SCIAMACHY VALIDATION BY MEASUREMENTS FROM AIRCRAFT PLATFORMS

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ABSTRACT

The first airborne main validation campaign has been successfully completed in September 2002 as part of the German Contribution to the Validation of SCIAMACHY level 2 and off-line data products. The three different remote sensing instruments, ASUR, AMAXDOAS, and OLEX aboard DLR's meteorological research aircraft Falcon 20, enabled simultaneous measurements of a number of important SCIAMACHY data products such as O_3, NO_2, N_2O, NO, BrO, H_2O, Aerosols and clouds for the first time. From extended latitudinal cross sections running from polar regions up to the tropics as well as longitudinal cross sections at polar latitudes at about 70°N, a unique data set has been generated which will enable detailed analysis of SCIAMACHY performances in different climates and at various geophysical locations. A second main validation campaign is planned to take place in February/March 2003.

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. It has been developed jointly by The Netherlands, Belgium and Germany as their national contribution to the ESA ENVISAT programme. SCIAMACHY measures electromagnetic radiation that is back scattered, reflected and transmitted from the atmosphere in the solar and near infrared spectral region in a variety of different viewing geometries. The measured spectrum contains the finger prints of absorbing and emitting species and, with this, information on the trace gas concentration of the atmosphere. Inversion of these measurements yields the amounts and distributions of stratospheric and tropospheric constituents.

The SCIAMACHY instrument has many unique features: its limb measurements will provide global information about the mesosphere, stratosphere and upper troposphere, its nadir measurements will yield total column measurements of key tropospheric and stratospheric constituents, and the combination of limb and nadir sounding will yield measurements of important atmospheric constituents of the troposphere [1]. In order to assess the quality of the SCIAMACHY data, dedicated validation is essential. The large volume and high quality of the SCIAMACHY data will require strong validation efforts. Particular attention is needed for the validation of vertically resolved data products. For validation of vertical trace gas profiles measured by SCIAMACHY balloon-borne measurements are performed.

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However, the most important restriction of the validation with balloon soundings is their limited number and thus their limited spatial and temporal coverage. Airborne campaigns will help to overcome this deficiency using state-of-the-art instrumentation to accurately measure atmospheric trace gases and aerosols. Moreover aircraft possess high flexibility to achieve close temporal and spatial coincidence with satellite overpasses almost everywhere on the globe and under most weather conditions.

This project is embedded in the German Contribution to the Validation of SCIAMACHY level 2 and off-line data products with measurements performed aboard DLR's meteorological research aircraft Falcon 20. The activity is closely related to balloon-flights also proposed as part of the SCIAMACHY validation effort. It particularly addresses extensive measurements in the frame of two main validation campaigns with a series of flights in the northern, mid- and tropical-latitudes, preferable in summer and winter times to observe seasonal variability.

The goal of this paper is to give a brief overview about the overall measurement strategy of this project which includes selection of both proper instrumentation and adequate flight routes to achieve the validation objectives. Detailed results from individual instruments as received from the first main validation campaign are listed separately [2-5].

2 INSTRUMENTS AND DATA PRODUCTS

In order to address a large number of data products, three different types of remote sensing instruments have been selected: The Airborne SUbmillimeter wave Radiometer (ASUR), operated by the University of Bremen, the Ozone Lidar EXperiment (OLEX) operated by DLR Oberpfaffenhofen and the Airborne MultiAxis Differential Optical Absorption Spectrometer AMAXDOAS developed and operated jointly by the University of Bremen and the University of Heidelberg. Each of the proposed instruments have already demonstrated their uniqueness in performing high quality trace gas measurements from an airborne (aircraft and/or balloons) platform. A summary of the data products from individual instruments is shown in Fig. 1. In the following sections brief description of each instrument and their contribution to SCIAMACHY data validation is given.

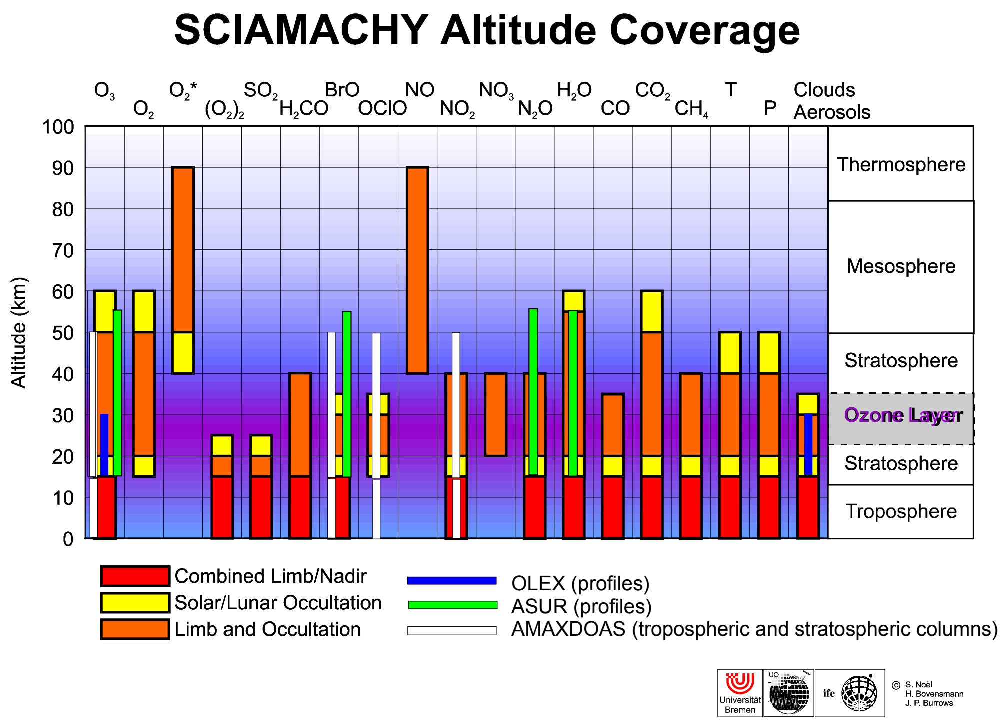

Fig. 1: Target species of the three instruments ASUR, OLEX and AMAXDOAS compared to SCIAMACHY data products. We note while ASUR and OLEX measure profiles the AMAXDOAS instrument provides stratospheric and tropospheric columns.

2.1 The ASUR Sensor

The Airborne Submillimeter Radiometer (ASUR) is a passive heterodyne sensor working in the frequency range 605 - 662 GHz. It detects thermal emission lines from stratospheric constituents such as ClO, HCl, N_2O, O_3, HNO_3, CH_3Cl, H_2O, HO_2, NO and BrO. Using non-linear inversion techniques 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. ASUR measures volume-mixing-ratio (VMR) profiles along the flight producing 2-dimensional cross sections of stratospheric composition, and also provides stratospheric columns 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 Helium-cooled superconducting sensor used in the ASUR receiver exhibits very low noise, and hence has a high sensitivity. The high stability and reproducibility of the measurements performed with ASUR make this technique well suited for validation campaigns of space borne sensors as successfully done for UARS (MLS, HALOE) [6], ATLAS (MAS), ERS-2 (GOME) and ADEOS (ILAS). During SCIA-VALUE the main objective of the ASUR instrument is the validation of operational level-2 near-real time, and off-line data products provided by the SCIAMACHY instrument such as O_3, N_2O, H_2O, BrO and ClO. The measured vertical profiles and column densities will be compared with the SCIAMACHY data products, differences will be analysed with respect to parameters affecting the SCIAMACHY data retrieval such as location and solar zenith angle, and recommendations on possible improvements will be given.

2.2 AMAXDOAS

The AMAXDOAS has similarities to SCIAMACHY as it measures the radiance reaching the aircraft from a selected set of viewing angles. The instrument basically consists of an UV/visible grating spectrometer with a CCD detector. It is similar to those widely used in ground-based and balloon-borne applications since many years. For the coverage of the whole UV-vis spectral range with an appropriate spectral resolution two AMAXDOAS instruments, one for the UV (≈300 to 400 nm) and one for the visible (≈400 to 700 nm) are required. To get some information on the vertical profiles of the measured species a new viewing geometry is applied measuring light from different directions below and above the aircraft. This set of (4 to 10) different atmospheric absorption paths allows (at least) to determine the vertical column densities separately for the stratosphere and the troposphere. This separation is of great importance for the validation of SCIAMACHY measurements because from the combination of Limb and Nadir observations it is possible to determine the tropospheric and stratospheric trace gas column densities for a number of species measured by SCIAMACHY. For some atmospheric trace gases (most probable for O_3 and NO_2) it will even be possible to resolve the atmospheric trace gas profiles with higher vertical resolution. A pre-cursor 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 [7].

2.3 The OLEX Instrument

OLEX is an active sensor measuring the atmospheric backscatter at four wavelengths 308, 355, 532, and 1064 nm with the additional capability to measure the cross-polarised return at 532 nm for particle phase discrimination. In the zenith looking mode the system provides high resolution two-dimensional cross sections of ozone number densities, aerosol extinction, and cirrus cloud cover information from about 2 km above aircraft flight level up to a height of 30 km. The ozone distribution will be calculated from 308 nm (absorbing wavelength) and 354 nm (non-absorbing wavelength) return signals using the well established differential-absorption LIDAR technique. The vertical resolution of the retrieved ozone profiles is better than 1 km. The horizontal resolution is limited by the integration time, and is better than 50 km. The particular high vertical resolution which can easily be matched to the resolution obtained by SCIAMACHY in limb mode make OLEX an excellent instrument for validating purposes. A key element for the validation are the aerosol extinction profiles not available from other instruments, and furthermore aerosol extinction data also needed for the AMAXDOAS retrieval. 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, SESAME on board of a Transall aircraft and recently during THESEO on the Falcon [8].

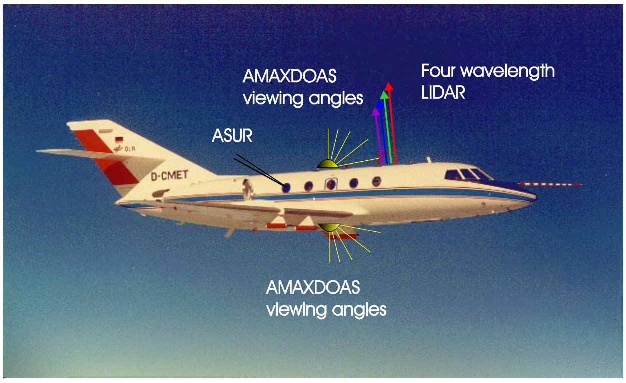

Fig. 2: The meteorological research aircraft Falcon 20 from DLR equipped with the three remote sensing instruments ASUR, AMAXDOAS, and OLEX for airborne validation of SCIAMACHY data products O_3, N_2O, NO_2, BrO, ClO, H_2O, OClO, and cloud and aerosol optical properties

2.4 The DLR Aircraft Falcon 20

The meteorological research aircraft Falcon 20 (D-CMET) operated by the German Aerospace Center (DLR) is a well established research platform for more than 20 years. Many features were added to the aircraft in order to allow the deployment of various in situ and remote sensing experiments including two large optical windows (diameter 40 cm) in the bottom and various other holes in the fuselage. For the ASUR instrument the rear passenger window on the right side has been replaced by a specially manufactured polyethylene window, transparent for microwaves. The increasing demands of the scientific users led to additional modifications over the last years: In 1995 the aircraft performance was significantly enhanced by new engines and electric generators. Additional remote sensing windows were added in 1997 (40cm diameter on the roof) and 1998 (universal adapter in a window plate). The aircraft carries a data acquisition system and an extensive instrument package capable of measuring for example position, altitude, static pressure and temperature The Falcon has a maximum endurance of 5h carrying a payload of 1100 kg and a maximum operating altitude of 45000ft. Due to the modifications (windows for LIDAR measurements nadir and zenith viewing) and the excellent range/height performance, the DLR Falcon is the only airborne European platform suitable for the proposed experiment. Fig. 2 shows the Falcon aircraft and viewing geometries of the three individual instruments. Details to the performance of the Falcon can be found at http://www2.dlr.de/FB/OP .

3 AIRCRAFT FLIGHT ROUTES

Airborne validation will be performed during two major campaigns in the northern hemisphere. Each campaign consists of several flight missions for dedicated case studies in the mid-latitude/Arctic as well as mid-latitude/tropical region. The different instruments ASUR, AMAXDOAS, and OLEX installed on the Falcon platform will be used to complement localised ground-based and balloon-borne validation efforts. Comparison with ground-based measurements is intended to be achieved at instrumented sites in the north: Bremen (53°N, 8°E, DOAS), Kiruna (68°N,20°E, DOAS, Lidar), and Ny-Ålesund (79°N, 12°E, DOAS, Lidar, MW).

The northern route indicated in Fig. 3 extends from Munich via Kiruna in northern Sweden to Spitsbergen and then across the Northern Atlantic to Iceland and Greenland. This enables both pollution measurements over Europe and studies of the composition of the stratosphere at the end of the summer prior to the development of the polar vortex.

The southern route shown in Fig. 4 ranges from Munich to Cameroun on the west side of Africa and then across to Kenya and to the Seychelles. This route has as its major objective the validation of SCIAMACHY data products of significance for air quality and the study of biomass burning, thunderstorms, and convective uplifting.

Fig. 3 Northern flight route from Munich - Spitsbergen -Kiruna - Greenland and back on 03-07/09/2002

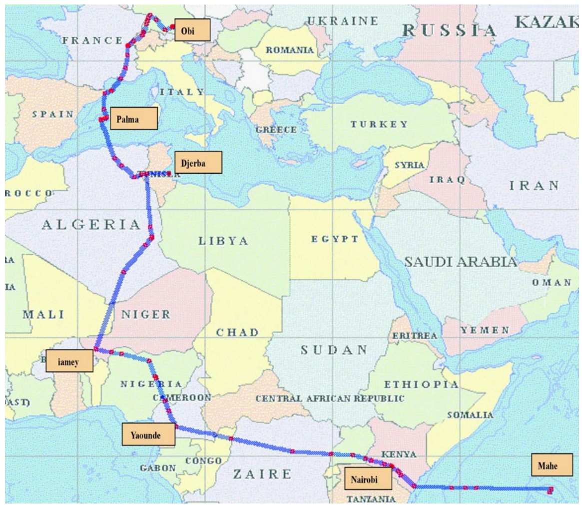

Fig. 4 Southern flight route from Munich -Yaounde - Nairobi -Mahé and back on 15-28/09/2002

4 FIRST MAIN VALIDATION CAMPAIGN

4.1 Orbit Selection

The first main campaign provided extended longitudinal and latitudinal atmospheric cross sections at various geophysical locations as planned. Starting in Oberpfaffenhofen near Munich on September , 3rd the campaign consisted

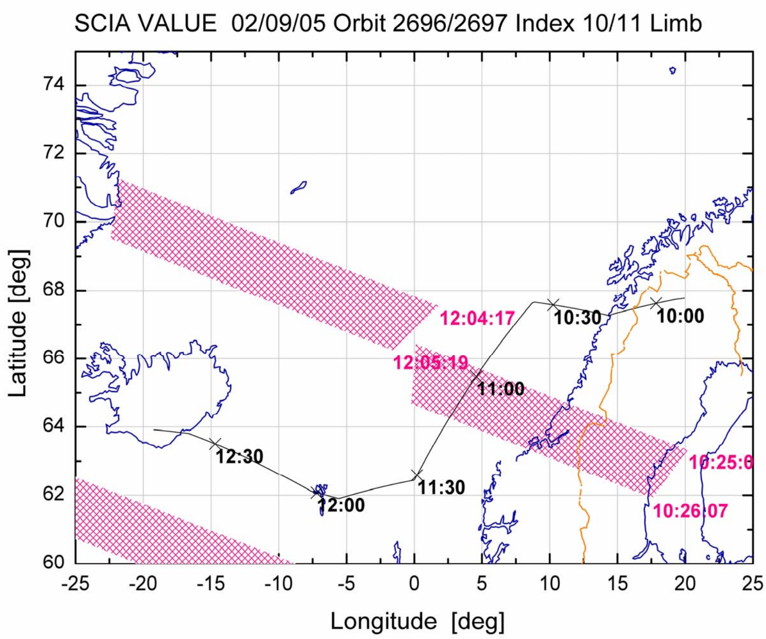

Fig. 5 SCIAMACHY limb pixel (red) of two adjacent orbits at high latitudes in the north. Footprint and timing of the limb pixels are taken from http://atmos.af.op.dlr.de/projects/scops/. The Falcon flight leg from Kiruna to Iceland is indicated by the black solid line.

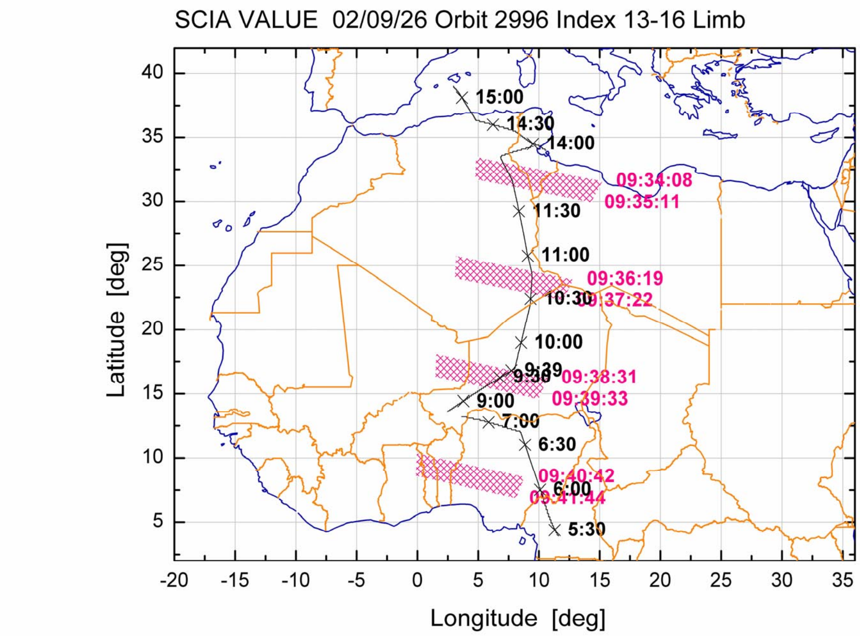

Fig. 6 Successive SCIAMACHY limb pixel and timing (red) of orbit 2996 as taken from http://atmos.af.op.dlr.de/projects/scops/. The Falcon flight route heading from Yaounde to Mallorca consists of three legs as indicated by the black solid lines.

of 14 legs to high and low latitudes each, while instruments collected data along 18 ENVISAT orbits. Missions in the east west direction at high latitudes have been flown, where more than one adjacent orbit of SCIAMACHY could be linked as shown in Fig. 5. Fig. 6 depicts another example from the southern flight route over the Saharan desert where up to 4 successive limb/nadir pixel of orbit 2996 could be underflown.

In most cases, the aircraft flight plan could be organised in order to obtain very good temporal and spatial coincidence

Tab. 1: 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 Route					
02/09/03	2667	10,11,12	Munich - Kiruna	08:00	10:30
02/09/04	2685, 2686	7,5	Kiruna - Kiruna via Spitzb.	16:00	19:30
02/09/05	2696,2697	10,11	Kiruna - Keflavik	10:00	13:00
02/09/06	2712, 2713	10. Nov	Keflavik - Sondre	12:50	15:00
02/09/07	2726, 2727	10	Sondre - Keflavik	12:30	14:30
02/09/07	2730	Occultation 61.8° lat., 351.9° lon.	Keflavik - Munich	18:20	22:00
Southern Route					
02/09/15	2839	12	Munich - 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 - Seychelles	05:00	07:30
02.09.24	2966	17,18	Seychelles - 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 - Munich	09:30	11:00

with the SCIAMACHY observations. About 56 flight hours within a period of 3-4 weeks have been used in total. A summary of the flight legs, orbits crossed as well as the Falcon departure and arrival times is given in Tab. 1.

4.2 Data Products and Instrument Performances

AMAXDOAS spectra in 4 viewing directions have been continuously measured in the visible and UV wavelength range during all flights of the campaign. 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 degrees. Wavelength calibration and dark signal measurements could be performed nearly every day during the campaign, and an attempt of a radiometric calibration was undertaken both before the first flight and during the stop in Oberpfaffenhofen between the two flight legs. After the last flight, an instrument function calibration was also performed. No serious instrumental problems occurred during the flights with the exception of the time period after the take off from Niamey when the Falcon was very warm and the instrument took about one hour to come back to thermal stability. The instrument performed as expected and is in good shape for the next campaign. From data quality checks and first quick look analysis high data quality is expected and good product accuracy throughout most of the measurements. Data analysis will take several months, and first preliminary results are shown in [2,3].

ASUR measured during all flights on both the northern and the southern route. Focus has been put on O_3 and N_2O. A comparison with SCIAMACHY ozone vertical profiles will be possible for nearly all of the performed satellite underflights. In most cases several ozone measurements have been accomplished above the area of one ground pixel to account for atmospheric variability. Profile comparisons for the molecule N_2O will also be possible for several SCIAMACHY ground pixels at different latitudes. Judged from the spectra the quality of ASUR ozone and N_2O data is good at all latitudes. A slight decrease in data quality might have occurred in the Sahel region due to overheated spectrometers. Ozone retrievals should be feasible in an altitude range between 15 and 50 km. If additional data from the newly implemented high-resolution spectrometer is used, the altitude range will be extended to 65-70 km. N_2O retrievals should be feasible in an altitude range between about 15 and 40 km. Further, NO was measured every 10-20 deg latitude with adequate data quality. Spectra for H_2O and BrO were also obtained. The instrument operated well during the whole campaign, only a few minor technical problems occurred. ASUR is currently checked in the laboratory and prepared for the upcoming winter/spring campaigns. No major problems are expected. Details of the measured profiles are given in [4].

Profiles of aerosol backscatter and ozone concentration along the flights have been measured with the OLEX system during all flights of the campaign. Comparison of particle backscatter coefficients and ozone observed with the lidar and the data from the SCIAMACHY instrument are possible from flight level up to about 27-30 km for the north route. Good measurement conditions, i.e. no high cirrus above the flight level, prevailed during nearly all northern flights except on the 6^{th} leg from Greenland to Keflavik, 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 by high background solar radiation entering the telescope. High quality ozone data is expected to an altitude of ~27 km. Small data gaps exist when the lasers shut off due to overheating which occurred at the very high 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 the tropopause. Mostly the SCIAMACHY pixels were met quite accurately. In the cases where some spatial deviation occur, the very homogeneous stratospheric conditions during the flights on the scales in question will probably allow a precise merging of the two data sets. Except the above mentioned small gaps due to overheating, OLEX operated reliably. Thus, there is no requirement necessary for modifying either the system nor the flight strategy for the upcoming spring campaign. Details of the measurements are outlined in [5].

5 SUMMARY

Validation of the measurements from space-borne sensors such as SCIAMACHY is a pre-requisite for the assessment of their quality and their use in both scientific and operational applications. The validation by airborne platforms is a cornerstone of the first phase of the SCIAMACHY Validation, taking place in the first year of the instrument's mission. This project comprises a complementary and novel set of experiments which provide validation of the SCIAMACHY data products from the mesosphere to the ground. The data collected by the combined airborne instruments ASUR, AMAXDOAS, and OLEX during the first main validation campaign form an unique data set for the validation of SCIAMACHY operational level 2 and off-line data products at various geophysical locations in the northern hemisphere. The DLR Falcon has proven to be an excellent platform for extensive validation campaigns in the northern, mid-latitude and tropical regions. During 14 legs to high and low latitudes the instruments collected data along 18 ENVISAT orbits. Missions in the east west direction at high latitudes have been flown, where more than one adjacent orbit of SCIAMACHY could be linked. The aircraft flight plan could be organised in order to obtain very good temporal and spatial coincidence with the SCIAMACHY observations in most cases. About 56 flight hours within a period of 3-4 weeks have been used in total.

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