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SCIAMACHY validation by aircraft remote measurements: design, execution, and first results of the SCIA-VALUE mission

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Abstract

For the first time three different remote sensing instruments – a sub-millimeter radiometer, a differential optical absorption spectrometer in the UV-visible spectral range, and a lidar – were deployed aboard DLR's meteorological research aircraft Falcon 20 to validate a large number of SCIAMACHY level 2 and off-line data products such as O_3, NO_2, N_2O, BrO, OClO, H_2O, aerosols, and clouds. Within two main validation campaigns of the SCIA-VALUE mission (SCIAMACHY VALidation and Utilization Experiment) extended latitudinal cross-sections stretching from polar regions to the tropics as well as longitudinal cross sections at polar latitudes at about 70° N and the equator have been generated. This contribution gives an overview over the campaigns performed and reports on the observation strategy for achieving the validation goals. We also emphasize the synergetic use of the novel set of aircraft instrumentation and the usefulness of this innovative suite of remote sensing instruments for satellite validation.

1. Introduction

SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) is one of the 10 instruments aboard Europe's research satellite ENVISAT, which aims at studying the composition of the Earth's atmosphere from space. The instrument is an successor of the GOME experiment (Burrows et al., 1999) and has been jointly developed by The Netherlands, Belgium and Germany as their national contribution to the ESA ENVISAT programme. SCIAMACHY measures electromagnetic radiation from the near ultraviolet to the near infrared spectral region. Along one orbit, the instrument alternates between nadir and limb measurements observing the radiation scattered or transmitted by the atmosphere. Solar and lunar occultation measurements are also performed where possible. Inversion of the measured spectra yields the amounts and distributions of a number of mesospheric, stratospheric, and tropospheric constituents (Bovensmann et al., 1999).

The measurements and data products from space-based instruments require dedicated validation, i.e. the assessment of the quality of the data derived from the satellite observations with independent measurements. The validation of the geophysical variables provides feedback to calibration, de-bugging and algorithm improvement of the satellite instrument. Only if the differences observed during validation are within satisfactory limits the process of validation is completed and a final quality statement of the data can be made.

In order to validate vertically resolved satellite data similar measurements obtained by other well-established instruments which are co-located in time and space as closely as possible are needed for a correlative analysis. For the validation of atmospheric chemistry instruments, balloon-borne measurements have widely been used to complement ground-based remote sensing (i.e. DOAS, FTIR, lidar, or microwave radiometers). However, the most serious restriction of the validation with balloon soundings is their limited number and thus their limited spatial and temporal coverage.

In contrast to most stratospheric balloons, which can reach higher altitudes at one location, aircraft have the ability to fly for many hours and are thus able to perform flights spanning several thousand kilometers. In addition, aircraft possess high flexibility to achieve close temporal and spatial coincidence with satellite overpasses almost anywhere on the globe and under most weather conditions. When equipped with remote sensing instruments that enable atmospheric profiling, extended 2-dimensional cross-sections can be delivered. These advantages make aircraft excellent platforms for the validation of satellite instruments. Despite these advantages it is astonishing that, up to now, only a handful of activities employing aircraft have been carried out to validate spaceborne sensors (see Table 1). It is also apparent from Table 1 that in most cases in-situ instruments were used. Only very few examples of validation activities are reported in the literature where remote sensing instruments have been deployed on aircraft such as the NASA DC-8 , the DLR Falcon or the M55-Geophysika (Crewell et al., 1995; Englert et al., 2000; Schoeberl et al., 2002; Sugita et al., 2002;

Kanzawa et al., 2003; Lumpe et al., 2003; Fix et al., 2003; Blom et al., 2003).

Here we report on the novel remote sensing instrumentation that was employed onboard the DLR Falcon during the SCIA-VALUE campaign (SCIAMACHY VALidation and Utilization Experiment) which is part of the German Contribution to the Validation of SCIAMACHY level 2 and off-line data products (GC-VOS). This activity is closely related to balloon-flights and satellite validation also proposed as part of the SCIAMACHY validation effort (Hoogen et al., 1999) and embedded into ESA's programme for the validation of products derived from the ENVISAT Atmospheric Chemistry Instruments.

SCIA-VALUE consisted of a series of validation flights to the northern, mid- and tropical latitudes, which have been performed in the first phase of SCIAMACHY validation, during the first year of the instrument's mission. The paper in hand is the introductory paper in a series of results from the SCIA-VALUE campaign. It gives an overview over the performance of the unique remote sensing payload, illuminates the synergetic use of its individual instruments, and describes the campaign activities in detail.

In Sect. 2 the complementary and novel set of experiments is introduced, which provides validation of SCIAMACHY data products from the mesosphere to the ground. Section 3 describes the flight routes along the ENVISAT orbits which have been selected to achieve optimum coincidence with the satellite. In Sects. 4 and 5, new results from combined validation efforts and aspects of synergy are presented.

Specific results from the measurements of the individual instruments will be presented in separate papers within this issue (Kuttippurath et al., submitted, 2004[1]; Heue et al., 2004) or elsewhere (Fix et al., in preparation, 2004[2]; Wang et al., in preparation,

[1]Kuttippurath, J., Kleinböhl, A., Bremer, H., Küllmann, H., Sinnhuber, B.-M., Notholt, J., and Künzi, K.: Seasonal and latitudinal variation of stratospheric ozone and nitrous oxide: Measurements and model calculations, Atmos. Chem. Phys. Discuss., submitted, 2004.

[2]Fix, A., Flentje, H., Ehret, G., et al.: Seasonal and latitudinal variations of ozone and aerosol distributions measured in 2002/2003, in preparation, 2004.

2004[3]).

2. Validation instruments

The SCIA-VALUE payload comprises three state-of-the-art experiments for atmospheric sounding:

- The Airborne SUbmillimeter wave Radiometer (ASUR), operated by the University of Bremen.
- The Airborne MultiAXis Differential Optical Absorption Spectrometer (AMAX-DOAS) developed and operated jointly by the Universities of Bremen and Heidelberg.
- The Ozone Lidar EXperiment (OLEX) operated by DLR Oberpfaffenhofen.

Figure 1 summarizes the SCIAMACHY data products measured by the individual instruments. In the following sections a brief description of each instrument and their contribution to SCIAMACHY data validation is given.

2.1. The ASUR Submillimeter Radiometer

The Airborne SUbmillimeter Radiometer (ASUR) is a passive heterodyne sensor operating in the frequency range 604–662 GHz (Küllmann et al., 2001). The sensor is characterized by a superconductive low noise mixer, a tunable local oscillator, and two spectrometers: an acousto-optical spectrometer with a bandwidth of 1.5 GHz and a resolution of 1.5 MHz, and a chirp-transform spectrometer with a bandwidth of 178 MHz and a resolution of 278 kHz. It allows for the spectral detection of stratospheric trace

[3] Wang, P., Richter, A., Bruns, M., Burrows, J. P., Heue, K.-P., Pundt, I., Wagner, T., and Platt, U.: AMAXDOAS tropospheric NO2 measurements in cloudy and cloud free situations, in preparation, 2004.

gases like O_3, N_2O, ClO, HCl, HNO_3, CH_3Cl, HO_2, H_2O, NO, and BrO. The pressure broadened lineshape of most of the rotational lines comprises altitude information adequate for a profile retrieval. Observations are made to the right of the aircraft with a constant elevation angle of 12°. Thus, vertical profiles from 15 to over 50 km altitude can be retrieved for most of the species with a vertical resolution of typically 6 km in the lower and 12 km in the upper stratosphere using data from the acousto-optical spectrometer. For ozone the retrieval has recently been extended into the lower mesosphere (~65 km altitude) using data of the chirp-transform spectrometer (Kleinböhl et al., 2004[4]).

ASUR measures volume-mixing-ratio (VMR) profiles along the flight producing 2-dimensional cross sections of stratospheric composition of the above mentioned species. The flexibility of the aircraft allows to investigate small and medium scale spatial variations in the stratosphere closing the gap between locally limited balloon measurements and synoptic satellite data. The high stability and reproducibility of the measurements performed with ASUR make this technique well suited for validation campaigns of spaceborne sensors as successfully done for UARS (MLS, HALOE) ATLAS (MAS), ERS-2 (GOME) and ADEOS (ILAS) (Crewell et al., 1995; Sugita et al., 2002; Kanzawa et al., 2003),

Throughout the SCIAMACHY validation campaign large latitudinal cross sections from the arctic to the tropics as well as longitudinal variations at high latitudes and near the equator have been observed (Kuttippurath et al., submitted, 2004[1]). Focus has been set on O_3 and N_2O measurements, other molecules have been observed alternately in between. The typical resolution and errors of the parameters retrieved are listed in Table 2.

[4]Kleinböhl, A., Bremer, H., Sinnhuber, M., Kuttippurath, J., Küllmann, H., Künzi, K., and Notholt, J.: Retrieval of stratospheric and mesospheric ozone profiles from airborne submillimeter measurements, IEEE Trans. Geosci. Remote Sensing, submitted, 2004.

2.2. The AMAXDOAS instrument

The Airborne Multi AXis DOAS (AMAXDOAS) instrument observes scattered sunlight in different lines of sight and thus has similarities to the SCIAMACHY instrument. Depending on the viewing direction the light contains specific information on stratospheric or tropospheric absorbers. All light reaching the instrument has passed the stratosphere and therefore shows the absorption structures of the stratospheric trace gases. If the AMAXDOAS instrument flies at tropopause height it will always be possible to detect these absorptions independent of the viewing angle. However, in good approximation, only the nadir viewing telescope detects the tropospheric trace gases.

The AMAXDOAS instrument uses this effect to separate stratospheric columns of different trace gases such as NO_2 O_3, OClO, HCHO, and BrO. Scattered light is observed using small telescopes mounted outside the aircraft. It is then led to two grating spectrographs via quartz fiber bundles and the analyzed light is detected by 2-dimensional CCD-cameras. Two spectrographs, one for the UV (≈320 to 400 nm) and one for the visible (≈400 to 560 nm) are required to cover the UV-vis wavelength range and to facilitate better spectral resolution in the UV (0.5 nm instead of 1 nm as in the visible domain) and also to improve straylight rejection.

According to a theoretical study (Bruns et al., 2004), some profile information can be retrieved from the measurements close to the flight altitude in addition to the separation of stratospheric and tropospheric columns. The best vertical resolution in the upper troposphere and lower stratosphere is achieved with observation lines of sight close to the horizon. Therefore besides the standard lines of sight nadir (−90°) and zenith (+90°) two telescopes pointing at +2° and −2° of the horizon are used. Measurements in all different viewing directions are taken simultaneously by the CCD cameras.

The data evaluation is based on the Differential Optical Absorption Spectroscopy (DOAS) method which has already been described elsewhere (e.g. Platt and Stutz, 2004). For each species, a dedicated wavelength interval is selected (e.g. 332–339 nm for O_3 and 420–444 nm for NO_2) and Slant Column Densities (SCD) determined with a nonlinear least squares fit. In a second step, the SCD are converted to Vertical Column Densities (VCD) using airmass factors (AMF) which are either calculated (e.g. Rozanov et al., 2001) or modeled (Friedeburg, 2003; Hönninger et al., 2004). For that purpose some assumptions about the atmosphere are made, e.g. trace gas profiles, ground albedo and cloud coverage.

The measurement principle and viewing geometry of the AMAXDOAS is similar to that of the SCIAMACHY instrument. Therefore, the two instruments observe the same species which is essential for validation. Also, the AMAXDOAS can separate tropospheric and stratospheric columns, and thereby provide direct validation of one of the key products of the novel limb-nadir matching capability from SCIAMACHY. The similarity of the two measurement systems also allows for direct comparison of lower level products such as slant columns and radiances which is a valuable addition to standard validation activities. However, this also implies that those aspects that are similar in the data analysis of the two instruments (such as the basic DOAS approach) can not be considered as independent validation.

A precursor instrument of AMAXDOAS has been successfully applied for measuring O_3, NO_2 and OClO on board of a Transall aircraft during SESAME in 1995 (Pfeilsticker et al., 1997). An overview over the measurement parameters of AMAXDOAS is given in Table 2.

2.3. The OLEX lidar

The OLEX system measures the atmospheric backscatter at four wavelengths 308, 355, 532, and 1064 nm with the additional capability to measure the cross-polarized return at 532 nm for particle phase discrimination. The three wavelengths at 1064, 532, and 355 nm are generated by a Q-switched Nd:YAG laser with harmonic generation having a total average power of ∼4 W at a repetition rate of 10 Hz. The 308-nm radiation is generated by a XeCl excimer laser. Specifically for this campaign, a new excimer laser (TUI Laser GmbH) was employed that can be operated at a repetition rate of up to 200 Hz (and an average power of up to 2.4 W) and replaced the formerly used 10-Hz system (Wirth and Renger, 1998). The new laser needs much less maintenance and is therefore much more appropriate for such an ambitious and time critical campaign to remote locations.

The receiver system uses a 35-cm Cassegrainian telescope. The received light is split into four channels, one for each wavelength. The 532-nm channel is further divided to sub-channels for depolarization detection. The backscattered light at 1064 nm is detected by means of a silicon avalanche photodiode (APD), whereas the light at the shorter wavelengths is measured by photo-multiplier tubes (PMT). In order to suppress the solar background radiation, adequate bandpass filters are placed in front of the detectors. The signals are digitized with a resolution of 14 bit at a sampling rate of 10 MHz and are interfaced to the data acquisition system and stored together with housekeeping and aircraft data.

OLEX is zenith viewing and its measurement range extends from about 2 km above flight altitude to about 30 km. The system provides high resolution two-dimensional cross sections of ozone number densities, aerosol extinction, color ratio and particle depolarization. In addition, cirrus or polar stratospheric cloud (PSC) cover information is determined.

The ozone distribution is calculated from the 308 nm (absorbing wavelength) and 354 nm (non-absorbing wavelength) return signals using the well established differential-absorption lidar (DIAL) technique. Over the whole measurement range the vertical resolution of the ozone distribution is less than 1.5 km, thus the vertical resolution of OLEX is much better than the resolution of the SCIAMACHY data products in the limb sounding geometry (∼3 km). In addition, the narrow field of view (∼1 mrad) and signal integration of typically 4 min give a footprint of about 50 km along track (in-flight direction) and 20 m across track.

A key element for the validation are the aerosol extinction profiles not available from other instruments. For the DOAS retrieval aerosol extinction data is needed to derive the AMF (see also Sect. 5). Besides ozone and aerosol optical properties, PSCs and cirrus clouds are also addressed by the OLEX instrument. The typical resolution of the parameters derived are listed in Table 2. It should be noted that the values for the resolution are much better, both horizontally and vertically, than the required resolution for SCIAMACHY. In order to match the SCIAMACHY resolution the airborne lidar data can be averaged over a larger vertical or horizontal range whereby the precision is generally enhanced.

The OLEX system presently operated on the Falcon employs state-of-the-art technology, which has already shown its excellent performance in a number of national and international campaigns. OLEX has been successfully flown during EASOE, and SESAME on board of a Transall aircraft (Wirth and Renger, 1998; Carslaw et al., 1998; Flentje et al., 2000) and recently during THESEO on the Falcon (Flentje et al., 2002, 2003, Peter et al., 2003).

2.4. Validation instruments on the DLR Falcon

The meteorological research aircraft Falcon 20 (D-CMET) operated by the German Aerospace Center (DLR) has been selected as the instrument platform. Many features make the Falcon an excellent aircraft for the validation experiment. Three large optical windows (diameter 40 cm) two in the bottom and one in the roof enable operation of large lidar experiments both for tropospheric (nadir-viewing) and stratospheric (zenith viewing) research. Specially manufactured polyethylene windows allow remote sensing in the microwave spectral region. The aircraft carries a data acquisition system and an extensive instrument package capable of measuring position, altitude, static pressure and temperature. The aircraft has a maximum endurance of 5 h and a maximum operating altitude of 45 000 ft (~13 km). Figure 2 depicts the viewing geometry of the validation instruments on the Falcon. The ASUR instrument uses a side-ward looking viewing geometry at zenith angle of 78°. This enables atmospheric profiling from about 15 km up to 65 km altitude. The AMAXDOAS instrument uses two view ports one on the roof and the other one on the bottom for simultaneously sounding the atmosphere above and below the Falcon aircraft. Each of the ports consist of five telescopes but only the viewing angles of 2° and 90°, respectively, were utilized here. The OLEX lidar uses the large optical window on the roof of the Falcon for measurements in the stratosphere. The Falcon payload is shown in Fig. 3.

Figure 4 indicates the footprint of the three airborne instruments crossing the footprint of the SCIAMACHY sensor. The AMAXDOAS footprint for the troposphere is of the order of 1 km across-track and several km along track depending on solar position. Therefore, the data have to be averaged for direct comparison with SCIAMACHY products. The measurement volume for the stratosphere depends on the solar zenith angle and is close to the aircraft position at high sun but can be displaced towards the sun by up to 100 km at twilight. As both, SCIAMACHY and AMAXDOAS observe scattered sunlight, the displacement is similar for both instruments. Because of the higher sampling characteristics of the OLEX system in the vertical direction, as mentioned above, vertical averaging of OLEX data is needed in order to match with the vertical resolution of SCIAMACHY data products in the limb sounding geometry which is about 3 km. On the other hand, the narrow field of view (~1 mrad) and signal integration of about 4 min results in a footprint of about 50 km along track (in flight direction) and 20 m across track, only. For the ASUR instrument the situation is somewhat different. In cross track direction the footprint ranges from 14–200 km caused by the special viewing geometry. The along track spatial resolution depends on the integration time for the individual data product. For ozone this is about 18 km (40 km in the mesosphere). Both, OLEX and ASUR, provide profiles for intercomparison over a height range of ~15–30 km.

3. Field campaigns

Two field campaigns have been performed with the goal to cover measurements at various geophysical locations from low to high latitudes at different seasons. These two campaigns took place in September 2002 (about six month after the launch of ENVISAT) and February–March 2003, respectively. At these times of the year homogeneous atmospheric conditions can be anticipated which are advantageous for the validation effort particular in view of the different footprints of the validation instruments. The flight routes have been selected to cover both, extended longitudinal cross-sections as well as flight legs in the east west direction at high latitudes, where more than one adjacent orbit of SCIAMACHY could be linked, and also at the equator. Logistic reasons constituted additional boundary conditions for the flight pattern. This concerned safe aircraft operation, ground support, as well as reliable supply of cryogenic liquids needed for the operation of ASUR. The flight planning was based on the predicted overpass tables provided by the SCIAMACHY Operations Support Team (SOST) (Gottwald et al., 2003). The individual parts of the campaign are briefly described in the following.

3.1. First main validation campaign

The first main campaign of this validation activity provided extended longitudinal and latitudinal atmospheric cross sections between 79° N–4° S and 60° W–55° E, respectively. Starting from Oberpfaffenhofen near Munich the campaign consisted of a northern part and a southern part. The northern route led from Oberpfaffenhofen to Kiruna, Spitsbergen, Kiruna, Iceland, Greenland, Iceland and back to Oberpfaffenhofen (see Fig. 5a). This part was carried out between 3–7 September 2002. A few days later (15 September) the southern flight route began via Palma de Mallorca, Djerba, Niamey, Yaounde, Nairobi, Mahé and back and ended on 28 September. The campaign consisted of 14 legs to high and low latitudes each, while instruments collected data along 18 ENVISAT orbits.

In most cases, the aircraft flight plan could be organized in order to obtain very good temporal and spatial coincidence with the SCIAMACHY observations. About 54 flight hours within a period of 25 days have been used in total. A summary of the flight legs, orbits crossed as well as the Falcon departure and arrival times of the first main campaign is given in Table 3.

3.2. Second main validation campaign

The second main campaign of this activity consisted of a similar flight pattern as the first one covering longitudes and latitudes between 79° N–4° S and 60° W–55° E, respectively (see Fig. 5b). Starting in Oberpfaffenhofen near Munich on 19 February and ending on 19 March 2003 the campaign consisted of 18 flight legs, again to both arctic and tropical latitudes. The instruments collected data along 16 ENVISAT orbits.

Several problems with ENVISAT and SCIAMACHY, respectively, were encountered during this part of the campaign. A failure of ENVISAT on 20 Feb. resulted in a deviation of 1 day from the original flight plan. SCIAMACHY may not have been in the nominal temperature regime on 23 February (Yaounde – Nairobi). SCIAMACHY was out of operation again between 15–19 March. Therefore, an extra flight was performed on 19 March (Oberpfaffenhofen – Oberpfaffenhofen – via Northern Denmark) compensating for the missing orbit.

Several minor deviations from the original flight plan had to be incorporated during the southern part: Due to strong headwinds on its way from Yaounde to Nairobi the Falcon had to land for refueling in Entebbe, Uganda, and then continued to Nairobi. On the way to Mahé a technical problem was encountered requesting for a landing in Mombasa, Kenia. Due to strong thunderstorms the Falcon had to land in Douala rather than in Yaounde on its way back. Nevertheless, in most cases a very good temporal and spatial coincidence with the SCIAMACHY observations was achieved.

Concluding the flight operations, about 59 flight hours within a period of 28 days have been used. A summary of the flight legs, orbits crossed, as well as the Falcon departure and arrival times of the 2nd main campaign are given in Table 4.

3.3. Operations' summary

Altogether, a sum of 113 flight hours have been flown within both field campaigns. 49 close SCIAMACHY limb scans were on target. However, taking into account all limb scans within a radius of 1000 km and a time difference of <6 h from the aircraft position this sums up to as much as 99 matches. The distribution of these matches in time and space are depicted in Fig. 6. Approximately the same holds true for SCIAMACHY nadir measurements due to the close relationship between limb and nadir footprints (see e.g. Bovensmann et al., 1999). Additionally, one solar occultation was covered near 62° N (see Table 3). The additional use of the trajectory hunting technique (Danilin et al., 2002) can even increase the data set suitable for validation. Trajectory hunting is a technique to find air parcels sampled by different platforms over the course of a few days with the help of forward or backward trajectory mapping.

This impressively demonstrates the advantages of airborne validation. Its strong point is the flexibility and the ability to meet many satellite matches along extended longitudinal and latitudinal cross sections in a comparably short time period without being prone to weather conditions on the ground.

4. Data products

4.1. AMAXDOAS

AMAXDOAS spectra in 4 viewing directions have been continuously measured in the visible and UV wavelength range during most flights of the campaign. In the Tropics the aircraft cabin temperature was a general problem for all the instruments, and the AMAXDOAS experienced several shut-downs as a result of overheating.

Small data gaps exist during tropical flights whenever the telescope shutters closed to avoid instrument damage when direct sunlight could enter the optics or during those flights when the solar zenith angle was larger than 92°. The quality of the data is generally better at higher latitudes, as during these flights larger solar zenith angles prevailed leading to larger absorptions and thus better signal to noise ratios.

Exemplary tropospheric columns measured by the AMAXDOAS are shown in Fig. 7. The figure shows the tropospheric vertical columns of NO_2 along the flight track on 2 September 2002 from Oberpfaffenhofen to Kiruna. In Germany, enhanced NO_2

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columns can clearly be attributed to densely populated areas like the Ruhrgebiet and Hamburg. Two smaller peaks were also observed over southern Scandinavia. In Fig. 8 the stratospheric vertical column is plotted together with the tropospheric one. As can be seen, there is not much variation in the stratospheric signal as expected, and all the variations occur in the troposphere.

4.2. ASUR

ASUR measured a set of molecules alternately (see Sect. 2.1) on both, the northern and the southern route. During SCIAMACHY overflights the focus has been put on O_3 and N_2O. In most cases, several ozone measurements have been accomplished above the area of one SCIAMACHY ground pixel to account for atmospheric variability. Profile comparisons for the N_2O molecule are also possible for many SCIAMACHY ground pixels at different latitudes. In Fig. 9 typical ozone profiles at tropical and high latitudes, respectively, are shown which are further discussed in Sect. 5. An example of an ASUR N_2O measurement is depicted in Fig. 10. This measurement was performed on 26 September 2002 and is compared to a nearby profile retrieved from the MIPAS instrument on ENVISAT (ESA operational product IPF V4.61, for a description of the MIPAS instrument see e.g. ESA, 2000). The agreement of the two N_2O measurements is well within the estimated errors. Frequent measurements of HNO_3 during all deployments at all latitudes allow to contribute to the MIPAS validation of O_3, N_2O, and HNO_3 data products as well. In addition, ASUR also measured NO every 10–20° latitude with reasonable data quality. Several spectra for H_2O and BrO were also obtained. However, on 23 February and 3 March 2003 no measurements could be taken due to the sudden unavailability of liquid cryogens in Africa.

4.3. OLEX

Profiles of aerosol backscatter and ozone concentration along the flights have been measured with the OLEX system during all flights of the campaign. Good measurement conditions, i.e. no high cirrus above the flight level, prevailed during nearly all northern flights except on the leg from Greenland to Keflavik (7 September 2002), where aviation traffic control restrictions prevented a climb above the cirrus during the first part of the flight over Greenland. On the southern route, particularly in the equator region, the data quality is limited to about 26 km by the high background solar radiation present around the equinoxes at the local ENVISAT overpass time. Small data gaps exist when the lasers shut off due to overheating which occurred at the very high cabin temperatures encountered during the Sahara transects and when the telescope shutters closed to avoid instrument damage at local noon time. Parts of the flight legs over the African continent were covered by extended layers of thin cirrus clouds at tropopause level.

Representative ozone and backscatter cross-sections measured by OLEX are shown in Figs. 11 and 12. Figure 11 shows the ozone distribution at mid-latitudes for the flight leg on 28 September 2002 that is depicted in Fig. 4. In Fig. 12 the backscatter ratio at 1064 nm is displayed showing an extended cirrus layer as has often been encountered at tropical latitudes during the SCIA-VALUE mission. According to Peter et al. (2003), the small structure at an altitude of 17 km at 49° E is an ultra-thin tropical cirrus cloud (UTTC).

5. Synergetic use of the instruments

5.1. ASUR – OLEX

ASUR and OLEX are complementary to each other in the sense that the OLEX measurements provide O_3 profiles with a higher vertical resolution up to an altitude of ~30 km whereas the ASUR measurement extends to 50 km and higher, but, with a somewhat lower vertical resolution (see Table 2). Both measurements can be directly compared over a height range of 15–30 km. A direct comparison of ASUR and OLEX is depicted in Fig. 9 where two OLEX and ASUR measurements are compared to each other and to ozone sondes.

In September 2002 and in March 2003 two ozone sondes have been launched near Nairobi, Kenya (Thompson et al., 2003), and near Ny Ålesund, Spitsbergen (von der Gaathen, 2003), suitable for a tentative comparison. The first was launched when the Falcon departed towards Yaounde, Cameroon, and the second during a local flight from Kiruna, Sweden. The corresponding volume mixing ratios are presented in the plots provided. Given are locations (latitude, longitude) and the launch time of the sondes and the measurement time for the Falcon instruments, respectively.

The concurrence of ASUR, OLEX, and sonde measurements is better than 2 h, and the distance is within 300 km. The sonde measurements reach up to 31 and 27.5 km altitude, respectively, and their different shape represents the alteration from tropical to arctic regions. The agreement with the lidar is excellent. The overall agreement with the microwave measurements is also very good and corresponds roughly to the estimated accuracy for ASUR O_3 observations of 15% and 0.3 ppm in the lower stratosphere.

5.2. AMAXDOAS – OLEX

The influence of clouds on the tropospheric measurements by the AMAXDOAS instrument have been studied recently (Wang et al., in preparation, 2004[3]). However, even for optically thin and sub-visible clouds AMAXDAOS observations can be affected. The simultaneous lidar measurements allow for quantification of such potential systematic errors. Especially in the Tropics cirrus clouds occur in altitudes higher than the standard flight altitude of the Falcon (11 600 m). Therefore the largest influence can be expected in the zenith viewing direction, and in the following only these data are presented. Usually, cirrus clouds are not taken into account for the simulation of the AMFs.

As an example, we tried to quantify the influence of a thin tropical cirrus cloud encountered on the flight on 19 September 2002. The backscatter ratio of this cloud measured by OLEX can be seen in Fig. 12. The cirrus ranged from ∼14 km up to ∼16 km altitude and extended over a distance of more than 1200 km from the African continent into the Indian Ocean. The cloud optical thickness (see Fig. 13) was determined calculating the total extinction of the cloud and assuming a height independent lidar ratio. The latter is defined as the ratio of the extinction coefficient to the backscatter coefficient. For tropical cirrus, lidar ratios of the order of 30 sr are reported in the literature (Chen et al., 2002). Using this lidar ratio, the maximum optical thickness τ of the cirrus reaches 0.04, thus this cloud is close to the threshold condition for subvisual cirrus (τ=0.03) (Sassen and Cho, 1992). A value of τ=0.04 was therefore used in the following to estimate the cloud effect on the DOAS retrieval.

Figure 14 shows the relative change of the AMFs, modelled with the ray tracing model "Tracy" (Hönninger et al., 2004). It is a direct measure of the cloud's influence on the observation. The data with the cirrus cloud are compared to the standard scenario without the cloud. The calculation was performed for λ=335 nm, which is a typical wavelength for the O_3 analysis in the UV. The AMF strongly depends on the Solar Zenith Angle, therefore a SZA range from 1° to 90° was simulated.

In general the influence of the cirrus clouds is larger for smaller SZAs. For O_3 the effect can be as large as 15%. Usually stratospheric UV/vis observations are performed during twilight, and here the influence is negligible.

The observed trend is caused by the different directions the light is scattered into. The phase function of the aerosol forming the cirrus cloud is forward-peaked, whereas for the Rayleigh scattering the phase function is symmetric. At smaller SZAs, the aerosols scatter more sunlight directly into the telescope than in the cloudless case. Here the Rayleigh scattering is dominant, allowing multiple scattering including ground reflection. In total the average optical light path through the atmosphere is shorter in the aerosol case, and thus the AMF decreases.

During the flight on 19 September 2002 the SZA ranged from 62° (05:15 UT)–19° (07:15 UT). At the location where the cloud is thickest the SZA amounts to ~57°. From Fig. 14 we therefore anticipate an effect on the VCD of the order of a 5% underestimation. Figure 13 shows the retrieved ozone vertical column. Indeed, there is a clear tendency towards lower values where the cloud is located. In comparison the vertical column measured by GOME (Burrows et al., 1999) is also shown. Assuming a baseline of the order of ~272 DU the effect of the cloud amounts to up to ~14 DU or ~5% which is in agreement with our estimate. The high variability in the O_3 data observed at this time may also be caused by a variable cloud cover below the aircraft.

In summary, in the presence of high cirrus clouds, the additional information provided by lidar measurements can reduce the systematic error in stratospheric columns retrieved from measurements of the AMAXDOAS measurements for low and medium SZA significantly.

6. Conclusions

An airborne mission to validate SCIAMACHY operational level 2 and off-line data products at various geophysical locations and different seasons in the northern hemisphere has been performed in the first year of the instrument's mission. For this purpose, the German Aerospace Center's research aircraft Falcon 20 was equipped with a complementary and novel suite of remote sensing instruments which provides validation of the SCIAMACHY data products from the mesosphere to the ground.

During 112 flight hours at high, mid-, and low latitudes, the individual instruments ASUR, AMAXDOAS, and OLEX collected data along 34 ENVISAT orbits. With the help of the SCIAMACHY operations support the aircraft flight plan could be organized in order to obtain very good temporal and spatial coincidence with numerous SCIAMACHY observations. A total of 99 SCIAMACHY limb scans have been hit within a time difference of <6 h and a radius around the aircraft position of 1000 km. At the same time, due to the special viewing geometry of SCIAMACHY, many more collocations with the smaller nadir pixels were obtained providing an excellent basis for the validation of tropospheric products.

The DLR Falcon has thus proven to be an excellent platform for extensive validation campaigns in the northern, mid-latitude and tropical regions even under difficult conditions concerning flight operations and logistics.

Since specific results from the measurements of the individual instruments will be presented in separate papers we restricted ourselves to giving a representative overview over the data quality. Also, the validation exercise will be treated in forthcoming papers as soon as the operational data products are available.

In addition, two aspects of the synergetic use of the instruments have been addressed. First, the joint use of ozone profiles derived from ASUR and OLEX results in either higher altitude extension or better vertical resolution than with one of these instruments alone. Second, the information of aerosol or cloud optical thickness derived from the OLEX lidar offers valuable information to reduce the systematic error in the stratospheric column retrieval of AMAXDOAS.

The results obtained during the SCIA-VALUE campaigns impressively demonstrate the benefit of this innovative suite of airborne remote sensing instruments for the validation of satellite-borne atmospheric chemistry instruments as well as for atmospheric case studies.

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Table 1. Validation of spaceborne atmospheric chemistry instruments using aircraft. It is distinguished between airborne in-situ and remote sensing instruments. The remote sensing instruments (in bold) are categorized as far-infrared (FIR), mid-infrared (MIR) or lidar (LIDAR).

Instrument	Aircraft	Species	Validation Instruments	Reference
ATMOS	NASA ER-2	N2O, O3, NOy, H2O, CH4, CO	In-situ	Chang et al., 1996a, b
GOME	DLR Falcon	NO_2	In-situ	Heland et al., 2002
	DLR Falcon	H_2O	In-situ	Wagner et al., 2003
	DLR Falcon	NO2, HCHO	In-situ	Ladstätter-Weißenmayer et al., 2003
	NCAR Electra / G1 Twin Otter / NOAA P3	NO2, HCHO	In-situ	Martin et al., 2004[5]
HALOE	NASA ER-2	H2O, CH4	In-situ	Tuck et al., 1993
ILAS	DLR Falcon	O3	In-situ	Sugita et al., 2002
	DLR Falcon	O3	**FIR**	Sugita et al., 2002
	NASA ER-2	H2O	In-situ	Kanzawa et al., 2002
	NASA ER-2	N2O, CH4	In-situ	Kanzawa et al., 2003
	DLR Falcon	N2O	**FIR**	Kanzawa et al., 2003
MAHRSI	DLR Falcon	OH	**FIR**	Englert et al., 2000
MIPAS	M55-Geophysika	HNO3, N2O, CH4, O3	In-situ	Heland et al., 2003
	M55-Geophysika	O3, HNO3, H2O, N2O, CH4	**MIR, FIR**	Blom et al., 2003
	DLR Falcon	H2O	**LIDAR**	Fix et al., 2003
MLS	NASA ER-2	ClO	In-situ	Waters et al., 1996
	DLR Falcon	ClO	**FIR**	Crewell et al., 1995
	MOZAIC	H2O	In-situ	Read et al., 2001
MOPITT	NASA DC-8	CO	In-situ	Heald et al., 2003
	NASA DC-8	CO	In-situ	Jacob et al., 2003
	DLR Falcon	CO	In-situ	Emmons et al., 2004
POAM III	NASA DC	O3	**LIDAR**	Schoeberl et al., 2002
	NASA ER-2	O3	In-situ	Schoeberl et al., 2002
	NASA DC-8	O3	**LIDAR**	Lumpe et al., 2003
	NASA ER-2	O3	In-situ	Lumpe et al., 2003
	MOZAIC	H2O	In-situ	Lumpe et al., 2003
	MOZAIC	O3	In-situ	Prados et al., 2003

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Table 2. Measurement parameters for the instruments considered in this work.

Instrument	Species	Altitude Range [km]	Resolution [km] Vertical	Horizontal	Error	Reference
OLEX	O_3	22	<1	<50	<4% below 22 km (low SZA) <10% below 22 km (high SZA)	(Wirth and Renger, 1998)
		30	1.5	<50	<17% below 28 km (low SZA) <25% below 26 km (high SZA)	
	Aerosol backscatter ratio	30	0.15	30	1–10% (typ. cond.)	
	Aerosol optical depth				1–10% (typ. cond)	
	Clouds, geometric distribution	30	0.05	0.1	na.	
ASUR	O_3 (stratosphere)	15–50	6–20	18	>0.3 ppm, <15%	(Kuttippurath et al., submitted, 2004[1];
	O_3 (mesosphere)	<65	12–20	40–150	>0.3 ppm, <25%	Kleinboehl et al., submitted, 2004[4])
	$N2_O$	15–45	8–16	30	>30 ppm, <15%	
AMAXDOAS	O_3		column	<50	5%	(Wagner et al., 2001)
	NO_2		stratospheric/ tropospheric column	<25	15%/ 1e15 molec/cm^2 (det. limit)/ 10% 1e15 molec/cm^2 (det. limit)	
	BrO		stratospheric/ tropospheric column	<50	25%/ 3e13 molec/cm^2 (det. limit)/ 20% 1e13 molec/cm^2 (det. limit)	
	OClO		stratospheric slant column	<100	20% 5e13 molec/cm^2 (det. limit)	
	SO_2		tropospheric column	<50	20% 1e16 molec/cm^2 (det. limit)	

Table 3. Summary of validation activity during the first main validation campaign on September 2002. The orbit index is related to limb observation.

Date	Orbit	Crossed Orbit Index	Flight Leg	Departure [UTC]	Arrival [UTC]
Northern Part					
02/09/03	2667	10,11,12	Oberpfaffenhofen - Kiruna	08:00	10:30
02/09/04	2685, 2686	7,5	Kiruna - Ny-Ålesund - Kiruna	16:00	19:30
02/09/05	2696, 2697	10,11	Kiruna - Keflavik	10:00	13:00
02/09/06	2712, 2713	10, 11	Keflavik - Kangerlussuaq	12:50	15:00
02/09/07	2726, 2727	10	Kangerlussuaq - Keflavik	12:30	14:30
02/09/07	2730	Solar Occ. 61.8° lat., 351.9° lon.	Keflavik - Oberpfaffenhofen	18:20	22:00
Southern Part					
02/09/15	2839	12	Oberpfaffenhofen - Mallorca	09:15	11:00
02/09/17	2867	13-17	Mallorca -Yaounde	05:45	15:30
02/09/18	2880, 2881	17,18	Yaounde - Nairobi	08:30	11:30
02/09/19	2894	18,19	Nairobi - Mahé	05:00	07:30
02/09/24	2966	17,18	Mahé - Nairobi	06:30	08:30
02/09/25	2981	17,18	Nairobi - Yaounde	06:30	09:45
02/09/26	2996	13-16	Yaounde - Mallorca	05:30	15:00
02/09/28	3025	11,12	Mallorca - Oberpfaffenhofen	09:30	11:00

Table 4. Summary of the Falcon flight legs during the second SCIA-VALUE campaign. The orbit index is related to limb observation of SCIAMACHY.

Date	Orbit	Crossed Orbit Index	Flight Leg	Departure [UTC]	Arrival [UTC]
Southern Part					
19/02/03	5086	11	Basel – Tozeur	8:00	10:30
20/02/03	5100	xx	Tozeur – Niamey - Yaounde	7:30	15:00
23/02/03	5142	16	Yaounde – Entebbe-Nairobi	8:30	13:45
24/02/03	5156	17	Nairobi – Mombasa-Mahé	9:00	15:00
26/02/03	5184	17	Mahé - Nairobi	6:30	9:00
28/02/03	5214	16	Nairobi – Douala	7:45	12:00
01/03/03	5229	13-16	Douala – Niamey - Tozeur	4:15	11:30
03/03/03	5258	11	Tozeur - Oberpfaffenhofen	8:30	12:20
Northern Part					
10/03/03	5358	9, 10	Oberpfaffenhofen - Kiruna	9:45	12:45
12/03/03	5387	7, 8	Kiruna - Ny-Ålesund - Kiruna	7:30	11:15
13/03/03	5402	9	Kiruna – Keflavik	9:30	13:15
14/03/03	5417 5418	9 9	Keflavik - Kangerlussuaq	12:00	15:45
15/03/03	5433	xx	Kangerlussuaq - Keflavik	13:00	15:00
17/03/03	5459	xx	Keflavik - Oberpfaffenhofen	10:30	14:15
19/03/03	5487	10, 11	Oberpfaffenhofen - Oberpfaffenhofen	7:15	11:00

xx: SCIAMACHY not operating

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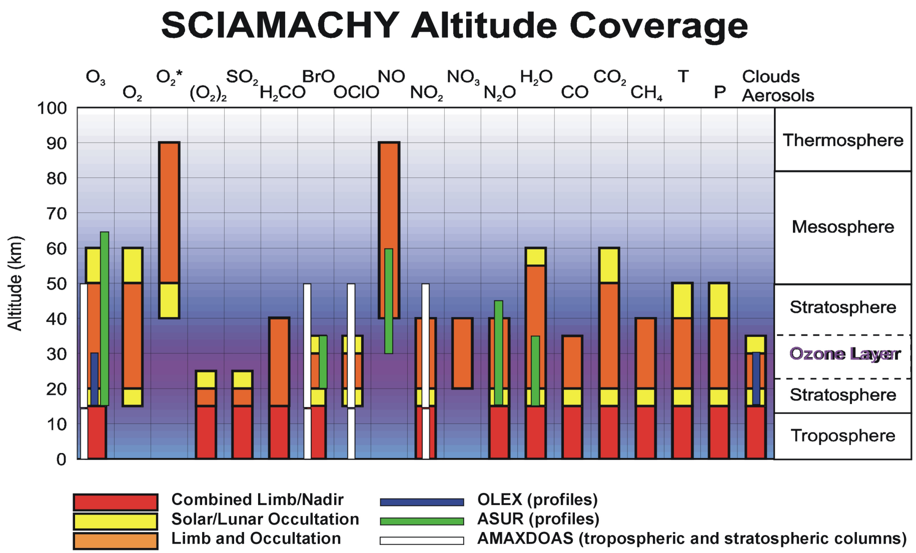

Fig. 1. Target species of the three instruments ASUR, OLEX and AMAXDOAS compared to SCIAMACHY data products. We note that ASUR and OLEX measure profiles while the AMAXDOAS instrument provides stratospheric and tropospheric columns.

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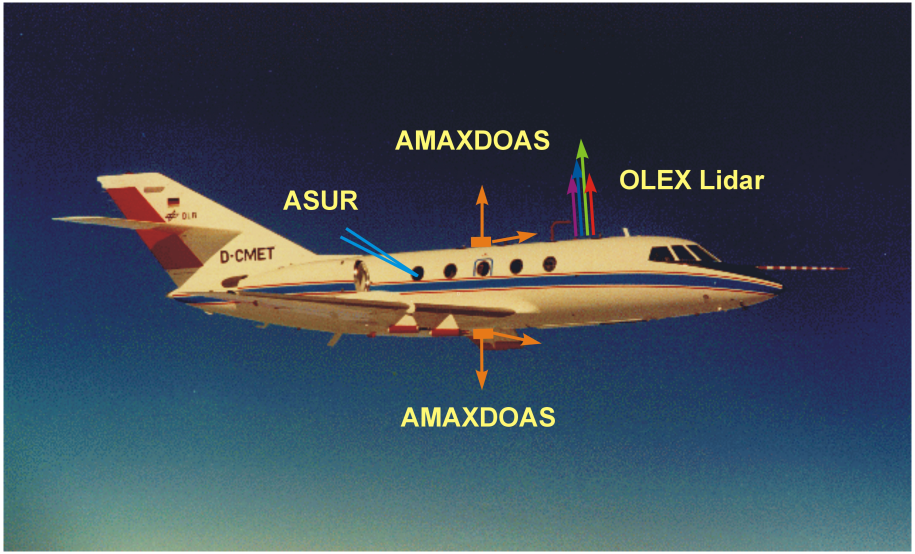

Fig. 2. The German Aerospace Center's meteorological research aircraft Falcon 20 equipped with the three remote sensing instruments ASUR, AMAXDOAS, and OLEX for airborne validation of SCIAMACHY data products O_3, N_2O, NO_2, BrO, H_2O, OClO, and cloud and aerosol optical properties.

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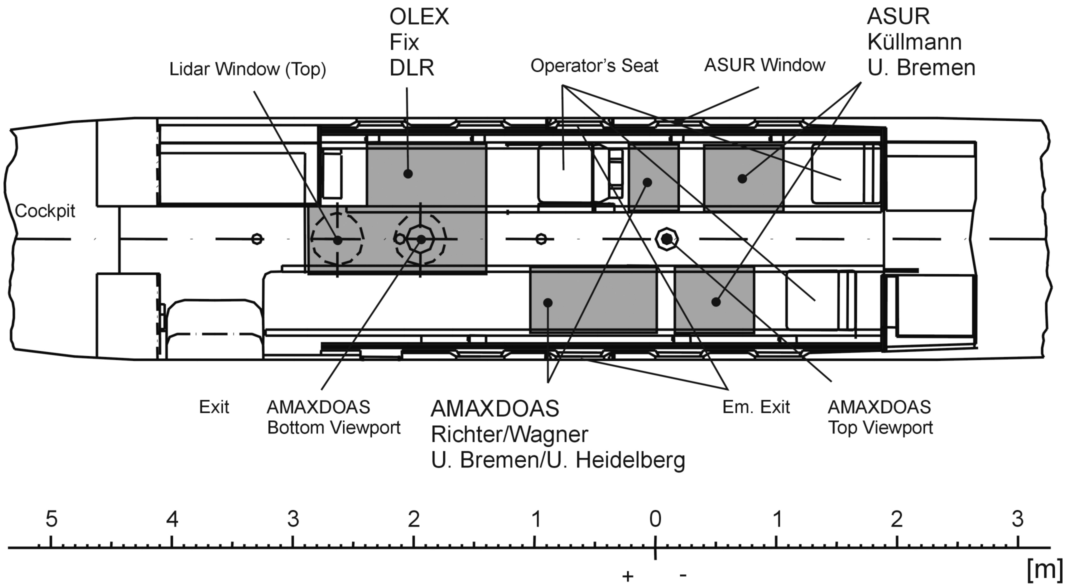

Fig. 3. Falcon aircraft payload during SCIA-VALUE.

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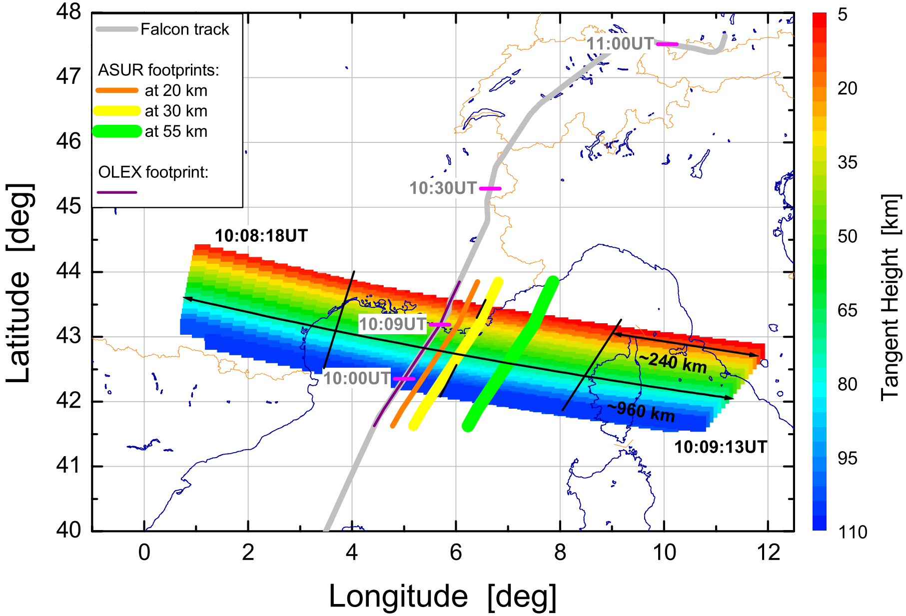

Fig. 4. The panel gives an indication of the footprints of OLEX and ASUR in relation to the SCIAMACHY limb measurements. On 28 September 2002, the Falcon crossed a SCIAMACHY pixel (Orbit No. 3025, state index 12) near Marseille, France, in northerly direction (gray line with time markers). At each tangent height of the SCIAMACHY measurement (height step = 3 km) the total swath of 960 km is divided into 4 separate measurements (read-outs) of ~240 km width. Details on the viewing geometry of SCIAMACHY can be found in (Bovensmann et al., 1999).

OLEX is zenith viewing. Due to its narrow field of view and a signal integration time of 4 min its footprint is ~50 km along track and 20 m across track, only. For ASUR the situation is somewhat different due to its elevation angle of 12°. In cross track direction the footprint thus ranges from 14–200 km which is indicated in the panel for three different heights of 20 km, 30 km, and 55 km, respectively. The along track spatial resolution for ozone is about 18 km. For the AMAXDOAS footprint, see text.

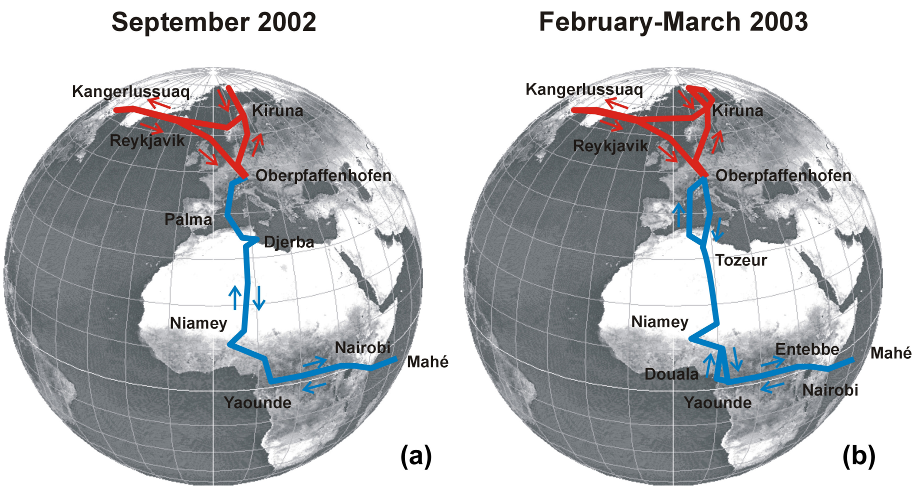

Fig. 5. **(a)** Northern flight route (red line) from Oberpfaffenhofen – Spitsbergen – Kiruna – Greenland and back on 3–7 September 2002 and southern flight route (blue line) from Oberpfaffenhofen – Yaounde – Nairobi – Mahé and back on 15–28 September 2002. **(b)** Southern flight route (blue line) from Oberpfaffenhofen – Yaounde – Nairobi – Mahé and back on 19 February–3 March 2002 and northern flight route (red line) from Oberpfaffenhofen – Spitsbergen – Kiruna – Greenland and back on 10–19 March 2003.

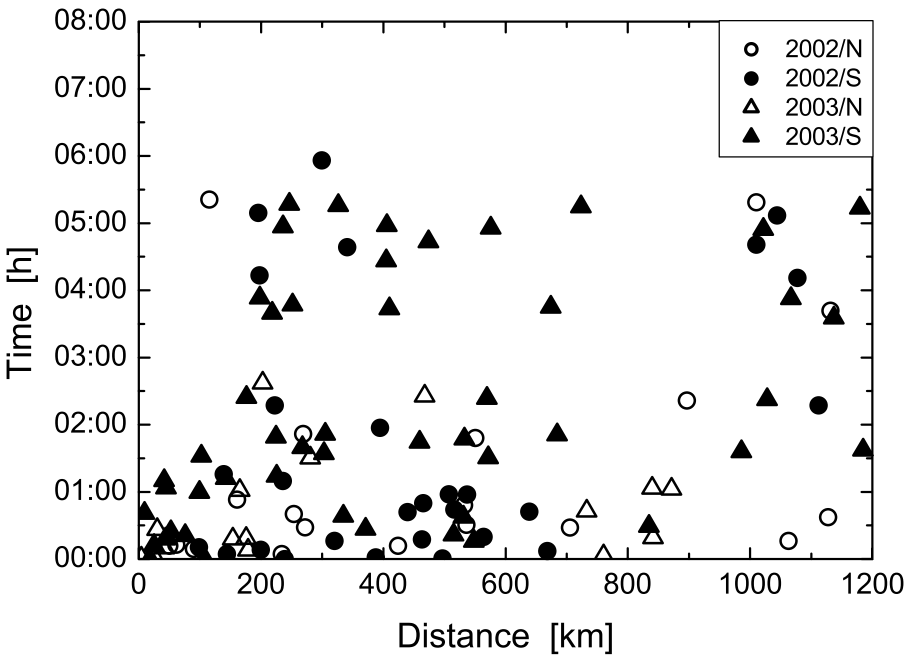

Fig. 6. Time-distance diagram of the coincidences with SCIAMACHY limb scans. Circles and triangles denote the matches in 2002 and 2003, respectively. Open symbols represent the northern parts of the respective flights, the closed ones the southern parts. In summary, 99 coincidences were met within the match criterion (<6 h, <1000 km).

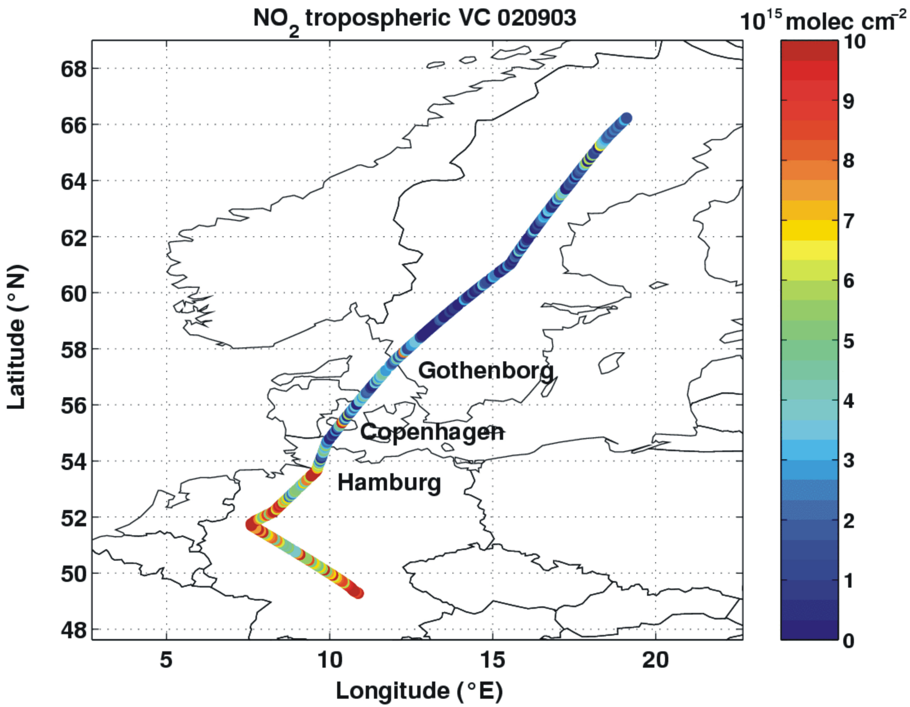

Fig. 7. AMAXDOAS tropospheric NO_2 vertical columns along the flight track on 3 September 2002 from Oberpfaffenhofen to Kiruna. Enhanced NO_2 columns are observed in regions affected by tropospheric pollution.

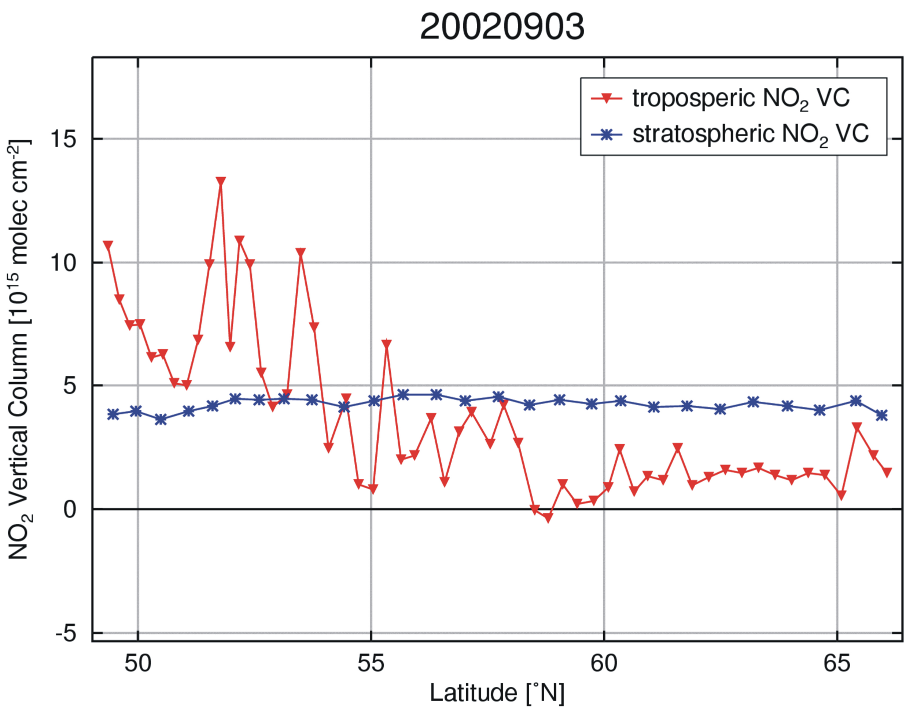

Fig. 8. AMAXDOAS vertical NO_2 columns for the stratosphere (blue) and troposphere (red) for the same flight as for Fig. 7. The stratospheric NO_2 did not change much during the flight, whereas in the troposphere pollution leads to strongly varying columns.

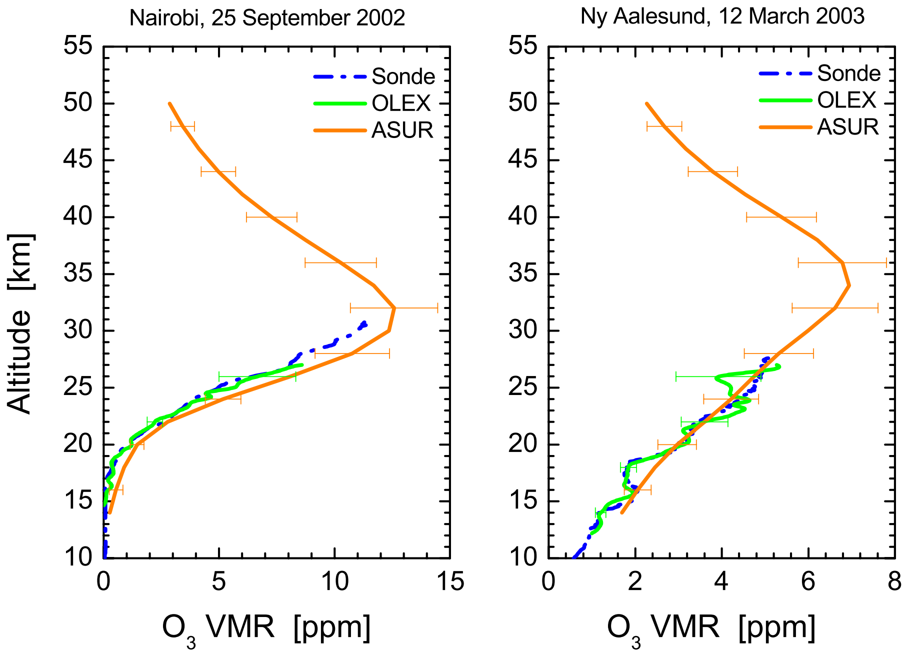

Fig. 9. ASUR, OLEX, and sonde O_3 profiles. Ozone sondes were launched in Nairobi (1.27° S, 36.80° E) at 07:23 UT and in Ny Ålesund (78.93° N, 11.95° E) at 10:54 UT. Corresponding ASUR measurements including error bars are at 06:52 UT (0.61° S, 34.60° E) and at 09:28 UT (78.83° N, 12.42° E), respectively. OLEX and ASUR profiles were recorded within a time difference of less than 10 min.

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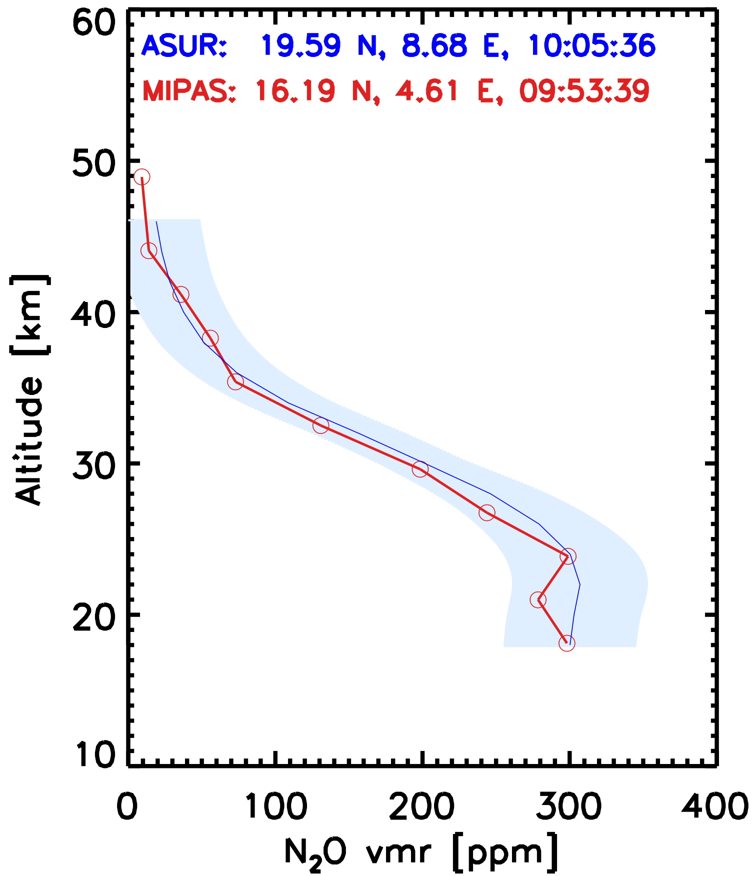

Fig. 10. Typical N_2O profile as measured by ASUR (blue line) including its error (shaded area). The data was recorded on 26 September 2002 south of the Saharan desert. The red line shows data retrieved from the MIPAS instrument on ENVISAT in comparison. Times and geolocation of the measurements are also given.

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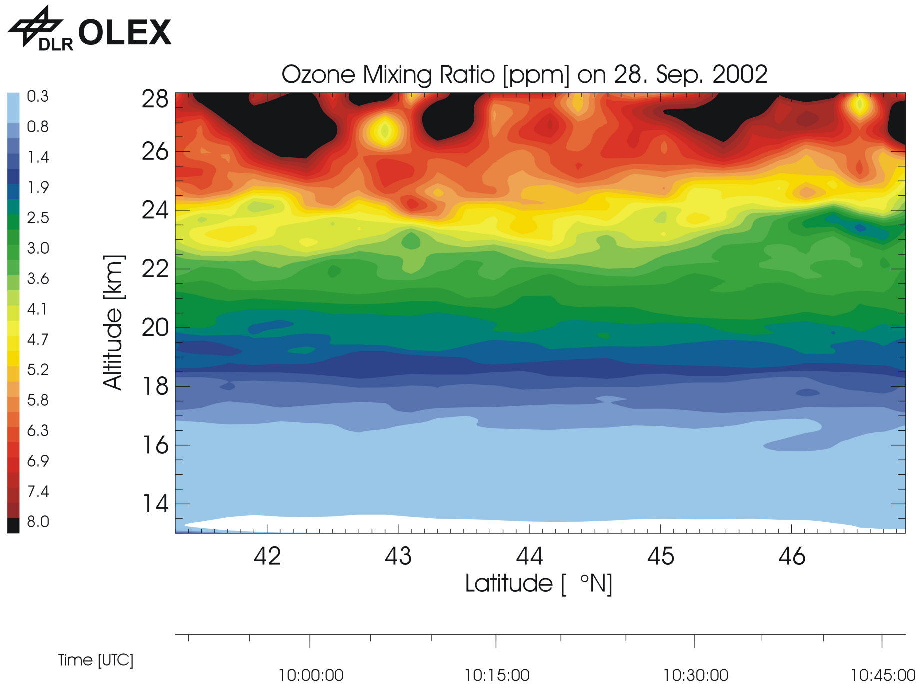

Fig. 11. OLEX measurement of the ozone distribution on the measurement flight on 28 September 2002. The Falcon flight pattern is given in Fig. 4. The overpass of SCIAMACHY took place at 10:09 UTC around 43° N.

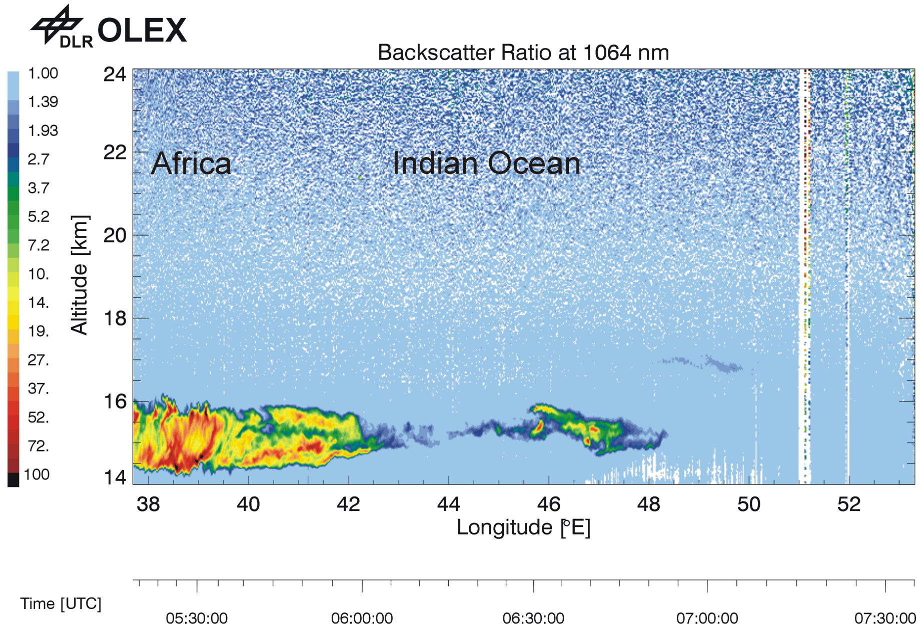

Fig. 12. OLEX measurement of the backscatter ratio at 1064 nm on the flight of 19 September 2002 from Nairobi to Mahé. An extended thin cirrus layer is seen that extends from the African continent into the Indian Ocean.

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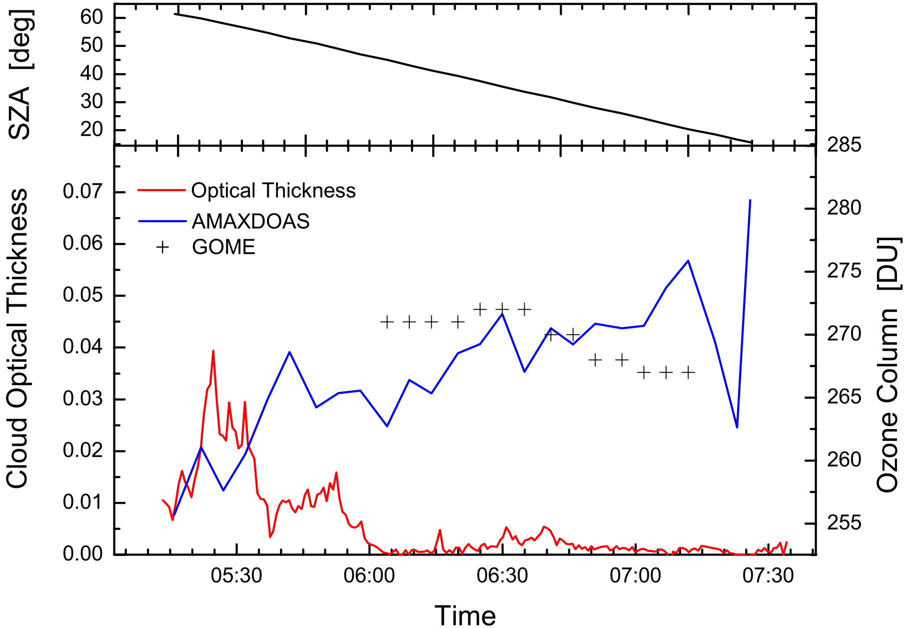

Fig. 13. Optical thickness (red line) of the thin cirrus clouds (see Fig. 12) observed on the flight from Nairobi to Mahé on 19 September 2002 calculated assuming a lidar ratio of 30 sr and the ozone column derived by AMAXDOAS (blue line) for the same flight leg. The crosses denote a corresponding ozone column measurement by GOME. As the solar zenith angle is important to estimate the error in the DOAS retrieval its value along the flight track is given in the upper panel. In the area affected by the cloud, the apparent O_3 column is lower by about 5% in agreement with the estimate based on radiative transfer calculations. For further details, see text.

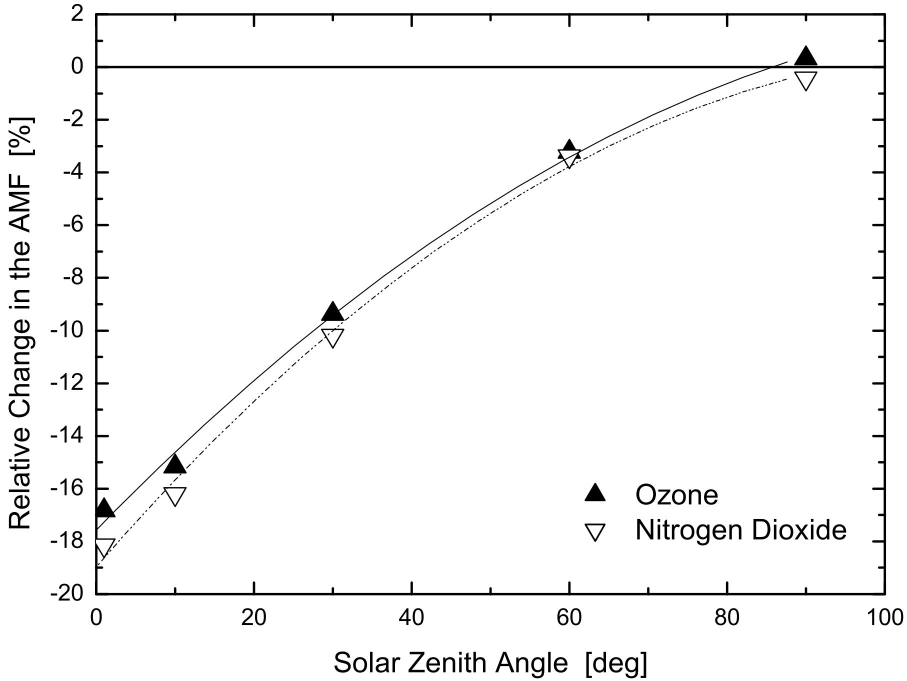

Fig. 14. Relative change of the AMF for stratospheric O_3 and NO_2 plotted as function of solar zenith angle. The cloud free case was used as norm and the influence of the cirrus clouds is given relative to this value. For a SZA of 57° a relative change of about −5% is given for the O_3-AMF which results in a 5% underestimation of the O_3 column when neglecting the cirrus cloud.