

# Technical Support for the Acquisition of Water Vapour DIAL and Aerosol Measurements:

Water Vapour Lidar Experiment WALEX 2005

# **Final Scientific Analysis Report**



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### **ABSTRACT:**

Design and performance studies for satellite missions measuring water vapour (e.g. WALES or SPACE-WAVES) require information on the real 2D structure of water vapour and aerosol/clouds in the troposphere, which can only be provided with sufficiently high spatial resolution and coverage by airborne water vapour lidar measurements. In this context the objective of WALEX 2005 is to extend the acquisition of representative lidar measurements of water vapour and aerosol/cloud properties to sub-Tropical and Tropical regions in the Indian Ocean and Micronesia, regions characterised by monsoon and intense inner tropical circulation. The opportunity to fly through these regions came with the EU-funded tropical campaign SCOUT-O3 (Stratospheric-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere).

The data provide unique illustrations of the mission concept showing a variety of meso-scale and synoptic scale structures in water vapour and aerosol/clouds. Nadir looking from the DLR-Falcon research aircraft, the profiles cover the troposphere between the flight level (10-11 km) and the ground if no dense cloud layers block the laser beam. The spectral and depolarisation information allows estimating the effective particle size and shape, i.e. the particles' phase (water/ice). Large variability of H2O mixing ratio and particle distribution reflect the complexity of transport mechanisms near frontal zones, stratospheric filaments and other PV anomalies. Dry intrusions of upper tropospheric - lower stratospheric origin typically penetrate down to below 4 km altitude with H2O mixing ratios varying about more than an order of magnitude. ECMWF analyses are used to trace the origin of the observed air-mass structures and retrieve the responsible meso- and synoptic-scale dynamical processes. Implications for the impact on relatively coarsely resolved satellite measurements and the benefit of a space-borne H2O-DIAL are drawn.

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## 1 Introduction

The challenges of a changing global climate have to impinge on our efforts to better monitor and understand atmospheric processes. In particular, the lack of accurate global water vapour data with high vertical resolution (1 km or better) impedes the determination of the flow of radiation within and out of the atmosphere, i.e. the local heating/cooling and the cooling to the space, which must balance the solar irradiation on the long run. More fundamentally, without better water vapour data also our knowledge about the natural greenhouse effect, and the mechanisms involved in the water vapour feedback remains incomplete. The lack of knowledge on water vapour transports in the atmosphere means a knowledge gap in the hydrological cycle, which makes an accurate forecast of cloud formation, release of latent heat, and precipitation difficult. This in turn, in particular regarding the formation of cirrus clouds, impedes a full assessment of homogeneous and heterogeneous chemistry in the near tropopause regime, which has an influence on the ozone distribution. Furthermore, the lack of water vapour data in the upper troposphere hinders the understanding of various issues like formation conditions of thin cirrus, stratosphere-troposphere exchange, and the possible increase of the stratospheric water vapour concentration.

Although the importance of water vapour is well recognized, its spatial and temporal variability is still poorly characterized by both observations and models. Its abundance influences the development of droughts or floods and consequently the regional climate with potential hazards. Actually, the prediction skill of warm season convective precipitation is poor, despite advances in the quality of numerical weather prediction (NWP) models and increased data assimilation efforts. This is mainly because the models must parameterize convection as a subgrid-scale process and because current water vapour measurements are inaccurate and incomplete (Weckwerth et al., 2004). High quality and high-resolution water vapour measurements are simply not available for assimilation into next generation NWP models. The currently operational water vapour observations are insufficient because radiosondes suffer from poor representativeness and passive satellite remote sensing observations have biases that are difficult to quantify and have insufficient vertical and horizontal resolution. First impact studies suggest that a space borne water vapour lidar system could be a major step towards the improvement of global NWP (Gérard et al., 2004).

After WALEX I (lidar water vapour and backscatter data obtained during flights across the North Atlantic Ocean) and II (flights across the Equatorial Atlantic Ocean), the WALEX III data presented in this report shall serve as real atmospheric input for end-to-end simulations of future satellite instruments like SPACE-WAVES. They will be capable to answer a number of important questions related to instrument design optimisation that cannot be addressed by previous studies and existing data to this extent and accuracy. They provide a unique opportunity for studying the influence of real water vapour and aerosol scenes with all their variability from mid-latitude, sub-tropical and tropical regions on the simulation results. In particular, the representativeness of single-overpass scenes for real water vapour and aerosol distributions can be assessed and the requirements for vertical raw data resolution and laser power fluctuations can be determined. The WALEX data allow to establish alignment constraints between on- and off-line soundings, to provide implications for depolarisation effects on the satellite instrument retrieval, to establish a Rayleigh-Doppler error correction scheme and to analyse effects of multiple scattering in clouds and aerosols.

## 2 Instrumentation

### 2.1 The DLR Falcon Research Aircraft



The meteorological research aircraft Falcon 20 (D-CMET; http://www.dlr.de/fb) operated by DLR is a wellestablished research platform for more than 30 years. The particular strength of the Falcon aircraft is its high flexibility and the possibility to quickly sample a large area in heterogeneous atmospheric situations extending up to synoptic scales. The Falcon has a maximum endurance of 5 h carrying a payload of 1100 kg and a maximum operating altitude of 12.8 km (Table 2-1). Due to its four 40 cm diameter windows for LIDAR measurements nadir and zenith viewing, the good range/height performance and the smooth in-flight behaviour, the DLR Falcon is the only European airborne platform suitable for such experiments.



Fig. 2-1: The DLR Falcon research aircraft.

Altitude [m]	3000	6000	9500	12500	
max. Range [km]	2100	2800	3200	3700	
max. Endurance [h]	04:10	04:15	04:45	05:00	

Table 2-1: Maximum range and endurance as function of flight altitude.

In addition to the DIAL instrument, the Falcon was equipped with a set of in-situ trace gas (NO, NO<sub>y</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, O<sub>3</sub>) and particle (condensation nuclei, aerosol size distribution) measuring instruments as well as sensors for essential meteorological parameters like humidity, pressure, temperature and wind. All these parameters were measured at flight level (in-situ) along the flight path with temporal resolutions of few seconds to minutes but are not under the operation or responsibility of the contractor.

## 2.2 The Differential Absorption Lidar (DIAL)



Differential absorption lidar is an appropriate technique for the remote sensing of atmospheric trace gases such as water vapor. A DIAL emits spectrally narrow and short pulses into the atmosphere at a wavelength tuned to the center of a molecular absorption line of water vapor. The comparison of these online signals scattered back by aerosols and air molecules with the reference offline signals yields the water vapor molecule number density as function of distance from the lidar. In addition the offline backscatter signal contains information about the aerosol load of the probed atmosphere.

The airborne water vapor differential absorption lidar of the German Aerospace Center (DLR) participated in numerous field experiments where it helped characterize the variability of humidity and aerosols within the boundary layer and at its top (Kiemle et al., 1997). In 1997 a new DIAL system was developed at DLR with the aim to perform accurate measurements of upper troposphere and lower stratosphere humidity (Poberaj et al., 2002). During extended flights across central Europe two-dimensional water vapor cross sections through stratospheric intrusions associated to potential vorticity streamers could be obtained (Ehret et al., 1999).

The DIAL transmitter is based on an injection seeded optical parametric oscillator (OPO) which provides the large tuning capability. Narrow band operation and high average power are achieved by pumping the OPO by an injection seeded Nd:YAG laser operated in the single longitudinal mode at 200 mJ per pulse and 100 Hz. In order to minimise the total electric power consumption aboard the aircraft, the Nd:YAG laser is chilled by means of a passive heat exchanger mounted at outside the fuselage. About half of its fundamental output at 1064 nm is converted to the second harmonic, serving as the pump for the OPO; the rest is used for atmospheric backscatter measurements. The maximum OPO output energy is 18/12 mJ at 925/935 nm per pulse according to the cavity performance at the different wavelengths. The system is designed to perform simultaneous polarisation-sensitive backscatter measurements at 532 nm and 1064 nm for aerosol detection. In-flight quicklooks of aircraft and lidar data including two-dimensional aerosol backscatter cross sections provide real-time information about the actual state of the system and the probed atmosphere.

Injection seeding of the OPO is performed by a single mode external cavity diode laser (ECDL). For wavelength calibration, a small 36-m path-length absorption cell filled with water vapour is used where the seed wavelength is automatically locked on the edge of the pre-selected absorption line (90% of the absorption peak value). The OPO cavity length is matched to the seed wavelength by minimising the OPO transmission through the additional 100 m path-length absorption cell. To maintain a high spectral performance output of the OPO the transmission of this second cell serves as a sensitive feedback signal for the computer controlled cavity length adjustment. The laser spectral purity is controlled on a pulse-by-pulse basis by the multipass absorption cell filled with water vapor. It could be shown that for aircraft flight altitudes of ~10 km the spectral purity of the useful online pulses is 99.4 % on average (Poberaj et al., 2002).





Fig. 2-2: Set-up of the DLR airborne H<sub>2</sub>O-DIAL.

In order to simplify dual-wavelength operation, a new DIAL technique was proposed by Fix et al., 1998. This technique takes advantage of the spectral properties of the seeded and unseeded OPO. Namely, the different spectral bandwidths of the seeded and unseeded OPO can be utilised to generate the absorbing (on-line) and non-absorbing (off-line) measurements. As an example, when the OPO is tuned to the strong absorption line at 935.427 nm and seeded the spectral width is about 140 MHz yielding an absorption cross section of  $1.89*10^{-25}$  m<sup>2</sup> for the line centre measurement. On the other hand, the unseeded OPO possesses a spectral bandwidth which is nearly three orders of magnitude larger: 90 GHz (0.26 nm) in comparison to the seeded one above, which yields an effective absorption cross section that is only about 3 percent of the seeded one at the same centre wavelength and can be utilised for the off-line measurement.

Dual-wavelength OPO operation is then implemented by chopping the seed beam at a repetition rate of 50 Hz. It should be noted that the atmospheric backscattering and residual atmospheric extinction are practically constant within the frequency interval of the broadband OPO radiation, thus no systematic error is introduced this way. The residual off-line absorption is iteratively corrected in the DIAL data retrieval scheme. At a typical aircraft speed of 200 m, the horizontal distance between the on- and offline beams is 4 m and in most atmospheric situations the sampled air mass can be considered homogeneous over that scale.





**Fig. 2-3:** Photographs of the H<sub>2</sub>O-DIAL system aboard DLR's meteorological research aircraft Falcon 20E. The system components are rigidly fixed in a supporting structure (rack), which is mounted on the seat rails of the aircraft cabin, using shock-suppressing mounts. Left photo: down looking telescope with the detection units. On the right photo (a view in flight direction): pump laser (bottom right), operator's terminal and multipass absorption cell (in front), and OPO with the injection seeder module (top).

The output beams at the different wavelengths are coupled out centrally with the telescope axis. The beams are expanded to fit their divergences to the field-of-view of the telescope. The back-scattered photons from the atmosphere are collected by a Cassegrain-type telescope with an aperture of 35 cm and a focal length of 500 cm. The field-of-view, which is typically set to 2 mrad can be adjusted by the field stop set at the focal plane of the telescope. The received light is split into three channels, for water vapour and aerosol measurements. In order to suppress unwanted solar background light, a temperature-controlled three-cavity interference filter with a bandwidth of 1 nm (FWHM) and a peak transmission of 70% is used in each channel.

The filtered light is detected by means of silicon avalanche photodiodes (APD). The individual signals from the APDs are amplified and digitised with a resolution of 14 bit at a sampling rate of 10 MHz. Note that the amplifier is built in-house and has extremely low noise. This leads to excellent SNR especially at 1064 nm where the high Rayleigh contrast enables the detection of ultrathin subvisible cirrus clouds or aerosol layers. A similar detector is used for the water vapour on- and offline signals around 930 nm.

Prior to further processing, the computer enables skipping of eventual bad shots with insufficient spectral purity. The data are stored on a hard disk, magnetic tape and removable magneto optic disk. The most important H2O-DIAL system characteristics are summarised in Table 2-2. More information about the water vapour DIAL and measurements can be found in Ehret et al. (1999) and Poberaj et al. (2002).



#### The DLR DIAL lidar delivers the following data products:

- Along-flight profiles of particle backscatter ratio at 532 (doubled Nd:YAG), 925 (offline OPO output) and 1064 nm (fundamental Nd:YAG line) as two-dimensional cross sections above or below the aircraft.
- Along-flight profiles of particle depolarisation ratio at 532 and 1064 nm as two-dimensional cross sections above or below the aircraft.
- Two-dimensional cross sections of water vapour mixing ratio above or below the aircraft.
- Geometrical extent of cirrus clouds; cloud top heights for other non-transparent clouds.
- Backscatter and extinction coefficient profiles and optical depth for selected profiles where lidar signal inversion is possible.
- Estimation of the variability of background radiation in different cloud and surface conditions.

In all data sets, the profile headers contain information needed for further processing of the data, such as aircraft attitude, altitude and speed, spatial resolution of the profiles and lidar housekeeping data.

# DLR DIAL System Parameters

Transmitter	Diode-laser-seeded optical parametric oscillator (OPO).		
	Pump source: Second harmonic of diode-laser pumped Nd:YAG.		
Energy/pulse	10 mJ (typ.)		
Pulse repetition rate	100 Hz (50 Hz on/off-line)		
Spectral width	< 200 MHz, < 50 MHz		
long-term stability	By active frequency stabilization on water vapour line.		
Spectral purity	99,4%		
Operating wavelength	925 – 935 nm for tropospheric and lower stratospheric research.		
Aerosol channels	532 nm, 1064 nm		
Aerosol depolarisation	Co- and cross-polarised at 532 nm and 1064 nm.		
Eye-safety	Eye-safe after a distance of 3000 m.		
Receiver	35 cm Cassegrain telescope.		
Detector	Avalanche photodiode (APD)		
Digitizer	12 bit 20 MHz		
Computer	SUN-VME bus-system, in-flight data analysis.		
Total weight	258 kg		
Power consumption	1.6 kW 28 V/DC + 1 kW 220V/DC		
Space consumption	1.5 m³		
Heat exchange	Separate cooling loop for Nd:YAG (~ 1kW).		

 Table 2-2: System parameters of the Aerosol/H<sub>2</sub>O-DIAL.





The transfer flights covered a large climatic range from mid-latitudes via subtropical to tropical regimes in wintertime. First, the flight path crossed the cloud-poor sub-tropical subsidence belt, before reaching the transition of the subtropical to the tropical tropopause marked by the sub-tropical jet. The final part of the transfer between



Figure 3-1. Transier night pauls non nonnen nennsphere miu-nandues (40 TV) towards Ivorun Australian itopical latitudes (12°S) across south Asia.





Figure 3-2: Flight Leg1 Oberpfaffenhofen EDMO – Larnaca LCLK





Figure 3-3: Leg 2 Larnaca LCLK – Dubai OMDB





Figure 3-4: Leg 3Dubai OMDB – Hyderabad VOHY 1400 NM













Figure 3-8: Overview of all SCOUT-O3 transfer flight paths with stopovers.



Flight	Date	Time UTC	H2O profiles	Remarks	Clouds
$OP \rightarrow Larnaca (Cyprus)$	4.11.05	6:55 – 9:25	12 – 18 km	stratospheric aerosol layers in 13 – 16 km, no H2O before 7:25	Cirrus below 12 km west of 15 E
Larnaca $\rightarrow$ Dubai (United Arab Emirates)	4.11.05	13:00 – 15:10	11 – 17 km	aerosol layers in 12 – 17 km	none
Dubai → Hyderabad (India)	9.11.05	5:05 - 8:00	12 – 16 km	aerosol layers in 14 – 17 km	Cirrus in 12 – 17 km east of 73 E
Hyderabad $\rightarrow$ U-Tapao (Thailand)	9.11.05	9:20 – 12:30	11 – 14 km	Thick impenetrable clouds between 10:25 – 11:15, 100% cloud cover	UTTC east of 90 E in 16 – 18 km
U-Tapao → Brunei	12.11.05	0:50 – 2:45	12 – 14 km	Thick impenetrable clouds between 2:00 – 2:10, 100% cloud cover	Cirrus up to 16 km
Brunei $\rightarrow$ Darwin (Australia)	12.11.05	6:00 - 9:15	13 – 15 km	100% cloud cover	Cirrus up to 16 km
Transfer back:					
Darwin → Brunei	9.12.05	23:25 – 1:35	5 – 11 km	Downward pointing on transfer back	In 8 – 12, 6 and 3 km
Brunei $\rightarrow$ U-Tapao (Thailand)	10.12.05	5:25 – 7:15	no H2O	100% cloud cover	From 0 – 11 km
U-Tapao $\rightarrow$ Hyderabad (India)	13.12.05	1:15 – 3:55	0.5 – 11 km	Falcon flew below cirrus	None below 11 km
Hyderabad → Dubai (United Arab Emirates)	14.12.05	3:35 – 6:10	0.5 – 10 km	Falcon flew below cirrus	None below 11 km
Dubai → Bahrain	16.12.05	3:30 – 3:50	0.5 – 9 km	Dry layer in 5 km	Scattered cumulus in 1 km
Bahrain → Larnaca (Cyprus)	16.12.05	6:45 - 8:20	0.5 – 9 km	Stratospheric intrusion (dry air) at 38 E	Scattered cumulus in 3 and 4 km
Larnaca → Brindisi (Italy)	17.12.05	7:20 – 8:45	0.5 – 9 km	Humid layer up to 8 km	ABL top clouds in 2 – 3 km
Brindisi $\rightarrow$ Munich	17.12.05	11:10 – 12:00	0.5 – 9 km	Humid layer up to 8 km until 45 N	Stratus in 4 – 5 km

**Table 3-2:** Overview of DLR DIAL measurements during the transfer flights to the SCOUT-O3 campaign in Darwin, Australia. During these 14 Falcon flights the total measurement time was roughly 30 h or 21.600 km, which is 74% of the total distance of table 3-1.

	Falcon mission	Date	Time UTC	H2O profiles	Remarks	Clouds
				range ASL		
1	Part 1: mapping of Hector upwind region to the N	16.11.05	6:10 – 7:40	no H2O	UTTC very flat in 9 – 10 S, UTTC lower and more structured in 11 S	scattered cirrus below 15 km, UTTC at 17 – 18 km



	Part 2: turns around Hector		7:40 – 8:50	no H2O	Thick partly impenetrable Hector anvil,	anvil cirrus below 15.5 km, UTTC at
					bad SNR due to ice on window	16 – 17 km above Hector
2	N – S trans. at 131.5 E: D. $\rightarrow$	19.11.05	4:00 - 7:00	12 – 16.5 km	100% cirrus cover, Hector outflow	Cirrus at 15 – 18 km, Hector outflow
	$15 \text{ S} \rightarrow 10 \text{ S} \rightarrow 12 \text{ S} \rightarrow 9 \text{ S}$				touches cirrus layer	up to 16 km
	$\rightarrow$ 15 S $\rightarrow$ D.					
3	SW – NE transects: D. $\rightarrow$ 7 S	23.11.05	4:40 - 7:50	11 – 16 km	Persistent aerosol layer at 17.5 – 19	Cirrus in NE at 15.5 – 16.5 km,
	$135 \text{ E} \rightarrow 10.5 \text{ S} 132.5 \text{ E} \rightarrow$				km, no cirrus in 10.5 S, deep	Hector outflow up to 16 km, UTTC at
	8.5 S 134 E → D.				convection in NE	16 – 17.5 km above Hector
4	mapping of Hector upwind	25.11.05	3:30 - 6:40	12 – 15 km	faint aerosol layer at 18 – 19 km, 100%	Irregular cirrus up to 15 km, patches
	region, turns around Hector				cirrus cover	of ultra thin cirrus up to 16.5 km,
						UTTC in 11 S at 17 km
5	mapping of Hector upwind	28.11.05	3:40 - 6:40	8 – 17 km	faint aerosol layer at 18 – 19 km, 90%	Cirrus outflow at 9 – 16.5 km, UTTC
	region, turns around Hector				cirrus cover, 10% UTTC cover, partly	at 17 km in 9.5 – 11.5 S, UTTC up to
	_				impenetrable Hector anvil	<mark>18 km in 13 – 14.5 S</mark>
6	N – S transects at 131.5 E:	29.11.05	5:40 - 8:50	8 – 17 km	Deep convection (impenetrable) in 14.5	In 9 – 15.5 S cirrus at 15 – 18 km with
	Darwin $\rightarrow$ 19 S $\rightarrow$ 9 S $\rightarrow$ 13				– 16 S, in 17 – 19 S no clouds but	Hector outflow below in 10 S, in 16 –
	$S \rightarrow Darwin$				aerosol layers at 14 – 19 km	17 S UTTC layers at 15, 16.5 and 18
						km
7	mapping of region N and S of	30.11.05	4:10 – 7:50	10 – 16 km	faint aerosol layer at 17 – 19 km, 100%	Cirrus at 12 – 17 km and up to 18 km
	Hector				cirrus cover, partly impenetrable Hector	close to Hector, UTTC at 17.5 km in
					anvil	<mark>9.5 – 11.5 S</mark>
8	mapping of Hector	30.11.05	11:50 – 15:30	11 – 15 km	100% cirrus cover, Hector outflow in	Cirrus at 11 – 17 km, UTTC patches
					water vapour data observed	at 17 - 18.5 km
9	N – S transect: D. $\rightarrow 23.5$ S	5.12.05	18:50 – 22:10	10 – 16 km	faint aerosol layer at 17 – 19 km	Anvil cirrus at 10 – 17 km in 13 – 20
	$131 \text{ E} \rightarrow 134 \text{ E} \rightarrow \text{D}$					S, UTTC at 17 km SE turn

 Table 3-3: Overview of local DLR DIAL measurements during the SCOUT-O3 campaign in Darwin, Australia. In total nine Falcon flights were undertaken, with a total measurement time of roughly 30 h or 21.600 km. These local flights are not part of the deliverables.



## 4 Data Analysis

#### 4.1 Data Storage

During the flights, the operating scientist on board continuously monitors the lidar system. He performs occasional adjustments on the base of a real-time preview of the most important system parameters and the measured atmospheric structures. He also checks the lidar raw data as well as auxiliary parameters (aircraft position, GPS- and meteorological sensors). The online preview capability during the flight allows checking for spurious signals, misalignment, system noise or artefacts in the data and thereby provides the excellent opportunity to eliminate immediately the causes.

All 100 Hz lidar data are simultaneously stored to DAT-DDS tapes as 20-profiles average (0.2 s) and on magneto-optical disks as 100-profiles average (1 s). This gives about 100 MB (20 MB) per measurement hour and per spectral channel on tape (disk). With 6 data channels, namely 532 nm (|| parallel and  $\perp$  perpendicular depolarisation), 925 nm on-line, 925 nm off-line (for H2O) and 1064 nm (|| and  $\perp$  depolarisation) this amounts to 360 MB on optical disk of 1 s averaged profiles for a 3 h DIAL measurement.

#### 4.2 Aerosols and Clouds

For the introduction of the used symbols, we start with the simplified lidar equation for the back-scattered signal that translates into a power on the detector  $P(R,\lambda)$ :

$$P(R,\lambda) = K(\lambda) \cdot \left(\frac{c\tau}{2}\right) \cdot \beta(R,\lambda) \cdot \frac{A}{R^2} \cdot P_0(\lambda) \cdot e^{-2\int_0^R \alpha_A(r,\lambda)dr}$$

 $K(\lambda)$  is a system function determined by the overlap of the laser beam with the receiver's field of view.  $P_0(\lambda)$  is the emitted pulse power,  $\beta(\lambda, R)$  is the total volume backscatter coefficient at range R, and A/R<sup>2</sup> is the acceptance angle of the receiving optics with a collecting telescope area A. The exponent represents the integrated transmittance to the range R and back.  $\alpha(\lambda, R)$  is the total atmospheric extinction coefficient.

The radiation scattered back by atmospheric particles is either given as backscatter coefficient  $\beta$  [m<sup>-1</sup>sr<sup>-1</sup>] or relative to Rayleigh scattering as backscatter ratio  $\gamma = (\beta_{\text{particle}} + \beta_{\text{molecule}})/\beta_{\text{molecule}}$ , the relative contribution of total to pure molecular scattering. Rayleigh scattering is calculated from air density profiles using climatological data. In order to be able to reproduce atmospheric cloud and aerosol structures with the highest possible spatial resolution, only offset- and range-correction are applied to the raw signal. The single backscatter profiles are calibrated using an estimated atmospheric backscatter value in a pre-selected normalisation height range.

Quantitative optical information is achieved by considering the attenuation of the laser beam in the atmosphere employing a Klett numerical inversion of the lidar equation. In this procedure, the lidar ratio (ratio of extinction to backscatter coefficient) and a reference value at some distance from the receiver are selected and the profiles are iteratively calculated. With the inferred lidar ratio, the extinction coefficient and its integral, the optical depth, are computed from the backscatter signal.



The inversion of lidar profiles, depending on the reference values at the starting points and the extinction/backscatter ratio (lidar ratio) - both highly variable and not known - imposes a considerable uncertainty on the backscatter data. However, for the main scope of this data set, the end-to-end simulation of the WALES instrument, an inversion is not necessary but even disadvantageous since the WALES simulation will be performed with range corrected backscatter profiles rather than (particle-) extinction corrected data. This approach is advisable because it circumvents the errors imposed by the inversion and naturally exploits a crucial benefit of the airborne lidar data, being the direct and complete input for the simulation, as it contains all necessary and all required atmospheric information in the relevant way. For this reason, it is advisable to provide the data set of the transfer measurements as range corrected, calibrated backscatter ratios rather than extinction corrected backscatter- or extinction profiles.

Yet, an inversion has additionally been performed for selected cases and the resulting backscatter- and extinction coefficients are provided as plots and as data files in ASCII format. Thereby, owing to the lack of additional particle information, the extinction coefficients are calculated from the backscatter coefficients by simply multiplying with a fixed estimated backscatter/extinction ratio  $\beta(r)/\alpha(r)$  (lidar ratio) of 0.02, which is an average value for the mid-latitude troposphere and the recommended value in the ESA Reference Model of the Atmosphere (RMA; ESA 2003). However, *this is only a rough estimate* since the lidar ratio is known to be highly variable, e.g.  $\alpha(r)/\beta(r) \approx 8.4$  for molecules, 14 for cirrus-, 20 for water clouds and about 50 or higher for aerosol particles (typical values). It further has to be noted that nearly all cirrus in the near-range as well as a large part of the stratus/stratocumulus clouds at lower levels caused signal saturation and hence the optical depth cannot be calculated for the clouds.

Accurate (particle-)extinction-corrected backscatter coefficients/-ratios can only be derived for those aerosol structures and clouds where complete overlap of the optical system has been reached before the scattering volume, where regions of known backscatter ratio can be found before and behind- and where the signal was not saturated or blocked within the scattering volume. For (mostly cirrus) clouds that occur at flight level (FL) or start nearer than about 1 km below, the first two criteria are violated. Frequently, low stratiform water clouds at the PBL top and occasionally mid-tropospheric cloud layers or thick cirrus block the beam, noticeable when there is no significant surface return signal below. Even an intermittent penetration may be not sufficient to perform the inversion. Thus, the fraction of data that can be evaluated quantitatively may be considerably degraded.

The following flow-chart briefly outlines the procedure of calculating individual profiles of backscatter ratio, depolarization ratio and colour ratio from the lidar raw signal, separately for the parallel (||) and the perpendicularly ( $\perp$ ) polarized channels:





The depolarisation ratio of the co- and cross-polarised signals  $\beta_{\perp} / \beta_{\parallel}$  contains information about the sphericity of the particles. Given our specific detector filter width of 1 nm FWHM, a depolarisation of 0.0048 (or 0.48%) corresponds to pure Rayleigh depolarisation by air molecules. With depolarising (non-spherical, solid) aerosol or cloud particles, the depolarisation can range between 0.0048 and 1 (or 0.48 - 100%). In case the lidar measures *only* spherical particles (liquid droplets) the depolarisation may fall below 0.48% since they only increase the intensity in the parallel channel.

The particle phase can be derived from the particle depolarisation, and the colour ratio of the backscatter coefficients at the different wavelengths indicates the effective particle size. Both quantities are measured as 2-D along-flight cross sections with sufficiently high spatial resolution to assign the observed structures to small- and meso-scale dynamical and microphysical processes. Even narrow aerosol or cloud layers (d < 100 m vertical depth) can be observed. Also low optical depths down to  $OD_{532nm} \approx 0.05$  are sufficient to derive optical parameters required to estimate the particle's microphysical properties and perform comprehensive radiation



transfer calculations. Thanks to the excellent low-noise detector at 1064 nm, ultra thin subvisible cirrus with  $OD_{1064nm} \approx 10^{-4}$  can be detected.

Clouds strongly attenuate the laser beam, decreasing the signal/noise ratio and reducing the penetration into the atmosphere. The signal may be blocked after some distance, typically if an OD  $\approx$  2 is exceeded. The S/N ratio therefore depends on the atmospheric extinction between the lidar and the scattering target. The detection limit is about  $\Delta \gamma \approx 1\%$  contrast between aerosol and molecular backscatter signals, under typical conditions errors range between about 1 and 10% for the backscatter ratio. In case of occasional saturation of the signal in nearby clouds, a quantitative retrieval is only possible in the part of the profile beyond a volume of known atmospheric backscatter. Particularly, the depolarisation ratio of co- to cross-polarised signal is useless if one of the channels is saturated. Multiple scattering is not taken into account.

The lidar profiles are range-corrected and geo-coded for each flight leg, i.e. each individual profile is delivered with its exact position in time and space. In addition, two-dimensional cross sections for the backscatter ratio are produced for each flight as overview plots (see section 5). Depending on the S/N ratio, aerosol backscatter and depolarisation are measured with a horizontal (vertical) resolution of few 100 m (30 m). The S/N ratio crucially depends on the optical depth between the lidar and the scattering volume and on the contrast between aerosol and molecular backscatter signals that lead to a detection limit of about 1% in backscatter ratio.

Another uncertainty of the backscatter coefficient is due to the atmospheric calibration at the starting point of the inversion. Lidar profile inversions based on the Klett or iterative method assume a reference backscatter ratio  $\beta 0(r0)$  at a selected distance r0 in the profile and a constant backscatter/extinction ratio  $\beta (r)/\alpha(r)$  (lidar ratio), although it actually is a function of the particle ensemble scattering function in a sampled air volume. The reference backscatter ratio  $\beta 0(r0)$  may be estimated from suitable simultaneous measurements or from standard atmospheric extinction profiles valid for the air-mass type of the sampled volume. An erroneous value results in an offset of the profile and thus stronger affects the low backscatter-coefficients. The uncertainties arising from the lidar ratio feign too large values if multiple scattering is not taken into account and are hardly inferable (but also negligible) in a clean atmosphere with low optical depth. The uncertainties propagate to the extinction coefficients and the optical depth that are calculated from the lidar ratio.

The random error is controlled by spatial averaging of the backscatter data from a raw data resolution of about 100 m horizontally and 15 m vertically. The trade off between resolution and accuracy depends on the particular objective and the scale of the observed structures. For the WALEX 2005 data where large scales dominate, typically a horizontal averaging of few km has been applied. This is sufficient to eliminate statistical noise from the data, except at higher altitudes in the stratosphere for the zenith viewing measurements.



#### 4.3 Water Vapour

The water vapour retrieval is based on the differential absorption of one broadband (off-line) and one narrowband (on-line) laser pulse at the wavelength of the selected H<sub>2</sub>O line. A water vapour absorption cell is installed on board to control and eventually adjust the spectral purity of the laser. Owing to the quasi-identical wavelengths, there is no aerosol bias from different aerosol extinction/backscatter coefficients. The retrieval is reliable outside of clouds and its penetration depth is limited to optical depths below saturation where all photons in the absorption line are absorbed. Hence, the range of the measurements is limited by the line strength of the selected water vapour line. This becomes evident in the tropics where measurements down to the ground are impossible with only one online wavelength.

The profile of water vapour molecule number density is measured at ~ 925 nm using the DIAL technique, which allows covering the range of typical concentrations found in the boundary layer at mid-latitudes up to the upper troposphere (Ehret et al., 1999). The trade-off between spatial resolution and signal noise requires the integration of a number of individual profiles depending on the ambient conditions and structures of interest. The horizontal and vertical resolution is sufficient to resolve relevant dynamical structures near typical frontal zones, or intrusions of dry stratospheric air into the troposphere. The data resolution for water vapour is about 5 km (0.5 km) horizontally (vertically) throughout the troposphere for obtaining an average statistical error (noise) of 10% for the nadir pointing measurements.

The smoothed on-line and off-line backscatter profiles are converted to water vapour concentrations  $N_{H2O}$  (R) with range R by applying the well-known DIAL equation:

$$N_{H2O}(R) \cdot \Delta \sigma(R) = \frac{1}{2 \cdot \Delta R} \cdot \ln \left[ \frac{(P_{off}(R_2) \cdot P_{on}(R_1))}{(P_{on}(R_2) \cdot P_{off}(R_1))} \right]$$

 $P_{on}$  and  $P_{off}$  are the measured signal obtained by the on-line and off-line retrievals at the boundaries of a range interval between  $R_1 - R_2$  and  $\Delta R = c\Delta t/2$  is the range resolution of the lidar signal. The effective differential absorption cross section  $\Delta \sigma(R)$  is calculated as function of pressure and temperature using the HITRAN 2004 database. Pressure and temperature profiles stem from climatological data. Since temperature-insensitive absorption lines were selected, small departures from the actual atmospheric values are not critical.

The pressure and temperature profiles also provide the means to translate from water vapour molecule number density N into mass or volume mixing ratio profiles using the following thermodynamic relationships:

Water vapour volume mixing ratio  $m_{vol} = N_{H2O}/N_{air}$  with  $N_{air} = p/kT$ ,

water vapour mass mixing ratio  $m_{mass} = 0.622 N_{H2O}/N_{air}$ .

Further uncertainties arise from the spectral impurity of the laser and the Rayleigh-Doppler broadening of the absorption line, both estimated to be within 1-2%. The overall systematic error (bias) is estimated to below 5%. See Poberaj et al. (2002) for a detailed error assessment.



## 5 Scientific Results

#### 5.1 Measurements Overview

Figure 5.1-1 gives an overview of the DLR DIAL backscatter and H2O measurements on the transfer flight to Australia, where the lidar was zenith viewing. Backscatter ratio and water vapour volume mixing ratio profiles are displayed as function of geographical position and altitude. The Falcon flight altitude is indirectly visible at the edge of the white (= no data) area in the bottom. The vertical white bars indicate data gaps near the stopover airports Larnaca, Dubai, Hyderabad, Thailand and Brunei. The cross sections are compressed horizontally by a factor of ~ 250 (aspect ratio), hence atmospheric structures and the shapes of clouds are distorted.

The transition between mid-latitudes, subtropical and tropical air masses becomes very evident in the water vapour overview: The gradually increasing height of the tropopause, visible through the distinct H2O gradient and increasing humidity in the upper troposphere and lower stratosphere (UT/LS) are clear indicators of this transition. The region between India and Australia is characterised by deep convection, pronounced cirrus cloud cover up to 18 km altitude and very high UT/LS humidity. It is hence called the "warm pool" region. Both the water vapour optical thickness and the attenuation due to cirrus cloud cover limit the maximum measurements range here.

Of high scientific relevance are the so-called "ultrathin tropical tropopause clouds" (UTTC) located at or near the tropical tropopause, because they may play a role in the dehydration of air entering the stratosphere, and in the Earth's radiation budget (Thomas et al. 2002, Peter et al. 2003, Luo et al. 2003). These clouds are visible between 15 and 18 km altitude in Fig. 5.1-1 between 95 and 100 E. They are characterised by low backscatter ratio (< 20 at 1064 nm). Thanks to the very low noise detector at 1064 nm, the high Rayleigh contrast at that wavelength enables the detection of these ultrathin subvisible cirrus clouds and of aerosol layers. Weak filament layers of background stratospheric aerosols are observed in the left part of Fig. 5.1-1 in the lower stratosphere between 13 and 19 km. Thick cirrus in the near range, as in the tropical right part of Fig. 5.1-1, is impenetrable and leads to blocking of the laser signal.

Figure 5.1-2 gives an overview of the DLR DIAL backscatter and H2O measurements on the transfer back from Australia, where the lidar was nadir viewing. Backscatter ratio and water vapour volume mixing ratio profiles are displayed as function of geographical position and altitude. The Falcon flight altitude is indirectly visible at the edge of the white (= no data) area in the top. The vertical white bars indicate data gaps near the stopover airports. The cross sections are compressed horizontally by a factor of ~ 300 (aspect ratio). The water vapour profiles' penetration depth is limited to optical depths below saturation where all photons in the absorption line are absorbed. This becomes evident in the tropics (here to the south of 20 N) where measurements down to the ground are impossible with only one online wavelength.

The first part of the transfer back was characterised by heavy cloud cover in the warm pool region between Australia and India, as expected. Fortunately, cloud gaps occurred and gave the opportunity to get profiles to the ground, and cloud cover generally was less than expected for the warm pool region.





Final data. Processed on 20-09-2008 Contact: DLR Institute of Atmospheric Physics. Gerhard.Ehret@dlr.de

**Figure 5.1-1:** Overview of the DLR DIAL measurements on the transfer flight to Australia. Backscatter ratio cross sections (top) at 1064 nm and water vapour volume mixing ratio (bottom) as function of geographical position and altitude. The mixing ratio is expressed in units of cm<sup>3</sup>/m<sup>3</sup> which is equivalent to one part per million by volume (ppmv). The measurement interruptions correspond to the stopovers in Larnaca, Dubai, Hyderabad, U-Tapao (near Bankok) and Brunei (see also Table 3-2).





Final data Processed on 20-09-2008 Contact: DLR Institute of Atmospheric Physics Gerhard Ehret@dlr.de **Figure 5.1-2:** Overview of the DLR DIAL measurements on the transfer flights back from Australia. Backscatter ratio cross section (top) at 1064 nm and water vapour volume-mixing ratio (bottom) as function of geographical position and altitude. The measurement interruptions correspond to the stopovers in Brunei, U-Tapao (near Bangkok), Hyderabad, Dubai, Bahrain, Larnaca and Brindisi (see also Table 3-2). Note that the Falcon was flying from right to left in this W-E cross section.



Owing to intense dynamical activity a variety of complex atmospheric structures was observed in Fig. 5.1-2 such as stratospheric intrusions, PV streamers, frontal zones, gravity waves, convection and patches of vertical turbulence. Stratospheric intrusions and extended dry layers in the middle and lower troposphere turn out to be the normal case rather than the exception. The large dynamical range of tropospheric water vapour is also impressively demonstrated. Striking similarities in water vapour heterogeneity with the WALEX 2002 and 2003 data are found, especially at subtropical latitudes.

## Water Vapor Mixing Ratio (g/kg) and Geopotential Height (m) at 200hPa ECMWF (T511/L60) VT: 04.11.2005 06 UT



**Figure 5.1-3:** *ECMWF analysis of water vapour mass mixing ratio (g/kg, colour scale) and geopotential height (m, isolines) at 200 hPa (~ 12 km altitude) on the first flight to Australia.* 

Figures 5.1-3 to 5.1-5 are a set of ECMWF analyses showing the water vapour horizontal distribution between Europe and Australia at ~ 12 km altitude on November 4, 9 and 12, the three transfer flight days. The ECMWF analyses, which serve to characterise the synoptic-scale state of the atmosphere and aid to judge the representativeness of the measurements, are six hourly data, stored on a regular latitude/longitude grid with a spatial resolution of  $0.5^{\circ} \times 0.5^{\circ}$  (T511) and with 60 model levels from the surface up to 0.1 hPa.

The strong humidity gradient between the humid tropical air masses and the drier subtropics is impressively reproduced. This corresponds to the regions where the tropopause hits the 12 km altitude level. The subtropical jet stream where the geopotential height contour lines are most dense is located at around 30 N. Intense dynamical activity in the UT/LS is expected there, and indeed found in the complex layering of stratospheric aerosol as visible in Fig. 5.2-2. During the period of the eastbound transfer flights, the subtropical jet stream was nearly zonally oriented with marginal undulations on 4.11.05. North of the subtropical jet the air is generally drier



at 200 hPa compared to the higher levels south of 30 N. The observed enhanced UT humidity values are well reflected by the operational ECMWF analyses.



ECMWF (T511/L60) VT: 09.11.2005 12 UT

Figure 5.1-4: ECMWF analysis t at 200 hPa; same style as in Fig. 5.1-3.





**Figure 5.1-5:** *ECMWF analysis of water vapour mixing ratio and geopotential height at 200 hPa; same style as in Fig. 5.1-3.* 

Water Vapor Mixing Ratio (g/kg) and Geopotential Height (m) at 500hPa ECMWF (T511/L60) VT: 10.12.2005 00 UT



**Figure 5.1-6:** *ECMWF T511/L60 analysis of water vapour mass mixing ratio (g/kg, same colour scale as the 200 hPa plots) and geopotential height (m, isolines) at 500 hPa (~ 5 km altitude).* 



ECMWF (T511/L60) VT: 13.12.2005 06 UT

**Figure 5.1-7:** *ECMWF analysis of water vapour mixing ratio and geopotential height at 500 hPa on 13.12.05 06 UT. Same units as in Fig. 5.1-3.* 



Water Vapor Mixing Ratio (g/kg) and Geopotential Height (m) at 500hPa ECMWF (T511/L60) VT: 17.12.2005 12 UT



**Figure 5.1-8:** *ECMWF analysis of water vapour mixing ratio and geopotential height at 500 hPa on 17.12.05 12 UT. Same units as in Fig. 5.1-3.* 

Figures 5.1-6 to 5.1-8 are a set of ECMWF analyses showing the water vapour horizontal distribution between Europe and Australia at ~ 5 km altitude on December 10, 13 and 17, at the beginning, in the middle and at the end of the back transfer week. Over that week, we witness a deepening of the strong humidity gradient between the humid tropical air masses and the drier subtropics above India. The Falcon crossed this region on Dec. 14, and Fig. 5.3-4 very clearly displays this highly interesting transition region.

In contrast to the period in November 2005, the subtropical jet stream meandered significantly during the westbound transfer flights. This can be seen by the undulating contour lines of the geopotential height at 500 hPa in Figs. 5.1-6 to 5.1-8 where the lower edge of the subtropical jet stream is located at around 30 N.

Figs. 5.1-9 to 5.1-10 depict the water vapour distribution, the potential temperature, the horizontal wind speed and the absolute temperature along the flight paths of the DLR Falcon for the eastbound transfer flights. The 6-hourly operational T511/L60 ECMWF analyses were interpolated spatially and temporally onto the flight paths.

As observed during the WALEX II mission in 2004, there is a strong variability of tropospheric water vapour in midlatitudes and in subtropical regions. As the tropopause height is at about 10-12 km altitude for latitudes north of 35 N the water vapour content is rather low as reflected by the DIAL observations. At about 30 N the subtropical jet stream with maximum horizontal windspeed of about 50 m/s is located at about 12 km altitude.



South of the subtropical jet stream, the tropopause gradually increases to about 18 km altitude for latitudes smaller than 18 N. At this location, an abrupt change into the warm pool region of the inner tropical convergence zone (ITCZ) is visible by higher water vapour values for altitudes higher than 12 km. Directly above this region, ECMWF analyses locate the cold point tropopause with temperatures of around 190 K. This temperature minimum in the topical tropopause at 100 E in 17.5 km altitude corresponds exactly to the region where ultra thin cirrus was measured in Fig. 5.2-4.

A similar composite of the operational ECMWF analyses for the westbound flights is shown in Figs. 5.1-11 and 5.1-12, respectively. The water vapour distribution is characterised by two separated dry intrusions at about 21 N and 31 N. Both features are associated with a maximum of the horizontal wind speed of 45 m/s at 12 km altitude. During both flight legs, the Falcon crossed the meandering subtropical jet stream.

The backward transfer is hence characterised by the fact that the subtropical jet stream was crossed twice by the Falcon, namely first between Hyderabad (India) and Dubai, on 14.12. at 21 N, and second between Bahrain and Larnaca (Cyprus) on 16.12.05 at 30 N, nicely visible in Fig. 5.1-11. Indeed, intense dynamical activity here is found in the complex aerosol and humidity structures visible in Fig. 5.3-6. Just in the end of the last transfer flight, the polar jet is touched. This coincides with the measurement of a stratospheric intrusion, dry air penetrating down to 5 km altitude between 45.5 and 46 N in Fig. 5.3-8.





**Figure 5.1-9:** *ECMWF cross sections of water vapour volume mixing ratio (µmol/mol), potential temperature (black isentropes; K) and horizontal windspeed (blue isolines; m/s). Composite of individual model analyses interpolated in space and time to the Falcon flight path and time during the transfer flights from Oberpfaffenhofen to Darwin.* 



**Figure 5.1-10:** *ECMWF cross sections of water vapour and air temperature (K), same region as Fig. 5.1-9. The temperature minimum in the topical tropopause at 100 E in 17.5 km altitude corresponds exactly to the region where ultra thin cirrus was measured in Fig. 5.2-4.* 





**Figure 5.1-11:** *ECMWF cross sections for the back transfer, same configuration as Fig. 5.1-9. The subtropical jet was crossed twice by the Falcon, namely first between Hyderabad (India) and Dubai, on 14.12. at 21 N, and second between Bahrain and Larnaca (Cyprus) on 16.12.05 at 30 N.* 



Figure 5.1-12: ECMWF cross sections for the back transfer, same configuration as Fig. 5.1-10.



### 5.2 Transfer to Australia

The following detailed plots illustrate all individual measurements taken during the six flights to Australia. All plots are in the same style for facilitating comparisons. There is one overview figure per flight. All figures display the backscatter ratio at 532 and 1064 nm, the volume depolarisation ratio at 532 and 1064 nm and the water vapour volume mixing ratio as vertical cross sections, as function of measurement time and altitude. The logarithmic colour scales give the possibility to display large dynamic ranges. The individual figure captions highlight special features visible in the respective plots.

The backscatter ratio data are extinction-corrected, assuming a constant extinction to backscatter ratio (= lidar ratio) of 30 (50) at 1064 (532) nm which proves to be an overall good choice, except for some cirrus clouds. For the zenith-viewing measurements, each individual backscatter ratio profile is normalized to 1.15 (1.03) at 1064 (532) nm in the far range between 18 and 20 km altitude where homogeneous atmospheric conditions can be assumed. This normalisation equalises e.g. laser power fluctuations or changes of the detector amplification settings.

The depolarisation ratio measurements also have to be calibrated. As outlined in section 4.2, the depolarisation ratio of the co- and cross-polarised signals  $\beta_{\perp}/\beta_{\parallel}$  contains information about the sphericity of the particles. Given our specific detector filter width of 1 nm FWHM, a depolarisation of 0.0048 (or 0.48%) corresponds to pure Rayleigh depolarisation by air molecules. For each individual lidar profile, the depolarisation ratio measurements are hence normalised to 0.48% in regions where Rayleigh scattering is found to dominate the signal. In the far range, the 1064 nm depolarisation profiles suffer from very weak Rayleigh scattering, in the absence of aerosols, compared to the 532 nm signals.

The zenith-viewing water vapour measurements have to be corrected for the Rayleigh-Doppler effect, because on their return path through the atmosphere the initial OPO online signals are spectrally broadened by the temperature dependent Doppler broadening of the Rayleigh molecular scattering, in the absence of aerosols. A radiation transfer scheme run with high spectral resolution revealed that neglecting this effect leads to an underestimation of the water vapour mixing ratio of ~ 5%. Hence, the zenith-viewing water vapour profiles were corrected by this amount to compensate for this effect.

All data outside the valid physical range, or data affected by too much noise are set to zero (= white areas in the plots). The HDF lidar data set, part of the deliverables, is identical to the plots shown in this section.



Figure 5.2-1: First transfer flight to Australia, from Oberpfaffenhofen to Larnaca. Clouds at flight altitude were present only in the very first part of the flight. Stable layers of background stratospheric aerosols with embedded wave activity are clearly detected at 1064 nm.



**Figure 5.2-2:** Second transfer flight to Australia, from Larnaca to Dubai. Due to the vicinity of the subtropical jet the stable layers of stratospheric aerosols with embedded wave activity exhibit a more complex structure than in Fig. 5.2-1. In addition, the humidity is significantly increased.



**Figure 5.2-3:** Third transfer flight to Australia, from Dubai to Hyderabad. No clouds at or above flight altitude until 18 N. Then a thick cirrus cloud with high depolarisation from ice crystals extends between 12 – 16.5 km. The stable layers of stratospheric aerosols are also present.



**Figure 5.2-4:** Fourth transfer flight to Australia, from Hyderabad to U-Tapao, near Bangkok. Many clouds at or above flight altitude are encountered, partly producing oversaturated lidar signal in the near range (making H2O retrievals impossible) and extinguishing the signals in the far range. Very thin cirrus layers are detected near the tropical tropopause south of 16 N.



**Figure 5.2-5:** *Fifth transfer flight to Australia, from Bangkok to Brunei. A persistent cirrus layer with high depolarisation from ice crystals and complex structure extends between 12 and 16 km. Water vapour measurements are only possible in unsaturated lidar profiles.* 



**Figure 5.2-6:** Last transfer flight to Australia, from Brunei to Darwin. The persistent cirrus layer with high depolarisation from ice crystals is geometrically and optically thicker than in Fig. 5.2-5. Water vapour measurements are only possible in unsaturated lidar profiles, hence sparse here.



## 5.3 Transfer Back

In the following, all eight flights are presented in the same style for facilitating comparison. There is one such overview figure per flight. All figures display the backscatter ratio at 532 and 1064 nm, the volume depolarisation ratio at 532 and 1064 nm and the water vapour volume mixing ratio as vertical cross sections as function of measurement time and altitude. The logarithmic colour scales give the possibility to display large dynamic ranges. The individual figure captions highlight special features visible in the respective plots.

The backscatter ratio data are extinction-corrected, assuming a constant extinction to backscatter ratio (= lidar ratio) of 30 (50) at 1064 (532) nm which proves to be an overall good choice, except for some cirrus clouds. For the nadir-viewing measurements, each individual backscatter ratio profile is normalized to 1.5 (1.1) at 1064 (532) nm in a mid-troposphere region where homogeneous atmospheric conditions can be assumed. This normalisation equalises e.g. laser power fluctuations or changes of the detector amplification settings.

The depolarisation ratio measurements also have to be calibrated. As outlined in section 4.2, the depolarisation ratio of the co- and cross-polarised signals  $\beta_{\perp}/\beta_{\parallel}$  contains information about the sphericity of the particles. Given our specific detector filter width of 1 nm FWHM, a depolarisation of 0.0048 (or 0.48%) corresponds to pure Rayleigh depolarisation by air molecules. For each individual lidar profile, the depolarisation ratio measurements are hence normalised to 0.48% in regions where Rayleigh scattering is found to dominate the signal. In the far range, the 1064 nm depolarisation profiles suffer from very weak Rayleigh scattering, in the absence of aerosols, compared to the 532 nm signals.

All data outside the valid physical range, or data affected by too much noise are set to zero (= white areas in the plots). The HDF lidar data set, part of the deliverables, is identical with the plots shown in this section.



**Figure 5.3-1:** First transfer flight from Australia, from Darwin to Brunei. Scattered cirrus, mid- and low-level clouds are partly extinguishing the lidar signals. Laser operation was not stable during the first part of this flight and water vapour profiles are missing therefore.



Figure 5.3-2: Second transfer flight from Australia, from Brunei to Bangkok. Dense cloud cover at nearly all levels, generating over-saturation and shadowing effects makes depolarisation and water vapour retrieval difficult.



**Figure 5.3-3:** Third transfer flight from Australia, from Bangkok to Hyderabad, with nearly cloud-free conditions. Due to very high humidity, measurements throughout the whole troposphere are impossible with only one online wavelength. Nevertheless, the backscatter and humidity profiles reveal interesting details in this data sparse region of the globe.



**Figure 5.3-4:** Fourth transfer flight from Australia, from Hyderabad to Dubai, again with nearly cloud-free conditions. The humidity profiles reveal very interesting heterogeneity and dry layers from dynamic activity in this data sparse region of the globe.



# SCOUT-O3 16-12-2005



Dubai -> Bahrain



**Figure 5.3-5:** *Fifth transfer flight, from Dubai to Bahrain, again under nearly cloud-free conditions; only scattered low-level cumulus clouds. Note that this was a very short flight where the laser operation was not stable so that the humidity profiles are scattered.* 



# SCOUT-O3 16-12-2005



Bahrain -> Larnaca



**Figure 5.3-6:** *Sixth transfer flight, from Bahrain to Larnaca, with cirrus and scattered mid- to low-level clouds. An interesting intrusion of dry air into the lower troposphere is detected between 30 and 34 N, just above the desert at the border between Saudi Arabia and Iraq. It comes with intense dynamical activity as witnessed by the aerosol backscatter signals.* 



**Figure 5.3-7:** Seventh transfer flight, from Larnaca to Brindisi, with a well-developed cloud deck in the lower troposphere. In the cloud gaps, profiling of the heterogeneous boundary layer down to the surface is possible.



**Figure 5.3-8:** Last transfer flight, from Brindisi to Munich, with a well-developed opaque cloud deck in the middle troposphere. Occasional cloud gaps enable profiling of the heterogeneous boundary layer down to the surface, showing complex layering and wave patterns.



#### 5.4 Selected Episodes of Particular Interest

The backward transfer is characterised by the fact that the subtropical jet stream was crossed twice by the Falcon, namely first between Hyderabad (India) and Dubai, on 14.12., and second between Bahrain and Larnaca (Cyprus) on 16.12.05. Hence, this section focuses on the individual back transfer flights.

Figure 5.4-1 shows a close-up of the water vapour cross section of the flight between Thailand and India. The large white areas in the bottom are regions where the one-way online water vapour optical depth exceeds 2, i.e. very humid air is encountered, as expected in the tropics. Water vapour data in these regions are not available because the optical depth is too large. Nonetheless, the plot gives interesting insight into the dynamical structure of this subtropical segment: a very humid tropospheric layer is observed up to roughly 8 km altitude, with marked undulations, and a thin dry layer in between at ~4 km. Above, in the upper troposphere, complex layering of water vapour is evident.



**Figure 5.4-1:** *DIAL water vapour volume mixing ratio cross section (colours; µmol/mol) on the transfer back, between Thailand and India, on 13.12.2005. ECMWF analysis water vapour cross section (white isolines) overlaid, interpolated in space and time to the Falcon position and time.* 





**Figure 5.4-2:** *ECMWF analysis horizontal wind (blue isolines) and equivalent potential temperature (grey) isentropes interpolated in space and time to the Falcon position and time, overlaid onto the DIAL cross section. Same region and colour bar as Fig. 5.4-1.* 

Superimposed on the DIAL observations are interpolated operational ECMWF analyses. The exponential decrease of water vapour with height as well as part of the mesoscale structures (e.g. enhancement of water vapour at 86 E and 6 km altitude) are well captured by the meteorological analyses. In the nearly cloud-free conditions of this morning flight there were not much active convective updrafts. This is reflected in the nearly horizontal isentropes with a mean gradient of about 5K/km, i.e. with a Brunt-Väisälä frequency of about 0.0125 Hz. The horizontal wind speeds in the troposphere section were most of the time less than 10 m/s.

Figure 5.4-3 shows the DIAL results between Hyderabad (India) and Dubai, on 14.12.2005. Thanks to an excellent SNR and the logarithmic scaling, a large dynamical range of about three orders of magnitude in H2O mixing ratio (10...10000 ppmv) can be covered with a single online wavelength. Total water vapour is in this region already lower than in Fig. 5.4-1 so that the one-way water vapour optical depth rarely exceeds 2. Again, the operational ECMWF analyses capture the gradients in the H2O field very well.

An interesting feature is a very thin and dry layer at 4 km altitude, extending throughout the area across 2000 km, above the very humid lower troposphere. The middle troposphere exhibits very heterogeneous humidity distribution: a 4 km thick humid layer in the west becomes thinner towards east and is replaced by very dry air in the east, advected from the subtropics by the subtropical jet stream whose maximum is found at 21 N in Fig. 5.4-4.

All observations show tropospheric air masses although the very low H2O concentrations near the subtropical jet stream might indicate a stratospheric origin of the air. North of 22.5 N the dynamical tropopause at 2 PVU (potential vorticity units) was located at 11 km altitude. This coincides with denser isentropes (thermal versus WMO tropopause definitions).





**Figure 5.4-3:** *DIAL water vapour profiles on the transfer back, between Hyderabad (India) and Dubai, on 14.12.2005. ECMWF analysis water vapour cross section (white isolines) overlaid, interpolated in space and time to the Falcon position and time.* 



**Figure 5.4-4:** *ECMWF analysis horizontal wind (blue isolines), equivalent potential temperature (grey) isentropes and 1.5/2/2.5 PVU potential vorticity lines (black) interpolated in space and time to the Falcon position and time, overlaid onto the DIAL cross section. Same region and colour bar as Fig. 5.4-3.* 



**Figure 5.4-5:** *DIAL profiles on the transfer back, between Bahrain and Cyprus, on 16.12.2005. Upper panel is r<sup>2</sup> corrected backscatter intensity in relative units on a logarithmic colour scale. Note that this plot is flipped horizontally when comparing to Figs. 5.4-6 and 5.4-7.* 

Figure 5.4-5 shows the DIAL results between Bahrain and Cyprus, on 16.12.2005. The upper panel is the  $r^2$ -corrected backscatter intensity in relative units, because normalisation is not possible for the whole cross section due to the presence of clouds at various levels. The lower panel is H2O mixing ratio. As Fig. 3-3 shows, the flight went along the Iraq border above the Saudi-Arabian desert. It is interesting to find a humid boundary layer with some low-level clouds in this area. In the middle of Fig. 5.4-5, a dry layer is close to the surface, and the humidity maximum is lifted to 2 – 3 km altitude. A similar structure is found in the aerosol plot, and cloud condensation seems to start just at the top of the humid layer in 3 km ASL.

In the upper troposphere a depression over the Mediterranean sea active the days before, brings very dry air down to 6 km, at 38 – 39 E. An interesting dynamical situation has obviously been encountered. Fig. 5.4-7 suggests that this particular flight was essentially along the axis of the subtropical jet stream: the height of the dynamical tropopause decreases gradually from 12 km to 10 km and the lower stratospheric wind speed was nearly uniform with 45-50 m/s. Directly beneath the tropopause the extended dry area with minimum values lower than 100 ppmv dominates the observations as well as the meteorological analyses.





**Figure 5.4-6:** *DIAL water vapour profiles on the transfer back, between Bahrain and Larnaca (Cyprus) on 16.12.2005. ECMWF analysis water vapour cross section (white isolines) overlaid, interpolated in space and time to the Falcon position and time.* 



**Figure 5.4-7**: *ECMWF analysis horizontal wind (blue isolines), equivalent potential temperature (grey) isentropes and 1.5/2/2.5 PVU potential vorticity lines (black) interpolated in space and time to the Falcon position and time, overlaid onto the DIAL cross section. Same region and colour bar as Fig. 5.4-6.* 



Figure 5.4-8: DIAL profiles on the transfer back, above the Adriatic Sea, on 17.12.2005. Note that this plot is flipped horizontally when comparing to Figs. 5.4-9 and 5.4-10.

There are essentially two different possibilities for formation of this dry region. First descent due to secondary circulations along the jet stream, or advection of dry stratospheric air masses, which were intruded by an earlier event, e.g. a tropopause fold associated with a low-pressure system above the Mediterranean Sea.

Figure 5.4-8 shows DIAL profiles on the last flight of the transfer back, from Brindisi (Southern Italy) to Munich, above the Adriatic Sea, on 17.12.2005. Very dense cloud cover with tops at 4 – 5 km is evident. The clouds and the absence of profiles that reach the ground make the laser adjustment somewhat more difficult. Hence, we find here more interruptions due to adjustments (vertical white bars). Nevertheless, the dominant large-scale atmospheric structures are evident: we find a humid layer extending up to 7 km above the clouds, vanishing towards North. Here, in the very right of Fig. 5.4-6, the cloud layer dissipates, and profiles of water vapour and aerosol in the boundary layer of the Po valley are available. The dissipating clouds may be related to another intrusion of dry air associated to the polar jet, as seen in Figs. 5.1-12 and 5.4-10.



**Figure 5.4-9:** *DIAL water vapour profiles on the transfer back, between Munich and Larnaca (Cyprus) on 16.12.2005. ECMWF analysis water vapour cross section (white isolines) overlaid, interpolated in space and time to the Falcon position and time.* 



**Figure 5.4-10:** *ECMWF analysis horizontal wind (blue isolines), equivalent potential temperature (grey) isentropes and 1.5/2/2.5 PVU potential vorticity lines (black) interpolated in space and time to the Falcon position and time. Same region and colour bar as Fig. 5.4-9.* 



## 6 Lidar Inversion for Selected Cases

The following cases were selected for further investigation and lidar inversions as outlined in section 4.2. They are limited to the nadir measurements of the return ferry. The plots display vertical profiles of the backscatter ratio at 934 nm (the H2O offline) obtained after application of an iterative inversion procedure. Backscatter and extinction coefficient profiles can easily be obtained from these according to the equations in section 4.2. The underlying Rayleigh backscatter coefficient profile and the lidar ratio were estimated following the ESA RMA (ESA 2003).



**Figure 6-1:** Backscatter ratio profile at 15 N, 94 E of a cloud-free area over the Andaman Sea. Total optical depth is 0.07.

Heavy cloud cover in the first flights of the ferry back, between Darwin and Bangkok prevented any useful treatment in these cases. The first profile in Fig. 6-1 is from a cloud-free area over the Andaman Sea, west of Bangkok. Since appropriate insitu measurements of aerosol properties are lacking, calibration in this case was performed by setting the lowest profile value at 3070 m to 1.1. The result shows good agreement with a standard atmospheric profile assuming a ground visibility of 40 km. The low values in the boundary layer display relatively clean air.



The next example in Fig. 6-2 shows a very similar situation over the Gulf of Oman, east of Dubai. Based on the same calibration method, the relatively clean air gives good agreement with the same 40 km visibility standard profile. The somewhat higher values in the upper troposphere are probably related to the appearance of cirrus clouds to the east, visible in Fig.5.3-4.



**Figure 6-2:** Backscatter ratio profile at 24 N, 59 E of a cloud-free area east of Dubai. The maximum extinction coefficient is 7\*10<sup>5</sup> m<sup>-1</sup> in 600 m. Total optical depth is 0.15.

Figure 6-3 shows in contrast a lidar inversion through a cirrus cloud complex south of Kuwait, in which the offline signal was not saturated. The lidar inversion method applied here has the specialty that for a selected vertical sub-domain, a different lidar ratio, compared to the tropospheric standard of 0.02, can be chosen. In this case, it is very likely that the cirrus cloud will have a different lidar ratio. Hence, a different lidar ratio between 7.5 and 9.5 km was applied in the lidar inversion scheme. Calibration with the standard atmosphere below the cloud and the assumption of standard values above it lead to a cloud lidar ratio of 0.026 and a total optical depth of 1.35. We note that this lidar ratio is not typical for cirrus and the case needs further investigation. The second peak in 4.5 km altitude can be attributed to very small, scattered clouds at the top of the aerosol layer (cf. Fig. 5.3-6).



**Figure 6-3:** Backscatter ratio profile at 28 N, 47 E through a cirrus cloud complex south of Kuwait. The maximum extinction coefficient is  $8^{104}$  m<sup>1</sup> in 8000 m. Total optical depth is 1.35.

During the last ferry flights, dense cloud cover prevents profiling the boundary layer, and the clouds signals are over-saturated. The last example in Fig. 6-4 is a profile through a very narrow cloud free area in northern Italy. The standard atmosphere with ground visibility of 40 km is very close. The low values in the boundary layer display even cleaner air, indicating somewhat higher visibility.

All profiles shown here are available in ASCII format in the CD-ROM with the deliverables, including backscatter and extinction coefficient profiles.



**Figure 6-4:** Backscatter ratio profile at 45.6 N, 12 E over northern Italy. The maximum extinction coefficient is  $1.4*10^5 \text{ m}^1$  in 1340 m. Total optical depth is 0.04.



## 7 Background Radiation

Former studies (e.g. ESA 2001) have shown that the statistical noise error and the signal/noise ratio of water vapour DIAL measurements are crucially affected by the solar irradiation entering the receiver, not correlated with the backscattering of the laser beam by atmospheric particles. This background radiation originates from sunlit clouds and ground. The intensity of radiation from the ground is mainly determined by its albedo, the radiation from clouds depends on their distance/altitude.

## 7.1 Variability over Different Clouds and Grounds

The level of the background radiation for each backscatter profile along the flight paths can be estimated from the raw signal (LSB digits) in the pretrigger signal, recorded directly before emission of the laser pulse. Note that these data are not suitable for detailed statistical analysis; they provide only a rough estimate of relative variations of the background radiation rather than absolute quantitative radiation levels.



#### Figure 7-1: Background radiation intensity between Brunei and Bangkok, over flight time.

Two examples from the return ferry with the nadir pointing system are shown in this section. All data from the return ferry are available as ASCII files in the CD-ROM with the deliverables. The files also contain the detector noise estimated from the standard deviation of all pretrigger channels within a one-minute averaged profile. Fig.



7-1 displays the radiation level at 934 nm, the offline channel, between Brunei and Bangkok. The scene is nearly 100% overcast and the flight was around local noon, resulting in relatively high radiation values.

In contrast, Fig. 7-2 displays the background radiation level between India and Dubai, a morning flight with only little cirrus encountered around 5:20 UTC. The higher levels at the beginning of the flight are above land (India), associated with low-level clouds and scattered cirrus. See for comparison of both examples Figs. 5.3-2 and 5.3-4.



Figure 7-2: Background radiation intensity between Hyderabad, India and Dubai, as function of flight time.



#### 7.2 Results from the LibRadtran Model

This section describes the calculation of the background radiation caused by reflection and scattering of solar radiation by the Earth's surface and by the atmosphere. The quantity of interest is the radiance in nadir direction at the top of the atmosphere. It was calculated for a small wavelength region between 935.0 and 936.5 nm within a water vapour absorption band.

The libRadtran package was used for all calculations. libRadtran has been developed by Arve Kylling and Bernhard Mayer over the last 15 years. For the WALES study (ESA 2001), libRadtran was extended to do line-by-line calculations in the infrared spectral range. Hence, all calculations done in this study include a rigorous treatment of multiple scattering effects.

In particular, the following data were used as input to libRadtran:

- For the radiative transfer calculations, a vertical grid with 50 layers between 0 and 120 km altitude was chosen. The grid spacing was 1km between 0 and 25 km, 2.5 km between 25 and 50 km, and 5 km above 50 km.
- Profiles of pressure, temperature and trace gas densities were taken from six standard atmospheres.
- Molecular (Rayleigh) scattering was calculated according to Nicolet (1984).
- Molecular absorption coefficients were calculated using GENLN2 version 4 by Edwards (1992).
- Aerosol properties were calculated according to Shettle (1989). Alternatively, aerosol extinction was calculated as prescribed in the ESA RMA (2003), in particular the "median profile". The Shettle (1989) data generally lead to higher values for the nadir radiance, as the amount of aerosol in higher altitudes is larger than for the ESA (2003) profile.

An exemplary water cloud was defined between 4 and 5 km, with a liquid water content of 0.5 g/m<sup>3</sup> and an effective droplet radius of 10  $\mu$ m. Microphysical properties were converted to optical properties according to the parameterisation of Hu and Stamnes (1993) leading to a total optical thickness of 80.2, a single scattering albedo of 0.99990, and an asymmetry parameter of 0.856. An example for a high cloud was placed between 9 and 10 km, with a liquid water content of 0.0040 g/m<sup>3</sup> and an effective radius of 20  $\mu$ m, corresponding to a total optical thickness of 0.31, a single scattering albedo of 0.99980, and an asymmetry parameter of 0.868. These can be considered typical examples of a thick midlevel cloud and a thin high-level cloud.

The extraterrestrial irradiance was set to a constant 855 mW/(m<sup>2</sup> nm) for the wavelength region under interest, namely 935.0 – 936.5 nm. DISORT version 2.0 (Stamnes et al., 1988) was used as radiative transfer equation solver for all calculations. The number of streams was set to 24, which is sufficient for nadir radiance calculations with the assumed scattering phase functions. DISORT is a plane-parallel model; hence, results for solar zenith angles larger than 80° would be biased by the assumption of a flat rather than a spherical Earth.

Figure 7-3 displays the resulting nadir radiance at the top of the atmosphere as function of wavelength. As a reference value, the nadir radiance in the absence of absorption for a surface albedo of 0.5 is 32.7 mW/(m<sup>2</sup> nm sr). In the presence of absorption, the radiance is reduced by one to three orders of magnitude. In regions of strong absorption (line centres) the surface is not "visible" from TOA. Some examples of cloudless and cloudy scenes are presented in Figure 7-3. A thick cloud at 5 km acts as a highly reflecting surface. In this case, the extinction above the reflecting surface is much less than in the clear case because the larger part of the absorber is below the cloud. Hence, the radiance is increased by up to two orders of magnitude compared to the clear case, except in regions of very strong absorption (around 935.68 nm).



In the presence of a thin high cloud, the enhancement of the radiation is smaller than for the midlevel cloud because the albedo of the optically thin cloud is smaller. In summary, due to the strong decrease of the water vapour concentration with altitude, the reflected radiance depends not only on the optical thickness (or liquid/ice water content of the cloud) but also strongly on the altitude of the cloud top. The lower the reflecting surface, the smaller is its contribution to the nadir radiance at the TOA.



**Figure 7-3**: Nadir radiance for different atmospheric conditions. All curves were computed for the US std. atmosphere, standard Shettle (1989) aerosol, and a solar zenith angle of 75°. The surface albedo was 0.5 in all cases, unless otherwise specified.

Calculations for different standard atmospheric profiles show no dependence of the radiance on the profile in the centre of the strongest line. Differences become obvious at low absorption (e.g. around 935.85 nm) where the surface is "visible" from TOA, and hence the full profile contributes to the extinction. At the surface, water vapour concentration increases from subarctic-winter, midlatitude-winter, US-standard, subarctic-summer, midlatitude-summer, to tropical. Consequently, the nadir radiances decrease in the same order. The radiances presented here are delivered as ASCII files on the CD-ROM.

## 8 Data Inventory and Deliverables

The following files are contained on the CD-ROM delivered to ESA:

Description	Format	Filename
WALEX 2005 Data Inventory	doc + pdf	WALEX 2005 Data Inventory
WALEX 2005 Final Report	doc + pdf	WALEX 2005 Final Report
WALEX 2005 Final Presentation	ppt + pdf	WALEX 2005 Overview
		WALEX 2005 Results
		WALEX 2005 FP Ehret
Along-flight profiles of particle backscatter and depolarisation	HDF	(date).bi.di.(part).hdf
Tallo at 1064 nm for each flight		
Along-lingni promes of particle backscatter and depolarisation	HUF	(date).bg.dg.n20.(part).ndi
Along flight profiles of particle backscatter ratio at 934 pm (the	HDE	(date) f(part) bdf
H2O offline) for each transfer flight	ПЛ	
Quicklooks of water vapour, backscatter and depolarisation ratio	png	sco(data).gidh.(part).png
at 532, 934 and 1064 nm for each transfer flight		sco(data).f(part).png
Backscatter and extinction coefficient profiles and optical depths	ASCII	sco(data).rf(part)_Mie
for selected cases, data and plots	ps	sco(data).rf(part)_Mie.ps
Background radiation variability on nadir pointing flights, data	ASCII	sco(data).rf(part)_bg_rad
and plots	ps	sco(data).rf(part)_ bg_rad.ps
Background radiance spectra in the 940 nm region from	ASCII	RADIANCE*.ASC
LibRadtran		
ECMWF analyses interpolated to Falcon flight routes, with all	binary	P(date)_fff_rf(part).dac
"primary" parameters including pressure, temperature, humidity	(IDL)	
IDL program to road ECMWE analysis	וחו	plot year 777 pro
LIDE program to read ECRIVIE analyses	IDL	

Note that the CD-ROM contains all HDF formatted lidar data from the SCOUT-O3 campaign, transfer and local flights, in one zipped archive named DIAL\_SCOUT\_HDF.zip.



## 9 Recommendations

Following the result obtained in the frame of this study, the following recommendations can be drawn. First, the study proves once again that high quality aerosol and humidity lidar observations can be gained from long-range ferry flights. Such airborne data, especially if gathered in data-sparse regions such as southeast Asia, are of high relevance for predicting and optimising the performance of future spaceborne lidar instruments.

Next opportunities will be during transfer and local measurements flights to upcoming field campaigns, especially in the frame of THORPEX, a global research programme dedicated to reduce the risk of high-impact weather to the society, the economy and the environment under the auspices of the WMO (www.wmo.int/thorpex). One of the key issues of THORPEX is to test new observing strategies for remote sensing instruments to obtain data in data-sparse regions.

In spring 2008, the DLR Falcon with water vapour and wind lidars on board will be employed across the Barents Sea between Norway and Spitsbergen during the IPY-THORPEX (International Polar Year) campaign. Additional long-range flights to Greenland or Iceland, not supported within THORPEX-IPY, could be feasible for the Falcon. Main interest here would be to collect lidar data over this remote polar region.

In fall 2008, participation of the DLR Falcon with water vapour and wind lidars on board was demanded by the organisers of T-PARC, the THORPEX Pacific Asian Regional Campaign. The goal of this large international experiment is to study tropical cyclone tracks, extra-tropical transitions of tropical cyclones, tropical warm-pool physics and downstream propagation using targeted observations in sensitive regions over the northern Pacific Ocean. The transfer flights would yield large data sets of great interest, as Asia would be completely crossed from west to east, and vice-versa. In addition to water vapour and wind lidar profiling from the Falcon, the validation of atmospheric motion vectors (AMV) using wind and cloud top information provided by the lidar is an interesting additional application.







Performance comparison between new (green) and old (red) DLR water vapour DIAL systems for measurements in the lower stratosphere.

In 2007, the new DLR 4-wavelength airborne H2O DIAL will replace the actual system. The development of this instrument is supported in the frame of a DLR internal project with the goal to test the instrument concept in view of a future realisation in space. Like the proposed space lidar "WALES", this "airborne demonstrator" will have three online wavelengths plus one offline for profiling the whole troposphere and the lower stratosphere. It is expected to perform significantly better, especially in the lower stratosphere, as shown in Fig. 9-1. In particular, the new system will have 6 times higher average output power, 3 times higher single pulse energy, 1.8 times larger telescope area and 2 times less detector noise. It will be an excellent new instrument for the upcoming campaigns mentioned above.



From 2009 on, HALO - The High Altitude and LOng Range Research Aircraft will replace the Falcon and will be the new Research Aircraft for atmospheric research and earth observation of the German Science Community (<u>www.halo.dlr.de</u>). The HALO aircraft is based on a production G550 business jet from Gulfstream Aerospace Cooperation. Modifications to transform the regular business jet into a research aircraft are currently in progress in Oberpfaffenhofen. The aircraft will be operated by the Flight-Department of the DLR in Oberpfaffenhofen. Scientific operation with HALO will presumably start in July 2009 with "demonstration missions" in which the new four-wavelength water vapour DIAL system will participate.



Fig. 9-2: HALO - The High Altitude and LOng Range Research Aircraft will be the new Research Aircraft for atmospheric research and earth observation of the German Science Community.

The concept behind HALO is to provide an optimal platform for airborne atmospheric science and Earth observation, a well-equipped flying laboratory that allows the scientists onboard to focus on their own experiment. The business jet aircraft G550 of Gulfstream was found to meet best the essential requirements of the future HALO users:

- range well above 10000 km or more than 10 flight hours for transcontinental experiments and long duration measurements;
- certified ceiling of more than 15 km,
- maximum payload of 3 tons,



- a large usable cabin area of 20-30 m<sup>2</sup> for simultaneous operation of several complementary instruments and scientific personnel from several groups (for multidisciplinary and international projects),
- potential for quick modifications for a wide variety of applications and for flexible use as research aircraft with different instrument configurations for various research projects.

The main strengths of the HALO aircraft are its long range and endurance, high ceiling altitude and large instrument load capacities, which are not available in such combination on any other research aircraft in Europe.



Fig. 9-3: HALO – maximum flight ranges from south Germany.



#### 10 References

- Behrendt, A., V. Wufmeyer, P. Di Girolamo, H.-S. Bauer, T. Schaberl, D. Summa, D. N. Whiteman, B. B. Demoz, E. V. Browell, S. Ismail, R. Ferrare, C. Kiemle, G. Ehret, J. Wang, 2006: Intercomparison of water vapor data measured with lidar during IHOP\_2002, Part 1: Airborne to ground-based lidar systems and comparisons with chilled-mirror radiosondes. JTECH, 2006.
- Behrendt, A., C. Kiemle, P. Di Girolamo, H.-S. Bauer, T. Schaberl, V. Wulfmeyer, 2004: Measurement and intercomparison of active, passive, and in-situ sensors during the International H2O Project for the verification of the specifications of the WALES experiment. ESA Final Report of Contract No. 16669/02/NL/FF, 56 pp.
- Edwards, D., 1992: GENLN2: A general line-by-line atmospheric transmittance and radiance model: Version 3.0 description and users guide. NCAR/TN-367+str, NCAR, Boulder, Colorado.

Ehret, G., K.P. Hoinka, J. Stein, A. Fix, C. Kiemle, and G. Poberaj, "Low-Stratospheric Water Vapor Measured by an Airborne DIAL," *J. Geophys. Res. 104*, 31,351-31,359 (1999).

- ESA (2001) ITT AO/1-3654/00/NL/DC, "Evaluation of Spaceborne Differential Absorption Lidar for Water Vapour, Ozone and Carbon Dioxide": Final Report, by G. Ehret, C. Kiemle and M. Wirth.
- ESA (2003). EOPP-FP/2003-09-828, "Concept Study for Advanced Lidar Instrument", statement of work, Appendix A: Reference Model for the Atmosphere (RMA).

Fix, A., V. Weiss, and G. Ehret, Injection-seeded optical parametric oscillator for airborne water vapour DIAL, *Pure Appl. Opt., 7*, 837-852, 1998.

- Gérard, E., D.G. H. Tan, L. Garand, V. Wulfmeyer, G. Ehret, and P. DiGirolamo, 2004: Major advances foreseen in humidity profiling from WALES (Water Vapour Lidar Experiment in Space). *Bull. Amer. Meteor. Soc.* 85, 237-251.
- Hu, Y.X., and K.Stamnes, 1993: An accurate parameterization of the radiative properties of water clouds suitable for use in climate models. J. Climate, 6, 728-742.
- Kiemle, C., G. Ehret, A. Giez, K. J. Davis, D. H. Lenschow and S. P. Oncley, 1997: Estimation of boundary-layer humidity fluxes and statistics from airborne differential absorption lidar (DIAL). BOREAS special issue of the *J. Geophys. Res.*, Vol. 102 No. D24, 29189-29203.
- Luo, B.P., Peter, T., Fueglistaler, S., Wernli, H., Wirth, M., et al.: Dehydration Potential of Ultrathin Clouds at the Tropical Tropopause. Geophysical Research Letters, 30, D11 (10.1029/2002GL016737), 2003, 11-1-11-4.
- Nicolet, M., 1984: On the molecular scattering in the terrestrial atmosphere: an empirical formula for its calculation in the homosphere. Planet. Space Sci., 32, 1467-1468.
- Peter, T., Luo, B.P., Wirth, M., Kiemle, C., Flentje, H., et al.: Ultrathin Tropical Tropopause Clouds (UTTCs): I Cloud Morphology and Occurence. Atmospheric Chemistry and Physics 3, 2003, 1083-1091.
- Poberaj, G., A. Fix, A. Assion, M. Wirth, C. Kiemle, and G. Ehret, 2002: Airborne All-Solid-State DIAL for Water Vapour Measurements in the Tropopause Region: System Description and Assessment of Accuracy. *Appl. Phys. B* 75 (DOI: 10.1007/s00340-002-0965-x), 165-172.
- Shettle, E., 1989: Models of aerosols, clouds and precipitation for atmospheric propagation studies, in: Atmospheric propagation in the UV, visible, IR, and mm-region and related system aspects, no. 454 in AGARD Conference proceedings.
- Stamnes, K., S. Tsay, W. Wisacombe, and K. Jayaweera, 1988: A numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. Appl. Opt., 27, 2502-2509.
- Thomas, A; Borrmann, S; Kiemle, C; Cairo, F; Volk, M; Beuermann, J; Lepuchov, B; Santacesaria, V; Matthey, R; Rudakov, V; Yushkov, V; MacKenzie, A.R.; Stefanutti, L., In situ measurements of background aerosol and subvisible cirrus in the tropical tropopause region. J. Geophys. Res. Vol. 107, no. D24, Dec 2002.
- Weckwerth, T.M., D. B. Parsons, S. E. Koch, J. A. Moore, M. A. Lemone, B. R. Demoz, C. Flamant, B. Geerts, J. Wang and W. Feltz, 2004: An overview of the International H20 Project (IHOP\_2002) and some preliminary highlights. *Bull. Amer. Meteorol. Soc.* 85, 253-277.