The 3 wavelengths lidar ALEX and other instrumentation onboard the FALCON during CLARE'98

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INTRODUCTION

During the CLARE'98 campaign from 5 to 23 October 1998 near Chilbolton, southern UK, the 3-wavelengths lidar ALEX and a set of in-situ sensors to measure standard meteorological, radiometric and aviation parameters were installed onboard the DLR FALCON aircraft (Figure 1). The sensors onboard the FALCON aircraft as well as their respective accuracy are given in Tables 1 and 2.

Figure 1: *FALCON 20-E5 jet aircraft with lidar beam in downward-looking mode*

Table 1: *FALCON 20-E5 basic sensor-systems*

Tempera-ture	• fast / slow Rosemount PT500 / PT100-sondes • OAT / TAT via Air-Data-Computer
Radiation	• Radiometer Barnes PRT-6 (down) • Pyrgeometer Eppley PSP (up/down) • Pyranometer Eppley PIR (up/down)
Humidity	• Thermoelectrically cooled dewpoint mirror • Dielectric sensor (relative humidity) • Lyman-alpha (absolute humidity) • Cryogenically cooled dew-point mirror (optional)
Pressure and wind	• Pitch sensor (nose-mast) for 3D-turbulence and wind-measurements • Absolute & differential pressure sensors • Barometric height (Air-Data-Computer)

Table 2: *Accuracy of quantities recorded by the avionic data acquisition system onboard the FALCON aircraft*

Static pressure	± 0.5 hPa
Temperature	± 0.5 K
Humidity	1 % to 5 %
Total Water Content	0.1 g/m^3
Solar Flux Eppley	± 2 %
Longwave Flux	± 5 %
Horizontal position GPS/INS	± 50 m
Pitch (Gyro)	± 0.1 deg
Roll (Gyro)	± 0.1 deg
Heading	± 0.5 deg

The standard meteorological and aviation data listed in Tables 1 and 2 (also available at the web-site of the DLR flight facility: http://www.dlr.de/FB) are recorded by the data acquisition system onboard the FALCON aircraft with a temporal resolution of 10 Hz. From these quantities the present position, i.e. latitude, longitude and pressure altitude as well as the true air speed are calculated with an effective resolution of one second. These parameters are online available and stored together with the lidar data which allows to process automatically updated quicklooks of the back-scattered signals during the flight. This is very useful for in-flight mission co-ordination.

THE BACKSCATTER LIDAR

The 3 wavelength lidar of the DLR (ALEX - see Figure 2) was operated in downward-looking mode. It makes use of a flashlamp-pumped Nd:YAG laser with a fundamental wavelength of 1064 nm. Frequency doubling and tripling provides simultaneous output at 532 nm and 355 nm. The instrument emits the laser beam in an off-axis mode via an extra window in the aircraft fuselage (Figure 2). Complete overlap of the laser beam and the receiver field-of-view is achieved after a distance of 1 – 1.5 km.

The receiver is a Cassegrain telescope (r = 17.5 cm) with 1 mrad field of view. Narrow band filters are positioned in front

of the detectors to minimise the contributions of the background illumination from the atmosphere and the surface. The received 532 nm signal is split into two perpendicularly polarised portions which allows to calculate the depolarisation of the light. The depolarisation contains information about the asphericity of the back-scattering particles which allows to characterise different aerosol or cloud particle types. The performance of the lidar system has been described on principle by [1].

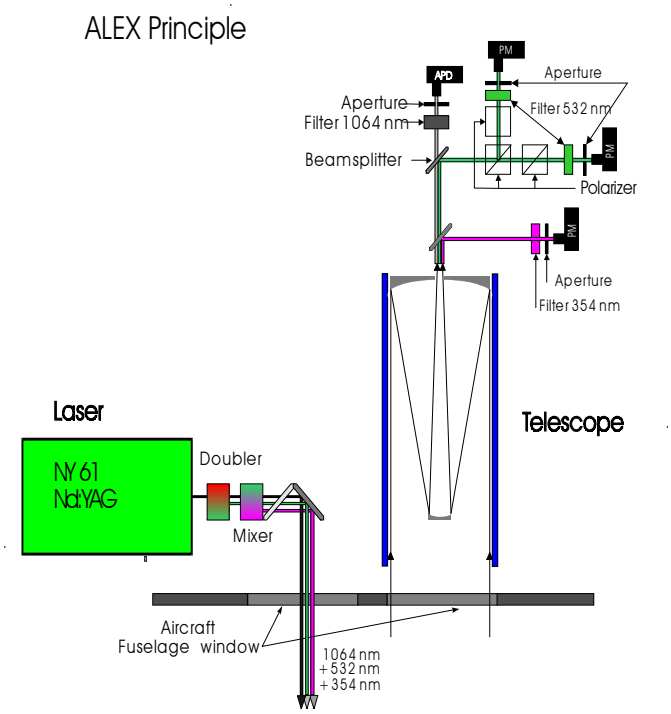

Figure 2: *Biaxial optical system and beam path of the ALEX lidar. Left side: transmitter and crystals for frequency conversion, right side: receiver and data acquisition system. The system parameters are listed in Table 3. Full overlap of the laser beam and the receiver field-of-view is achieved after a distance of about 1 - 1.5 km.*

With a repetition rate of 10 Hz and a typical aircraft speed of 150 m/s the raw data resolution is 15 m horizontally. Vertically the 10 MHz ADC sampling rate results in a resolution of 15 m. However, depending on the specific demand a trade-off between signal noise and spatial resolution is performed. In order to qualitatively investigate small scale structures in an inhomogeneous environment (e.g. for comparison of cloud boundaries obtained from ground based radar and airborne lidar) only few shots (< 1 s) are averaged degrading the horizontal resolution to about 100 m. For the derivation of quantitative optical parameters like optical depth or the multiple scattering contribution the signal is typically averaged over 10 – 20 s and slightly smoothed vertically which leads to a resolution of 1 – 3 km horizontally and 30 m vertically.

Table 3*: Aerosol Lidar EXperiment (ALEX) system parameters*

Transmitter	Continuum Nd:YAG-laser NY61
Pulse energy at λ	150 mJ @ 1064 nm
	120 mJ @ 532 nm
	150 mJ @ 355 nm
Pulse length	6 ns
Beam divergence	0.7 mrad
Pulse repetition rate	10 Hz
Telescope	B. Halle Nachf.
Type	Cassegrain
Diameter	35 cm
Field of view (full angle)	1 mrad
Focal length	5 m
Filter (Comp., Half width, max. Transmission)	1064 nm: LOT, 1.0 nm, 40%
	532 nm: LOT, 0.5 nm, 60%
	355 nm: FHE-Jena,1.5 nm, 45%
Detector	Hamamatsu R5600U
PMT (355 nm, 532nm)	Advanced Photonics 197-70-7X-520
APD (1064 nm)	
Transient-recorder	DLR, 12 bit / 20 MHz
	DLR, 14 bit / 10 MHz
Data handling	VME-BUS: (FORCE-Computer)
CPU:	SUN SPARC 10
Data storage medium:	Magneto-optical disks (2 GB) and DAT (3 GB)

The attenuated atmospheric backscatter directly measured by the lidar is either given absolutely as backscatter coefficient [$m^{-1}sr^{-1}$] or relative to Rayleigh scattering (calculated from air density) as backscatter ratio $\gamma = (\beta_{particle} + \beta_{molecule})/\beta_{molecule}$, the relative contribution of total to pure molecular scattering (cf. [2] this issue). The attenuation of the laser beam in the atmosphere is considered employing a numerical Klett-type [3] inversion of the lidar equation whereby an extinction/backscatter coefficient ratio (lidar ratio) and a starting value at some distance from the receiver have to be assumed to iteratively derive the profiles. With the inferred lidar ratio the extinction coefficient and its integral, the optical depth, can be estimated from the backscatter signal. The ratio of the orthogonal and parallel (to the incident beam) polarised 532nm signals $\beta_{\perp}/\beta_{\parallel}$ i.e. the depolarisation of the light by the scattering particles contains information about their sphericity. A volume depolarisation of 0.014 (or 1.4%) occurs if only the unsymmetrical air molecules contribute to the depolarisation. If the sampled volume contains depolarising (non-spherical, solid) particles, the volume depolarisation is between 0.014 and 1 depending on the concentration and shape of the scattering particles. Clouds with *only* spherical (liquid) particles may cause volume

depolarisation below 1.4% since they increase only the intensity in the parallel channel.

LIMITATIONS

Lidar measurements under optically dense conditions typically suffer from several constraints. Strong atmospheric attenuation of the beam along its path increases the signal/noise (S/N) ratio and reduces the penetration depth of the laser beam. In clouds the signal may be blocked after a short distance. The S/N ratio therefore depends on the optical depth of the atmosphere between the lidar and the scattering target. If the optical depth along this path is low, the detection limit (defined as the equivalent noise superposed to the offset) is $\Delta\beta \approx 2...5 \cdot 10^{-10}$ $m^{-1}sr^{-1}$ or below $\Delta\gamma \approx 1\%$ in terms of the backscatter coefficient β or the backscatter ratio γ at 1064 nm, respectively. At the lower wavelength channels the offset is somewhat higher, and the equivalent noise is of the order of $\Delta\beta \approx 10^{-9}$ $m^{-1}sr^{-1}$ to 10^{-8} $m^{-1}sr^{-1}$ in terms of the backscatter coefficient. Due to the increase of the Rayleigh scattering efficiency with decreasing wavelength the detection limit expressed as a backscatter ratio is also $\gamma < 1\%$ at 355 nm and 532 nm. These values all refer to integration times of at least 30 s (i.e. 300 pulses).

Another problem occasionally arises when the signal is saturated in one or more channels due to transient very strong back-scattering by nearby clouds which destroys all quantitative information about the scatterers in the corresponding channels. Especially the relation between the co- and cross polarised 532 nm signals is affected if one (or both) of them is saturated. Since the parallel signal generally is higher (or equal) than the cross-polarised signal, this means always a relative enhancement of the cross-polarised signal and thus leads to an erroneously high depolarisation ratio. Not taking into account the multiple scattering effect also feigns a stronger depolarisation [2].

Third, an uncertainty of the absolute value of the backscatter coefficient is caused by possible errors in the atmospheric calibration at the starting point of the inversion. Presently applied lidar inversion algorithms based on the Klett-method [3] need to assume two independent parameters for the retrieval of each profile. These are the reference backscatter ratio $\gamma_0(r_0)$ at a selected distance r_0 in the column and the backscatter/extinction coefficients ratio $\beta(r)/\alpha(r)$ (lidar ratio) which mostly (but not properly) is assumed to be range independent, although it actually is a function of the particle ensemble scattering function and the particle number density in the sampled air volume. The reference backscatter ratio $\gamma_0(r_0)$ may be estimated from suitable simultaneous measurements, from standard atmospheric extinction profiles respecting the air-mass type of the sampled volume or by (however vague and subjective) visibility observations. An erroneous value results in an offset of the profile, which depends on the quality of the reference estimate, and thus stronger affects the low backscatter-coefficients. Larger uncertainties arise from the lidar ratio, which tends to be too large if multiple scattering is not taken into account and may be only vaguely inferable in a clean atmosphere with low optical depth. This uncertainty propagates especially to quantities which are calculated from the inferred lidar ratio like the optical depth. Though the discussed errors are mostly of the order of a few percent, they may occasionally become a factor of two or more.

REFERENCES

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