New techniques to sound the composition of the lower stratosphere and troposphere from space

Presentation by B.Kerridge on behalf of RAL Remote-Sensing Group

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4. Tomographic limb-sounding
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1. Background

RAL Remote-Sensing Group:  
Brian Kerridge  
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Victoria Jay and Barry Latter

Collaborations:  
• RAL colleagues (eg Martin Juckes)  
• NERC DARC  
  – Co-supervision of doctoral students  
• Other groups in UK and Europe  
  – ESA, EU & Eumetsat projects
**Expertise:**

- Development and application of *radiative transfer models* and *retrieval schemes* for *satellite* and *airborne* remote-sensors:
  - Wavelengths from UV through IR to mm-wave
  - Nadir-, limb- and slant-viewing
- Processing, validation and scientific interpretation of data
- Retrieval simulations to define and optimise new sensors

**Scientific Focus:**

- Composition of troposphere & lower stratosphere
- Interactions with climate via radiative forcing & feedback (eg O₃ & H₂O), transport (eg O₃ & H₂O) and chemistry (eg O₃ & CO).

> **Aim:** To produce novel data-sets on tropospheric and lower stratospheric constituents of importance to global change.
2. Ozone profiles from GOME

1. Stratospheric Ozone Profile
   - Hartley band (260-306 nm)
   - Opacity strong & wavelength dependent

2. Lower Stratosphere + Troposphere
   - Huggins bands (324-335nm)
   - Temp. dependent cross-section
   - Vertical temperature gradient
   - Relies on differential structure not absolute calibration

RAL RSG first to use from space instrument
Composite $O_3$ Averaging Kernels

Band 2 + Band 1

240-340 nm, Floor: 0.1%

Band 1 only

240-300 nm, Floor: 1%

$A \text{ priori}$ uncertainty 100% at all levels
AK Eigenvectors and values: IFE & KNMI

IFE v50 GCL

6 highest eigenvalues

KNMI GCN

13-Jan-1997 10:41:12 (50.85°; 3.57°)
Next phase: to intercompare with ozonesondes exhibiting tropospheric $O_3$ excursions
Processed Data

- $O_3$ profiles available at [www.badc.rl.ac.uk](http://www.badc.rl.ac.uk)
- Sub-sets of GOME data 1995-9 processed for a variety of applications (>30 users)
- Validated against ensemble of sondes
Zonal-mean time series 1995-9

1 or more days per month sampled from Jan’96
3 days per month *narrow-swath* from Apr’98 – Mar’99
Zonal-mean time series 1995-9

Only cloud-free ground pixels selected
Seasonal Climatology 1995-98

Dec-Jan-Feb

Mar-Apr-May

Jun-Jul-Aug

Sep-Oct-Nov

Lower Tropospheric O₃
Seasonal Climatology 1995-98

Dec-Jan-Feb

Mar-Apr-May

Jun-Jul-Aug

Sep-Oct-Nov

TRMM fire count 1997
- Correction needed in Band 1 after 1998 to retrieve O₃
- *Empirical* scheme devised assuming climatology in RT
Ozonesonde comparisons before and since scan-mirror uv degradation

- Only cloud-free GOME scenes selected
- N.Hem winter/spring not sampled in 2002, so a priori variance much lower
Comparison of assimilated GOME to SAGE-III, HALOE and MIPAS profiles

- Assimilation on 650K surface using ECMWF winds (splitting vortex) by M.Juckes
Processing the 8-year Mission

• Degradation correction satisfactory
• Increase (x3) in efficiency recently achieved.
• Aim: to process the 8-year mission within a 12 month period.
  → Interannual variability in troposphere & LS
• Cloud/surface properties to be produced for GOME from ATSR-2 in parallel project.
3. Limb-nadir Synergy

Purpose: Constrain GOME O$_3$ retrieval with stratospheric information from MIPAS

- In stratosphere, MIPAS L2 agrees with standard GOME retrieval to +/-10% (MIPAS vertical res lower than anticipated)
- In upper troposphere, MIPAS contaminated by cloud
- Two GOME Band-2 retrievals:
  1. GOME Band-1 as a priori (standard)
  2. MIPAS L2 product as a priori <100hPa

- Combined MIPAS-GOME retrieval:
  - follows MIPAS a priori in stratosphere
  - is not affected by cloud contamination in UT cf MIPAS
  - follows standard GOME retrieval in troposphere
  - covers south Atlantic anomaly (unlike GOME Band 1 retrieval)

→ Satisfactory first demonstration of limb-nadir synergy in retrieval domain
4. Tomographic Limb Sounding

- Conventional limb-sounding assumes \textit{spherical symmetry}:
  - at best, retrieved profiles \textit{average} the true field;
  - at worst, retrievals compromised by inconsistencies between observed and modelled radiances

- \textit{Tomographic} limb-sounding intended to address these problems
4. Tomographic Limb-Sounding Principles

- Assumption of spherical symmetry dropped in favour of fully 2-D RTM
- State-vector comprises fields on 2-D grid instead of 1-D profile
- Measurement vector comprises set of limb-scans which are inverted simultaneously
- Limb-scan spacing along-track (<100km) fine enough to oversample retrieval grid
- Given air volume viewed from many different directions -> tomography
Tomographic Limb Sounding

$\cong 100\text{ km}$
Iterative solution to *Optimal Estimation* equation:

\[
x_{i+1} = x_i + (S_a^{-1} + K_i^T S_y^{-1} K_i)^{-1} K_i^T S_y^{-1} [y - F(x_i)]
\]

- \( S_a \) is *a priori* covariance matrix of \( x \)
- \( K_i \) is weighting function matrix w.r.t. \( x \)
- \( S_y \) is measurement error covariance matrix

- Memory limitations preclude storage of matrices which have dimension \( N_y \)
- Provided \( S_y \) is diagonal, matrices such as \( K^T S_y^{-1} K \) can be *accumulated sequentially* on limb-view by limb-view basis
- Since \( N_x \) is also large, further matrix manipulation required to make the problem computationally viable.
H$_2$O 2-D Retrieval for Limb-mm Linear Diagnostics

The diagrams illustrate the percentage precision and horizontal resolution for different altitudes, with lines representing MASTER and MLS. The vertical resolution is also shown for comparison.
Iterative 2-D H$_2$O simulation for mm-wave limb-sounder (MASTER)

MASTER 325 GHz band

ECMWF

Retrieved

$1^{st}$ guess = $A$ priori with no horizontal structure
Iterative 2-D H$_2$O simulation for mm-wave limb-sounder (MASTER)

- MASTER 325 GHz band
- Tropospheric penetration limited by limb-opacity, controlled by H$_2$O
  $\rightarrow$ Structure recovered with good fidelity up to $\sim$300ppmv
Iterative 2-D O$_3$ simulation for mm-wave limb-sounder (MASTER)

- MASTER 300 GHz band
- Temperature and pointing errors added to synthetic measurements in addition to noise.

- Next step: cloud to be added to simulations
MIPAS Limb-Geometry for Standard Mode and UTLS Special Mode (S6)

Spectral resolution reduced to 0.1 cm\(^{-1}\)
(cf 0.025 cm\(^{-1}\) for standard mode)
MIPAS O$_3$ 2-D simulation for UTLS Special Mode

- Simulation for S6 mode by M. Parrington (Oxford) using RAL scheme
- No errors except instrument noise.
Summary and Future Work

• Challenge for satellite remote-sensing:
  – to measure global distributions of important trace gases on spatial scales required.
• Different techniques have complementary attributes, eg:
  – measurable species
  – vertical and horizontal resolution/sampling
  – penetration into troposphere
  – susceptibility to obscuration by cloud
• Nadir-viewing required to sound lower troposphere
• Contemporary nadir-uv sounders can retrieve O$_3$ profiles spanning troposphere and stratosphere.
• Plan to process >8-year GOME mission
• Explore assimilation of profiles & derived quantities
Summary and Future Work (contd)

• Envisat offers the first opportunity to pioneer two new techniques:
  1. Limb/nadir synergy (eg O$_3$ and H$_2$O)
  2. Tomographic limb-sounding

and compare implementations via retrieval and assimilation (eg DARC)

• Next steps at RAL:
  – MIPAS H$_2$O & O$_3$ scheme optimised for low altitudes (UTLS)
  – Tropospheric H$_2$O/aerosol profiling from SCIA-nadir (near-IR)
  – Additional trace gases

• Longer term:
  – GOME-2 & IASI on MetOp offer advances on SCIA-nadir for tropospheric O$_3$ & H$_2$O, again in combination with MIPAS
  – Future mission to sound atmospheric composition should exploit these new techniques and advanced sensors (eg mm-wave).