

ESA Summer School

ESRIN

13th August 2010

Lecture 3 by B.Kerridge

Part 1: Solar Shortwave Nadir Spectrometry

Part 2: Integrated Approach to Composition Sounding

Outline

Lecture 3

Part 1 - Solar shortwave nadir spectrometry

1. Principles
2. Applications
   a) *uv* ozone profiling
   b) *vis* tropospheric NO_2 mapping
   c) *nir* aerosol profiling
   d) *swir* methane & CO
3. Summary and future advances

Part 2 - Integrated Approach to Composition Sounding

1. mm-wave + ir limb emission
2. limb + nadir
3. ir + shortwave nadir
4. spectrometer + imager

Conclusions

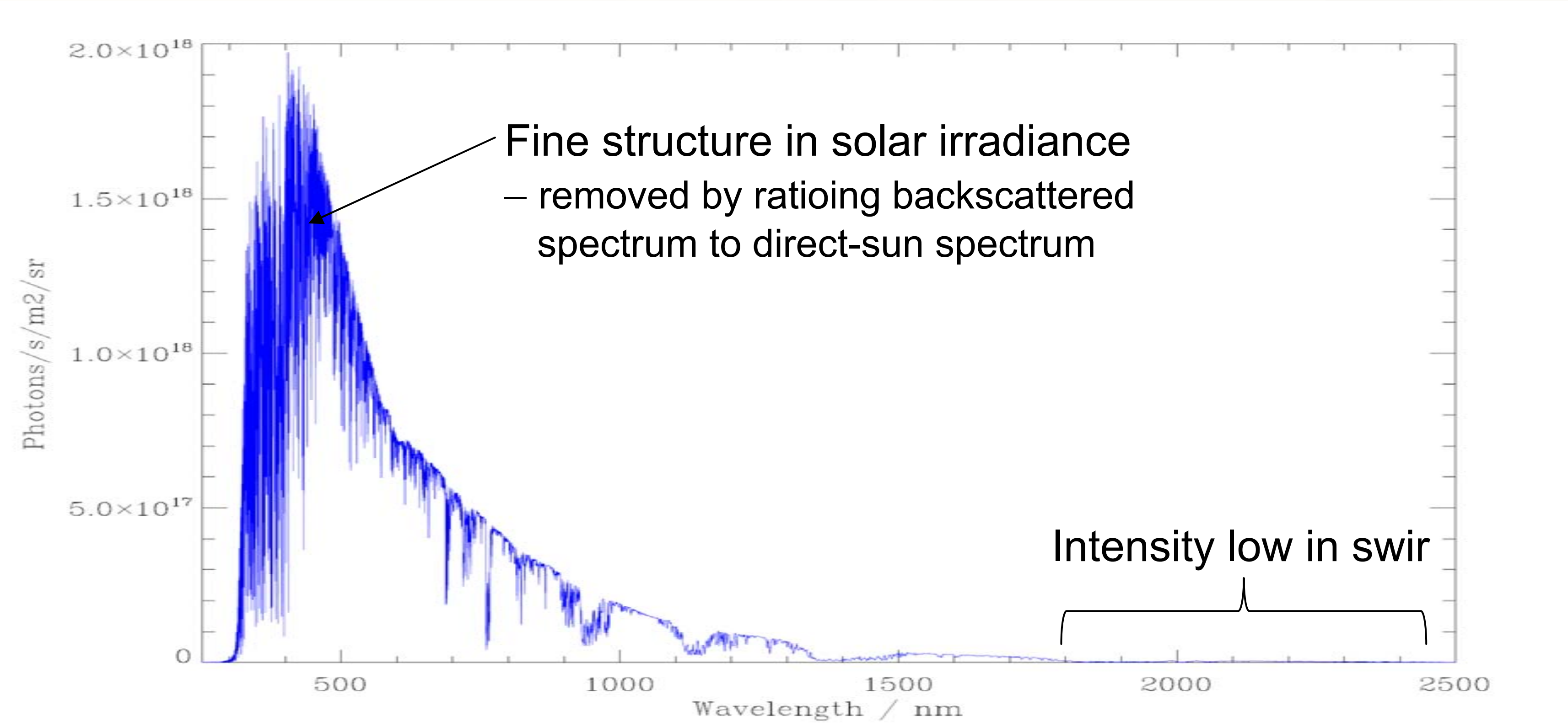
Part 1 - Nadir Shortwave Spectrometry

- Sensitivity to near-surface layer
  - *where primary emissions occur*

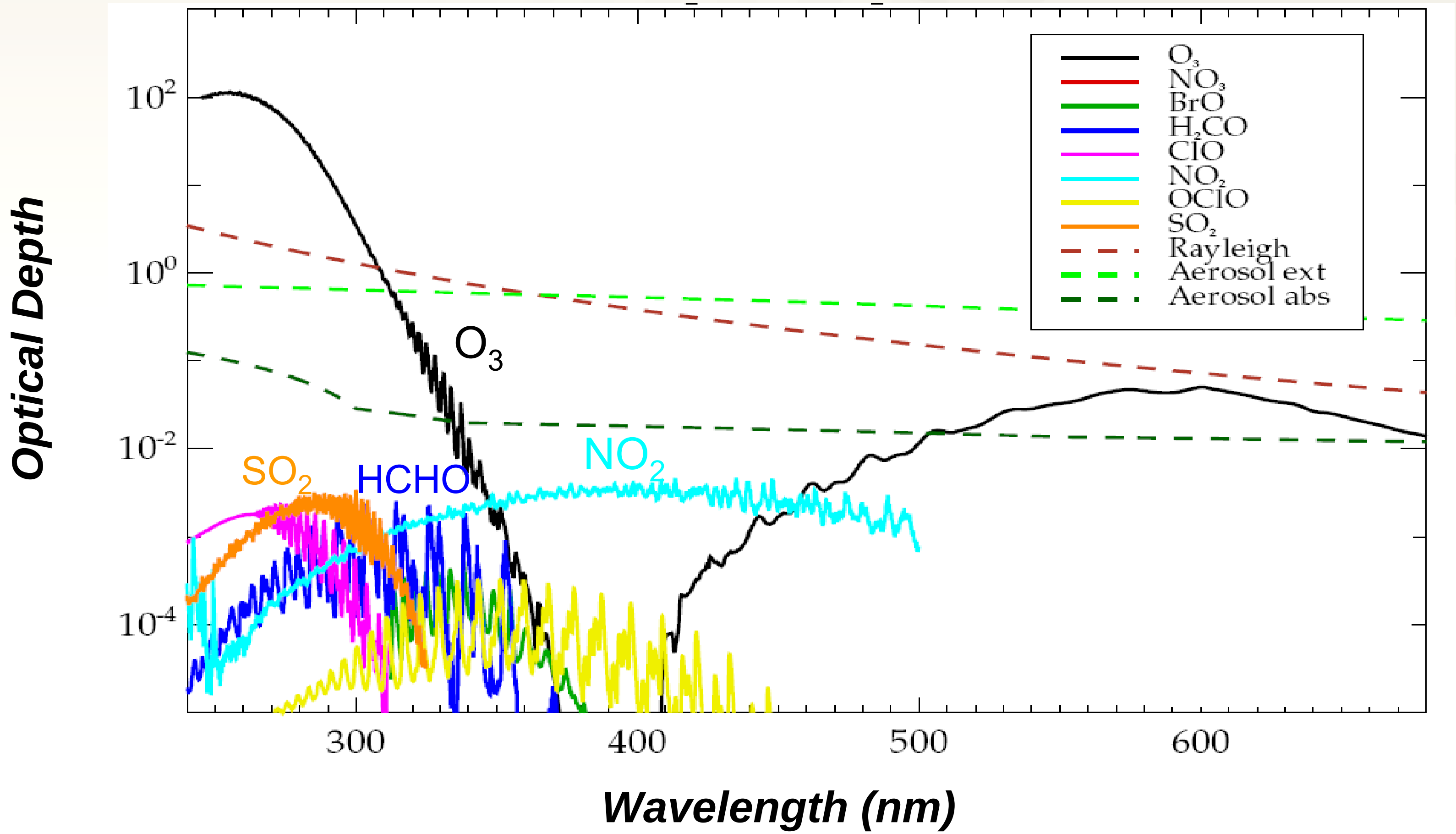
Principles of Nadir Shortwave Spectrometry

- Trace gas absorption signatures in spectra of backscattered sunlight
- Ozone absorption in Hartley band is strong and varies with wavelength
  - → *Spectral intensity of backscattered uv radiation yields stratospheric profile information*
- Ozone absorption signature in Huggins bands is less strong
  - → *Temperature dependence adds ozone profile information in troposphere*
- In near-uv/vis/near-ir, solar radiation can penetrate to surface
- For weak absorbers (eg NO_2, SO_2, HCHO), line-of-sight column proportional to depth of absorption features in *reflectance spectrum*.
- Conversion to vertical column requires knowledge of surface reflectance, scattering profile and other *prior* assumptions

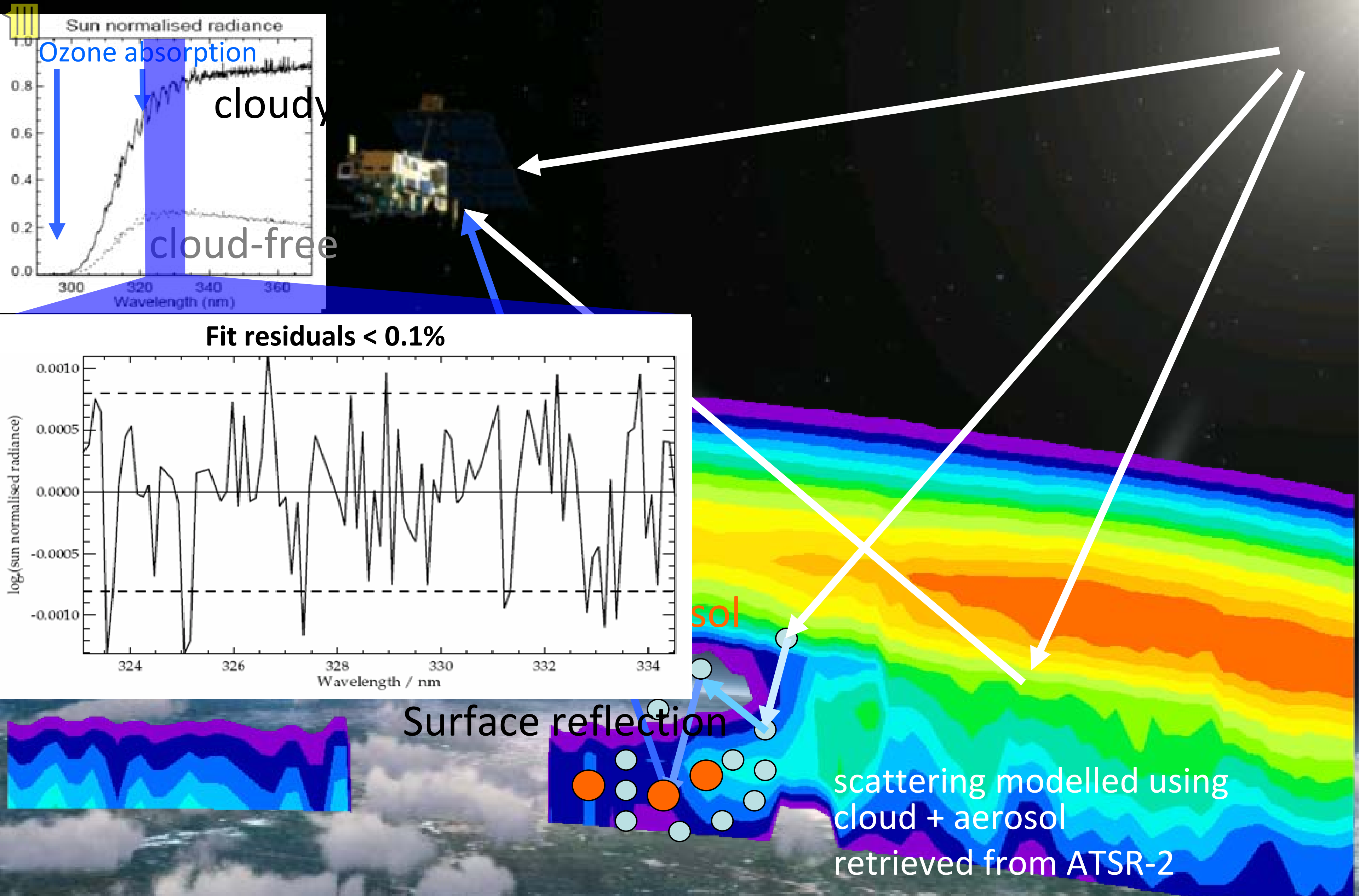
Spectral Intensity of Backscattered Solar Shortwave Radiation



Trace gas signatures in uv/vis region

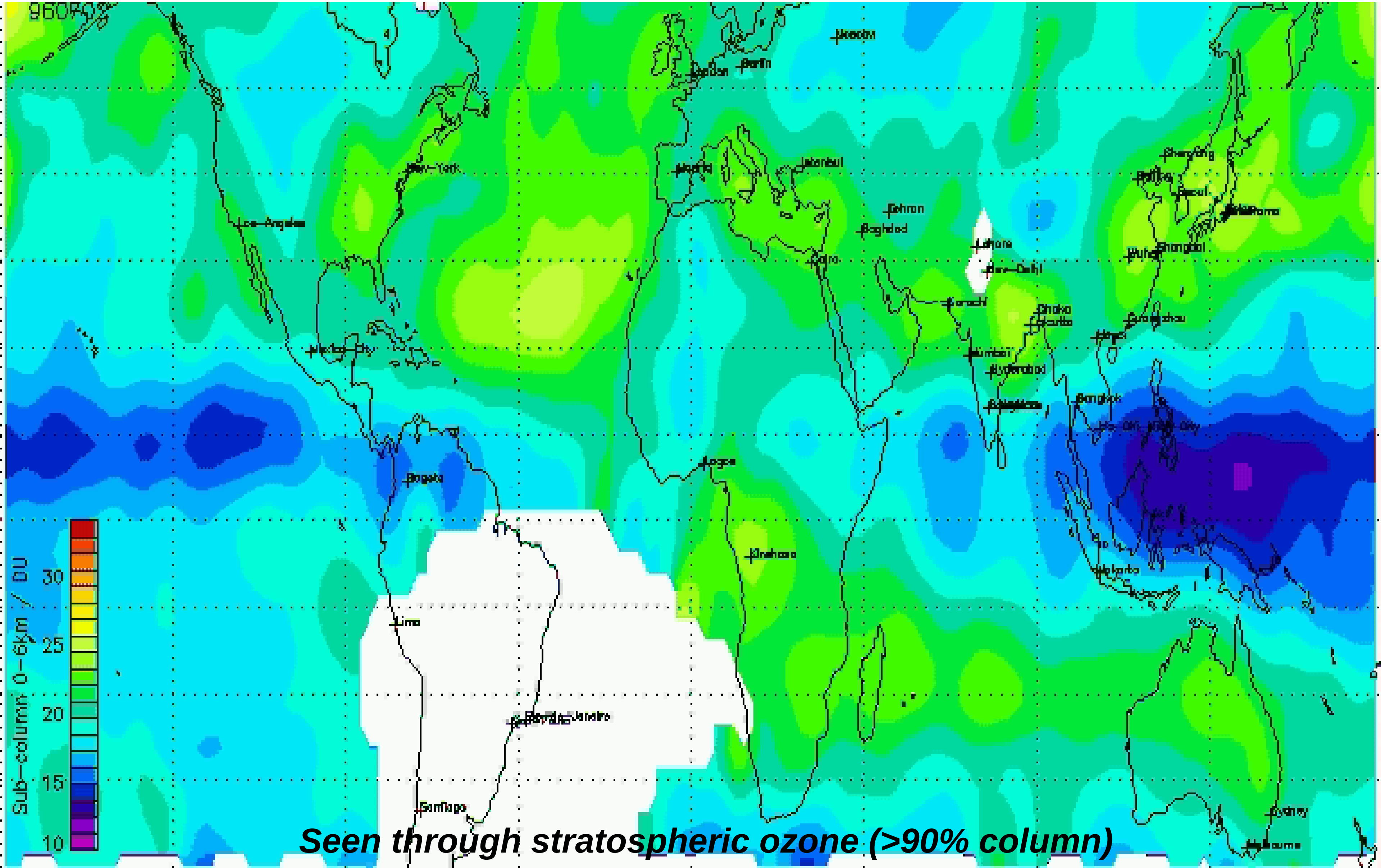


→ RMS fitting precision of <0.1% necessary for tropospheric ozone & other gases



RAL scheme for GOME-1 ozone profile retrieval
(Munro et al, Nature, 1998)

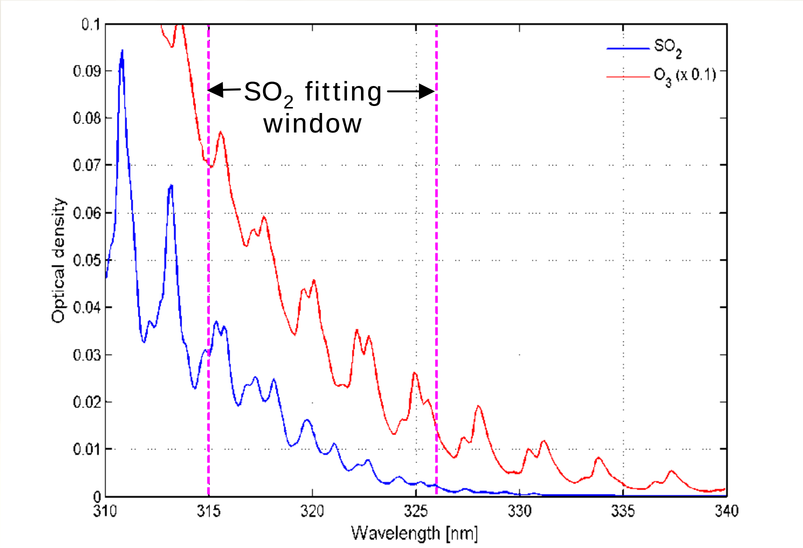
Evolution of Lower Tropospheric Ozone 1996-99 from ERS-2 GOME-1 observations



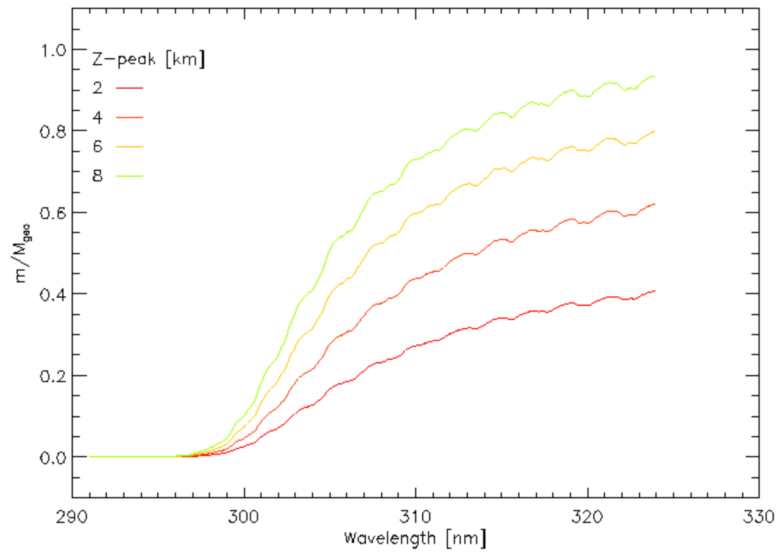
Seen through stratospheric ozone (>90% column)

Volcanic SO_2 plume

– Information on plume height available *if* perturbations to integrated column & plume height affect reflectance spectrum differently

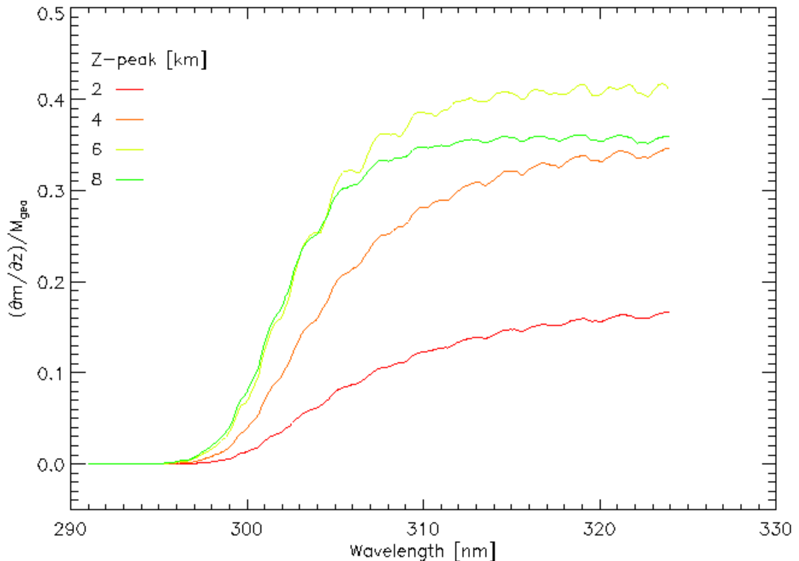


SO_2 air mass factor



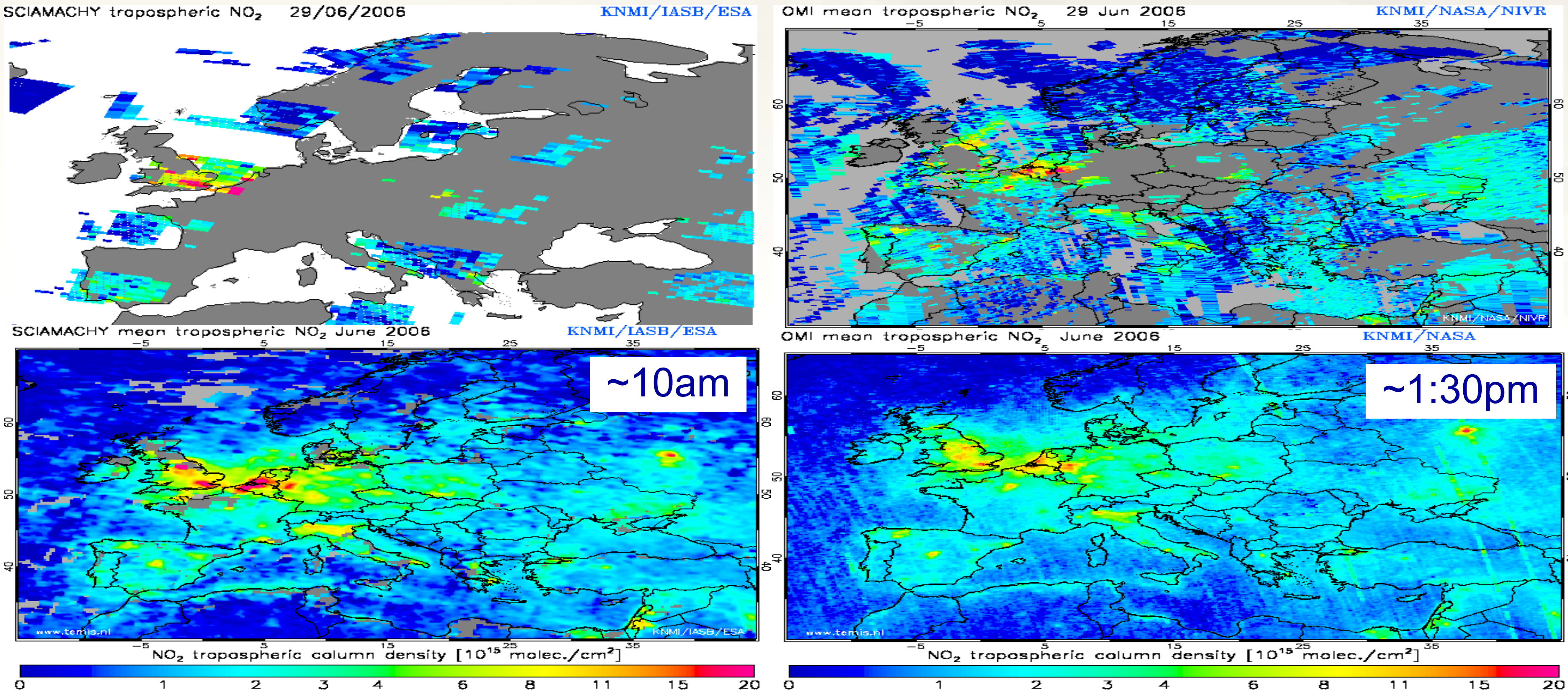
M_{GEO}=geometrical AMF

SO_2 air mass factor vertical gradient



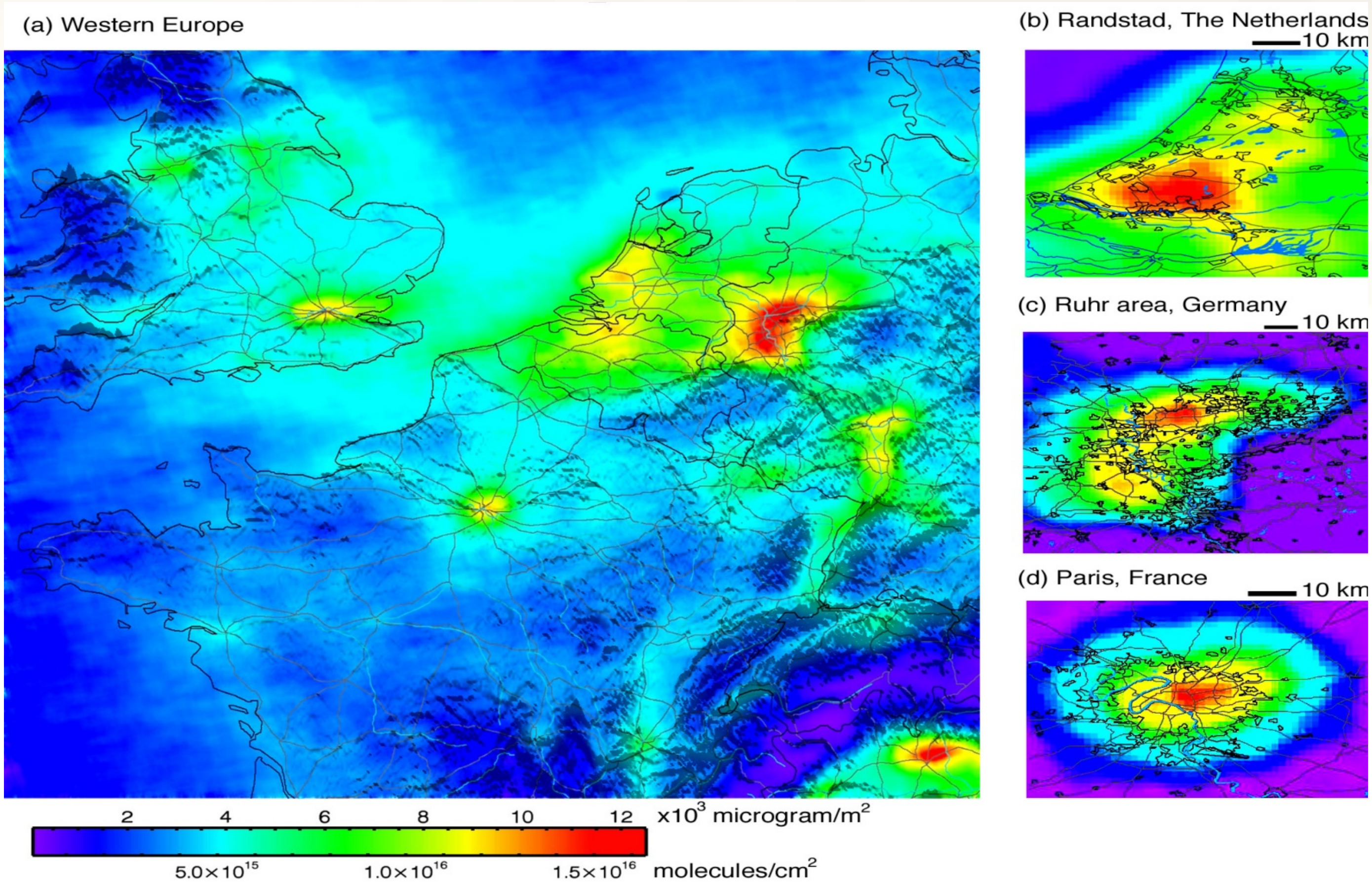
Courtesy, J.van Gent, IASB-BIRA

Comparison of Tropospheric NO_2 from SCIA and OMI



Courtesy: van der A and Dirksen, KNMI (www.temis.nl)

OMI Tropospheric NO_2 annual mean: Dec'04-Nov'05



Simulations for O_2 A-band (764nm) for Sentinel-4 UVN

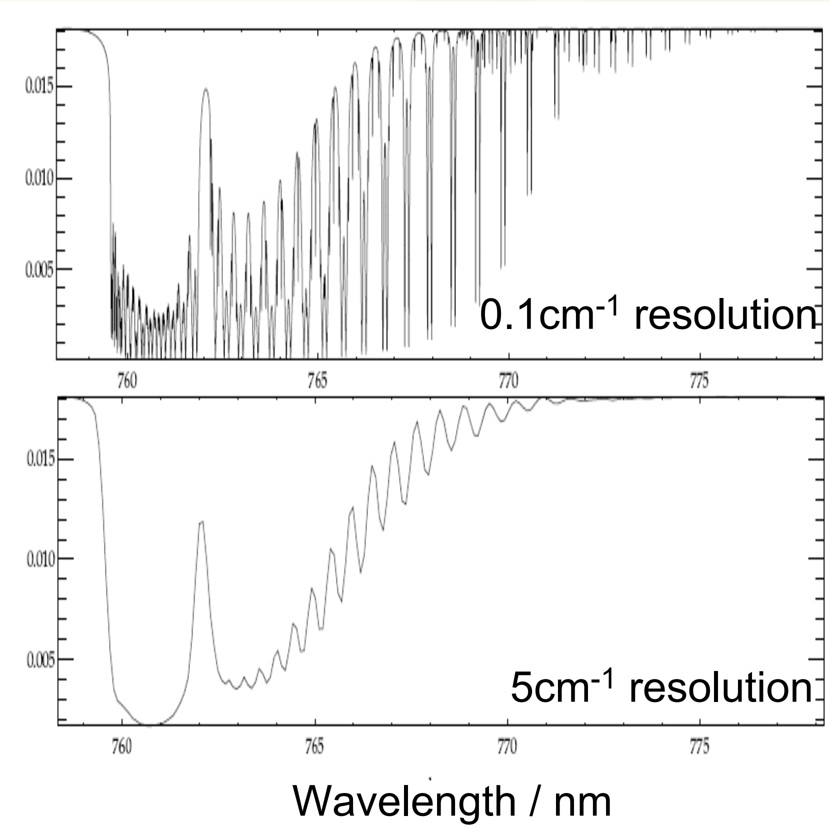
- O_2 A-band: opaque at line centres
  - – Effective scattering height a strong fn(λ)
  - – O_2 mixing ratio known
  - → *Retrieve scattering profile*

- Sensitive to $\delta\lambda$, S/N and other errors

- Requirements assessed for height-resolved aerosol retrieval from Sentinal-4 UVN A-band

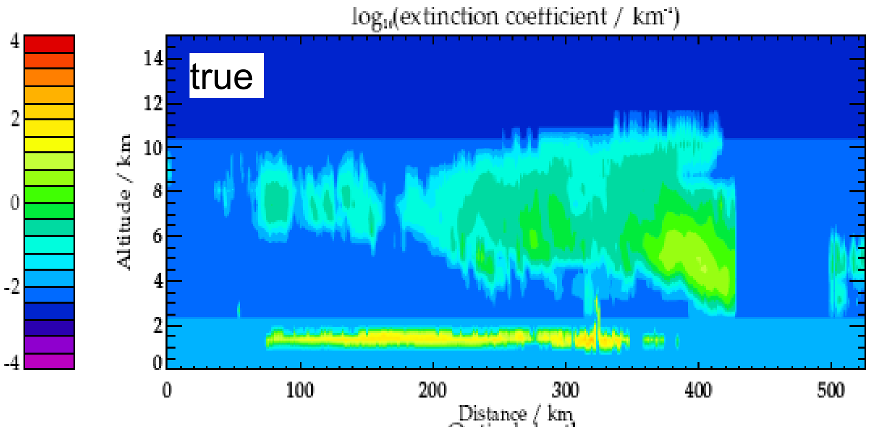
Siddans et al, EUM/CO/05/1411/SAT, 2007

Sun-normalised radiance

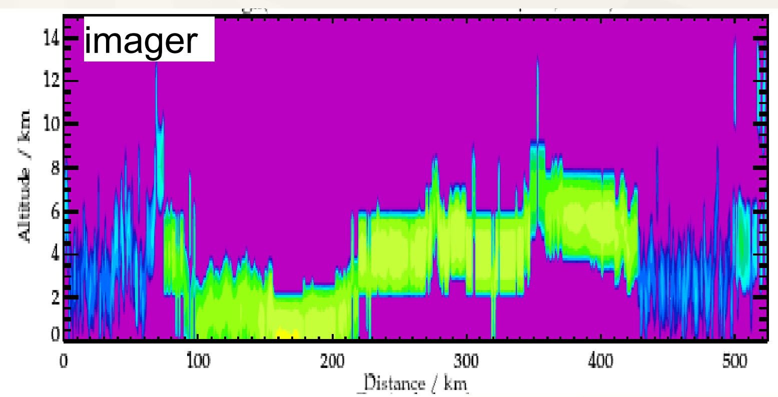


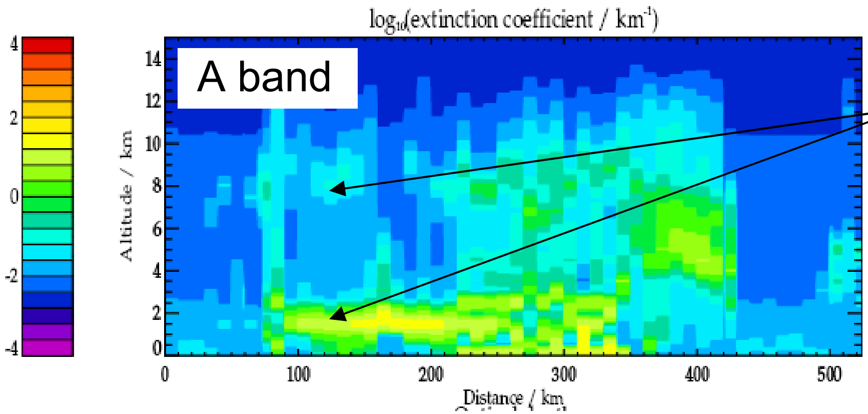
Aerosol retrieval simulation for O_2 A-band (764nm)

4th Jun'03 0.55μm extinction



Single-layer multi-channel imager retrieval





- *Near-surface aerosol discriminated from cirrus & aerosol in higher layers*

→ Particulate sources & transport → AQ

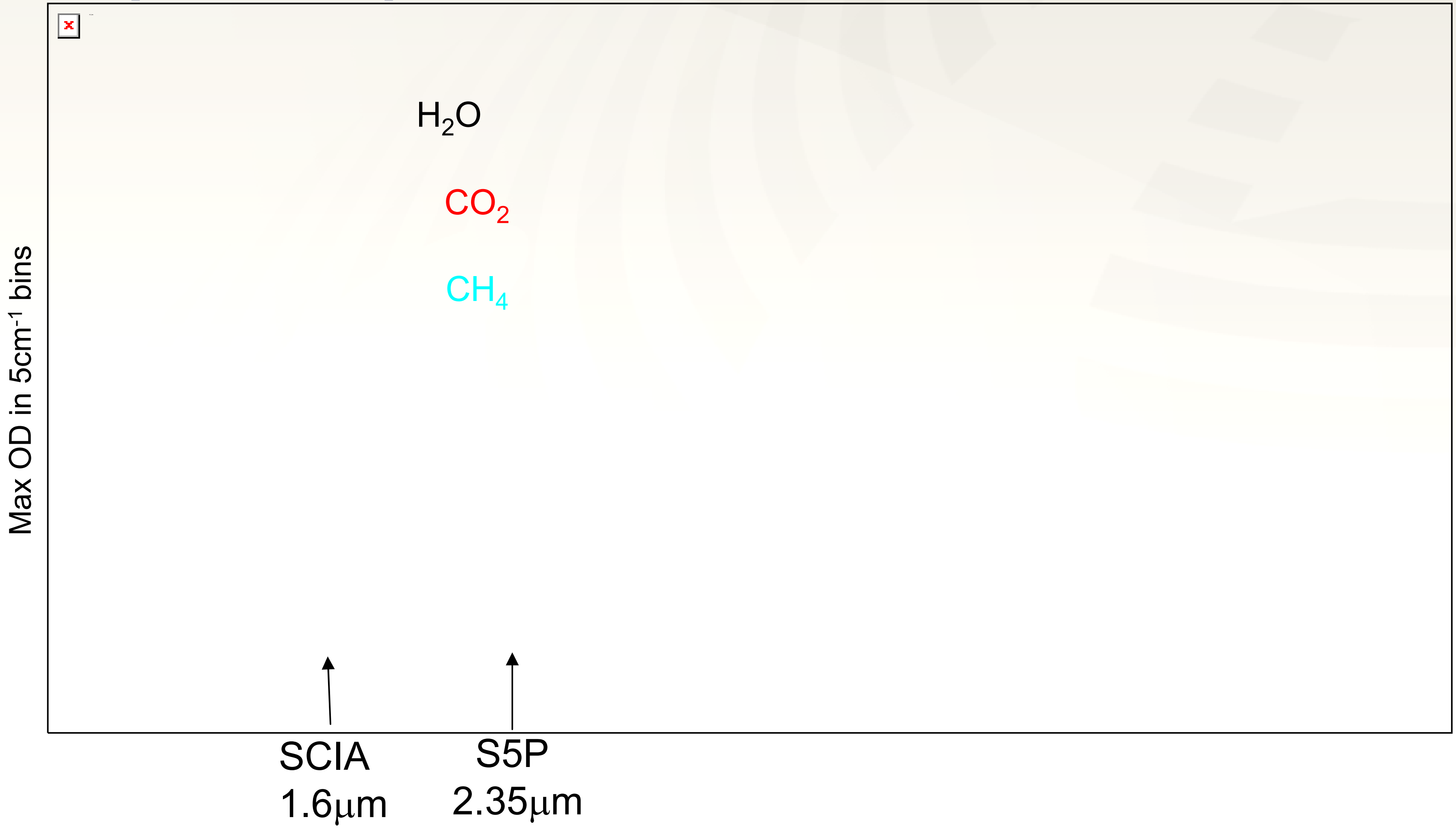
- *Represent scattering profile in trace gas retrievals*

→ More retrieval of gaseous pollutants

O_2 A-band retrieval:

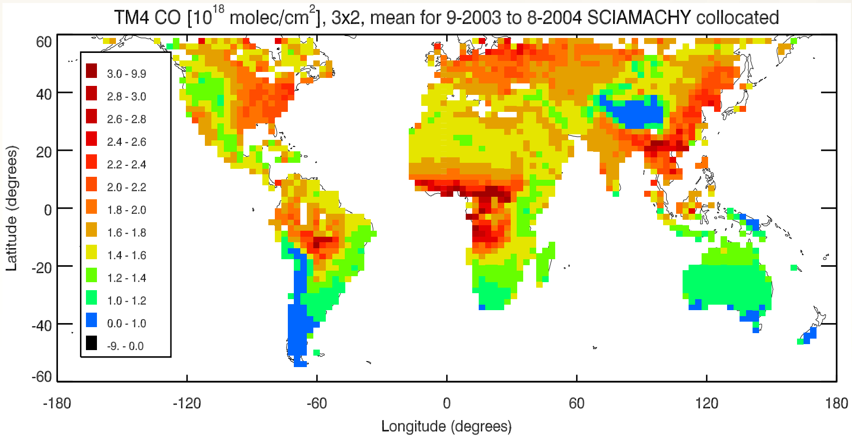
$\delta\lambda$ = 1cm^{-1}, S/N = 2500, δz = 1km

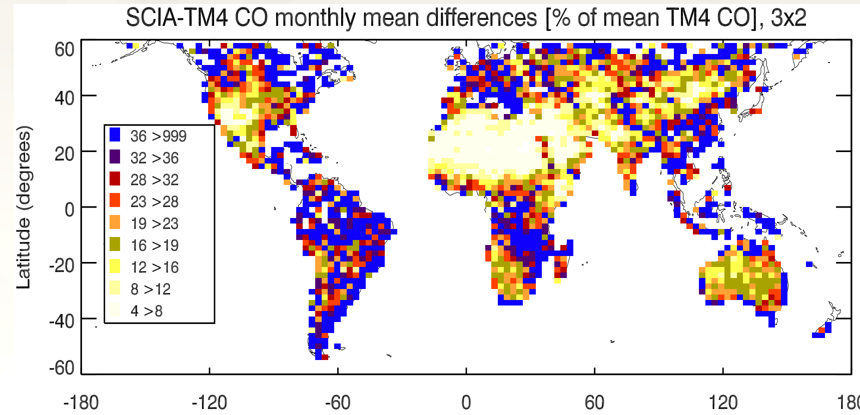
Optical Depths in Short-wave IR

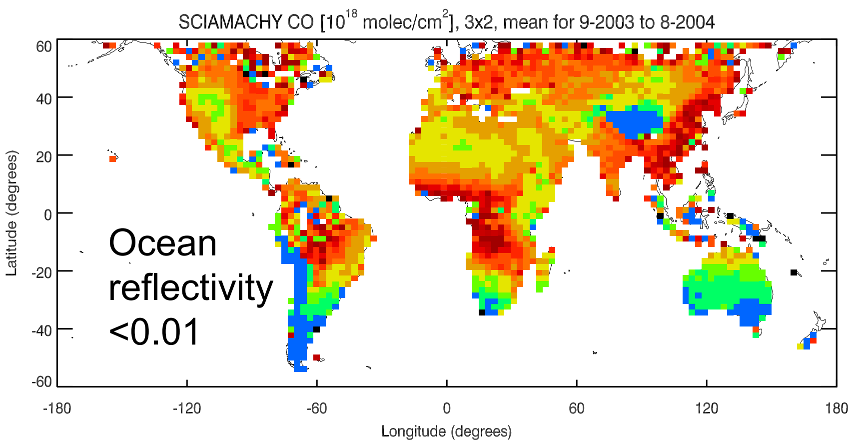


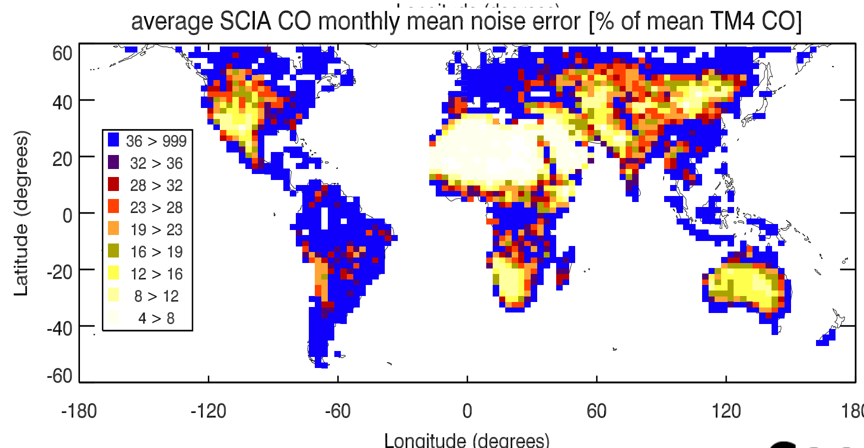
– In short-wave ir, spectral structure of vibration-rotation bands exploited, as in mid-ir.

Comparison of SCIA & TM4 CO over land
Annual mean: Sep’03 – Aug’04





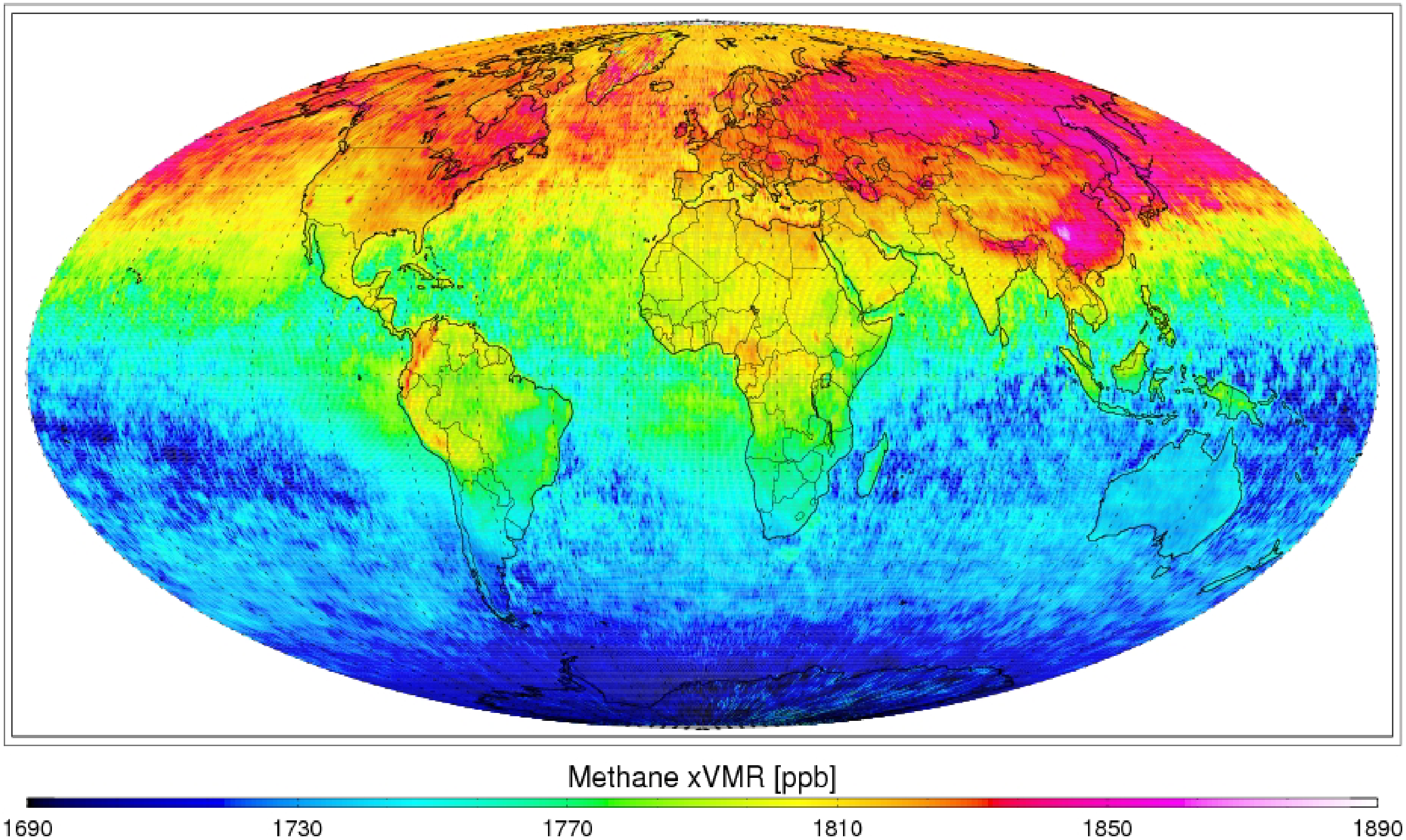




SRON

- SCIA – TM4 monthly mean difference spatially correlated with SCIA monthly mean noise
- SCIA errors dominated by 2.35μm detector noise → large potential improvement for S5P & S5

Global Mean CH_4 Distribution for 2003-4 from SCIAMACHY

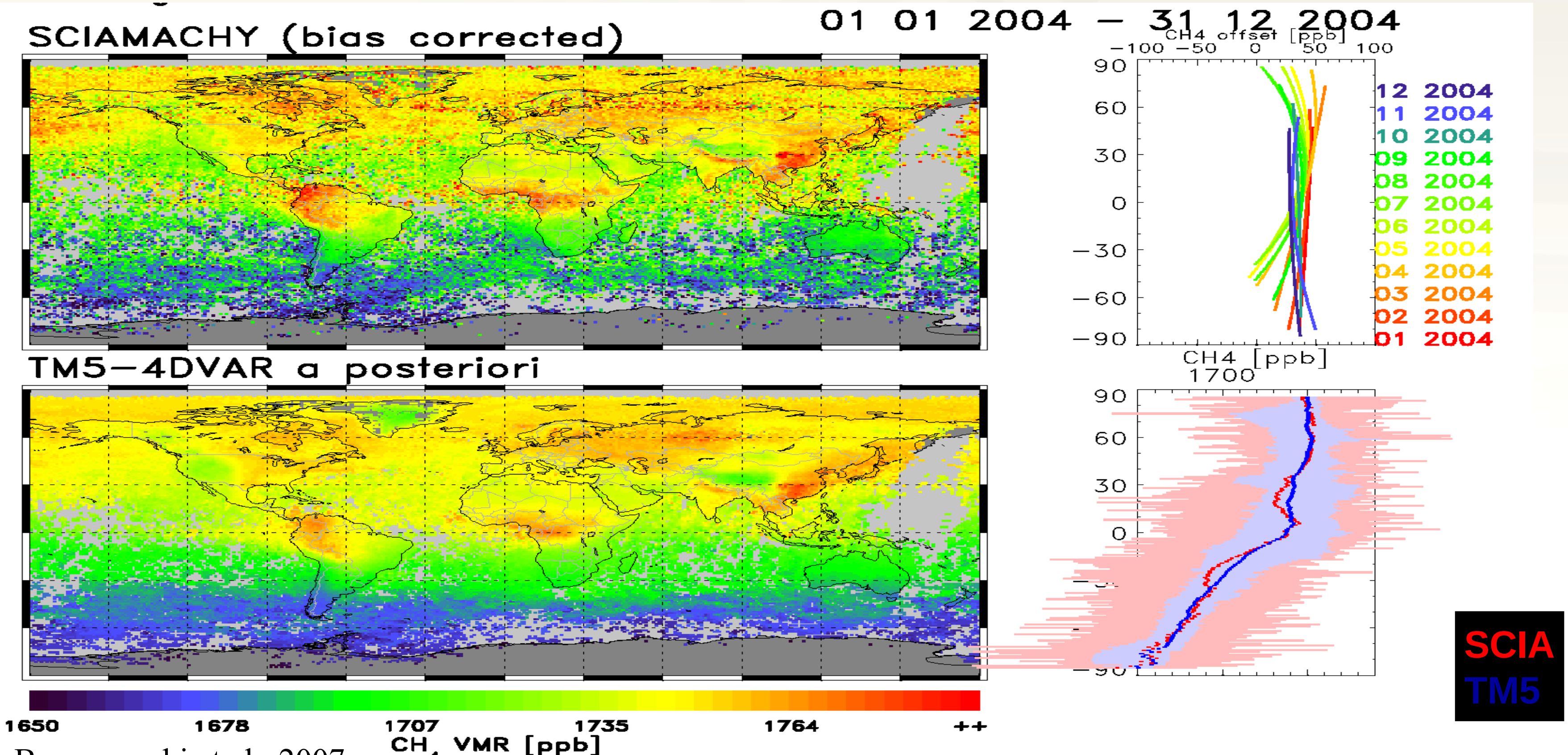


– Fluctuations from uniform mixing are small

→ *Accuracy requirements are challenging*

SRON

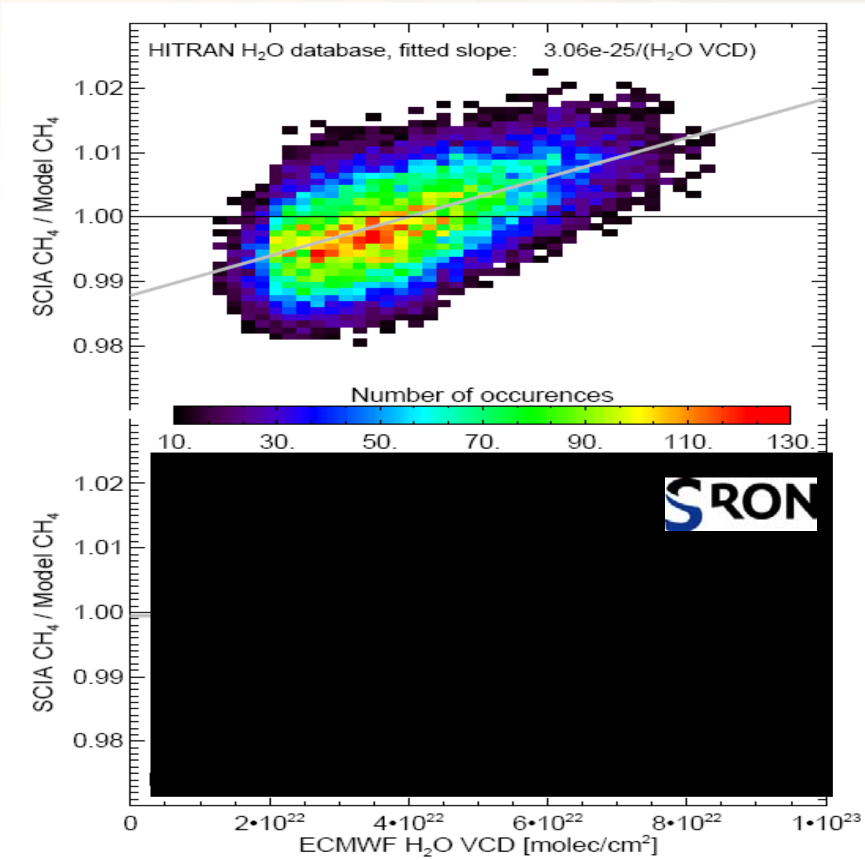
Methane Annual Mean - 2004
Comparison of SCIAMACHY & TM5



Bergamaschi et al., 2007

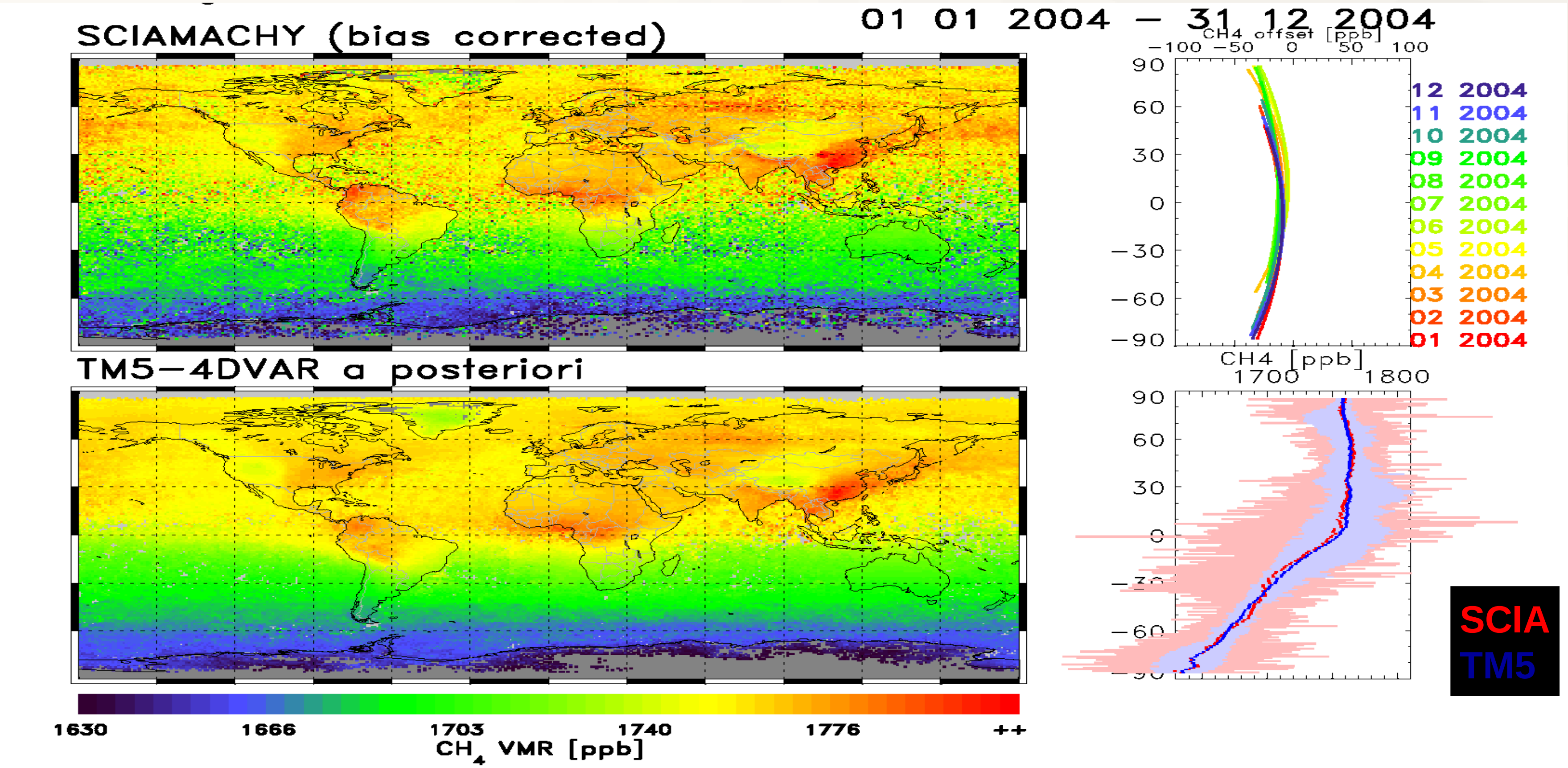
SCIA seasonal / latitudinal bias w.r.t. surface obs

Correlation of SCIA CH_4 retrievals with column water vapour



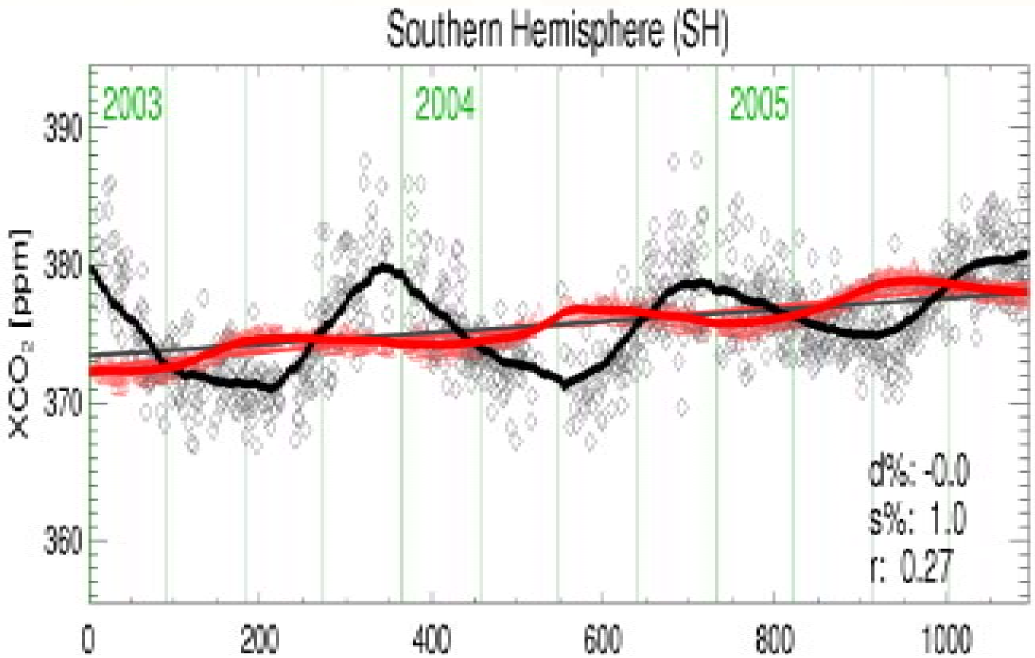
Frankenberg et al
GRL 2008

Methane Annual Mean - 2004
Comparison of SCIAMACHY & TM5

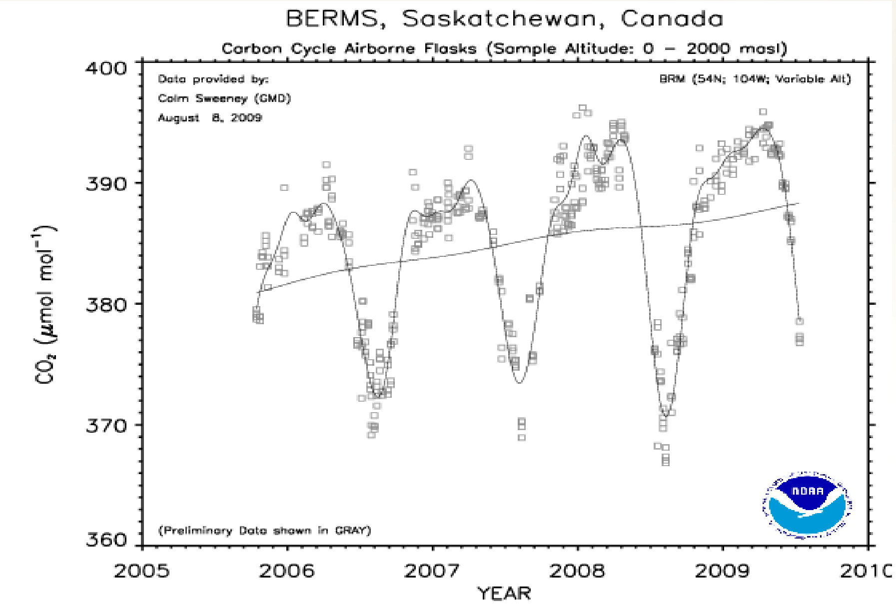


Seasonal varn. in bias removed by improved H_2O (& CH_4) spectral data

- SCIA measures CO_2 absorption simultaneously with CH_4 in 1.6μm band
- CH_4 column-average mixing ratio actually derived as ratio to CO_2, which is much closer to being uniformly-mixed.
  - *ratio approach allows some errors in knowledge of atmospheric physics and instrument to be accommodated in deriving CH_4*
- Q: Might perturbations from uniform-mixing be detectable for CO_2?



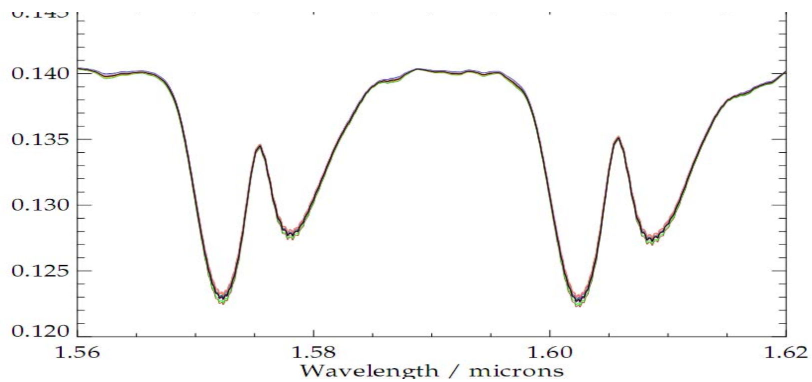
Influence of geophysical factors on seasonal variation in 1.6μm reflectance spectrum



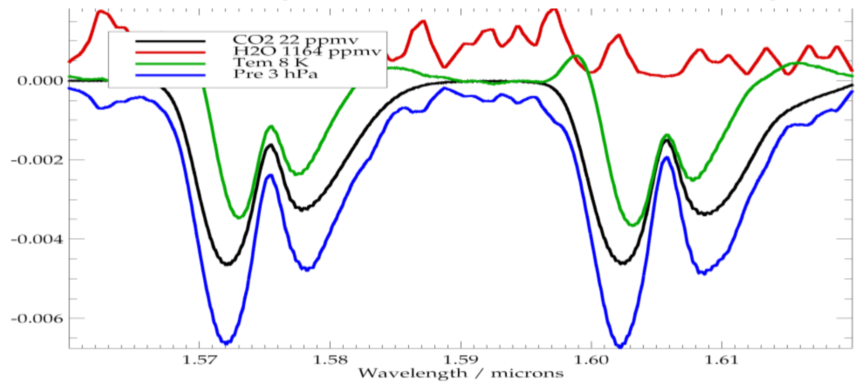
– 1.6μm reflectance spectrum influenced by geophysical factors additional to CO_2

– Detection of CO_2 seasonal variation (~few % pk-pk) depends on spectral correlation and how accurately these other factors can be known.

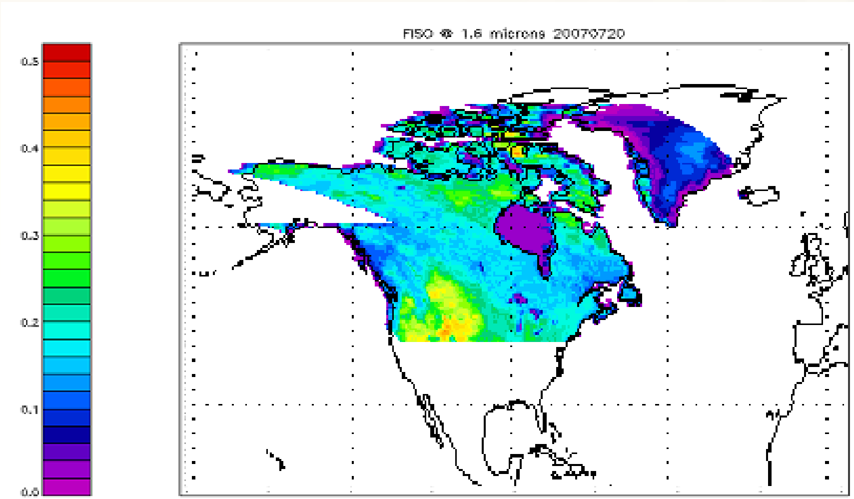
Spectra calculated for seasonal amplitudes



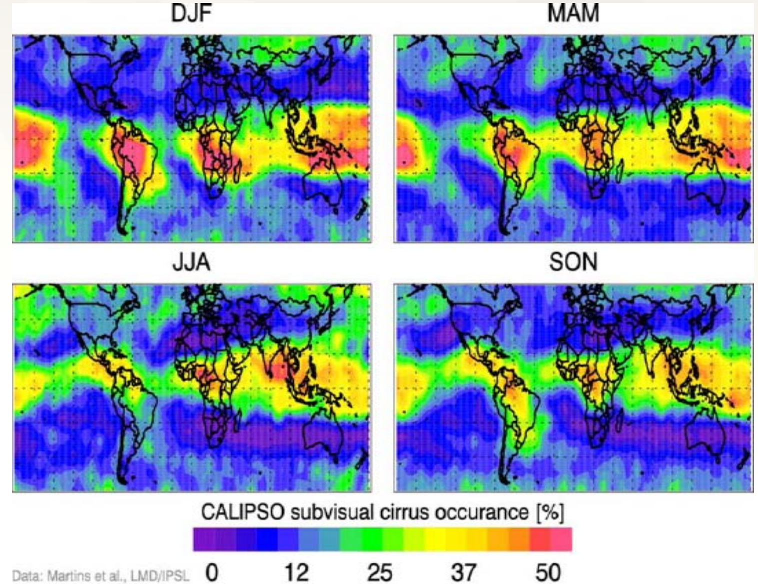
Normalised spectra for seasonal amplitudes

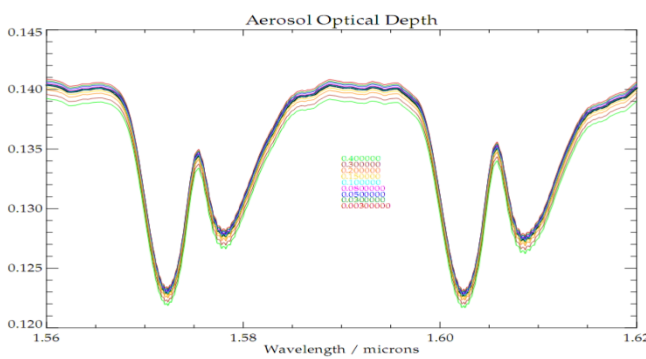


Influence of geophysical factors on seasonal variation in 1.6μm reflectance spectrum (contd.)



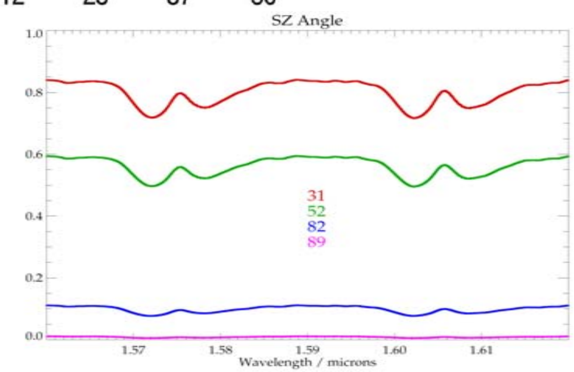
BRDFs for season and location from MODIS.





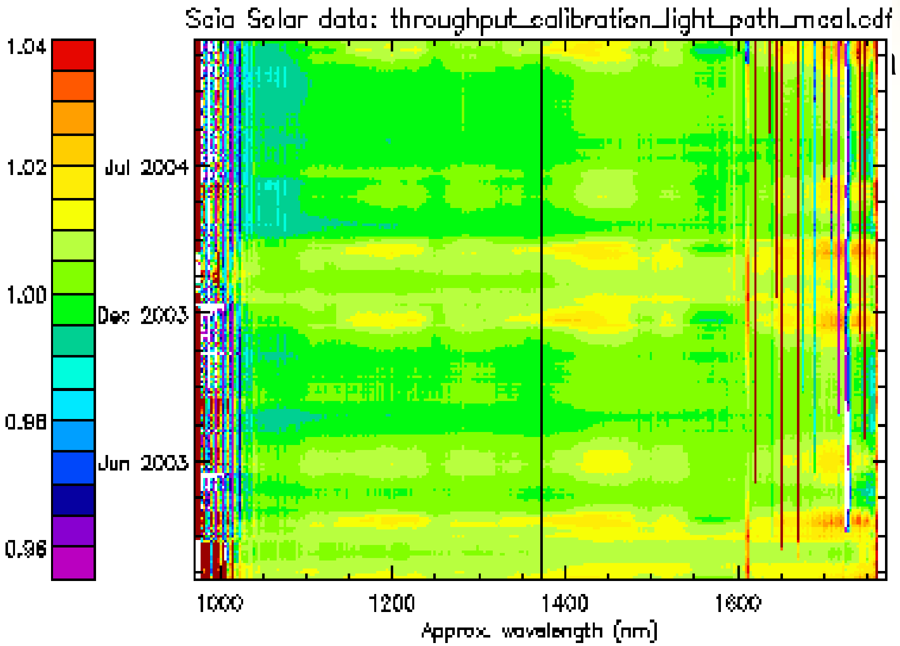
Derivation of column-average vmr also depends on accurate knowledge of scattering ie:

– Solar zenith & viewing angle
– Surface BRDF
– Profiles of aerosol & thin cirrus
– Residual cloud contamination

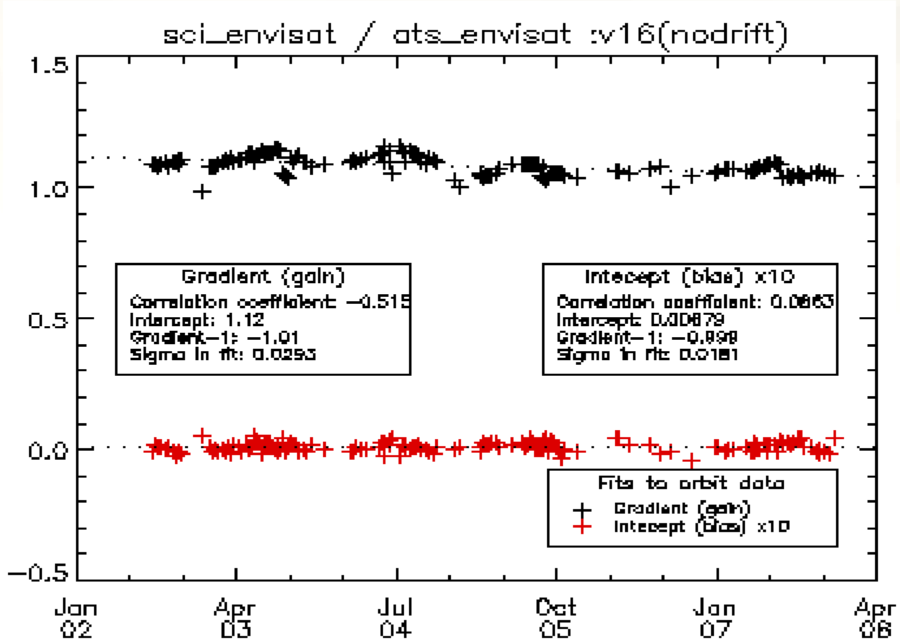


Influence of instrumental factors on seasonal variation in 1.6μm reflectance spectrum

SCIA normalised solar spectrum

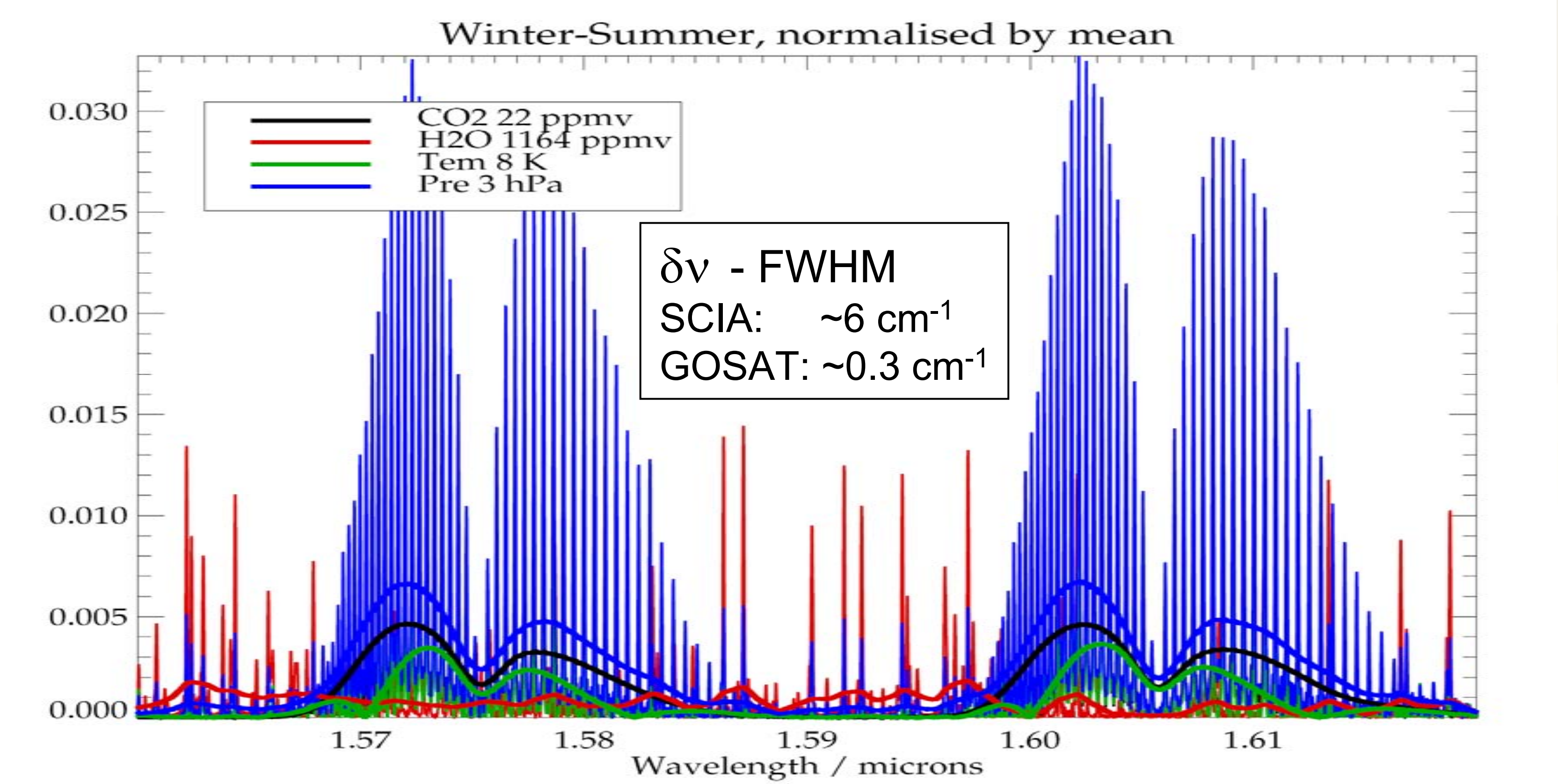


SCIA integrated 1.6μm *reflectance* v AATSR



- To detect regional perturbations from uniform mixing at accuracy (≤1%) needed for inverse modelling, near-perfect knowledge of other geophysical and instrumental factors is required.

Spectral signatures at resolutions of SCIA & GOSAT



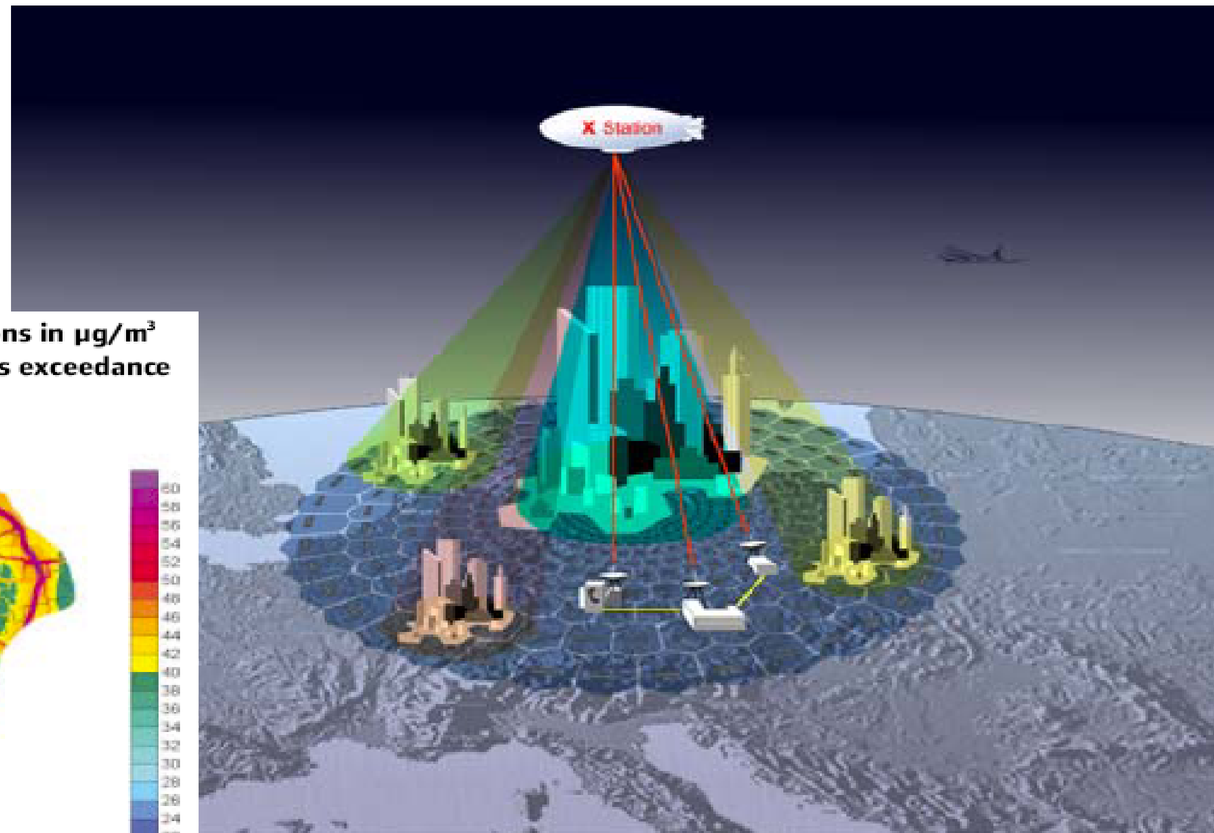
- GOSAT: optimized for CO_2
  - additional bands (2μm & IR); 20x higher spec. res., cloud imager
- *GOSAT (FTS) and OCO-II (grating) should allow potential for CO_2 to be assessed more fully.*

Advances: solar shortwave nadir-spectrometry

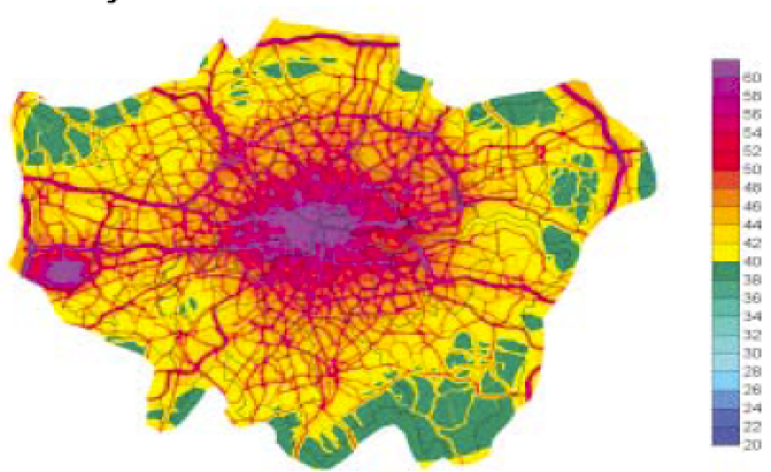
- **Improve accuracy:**
  - Discriminate trace gases & aerosol more cleanly from cloud & surface
- **Improve height-resolution:**
  - Spectral resolution in O_2 A-band & swir vibration-rotation bands
- **Improve sampling of lower trop. → monitoring/forecasting**
  - *Polar orbit:*
    - smaller ground-pixel to see more often between clouds
    - sample several LTs: 9:30am (MetOp → S5/post-EPS) & 1:30pm (S5P → JPSS)
  - *Geo orbit (S4/MTG-S)*
    - denser spatio-temporal sampling of observable disk (if px size same as polar)
      - photon flux ~1600x smaller; compensated by t_{int}, optics size & ground px size

Geostationary Platform in Stratosphere

Bridge the gap from street-level to satellite



Modelled 1999 annual mean NO_2 concentrations in µg/m^3 (poor weather year), above 40 µg/m^3 indicates exceedance of 2005 objective



Part 2 – Integrated Approach

1. Complementarity of IR and mm-wave limb sounders

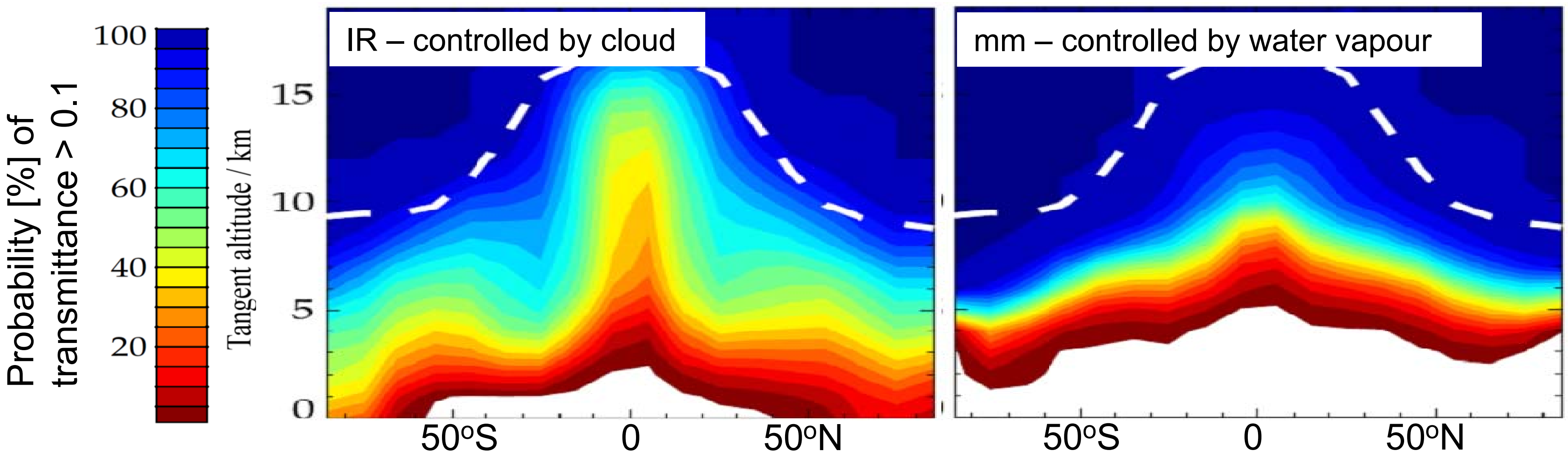
- Target trace gases:

  IR: CH_4; organic compounds; nitrogen oxides
  mm-wave: CO; HCN & CH_3CN (biomass burning indicators); halogens

- Sensitivity to cirrus particle size

  IR: $R_e < 100\mu m$
  mm-wave: $R_e > 100\mu m$

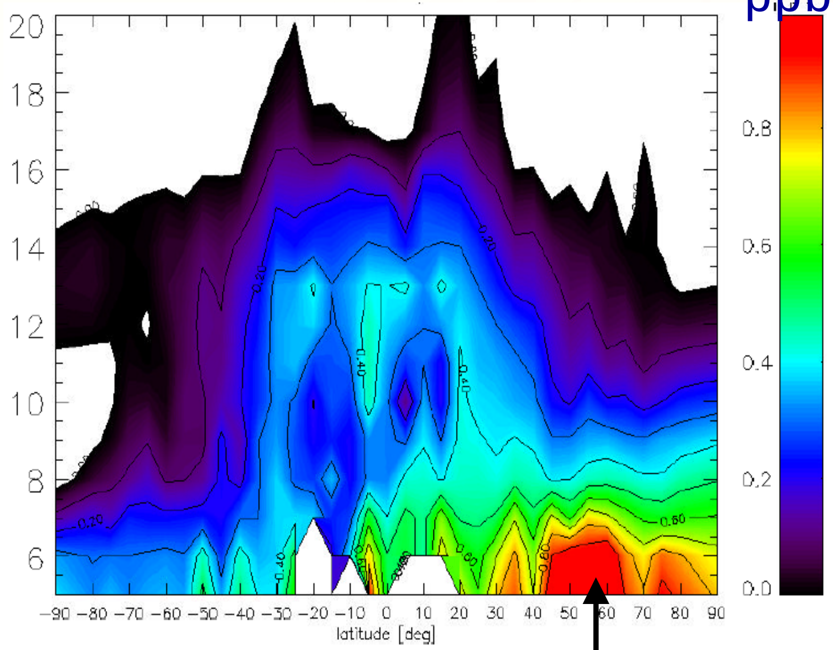
  → *Different penetration depths into troposphere*



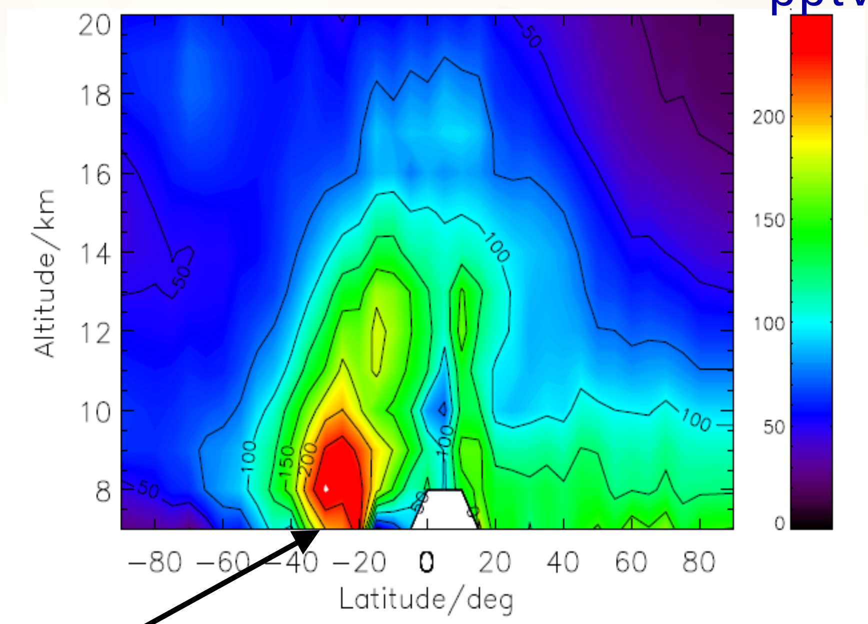
Zonal-Mean Cross-Sections of Ethane & PAN from MIPAS

- In addition to profiling many gases in the stratosphere, MIPAS can also probe the upper troposphere.

Ethane (C_2H_6) – 16/11/02



PAN 10-day mean 4/10–1/12 2003



G.Stiller, pri.comm.

Anthropogenic emissions

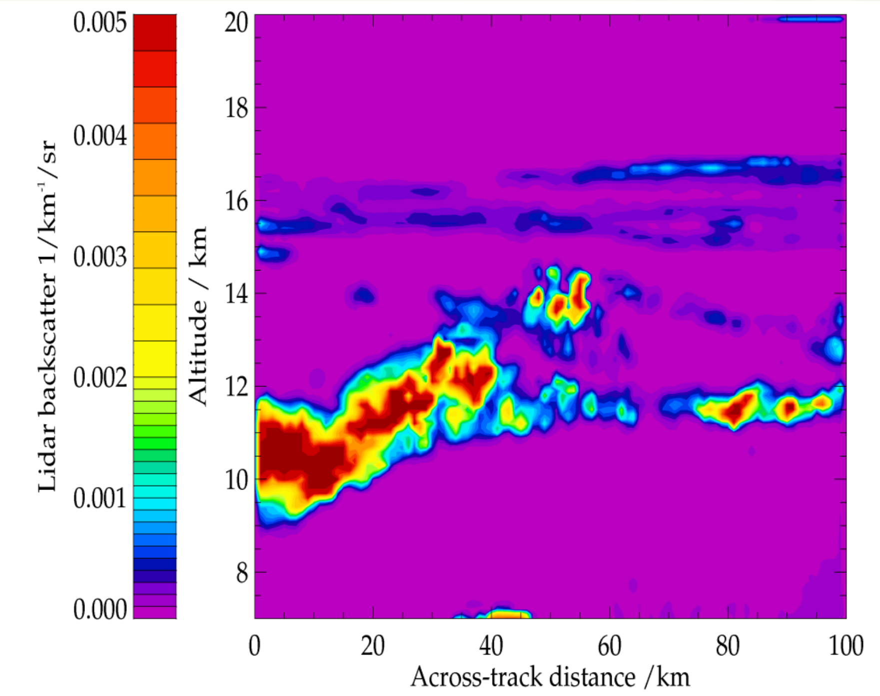
Biomass burning

PAN: secondary product from VOCs & NO_x

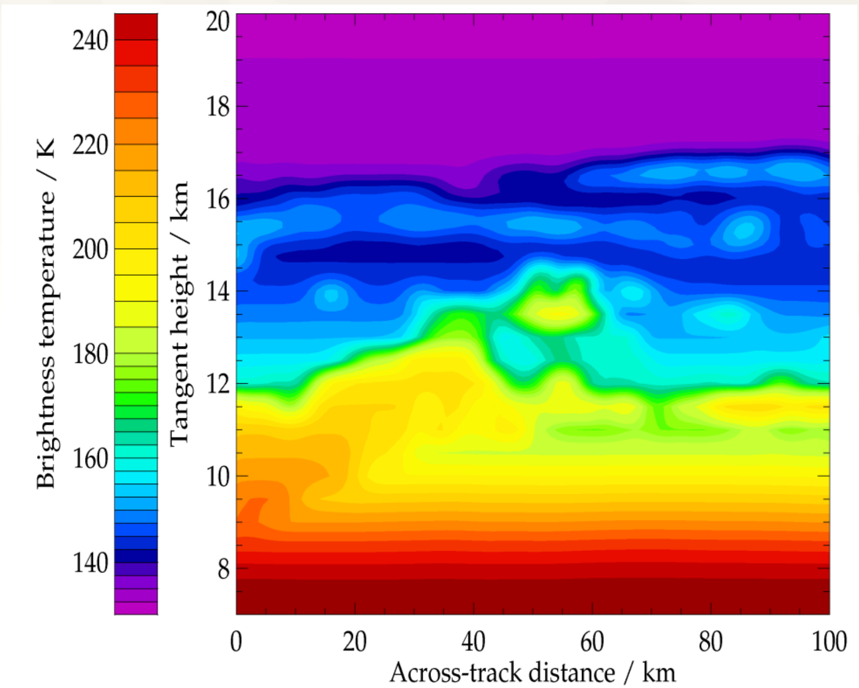
Glatthor et al, ACPD, 7, 2775-2787, 2007

Thin cirrus layers near the tropical tropopause

ER-2 lidar backscatter



Simulated IRCI 12μm image



– Thin cirrus layers influence water vapour transport through TTL
– Difficult to detect by satellite lidar but observable by high-resolution IR limb imaging
– These thin layers are transparent in mm-wave → retrieval of H_2O & other gases unaffected

– Height of volcanic ash layer could also be determined precisely through IR limb imaging

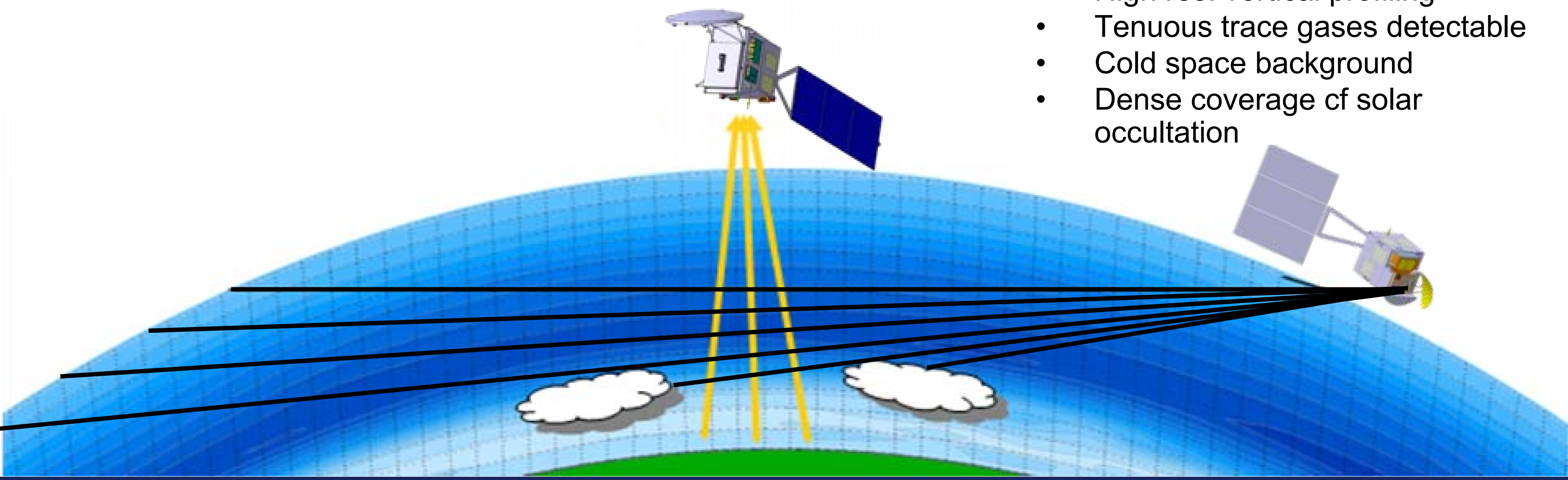
2. Limb – nadir combination

Nadir-sounding

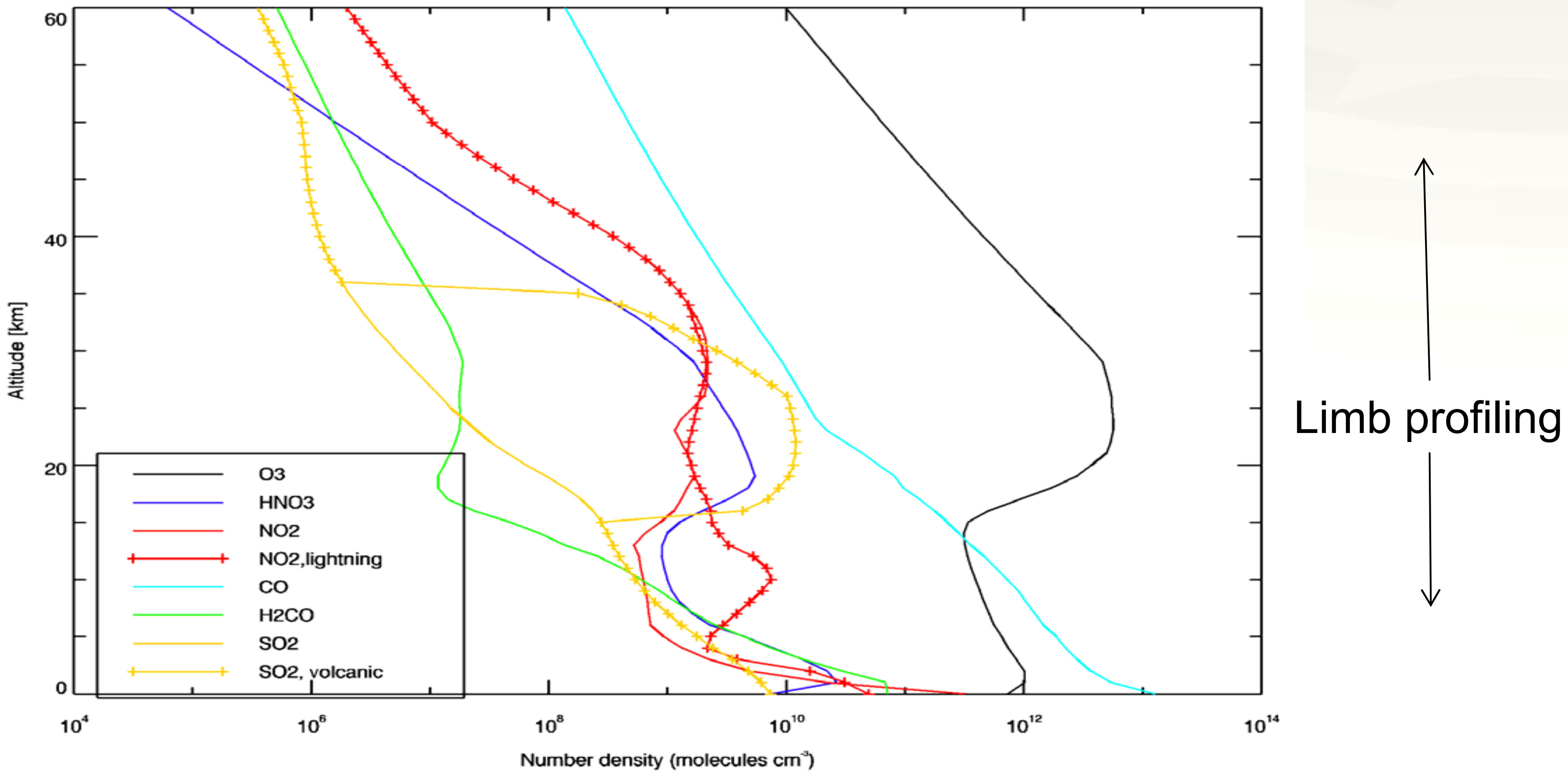
- Near-surface layer seen between clouds *but*
- Little or no vertical resolution

Limb-emission sounding

- High res. vertical profiling
- Tenuous trace gases detectable
- Cold space background
- Dense coverage cf solar occultation

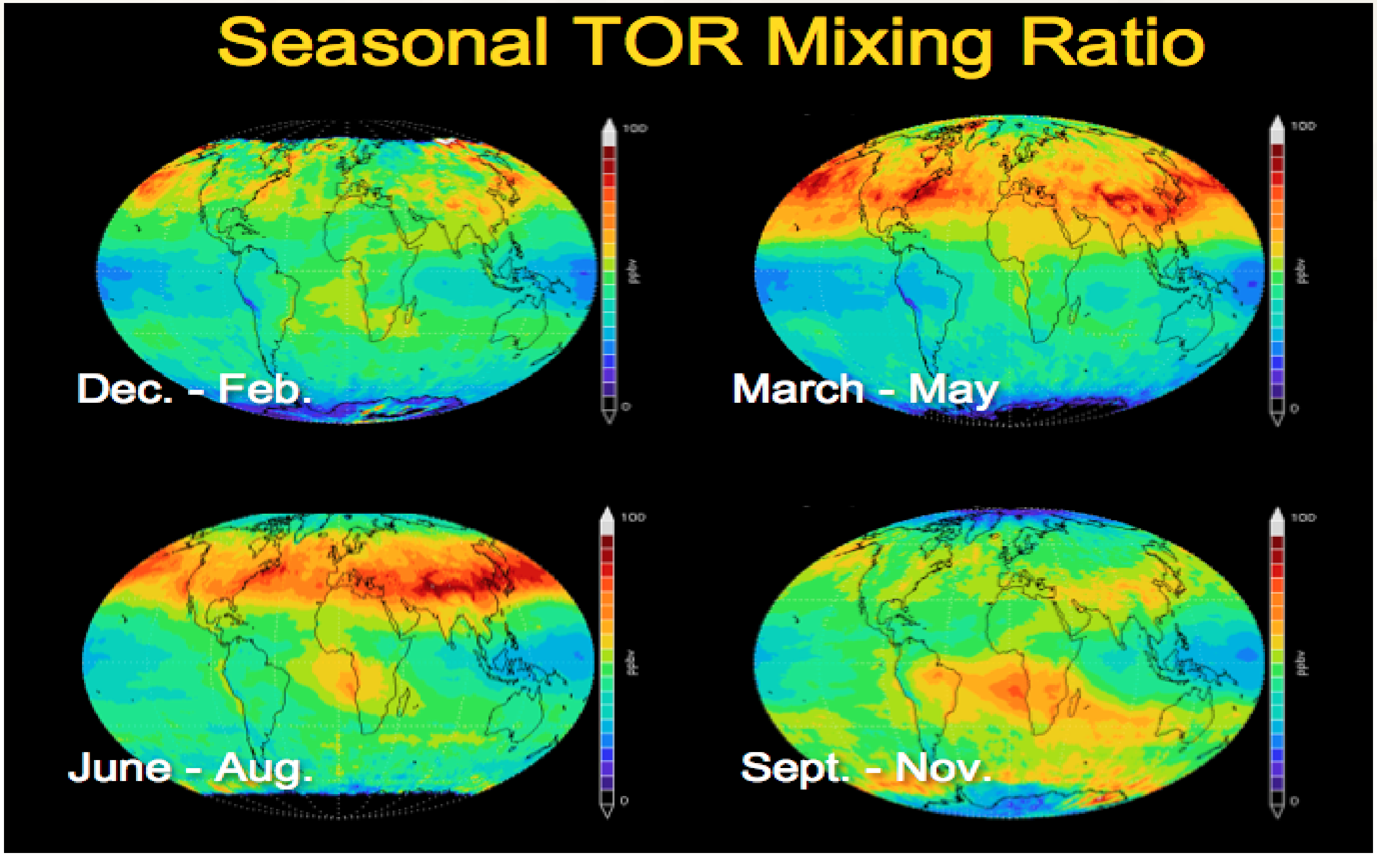


Vertical Profiles: Number Density



Limb – nadir combination (contd)

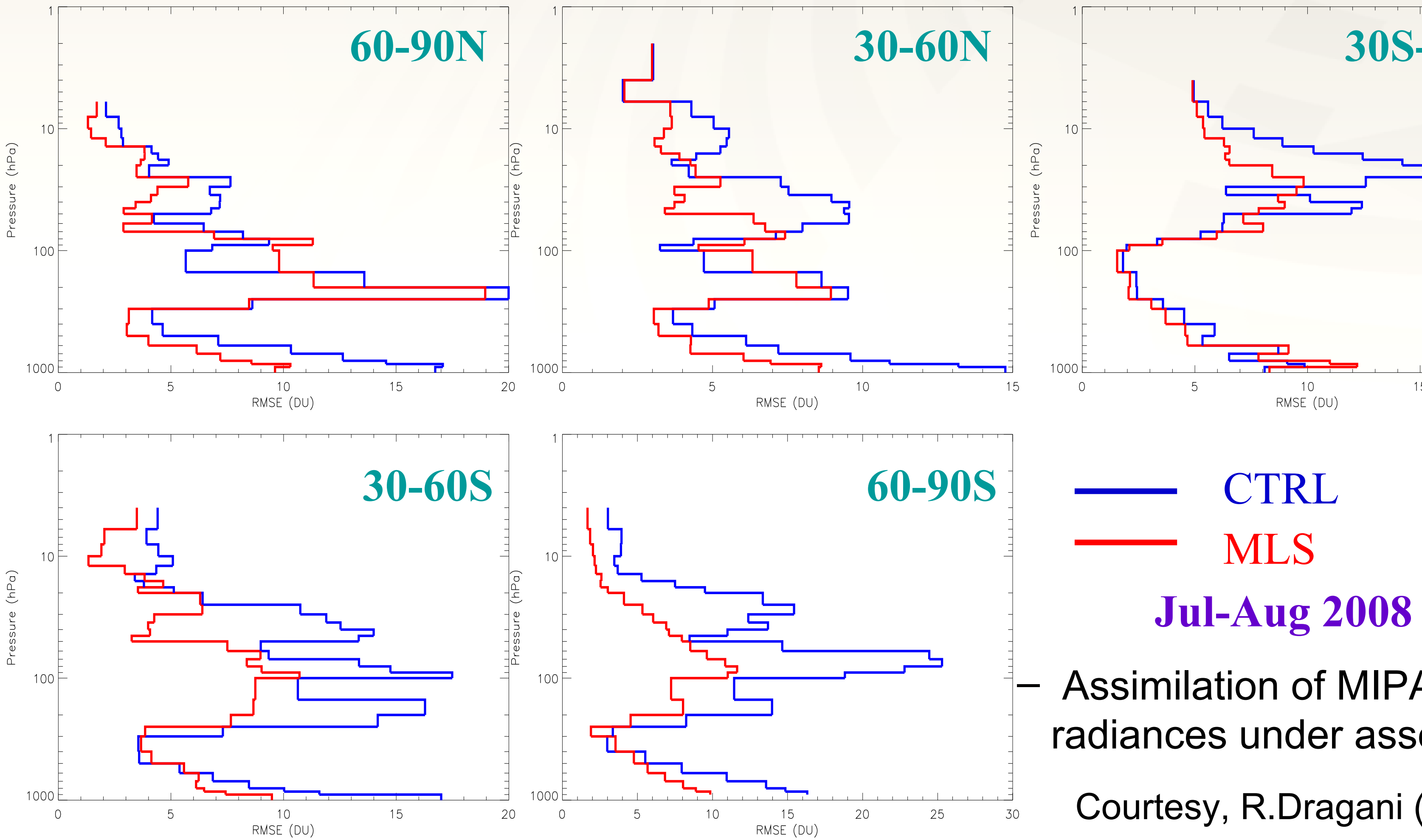
Aura
MLS – OMI



Schoeberl et al. 2007

Impact of Limb Emission Data in Assimilation

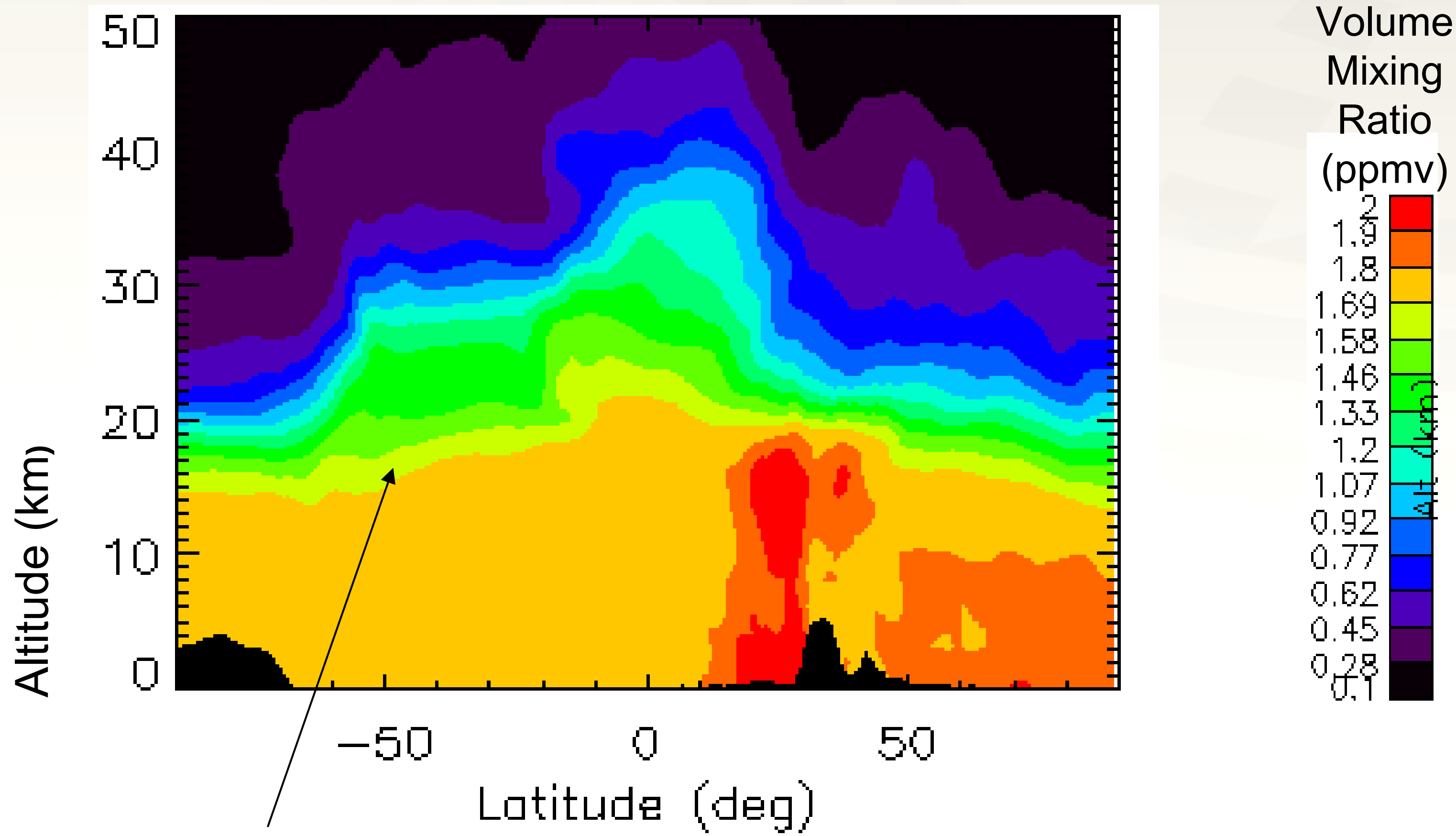
ECMWF analysis – sonde RMSE comparison: Aura MLS O_3 NRT data



– Assimilation of MIPAS NRT radiances under assessment

Courtesy, R.Dragani (ECMWF)

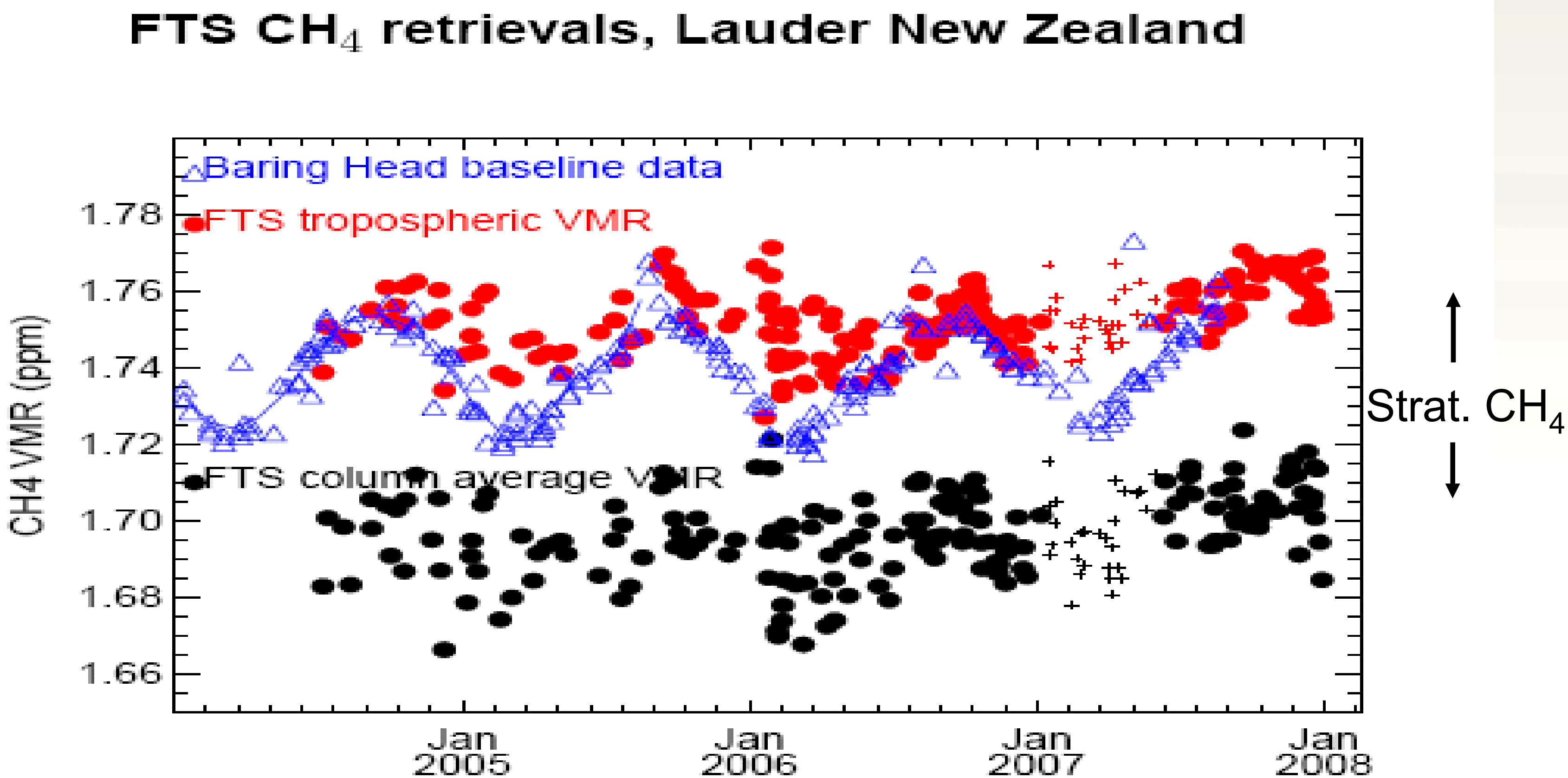
Methane Latitude-Height Cross-Section



~10% of column <200hPa where variability is high

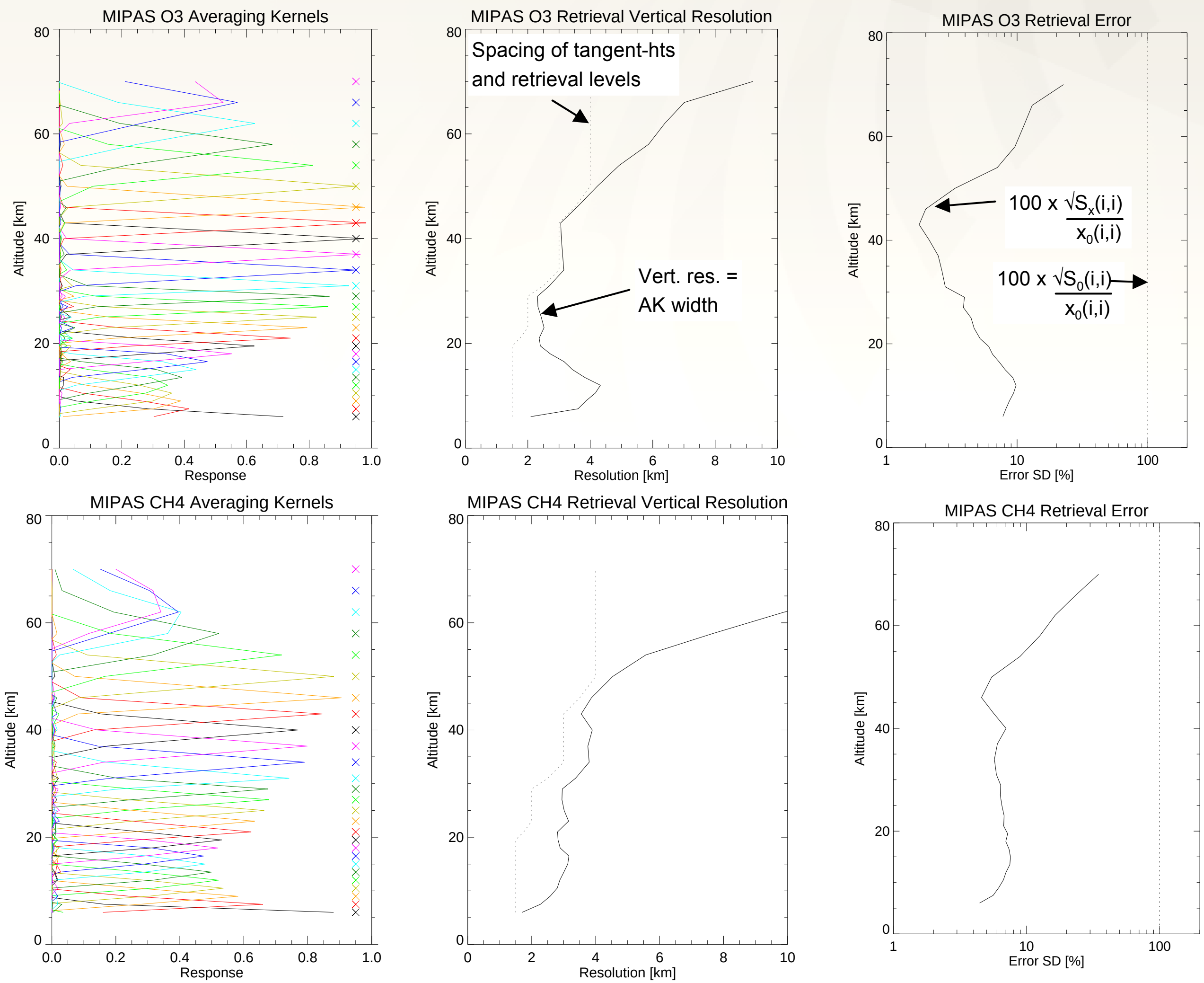
→ *tropospheric column mean vmr* "cleaner" than *total column mean vmr* for inverse modelling of methane surface sources

Column-average CH_4 mixing ratio



Tropospheric column averaged vmr from ground-based FTS closer to surface values and less variable than *total column average vmr*.

O_3 & CH_4 Linear Retrieval Diagnostics for Envisat MIPAS – IR limb-emission sounder



– Ozone and methane profiles extend to mid-troposphere in absence of cloud

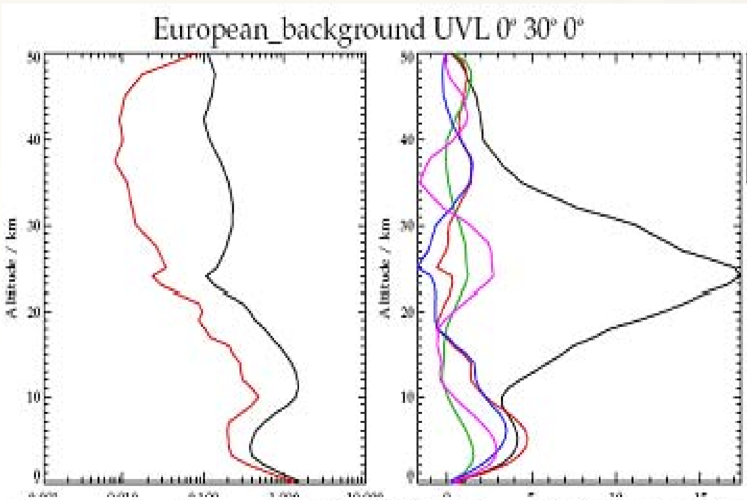
→ *Potential for limb – nadir combination with SCIA & MetOp IASI/GOME-2*

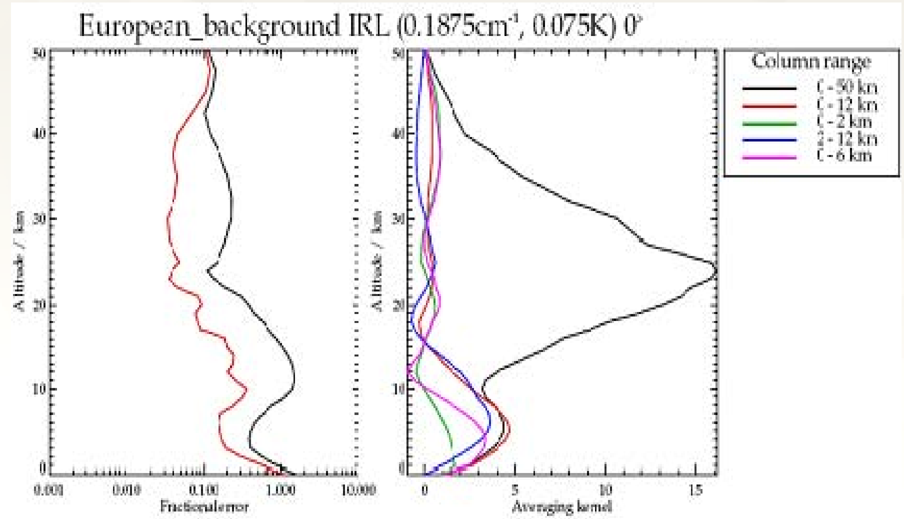
– Vertical resolution generally limited by IFOV (~3km)

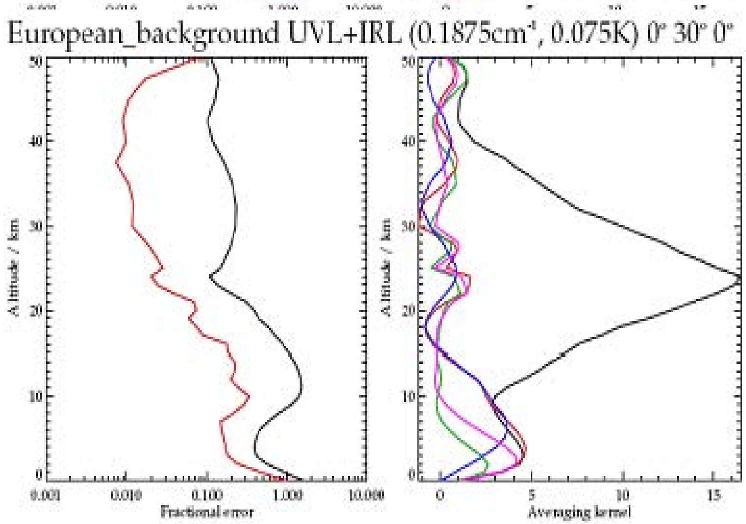
→ *Potential to increase vertical resolution (<1km) for future FTIR limb-imager.*

Courtesy, A.Dudhia, U.Oxford

3. Simulation of combined nadir/uv-ir O_3 retrieval



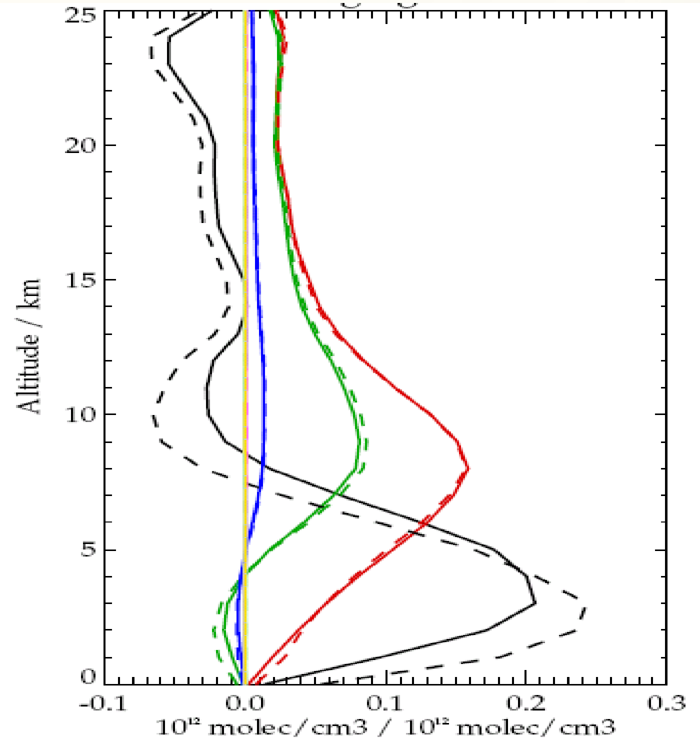




- Different height sensitivities in UV & IR
  - UV & IR kernels for 0-2km and 0-6km layers are sharpened by combining them
  - → *should improve mid/lower trop. O_3*
  - eg GOME-2 + IASI combination

Averaging Kernels for IR & SWIR CH_4 retrieval

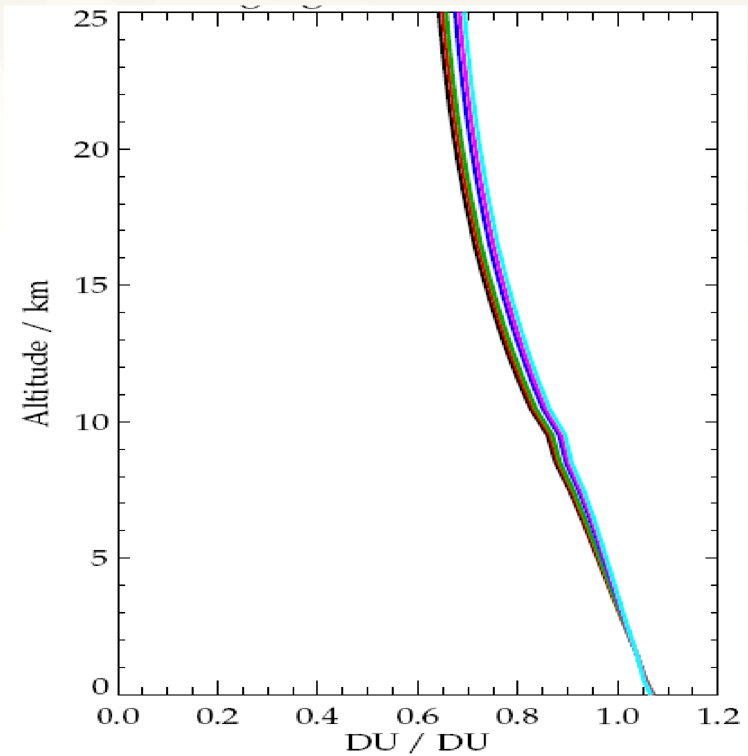
- IASI averaging kernels using 1240-1290 cm^{-1}



- Assumes 0 (solid) or 10K (dashed) air/surface temperature contrast

➢ *IASI has height-resolution in troposphere*

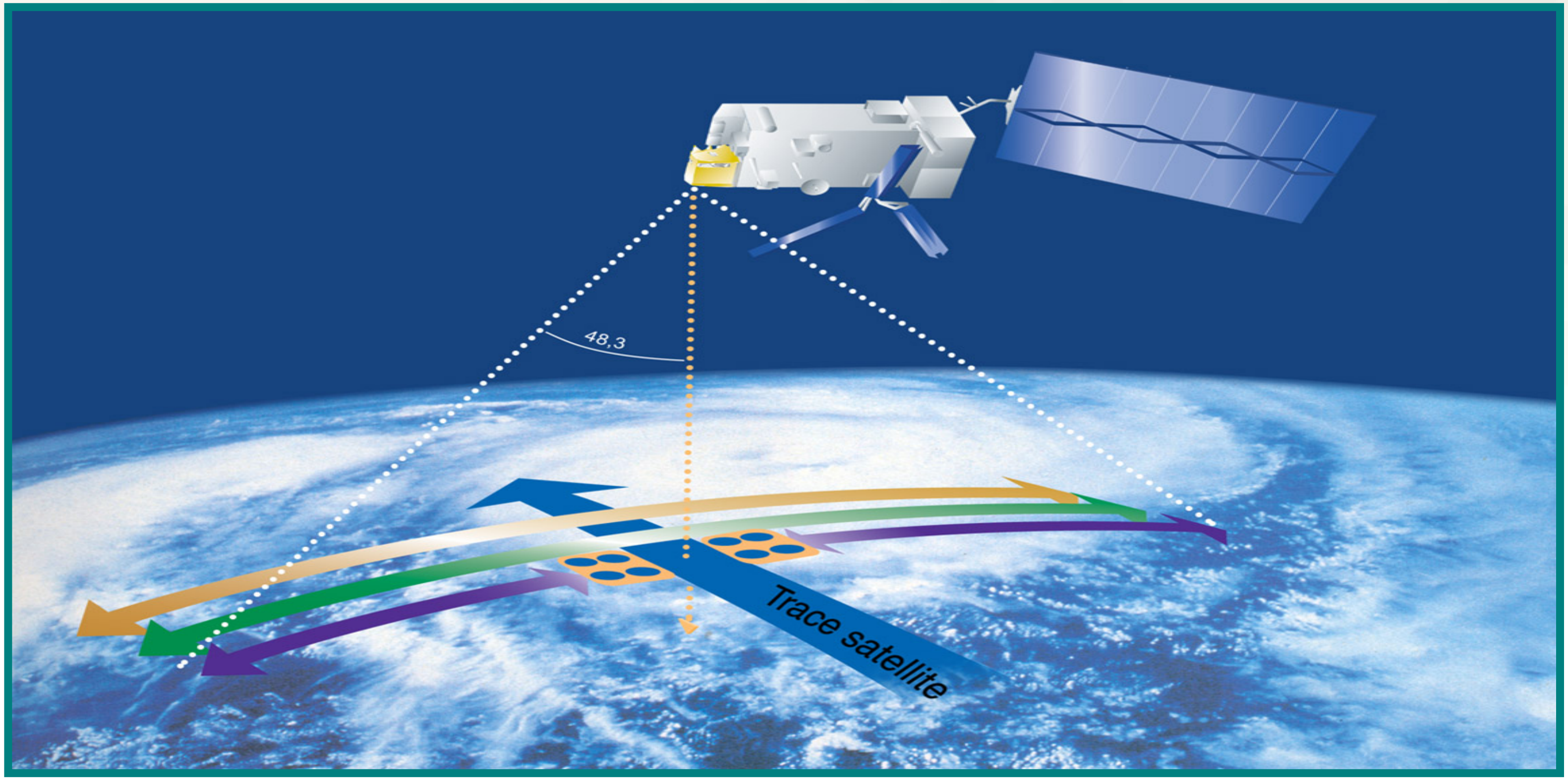
- SCIA 1.6 micron averaging kernels for integrated column retrieval



- For surface albedo 0.16 (typical vegetated land)

➢ *SCIA more sensitive near surface over land*

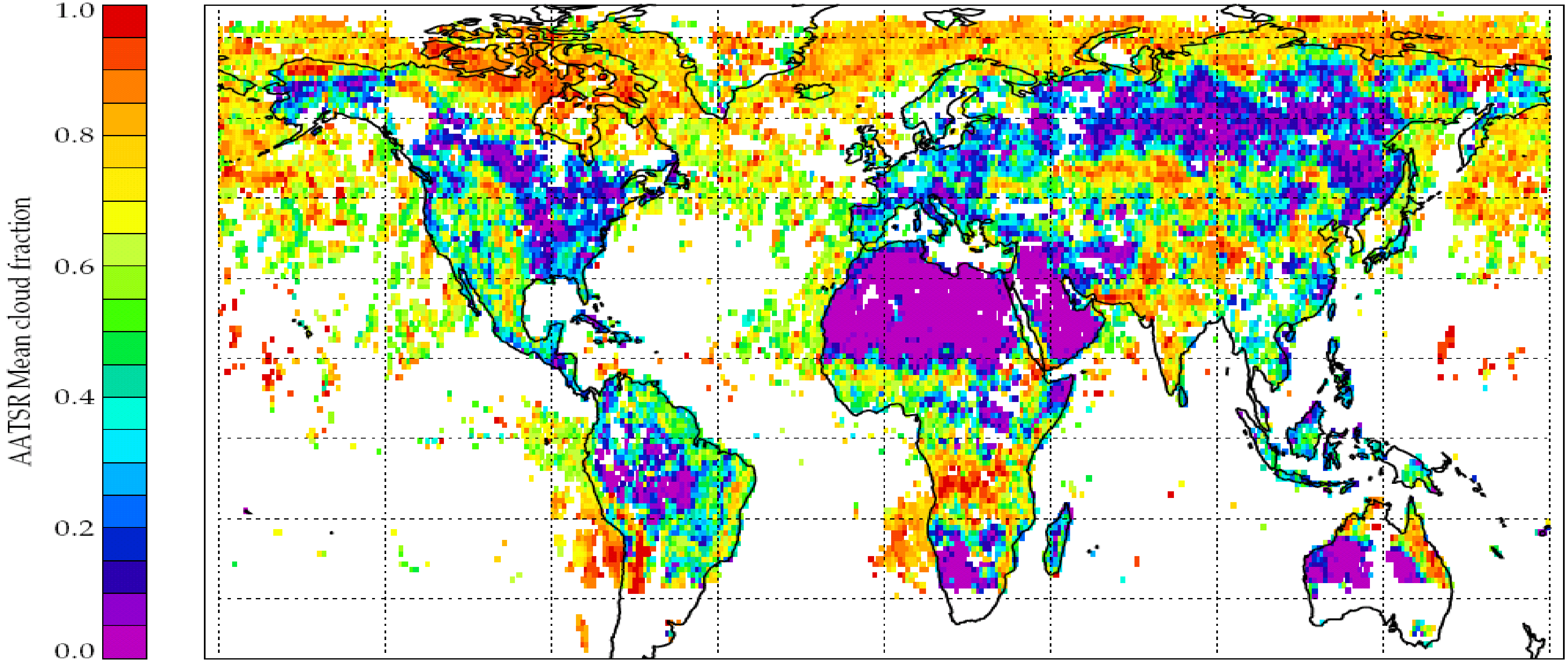
4. Spectrometer - Imager



- Cloud and surface properties affect radiative transfer in *non-linear* ways
- Many scenes viewed by spectrometers are *inhomogeneous*
- Co-located imager → *sub-pixel distributions of cloud, aerosol & surface properties*
- eg Envisat & MetOp

AATSR cloud fraction for SCIA scenes which pass CH_4 QC

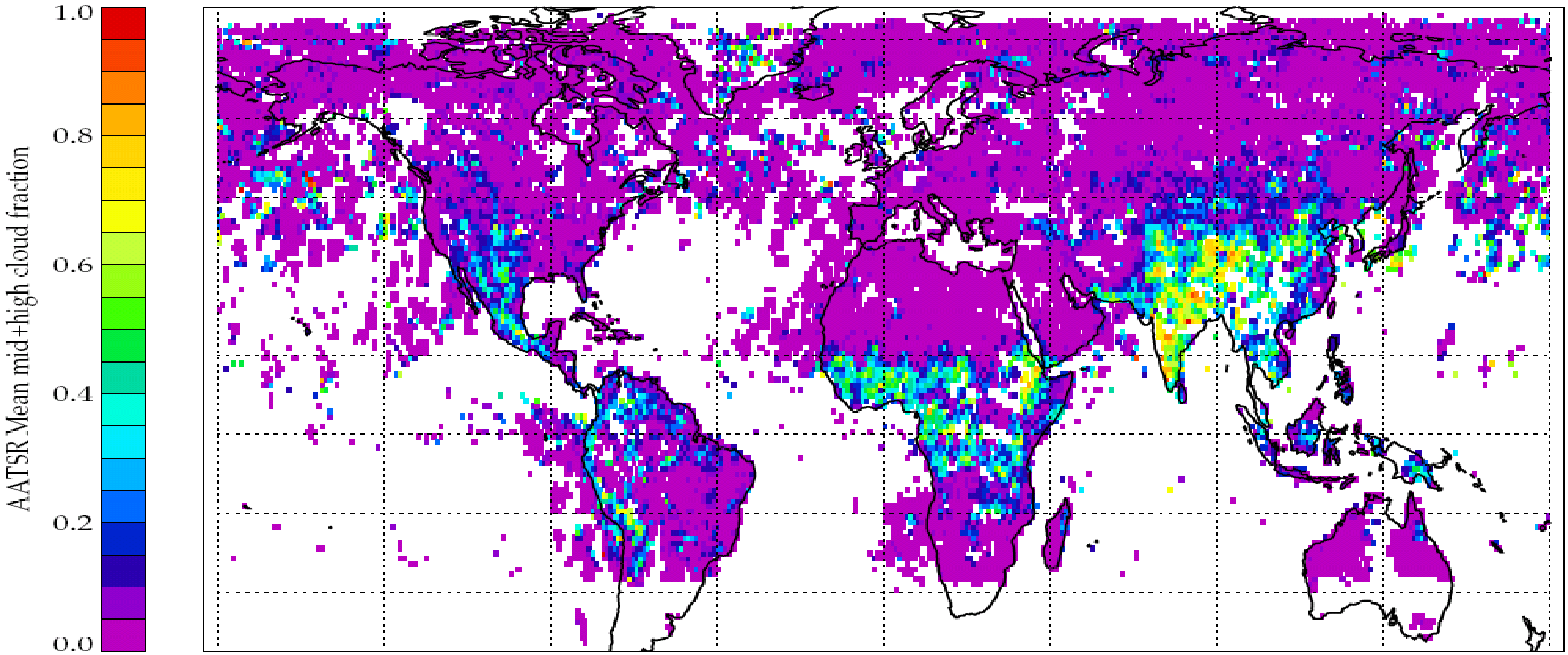
– SCIA QC includes cloud screening based on CO_2 column



- ~Half SCIA's swath covered by AATSR swath (512km)
- Where AATSR cloud fraction is high, SCIA sensitivity to boundary layer CH_4 is low

AATSR mid/high level cloud fraction in SCIA scenes

– Fraction of SCIA scene occupied by cloud <650 hPa.



- Sensitivity to mid tropospheric CH_4 compromised eg over Indian sub-continent.
- *Co-located AATSR data can identify SCIA scenes affected by cloud*
- *Partially cloudy scenes could be post-processed using cloud properties from AATSR to characterise better SCIA's vertical sensitivity to* CH_4*.*

Conclusions

- There is a strong scientific imperative to sound atmospheric composition from space, to complement surface & airborne observations.
- The challenge is to resolve atmospheric structure on finer scales while maintaining and improving accuracy.
- Coupling between layers is crucial, both for science & for retrieval/assimilation
- Advanced techniques are in development to exploit better the data from existing and planned satellites.
- New satellite missions are needed to address **major scientific issues** and also to serve new **operational applications** (GMES Atmosphere Service).
- These will be designed to exploit new technology and to combine optimally different observing techniques.