Observations from the UK Met Office 94 GHz FMCW cloud radar

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ABSTRACT

A new solid state frequency modulated continuous wave (FMCW) cloud radar operating at 94 GHz has been developed in the UK by the STFC Rutherford Appleton Laboratory, for the UK Met Office. In addition to providing independent high spatial (order 10 m) and temporal (order 10 s) resolution of cloud vertical structure, the radar will also be used in developing integrated networks of surface-based remote sensors, with the aim of improving cloud observation for input into numerical weather prediction models. Such an instrument has to be relatively inexpensive, allowing several systems to be purchased and deployed around the UK. The radar has been operating near-continuously for over two years, initially at a site in south west England co-located with other surface-based atmospheric profilers including a 915 MHz wind profiler and CHM15k 1064 nm Lidar. The cloud radar was then deployed at Chilbolton Observatory in southern England from September 2008 for comparison against resident 94 and 35 GHz pulsed cloud radars. An account of the initial performance of this new cloud radar is provided, with examples of data gathered during different meteorological conditions, including comparisons with other cloud radars and vertical profilers.

1. INTRODUCTION

A key feature of cloud radar compared to optical remote-sensing is the ability to provide information on multiple cloud layers, even if the lowest layer completely obscures the sky. This ability should 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 as well as cloud type are important. For instance, the cloud radar will be able to determine whether a Cumulonimbus is embedded within a layer of low stratiform cloud. Cloud profiles also benefit the meteorological research community, such as by providing observations to evaluate meteorological models, either directly or as part of an integrated profiler system to retrieve information on cloud liquid and ice water contents [1].

Continuous recording of the cloud profile can produce a cloud profile climatology such as that reported by [2] which allows investigation of numerical weather prediction model performance for cloud at a particular site. The cloud radar was built by the Millimetre Wave Technology Group at the STFC Rutherford Appleton Laboratory in the UK in collaboration with the Met Office [3]. The 94 GHz operating frequency is ideal for observing cloud as it lies within a part of the spectrum which experiences relatively low absorption in the atmosphere. With a wavelength of approximately 3 mm, scattering from cloud droplets is by Rayleigh scattering [4]. The 94 GHz frequency was chosen to provide the best resolution of cloud and fog in the lower troposphere, with the frequency assigned for observing cloud from satellites.

The radar is sufficiently compact and lightweight to be readily transported: Figure 1. The frequency modulated continuous wave (FMCW) approach 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 implemented at present.

Figure 1: *The Met Office 94 GHz cloud radar. Image from [3].*

The radar emits a continuous narrow (~0.5 degree) beam of 200 mW power, which although weak compared to typical emissions from pulsed cloud radars, has demonstrated the capability to penetrate dense, thick cloud layers allowing a complete scan of deep clouds from base to top.

The cloud radar produces a new vertical profile at a temporal resolution of up to 5 seconds, with a vertical resolution of 4 m for a range up to 2 km, or 16 m for a range of 8 km, 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 11 km (the maximum height of initial trials, although the radar is capable of detecting cloud higher than this, with a limit of 16 km). The radar can detect the presence of cloud as low as ~30 m, 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.

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2. CASE STUDIES

The use of 94 GHz to detect multiple cloud layers in the atmospheric column is demonstrated by the identification of high cloud above a layer of low Stratus and fog during the radar's deployment at the STFC Chilbolton Observatory in central southern England during the morning of 22 December 2008. The output of the Met Office cloud radar during this event is shown in Figure 2, with corresponding data from the resident 94 GHz pulsed cloud radar (Galileo). The two cloud layers are clearly identified by both radars, although the Met Office radar appears more sensitive to the high cloud. The Met Office radar was also able to identify the low cloud base when it lifted above the surface, but still below the minimum detectable range of Galileo.

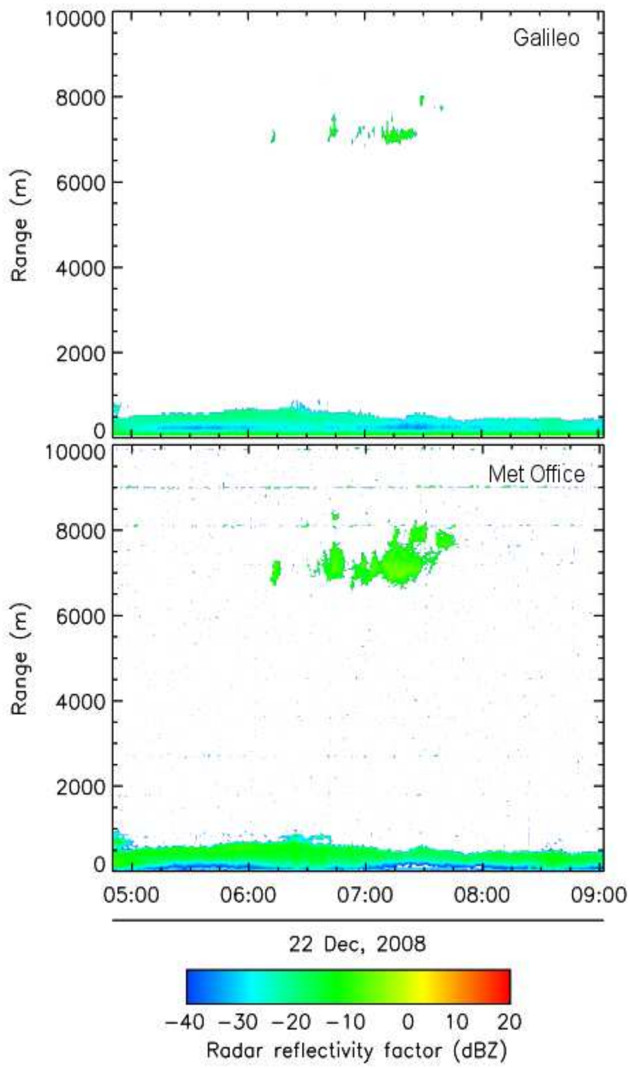

Figure 2: *Cloud radar reflectivity showing a layer of low Stratus producing overcast conditions at the surface. Both the Met Office and Galileo cloud radars penetrate this low cloud and detect high cloud above. The weak horizontal lines in the Met Office plot at 8 and 9 km are artefacts due to electrical interference. Galileo Data courtesy of Ewan O'Connor, Reading University.*

The fog top detected by the radar is shown in Figure 3a, which can be compared to the co-located radiosonde ascent at 11UTC on 4 May 2008. The altitude of saturated air is identified in the radiosonde profile where the dew-point equals the dry-bulb temperature. From this ascent it can be inferred that a layer of fog extended to a height of approximately 200 m AMSL. The radar profile reports cloudy air to a range of approximately 110 m at 23UTC. The site is 88 m AMSL so this equates to a radar-derived top of approximately 200 m AMSL, in agreement with the fog top inferred from the radiosonde ascent.

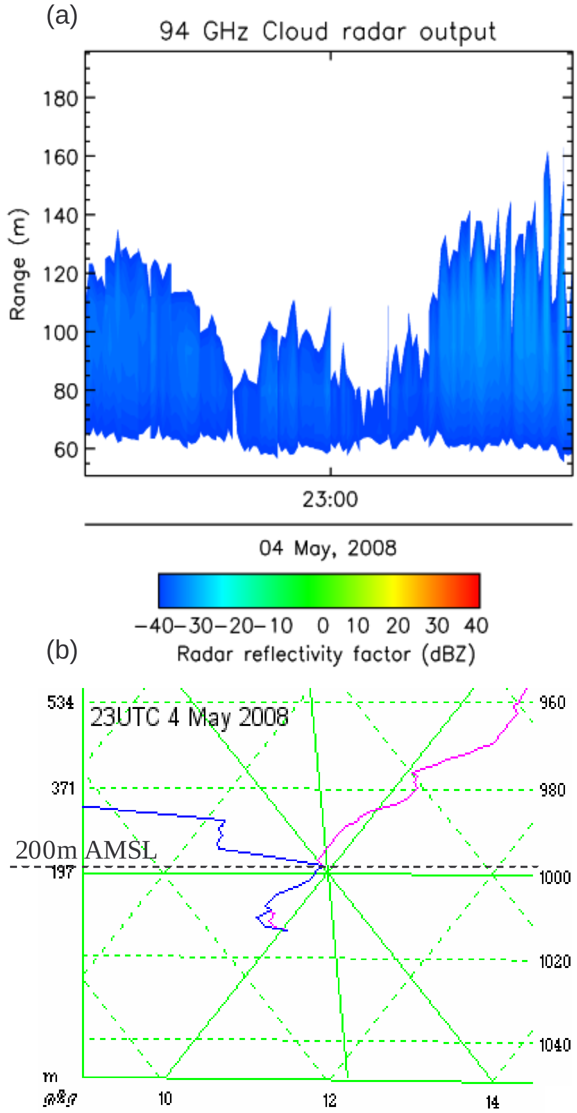

Figure 3: *Fog top detected by (a) the cloud radar and (b) a co-located radiosonde ascent at 23UTC on 4 May 2008. The blue and purple lines represent dry-bulb and dew-point temperature respectively. The site (Camborne Met Office, Cornwall) was 88 m AMSL.*

The advantage of the cloud radar over lidar for observation of low cloud thickness is evident in Figure 4, with the radar detecting the cloud top whilst the lidar beam is completely attenuated within the cloud layer. However, the lidar data complements the cloud radar profile as it aids discrimination between the low cloud base and hydrometeors falling into the sub-saturated air below, to which the cloud radar is more sensitive due to the greater dependence of particle size on return power for millimetre wavelengths than for near optical wavelengths.

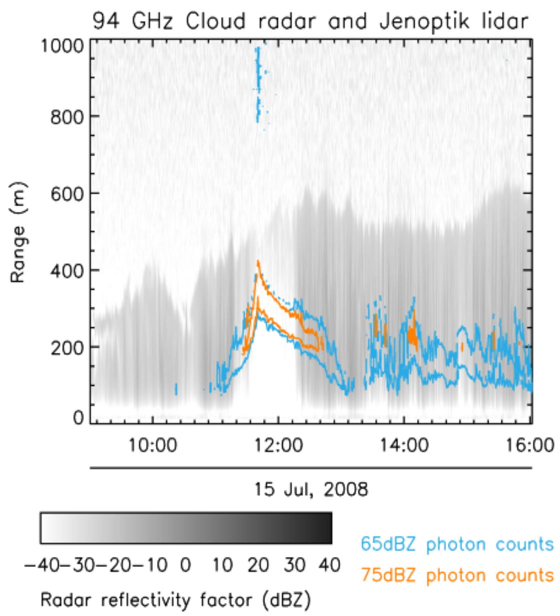

Figure 4: *Cloud radar reflectivity factor (greyscale) and Lidar backscattered photon count (coloured overlay) during low cloud. The blue contour marks the limits of the Lidar backscattered signal, with the most intense returns enclosed by the orange contour*.

The Met Office cloud radar was also compared to the 94 GHz pulsed cloud radar (Galileo) under rainfall conditions. An example of this comparison is shown in Figure 5. It can be seen that the radar reflectivities correspond well and the FMCW radar was capable of resolving the same amount of cloud structure detail as the pulsed radar. A major difference however is the presence of the vertical band artefact with the FMCW radar. This artefact is considered to be due to saturation of the return signal in the lowest range gates during precipitation. The Rutherford Appleton Laboratory (RAL) who designed and constructed the Met Office's radar are currently working to resolve this issue. Another observable difference between the two radars is that the FMCW radar is capable of resolving the reflectivity profile to a lower range than the pulsed radar. As previously discussed, this feature makes the FMCW radar ideal for observation of fog.

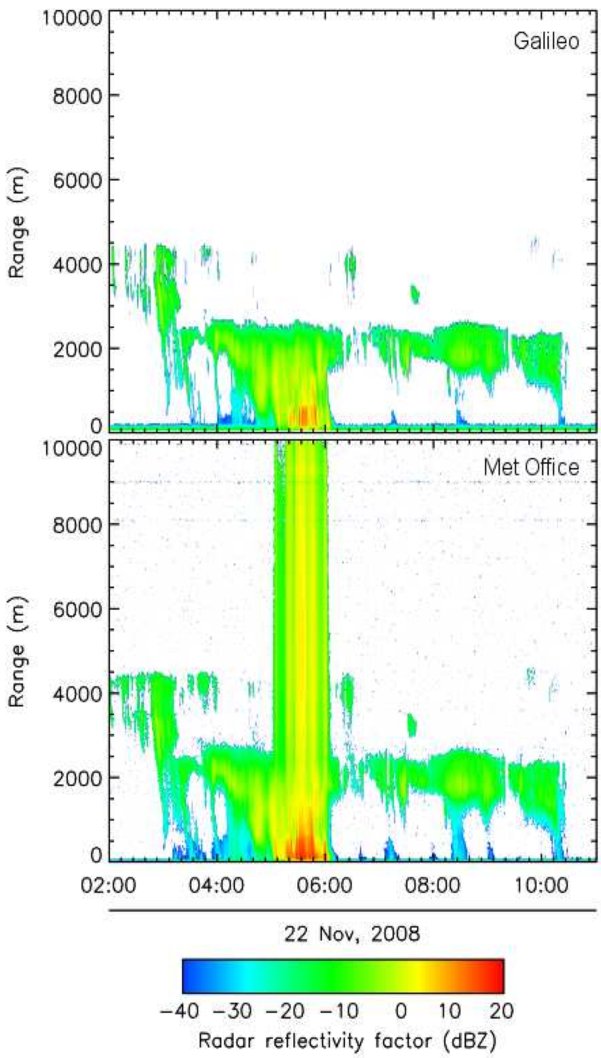

Figure 5: *Comparison between the Met Office FMCW cloud radar and the co-located 94 GHz pulsed cloud radar (Galileo) at the STFC Chilbolton Observatory. Galileo Data courtesy of Ewan O'Connor, Reading University.*

3. CONCLUSIONS

The 94 GHz FMCW cloud radar deployed by the Met Office has demonstrated an ability to continuously monitor the vertical cloud profile from the surface to at least 11 km for non-precipitating cloud, and in some cases of lightly precipitating cloud. Once the vertical band artefact present during precipitation has been removed, the performance of the FMCW radar during rainfall can be assessed. The FMCW nature of the radar delivers a high sensitivity considering the ~200 mW output power and the approach requires less expensive components than similar frequency pulsed radars. As the radar can detect cloud with a minimum range of ~30 m the fog depth can also be assessed. A vertical resolution of 4 m from the surface to 2 km 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 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 similar to that described by [1] will also be investigated in test-bed deployments from 2009 to 2011.

REFERENCES

[1] Illingworth, A. J., R. J. Hogan, E. J. O'Connor, D. Bouniol, M. E. Brooks, J. Delanoe, D. P. Donovan, J. D. Eastment, N. Gaussiat, J. W. F. Goddard, M. Haeffelin, H. Klein Baltink, O. A. Krasnov, J. Pelon, J.-M. Piriou, A. Protat, H. W. J. Russchenberg, A. Seifert, A. M. Tompkins, G.-J. van Zadelhoff, F. Vinit, U. Willen, D. R. Wilson and C. L. Wrench., 2007: Cloudnet - continuous evaluation of cloud profiles in seven operational models using ground-based observations, *Bull. Am. Meteorol. Soc.*, **88,** 883-898.

[2] Brooks, M. E., Hogan, R. J. and Illingworth, I.J., 2004: A long term comparison of cloud properties observed by vertically pointing radar and lidar with their representation in operational NWP models *Proc. 14th Int. Conf. on Clouds and Precipitation, Bologna, Italy,* 1293-1294.

[3] Huggard, P. G., Oldfield, M. L., Moyna, B. P., Ellison, B. N., Matheson, D. N., Bennett, A. J., Gaffard, C., Oakley, T., and Nash, J., 2007: 94 GHz FMCW cloud radar, Proceedings of the SPIE Symposium on “Millimetre Wave and Terehertz Sensors and Technology”, 15-18 September, Cardiff, UK.

[4] Lhermitte, R., 1987: A 94-GHz Doppler Radar for Cloud Observations, *Journal of Atmospheric and Oceanic Technology*, **4** 36-48.