

SCIAMACHY on Envisat: Trace Gas Profil Retrieval from Solar and Lunar Occultation

K. Bramstedt F. Azam S. Noël A. Rozanov H. Bovensmann
J.P. Burrows

Inst. of Environmental Physics (IUP)
University of Bremen



Outline

- 1 SCIAMACHY instrument
 - Envisat
 - The Instrument
 - Highlights
- 2 Solar occultation
 - The Measurements
 - Tangent height determination
 - Onion peeling DOAS Approach
 - Optimal Estimation Approach
- 3 Lunar occultation
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- 4 Summary and Outlook

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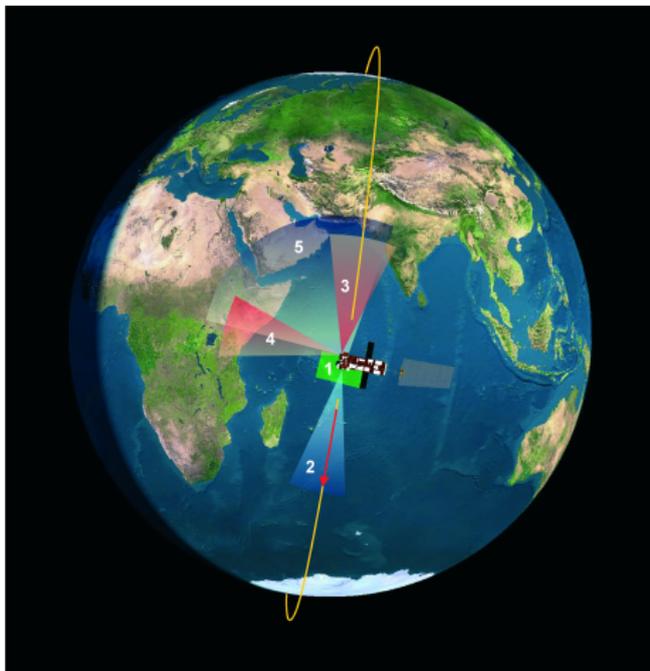
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Envisat in orbit



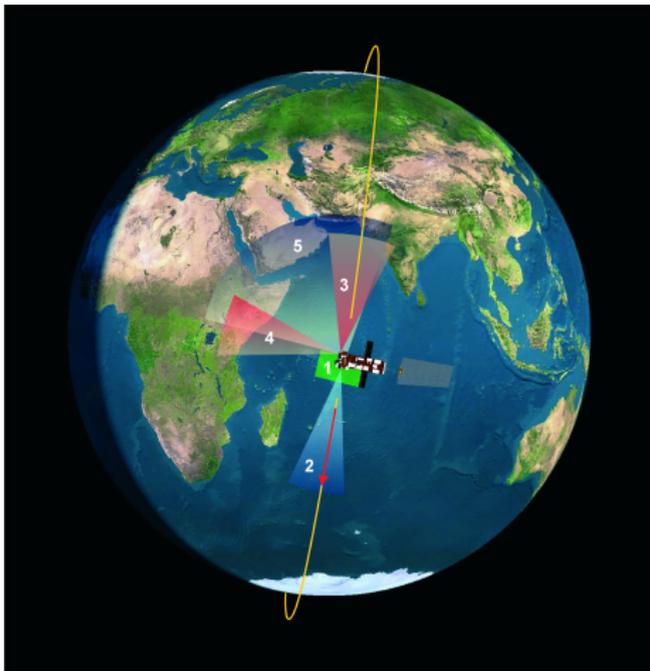
Viewing directions:

- SCIAMACHY : (1) nadir, (2) flight direction
- MIPAS: (3) backwards, (4) sideways
- GOMOS: (5) backwards to sideways

- Launch from Kourou April 2002
- Polar, sun-synchronous orbit
- Inclination 98.55°
- Equator crossing time 10:00 a.m. (descending node)
- Mean altitude 799.8 km
- ~ 14 orbits/day
- 2nd mission extension until 2013
- \Rightarrow Orbit change Oct. 2010



Envisat in orbit



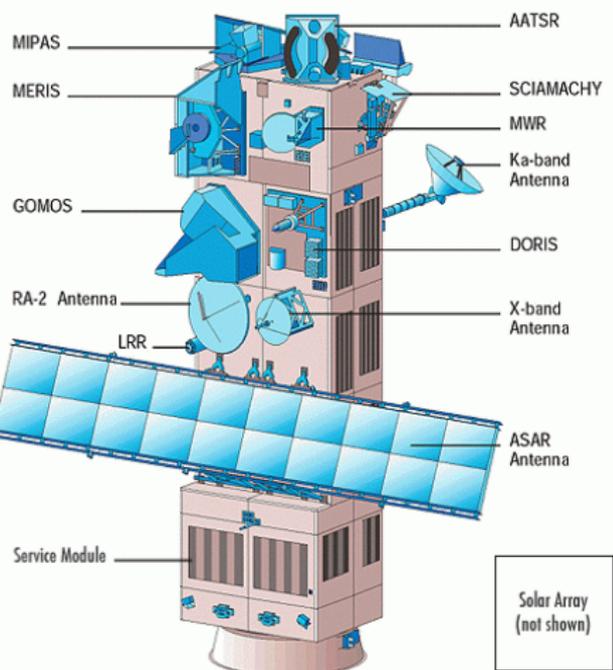
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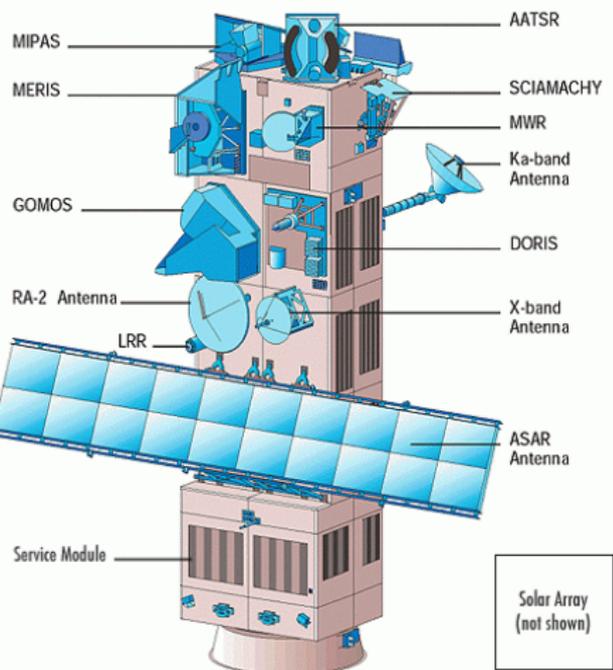


Instruments on-board Envisat



- GOMOS** (Global Ozone Monitoring by Occultation of Stars)
- MIPAS** (Michelson Interferometer for Passive Atmospheric Sounding)
- SCIAMACHY** (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY)
- RA-2** (Radar Altimeter 2)
- MWR** (MicroWave Radiometer)
- AATSR** (Adv. Along-Track Scanning Radiometer)
- ASAR** (Adv. Synthetic Aperture Radar)
- MERIS** (MEdium Resolution Imaging Specrometer)
- DORIS** (Doppler Orbitography and Radio-positioning Integrated by Satellite)

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Primary SCIAMACHY Objectives

- Air Pollution

- Extend and variability of air pollution globally
- Air pollution changes

- Climate Change

- Green house gases

- Ozone

- Ozone layer recovering
- Interaction climate change and ozone recovery



SCIAMACHY History

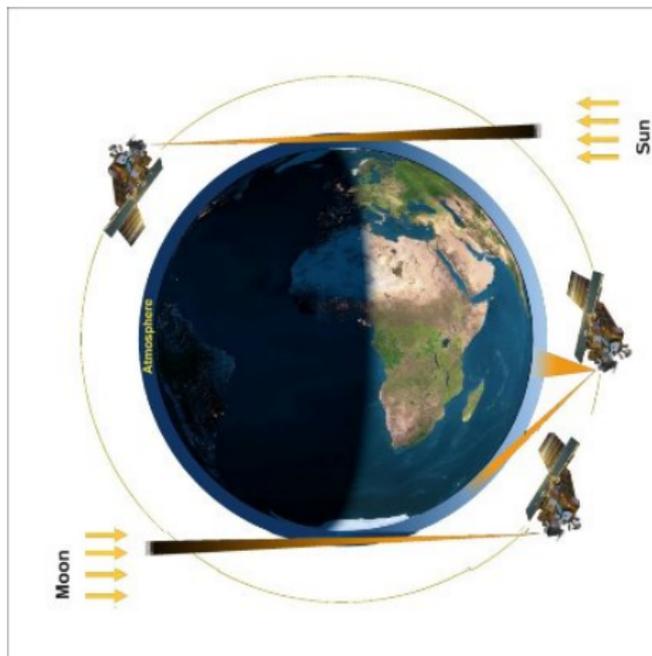
- 1985 Stratospheric ozone hole observed by Farman et al. (Nature)
- 1985-1988 **SCIAMACHY proposed to ESA**
- 1988/89 Proposal of SCIA-mini/GOME (Global Ozone Monitoring Experiment) for ERS-2
- 1989-2002 **Design and Development of SCIAMACHY as German/Dutch/Belgian contribution to ENVISAT**
- Apr 1995 Launch of ERS-2 with GOME
- 1997-2000 Selection of GOME-2 for the EUMETSAT operational series MetOp
- Feb 2002 **Launch of ENVISAT with SCIAMACHY**
- Jul 2004 AURA launch with OMI
- Oct 2006 MetOp launch with GOME-2



SCIAMACHY:

Scanning Imaging Absorption spectroMeter for Atmospheric CHartography

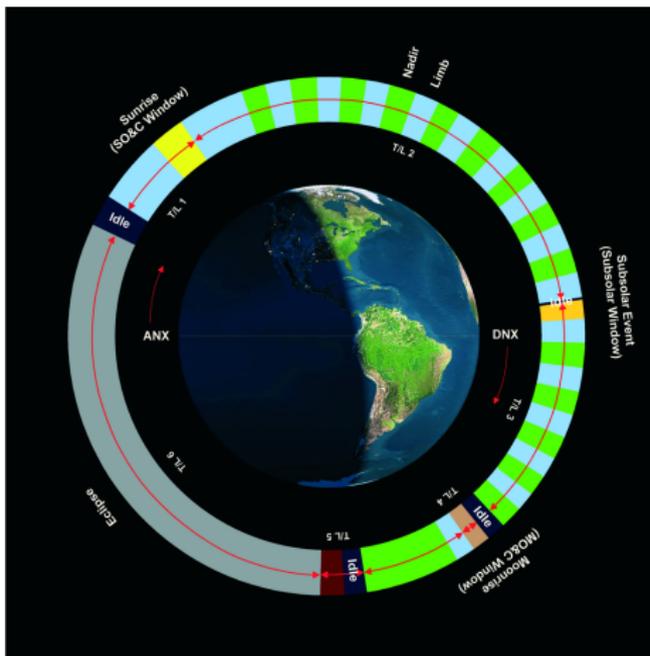
SCIAMACHY



- Imaging spectrometer
240 - 2380 nm
- 8000 spectral points, divided in 8 channels + 7 broad-band PMDs (Polarization Measurement Devices)
- 0.2 - 1.5 nm spectral resolution
- Viewing Geometries:
 - Nadir: trace gas columns and clouds
 - Limb: trace gas profiles with global coverage
 - **Solar and lunar occultation**: high precision trace gas profiles



Measurement Sequence

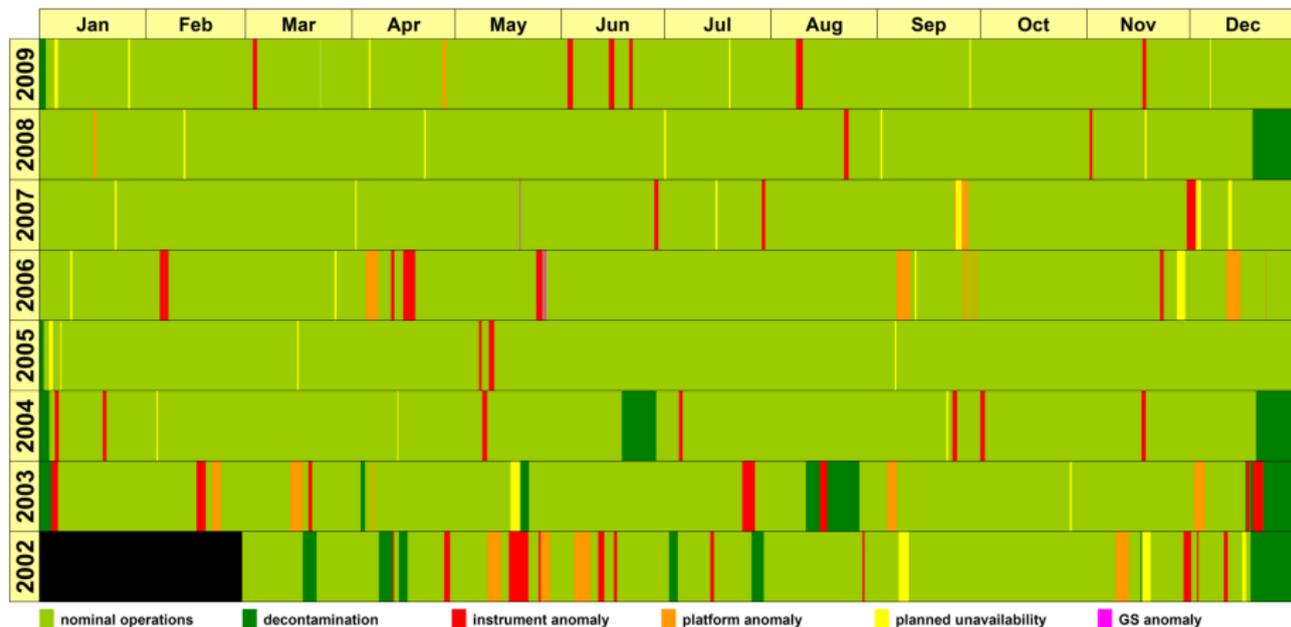


Measurements along the orbit:

- Sunrise: **solar occultation**
- Day-side:
 - Alternating limb/nadir (matching air-masses)
 - Solar measurements (daily / weekly / monthly calibration)
- Moon-rise: **lunar occultation** (if possible)
- Eclipse:
 - Limb mesosphere measurements
 - Dark current measurements



Availability 2002-2009



Light green: Nominal operations ⇒ **SCIAMACHY is in excellent condition!**

SCIAMACHY Level 2 Data Products

Products in (upcoming) operational SCIAMACHY Level 2 Ver 5.01:

- Nadir trace gas columns:
 - UV/VIS: O₃ , NO₂ , BrO, OCIO, SO₂ (volcanic & anthropogenic), H₂O
 - SWIR: CO
- Cloud Fractions, Absorbing Aerosol Index (AAI)
- Limb trace gas profiles:
 - UV/VIS: O₃ , NO₂ , BrO
- Limb cloud flagging

Incomplete list of additional scientific algorithms:

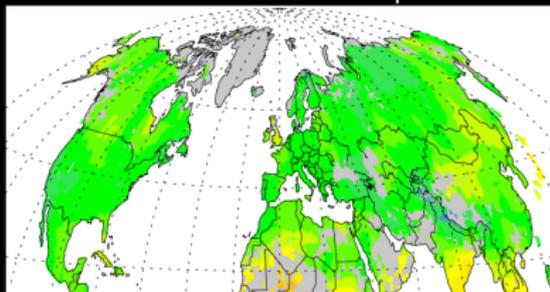
- Nadir columns: HCHO, CO₂ , CH₄ , glyoxal, phytoplankton
- Cloud top height, cloud optical thickness
- Limb profiles: OCIO, H₂O ,
- NLCs
- Mesosphere metals Fe, Mg, Na, Si, Cr
- Solar activity (Mg-II index)
-
- **Occultation trace gas profiles!**

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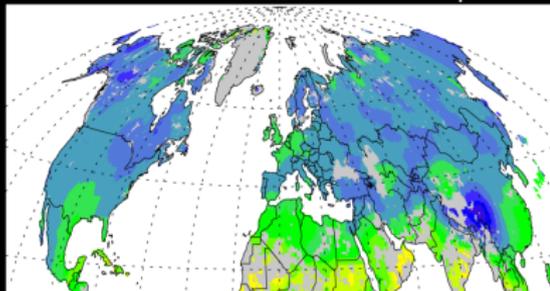
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SCIAMACHY CO₂

Apr-Jun 2003



Jul-Sep 2003



356

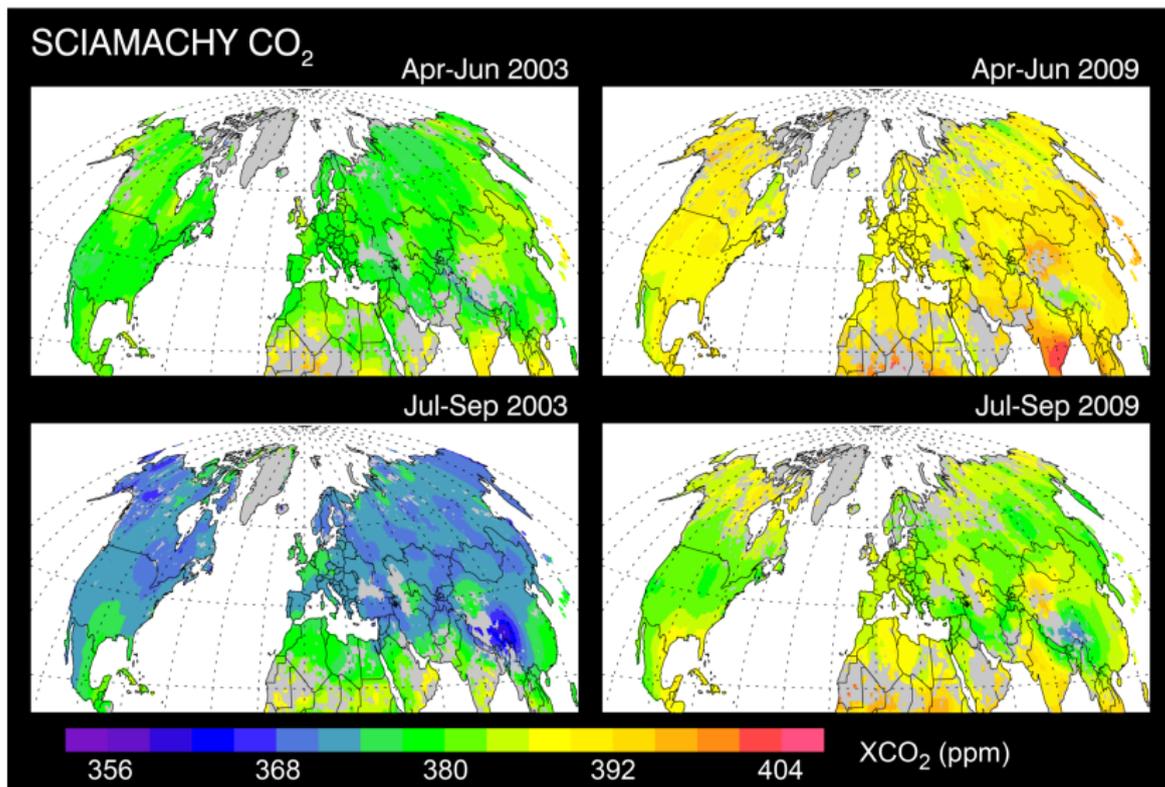
368

380

392

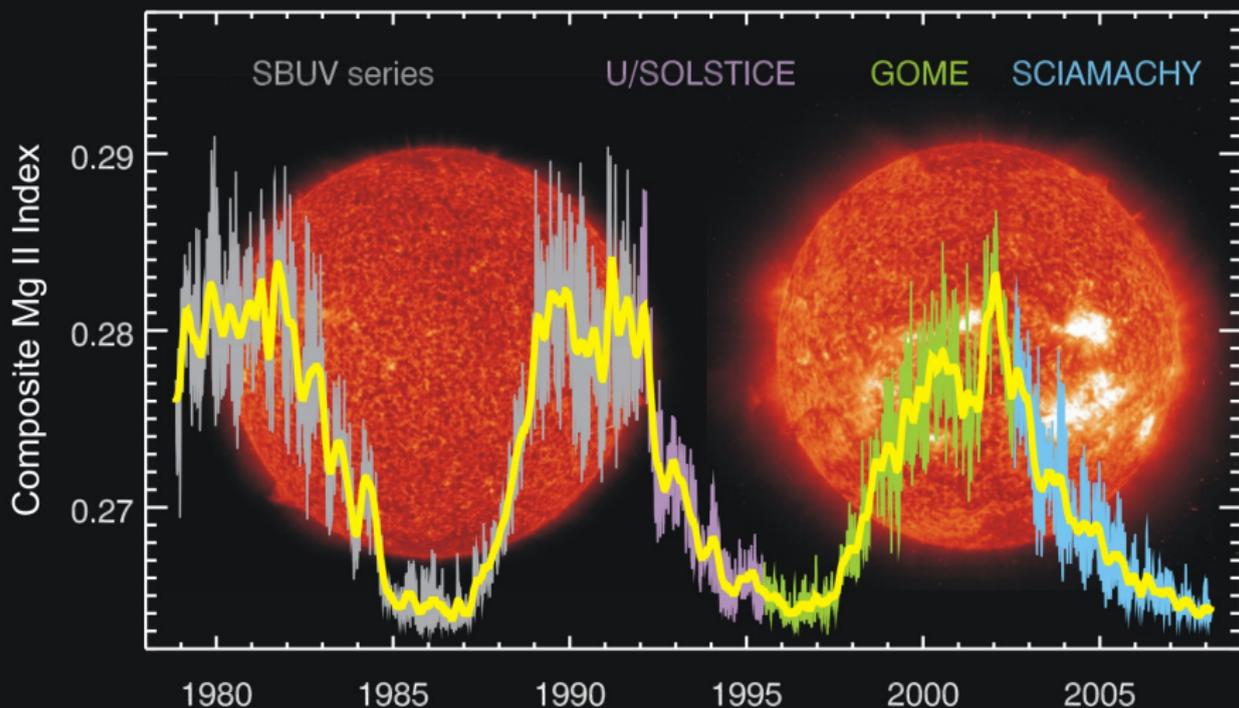
- Seasonal variation of CO₂ in the northern hemisphere (2003).
- Decrease of CO₂ during summer by the uptake of CO₂ by growing vegetation.
- Seasonal variation globally ~9 ppm CO₂ .

Increase of CO₂ by ~8 ppm from 2003 to 2009!

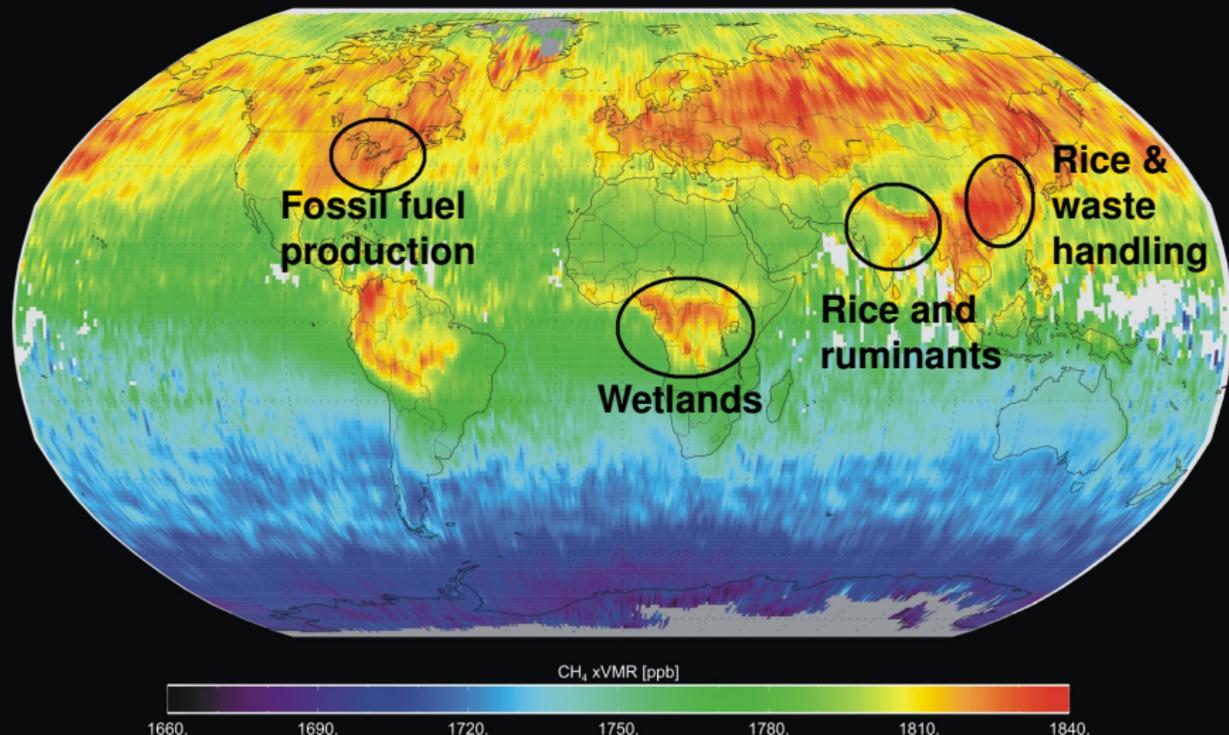


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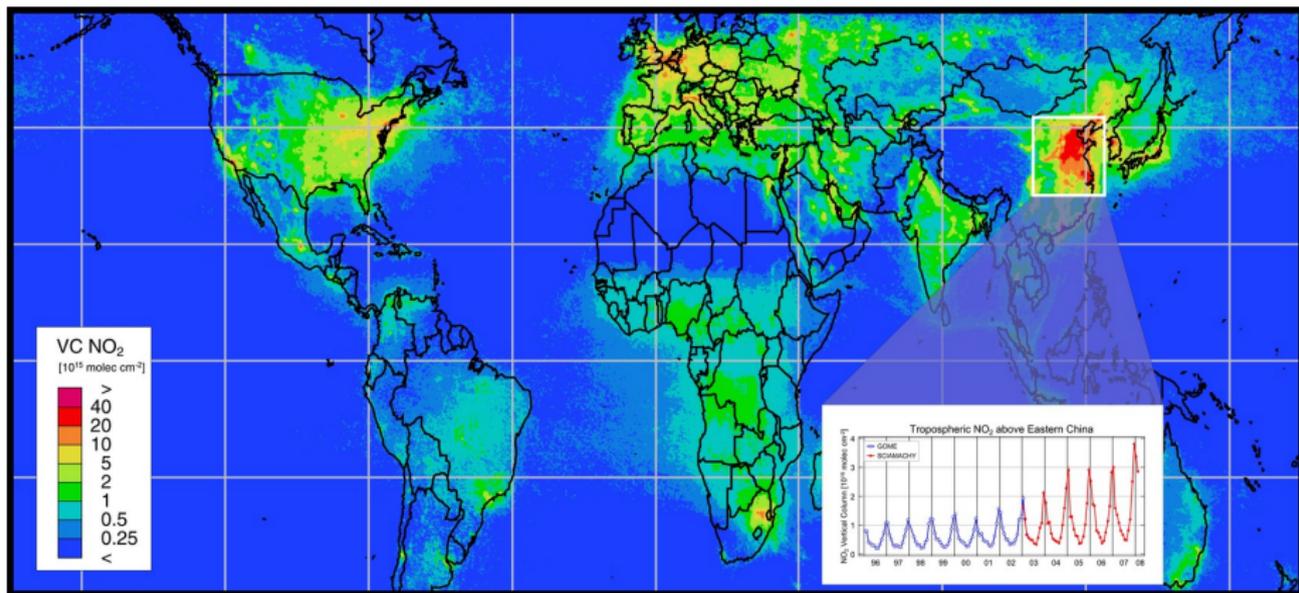
Solar Activity from GOME and SCIAMACHY



Tropospheric methane as seen from SCIAMACHY in 2004

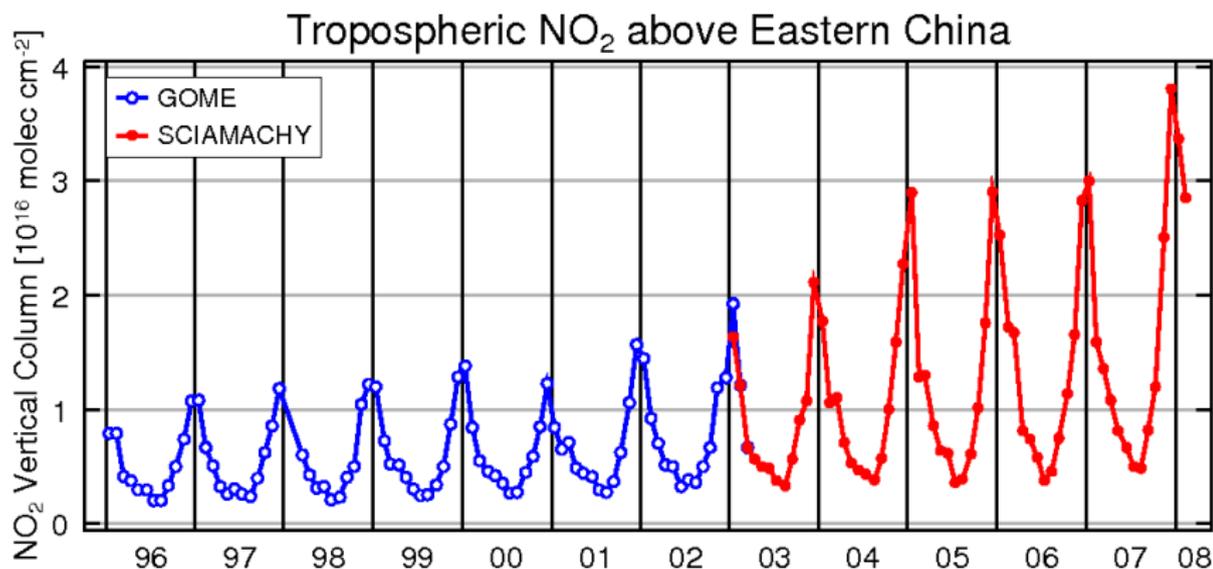


Tropospheric NO₂ columns



Increase of air pollution above eastern China due to economic growth.

Tropospheric NO₂ columns

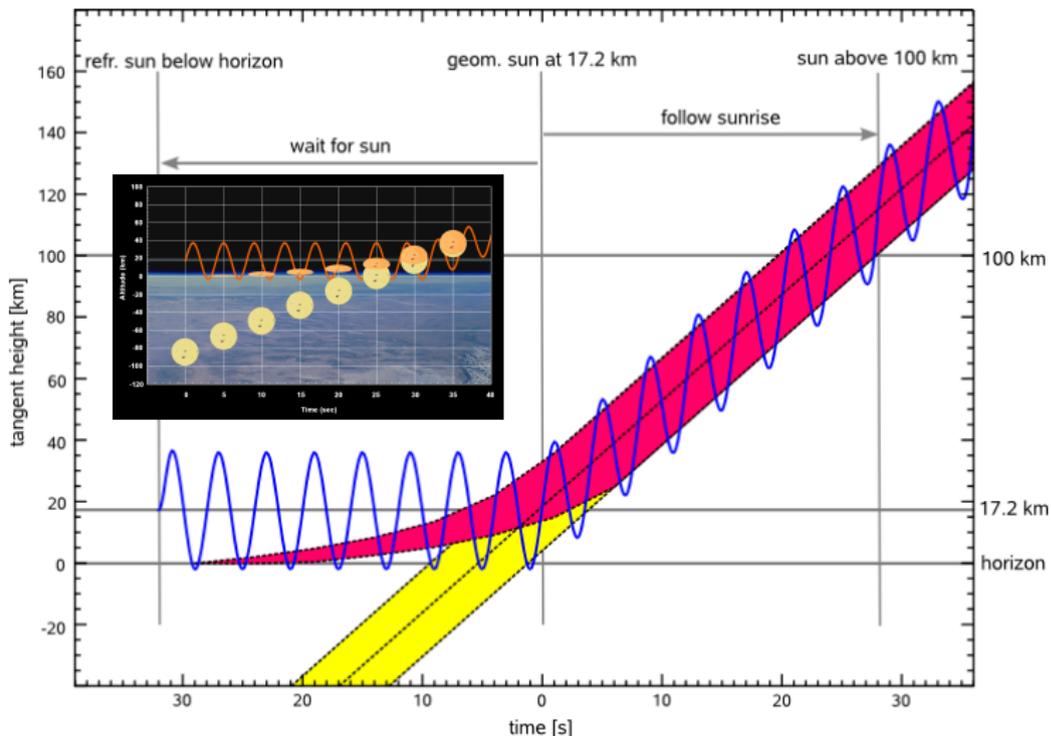


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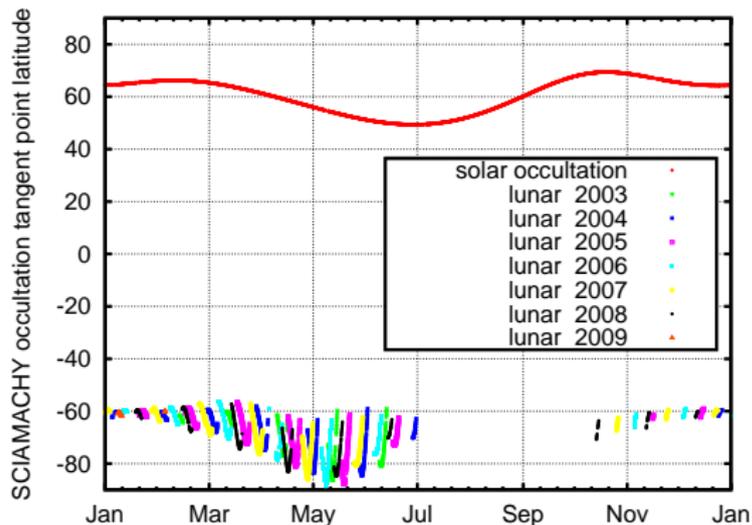
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Solar Occultation Measurement Sequence



- Scan over solar disk!
- Wait for sun, until geometric sun reaches 17.2 km
- Follow sunrise with pre-calculated rate up to 280 km
- Observed is sunset on ground!

Geographical Distribution



Solar Occ. Tangent points



Solar occultation: Each orbit, 49° N – 69° N , fixed seasonal pattern.

Lunar occultation: ~450 events per year (Nov – Jun), 56° S - 89° S .



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Tangent Height Algorithm

Pointing of SCIAMACHY is not perfect.
Scan over solar disk can be used:

- Horizontal FOV covers full sun.
- Intensity during scan over solar disk:

$$I(t) = 2\sqrt{r^2 - (t - t_{cen})^2}$$

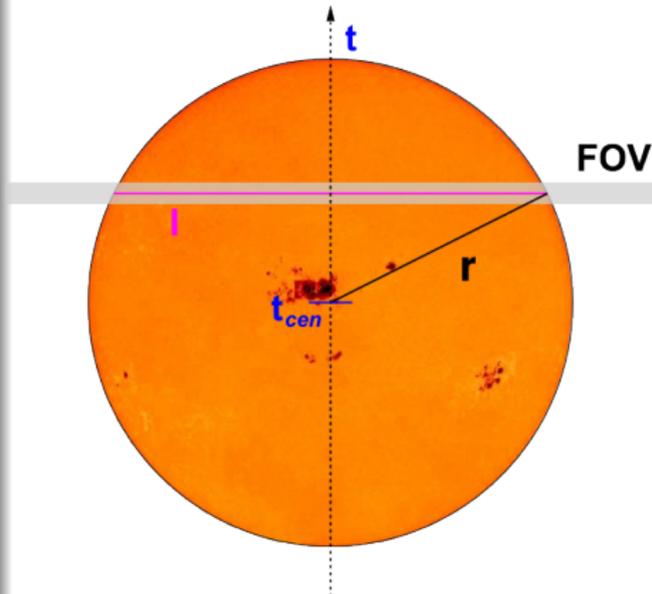
$I(t)$: measured intensity.

t_{cen} : t of sun center

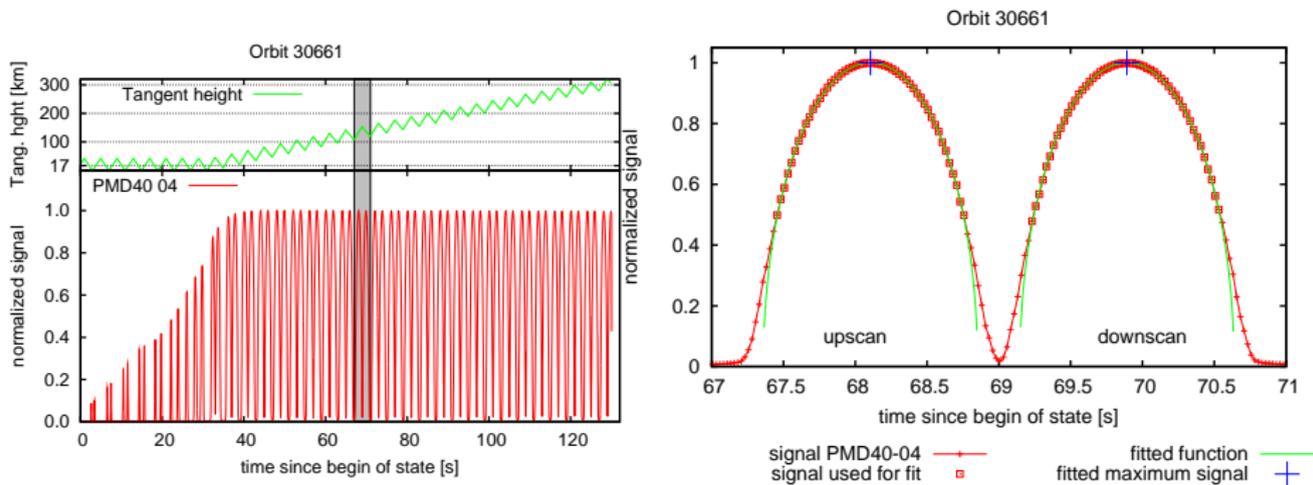
r sun radius (in time units)

t_{cen} and r are fitted.

- Compare at time t_{cen} :
 - Viewing direction towards sun.
 - Viewing direction, using satellite attitude + mirror angles (L1b).
- Use difference to improve tangent height knowledge.



Tangent Height Algorithm Measurements

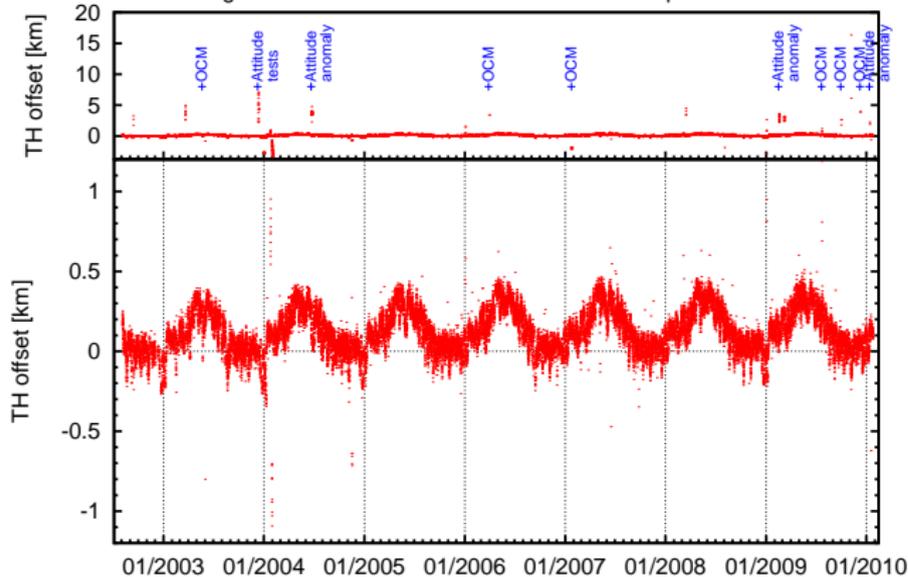


- Scans above the atmosphere (>100 km) used (15 up-scans/15 down-scans)
- Raw signal of PMD 4 (highest frequency with $40 \text{ Hz} \doteq 80$ measur. per scan).
- *Right Panel*: **Green line**: Fitted $I(t)$, **Blue cross**: t_{cen} (fitted solar center).
- Extrapolation of derived tangent height offsets to lower altitudes.

⇒ **Tangent height correction.**

Time Series Tangent Height Offset

Tangent offset SCIAMACHY solar occultation - up-scan



Some larger TH events could be identified as platform anomalies:

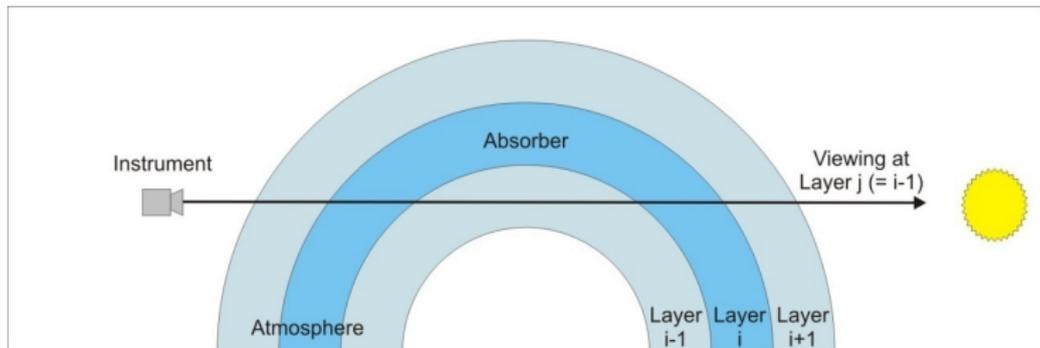
- OCM: after an orbit control manoeuvre.
- Attitude tests (before platform attitude improvements end 2003)
- Attitude anomalies

- Seasonal pattern 0 to +250 m (from *up-scans*); short term TH variations ~ 200 m.
- TH offset from *down-scans* always ~ 400 m lower. Reason??
- *Remark: Standard TH is already very good!*

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Scheme Onion Peeling DOAS



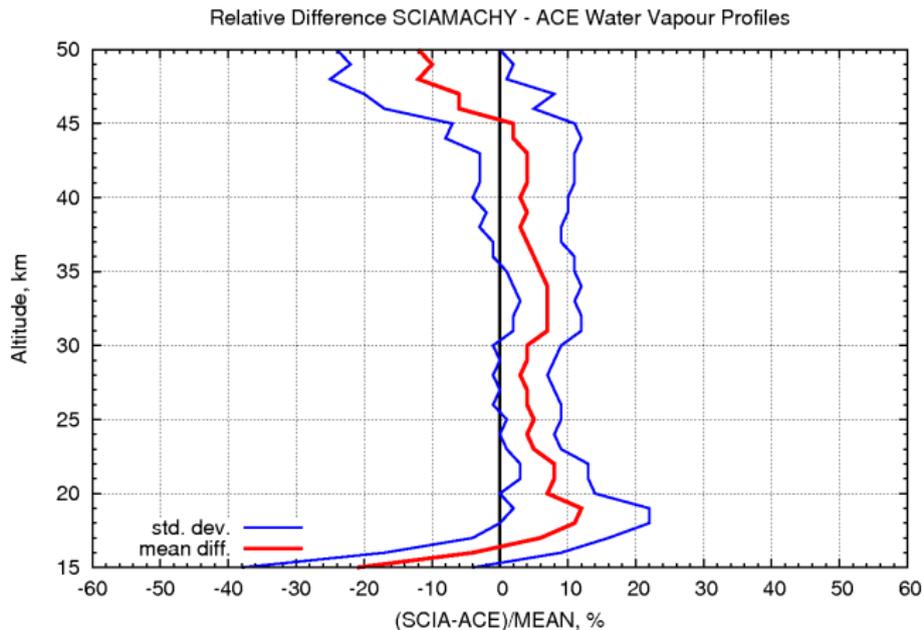
- Atmosphere divided into **horizontal layers**
- Retrieval: start at top layer and **propagates downwards**
- Absorption of whole atmosphere: **sum of absorption of individual altitude layers**
- Fit **scaling factors** for number densities in different layers
- **Polynomial** to handle broadband effects
- Additional correction of **saturation** effects (limited spectral resolution)

Setup Onion Peeling DOAS

- Fit intervals:
 - 928 - 968 nm (H_2O), secondary absorber O_3
 - 1559 - 1595 nm (CO_2), secondary absorber CH_4
 - 1630 - 1671 nm (CH_4), secondary absorber CO_2
- Retrieval altitude grid: 0 - 50 km, 1 km steps
- SCIAMACHY transmission spectra are interpolated to retrieval grid before retrieval (required by method)
- Retrieved profiles are smoothed with SCIAMACHY vertical field of view (2.6 km) after retrieval:
 - ⇒ Takes into account vertical resolution of measurement
 - ⇒ Removes oscillations in retrieved number densities

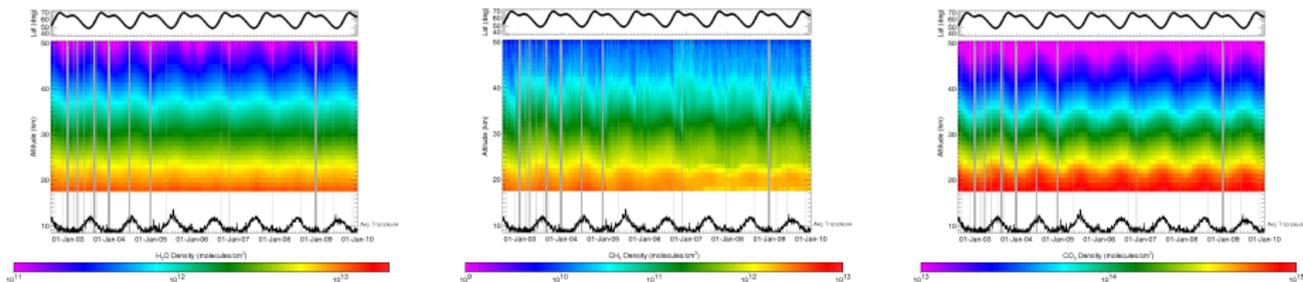


H₂O Profiles: Validation with ACE



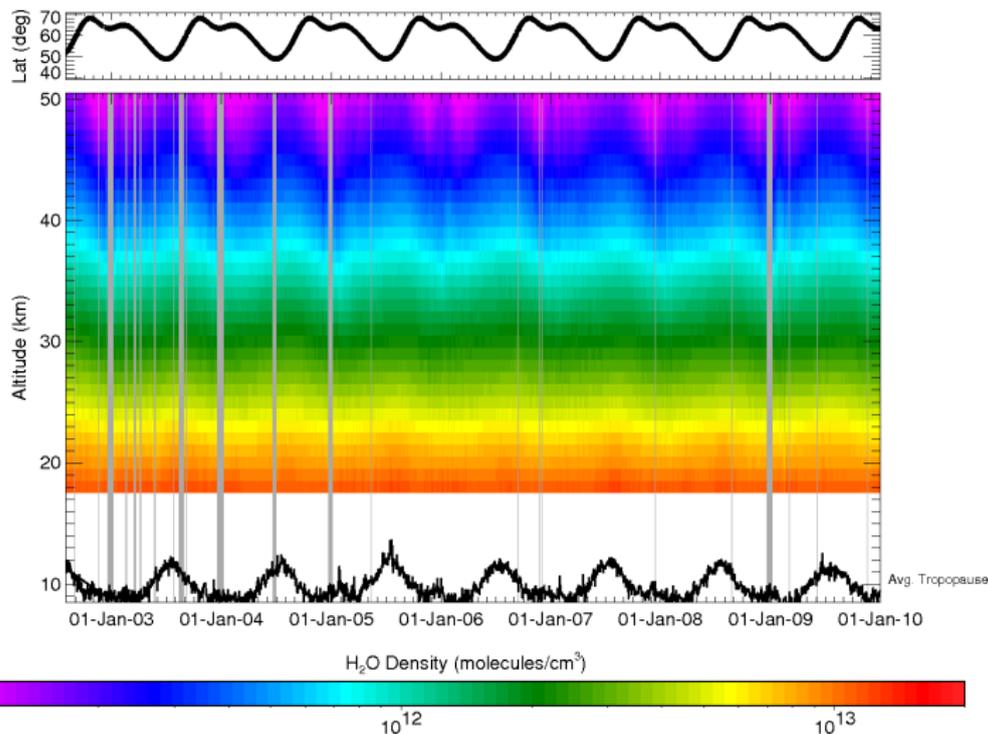
- ~ 400 collocations 2003 - 2007.
- Agreement with ACE-FTS within 6% from 23 - 46 km.

Time Series: H₂O – CH₄ – CO₂



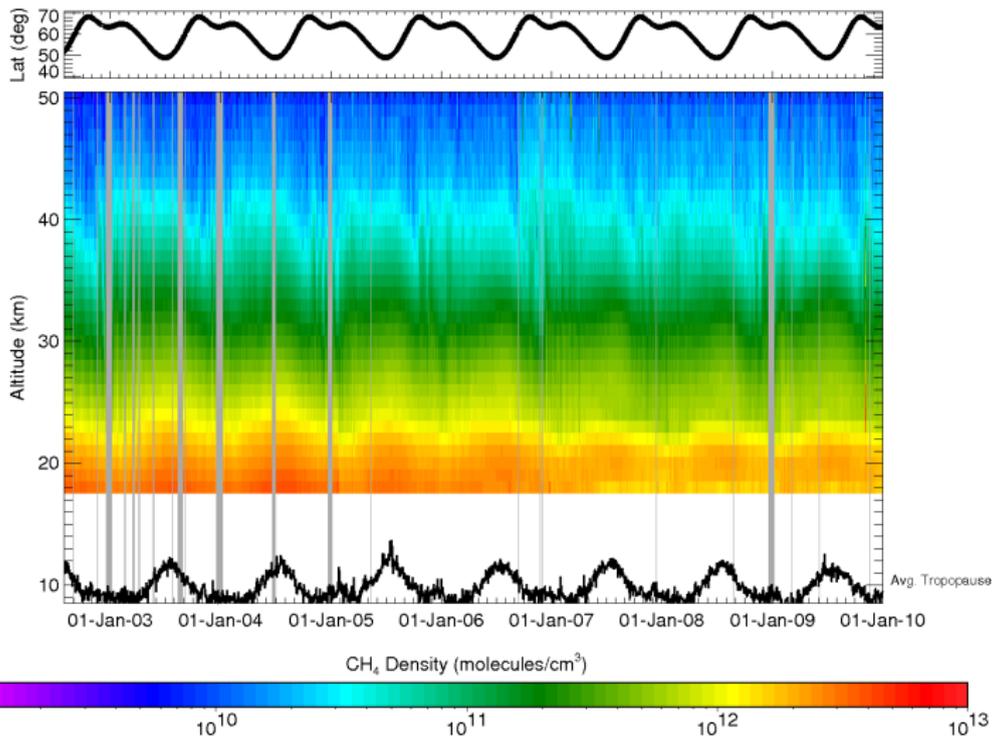
- Aug 2002 - Dec 2009, decontaminations & instrument switch-offs masked out
- Daily averaged data (~13 profiles per day at different longitudes)
- Tropopause height derived from collocated ECMWF data
- Seasonal effects: Variation with latitude and tropopause height
- H₂O : Ref. profiles: p, T, H₂O from ECMWF (10 Nov 2005, 67.5° N , 30° W).
- CH₄ : Ref. profiles: p, T from ECMWF 26 July 2005, CH₄ US Std. Atmos.
- CO₂ : Ref. profiles: p, T from ECMWF 26 July 2005, CO₂ VMR 380 ppmv.



Time Series: H_2O – CH_4 – CO_2  H_2O

Agreement
with ACE-FTS
within 6% from
23 - 46 km.

Time Series: H₂O – CH₄ – CO₂

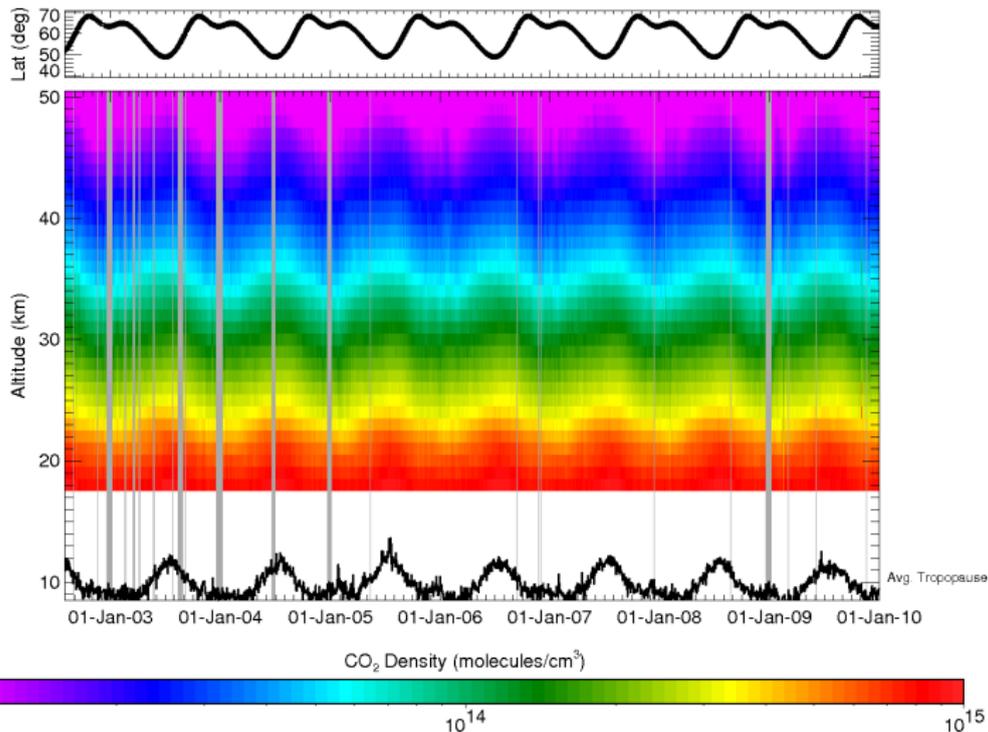


CH₄

Trend in lower stratosphere?



Time Series: H₂O – CH₄ – CO₂



CO₂

Variability too high (only 2ppm/year expected from CarbonTracker)

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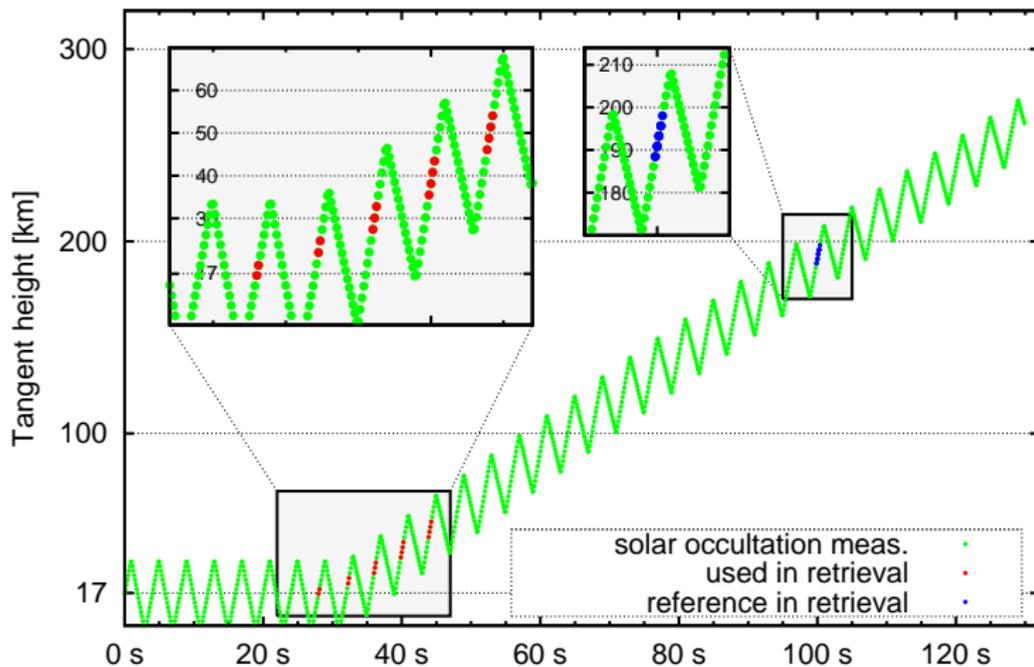
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Optimal Estimation Retrieval Setup

Retrieval setup:

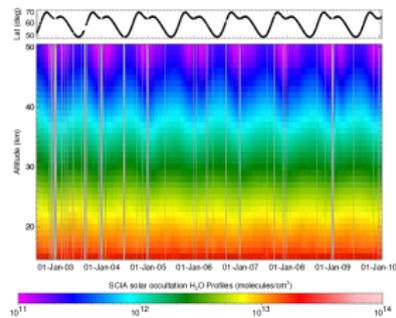
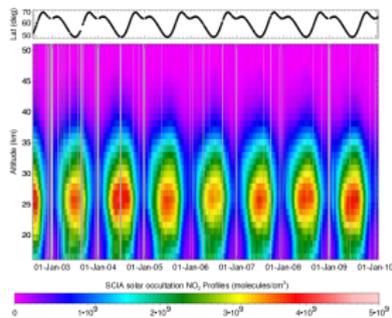
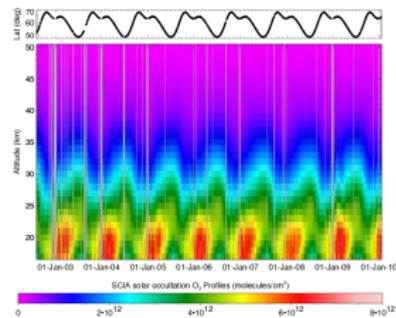
- Forward and retrieval code: SCIATRAN 3.0
- Optimal estimation with Tikhonov regularization
 - H₂O (1300 - 1540 nm): line absorber
 - ⇒ ESFT (Exponential Sum Fitting of Transmittance function) in forward model is used
 - O₃ (525 - 590 nm) and NO₂ (425 - 453 nm) are simultaneously retrieved
- SCIAMACHY Level 1b version 6.0x products
- 15 up-scan measurement (~ 17 - ~ 58 km, references to calculate transmission ~ 200 - 250 km) selected \Rightarrow *next slide*.
- p,T profiles: ECMWF.
- Tangent height correction is used.





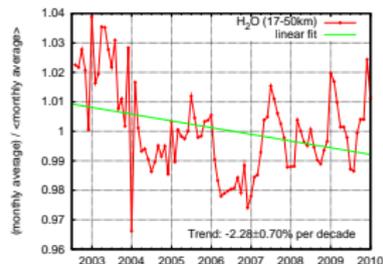
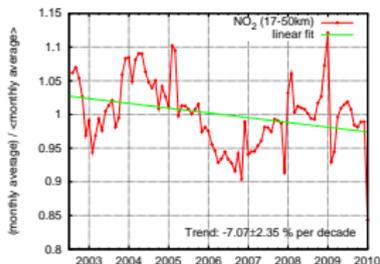
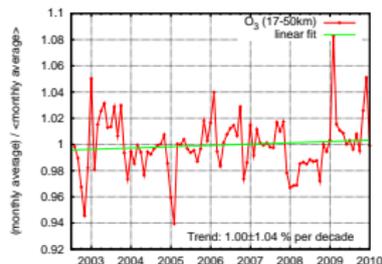
- 15 up-scan measurement ($\sim 17 - \sim 58$ km).
- Corresponding references to calculate transmission: $\sim 200 - \sim 250$ km.
- *Similar setup for Onion Peeling DOAS.*

Time Series: O₃ – NO₂ – H₂O



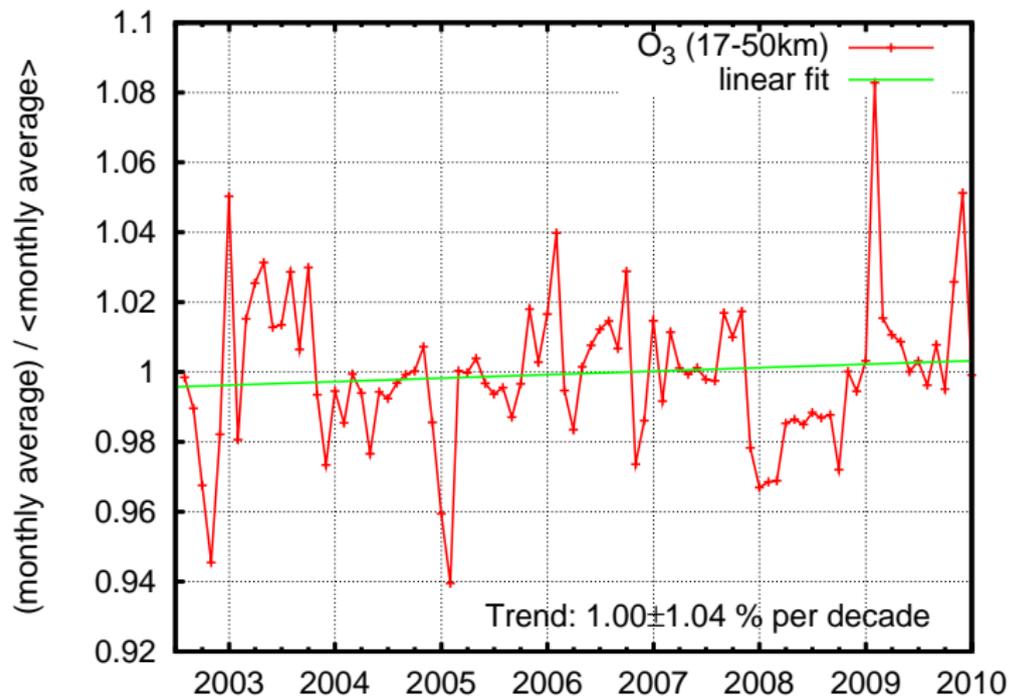
- Daily averaged data (~13 profiles per day at different longitudes)
- Overall variation driven by season and latitude pattern
- O₃ : Enhanced ozone loss in early 2005 and 2008 visible.
- NO₂ : High variability of NO₂ observed
- H₂O : Variation driven by season and latitude variation

Trend analysis: O₃ – NO₂ – H₂O



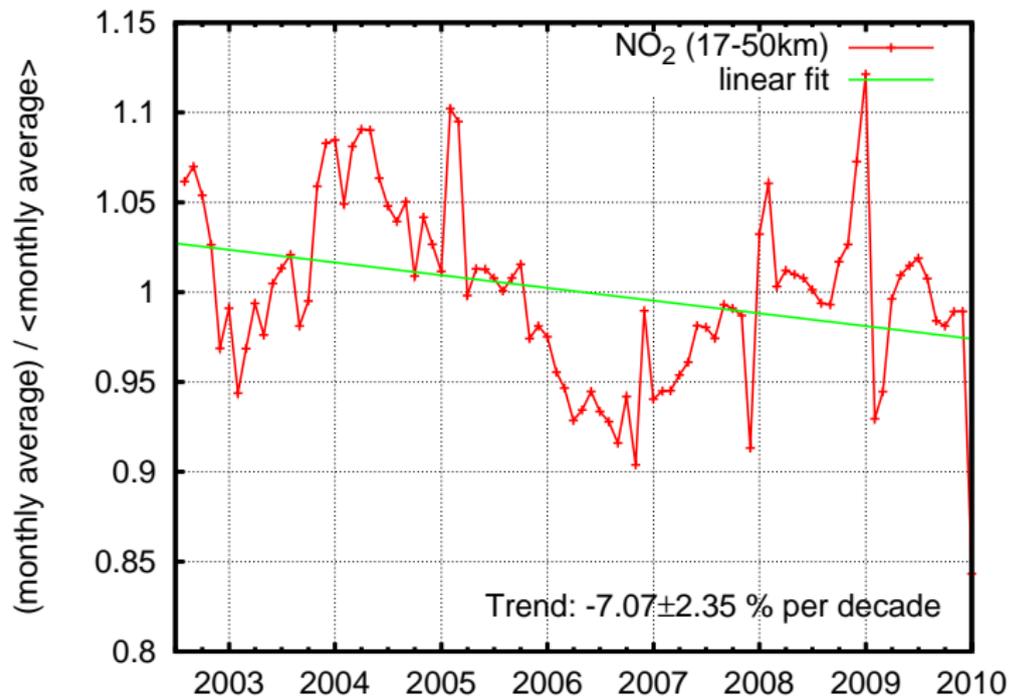
- Analysis based on monthly means for the trace gas content 17 - 50km.
- For **each month**: Individual monthly mean is divided by **the mean of all corresponding monthly means** ⇒ get rid of seasonal pattern!
- O₃ : Increase of 1.0% per decade, but **not** significant.
- NO₂ : Observed is an NO₂ decrease of $-7.0 \pm 2.4\%$ per decade
Last value an outlier? (5% / decade)? Periods in the data?
- H₂O : Observed is an H₂O decrease of $-2.28 \pm 0.7\%$ per decade.
Decrease 2003-2007, then increase.



Trend analysis: $O_3 - NO_2 - H_2O$ 

Trend O_3 :
Increase of
1.0% per
decade, but
not significant.

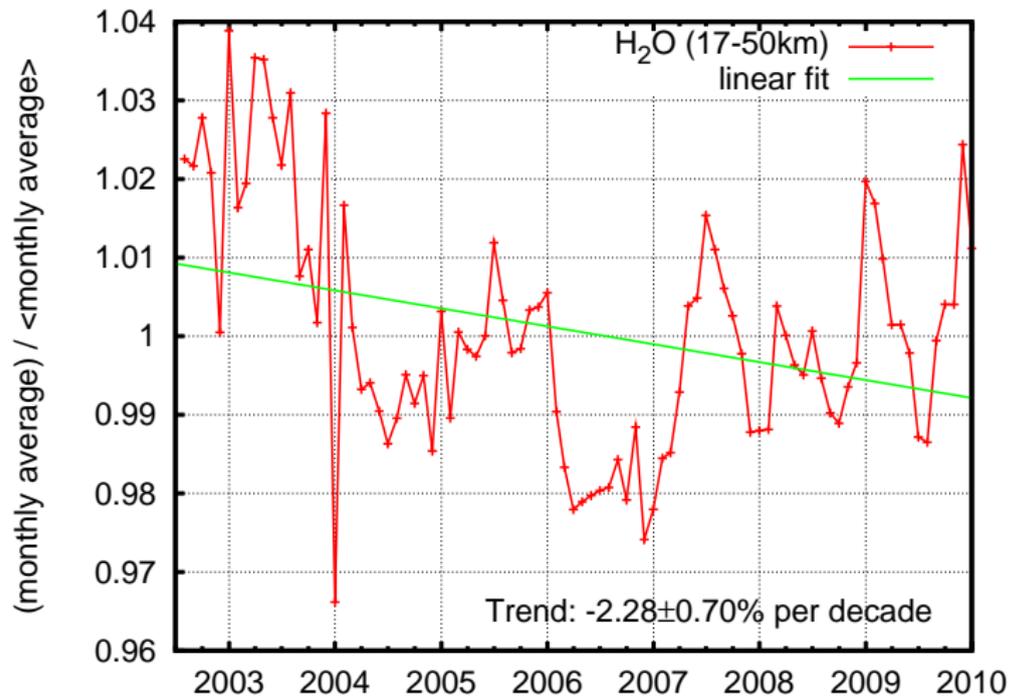


Trend analysis: O_3 – NO_2 – H_2O Trend NO₂ :

Observed is an NO₂ decrease of -7.0 ± 2.4 % per decade.

*Last value an outlier?
Periods in the data?*



Trend analysis: O₃ – NO₂ – H₂OTrend H₂O :

Observed is an H₂O decrease of $-2.28 \pm 0.7\%$ per decade.

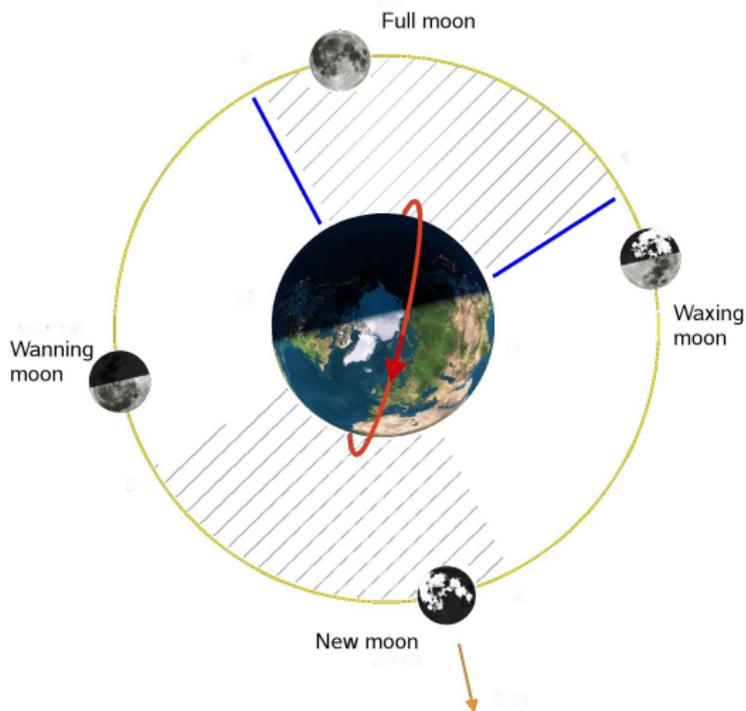
Decrease 2003-2007, then increase.

In line with other observations (Urban, COSPAR 2010).

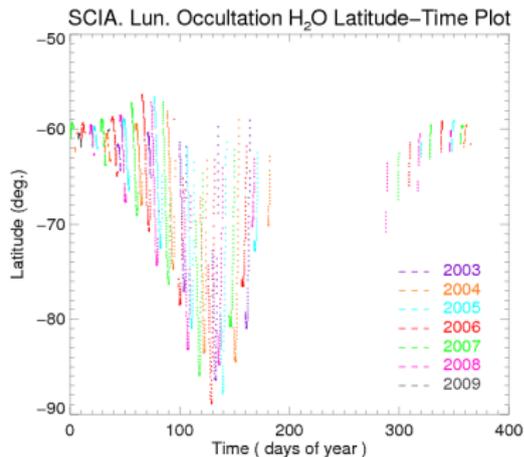
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Lunar occultation



- Southern hemisphere
- Night side
- Lunar visibility:
 - Moon phase ~ 0.5 till shortly after full moon
 - 6-8 days per month for 6 month per year
 - ~ 400 measurements per year
- MFD (moon follower device) adjusts to brightest point on the moon
- Tangent height range $\sim 17 - 350$ km
- Vertical resolution ~ 3 km
- Horizontal resolution $\sim 30 \times 400$ km²

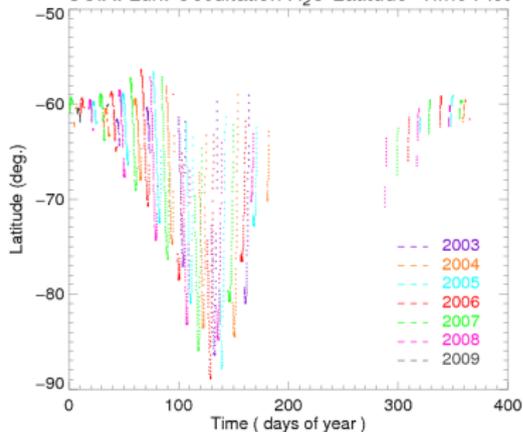
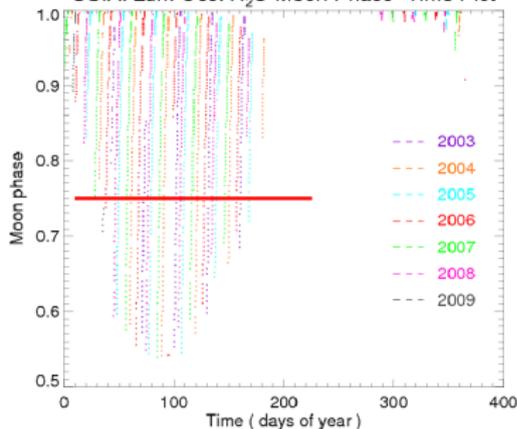


- ~ 450 events per year (Nov – Jun),
 $56^\circ \text{ S} - 89^\circ \text{ S}$.

- Criteria for selecting measurements with sufficient signal:

- Moon phase > 0.75 (strong signal)
- Solar Zenith Angle (SZA) $> 96^\circ$ (avoid solar stray light)

⇒ 1786 profiles

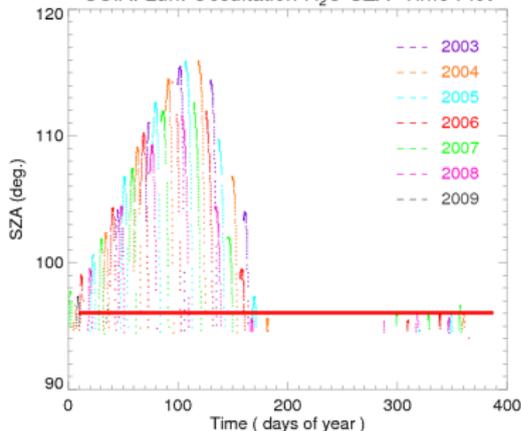
SCIA. Lun. Occultation H₂O Latitude–Time PlotSCIA. Lun. Occ. H₂O Moon Phase–Time Plot

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SCIA. Lun. Occultation H₂O SZA–Time Plot

Outline

- 1 SCIAMACHY instrument
 - Envisat
 - The Instrument
 - Highlights
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 - Onion peeling DOAS Approach
 - Optimal Estimation Approach
- 3 Lunar occultation
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 - **Optimal Estimation Approach**
- 4 Summary and Outlook

Optimal Estimation Retrieval Setup

Retrieval setup:

- Forward and retrieval code: SCIATRAN 3.0
- Optimal estimation with Tikhonov regularization
 - H₂O (1300 - 1420 nm): line absorber
⇒ ESFT (Exponential Sum Fitting of Transmittance function) in forward model is used
 - NO₃ : 610 - 680 nm
 - O₃ and NO₂ (425 - 600 nm) are simultaneously retrieved
- SCIAMACHY Level 1b version 6.0x products
- 10 measurements ~17 - ~50 km used, references to calculate transmission ~135 km
- p,T profiles: ECMWF

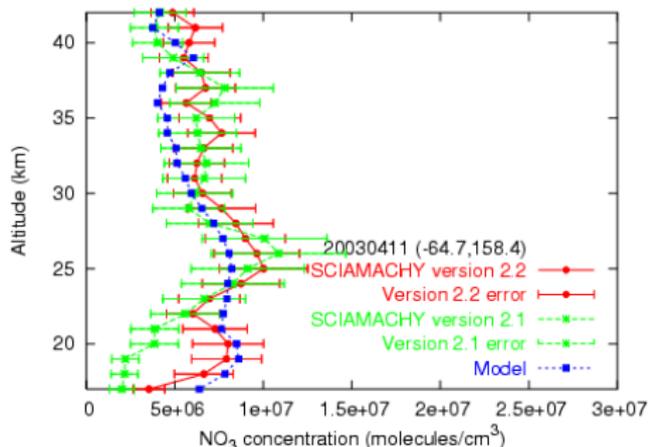
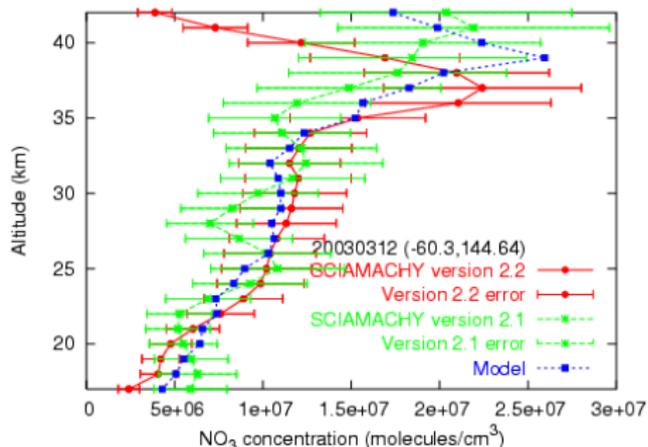


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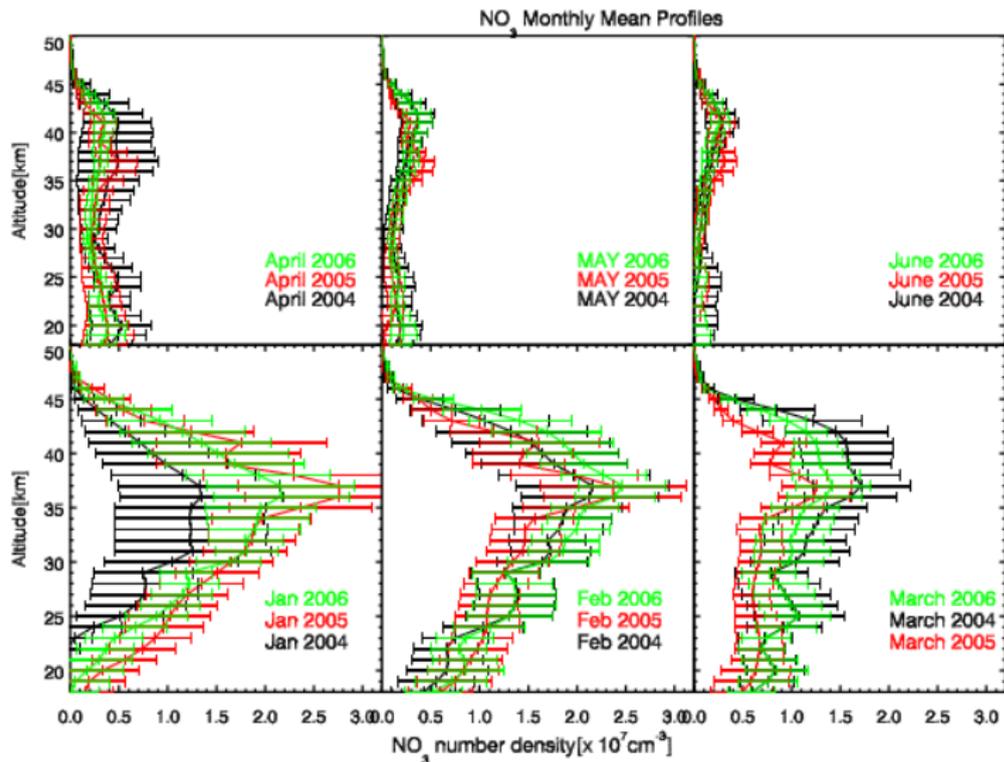
NO₃ Model Comparison



- Latest version compared with simple model.
- Model assumed steady state condition for NO₃ formation.
- NO₃ compared with model: promising results, accuracy < 30%.



NO₃ Monthly Mean Profiles

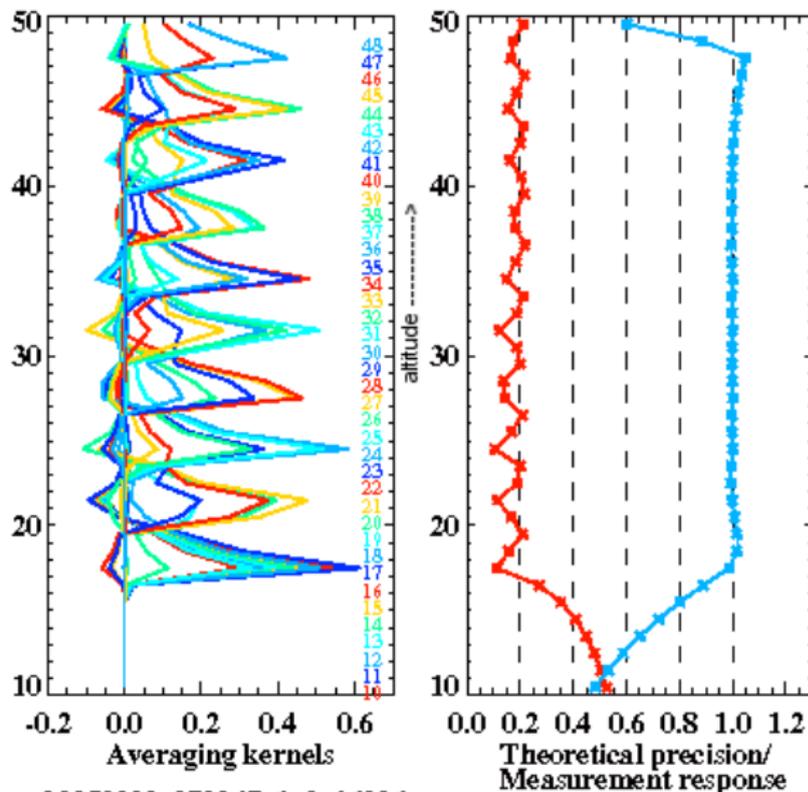


Monthly
means:

NO₃ is strongly
temperature
dependent.



H₂O : Averaging Kernels and Measurement Response



20050323_072247_1_0_16006

Averaging Kernels:

- Peaks at measurement altitudes.

Measur. Response:

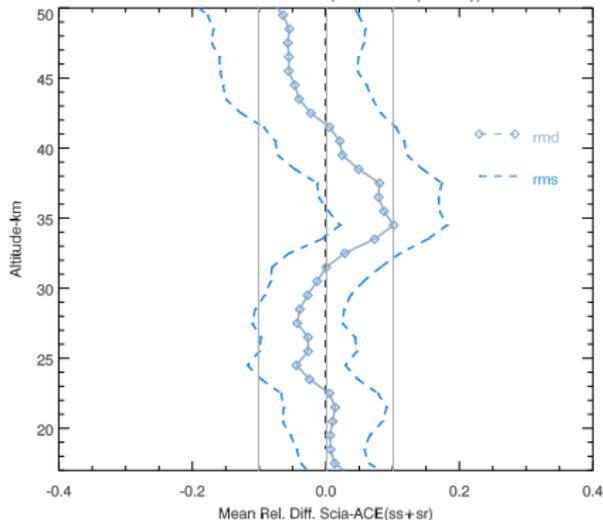
- Profile 17 - 47 km determined by the measurements.



Validation H₂O

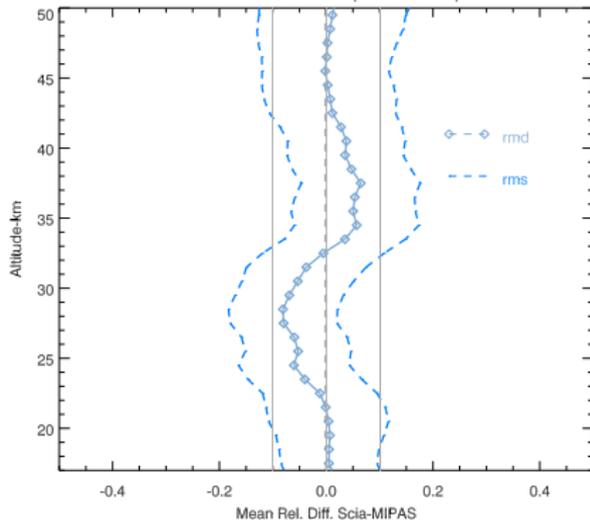
ACE : 323 co-locations

Mean Rel. Diff Plot (Scia-ACE(ss+sr))



MIPAS : 571 co-locations

Mean Rel. Diff Plot (Scia-MIPAS)



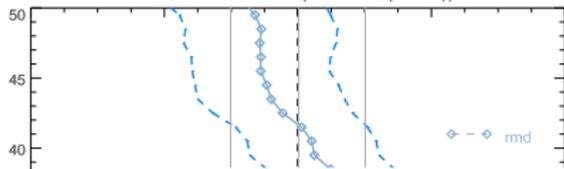
- Collocation Criteria: Distance < 1000 km & time diff. < 12 h.
- **ACE**: Within 6% from 17–50 km, except 33–39 km: <10%.
- **MIPAS**: Within 7% from 17–50 km.

⇒ Very good agreement.

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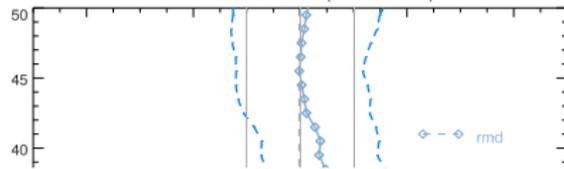
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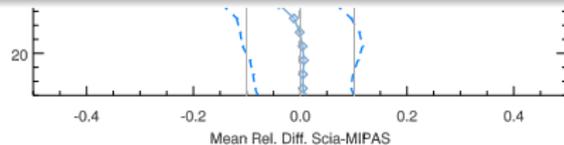
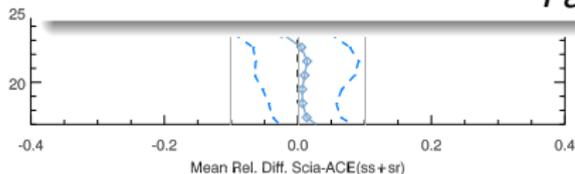
POSTER

SCIAMACHY Lunar Occultation

Water Vapor measurements: Retrieval and Validations

Faiza Azam

Altitude-km



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Summary and Outlook

Summary

SCIAMACHY occultation measurements successfully used to provide useful datasets for various trace gases.

Outlook

- Solar occultation: Onion peeling DOAS
 - Further investigations of greenhouse gas retrievals.
 - Temperature retrieval from the O₂ A Band?
- Solar occultation: Optimal estimation approach
 - Retrieval of greenhouse gases
 - Investigate line-by-line (H₂O / greenhouse gases): slower, but more precise?
- Lunar occultation
 - Investigate line-by-line for H₂O : slower, but more precise?
 - Retrieval of CH₄ .
 - Interpretation/analysis with respect to physical/chemical processes in the southern hemisphere

Thanks for your attention!



Acknowledgment:

SCIAMACHY is a national contribution to the ESA ENVISAT project, funded by Germany, The Netherlands, and Belgium. SCIAMACHY Level 1 data have been provided by ESA. We thank HALOE and SAGE II teams at Hampton University and NASA LaRC, the ACE team at the University of Waterloo, Canada, and the MIPAS team, Karlsruhe, for providing data. This work has been funded by BMBF, by DLR-Bonn, and by the University of Bremen.