SCIAMACHY SOLAR OCCULTATION: OZONE AND NO_2 PROFILES 2002-2006

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ABSTRACT

The spectrometer SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) on-board ENVISAT is measuring solar irradiances and Earthshine radiances from the UV to the NIR spectral region in nadir, limb and lunar/solar occultation geometry.

Solar occultation measurement are performed during sunrise at northern latitudes (49N to 69N, depending on season). Using an optimal estimation approach with the radiative transfer and retrieval code SCIATRAN 2.1, these measurements are used to derive vertical profiles of ozone and NO2. Precise tangent height information is derived from the scanning over the solar disk. Here we present an almost complete dataset from August 2002 to December 2006, including validation results with independent measurements from other satellites.

1. INTRODUCTION

SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) is a passive remote sensing moderate-resolution imaging UV-Vis-NIR spectrometer on board the European Space Agency's (ESA) Environmental Satellite (ENVISAT), launched in March 2002 from Kourou, French Guiana. The instrument observes the Earth atmosphere in Nadir, limb and solar/lunar occultation geometries and provide column and profile information of atmospheric trace gases of relevance to ozone chemistry, air pollution, and climate monitoring issues (Bovensmann et al., 1999).

Since 2002 SCIAMACHY has been making observations of sunrise event in every orbit over the northern hemisphere (49^o N – 70^o N depending on season, see Figure 1) using the well-established and proven solar occultation technique, with a total of approximately 14 events per day. The SCIAMACHY solar occultation measurements are performed in sun scanning mode. Usually the sun disk is scanned permanently, while spectral measurements are performed every 62.5 msec. Only directly transmitted light contributes significantly in occultation geometry. Transmissions are calculated dividing atmospheric measurements by an appropriate measurement from above the atmosphere. Due to the sun fixed orbit and the position of SCIAMACHY on ENVISAT, the instrument is not able to measure the sunset events in the southern hemisphere. However, during local nighttime in the southern latitudes (30^o S–90^o S) SCIAMACHY performs lunar occultation measurements (Amekudzi et al., 2005, 2007). Detailed information on SCIAMACHY solar occultation measurements are provided in Meyer (2004); Meyer et al. (2005).

2. TANGENT HEIGHT DETERMINATION

Uncertainties in the viewing direction are a prominent error source in the retrieval of trace gas profiles from SCIAMACHY limb and occultation measurements. In the case of solar occultation, we use the sun as well known target in space to derive a very precise knowledge of the viewing direction to avoid this source of error.

Figure 2 illustrate the scanning sequence of the usual solar occultation measurements. In the first part, SCIAMACHY scans the estimated sunrise region above the horizon. When the geometric centre of the sun reaches a tangent height of 17.2 km, the FOV starts to move up with a pre-calculated elevation rate up to an altitude of about

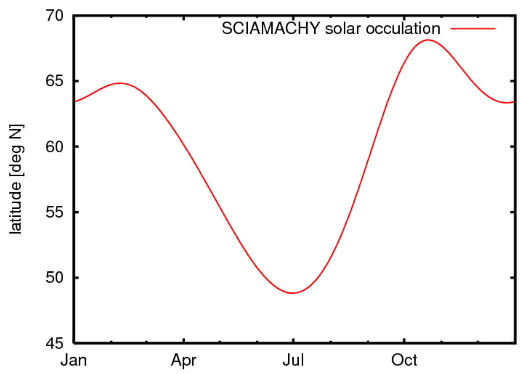

Figure 1. Latitudinal distribution of SCIAMACHY solar occultation events with season.

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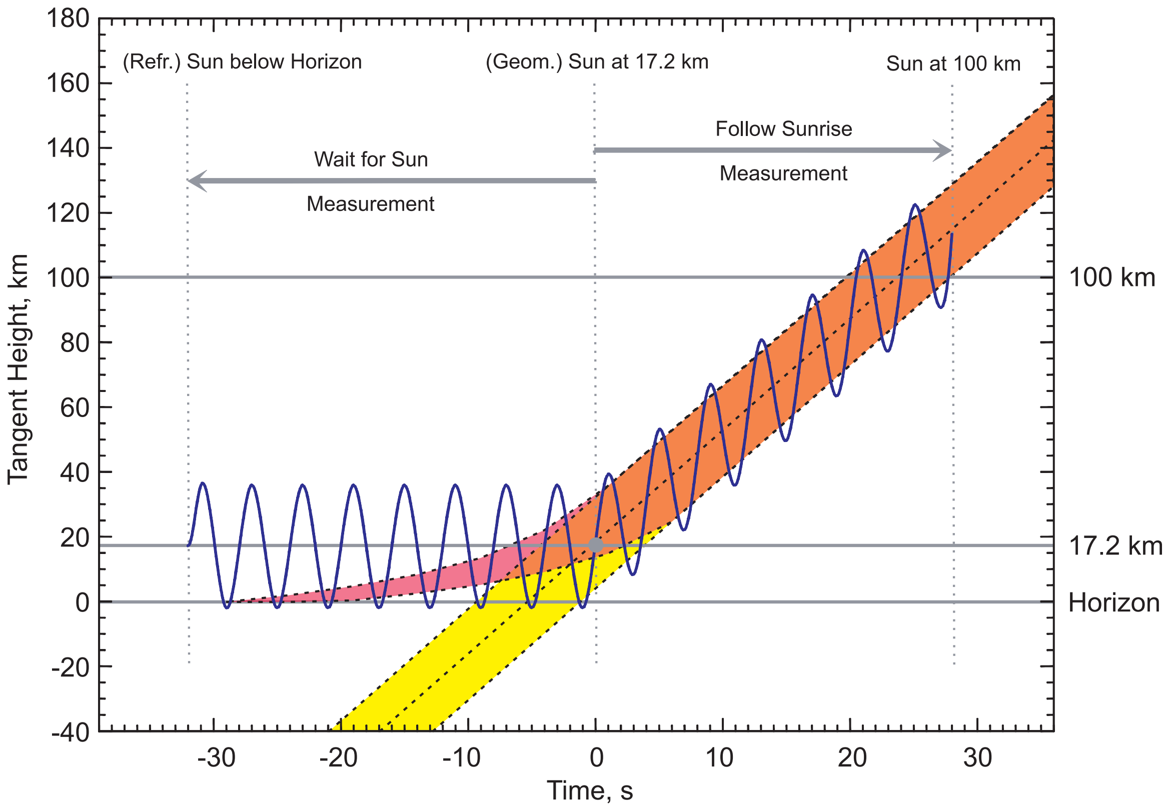

Figure 2. Schematic view of a solar occultation measurement sequence. Tangent height in km is plotted vs. time in seconds. The blue line represents the movement of SCIAMACHY's FOV, the shaded areas illustrate the refracted and the imaginary true Sun, respectively.

290 km. During the whole sequence, the sun is scanned up and down over the full solar disk.

The scanning sequence above the atmosphere (without refraction effects) is used to determine the exact position of the centre of the sun. The intensity function for

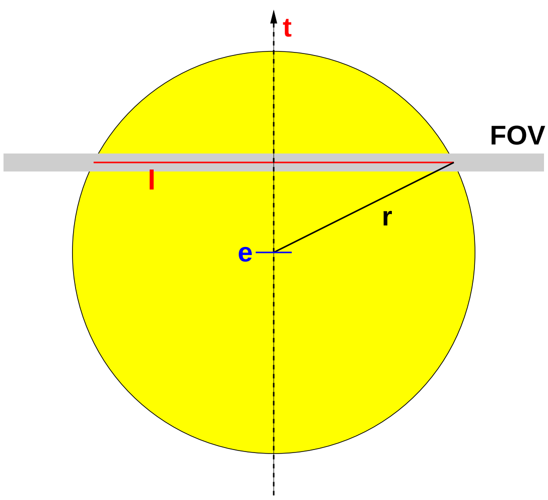

Figure 3. Sketch for deriving the intensity function of a the over the solar disk. l is the function $sun(t)$, see text.

one scan over the solar disk is proportional to the length of the secant defined by the horizontal extent of SCIAMACHY's field of view (FOV). By using the theorem of Pythagoras, we get

$$sun(t) = 2c\sqrt{r^2 - (t-e)^2} \qquad (1)$$

with

- t : vertical direction proportional to the time during scan.
- r : radius of the sun (in time coordinate)
- e : centre of the solar disk (in time coordinate)
- c : scaling factor to the measured intensities

The maximum measured intensity is than given by

$$I_{max} = 2cr \qquad (2)$$

This function is fitted via the parameters r, c, and t with a non-linear least–square algorithm (Levenberg–Marquard) to the scans over the solar disk above the atmosphere. Figure 4 shows an example for two scans of

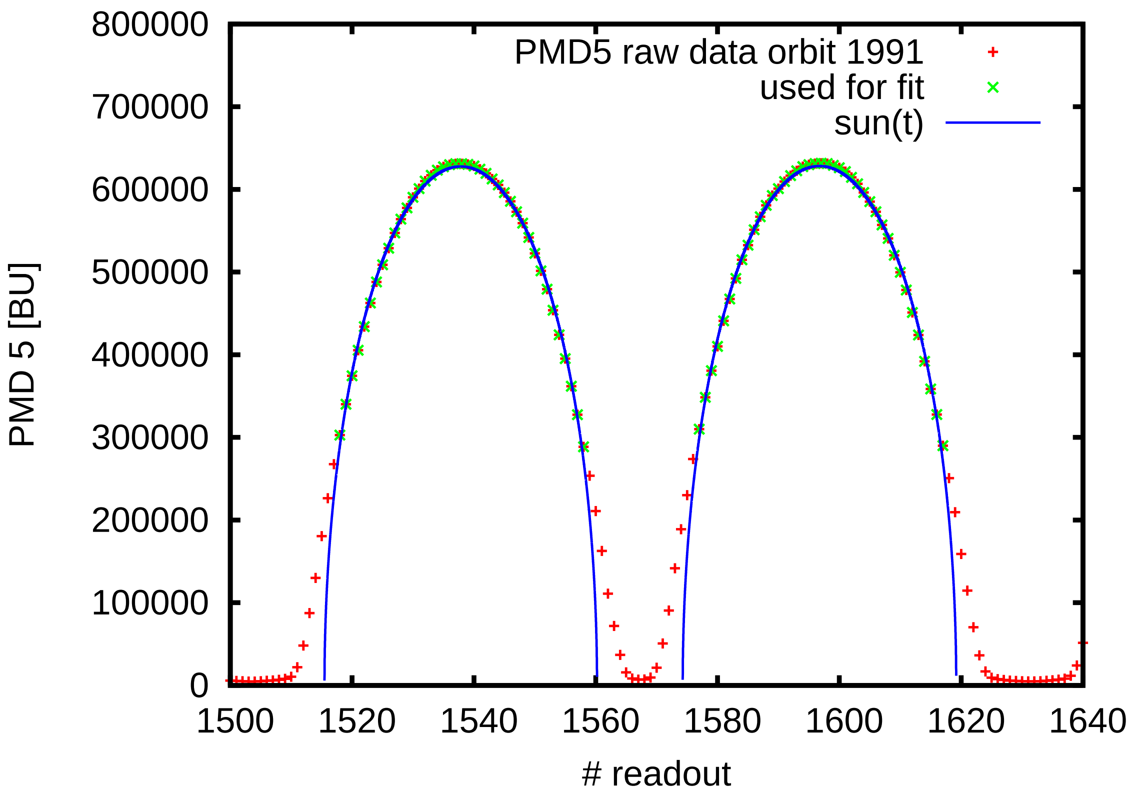

Figure 4. Fitting of two scans over the solar disk with equation 1. Red crosses are measured intensities (taken from PMD 5), green crosses are intensities used for the fit and blue are the fitted functions.

the solar occultation measurement in orbit 1991. As intensities measurements of PMD 5 are used, as the PMDs have a higher sample rate. Important is to exclude the points near the edge of the sun to avoid disturbance by seeing more and more parts of the solar corona in the field of view. Only the green point in Figure 4 are used for fitting $sun(t)$. After the fit, e gives the precise time, when SCIAMACHY is looking towards the centre of the solar disk.

Using the ENVISAT Orbit propagator software library CFI (ESA, 2006) and the actual orbit parameters delivered with each SCIAMACHY product, the precise tangent height above Earth's surface for the line *satellite – centre of the solar disk* can be calculated for each position in orbit. For the derived time when SCIAMACHY points to the centre of the sun, the tangent height is compared to the tangent height given for that time in the product (which is calculated using the (uncertain) satellite attitude and mirror positions). The difference between these two tangent heights is the tangent height offset. It is calculated for all scans above the atmosphere and than extrapolated to the retrieval tangent height around 25 km.

This method was also used to verify the improved misalignment values recently derived for SCIAMACHY (Gottwald et al., 2007). All following results in this paper use corrected tangent heights.

3. RETRIEVAL SCHEME

The SCIATRAN version 2.1 radiative transfer code (Rozanov et al., 2005) is used for the forward modelling and the retrieval. The global fitting method coupled with the differential optical depth approach is used to fit simultaneously NO_2 and ozone in the spectral window of 425 – 453 nm and 524 – 590 nm respectively at the spectral resolution of the SCIAMACHY instrument. In the current retrieval scheme, the a priori trace gases profiles as well as the a-priori pressure and temperature profiles are taken from the MPI data base. Exception are the a-priori ozone profiles, which are take from the Fortuin and Kelder ozone climatology (Fortuin and Kelder, 1998).

Broadband absorption features of the atmosphere and broadband instrument effects were removed from the measured spectrum by subtracting a third order polynomial. Furthermore, NO_2 and O_3 profiles are retrieved using the optimal estimation method described in Rodgers (1976, 2000). Smoothing constraint parameters (Twomey-Tikhonov regularisation) are applied to smooth the retrieved profiles.

The SCIAMACHY L1b spectra used are equivalent to version 6 of the SCIAMACHY L0–1B processor version (Slijkhuis and von Bargen, 2005). Version 5.04 level 1b products were patched with the auxiliary files already

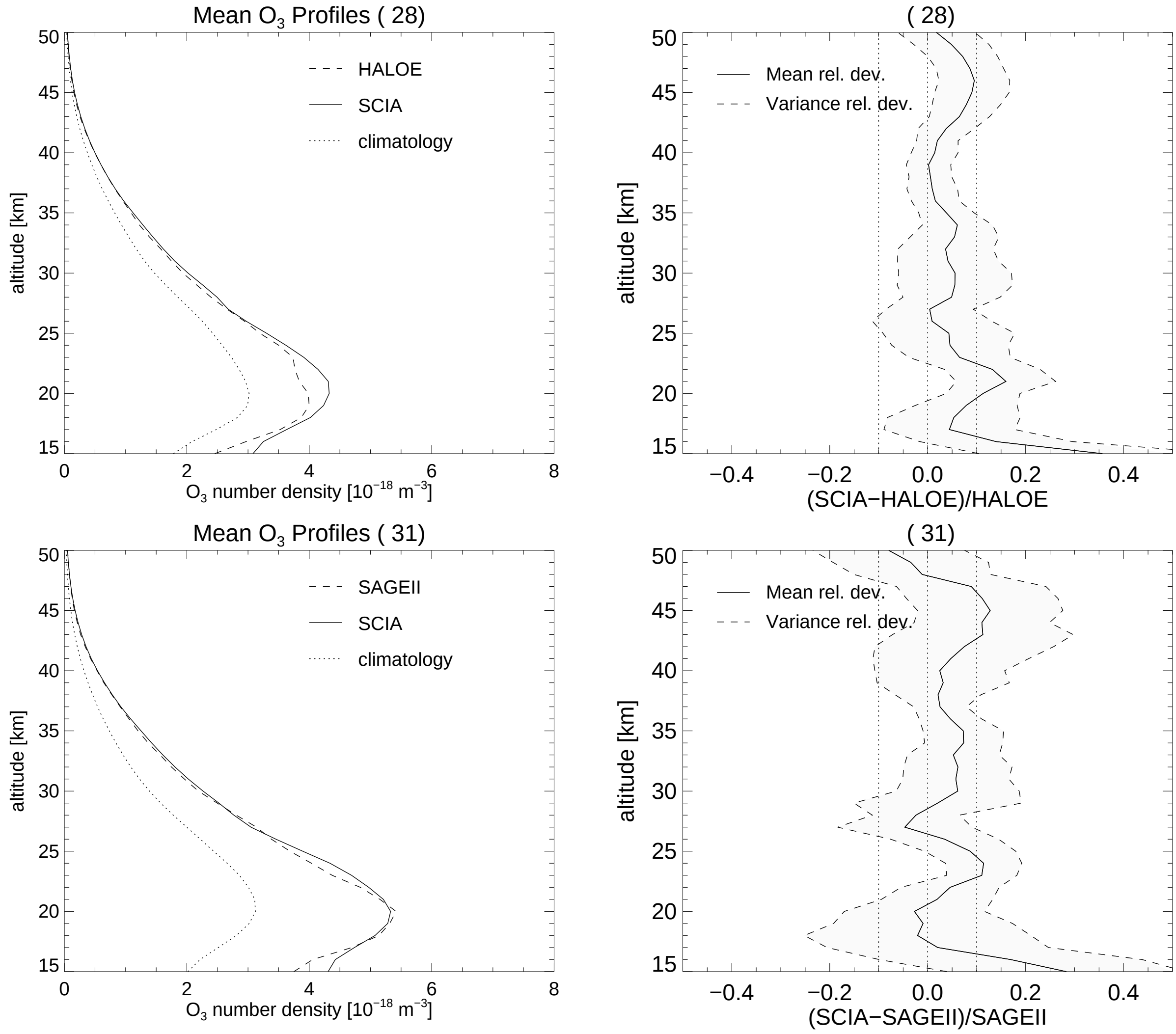

Figure 5. Validation results of ozone profiles from SCIAMACHY solar occultation with HALOE and SAGE II. Left column shows the mean profiles of the dataset (climatology is the a-priori profile used in the SCIAMACHY retrieval). Right column shows the mean relative deviation and its variance. At top are the results for HALOE, at bottom are the results for SAGE II.

prepared by ESA for the next re-processing, expected to start end of April 2007. The memory effect calibration was recalculated with a version 6 equivalent algorithm, the stray-light algorithm has not changed from version 5.04 to 6. From May 2006 onwards, the NRT products of version 6.02 are used.

4. VALIDATION WITH THE SATELLITE INSTRUMENTS HALOE AND SAGE II

HALOE was launched on the Upper Atmosphere Research Satellite (UARS) spacecraft in September 1991, operations stopped in November 2005. The experiment uses solar occultation to measure vertical profiles of ozone and other trace gases. Version 17 of the HALOE ozone products were extensively validated against ground based and airborne ozone measurements as well as satellite measurements Brühl et al. (1996). In most cases, the relative deviation was below 10 % in the stratosphere and the lower mesosphere. A comparison of HALOE version 18 ozone profiles with SAGE II measurements showed an even better agreement than with version 17, mainly in the lower stratosphere Jianjun et al. (1997). For this work, the current version 19 of HALOE data was used.

The solar occultation instrument SAGE II which was launched on the Earth Radiation Budget Satellite (ERBS) in October 1984 and stopped operation in August 2005. For ozone, an uncertainty of less than 10 % in the altitude range 15 – 60 km is give in Cunnold et al. (1989). In this paper, the current version 6.2 is used for the comparisons.

In this study, very strict coincidence criteria are used. The measurement tangent points have to be within 200 km and within 2 hours. We found 28 coincidences with HALOE

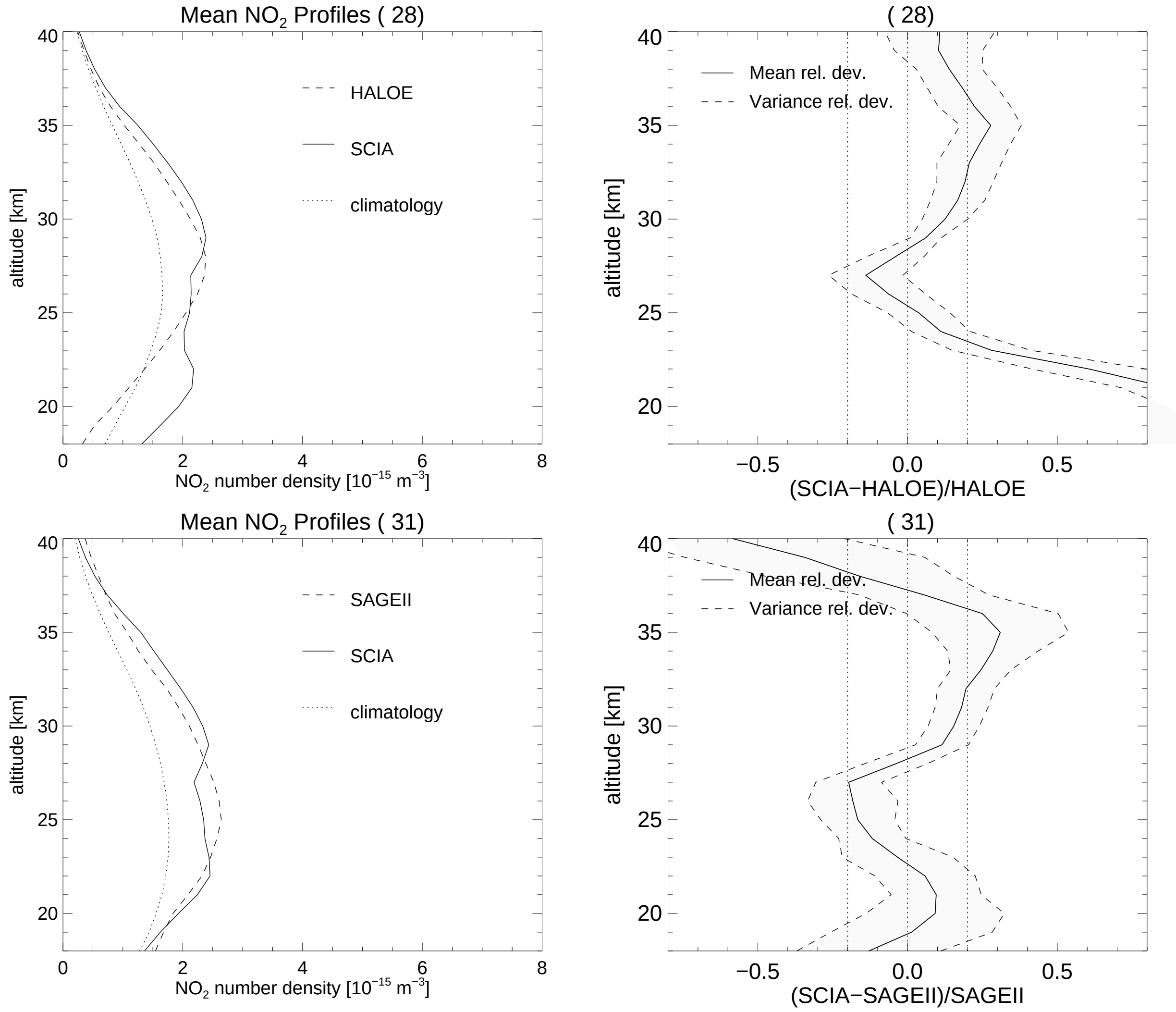

Figure 6. Validation results of NO_2 profiles from SCIAMACHY solar occultation with HALOE and SAGE II. Left column shows the mean profiles of the dataset (climatology is the a-priori profile used in the SCIAMACHY retrieval). Right column shows the mean relative deviation and its variance. At top are the results for HALOE, at bottom are the results for SAGE II.

and 32 with SAGE II, which are used for the validation.

Figure 3 shows the mean ozone profiles and statistics of the coincident measurements for both instruments. There is a very good agreement from 17 to 50 km with deviations mostly within 10 %. In general, SCIAMACHY tends to give slightly higher ozone values.

As the NO_2 concentration has a diurnal cycle, the comparisons have to be restricted to the sunset measurements of HALOE and SAGE-II. Because of the hard time restriction of 2 hours, this is ensured anyway. Thus, no photochemical correction is needed here, in contrast to NO_2 profiles from SCIAMACHY lunar occultation or limb measurements. Figure 6 shows the mean NO_2 profiles and statistics of the coincident measurements. We found an agreement within 25 % in the altitude region from 24 to 38 km. Nevertheless, a prominent structure around 25 km is visible in the mean profiles, the reason for this has to be investigated.

5. OZONE AND NO_2 PROFILES 2002 - 2006

We have evaluated about 31500 solar occultation measurements from the begin of life of SCIAMACHY to the end of 2006, which is an almost complete dataset for this time period. Not evaluated so far are measurements of state 47, the usual occultation state is 49. In state 49, the solar disk is scanned up to an altitude of 290 km. In state 47 performed once per day, scanning stops shortly above the atmosphere and SCIAMACHY points to the centre of the solar disk for a short time. The current setup does not handle this different behaviour.

Figure 7 shows the tangent points of the solar occultation measurements used on the following plots. In the region

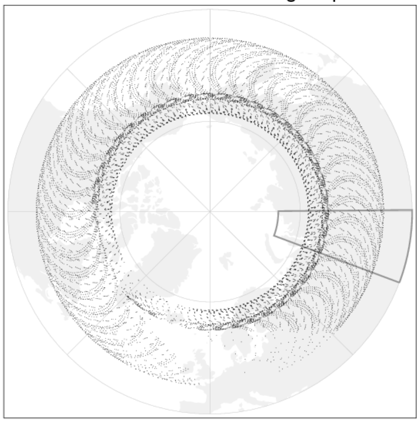

Figure 7. Geographical distribution of SCIAMACHY solar occultation events. The occultation measurements inside the marked area are used for the following plots.

from Europe to Greenland without tangent points, state 47 is executed. Because of the Envisat repeat cycle of 35 days, the tangent points are replicated after a cycle and do not fill up the occultation latitude band.

In Figure 7 a region over Siberia from 69° E to 90° E is marked. Exactly one occultation measurement is performed per day in this region. Figure 8 shows time series of the ozone and NO_2 profiles for that region.

The overall variation in the time series of the NO_2 profiles mainly represents the different latitudes at which the occultation measurements are performed over the year. From September to March, solar occultation is performed in higher latitudes and lower NO_2 concentrations are observed. From April to September, solar occultation measurements are moved to mid latitudes with increased NO_2 values.

The overall variation in the ozone time series of course also reflects the change in latitude over the year. From May to November, ozone concentrations as expected for mid–latitudes in summer and autumn are observed. From December to April, the measurements at higher latitudes are influenced by the development of the arctic ozone hole. In 2003 and 2005, higher ozone loss in the arctic ozone hole season than in the years 2004 and 2006 took place. This can be clearly seen in the ozone time series.

For winter 2003, Figure 9 gives a detailed insight of the observed profiles. An ozone time series covering February to April 2004 is given. Two dates are marked: March, 11 and April, 1. For that days GOME WFM-DOAS (Coldewey-Egbers et al., 2005) total ozone maps for the northern hemisphere are shown, including marks of the location of the given solar occultation measurement.

The total ozone map over March, 11 is representative for the whole March 2003, a monthly mean looks very similar to the map given here. The arctic ozone hole is moved toward Siberia and Europe. This is visible in the profile time series with low ozone values until end of March. Around April, 1 an episode with higher ozone values is observed in the profiles. The total ozone map shows, that the weakened ozone hole is then centred over the pole. Total ozone maps and the observed profiles coincide quite well.

6. CONCLUSIONS

By using the sun as well–known target in space, the pointing problems of the SCIAMACHY and the ENVISAT platform can be circumvented, which otherwise is a prominent source of error for SCIAMACHY occultation and limb retrievals.

SCIAMACHY solar occultation gives ozone profiles of excellent and NO_2 profiles of reasonable quality in the Northern hemisphere as shown by comparison with co-located measurements of HALOE and SAGE II.

For the first time, an almost complete dataset from SCIAMACHY solar occultation has been evaluated. First geophysical application have been presented here.

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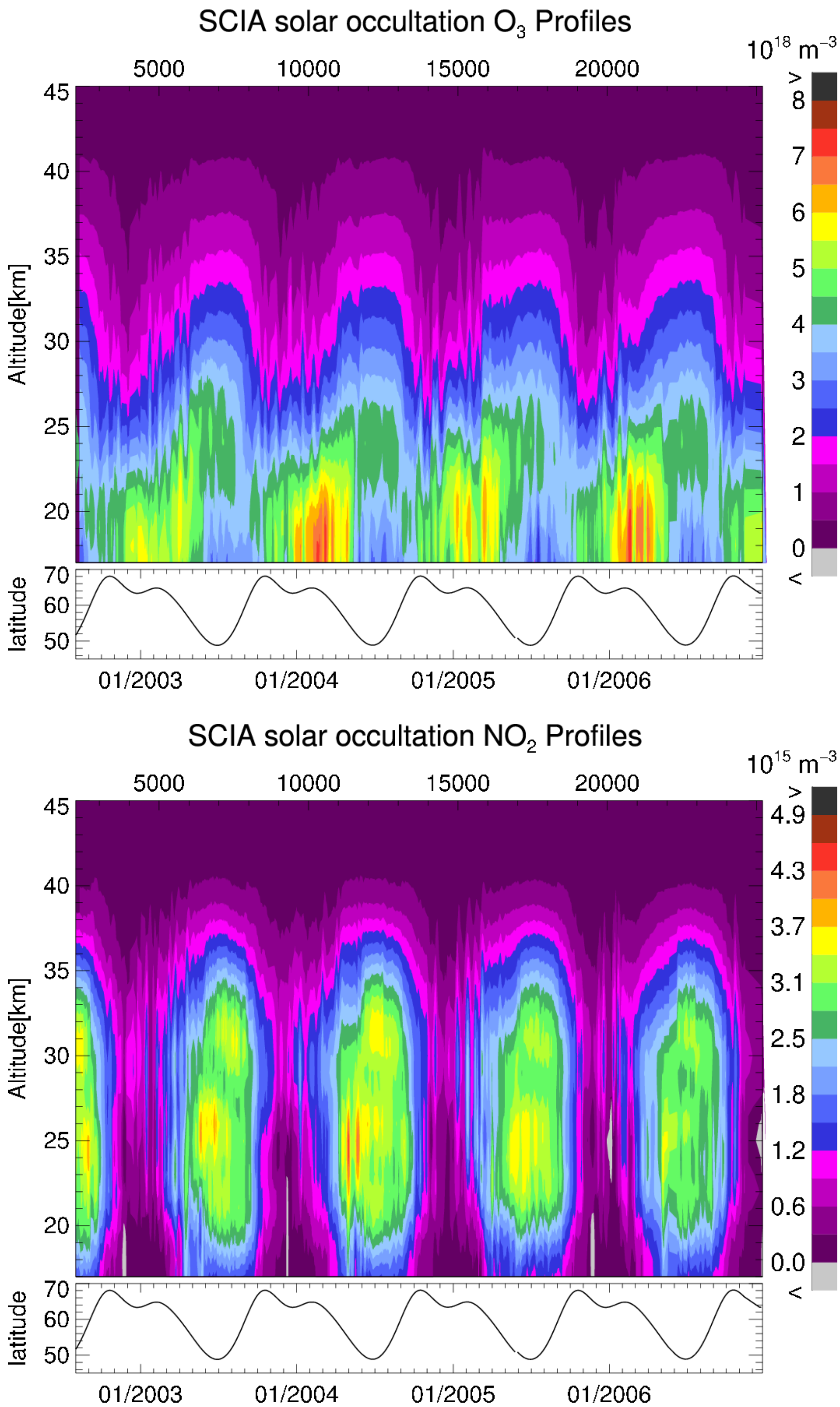

Figure 8. Time series of NO_2 (top) and ozone (bottom) profiles derived from the solar occultation measurements over Siberia between 69° E and 90° E with one measurement per day. The small chart below the time series indicate the latitudes of the tangent points of the measurements.

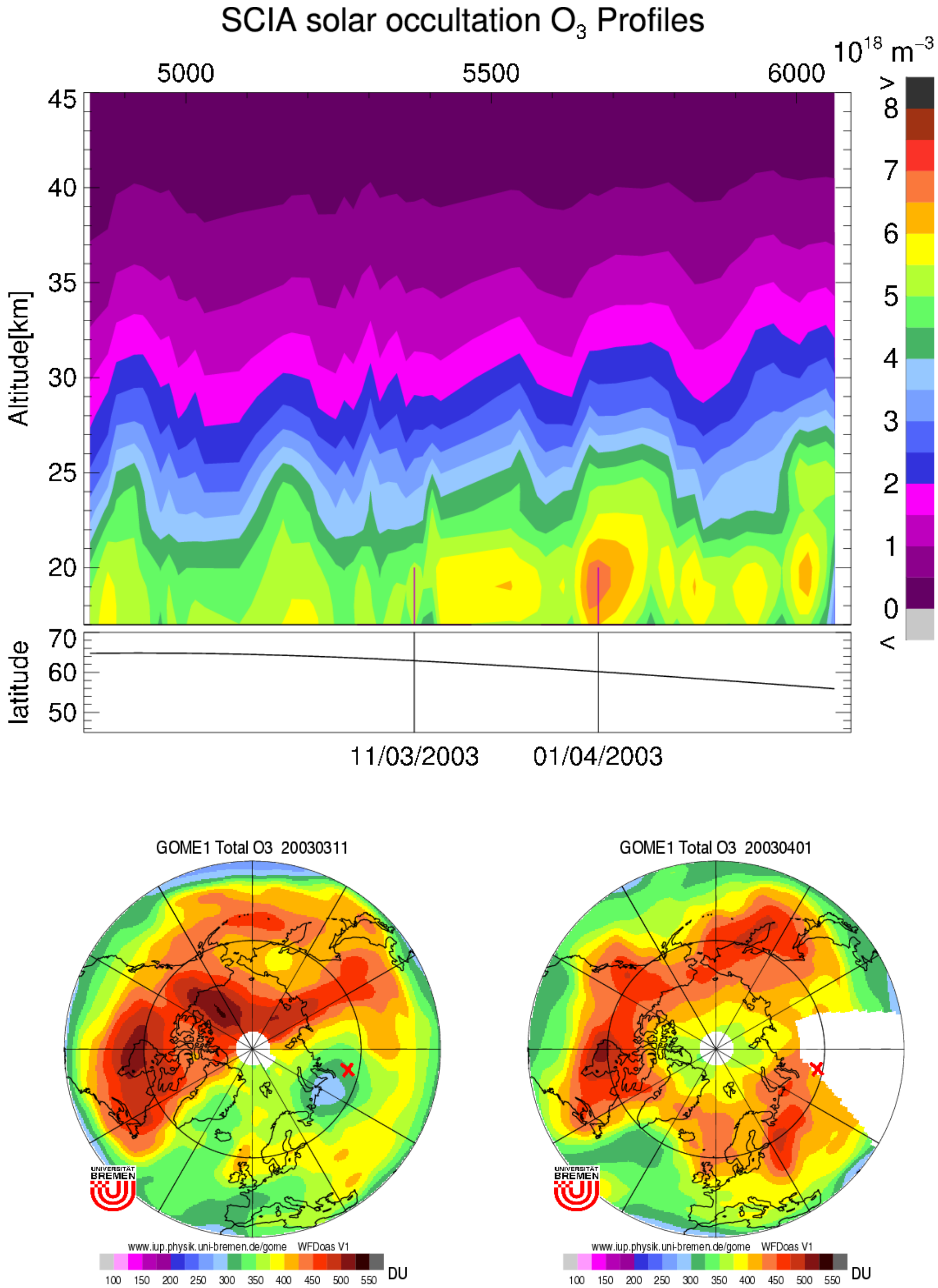

Figure 9. Top: Time series of ozone profiles derived from the solar occultation measurements over Siberia between 69° E and 90° E with one measurement per day from February to April 2003. Bottom: GOME WFM-DOAS total column for March, 11 2003 and April, 1 2003. The red crosses mark the location of the occultation measurement of that day.

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