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Validation of SCIAMACHY tropospheric NO_2-columns with AMAXDOAS measurements

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Abstract

Vertical and slant tropospheric NO_2-columns from the new satellite instrument SCIAMACHY on ENVISAT are validated by measurements of the Airborne Multi AXis DOAS (AMAXDOAS) instrument on board the DLR Falcon. The results presented here were obtained in February 2003 on a flight over the Alps, the Po-Valley and the Mediterranean. The tropospheric vertical column measured by AMAXDOAS varied between 12.8 and $27.2{*}10^{15}$ molec/cm^{2}over the Po-Valley where SCIAMACHY data resulted in 14.4 to $27.5{*}10^{15}$ molec/cm^2. Over less polluted areas a similarly good agreement was found. The overall correlation between the two datasets results in a slope of the linear fit of 0.89. The slight differences observed might be attributed to the different spatial resolution and the temporal mismatch between the measurements over the Po-Valley.

1. Introduction

The ENVISAT satellite was launched on 1 March 2002; apart from other instruments it contains the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY).

The SCIAMACHY instrument analyses the sunlight reflected from the earth or scattered in the atmosphere. This can be used to retrieve column densities of many tropospheric trace gases such as O_3, BrO, SO_2, NO_2, CO, CO_2, CH_4, H_2O and N_2O (Bovensmann et al., 1999; Frankenberg et al., 2004) The results of several scientific products can be found at the web-pages of the according institute e.g.: http://satellite.iup.uni-heidelberg.de, http://www.doas-bremen.de. These observations help to improve the knowledge of the physics and the chemistry of the earth's atmosphere. With the global coverage of the satellite instruments it is in particular possible to study transport phenomena as well as regional variations in urban centres and in remote areas.

In the troposphere NO_2 is produced by both anthropogenic and natural sources such as bio mass burning or lightning. One major source is fossil fuel consumption. Many sources do not emit NO_2 but NO, which is rapidly oxidized to NO_2. Because of the fast interchange between the two species the sum of NO plus NO_2 is usually referred to as NO_x. In Europe the Po-Valley provides ideal opportunities for the NO_2 validation study because of its high tropospheric concentrations and the clean air in the high Alps nearby (Beirle et al., 2004).

The Airborne Multi Axis DOAS instrument was especially designed for the comparison with SCIAMACHY on ENVISAT. Like SCIAMACHY it was laid out to separate the stratospheric and the tropospheric column of several trace gases like BrO, NO_2 and O_3 (Wagner et al., 2001). As the conversion of the measured slant columns into vertical columns is known to be a major uncertainty (Boersma et al., 2004), the idea was to build an instrument which yields similar intermediate products – slant column densities. They can be compared without the additional uncertainties of the conversion to vertical columns. As the solar zenith angle of both observations is not exactly the same a better agreement between the vertical columns is to be expected, although the influence of the SZA on the tropospheric AMF is small.

In the past a variety of DOAS-airborne-measurements were performed by different groups (Pfeilsticker and Platt, 1994; McElroy et al., 1999; Pertitoli et al., 2002; Melamed et al., 2003) in different altitudes and regions. In contrast to these observations, we concentrate on tropospheric NO_2 for satellite validation.

2. Description of the instruments and data analysis

Here the measurements of two different instruments SCIAMACHY and AMAXDOAS are compared to each other. Therefore a brief description of both instruments and the analysis is given. For SCIAMACHY the most relevant features of the instrument and the analysis of the tropospheric columns are given here. More details on the SCIAMACHY instrument and its mission are described by Bovensmann et al. (1999).

The AMAXDOAS instrument observes scattered or reflected sunlight in different lines

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of sight above and below the aeroplane. For an aeroplane flying below the stratosphere all viewing directions will be influenced by the stratospheric absorptions, and therefore these absorptions will be detected in every viewing direction (Bruns et al., 2004). But only light, received by the downward looking telescopes which is scattered in lower altitude or reflected at the ground, shows the absorption structures of the tropospheric gases. This concept of different lines of sight enables us to derive partial VCDs for both the stratosphere and the troposphere (Wagner et al., 2001; Wang et al., 2003; Heue et al 2003). In addition limited profile information can be derived (Bruns et al., 2004).

The tropospheric and stratospheric columns can be separated in a related way from SCIAMACHY observations. In Nadir mode SCIAMACHY observes the total column. In limb mode, the stratospheric profile and thus the stratospheric column is measured. (Bovensmann et al., 1999).

2.1. The AMAXDOAS-instrument

2.1.1. Instrumental setup

In Fig. 1 a sketch of the instrumental setup is shown. There are different lines of sight above and below the aeroplane. According to Bruns et al. (2004) the best vertical resolution in the Upper Troposphere and Lower Stratosphere region is achieved by using small elevation angles, therefore in addition to Nadir and Zenith two telescopes with +2° and −2° viewing direction relative to the horizon were installed.

Small telescopes with a diameter of 10 mm and 0.2° half aperture are used to observe the scattered sunlight. These telescopes are mounted inside housings outside the aeroplane. The light is led to spectrographs via quartz fibres. Two different spectrographs are used for the ultra violet and visible light. The UV spectrograph has a spectral resolution of 0.5 nm FWHM whereas the resolution of the visible is 1 nm. Together the instruments cover the wavelength interval from 300 nm to 550 nm. Two-dimensional CCD-cameras are used as detectors, so all the lines of sight are observed simultaneously. The lines of sight and the corresponding area on the CCD-chip of the "visible" spectrometer are shown in Figs. 2a and b.

The total integration time was 30 s for both spectrographs, as the ground speed of the Falcon is about 760 km/h the horizontal resolution of the measurements is about 6.5 km≈0.075°. Perpendicular to the flight direction the horizontal resolution in given by the flight altitude (11 600 m) and the aperture and can be estimated to be around 80 m.

2.1.2. Data analysis of AMAXDOAS data

The measured spectra were analysed using the DOAS technique (Platt and Stutz, 2004). Several cross-sections of the trace gases which show structured absorptions in the respective wavelength regions are fitted to the logarithm of the measured spectrum I(λ) divided by a solar reference spectrum I$_0$(λ) using a non linear least squares algorithm.

$$\ln\left({}^{I(\lambda)}/_{I_0(\lambda)}\right) = -\sum_i \sigma_i(\lambda)\int c_i(l)dl + P(\lambda) \qquad (1)$$

$\sigma(\lambda)$ is the cross section of the specific trace gas (i) and $c(l)$ the corresponding concentration along the light path. A polynomial P is added to account for slowly varying extinction caused by Rayleigh- and Mie-scattering. The integral $\int c(l)dl$ is called Slant Column Density (SCD).

In contrast to satellite observations where the solar reference spectrum (direct sun light) contains no atmospheric absorption structures, the AMAXDOAS analysis does not yield absolute atmospheric column density (SCD) but the difference in the column densities between the measurement, and the solar reference spectrum. The reference spectrum was chosen according to the following conditions:

- Use of the same telescope to minimise instrumental differences,
- Small solar zenith angle SZA – this will keep the influence of stratospheric absorptions as low as possible.

- No clouds – the light path inside a cloud is not known. Although normally a cloud leads to lower absorptions, there are also cases where higher absorptions are observed above clouds. More details about the influence of clouds are described by Wang et al. (2004).

- High intensity – the noise of the data is ruled by the statistical photon noise, and thus the signal to noise ratio increases with increasing intensity.

- Clean air – as described later on it is necessary to separate the stratospheric from the tropospheric signal, and this is easier if the SCD in the reference is small.

The WinDOAS-software (Fayt and Roozendael, 2001) was used to analyse the AMAX-DOAS data. The data presented here were all observed with the vis-spectrometer. For the NO_2 analysis, the wavelength region 420–444 nm was used; 460–500 nm for the O_4. The cross sections for NO_2 (Burrows et al., 1998), O_3 (Burrows et al., 1999), O_4 (Hermans et al., 1999) and H_2O from HITRAN (Rothman, 1998) were used. The Ring effect was considered by using a Ring spectrum calculated with WinDOAS.

In Fig. 3 we show a typical DOAS-fit of the flight from Basel to Tozeur (Tunisia). The spectrum was taken at 08:14:30 UT close to Zürich, the reference was taken at 08:30:14 UT, when flying over the clean air of the Alps.

To derive the tropospheric vertical column the stratospheric signal has to be subtracted from the total column. The stratospheric NO_2 is known to vary slowly in time and space, at least for the flight distance of 3000 km in mid-latitudes this can be assumed.

In the nadir view the tropospheric absorption is added to this slowly varying signal. In the troposphere most of the emissions originate, so the temporal and spatial variations are much larger. This means the general trend has to be separated from the variations. A linear function was used to describe the slowly varying stratospheric slant columns and subtracted from the total nadir signal. The minimum of the tropospheric signal was assumed to be 0 molec/cm^2 over the clean regions; here the Alps and the Mediterranean north of Sardine were used. The result is called tropospheric slant column, and by dividing through the corresponding Air Mass Factor (AMF) the tropospheric vertical column is determined.

2.2. The SCIAMACHY instrument

2.3. Description of the instrument and its mission

The ENVISAT satellite orbits the earth in about 800 km altitude in a sun-synchronous polar orbit, crossing the equator at 10:00 local time. The SCIAMACHY instrument is a 8 channel spectrometer designed for measuring the sunlight in the UV, visible and near infrared region (240–2380 nm). Depending on the channel the resolution varies between 0.22 and 1.48 nm. The NO_2-columns are retrieved in the wavelength region of 425 to 450 nm (channel 3) where the resolution of the instrument is 0.44 nm.

Measurements are performed alternatingly in nadir and limb direction, changing within 2 min and observing nearly the same air mass in both modes. With this method the total column and the stratospheric column are measured independently. At the beginning and the end of each orbit, solar and lunar occultation measurements are also performed.

The horizontal resolution of the instrument in the nadir is $30\times60\,km^2$ in the region of interest. Global coverage is achieved after 6 days (Bovensmann et al., 1999).

2.3.1. Data Analysis for SCIAMACHY

Details on the spectral NO_2 analysis of SCIAMACHY data can be found in Richter et al. (2004). Both DOAS-Analysis programs used here, WINDOAS and the one used in Bremen for satellite data retrieval are well established and agree well. For this study, the tropospheric vertical columns are derived in a manner similar to that used for GOME measurements. Slant columns measured over a clean air region (Pacific Ocean) at the same latitude and on the same day are subtracted from the slant columns retrieved over polluted regions to obtain the tropospheric slant columns. Division by a tropospheric AMF yields the tropospheric vertical columns (Richter and Burrows, 2002).

It should be pointed out that this approach is very similar to the one used for the AMAXDOAS measurements. In both cases the slant columns from a clean air region were subtracted; for AMAXDOAS a linear interpolation of the lowest columns measured was used whereas for SCIAMACHY a remote region was taken. The different methods of correcting the stratospheric absorptions might lead to a small offset between the data.

The SCIAMACHY data used for this comparison have been retrieved at the University of Bremen from raw radiances and they are referred to as “scientific products”. Operational SCIAMACHY products will soon be available from DLR and ESA, but currently verification of these products is still ongoing.

2.4. Slant and vertical columns

Both analyses methods described above resulted in tropospheric slant columns. They therefore depend on the light path through the atmosphere to the detector. The light path depends on many parameters like solar zenith angle, aerosol load, ground albedo, and the vertical distribution of the absorber. For a better comparison usually the vertical column is calculated:

$$VCD = \int_0^\infty c(z)dz, \tag{2}$$

where z equals the altitude above ground, and c again is the concentration of the trace gas. It is obvious that the vertical column density does not depend on the light path.

To convert the slant column in the vertical column the influence of all the above mentioned parameter is calculated and expressed as air mass factor (AMF)

$$AMF = {}^{SCD}/_{VCD}. \tag{3}$$

The air mass factors describe the sensitivity of the instrument for a trace gas under certain conditions in the atmosphere.

Here, the AMFs for the AMAXDOAS were calculated with a Monte Carlo based ray tracing program (Friedeburg, 2003; Hönninger et al., 2004). For SCIAMACHY, the same atmospheric settings were used to calculate the AMF with the SCIATRAN program (Rozanov et al., 2002). A comparison between both programs showed good agreement for the SCIAMACHY-AMFs. The difference between the AMFs was less than 8%, in the interesting interval of solar zenith angles and the settings used for the Po-Valley. For the SZA-range between 10° and 60° it was even better.

As the measurement principles of SCIAMACHY and AMAXDOAS are in general comparable, the effects of the AMF are as well. This is why it is very important that the AMFs are calculated with comparable settings. Of course some of the AMF-settings must be different, such as the detector's altitude, field of view, solar zenith angle. The important values for the AMF-calculations that should be the same are:

- The aerosol and their main characteristics such as single scattering albedo and profile,
- the NO_2-profile in the troposphere,
- the ground albedo.

For the calculation of these AMFs, an urban aerosol type was used with a constant visibility of 4.8 km in the boundary layer (1000 m), above this altitude the visibility increases linear to 80 km in 2000 m altitude. A typical background aerosol-load was used for the higher altitudes. The NO_2-concentration was assumed to be constant (2 ppb) within the mixing layer (1000 m) and to decrease linear with height between 1 km and 2 km, above 2 km the concentration was 0. For this calculation the albedo was set to 4% which is a value typical of winter fields (Feister and Grewe, 1995).

In Fig. 4 the AMFs for both instruments AMAXDOAS and SCIAMACHY are shown. The AMFs for the AMAXDOAS are generally higher than those for the SCIAMACHY instrument. For the satellite observations, more light scattered in higher altitudes contributes, and the measurement therefore is less influenced by tropospheric absorbers than in the case of airborne measurements.

As can be seen in Fig. 4, the AMFs are slightly enhanced by the aerosols, at least for the smaller solar zenith angles. Here the aerosols scatter most of the light and therefore enhance the light path in the boundary layer. As a result of the forward peaked phase function, more light is scattered in the boundary layer or to the surface when the solar zenith angles are small. For large SZAs it is also possible that more light is scattered above the NO_2 layer or absorbed by the aerosol; this would clearly reduce the AMF. In our simulations this effect can be observed. In this case the phase function leads to the opposite effect, now less light is scattered to the boundary layer, compared to a pure Rayleigh-atmosphere.

The atmospheric condition during the measurement varied quite often. Over the Alps there was snow, and clear visibility, whereas in the Po-valley it was quite hazy during the overpass of AMAXDOAS and the albedo was lower than over the mountains. As it is impossible to get detailed information on the visibility, the aerosol concentration and optical properties, the ground albedo and the NO_2 profile we used the AMF described above for the complete dataset. These settings should be realistic for the Po-Valley, where the highest column densities were observed.

3. Results and discussion

In this section we first present the AMAXDOAS results and discuss them briefly for the whole flight on 19/02/2003. The focus however is on the comparison with collocated measurements of SCIAMACHY in the Alps, northern Italy and the southern Mediterranean and northern Africa.

3.1. From Basel to Tozeur on 19/02/2003

Two major campaigns reaching with 28 flights from Greenland to the Seychelles were flown in September 2002 and February/March 2003. Details on the whole campaign will be published in Atmos. Chem. Phys. Discuss. in an extra article by Fix et al. in 2004 (Fix et al., 2004). Here we concentrate on the flight on 19 February for several reasons:

- The weather conditions were very good.
- We overflew both clean and heavily polluted areas.
- SCIAMACHY data are available for the same day and time.

In Fig. 5 the flight track is shown, in the background a satellite image (NERC, 2004) showing the clouds over Italy and the Mediterranean. After a short stop in Basel the Falcon flew south-east crossing the Alps and the Po-Valley, flying along the Italian coast over Sardinia to Tozeur in central Tunisia.

The Alps were still covered with snow. There was no cloud over the southern Alps, the Po-Valley and from the Apennine to the Italian coast. During the first part of the flight from Basel to the mountains there was fog below the aeroplane. Additional cloudy regions were observed east of Sardinia and north of Tunisia.

In the southern Alps the large Adige-Valley can be recognized. One of the few highways crossing the mountains runs through this valley.

This distribution of clouds and snow was also confirmed by simultaneous O_4 measurements and the observed intensity in the nadir viewing telescope. The retrieval of cloud information from O_4-SCDs is described by Wagner et al. (2002) and Wittrock et al. (2003).

The Po-Valley is known to be one of the most polluted areas in Europe (Beirle et al., 2004). The geographical conditions and the Italian industrial centres concentrated in this plain cause the pollution observed.

3.2. Discussion of the AMAXDOAS results

The AMAXDOAS was built to separate the tropospheric and the stratospheric columns. As expected, a strong enhancement in the total vertical column of the Nadir telescope was observed over the Po-valley (Fig. 6, 08:44 UT). If the zenith viewing telescope would only be affected by stratospheric absorption, a more or less constant NO_2 signal would be expected. However, over the heavily polluted regions, we measured a slightly increasing NO_2-signal in the zenith as well. Simulations with a ray tracing model can reproduce this effect caused by multiple scattering and tropospheric pollution. A small part of the light observed in the zenith telescope was scattered in lower altitudes or even reflected on the surface and is therefore influenced by tropospheric absorbers. So we still assume the stratospheric NO_2 to vary slowly in time and place.

The vertical column densities of both viewing directions showed a similar effect just north of the Alps at about 08:11 UT. At this time the aeroplane was passing the region of Zürich. As this area was not covered by SCIAMACHY pixels on this day (Fig. 7), we do not discuss this enhancement in detail here. However, the observed NO_2 enhancement is in good agreement with a smog event reported for Zürich on these days (NZZ, 2003).

From now on only the tropospheric NO_2 shall be discussed in a more detailed comparison. This can be done as the temporal and regional variations in the stratospheric NO_2 can still be assumed to be small as explained above.

3.3. Comparison between AMAXDOAS and SCIAMACHY

For a first comparison the reader may have a closer look at Fig. 7, here the tropospheric vertical columns of NO_2 are shown; for both datasets the same colour scale is used. They show the same horizontal distribution, concerning the sparsely populated Alps, the heavily polluted Po-valley, the Apennine and the Italian coast. Also South of Sardine and in northern Africa, a good agreement can be observed.

As the AMFs might have a large influence on the results, the comparison of both slant and vertical column is shown here, so the influence of the AMFs is excluded.

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This can be done as the measurement principle and viewing geometry of both participating instruments is nearly the same. Compared to validation efforts using in situ measurements (Heland et al., 2002), this is a big advantage of the AMAXDOAS instrument. On the other hand, the light path is still unknown for both SCIAMACHY and AMAXDOAS and therefore the retrieved vertical columns might have similar errors.

SCIAMACHY's overpass over the Falcon was about 09:50 UT near Sardinia, so it was passing the Po-valley a few minutes earlier whereas the Falcon had been there about one hour before. For a detailed comparison between these two datasets this slight temporal mismatch has to be kept in mind. Within this interval between the two measurements the NO_2 concentration might have changed and of course the solar zenith angle is different for both measurements. Between 08:30 and 09:06 UT when the Falcon overflew the Po-Valley the SZA changed from 68.6° to 66.3°. One hour later the SCIAMACHY measurements were made with a SZA of about 61°±1°. From Fig. 4 the AMFs for AMAXDOAS for 67.5° and 61° can be estimated, this change in the SZA results in 5% change in the AMF.

In Fig. 8 the tropospheric slant columns for both instruments are plotted as a function of latitude. The zigzag of the flight track (Figs. 5 and 7) was taken into account, and only the collocated measurements were compared. A grid with 0.075° was laid over the SCIAMACHY data and only grid boxes were used with at least one matching AMAXDOAS measurement point. As SCIAMACHY pixels are larger than 0.075°×0.075°, several SCIAMACHY data points have the same values. Both measurements show similar results for the Po-valley (45°30′ N–44°20′ N) and the region south of Sardinia (38° N–36° N). Over the southern Alps (∼46° N) and the southern Apennine (∼43°40′ N) a difference can be made out, which might be due to a different response of the instruments to some NO_2 in the valleys (e.g. Adige) between the snow capped mountains. According to the higher spatial resolution, the AMAXDOAS is able to detect the NO_2 in the valley, whereas SCIAMACHY's signal is mainly influenced by the clean air over the snow capped mountains. Especially in the region of the southern Alps a high variability in the AMAXDOAS data can be observed, which also indicates the influence of the mountains and the valleys.

Figure 9a shows the correlation of the SCIAMACHY slant columns with the ones measured by AMAXDOAS. As can be seen, the correlation between the two data sets is good, the derivation of the fitted line equals 0.95±0.04. There seems to be a slight overestimation of the SCIAMACHY data compared to the AMAXDOAS measurements. The reason of this overestimation is not yet fully understood, especially as one would always expect the satellite to be less sensitive for tropospheric absorbers than an airborne instrument flying in the tropopause (Fig. 4).

There is also a small offset ($1.09*10^{15}$) in the AMAXDOAS measurements compared to SCIAMACHY. This might be attributed to the different methods of correcting the stratospheric NO_2. In this case it seems that for the SCIAMACHY data the stratospheric NO_2 is overestimated. As we concentrate on the retrieval normally used, we don't discuss this in detail here. However using a similar background correction for SCIAMACHY as it is done for AMAXDOAS reduces the offset to $(4.17\pm3.89)*10^{14}$ molec/cm^2. Therefore the offset seems to originate from longitudinal variations in the stratospheric NO_2.

As SCIAMACHY overestimates the slant column and the AMFs for the satellite instrument are smaller than the ones for AMAXDOAS the vertical columns are even more overestimated as can be seen in Fig. 9b. This however demonstrates the importance of comparing both slant and vertical columns and the uncertainties of the AMF calculations. In the time period between the two measurements the NO_2 concentration might have changed as well as the height of the boundary layer, and therefore the vertical distribution of the NO_2 and the aerosols.

Unfortunately no ground based measurements from the Po-Valley on this day are available. This would help to exclude a change in the tropospheric NO_2-concentrations during the most interesting time interval from 08:40 to 09:40 UT (09:40 to 10:40 local time in Italy).

Overall a far reaching agreement between the two instruments was achieved.

4. Conclusions

Tropospheric NO_2 VCDs measured by the AMAXDOAS were presented here and compared to SCIAMACHY. Measurements from the same day and region were used for the comparison and no trajectory calculations were necessary here.

In general the comparison with SCIAMACHY has shown very good agreement for both slant and vertical tropospheric columns. The correlation gets slightly worse when the AMF and therefore the change of the solar zenith angle is taken into account.

The observed differences of the measurements e.g. edge of the Alps and the Apennine seems to be attributable to different spatial resolutions of AMAXDOAS and SCIAMACHY. The observed offset between the measurements is caused by the different correction for the stratospheric NO_2.

The results presented here will be of major interest for the future work with either of the two instruments.

The strength of the AMAXDOAS instrument is its sensitivity to atmospheric changes like that of clean and polluted air with a high spatial resolution and high sensitivity to tropospheric trace gases. The measurement conditions on 19702/2003 were excellent. No large cloud covered areas were observed and the small clouds observed were not in such areas of major interest but might interesting by themselves like over Zürich.

Although only results from nadir and zenith were presented here, additional information from the other lines of sight can be retrieved especially for the upper troposphere lower stratosphere that might be presented in another publication.

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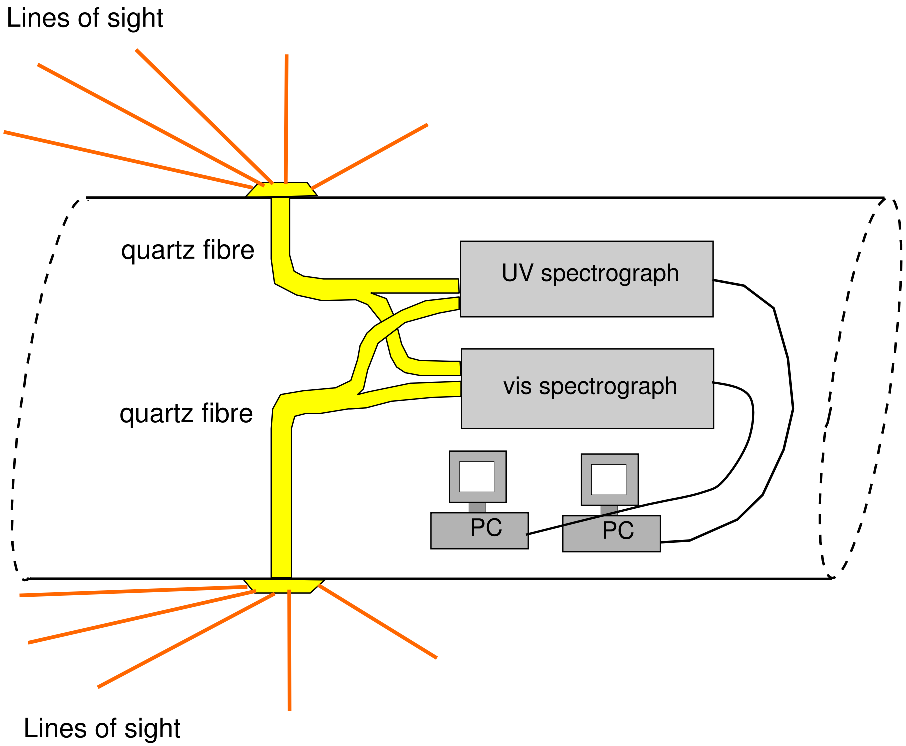

Fig. 1. Sketch of the instrumental setup. Here 2×5 lines of sight are shown. The scattered sunlight is observed using small telescopes and is lead to two spectrographs via quartz fibres. Here it is analysed and the spectra are saved on a PC.

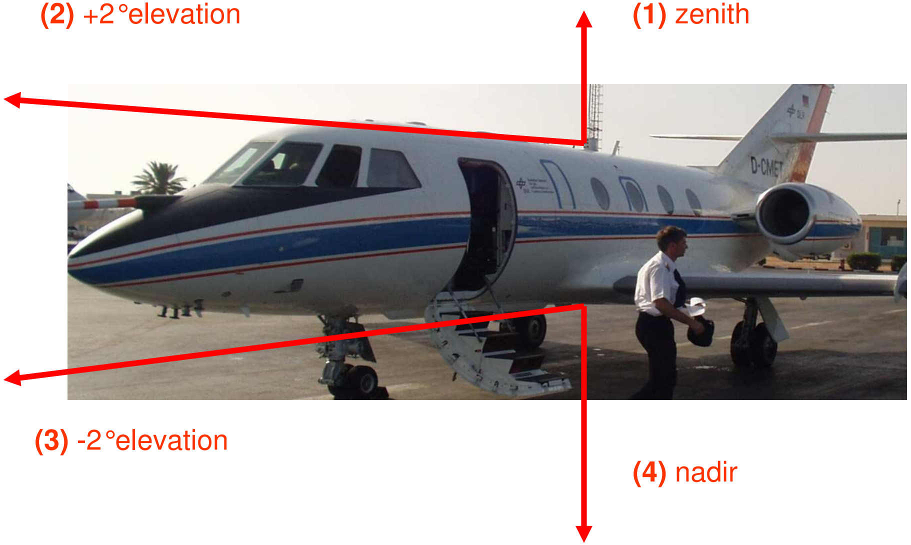

Fig. 2a. Pictures of the DLR-Falcon, including a sketch of the used lines of sights.

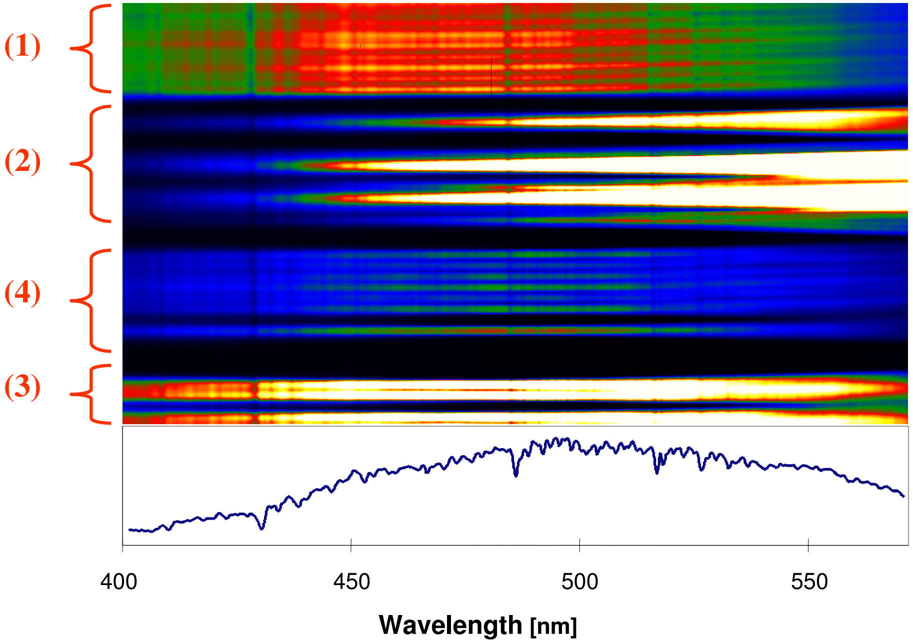

Fig. 2b. Typical image of vis CCD – the different viewing directions are separated from each other by dark lines. The numbers on the left side belong to the different LOS as marked in Fig. 2a. Usually the direction −2° was the brightest one and therefore it has only very little space on the chip.

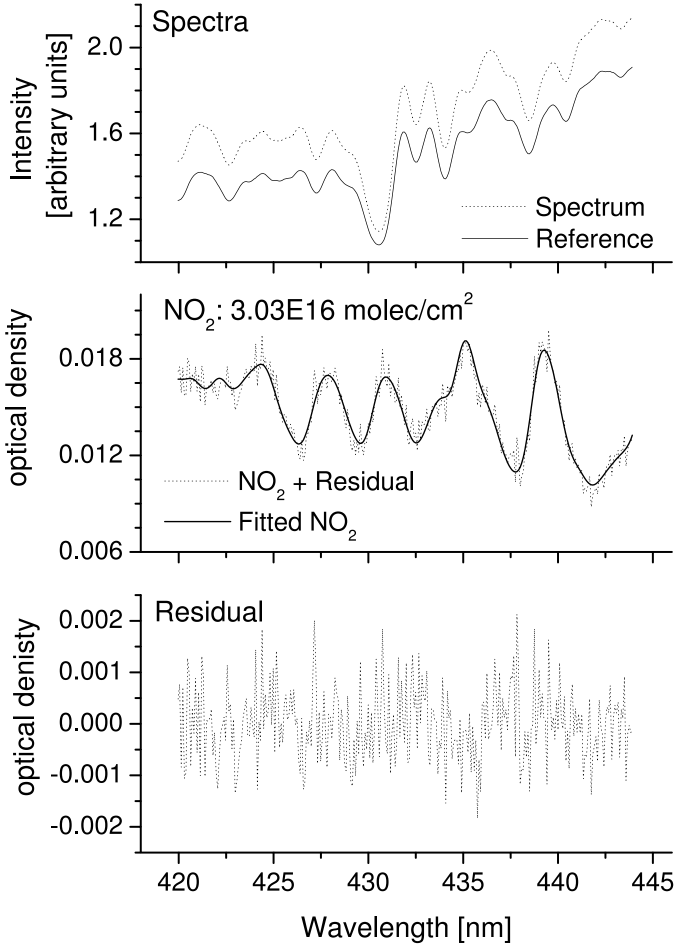

Fig. 3. NO$_2$-fit for a Nadir spectrum, the measurement was done on the flight on 19/02/2003 from Basel to Tozeur at 08:14:30 UT close to Zürich, the reference was taken about 15 min later in the clean air of the Alps.

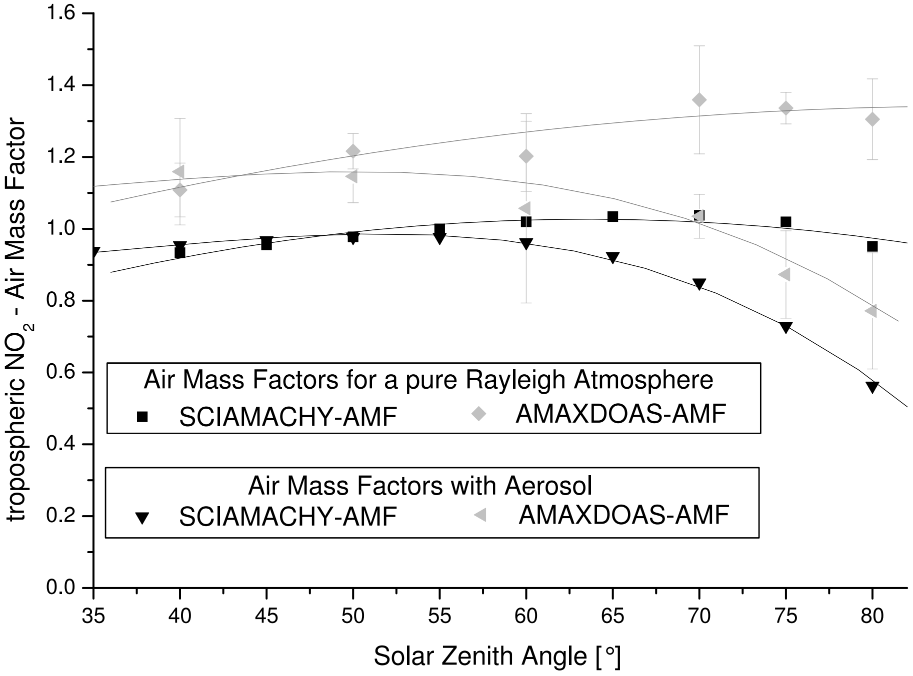

Fig. 4. The AMF for both instruments SCIAMACHY and AMAXDOAS. In general AMAXDOAS is more sensitive to tropospheric pollution than SCIAMACHY. The NO_2 was assumed to be well mixed within the boundary layer (1 km) and to decrease to 0 within the next km. For the aerosol case, a visibility of 4.8 km and an urban aerosol type was assumed in the boundary layer.

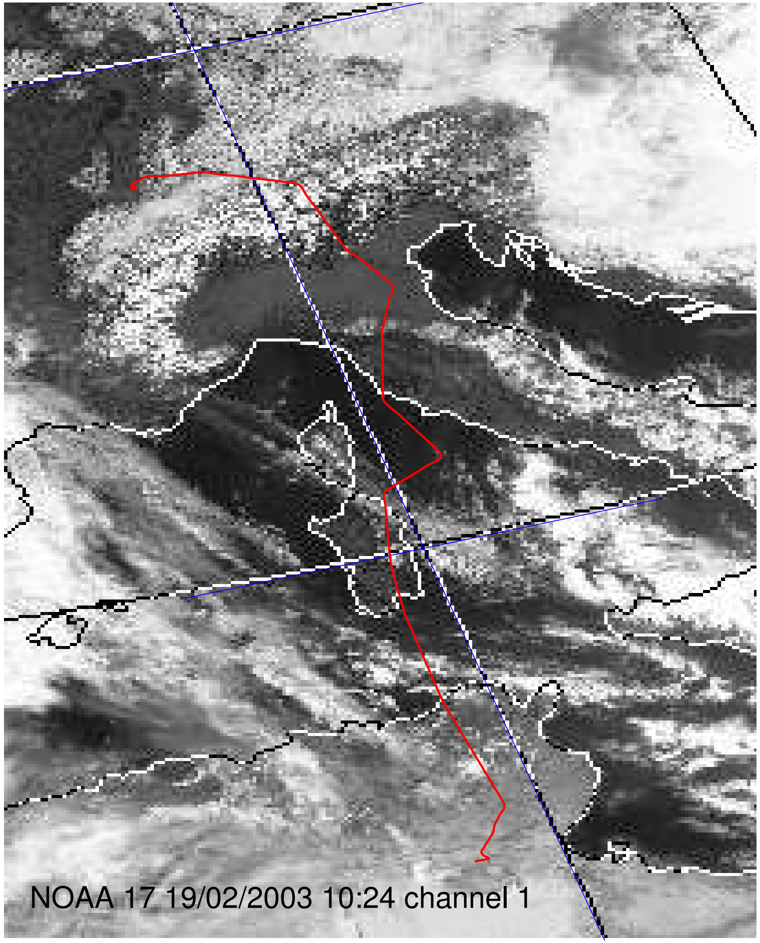

Fig. 5. NOAA-17 Satellite image was published by the University of Dundee on the according web-page in 2004 (http://www.sat.dundee.ac.uk/auth.html). The image shows the cloud coverage over southern Europe and the Mediterranean on 19/02/2003. For comparison the flight track of the FALCON is shown as well.

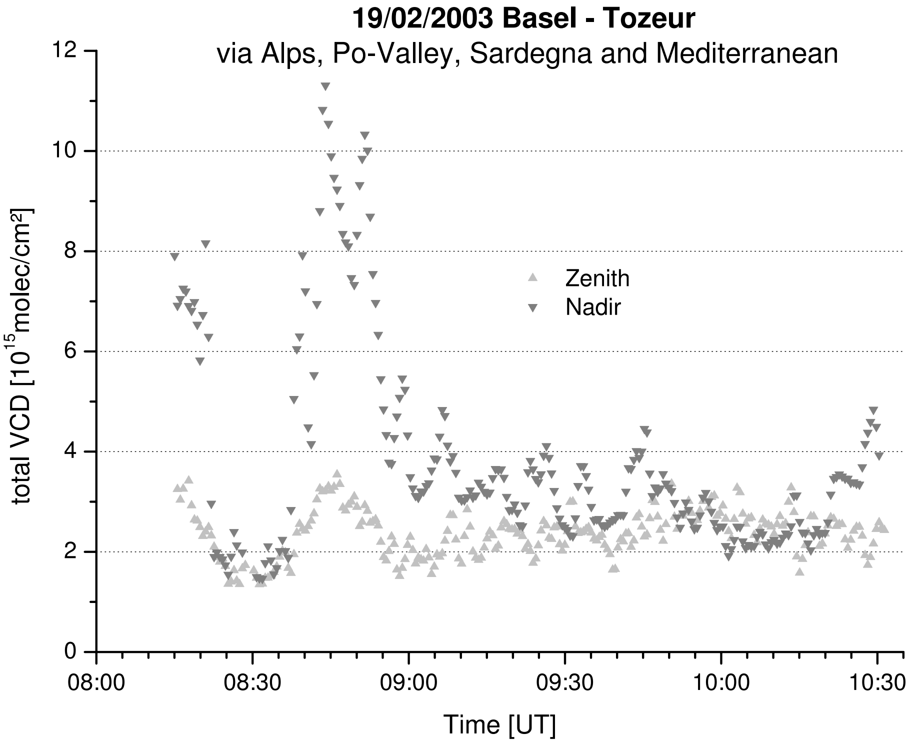

Fig. 6. Time series of the vertical NO_2 columns for AMAXDOAS Nadir and Zenith observations. In Nadir a strong enhancement is observed from 08:40 until 08:55 UT. Here stratospheric AMFs were used, to show the slowly varying stratospheric signal and the influence of tropospheric pollution on the zenith viewing telescope.

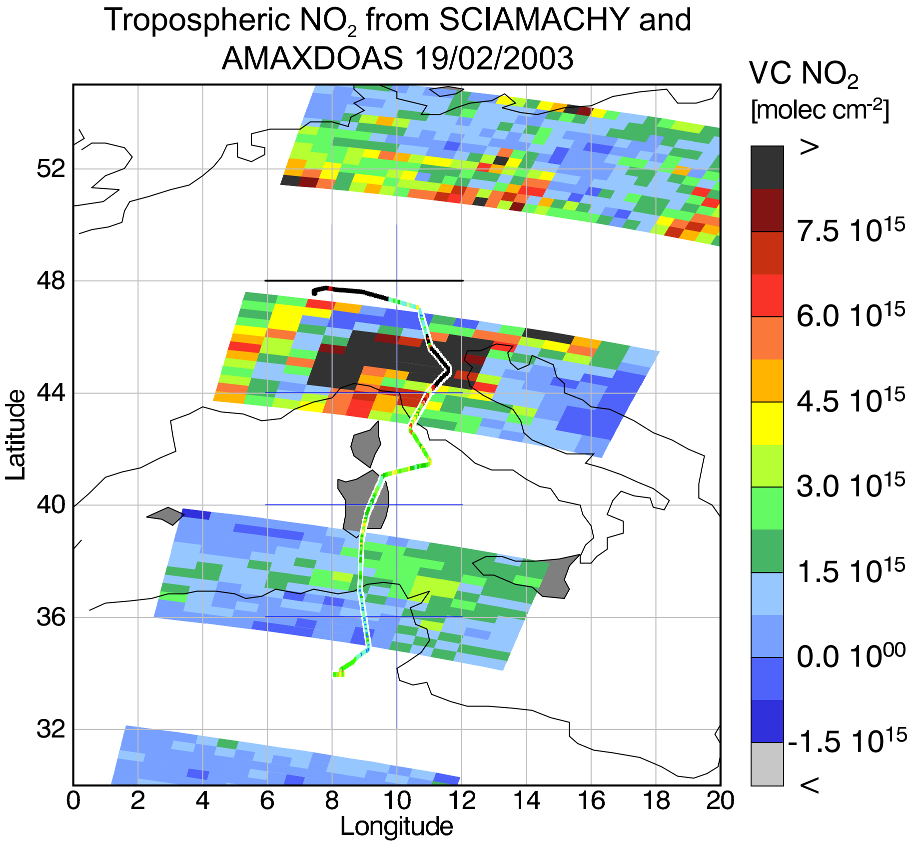

Fig. 7. Tropospheric vertical NO_2 column measured by AMAXDOAS and SCIAMACHY. The AMAXDOAS data were overlaid over SCIAMACHY's pixel in the same scale using similar colours. Zürich is not covered by SCIAMACHY's pixel on this.

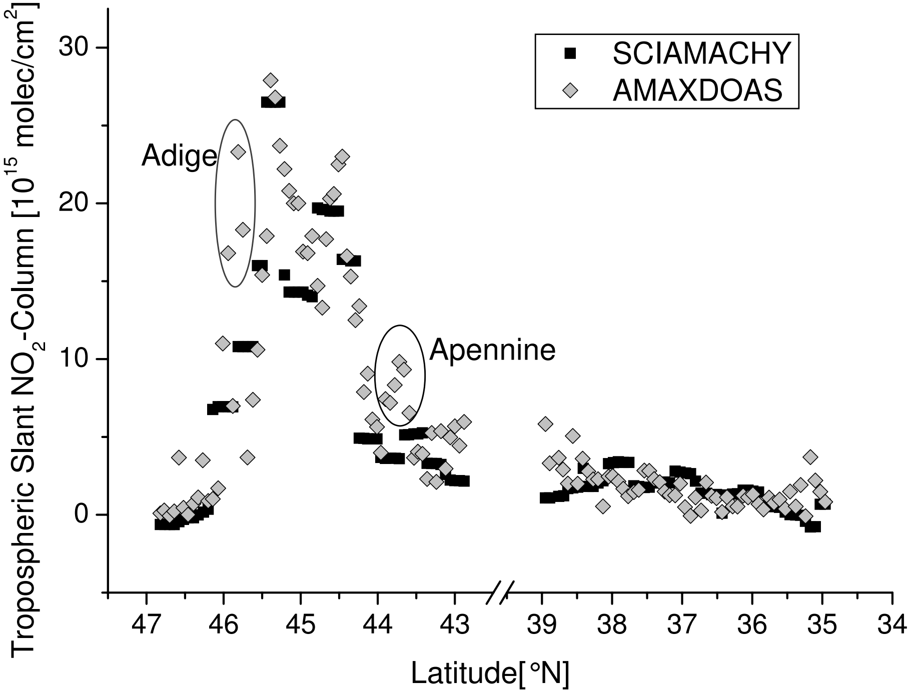

Fig. 8. Slant NO_2 columns measured by SCIAMACHY and AMAXDOAS. In the gaps between two SCIAMACHY Nadir scans no data are shown.

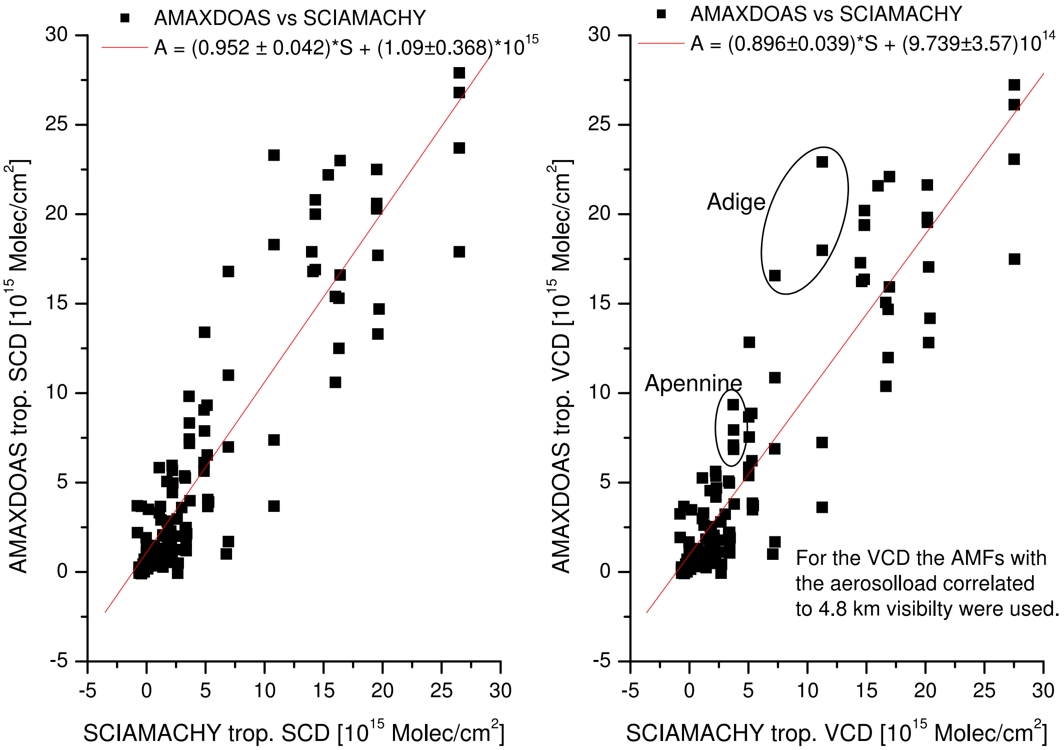

Fig. 9. Left panel: Correlation between the tropospheric slant column densities measured by SCIAMACHY and AMAXDOAS. Right panel: Correlation plot for the vertical column densities including a linear fit.