

MIPAS VALIDATION WITH THE DLR FALCON

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ABSTRACT

The DLR airborne water vapour differential absorption lidar (H₂O DIAL) was employed as the core instrument on board the research aircraft Falcon 20 to validate the water vapour products of MIPAS on ENVISAT. During a dedicated campaign which was co-ordinated with the high-flying aircraft M55 Geophysika the H₂O DIAL measured the 2-dimensional water vapour distribution as well as aerosol properties on several flights at mid latitudes between 37N-52N. Additional goals next to the validation of MIPAS was the intercomparison of the results with several of the passive remote sensing and in-situ instruments aboard the Geophysika and, if applicable, the measurement of small-scale structures in the tropopause region. Several in-situ instruments on the Falcon to measure H₂O, O₃, and aerosol properties contributed to this task. In this Paper, a representative overview is given about the results achieved during this validation campaign which was based in Forlì, Italy and took place in October 2002.

1. INTRODUCTION

Water vapour plays a fundamental role for chemistry, dynamics, and the radiation budget of the atmosphere. Despite its importance to atmospheric processes over a wide range of spatial and temporal scales, water vapour in the upper troposphere and lower stratosphere (UT/LS) is one of the least understood and poorly described components of the Earth's atmosphere. MIPAS on ENVISAT continuously observes the atmosphere on a global scale down to about 6 km and is expected to deliver high quality profiles of water vapour also in this region of the atmosphere. In order to establish the reliability and accuracy of these water vapour measurements an adequate data set for the validation has to be derived from independent measurements. Particularly, airborne measurements are an important component of the ENVISAT validation activities, because they provide the flexibility to sound the atmosphere exactly where the satellite instrument is measuring and are in general less affected by meteorological conditions than ground-based measurements.

In order to help validating the water vapour level-2 data products of MIPAS the DLR near-infrared airborne water vapour differential absorption lidar (H₂O DIAL) was employed as the core instrument on board the research aircraft Falcon 20. During a dedicated campaign which took part in October 2002 in Forlì, Italy, the H₂O-DIAL was used to measure 2-dimensional cross sections of water vapour and aerosol above the aircraft flight level near the tropopause region on several flights (at both daylight and night-time) at mid-latitudes. This campaign was co-ordinated with the mid-latitude validation activities of the high-flying aircraft M55 Geophysika which is major component of ESA's airborne validation activities of ENVISAT. A second objective of this campaign was to perform correlative measurements with the instruments aboard the Geophysika, in particular the remote sensing chemistry instruments MIPAS-STR and SAFIRE-A as well as the in-situ sensors for water vapour (FISH, FLASH) and the aerosol instrumentation (MAL, MAS, FSSP, ABLE).

The advantage of the lidar technique for validation purposes is that the geophysical quantity as function of altitude can be determined with great accuracy and high resolution. In addition, the instrument parameters can be tuned to adapt resolution, accuracy and range to the validation requirements. The H₂O DIAL was specifically designed to be run at the strong 3v vibrational absorption band of water vapour lying in the 940 nm spectral region. It therefore has the advantage of a high measurement sensitivity in regions of low water vapour content in the UT/LS. At the same time the residual pump radiation at the fundamental and second harmonic of the pump laser (1064nm and 532nm) is used to measure the aerosol backscatter on two orthogonal polarisations for each wavelength. Consequently, the H₂O-DIAL is an excellent instrument for the validation of the MIPAS water vapour products and aerosol in the UT/LS region of the atmosphere.

Fortunately, a number of in-situ instruments could additionally be installed on board the Falcon and measured water vapour, ozone, and aerosol properties at flight altitude and helped to improve the quality of the collected data set.

In the following Chapter a brief description of the H₂O DIAL system and the in-situ instrumentation of the Falcon is given. It is followed by a report about the operational aspects during the Forlí campaign. Finally, measurement results will be presented with the focus on the few cases where MIPAS data are already available. These results also demonstrate the quality of the lidar data.

2. INSTRUMENTATION

2.1. The H₂O DIAL Instrument

Owing to its spectral properties the airborne DLR H₂O DIAL currently is the only system of its kind that is able to precisely measure water vapour at high-tropospheric or low-stratospheric concentrations [1-4]. Its schematic set-up is shown in Fig. 1. The DIAL transmitter is based on an injection seeded OPO at a wavelength of 935nm using the nonlinear crystal KTP. The OPO is pumped by the second harmonic of a Q-switched, diode-pumped Nd:YAG laser. This laser operating at a repetition rate of 100 Hz provides an average output power of more than 20 W in a single longitudinal mode at 1064 nm. Approximately 50% of the fundamental energy at 1064 nm is converted to the second harmonic. With a pump energy of 110 mJ a signal output energy of ~14 mJ at 935 nm is achieved, resulting in an average power of 1.4 W. The rest of the laser light at 1064 nm and 532 nm is used for high-spatial-resolution aerosol backscatter measurements.

The DIAL technique requires the transmitter bandwidth to be an order of magnitude narrower than the width of the

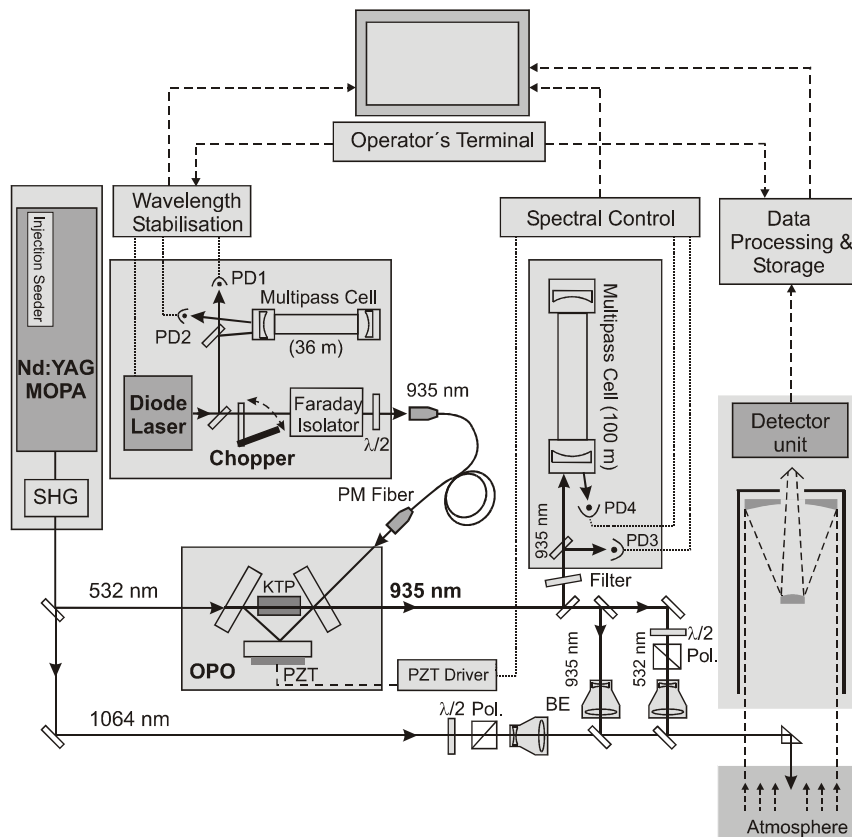


Fig. 1: Schematic set-up of the H₂O DIAL system

Table 1: Summary of the DLR H₂O-DIAL system characteristics

Wavelength (nm)	935 +/- 15	1064	532
Pulse energy (mJ)	12	50	40
Repetition rate (Hz)	50 (on/off)	100	100
Pulse length (ns)	7	15	11
Bandwidth (GHz)	0.14 / 90	0.05	0.05
Spectral purity (%)	> 99	---	---
Detector	Si:APD	Si:APD (s & p pol)	PMT (s & p pol)
Filter FWHM (nm)	1	1	1
Filter trans. (%)	65	40	55
Telescope	Cassegrain, Ø35 cm; field-of-view: 1 - 2 mrad		
Data acquisition	14 bit, 10 MHz		

absorption line, which amounts to approximately 1-2 GHz for UT/LS water vapour. Here, spectrally narrowband OPO output is achieved by means of injection seeding using a single-mode diode laser. A H₂O absorption cell with an effective path length of 36 m is used for wavelength calibration and stabilisation. The seed beam is injected into the OPO cavity via a single mode polarisation maintaining (PM) fiber and the OPO cavity is actively matched to the seed wavelength. The signal bandwidth of the OPO at 935 nm is on the order of 140 MHz when seeded and approximately 90 GHz (0.26 nm) in unseeded operation. Since the spectral width in unseeded operation is much broader in comparison to the linewidth of one particular water vapour absorption line (1-2 GHz), the unseeded multimode signal can be used for the nonabsorbing off-line or reference measurement [5]. When tuned to the strongest line at 935.684 nm, the broadband OPO signal absorption is only 3% of the on-line absorption. Dual-wavelength operation is therefore simply achieved by chopping the seed beam for successive broad- and narrow-band operation at a repetition rate of 50 Hz. Another important parameter for the precise determination of the water vapour concentration is the spectral purity of the DIAL transmitter which, in the present configuration, is monitored on a shot-to-shot basis using a 100-m absorption cell. The transmission of this cell is simultaneously used to apply a computer-controlled feedback loop to minimise the spectral purity. During in-flight conditions values of the spectral purity of ~99% can routinely be achieved over most of the time.

The DIAL aboard the aircraft can be positioned to look either downward or upward. The latter was, for the first time (apart from test flights), employed during the described validation activities. The backscattered photons are collected by means of a Cassegrainian-type telescope with a diameter of 35 cm. The received light is split into three channels: one for water vapour measurements at 935 nm and two for aerosol measurements at 532 nm and 1064 nm which are further divided to sub-channels for depolarisation detection. The backscattered light, appropriately filtered for solar background radiation, is detected by means of silicon avalanche photodiodes or photo-multiplier tubes, respectively. The signals are digitised 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.

The DIAL system characteristics are summarised in Table 1.

2.2. The in-situ instruments

In order to assist the measurements of the lidar several in-situ instruments could additionally be installed on the Falcon to measure humidity, ozone, and aerosol properties.

A cryogenically cooled frostpoint hygrometer [6] measured the water vapour concentration. This is not only helpful for the monitoring of the humidity at flight level but, together with an UV-absorption photometer [7] to measure the ozone concentration, the flight altitude with respect to the tropopause can be estimated.

The payload for the measurement of aerosol properties consisted of the following instrument package [8]: A Passive Cavity Aerosol Spectrometer Probe (PCASP-100X) measured the size distribution of aerosol particles and cloud droplet residuals (dried to 20% relative humidity) in the diameter range of 0.1 – 3 µm by light scattering. Particle size distributions in the range of 0.3 – 20 µm and 5 - 95 µm particle diameter were measured in-situ by means of two

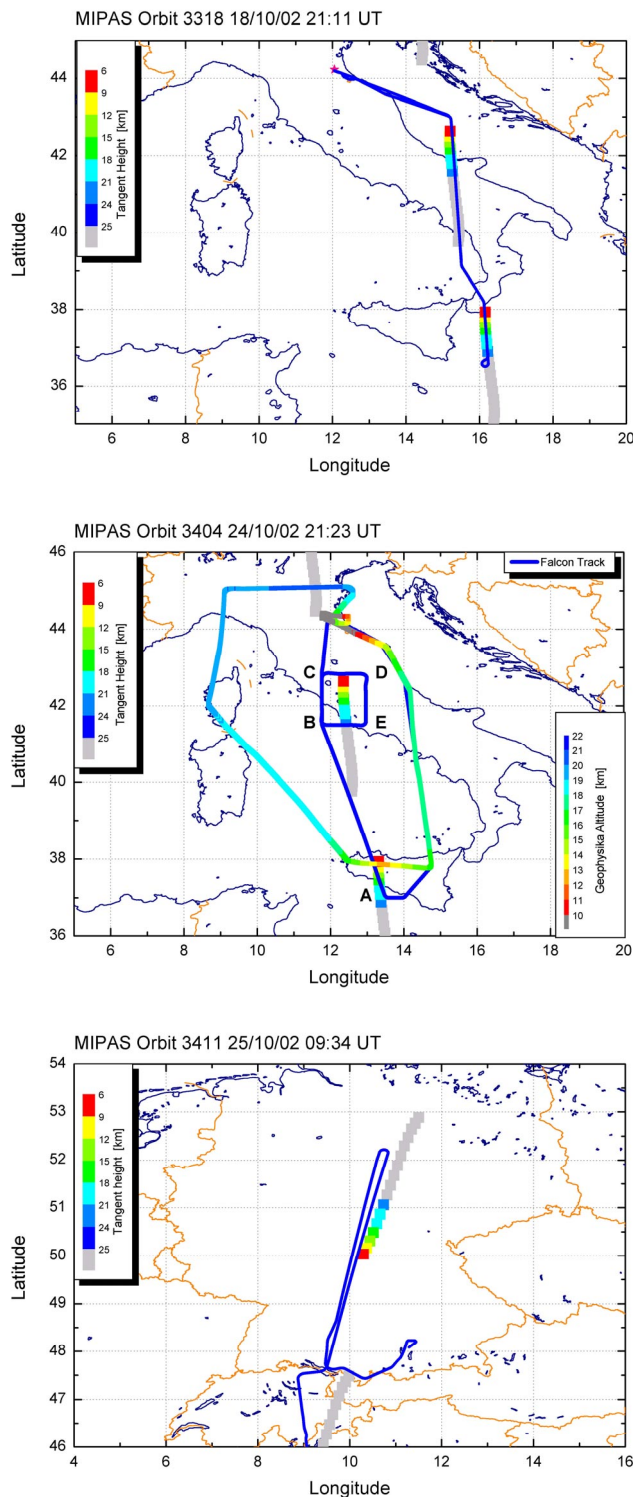


Fig. 2: Falcon flight legs (blue line) for the measurement flights on 18, 24, and 25 October, 2002. On each map the MIPAS elevation scans are shown colour-coded as function of the tangent altitude. A good spatial coincidence was achieved on all these flights. On 24 October (middle panel) the Falcon flight was co-ordinated with the Geophysika. The Geophysika flight leg and altitude (colour-coded) are shown.

Forward Scattering Spectrometers Probes, FSSP 300 and FSSP100, respectively. Information on the particle size distribution in the ultrafine size range was obtained using a Condensation Particle Size Analyser (CPSA), consisting of four condensation particle counters which measured the particle number concentrations of particles > 3.5, 7, 9, 20 nm respectively. A thermodenuder in combination with two condensation particle counters determined the fractions of particles with a diameter of > 14 nm which are stable at 125°C (semi-volatile) and 255°C (non-volatile). The particle absorption coefficient was measured by means of a Particle Soot Absorption Photometer (PSAP), at a wavelength of 565 nm.

Additionally, the aircraft standard instrumentation recorded routinely parameters such as flight attitude, pressure, temperature, wind, and tropospheric humidity.

3. OPERATION

The Falcon validation campaign consisted of a total of 8 flights (plus a technical test flight) including the transfer flights from the Falcon home base in Oberpfaffenhofen to Forli and back which were already organised to match with ENVISAT overpasses. 4 flights each were carried out under night-time and daylight conditions, respectively. Four flights (one at night-time, three at daylight) were co-ordinated with the M55 Geophysika. The aircraft flight plan could be organised in order to obtain very good spatial and temporal coincidence with the expected MIPAS observations in most cases. The largest part of MIPAS scans were met within the Italian air space. A total of 25.5 flight hours have been used within the period 14/10/2002-28/10/2002. A summary of the flight legs, orbits and scans crossed, Falcon departure and arrival times as well as additional information is given in Table 2. Several flight patterns for which in the following Section measurement examples will be given are shown in Fig. 2.

All instruments performed well throughout all flights indicated in Table 1. No serious problems occurred with the exception of icing problems for the DIAL due to a defect air duct during the 3rd flight. This problem could already be fixed during that flight.

Table 2: Summary of the Falcon's flights.

Flight No.	Date	ENVISAT Orbit	MIPAS Scan Index	Flight Leg	Departure [UTC]	Arrival [UTC]
Test	14/10/02			EDMO-EDMO	10:30	12:20
1	14/10/02	3261	7, 8	EDMO-LIPK	18:50	21:15
2) ^{*)+}	17/10/02			LIPK-LIPK	08:45	12:10
3	18/10/02	3318	6, 7	LIPK-LIPK	18:45	21:45
4)*	22/10/02	3368	26, 27	LIPK-LIPK	07:10	10:50
5	23/10/02	3390	7	LIPK-LIPK	18:45	21:50
6)*	24/10/02	3404	6, 7	LIPK-LIPK	18:50	22:10
7	25/10/02	3411	25, 26	LIPK-EDMO	09:05	11:45
8)*	28/10/02	3454	26, 27	EDMO-EDMO	07:10	10:45

EDMO: Oberpfaffenhofen, Germany

LIPK: Forlì, Italy

)^{*} :co-ordinated flight with the M55 Geophysika

)⁺ :Upper-Troposphere-Lower-Stratosphere Mission of the M55 Geophysika

Good measurement conditions for the DIAL instrument, i.e. no high cirrus above the flight level, prevailed during most of the flights except for the first two, where persistent cirrus clouds at or slightly above flight level heavily degraded the measurement performance. A planned flight together with the Geophysika on 21/10/02 had to be postponed due to a forecasted high cloud cover.

For the remaining flights good 2-dimensional cross-sections of water vapour concentration and aerosol backscatter above the flights could be measured up to an altitude of 16km during daylight conditions and somewhat higher at night.

4. RESULTS

4.1. Measurements

In this Section, several results from the DIAL measurement shall be given with the goal to representatively demonstrate the data quality of the measurements. However, the DIAL is still preliminary as further data evaluation is currently going on.

On the evening of 18 October the Falcon flew southward thereby passing two MIPAS elevation scans (see Fig. 2a) of ENVISAT orbit no. 3318. The tangent height of the MIPAS observations between 6-25 km are colour coded in this diagram. The 2-dimensional water vapour field measured by means of the DIAL on this flight from 11.5-17.5 km is shown in Fig. 3. High cirrus clouds were present between 40.6N and 37.8N. Therefore, the water vapour cannot be determined where the clouds block the field of view. The horizontal and vertical resolution of the H₂O volume mixing ratio is altitude dependent. At 11.5km the horizontal and vertical resolutions are 30km and 100m and increase linearly to 60km and 2500 m at 17.5km, respectively. This readily explains the funnel-like shadow of the clouds. Additional cloud information can be obtained by evaluation of the lidar's aerosol channels. From Fig. 3 it can be seen how the tropopause altitude increases towards the turning point at 36.5N which was reached at 20:13 UT. The symmetry around the turning point shows the reproducibility of the measurement.

The next example shown is from a Falcon flight that was co-ordinated with the Geophysika on the evening of 24 October. The flight path of the Falcon (blue) and the Geophysika (colour-coded as function of altitude) can be seen in Fig 2b together with the footprint of the MIPAS observation. The flight pattern was organised to enable comparisons with both the in-situ and remote sensing instruments aboard the Geophysika and to obtain a best possible match of both aircraft with the satellite observation. Again, the Falcon attempted to achieve a coincidence with two MIPAS elevation scans at 38N and 42N of ENVISAT orbit no. 3404. The DIAL result shown in Fig. 4 originates from the flight leg from point A to the North and includes the box (BCDE) that was flown around the MIPAS footprint.

The resolution of the water vapour field as measured by means of the H₂O DIAL is as follows. At 12.9 km the horizontal and vertical resolutions are 12km and 100m and increase linearly to 30km and 2500 m at 16.5km,

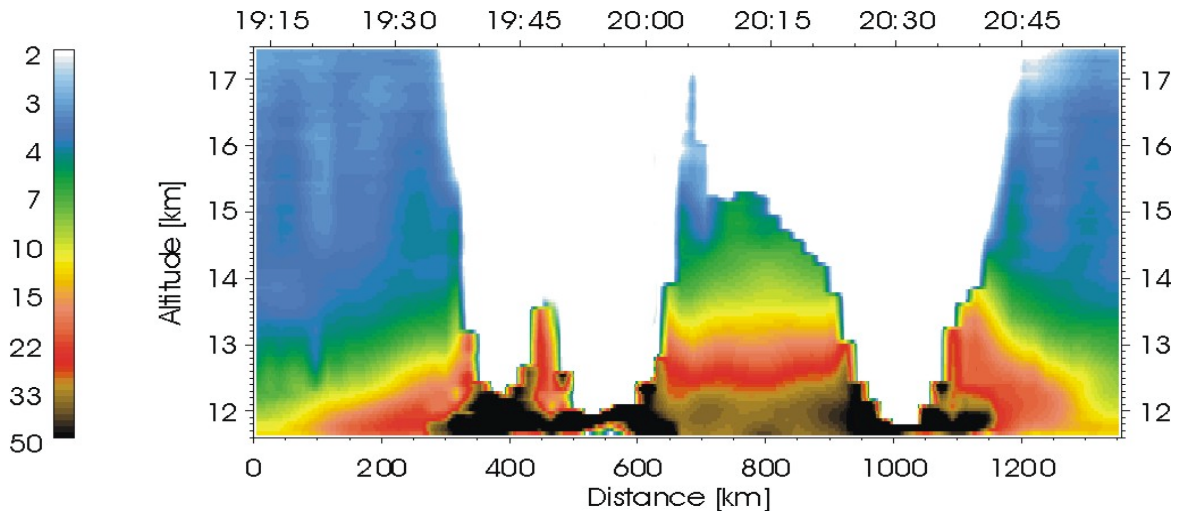


Fig. 3: Water vapour mixing ratio in ppm as measured by the H₂O DIAL on 18 October, 2002. The white region means no water vapour information because of the occurrence of high cirrus clouds between between 40.6N and 37.8N which could not be penetrated.

respectively. Near Sicily the lowermost stratosphere is found to be much moister than further towards the north. Beyond altitudes of ~15 km the water vapour distribution is fairly homogeneous.

As an example, the results of the in-situ instruments - the chilled mirror hygrometer and the UV absorption photometer - are displayed in Fig. 4 (b/c). At an altitude of 11.7 km the water vapour mixing ratio is on the order of 40 ppm. At 20:45 the flight altitude was changed to 12.3 km and the H₂O mixing ratio at this range shows values between 23ppm-35ppm. The anti-correlation to the ozone values can clearly be seen. Near waypoint D the in-situ water vapour is lowest and at the same time the ozone is highest.

The last example is from the flight on 25 October when the Falcon flew from Forlì back to Oberpfaffenhofen via central Germany where another attempt was performed to achieve a good coincidence with a MIPAS elevation scan (near 50N of orbit 3411). In Fig. 5 the water vapour field is shown in the altitude range from 11.2-15.5 km. This measurement was performed under daylight conditions, thus the measurement range is smaller due to a higher level of ambient sunlight and the data needs more averaging to achieve a similar accuracy. Here, the resolution at the lowest altitude is 30 km horizontally and 100m vertically and increase to 90km and 3000 m at the highest altitude, respectively. The lower stratosphere is drier in the north than in the south and, again, the symmetrical behaviour of the data shows the good reproducibility of the measurement. However, as the DIAL data at the end of the measurement range show absolute numbers that are rather low compared to climatological values the DIAL data is still subject to further inspection.

4.2. Comparison to MIPAS on ENVISAT

From all crossed ENVISAT orbits MIPAS water vapour profiles are presently only available for orbit 3404 and 3411, respectively. These profiles were extracted from the level 2 NRT/meteo product which is a subset of the level-2 data. During these orbits MIPAS was measuring in its nominal operation mode. The data was processed with software version MIPAS/4.53. The MIPAS data points for those scans whose geographical locations can be extracted from Fig. 2 are depicted in Fig. 6 together with the profiles derived from the H₂O DIAL. As currently the altitude assignment of the processed MIPAS data is still erroneous [H. Nett, private communication], the profiles are plotted against pressure. For the DIAL data the pressure had to be calculated from the geometrical altitude using the radiosonde data of Trapani (37.92N 12.50E, 24/10/2002 23UTC), Pratica di Mare (41.65N 12.43E, 24/10/2002 23UTC), and Meiningen (50.57N 10.38E, 25/10/2002 10UTC), respectively. From the comparison of the two DIAL profiles measured at the same geographical location on the flight to the north and south, respectively, the statistical error of the DIAL measurement can be estimated.

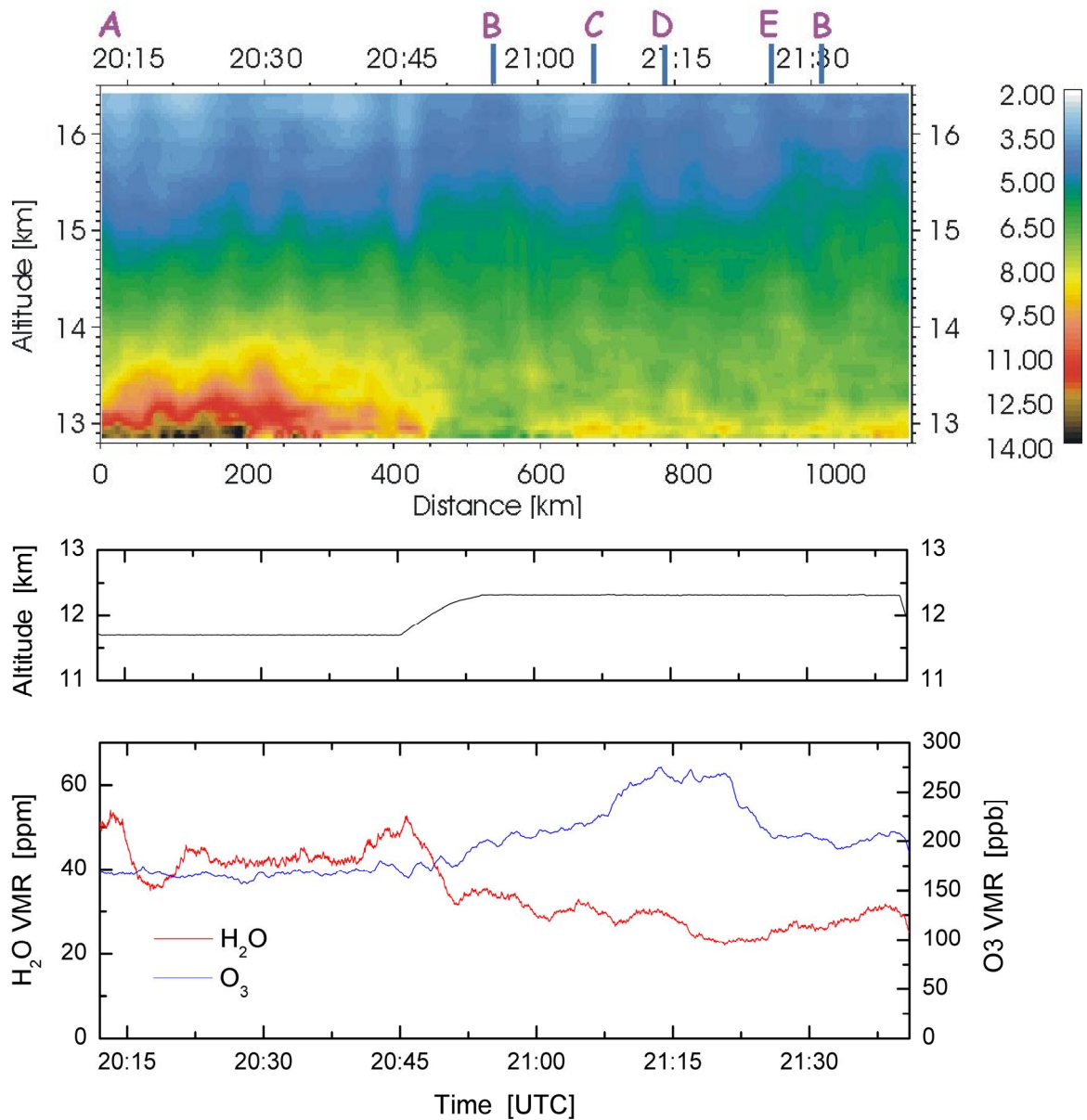


Fig. 4: (a) Upper panel: Water vapour mixing ratio as measured by the H₂O DIAL in ppm as function of flight time along the flight leg shown in Fig. 2b. (b) Middle panel: Flight altitude of the Falcon (c) Lower panel: In-situ values of the water vapour (red) and ozone (blue) mixing ratio at flight altitude.

Presently the MIPAS data are not processed below a tangent altitude of ~12 km (although the lowest line-of-side tangent altitude is 6km). Therefore only 2 data points per MIPAS profile can currently be compared by means of the H₂O DIAL. It is clear, that no statistical significant answer can be deduced from only 3 data sets. However, the lowest of these data points seems to be significantly to low. It is not only lower than the DIAL measurements but also deviate significantly from climatological values. From radiosonde observations and ECMWF analysis the tropopause height was found to be on the order of 210hPa (24/10/02) and 240 hPa (25/10/02) thus MIPAS clearly probed stratospheric air.

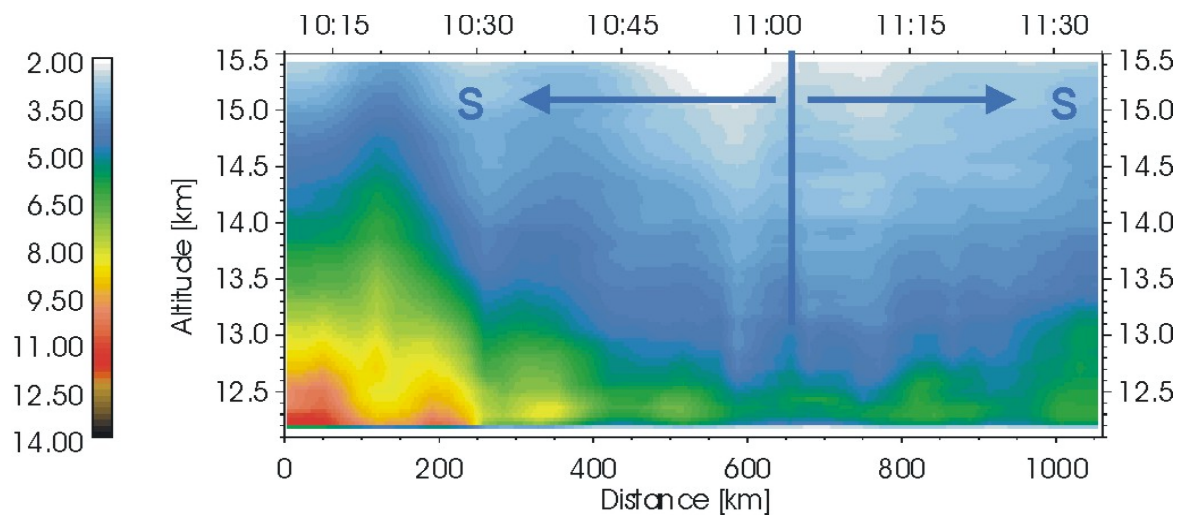


Fig. 5: Water vapour mixing ratio in ppm as measured by the H₂O DIAL on 25 October, 2002. The turning point at 52.2N (see Fig. 2 for the flight leg) is marked.

5. CONCLUSION AND OUTLOOK

In conclusion, the DLR airborne water vapour differential absorption lidar (H₂O DIAL) was successively flown aboard the Falcon 20 research aircraft. A total of 25 hours of flight operation were carried out in October 2002. About 13 matches with MIPAS observations were achieved. The payload worked reliably throughout all flights, however, some flights were affected by unexpectedly high cirrus clouds. Within this Paper, representative but preliminary examples of water vapour measurements were shown for several flight of the Falcon research aircraft at mid-latitudes.

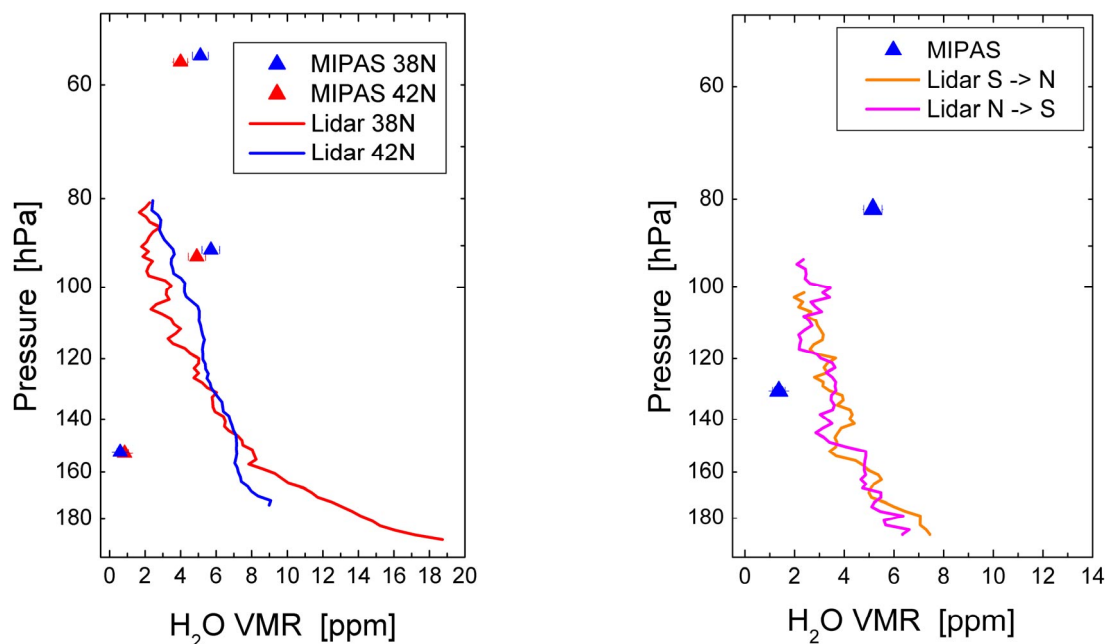


Fig. 6: Comparison of the measured water vapour mixing ratio (VMR) of H₂O DIAL and MIPAS on ENVISAT as function of pressure on 24 October (left) and 25 October (right). For further details, see text.

An important data set was gathered for the validation of MIPAS level-2 data products. This exercise will be performed once the complete set of MIPAS water vapour profiles for the observation period in question is available. Currently, only 3 MIPAS profiles could be compared to the lidar. It seems that the humidity for the lowest retrieved tangent altitude (~12km) is too low.

The measurement of the extended cross sections of water vapour profiles is not only valuable for a direct comparison with the satellite instrument, but, due to its 2-dimensional nature, it readily depicts the variability of the surrounding scene which is important because the MIPAS viewing geometry causes the information to originate from an elongated air volume.

The comparison of the lidar data to the instruments of the Geophysika is in due course for the four flights where both aircraft did correlative measurements. Another important product is the aerosol optical property that has not been investigated so far. A full analysis of the lidar data with respect to the aerosol channels need to be performed as aerosol properties and clouds may affect the MIPAS retrieval. In addition, the aerosol properties measured by the in-situ payload not shown within the context of this Paper is available and may prove to be helpful in conjunction with the development of the prospective aerosol products of MIPAS.

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