# AIRBORNE BACKSCATTER LIDAR: LITE VALIDATION AND CO-LOCATED GROUND-BASED RADAR MEASUREMENTS DURING CLARE '98

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## 1. INTRODUCTION

Clouds and aerosols play a major role in atmospheric radiative transfer as well as chemical and micro-physical processes and therefore in earth's climate. The most powerful tools for space-borne operational observation of cloud and aerosol parameters on a global scale and coverage are lidar and radar systems. Actually, only these active remote sensing techniques are capable of providing information from dark regions as e.g. the polar winter atmosphere and with high vertical and horizontal resolution.

The macroscopic properties of clouds like altitude, boundaries, internal structure and predominating phase can be retrieve*d from combined radar and lidar data with much higher accuracy than from either instrument alone. Combined cloud radar and lidar data has previously been used to obtain information on cloud boundaries, e.g. Uttal et al. (1995), Weitkamp et al. (1999), Clothiaux et al. (1999), or cloud micro-physical structure (Intieri et al. (1993)), however of either ice or water clouds. No systematic investigations on mixed phase clouds are available. Thus the examples of this study show the potential of the complimentary information in radar and lidar data.

That these capabilities are transferable to a space deployment of active remote sensing instruments, is confirmed by comparing space-borne and airborne lidar profiles during the first Lidar In-space Technology Experiment (LITE) in 1994. The only relevant constraints of the space-borne- as compared to the airborne instrument turned out to be the reduced resolution due to a larger observed area and the enhanced contribution of multiple scattering to the signal affecting the distance assignment and the derived optical depths. A selected measurement of this experiment is discussed in the 2nd chapter.

The 3rd section contains results of the CLARE'98 campaign from 5 – 23 October 1998 at Chilbolton, UK, where a ground based 95 GHz radar (GKSS) and an airborne 3 wavelengths lidar (DLR) were operated simultaneously. During the overpasses of the aircraft over the radar site nearly the same air-volumes were profiled.

## 2. LITE VALIDATION EXPERIMENT

The first Lidar In-space Technology Experiment (LITE) was operated on board the space shuttle in September 1994. The system was designed to measure range-resolved backscatter of laser pulses at 1064nm, 532nm, and 354nm wavelengths (cf. Figure 1, Table 1). It was able to detect cloud top heights cloud geometrical and optical depths, as well as profiles of backscatter and extinction coefficients and boundary layer top heights Kiemle et al. (1997), Flentje et al. (2000), Flentje et al. (2000).

During the shuttle-borne LITE experiment correlative lidar measurements were performed at many places. The European contribution ELITE was co-ordinated and partly funded by the Technical centre of the European Space Agency ESA/ESTEC. DLR performed airborne backscatter Lidar measurements similar to, and correlated with overpasses of the shuttle-borne LITE instrument.

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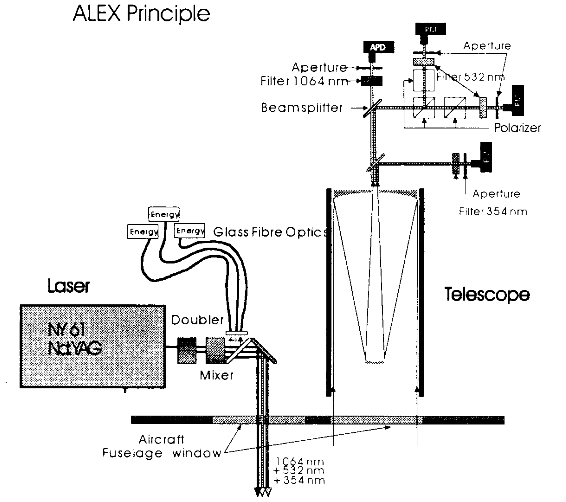


Figure 1: *Biaxial optical system and beam path of ALEX lidar. Left side: transmitter, right: receiver. System parameters according to Table 1. Overlap of the laser beam and the receiver field-of-view is achieved after a distance of about 1-1.5 km.*

Table 1*: ALEX system parameters*

| | |
|---|---|
| Transmitter | Continuum NY61 |
| Wavelengths, Energy per pulse, detector type | 1064 (150mJ) APD<br>532 (120mJ) PMT<br>354 (150mJ) PMT |
| Pulse lengths | 6 ns |
| Beam divergence | 0.7 mrad |
| Pulse repetition rate | 10 Hz |
| Telescope radius | 175 mm |
| Field of view | 1 mrad |
| Focal length | 5 m |

The backscatter Lidar (ALEX) was operated in downward looking mode on board the DLR meteorological research aircraft Falcon 20 cruising at an altitude of typically 12 km. It makes use of a Nd:YAG laser emitting at 1064nm. Frequency doubling and tripling provides 532nm and 354nm channels. The received 532nm signal is split into the two perpendicularly polarised portions which allows to calculate the depolarisation of the light. With a repetition rate of 10Hz for typical aircraft speed of 150m/s the raw data resolution is about 15m horizontally and 12m vertically. However, to improve the S/N ratio the compromise between signal noise and resolution leads to a respective processed data resolution of some 100m/some 10m horizontally/vertically. Four nighttime flights in northern Germany and over the North Sea, covering a total of seven overpasses of the space shuttle have been carried out. ALEX measurements have been performed for theses overpasses on distances of about 300 km. However, this length was crossed by the shuttle in about 40 seconds, whereas the Falcon aircraft took roughly 30 minutes. The actual overpass corresponds to about the middle of each leg, resulting in a maximum time difference of 15 minutes between the measurements from LITE and ALEX. Fig. 2 depicts the backscatter returns for both instruments at 532nm wavelength for orbit 32. The agreement between the two cross sections is striking. There is an extended cirrostratus throughout the whole distance with a top height of about 8.4 km just below the tropopause, sometimes in two layers, the cloud base lying between 5 and 7 km. There are broken, thick clouds in several layers in several layers top heights between 0.5km and 4 km. Mostly they are not thick enough to mask the ground return signal (at 0 km)

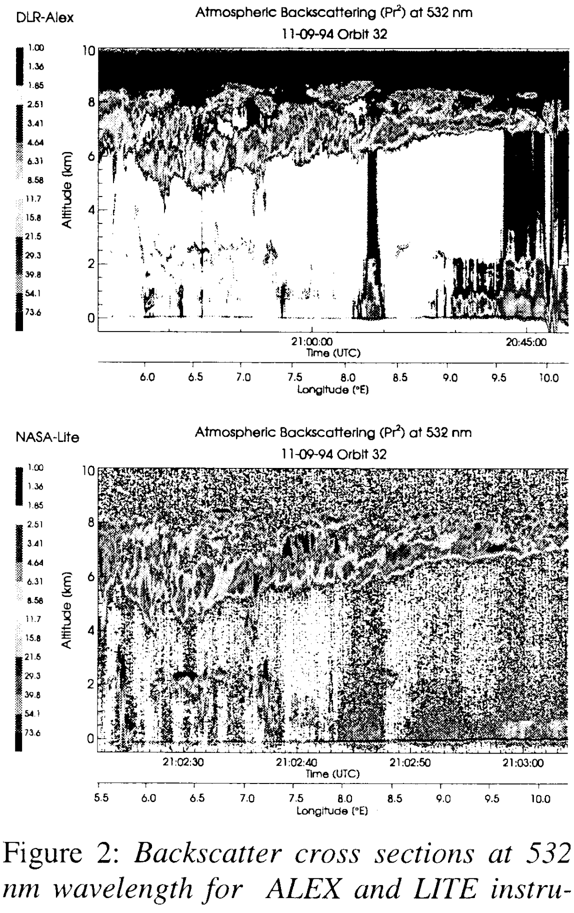


Figure 2: *Backscatter cross sections at 532 nm wavelength for ALEX and LITE instrument.*

The Rayleigh and Mie components of the mean backscatter profile for the return at 532nm is shown in Figure 3. The Rayleigh component is depicted by the straight line. The solid lines refer to an analysis including multiple scattering effects, while the broken lines refer to conventional single scattering analysis. The shape of the cloud and the backscatter values are reproduced well, although there are slight differences in the cloud bases (LITE thin line being about 300 m lower). They can partly be attributed to different sampling volumes in a highly variable cirrus cloud of the two instruments, since the spot sizes differ between about 5 m for ALEX to about 800 m for LITE. It is obvious that mean backscatter profiles from both instruments agree very well.

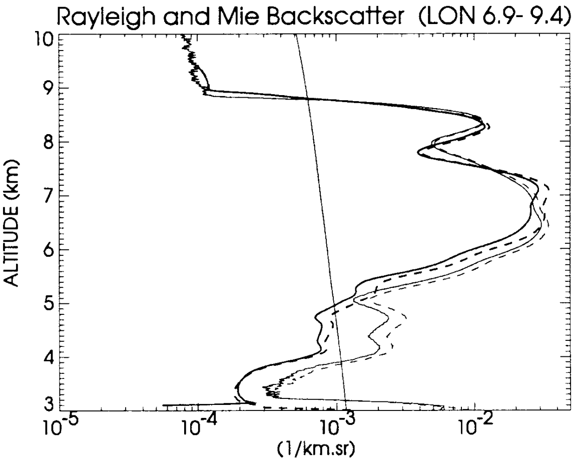


Figure 3: *Backscatter profiles at 532 nm with ( — ) and without (----) multiple scattering effects included. Thick: ALEX, thin : LITE instrument*

Optical depths of the cirrus and maximum Mie backscatter coefficients both as function of longitude are shown in Figure 4. Despite the different horizontal resolution of the ALEX ($\Delta x$ = 5km) and LITE ($\Delta x$ = 52km instruments, the values agree reasonable well. We have to note that optical densities derived from ALEX measurements are almost independent of whether multiple scattering is calculated or not. This is a result of the 2-level clear air calibration applied for the lidar inversion and of the small absolute laser beam diameters in the sampling volume. The latter is much larger in case of the LITE instrument because of the large distance between lidar and sampling volume. Therefore, optical densities retrieved from LITE data are much more sensitive to multiple scattering effects. Comparing the two instruments, optical thickness of the ALEX instruments come out to be about 30 % higher than those from the LITE instrument.

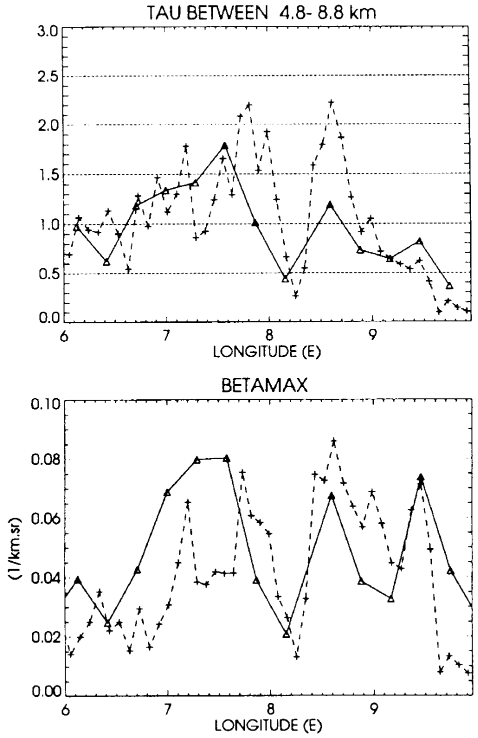


Figure 4: *Optical depths and maximum Mie-backscatter coefficient of ALEX (+----+) and LITE (Δ—Δ) instruments as function of longitude*

## 3. THE CLARE '98 CAMPAIGN

As during LITE, for the CLARE'98 campaign the 3 wavelengths lidar ALEX (cf. Figure 1) was operated in down-looking mode onboard a FALCON 20 aircraft. Further the GKSS cloud radar MIRACLE (Danne and Quante (2000)) was used which is currently taken for various studies of cloud properties, e.g. Quante et al. (1996), Danne et al. (1999), Fujiyoshi et al. (1999).

*Meteorological situation*: Throughout the FALCON-campaign the synoptic situation in western Europe was dominated by a pronounced westerly current in which short wave disturbances in rapid succession affected South Britain. The associated fronts passed nearly daily and caused distinct airmass transitions between the pre- and post frontal flows. Thus overcast and changeful conditions prevailed with multi-level mixed phase clouds frequently occurring throughout the troposphere. Thus this period was especially suitable to investigate the differences between the airborne lidar- and the ground-based 95 GHz radar profiles within the highly inhomogeneous mixed phase clouds. Due to their different attenuation and sensitivity to particle size and phase both instruments provide complementary information of cloud boundaries and cloud structure. Case studies from 20 and 21 October from the two week field campaign in marine air-masses over Southern UK are presented. For the interpretation in-situ measurements of instruments installed on board a Hercules C-130 aircraft of the UKMO are also considered.

Table 2: *Date, time, position, and applied lidar ratio for selected overpasses of the Falcon at the radar site. The position difference is given in meters as indicated by the navigation system of the Falcon relative the ground site co-ordinates.*

| Date | Time UTC hh:mm:ss | indicated rel. position | applied lidar ratio |
|---|---|---|---|
| 20 Oct.98 | 14:20:29 | 170 m south | 15 |
| 20 Oct.98 | 14:32:53 | 40 m south | 11 |
| 21 Oct.98 | 10:19:03 | 220 m south | (170)* |
| 21 Oct.98 | 10:49:54 | 50 m south | 25 |

* strong attenuation

On *20 October 98* starting already before noon a rapid formation of cirrus was observed above 8 km height due to the approaching occluded cold front of low VALERIE II. In a strong westerly current (≈ 15 m/s) a narrow altostratus cloud layer in 3.8 – 4.2 km altitude appeared above a dense stratocumulus cloud cover at the top of the boundary layer near 2 km. The altostratus layer with backscatter ratios of more than 1000 in the infrared channel blocked the lidar beam nearly completely (see Figure 5). The low depolarisation ratio of less than 5% (lower panel of Figure 5) indicates, that the narrow stratocumulus layers consisted of mainly liquid (spherical) particles.

Radar reflectivity and lidar backscatter coefficient profiles for the overpass are directly intercompared in Fig. 6. The altitudes are given with respect to sea level, their accuracy is estimated to be about ±30 m. The lidar profile is averaged over 1 s which corresponds to a horizontal cloud scale of 220 m. The radar data has been averaged over 9 s in order to match the spatial scale of the lidar data at an altitude of 4 km. These time-space conversions used the wind measurements obtained by the Hercules. For the displayed time segment the radar was operated in FFT-mode, therefore data is available only for the range window between 2.8 and 5.2 km. Comparison of the profiles in the overlapping height band reveals a different behaviour for the sensors. While the lidar detected two narrow, well separated peaks, the radar profile is much broader and the main peak occurs at a lower height. Also the relative amplitudes of the peak values differ. The lidar signal probably experienced strong attenuation along the in-cloud path. The thin layers did not appear as a clearly distinguishable feature in the radar data.

The differences between the profiles are most probably due to the different micro-physical properties of individual layers in the cloud region. In Rayleigh approximation the radar signal is proportional to $D^6$, while the lidar signal is proportional to about $D^2$ , with D denoting the diameter of the scattering particles. In addition the phase of the particles plays a role. It is assumed that the extended thin layers detected by the lidar consisted of liquid water while the rest of the cloud was dominated by ice crystals. As can be seen in Fig. 5, the depolarisation of the lidar signal around 14:20 UTC was very low in the three narrow layers suggesting the existence of spherical scatterers. Depolarisation ratios of less than 10 % were found. Linear depolarisation ratios as measured by the radar only indicate the presence of crystals in the lower part of the cloudy region, but there is no evidence for a decreased LDR around the lowest lidar peak at 4 km.

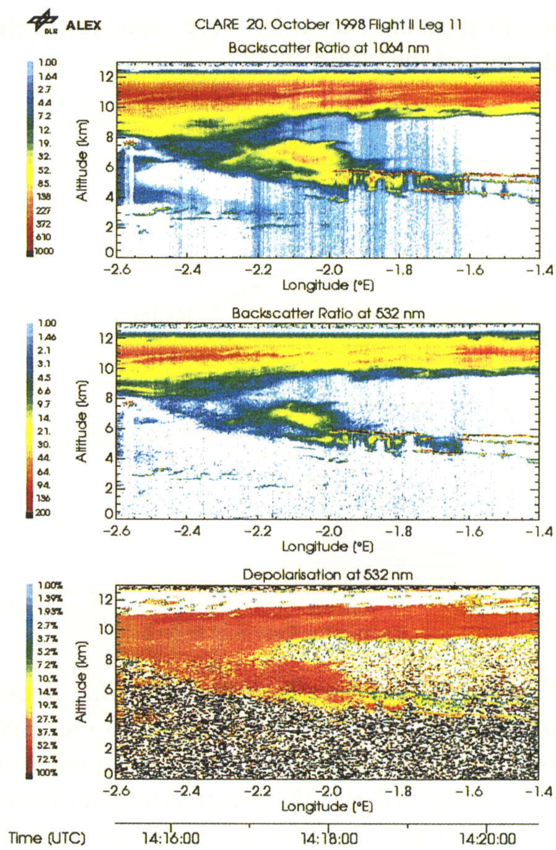


Figure 5: *Lidar backscatter ratio @ 1064nm, 532nm, depolarisation ratio at 532nm on 20 Oct. 98, 14:15 - 14:21 UT. Chilbolton is located near –1.43E.*

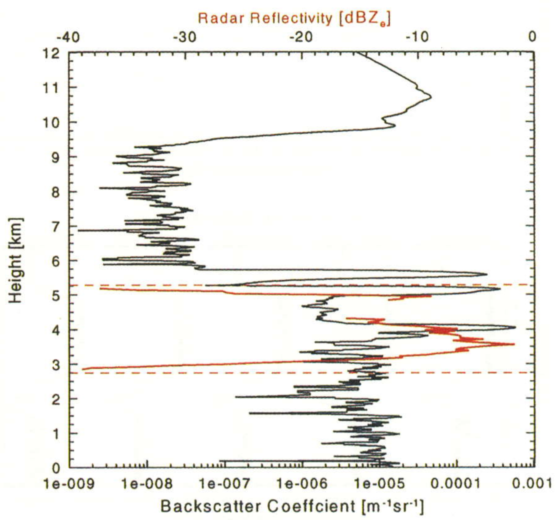


Figure 6: *Vertical profiles of radar reflectivity (red) and backscatter coeff. @ 1064 nm (black) at 14:20:29 on 20 Oct.98. Lidar data is averaged over 1 s (about 218 m), the radar data was averaged over 9 s to represent the same spatial scale.*

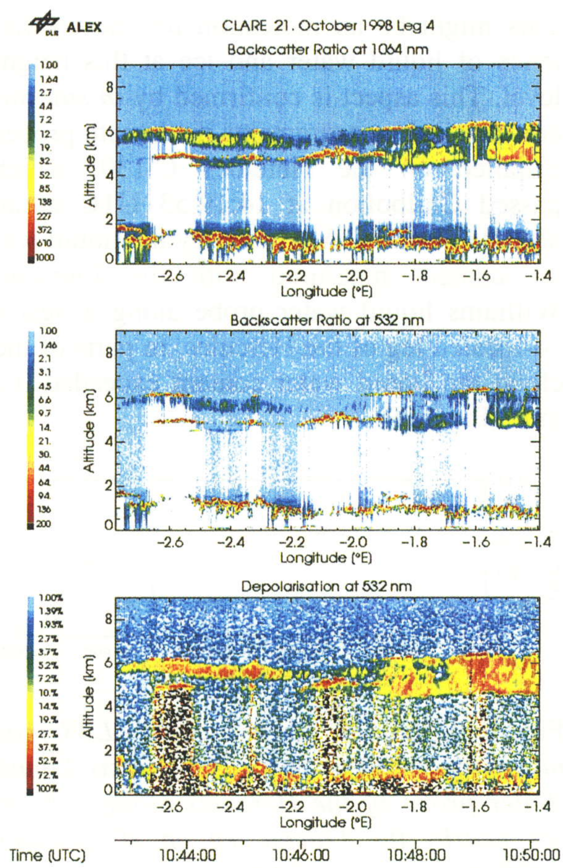


Figure 7: *Lidar backscatter ratio @ 1064 nm, 532nm, depolarisation ratio at 532nm on 21 Oct. 98, 10:43 – 10:50 UT. Chilbolton is located near –1.43E.*

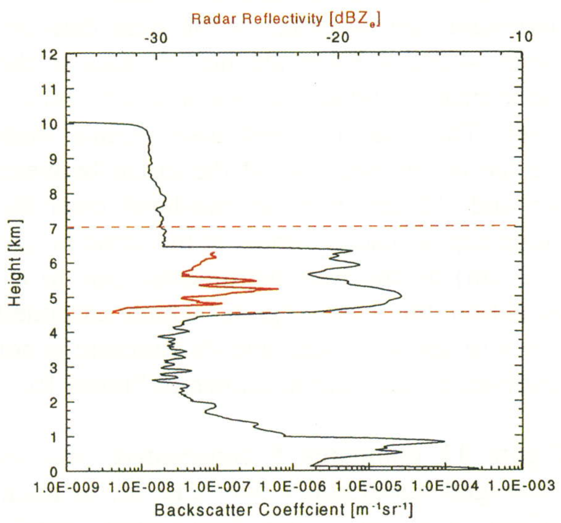


Figure 8*: Radar reflectivity and backscatter coefficient on 21 Oct. 98, 10:49:54. Lidar data is averaged over 1 s (≈ 185 m), the radar data was averaged over 6 s. Red dashed lines mark the range window for the radar.*

This might be an indication for the coexistence of liquid water and ice at this height level. This aspect is confirmed by *in situ* micro-physical measurements made with probes installed on the Hercules C-130, which passed Chilbolton at 14:19:53 UTC at an altitude of 4 km. As shown by the liquid water content measured with the Johnson-Williams liquid water probe along a nearly co-located leg of the Hercules, in parts of the cloud the liquid water content exceeded 0.1 $gm^{-3}$ (Figure 9).

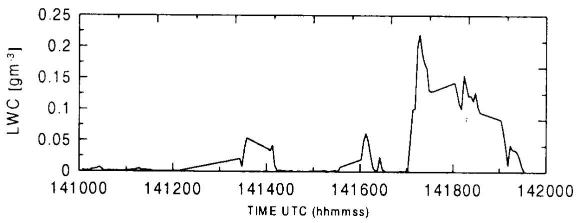


Figure 9: *Liquid water content (LWC) as measured with the Johnson-Williams Liquid Water probe of the Hercules along a flight leg nearby the Falcon leg on 20 October 1998 at an altitude of 4 km.*

At 14:32:59 UTC the radar was profiling the entire troposphere and therefore a signal from the cirrus layer with reflectivities around –30 $dBZ_e$ also appears. Again the two dominant narrow peaks in the lidar data between 4 and 4.5 km are not obvious in the radar profile, which shows a much thicker layer. The lidar received also signals from the ice dominated part of the cloud between 4.5 and 5.2 km. For the mid-level layer the cloud top is placed almost at the same height (5.2 km) by the two instruments. Due to attenuation the base region, which extended down to about 2.5 km, and its structure is not resolved by the lidar as shown in Figure 10.

Figure 11 compares 5 consecutive profiles (averaged horizontally over 212 m) of radar reflectivities and lidar backscatter coefficients around the overpass time. It can be seen that the lowest lidar peaks, which are again associated with a thin, presumably liquid layer, decrease in altitude, while the radar peaks stay almost at a constant height. This might indicate that they were detached from the rest of the cloud.

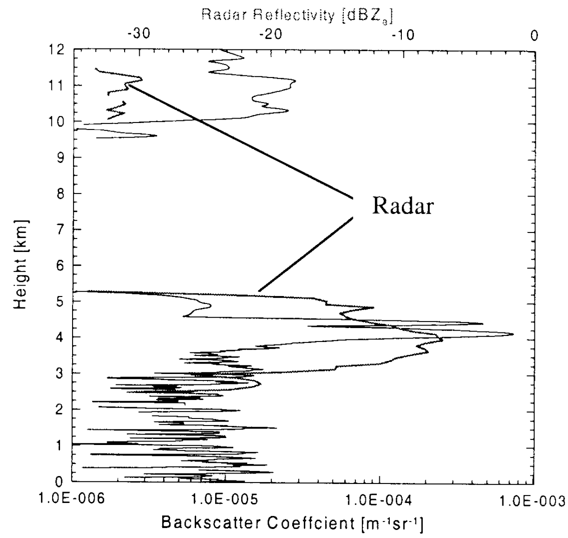


Figure 10: *Radar reflectivity and lidar backscatter coefficient @ 1064nm on 20 Oct. 98, 14:32:53. The lidar data was averaged over 1 s (about 212 m), the radar data was averaged over 8 s in order to match the spatial scale.*

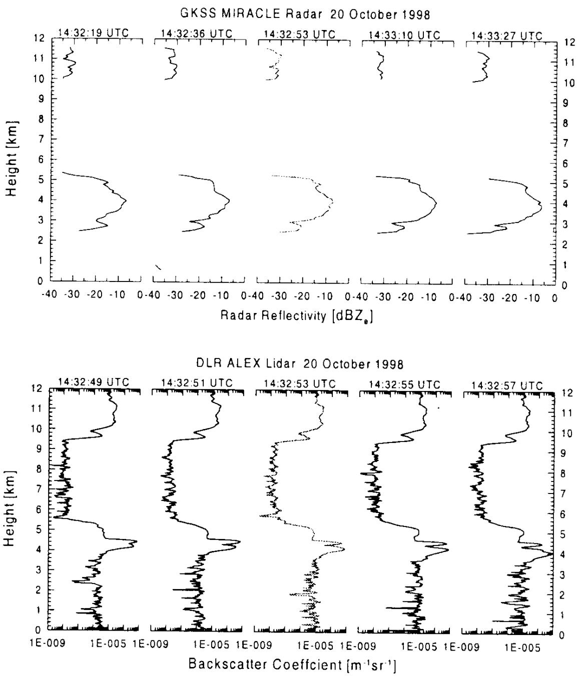


Figure 11: *Five consecutive profiles of equivalent radar reflectivity and lidar backscatter coefficient at 1064 nm for the overpass at 14:32:53 UTC on 20 October 1998.*

On *21 October 1998* the cold front of the previous day had passed by. Post frontal the cloud cover broke up and mid-level clouds reaching from 4 km to 6.5 km in altitude passed Chilbolton in a strong westerly flow. The top of the boundary layer around 1-1.5 km was marked by low cumulus clouds. Both cloud layers can be seen in the lidar back-scatter signal as well as in the time series of radar reflectivities shown in Figure 7 and 13, respectively. Typical radar reflectivities ranged between –10 $dBZ_e$ and –25 $dBZ_e$.

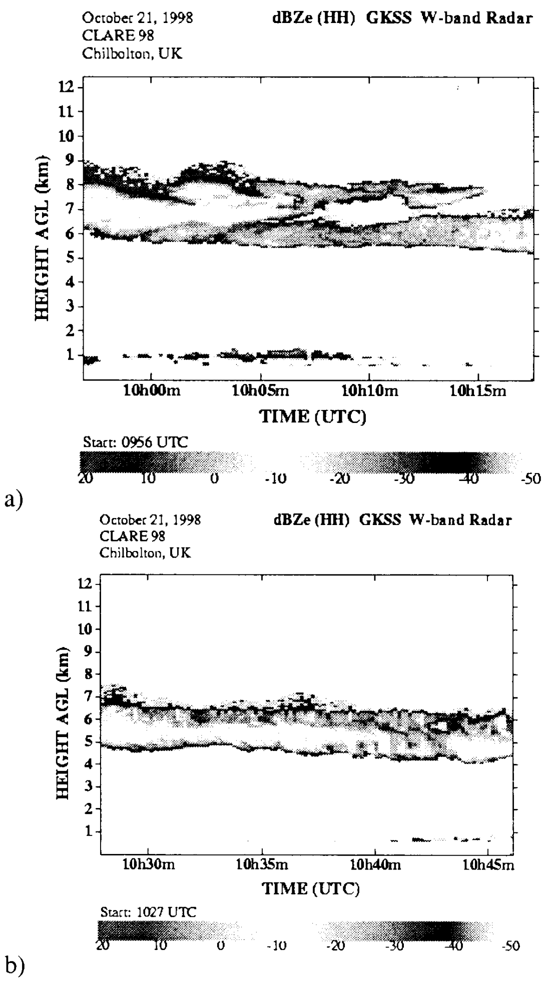


Figure 13: *Time series of profiles of equivalent radar reflectivities in $dBZ_e$ for time segments a) 9:56 to 10:17 UTC and b) 10:27 to 10:46 UTC on 21 October 1998, which was each short before the Falcon overpasses.*

The mid-level cloud layer reveals a vertically disrupted band like structure which however at the time of the Falcon overpasses around 10:19 UT and 10:50 UT appears to be better resolved by the lidar. Actually the upper band disappeared from the radar signal shortly before 10:19 UT, probably leaving quite small evaporating particles behind, which due to the much smaller wavelength still could be detected around 6.7 km height by the lidar as shown in Figure 14. The maximum radar reflectivities occur about 1 km lower at 5.5 km and may be due to relatively few larger ,e.g. precipitating, particles, which only produce a small backscatter signal. However the lidar beam does not penetrate this cloud, thus its overall structure can only be resolved by the synergetic information from both instruments.

During the 10:49:54 UT overpass (see Figures 7, 8) the cloud had become weaker and more homogeneous. From the in-situ measurements of the Hercules it can be concluded that by this time there were neither small liquid (evaporating) nor large precipitating (ice-)particles. Thus cloud boundaries and internal structure of radar and lidar agree quite well except for the smallest scales.

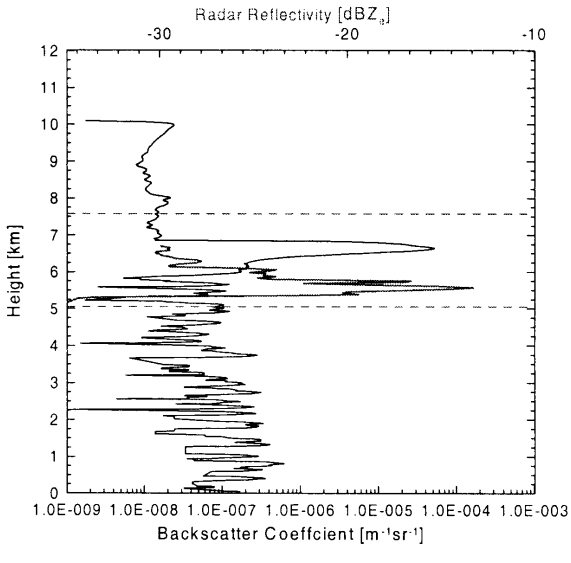


Figure 14: *Radar reflectivity and lidar backscatter coefficient @ 1064nm on 21 Oct. 98, 10:19:04. The lidar data is averaged over 1 s (about 175 m), the radar data was averaged over 6 s in order to match the spatial scale. Red dashed lines mark the range window for the radar.*

## 4. SUMMARY

Two comparisons of remote sensing instruments have been discussed in this study: An airborne lidar towards a space-borne lidar and to a ground based radar.

In the first case the different target-receiver distance leads to a stronger affection of the space-borne system by multiple scattering. The general structure of the clouds mostly agreed, except for few cases where the cloud base was washed out due to longer pathlengths of multiply scattered photons disturbing the distance determination. Due to the larger observed volume the optical densities of the clouds were determined by up to 30% lower from the space-borne than from the airborne data.

The comparison of ground based cloud radar and airborne lidar measurements clearly reveals the enormous information gain by a synergetic use of both systems. Their largely different wavelengths results in different sensitivities to particles size distributions and signal attenuation. Different regions of the clouds were highlighted by the instruments and only their synergetic use revealed the entire structure of the mixed phase clouds with liquid layers and fallstreaks below the cloud base.

The agreement between lidar and radar tends to increase with decreasing spatial displacement between the observed volumes (Table 2), since inhomogeneities within the observed clouds occur on small (Figure 11). Thus, a closely co-located positioning of both instruments is essential.

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