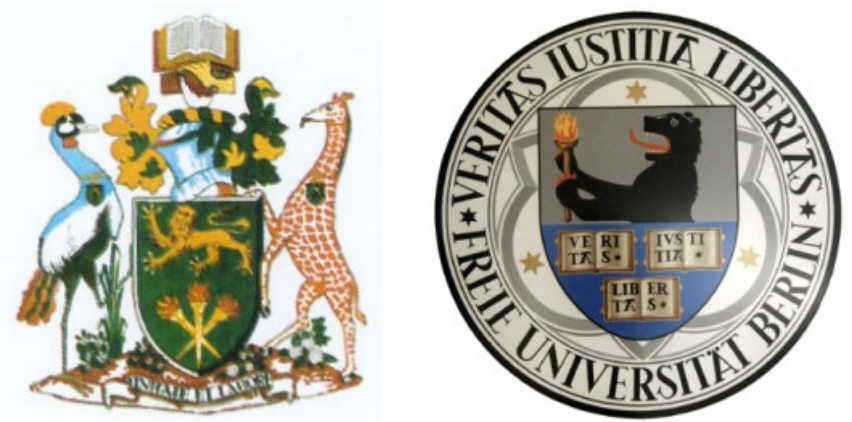


VALIDATION OF SATELLITE OZONE MEASUREMENTS OVER NAIROBI USING MAX-DOAS 2003-2004



A fourth year project at the
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Introduction

Spectroscopic measurements of atmospheric ozone have been made since the 1930s (e.g. Dobson Spectrometers). In the 70s the DOAS method was developed. A current development is the implementation of MAX-DOAS (Multi-Axis DOAS) in which measurements at different zenith angles with varying lightpaths in the troposphere are used to extract limited information on the vertical distribution of ozone [4].

Since August 2002 the University of Bremen has been operating a MAX-DOAS system at the UNEP campus in Gigiri, Nairobi (1°S, 36°E). It has been measuring continuously in the UV region. A second spectrometer for visible light was added during January 2004. The DOAS instrument can be used to measure the columns of atmospheric trace gases, such as O₃, NO_x, BrO or OCIO. It is part of a Bremen based network with stations in different latitudes offering possibilities for the validation of satellite based measurements of trace gases. Such measurements are for example carried out with the EP/TOMS, GOME or SCIAMACHY instruments. The Nairobi DOAS station, in continuously monitoring the atmosphere, also fills a gap of measurements in a tropical, especially urban, location. Though its main focus are total columns of trace gases, with the off-axis measurements being directed towards the city center of Nairobi, the measurements also yield some information about the smog situation in Nairobi.

In this work satellite ozone data from the TOMS, GOME and SCIAMACHY instruments was compared to total column ozone retrieved with the ground-based DOAS station in Nairobi using a fit in the UV region for the years 2003 and 2004.



The telescope of the DOAS instrument at UNEP in Nairobi. [IUP Bremen]

The DOAS Algorithm

The basic equation underlying all absorption spectroscopical measurements is the *Lambert-Beer-Law*, stating that in a homogenous absorbing medium the intensity I of light is decreasing exponentially with the distance s travelled within the medium:

$$I(\lambda) = I_0(\lambda)e^{-s\rho\sigma(\lambda)}$$

This formula is integrated along the light path and the sum over all absorbers with a distinguished differential cross section in the wavelength interval considered is taken. The slowly varying part of the cross sections, as well as scattering processes are approximated with a polynomial. Replacing the path integral over the particle densities with the slant columns SC_j gives the DOAS equation:

$$\ln I(\lambda) = \ln I_0(\lambda) - \sum_j \sigma_j'(\lambda) SC_j - \sum_p a_p \lambda^p$$

The slant columns given by the DOAS equation indicate the concentrations of absorbers along the actual light path. To get the total column ozone, i.e. absorber amounts in a virtual vertical column above the instrument it is necessary to convert the slant columns using a so called air mass factor: $AMF = SC / VC$. The AMF can be calculated (numerically) with a radiative transfer model simulating the light path of the observed photons for different viewing modes.

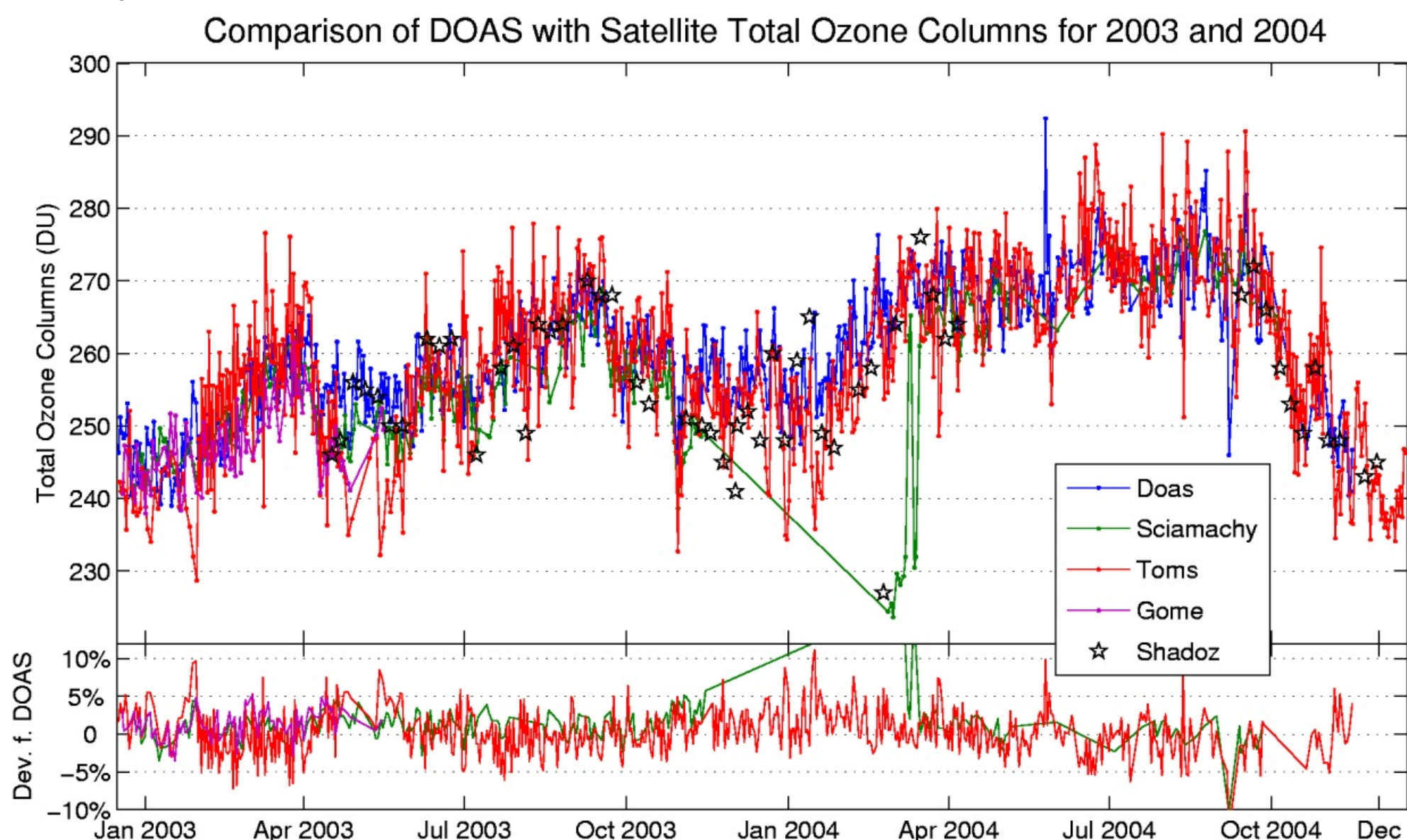
Satellite Validation

From the mean and RMS values of the difference between the DOAS, TOMS, GOME and SCIAMACHY instruments and the sonde data it was concluded that they show a very good agreement in trend. The mean differences are never above 4 DU, which is a deviation of less than 1.5%, and the RMS values don't go above 9 DU or 3.5%. The lower mean differences show that the trend agrees well, while there are slightly higher short term deviations. Part of this difference could be a result of the measurements not being carried out simultaneously. On the other hand, there are so many meteorological factors influencing the results and the algorithms to calculate them are so complex that the observed deviations cannot be clearly assigned to any of these. The observed RMS values agree well with margins set by other validation efforts for TOMS and GOME.

TOMS shows a slightly higher short term fluctuation than the other instruments: 20 instead of 10 DU. The interval in which the data is scattered is slightly bigger as well, being between 230 and 290 DU, instead of between 240 and 280 DU. Still TOMS is the most reliable of the instruments in terms of the temporal coverage, with daily measurements and few failures during the operational period. The least reliability in this sense is that of the SHADOZ ozonesondes, but anyway they are not the best method to retrieve total column ozone and their extrapolated data was only included for comparison.

Correlation between the different data sets is very good during most of the time considered: The deviation is centered roughly around zero and hardly goes beyond 5%. During late April and early June 2003 most instruments disagree with DOAS - this is the most distinct feature. TOMS also disagrees with DOAS around the turning of the years. SCIAMACHY shows a few periods of slight disagreement with DOAS during 2003, especially during the third quarter of the year.

The long-term picture shows regressions around the turns of the years, more distinctly for the beginning of 2003 and the end of 2004 than at the turn of these years. This, in agreement with the longer TOMS record, shows a clear annual and biennial variation. The latter implies that exactly one cycle of the Quasi-Biennial Oscillations is covered in this report. Further studies linking these variations with the influence of the QBO of global wind fields have been done by others [2].



Conclusions for SCIAMACHY

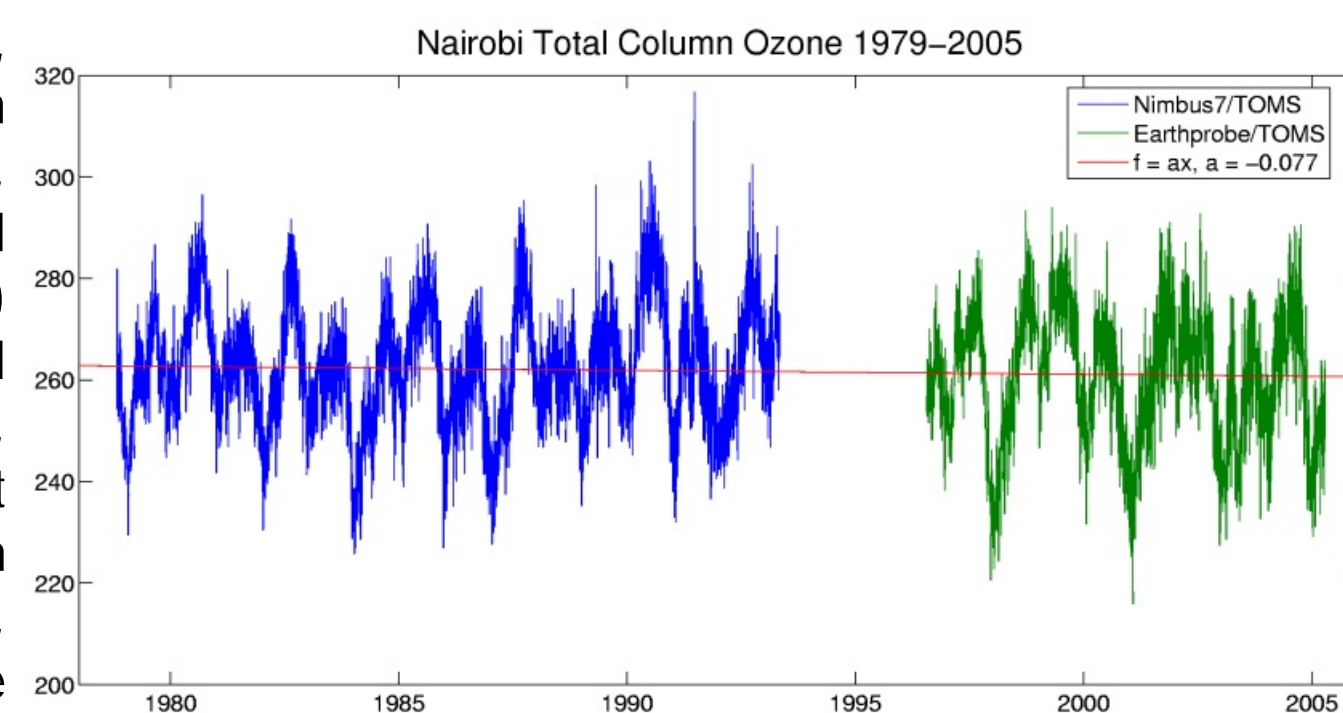
Focusing on the validation of SCIAMACHY the evidence from the comparisons shows that for the Nairobi location the Bremian algorithm yields good results for the total ozone data received from this instrument's measurements. ENVISAT does not pass over every equatorial location on a daily basis and so the data record is less frequent. A failure during December 2003 through March 2004 suggests less reliability for continuous measurements than for example given by TOMS, an instrument with a much simpler setup. There are some slight anti-correlations to the other instruments, but generally SCIAMACHY shows very good agreement to DOAS and TOMS and represents the trends very well - the mean and RMS values of the deviation from DOAS actually being a little better than for the other records. SCIAMACHY also shows less short term fluctuation than TOMS. In conclusion this instrument will definitely make valuable contributions to atmospheric science, especially as total columns of ozone are only one of its many features.

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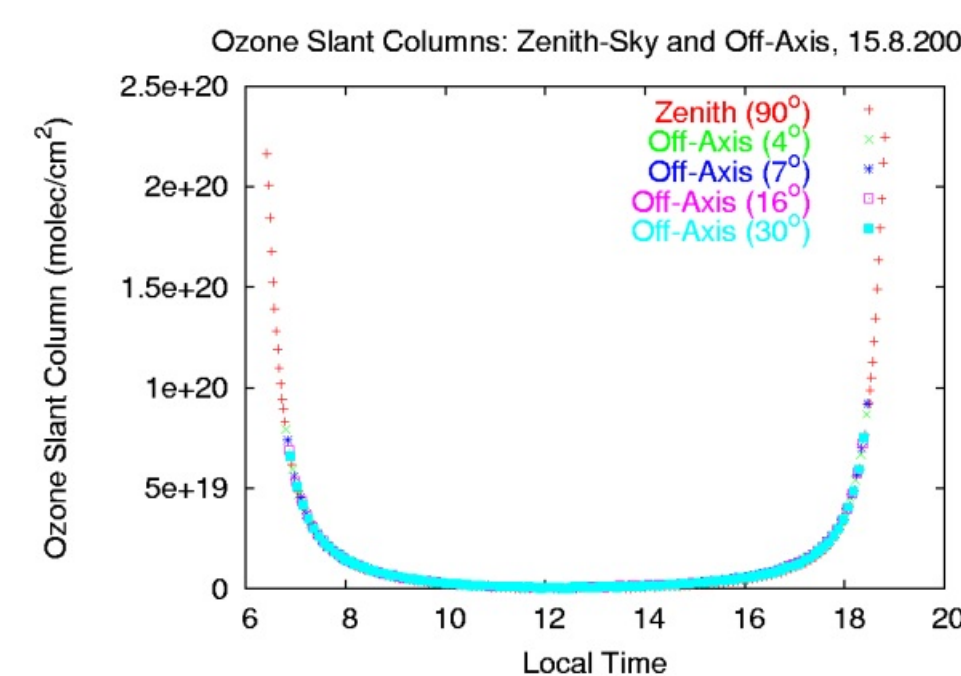
Long-Term Trend

The long-term trend of TOMS, the instrument that has given the longest record available, was shown; annual and biennial (two-year) oscillations between 40 and 60 DU are clearly visible, while the average lies at 260 DU. A good long-term stability was detected, implying no depletion of the total ozone columns.

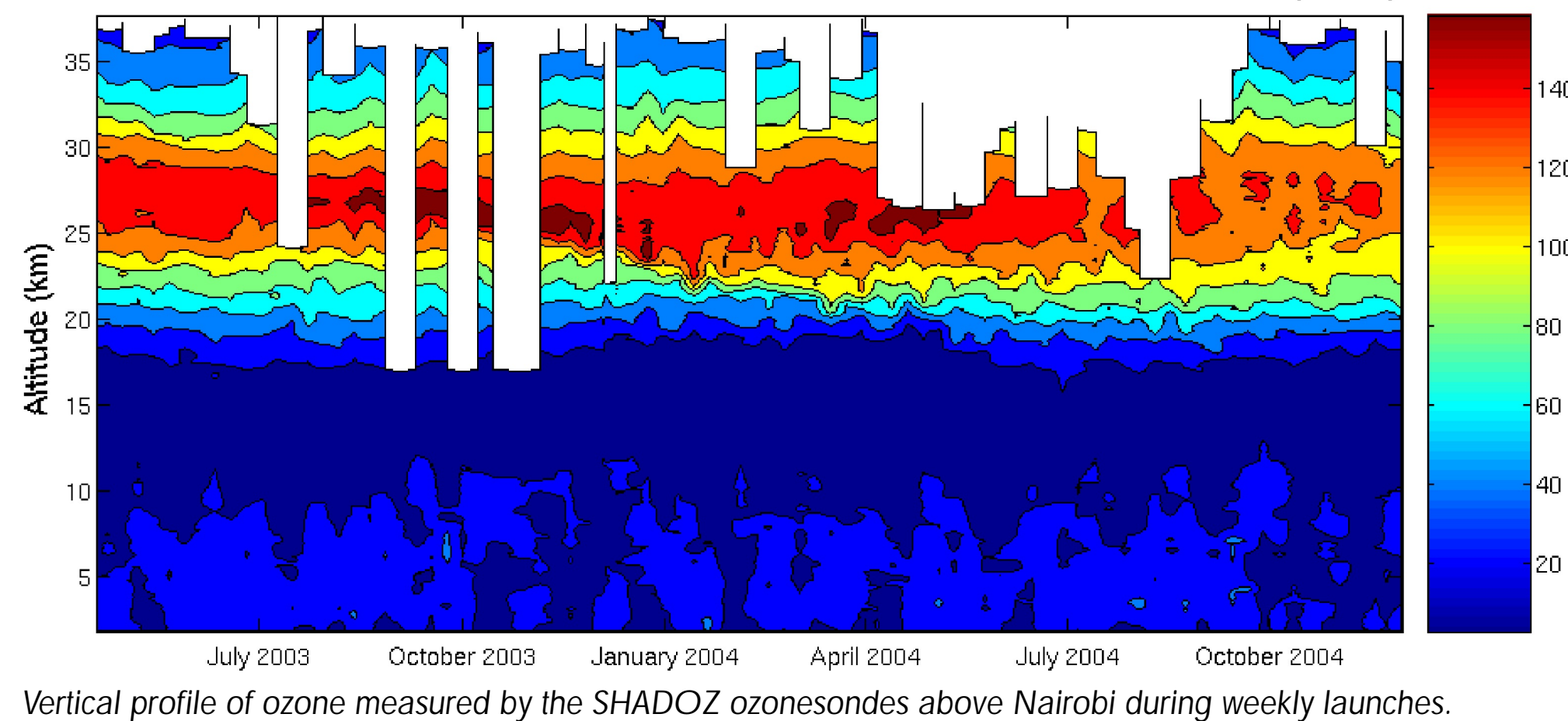


Vertical Distribution

An analysis of the vertical distribution of ozone using sonde data and the DOAS off-axis measurements shows that stratospheric ozone outweighs tropospheric amounts so far that a separation of these atmospheric layers seems very hard for the remote sensing instruments considered. For the DOAS instrument in Nairobi the ozone slant columns of different viewing directions (see graph to the right) are so close to each other that no separation of the tropospheric information (for example about the Nairobi smog situation) is possible. This is different for other absorbers with a not so strong stratospheric dominance, like NO₂ [1]. Efforts are being undertaken to achieve a troposphere/stratosphere separation for the different satellite instruments.

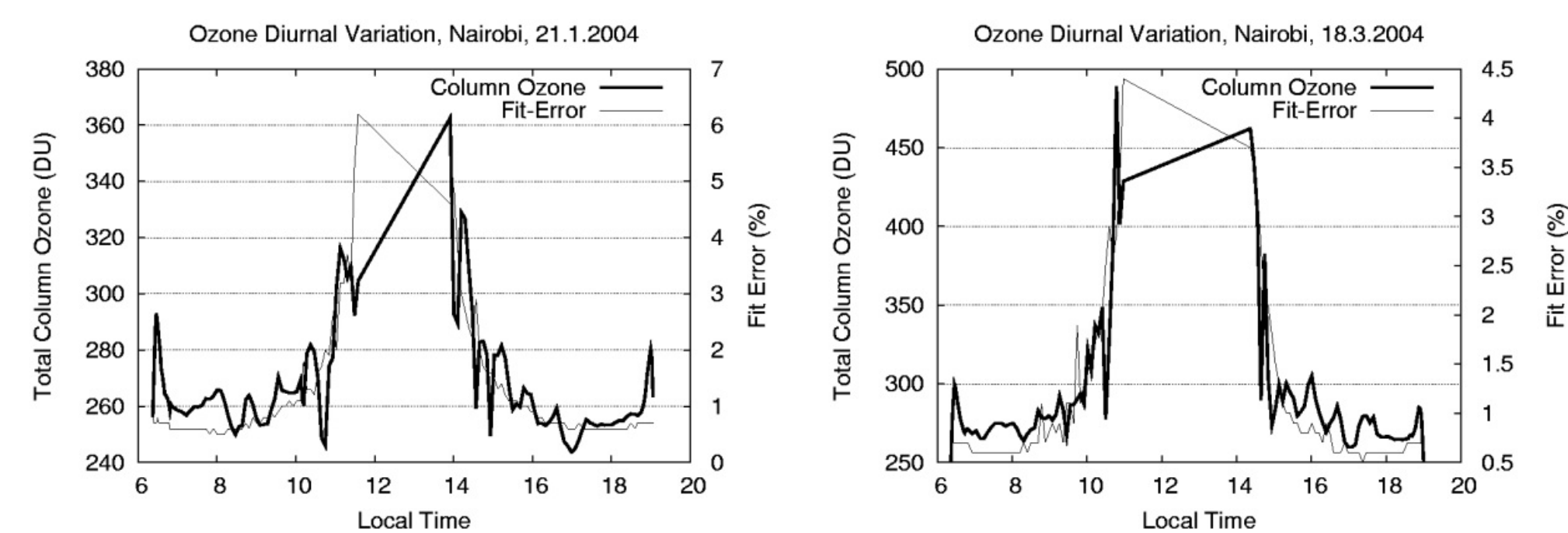


Ozone Vertical Profile Above Nairobi 2003/2004; Partial Pressure (nbar)



Diurnal Variation

An examination of the diurnal variation observed by DOAS suggests a relative stability of the total ozone columns. Most of the existing stronger fluctuations can be attributed to instrumental effects: A longer period around noon does not yield reliable information due to the impossibility of zenith-sky measurements at very small SZA and the use of a noon background spectrum, which makes calculations for SZA close to the one of the background spectrum highly unreliable. For sunrise and sunset a rise in ozone is observed that could be a result of the "Umkehr Effect" not being completely considered in the OD-Spectrum for great SZA. Smaller fluctuations might be a result of weather changes, e.g. cloud cover.



Diurnal variation of ozone vertical columns as measured by the Nairobi DOAS station for two sample days of 2004. The large deviation around noon is a consequence of the use of a noon spectrum for the background during the fit.

Outlook

As this study has shown very good agreement between the different ozone data sets for Nairobi, further work could examine the trend agreement of SCIAMACHY and DOAS for other absorbers.

While information on tropospheric ozone cannot be obtained from DOAS in Nairobi, this looks more promising for other trace gases. A retrieval for tropospheric columns from the measurements in the off-axis directions has been recently written at the IUP Bremen and gives good results for NO₂. The regional wind fields, however, make it unlikely to retrieve a signal from the African biomass burning regions [Sixten Fietkau, private communication]. Further work to examine traffic pollution, but maybe even waste burning and other city emissions, would now be desirable.

For the continuous verification of satellite measurements and to obtain records of long-term observations it is very desirable to keep up the Nairobi DOAS station. Dobson spectrometers have yielded a very valuable record of total column ozone in many places around the world, but the clear advantage of DOAS lies in the different absorbers it can observe. As tropical data is still scarce and most stations are operated in mid and high latitudes a special focus should be laid on maintaining the observations in Nairobi. The launch of SHADOZ ozonesondes nearby provides another valuable addition. Therefore every effort should be made not only to operate the instrument, but also to continuously evaluate the retrieved data.

Acknowledgements

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DOAS Geometry

For classic zenith sky measurements the light-path is mostly within the stratosphere (see graph below, left part), also for changing SZA angles. Therefore, the slant columns for stratospheric absorbers are much greater during early and late hours than at noon (see graph of slant columns in the section on vertical distribution).

Off-axis directions close to the horizon have a much higher sensitivity to tropospheric absorbers than the zenith sky measurements, because in this viewing mode the lightpath through the troposphere is considerably longer than for zenith sky observations (see graph below, right part). Recently this fact has been used to separate tropospheric from stratospheric columns in ground-based measurements. For the geometry in zenith viewing only the solar zenith angle (SZA) is of importance, in contrast to off-axis modes, where also the relative azimuth, which is the azimuth angle between the direction of the sun and that of the telescope, has to be considered for the calculations of the light-path. The elevation angle of the telescope is given as angle above a tangential plane to the earth's surface, i.e. for the zenith it is 90°.

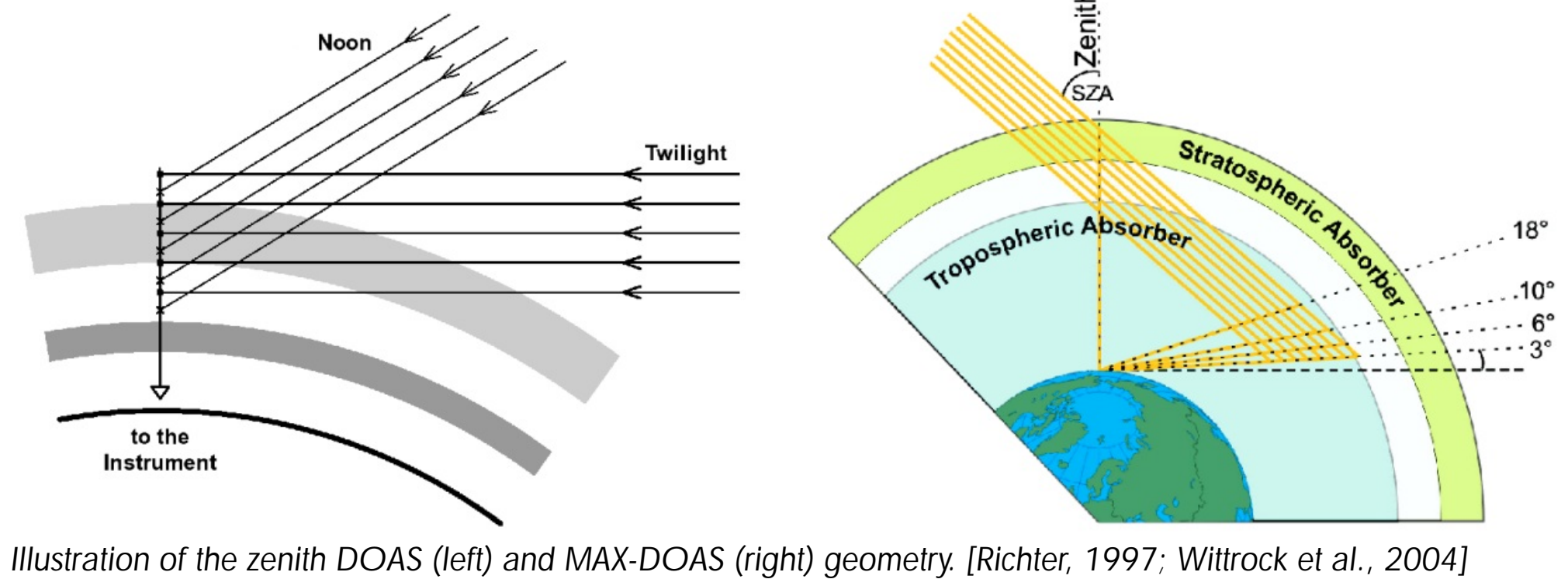


Illustration of the zenith DOAS (left) and MAX-DOAS (right) geometry. [Richter, 1997; Witlock et al., 2004]

For the full project report please refer to www.laehnemann.de/does
Further information on DOAS www.doas-bremen.de