CLOUD RADAR - INITIAL MEASUREMENTS FROM THE 94GHZ FMCW RADAR

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ABSTRACT

A new solid state Frequency Modulated Continuous Wave (FMCW) cloud radar operating at 94GHz has been developed in the UK by the STFC Rutherford Appleton Laboratory, for the UK Met Office. This vertical-profiling cloud radar incorporates technological and operational advances over a previous demonstration instrument, which operated at 78GHz. In addition to providing independent high spatial (order 10m) and temporal (order 10s) resolution of cloud structure, the radar will also be used in testing integrated networks of surface-based remote sensors, with the aim of improving cloud observation for input into numerical weather prediction models. A further requirement of the instrument is that it should be relatively inexpensive, allowing several instruments to be purchased and deployed around the UK.

An account of the technological aspects and initial performance of this new cloud radar will be provided, as will examples of data gathered during different meteorological conditions, including comparisons with other vertical profilers.

INTRODUCTION

The cloud radar was built by the Millimetre Wave Technology Group at the STFC Rutherford Appleton Laboratory in the UK for and in collaboration with the UK Met Office. The radar operates at 94GHz: this frequency is ideal for observing cloud as it lies within a part of the spectrum which experiences relatively low absorption in the atmosphere, whilst being high enough to resolve small particles like cloud droplets by Rayleigh scattering (Lhermitte, 1987). The 94GHz frequency is also assigned for observing cloud from satellites.

The radar is sufficiently compact and lightweight to be readily transported: Figure 1. It exploits the frequency modulated continuous wave (FMCW) approach, which uses generally less expensive, more durable and lower power components than the more common pulsed radars. In addition, the radar is Doppler capable, so the vertical hydrometeor velocity can also be measured, although this feature has not been investigated at present.

The 94GHz radar beam is capable of penetrating dense, thick cloud layers allowing a complete scan of deep clouds from base to top. A key feature of the cloud radar is the ability to provide information on multiple cloud layers, even if the lowest layer completely obscures the sky. This ability will be useful for routine observation of overhead cloud at meteorological reporting sites and for aviation, where knowledge of the heights of cloud base and tops are important. Cloud profiles also benefit the meteorological research community, such as by providing observations to evaluate meteorological models by, either directly or as part of an integrated profiler system to retrieve information on cloud liquid and ice water contents (Illingworth et al., 2007).

The cloud radar produces a new vertical profile at a temporal resolution of up to 5 seconds, with a vertical resolution of 4m for a range up to 2km, or 16m for a range of 8km, allowing fine cloud structures to be resolved. Despite the low power output, the sensitivity of the radar allows cloud to be detected to a height of at least 8km (the maximum height of initial trials, although the radar is capable of detecting cloud higher than this, with a limit of 16km). The radar can detect the presence of cloud as low as ~30m. Below which the signal is somewhat ambiguous due to ground clutter and parallax errors). This low altitude detection capability permits observation of mist and fog depth. Continuous monitoring of the fog depth has applications for both aviation as well as meteorological research.

The radar is operated using simple interactive software installed on a desktop PC. The interface and signal generation/processing hardware are contained in a small 19” instrument rack (Figure 2). The output profile is displayed in real-time on the PC monitor using the same software package that operates the radar. Factors such as height-dependent gain and maximum reporting range can be adjusted immediately using the software, including the ability to pause the radar temporarily (i.e. for manual inspection). An improvement of this radar over the demonstration model is its greatly improved thermal stability, with the internal environment of the radar (regulated by a solid state heating/cooling system) continuously monitored and reported by the software for quality control.

Although some mechanical aspects of the current radar were derived from the earlier demonstration model (Lyth and Nash, 2005), all the transmit and receive electronics have been built to a new design. It is hoped that this design can then be engineered to provide cost-effective operational systems.

Figure 1 – Cloud radar front-end deployed at Camborne Met office, UK. The Jenoptik Lidar used for comparison can also be seen in the background (grey rectangular unit near the left edge of the figure).

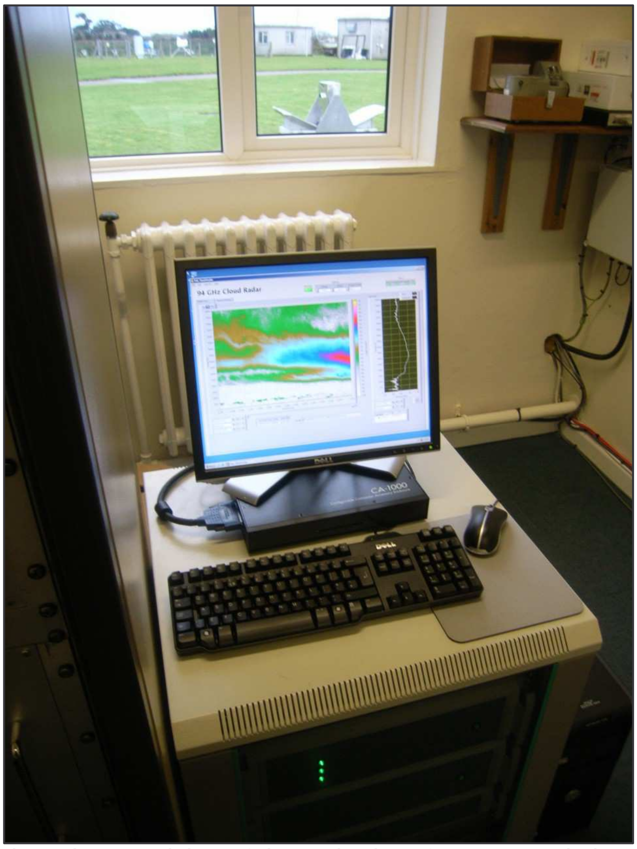

Figure 2 – Cloud radar back-end, comprising of the radar interface PC and signal generation/processing hardware.

CASE STUDIES

Between January and July 2008 the cloud radar was deployed at Camborne Met Office, located in the South Western peninsula of England, as part of a suite of vertical profilers. This co-location allows output from the radar to be compared to that of a wind profiler (a radar measuring horizontal and vertical wind components from the surface to 8km) and a lidar (which uses backscatter from a laser to detect cloud).

A layer of fog over the observation site during 4-5 May 2008 provided an opportunity to assess the ability of the cloud radar to detect the height of the fog top. This height was determined by a radiosonde ascent, with the fog top clearly identified by the increased dew point depression from 200m AMSL (Figure 3). The cloud radar also reported a fog top of approximately 200m AMSL at the time of this ascent (Figure 4).

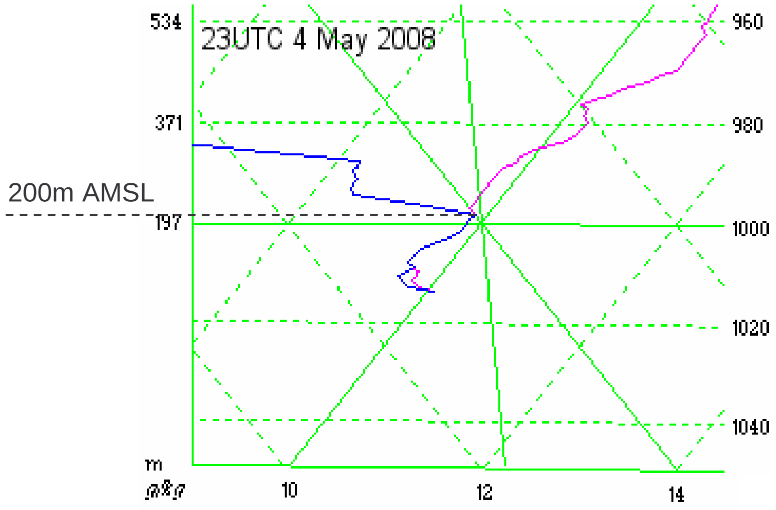

Figure 3 – Tephigram of the 23UTC radiosonde ascent at Camborne Met Office on 4 May 2008. The pronounced decrease in dew point temperature compared to that of the dry-bulb at 200m AMSL identifies the top of the fog layer.

From the cloud radar observations (Figure 4) the fog was observed to dissipate at approximately 10:00 UTC. During this time, the wind profiler signal-to-noise ratio was observed to increase in the region immediately above the fog top (Figure 5), suggesting an increase in air turbulence near the fog top (Figure 4) as dissipation occurs.

Due to the rapid attenuation of a lidar beam in cloudy air, the cloud radar is a more appropriate instrument to quantify the depth of fog and elevated cloud, as demonstrated by Figure 6. The lidar is needed to aid discrimination between the cloud base and falling hydrometeors into the sub-saturated air below, as the lidar backscatter differs more above and below the cloud base than the radar reflectivity factor. Therefore the combination of lidar to detect cloud base and cloud radar to detect cloud internal structure and top is considered a suitable sensor combination for the remote detection of cloud profiles.

The radar's ability to scan through deep convective cloud and resolve multiple layers of thin cloud are demonstrated by Figure 7 and Figure 8 respectively. Although profiles of deep clouds are possible with the cloud radar, as with all radars of a similar frequency the transmitted power is scattered by an amount proportional to the sixth power of the back-scattering particle's diameter (e.g. Frisch et al., 1998). Therefore the return signal intensity from precipitation is considerably larger than that from cloud droplets. This means that the radar's beam is attenuated significantly during precipitation, so the height of cloud tops from precipitating clouds may be more ambiguous as it is not known whether the beam has been completely attenuated before it reached the cloud top. However, for non-precipitating cloud, the frequency of the cloud radar allows fine detail in the cloud structure to be resolved. For instance, Figure 9 shows the merging of two layers of low cloud, with the upper layer having distinct undulations within it (Stratocumulus undulatus). As the upper layer begins to precipitate, the radar returns from this layer merges with the lower cloud layer, with drizzle evident at the surface as an increase of return signal intensity.

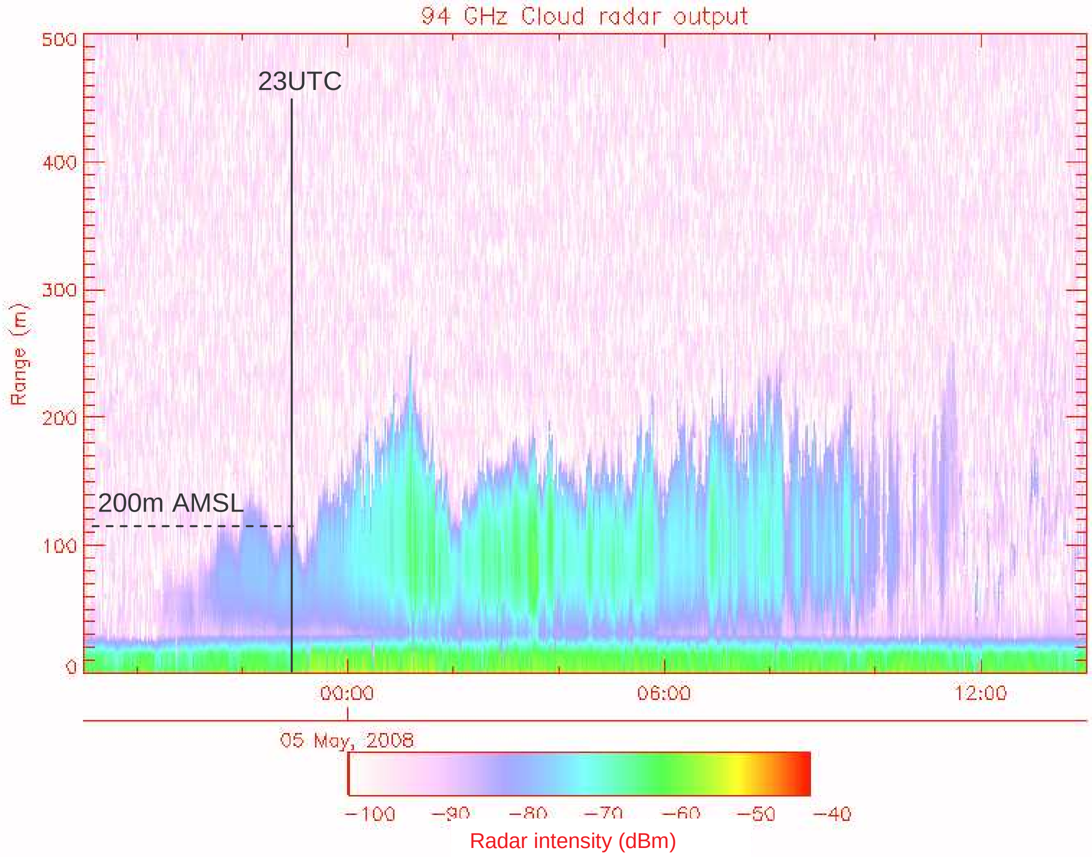

Figure 4 – Cloud radar output showing a layer of fog over Camborne Met Office between approximately 20:30UTC on 4 May 2008 and 11:00UTC on 5 May 2008. Camborne is 88m above mean sea level (AMSL). The radar identifies the height of the fog top at 23:00UTC on 4 May as 200m AMSL, which is in agreement with the radiosonde ascent made at this time.

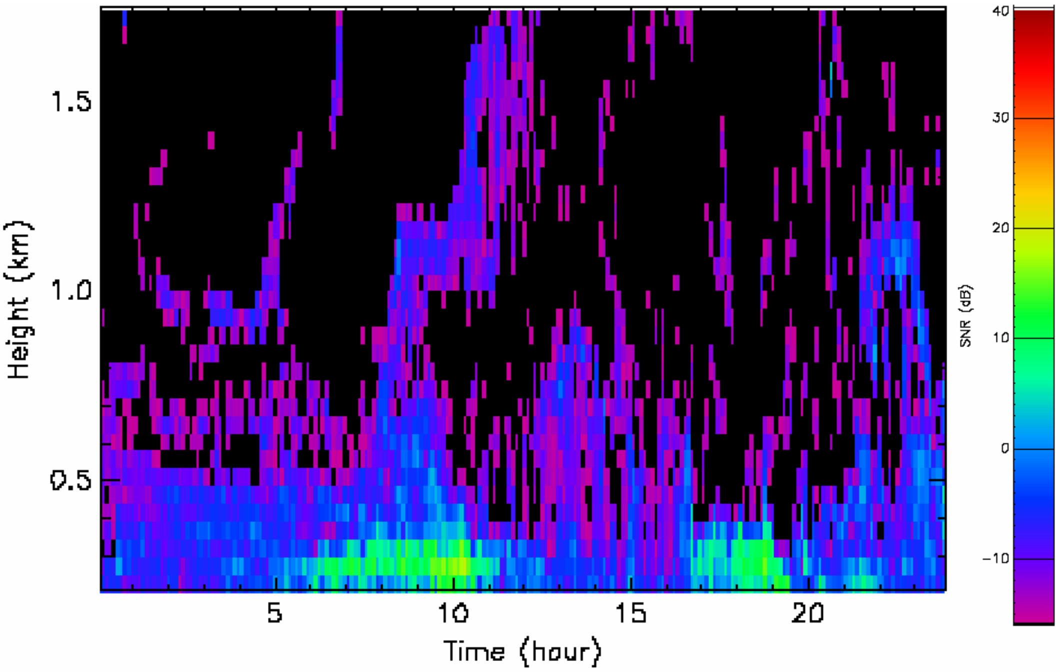

Figure 5 – Signal to noise ratio of the 915MHz wind profiler at Camborne Met Office during 5 May 2008. The signal to noise ratio is a function of the air turbulence, and shows an increase at around 10:00UTC. This increase in turbulence is coincident with the dissipation of the fog, as seen using the cloud radar (Figure 4).

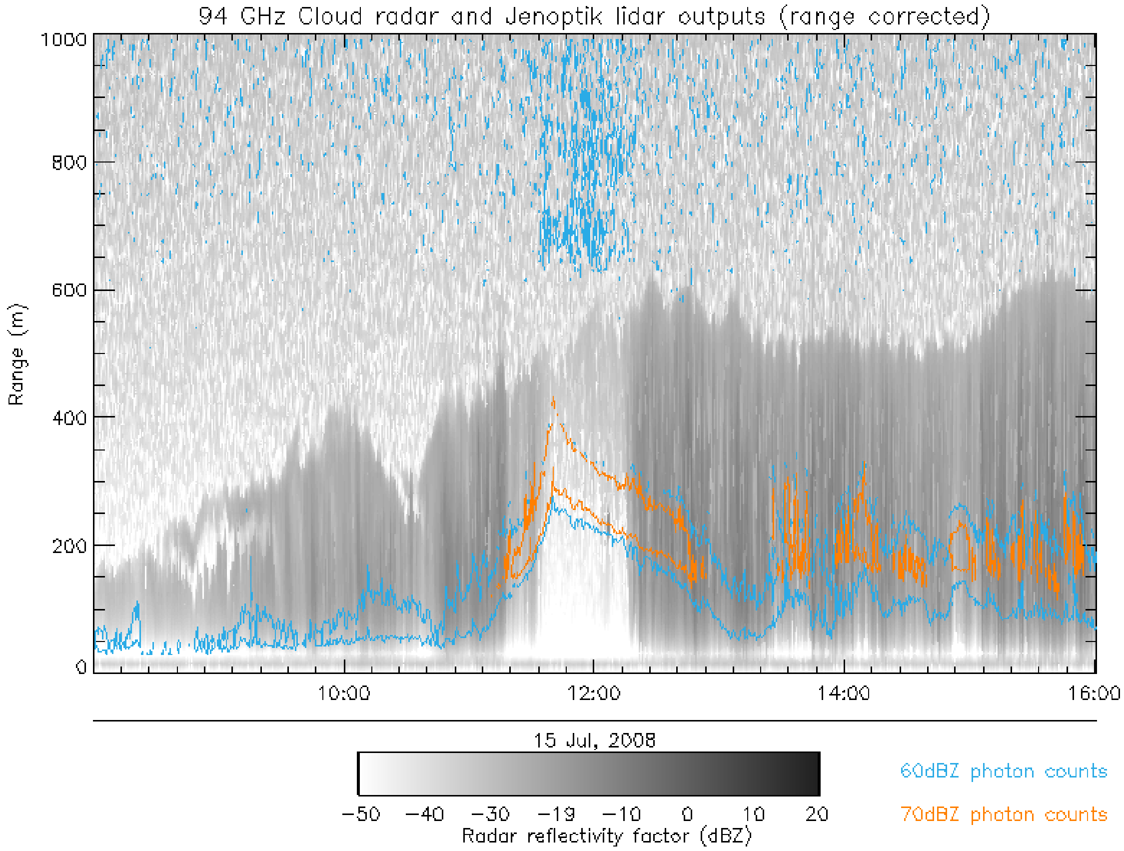

Figure 6 – Cloud radar reflectivity factor (greyscale) and Lidar backscattered photon count (coloured overlay) during low cloud. The blue contour marks the limits of the Lidar backscattered signal, with the most intense returns enclosed by the orange contour. The advantage of the cloud radar over lidar for observation of cloud thickness is evident in this example, with the radar detecting the cloud top whilst the lidar beam is completely attenuated within the cloud layer. However, the lidar is needed to aid discrimination between the cloud base and falling hydrometeors into the sub-saturated air below.

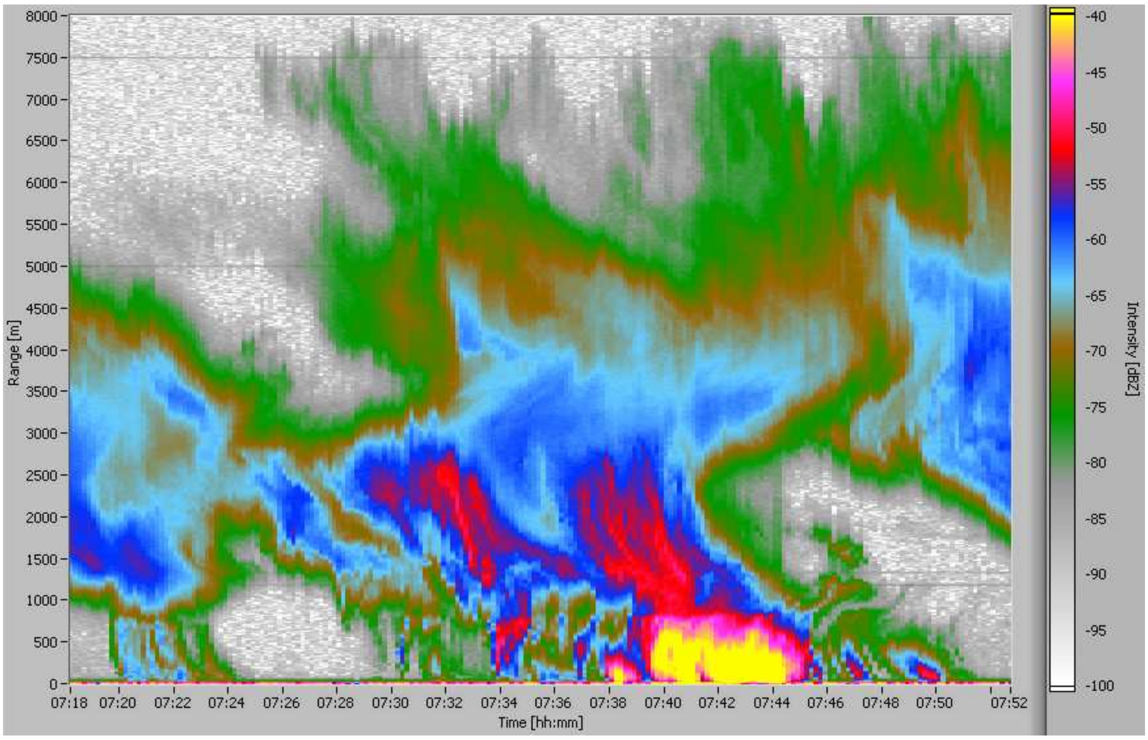

Figure 7 – Cloud radar intensity plot showing deep convective cloud over Camborne Met Office. The radar beam is capable of penetrating deep cloud layers whilst retaining sufficient sensitivity to resolve small-scale

features in the cloud structure. The region of maximum intensity around 07:40 to 07:44 (yellow) indicates light rainfall.

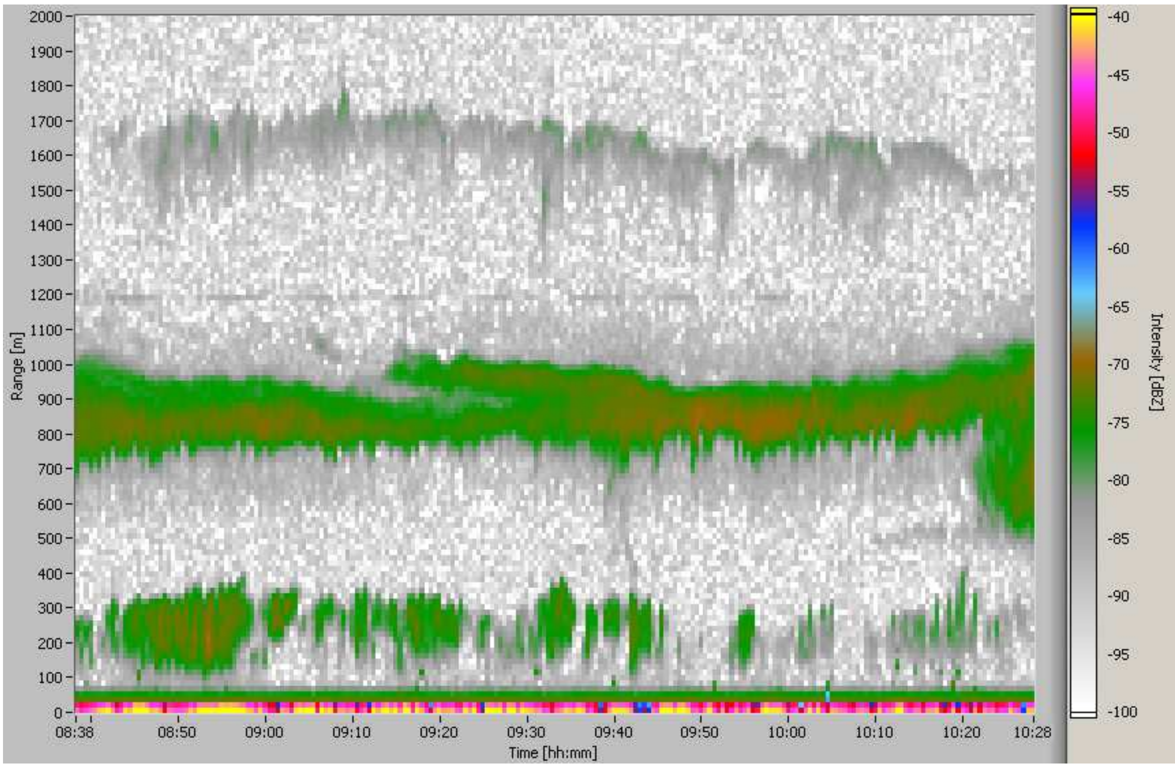

Figure 8 – Cloud radar observation showing multiple cloud layers.

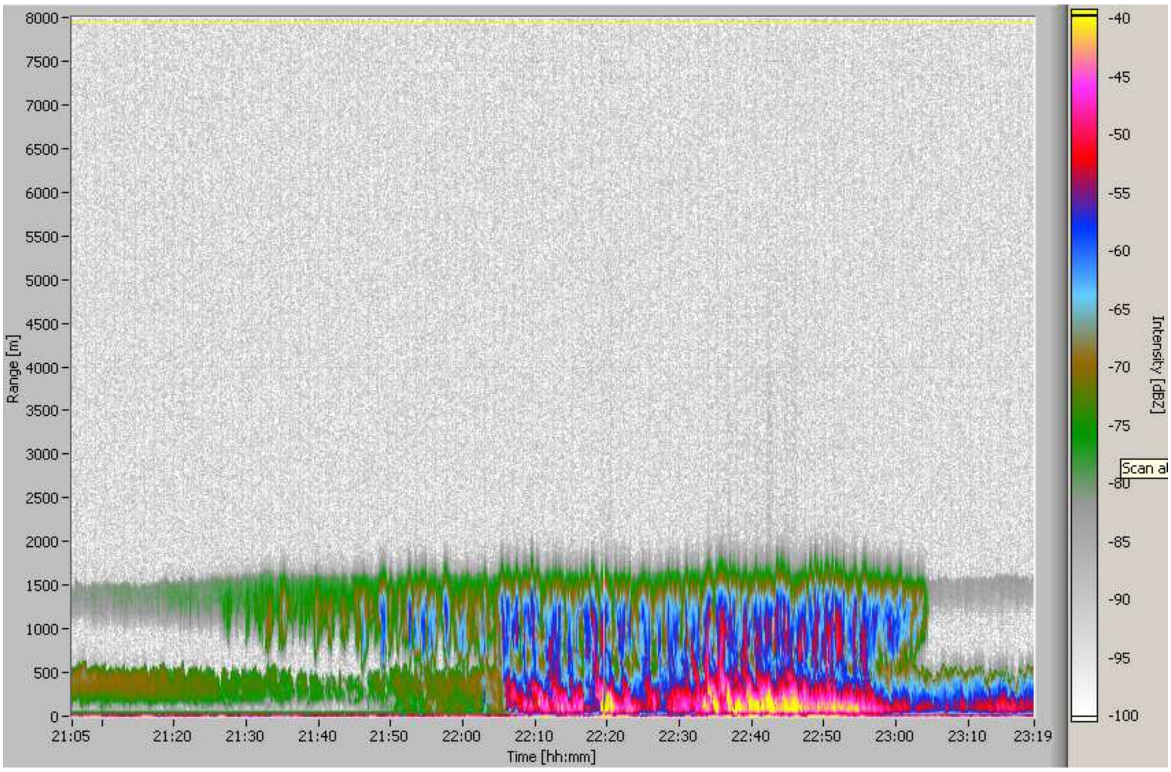

Figure 9 – Cloud radar observation of complex structure within a Stratocumulus layers. The higher layer of cloud was composed of horizontal rolls (undulatus), identified by the regular increases in return signal intensity as the rolls passed over the radar. The two layers merge between approximately 22:00 – 23:00 UTC as the upper layer appears to precipitate through the lower layer, increasing the return signal intensity as the drizzle reaches the surface.

CONCLUSIONS

The 94GHz FMCW cloud radar deployed by the UK Met Office has demonstrated an ability to continuously monitor the vertical cloud profile from the surface to (at least) 8km for non-precipitating cloud, and in some cases of lightly precipitating cloud. The FMCW nature of the radar delivers a high sensitivity and the approach requires less expensive components than similar frequency pulsed radars. As the radar can detect cloud down to a range of ~30m the fog depth can also be assessed. A vertical resolution of 4m from the surface to 2km permits fine cloud structures such as multiple layers of low-level thin cloud to be resolved.

A combination of lidar and cloud radar will be used by the UK Met Office to monitor cloud structure and fog development at airfield sites. The advantages of combining a cloud radar, lidar, microwave radiometer and wind profiler for future integrated profiling systems will also be investigated in test-bed deployments from 2009 to 2011.

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