Calibration of the ground-based radars during CLARE'98

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INTRODUCTION

During the CLARE'98 campaign between 5 and 23 October 1998 at Chilbolton, England, four ground-based radars were in operation. These were the 3 GHz Chilbolton Advanced Meteorological Radar (CAMRa), the 35 GHz 'Rabelais', the 94 GHz 'Galileo' and the 95 GHz 'Miracle'. Throughout the duration of the experiment the Rabelais was mounted on the side of the steerable 25 m antenna of CAMRa. The Galileo radar was operated in a zenith-pointing configuration from the receive cabin at Chilbolton, 100 m from the main 25 m dish. The Miracle radar was also vertically pointing, and was situated just outside the workshop at Chilbolton, around 40 m from the main dish.

The approach used to calibrate the radars is to start with the absolute calibration provided by the polarisation variables of the 3 GHz radar in heavy rain, then to match up with the reflectivity measured by the Rabelais radar in Rayleigh-scattering light rain or cloud. Finally the W-band radars are calibrated by comparing them with the calibrated Rabelais at vertical incidence in Rayleigh-scattering liquid-water cloud. At each stage the comparison must be performed at a close enough range that the atmospheric attenuation at the higher frequency is minimised, yet at a far enough range that the far-field approximation is reasonably good at both frequencies. These uncertainties mean that a certain amount of error is introduced at each stage of the process.

Table 1 summarises the calibration figures that need to be applied to the raw reflectivity data from the four radars. All the **vertically-pointing** data on the CLARE'98 FTP site has been calibrated using the old calibration values, which are **2 dB less** than the new values; i.e. 2 dB should be added to these data. The reflectivity in the scanning 3 GHz HDF files on the site has **not** been calibrated; **5 dB** needs to be added to these data. The last column gives an estimate of the likely accuracy of the calibration for each system.

CALIBRATION CONVENTION

It is very important to understand the convention used in the intercalibration of radars of different frequencies because of the temperature dependence of the $|K|^2$ parameter of liquid water at millimetre wavelengths. In this paper the radars have been calibrated such that Rayeleigh-scattering liquid water droplets at 0°C produce the same reflectivity factor Z at all frequencies. For example, a population of 100 µm droplets with a concentration of $10^6\,\mathrm{m}^{-3}$ at 0°C would have a Z of 0 dBZ at all frequencies. Hence a radar at frequency f after calibration will report an effective reflectivity given by

$$Z_f = \int_0^\infty \frac{|K_f|^2}{|K_{f,0}|^2} n(D) D^6 \gamma_f(D)\, dD,$$

where γ_f is the Mie/Rayleigh backscatter ratio. $|K_{f,0}|^2$ is the dielectric parameter of liquid water at 0°C, and is 0.93 at 3 GHz, 0.877 at 35 GHz and 0.668 at 94 GHz. Because the $|K|^2$ of liquid water varies with temperature at 94 GHz, if the example above were repeated at 20°C, a 94 GHz radar using this calibration convention would report a Z of $+0.82$ dBZ while a 3 GHz radar would still report 0 dBZ. Formulae for the dielectric constants of ice and liquid water at these frequencies can be found in Liebe et al. (1989).

3 GHZ CAMRA

The shape of raindrops is a unique function of size, and it turns out that at centimetre wavelengths the three radar variables Z, Z_{DR} and ϕ_{DP} are not independent in rain. Goddard et al. (1994a) showed that this property could be exploited to calibrate a polarimetric radar since only the correct calibration of Z will permit the three variables to be self-consistent. The procedure is to examine rays through heavy rain in which there is at least 10° of differential phase shift (ϕ_{DP}), and to use the values of Z and Z_{DR} along this path to calculate the ϕ_{DP} that should be observed. Z is then adjusted until the calculated and measured values of ϕ_{DP} match up. Z_{DR} can be calibrated fairly easily by setting it to zero in light drizzle in which Z is around 0 dBZ, since here the drops will be spherical. It is important to ensure that the beam is well below the melting layer, that the rain is not so intense that differential or total attenuation becomes important (indicated by regions of negative Z_{DR} at the back of the rain), and also that there is no contamination by hail. The technique is reported by Goddard et al. (1994a) to be accurate to 0.5 dB, provided the correct drop shapes are used. This small error is due to residual uncertainties in the drop shapes, and the fact that the shape of the distribution can vary somewhat from event to event.

Comparisons with raingauges have been carried out since the technique was first employed at Chilbolton, and they confirm its accuracy. Figure 1 is an example of comparisons between CAMRa and a drop-counting raingauge obtained during the HYREX project, on 13 September 1994. The time series plot on the left shows raingauge data integrated over 30 seconds and 90 seconds, and two radar estimates of rainfall rate, one using a standard Z-R relationship and the second using Z and Z_{DR}

System	Freq. GHz	Recording mode	5/10/98–28/10/98 (CLARE'98)	29/10/98–6/11/98	from 6/11/98	FTP site data	Error dB
CAMRa	3	scanning	add 5 dB			uncalibrated	±0.5
Rabelais	35	scanning	see text	?	subtract 5 dB	not on site	±1
		vertical	subtract 15.5 dB	subtract 25 dB		old	±1
Galileo	94	vertical	add 16 dB			calibration:	±1.5
Miracle	95	vertical	add 2 dB			add 2 dB	±1.5

Table 1: Summary of the calibration figures that need to be applied to the **raw** data from each of the radars used in CLARE'98. The second-to-last column indicates whether the data on the CLARE'98 FTP site have been calibrated or not.

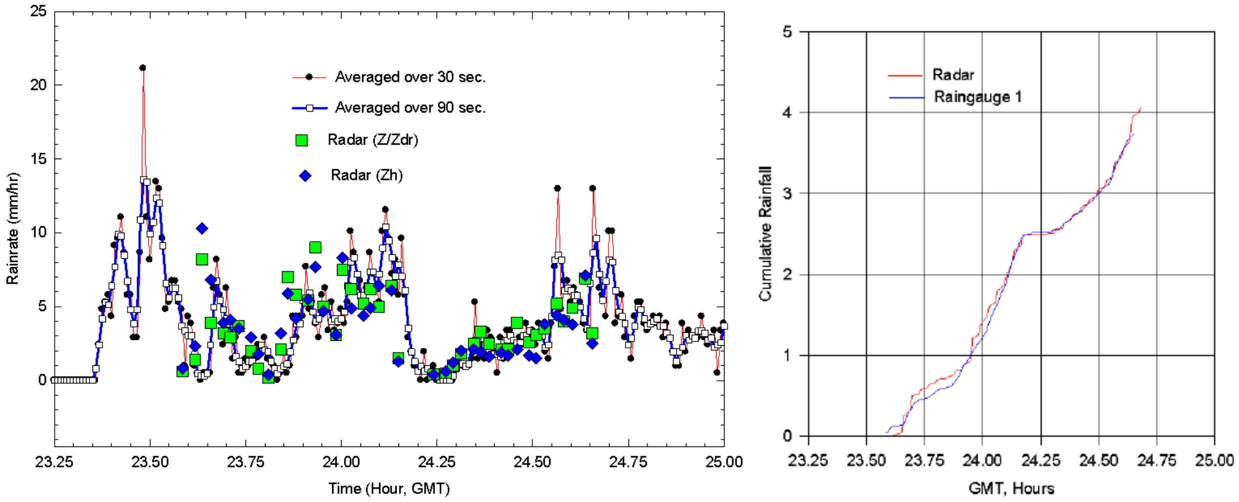

Fig. 1: Comparison of radar retrievals of rain rate with values measured by a raingauge on 13 September 1994.

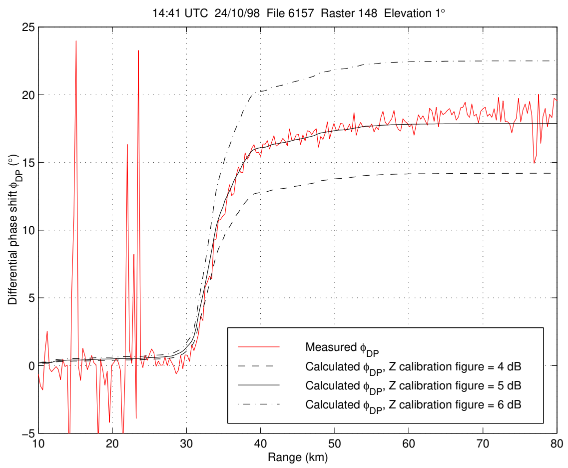

Fig. 2: The result of the Z-Z_{DR}-ϕ_{DP} calibration technique on 24 October 1998, just after the end of CLARE'98. Measured ϕ_{DP} is shown, together with that calculated from Z and Z_{DR} after 4, 5 and 6 dB has been added to raw Z. Clearly the correct calibration figure is 5 dB. The fluctuations at 15 and 22 km are due to ground clutter.

with an exponential drop-size distribution. The radar calibration was performed with what was then the new Z-Z_{DR}-ϕ_{DP} technique. (See also Goddard et al. 1994b). The right panel of Fig. 1 shows the accumulated rainfall rates from the raingauge and from the radar Z-Z_{DR} estimate of rainfall. The final difference in totals is around 10%.

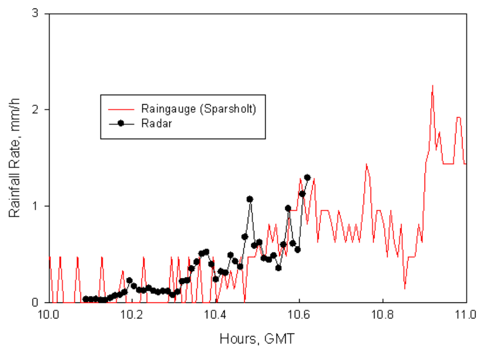

Fig. 3: A comparison of radar and gauge rain rates from 19 January 1999 using the same radar calibration as during CLARE'98.

The calibration method has been performed using events in October and November 1998. Figure 2 shows measured and calculated ϕ_{DP} for an event on 24 October 1998, just after the end of the campaign. We conclude that **5 dB should be added to all CAMRa reflectivity data taken since 5 October 1998, including those in the HDF files on the CLARE'98 FTP site.** After this calibration figure has been added the 3 GHz radar has a noise-equivalent reflectivity at 1 km of **−36.7 dBZ**. This value is fairly stable and is a useful reference to verify whether data has been calibrated or not. It can also be regarded as a crude indicator of the absolute sensitivity of the radar. Figure 3 shows a recent comparison (19 January 1999) between the CAMRa

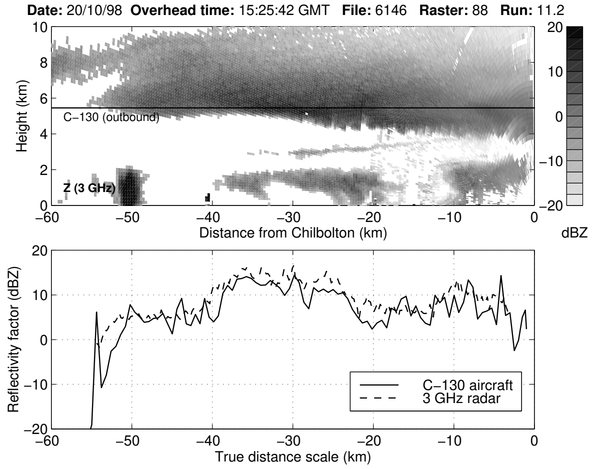

Fig. 4: A comparison of CAMRa reflectivity and that calculated from C-130 size spectra in ice cloud during a CLARE'98 flight.

radar and a raingauge situated at Sparsholt, 7.8 km away at from Chilbolton. These data are not ideal because they were obtained from routine scans along the Earth-Space path to the ITALSAT satellite. Radar gates close to the Sparsholt gauge at a height of around 500 m were used to estimate the rainfall rate. The same radar calibration was used here and during the CLARE'98 campaign. Figure 4 shows a comparison of radar reflectivity in ice cloud during one of the CLARE'98 flights, with that calculated from simultaneous C-130 aircraft measurements of size spectra. The established mass-diameter relationship for ice crystals of Brown and Francis (1995) was used, and the agreement is good to within a few dBs. It is clear from these comparisons that the calibration of the 3 GHz radar is reliable.

35 GHZ RABELAIS

The Rabelais radar can reasonably be regarded as the weak link in the chain of calibration. The main problem has been that until the beginning of the CLARE'98 campaign it had been understood that the configuration of the logarithmic amplifier and the voltage range of the 8-bit A-to-D converter was such that a 1-bit change in the output of the A-to-D converter corresponded to a 0.25 dB change in signal power. On examination of the instrument near the beginning of the campaign, Gilbert Despaux reported that the correct value should in fact be 0.2 dB per bit. An accurate calibration of this part of the data acquisition system by Jon Eastment after the campaign had finished confirmed that the correct value should be somewhere between 0.2 and 0.21 dB per bit (the response of the logarithmic amplifier not being exactly constant throughout its dynamic range). The data acquisition software for the instrument in vertically-pointing configuration was changed to 0.2 dB per bit before any such data was taken in CLARE'98, but the software for recording the data in scanning mode continued to use a value of 0.25 until 6 November. The data can be corrected in retrospect, but this does introduce some uncertainty with regard to calibration.

The receiver circuitry of the Rabelais radar has an attenuator such that the level of the received signal can be adjusted manually in order that the normal dynamic range of the signal is matched well with the range of the logarithmic amplifier. A further possible problem was revealed on 28 October when it was discovered that this attenuation was set too high, and at low signal-to-noise ratios the received power was into the region at the bottom end of the range of the logarithmic amplifier where the correspondence between its output voltage and the logarithm of its input voltage is not linear.

The effect of this on CLARE'98 data is that the range of measured powers is 'compressed' in the vicinity of the noise floor. It turns out that when the thermal/receiver noise is subtracted from the measured power (standard practice in the analysis of cloud radar data), this compression effect is removed and the *relative* values of reflectivity can be trusted right down to the minimum measurable signal, although it makes absolute calibration a little more difficult. All 35 GHz data on the CLARE'98 FTP site has had noise subtracted. At 18:00 UTC on 28 October the attenuator setting was changed by a nominal 10 dB to bring the input power up into the main part of the dynamic range of the logarithmic amplifier. The exact value of this attenuation was later measured by Jon Eastment to be 9.5 dB.

With all this information it is possible to work out the calibration figure of the Rabelais in vertically-pointing configuration. The first approach is to use comparison events on dates after these two problems had been rectified. A number of events from 12 November (Chilbolton file 6180) have been examined. Figure 6 shows a comparison of the 35 GHz and calibrated 3 GHz radars on this date. A correction for two-way gaseous absorption at 35 GHz has been performed using the thermodynamic variables of the ECMWF model. The two radars agree well to a range of 15 km (where the melting layer was encountered) provided **5 dB** is subtracted from the raw 35 GHz reflectivity. This calibration figure is valid for data recorded in scanning mode from 7 November onwards. For data storage reasons the vertically-pointing data acquisition system adds an arbitrary 20 dB to the reflectivity, so for vertically-pointing 35 GHz data recorded from 29 October onwards, **25 dB** should be subtracted from the raw reflectivity to obtain the correct value. Comparison of the noise floor from 35 GHz scanning file 6180 and all the 35 GHz vertically-pointing files from this period confirm that after applying this calibration they have the same noise-equivalent reflectivity at 1 km, of around $-$**29.7 dBZ**.

For the vertically-pointing data taken on 28 October and before (i.e. during CLARE'98), we need to include the effect of the 9.5 dB change in the attenuator, with the result that **15.5 dB should be subtracted from the raw reflectivity.** The data on the CLARE'98 FTP site was calibrated using the old figure of 17.5 dB, so **2 dB should be added to this and all the other vertically-pointing data on the CLARE'98 FTP site.** The noise-equivalent reflectivity at 1 km of this data after calibration should be around $-$**25.2 dBZ**. The 4.5 dB difference between this and the figure for the data taken after 28 October is presumably due to the 'compression' problem at low signal-to-noise ratios that was described earlier.

The scanning data taken during CLARE'98 still suffers from being recorded using 0.25 dB per bit, so to needs to be rescaled as well as calibrated before it can be used quantitatively. This is done by removing the range correction, multiplying by

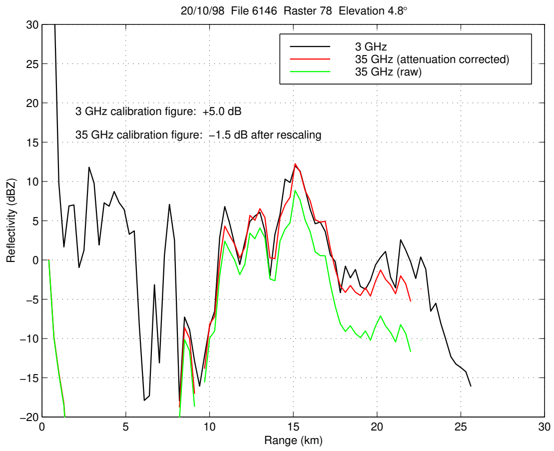

Fig. 5: A comparison of CAMRa and Rabelais reflectivity in scanning mode through drizzle on 20 October 1998, after rescaling the Rabelais. The signal at 3 GHz in the first 8 km is entirely due to ground clutter.

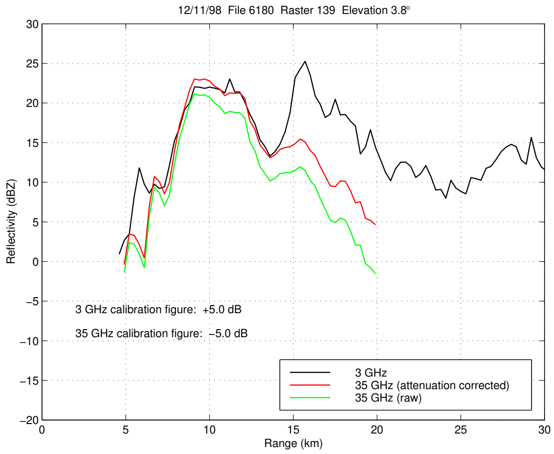

Fig. 6: A comparison of CAMRa and Rabelais reflectivity in scanning mode through a weak rain cell on 12 November 1998. On this occasion the melting layer was at an altitude of 1.1 km which explains why the two rays suddenly diverge at 15 km.

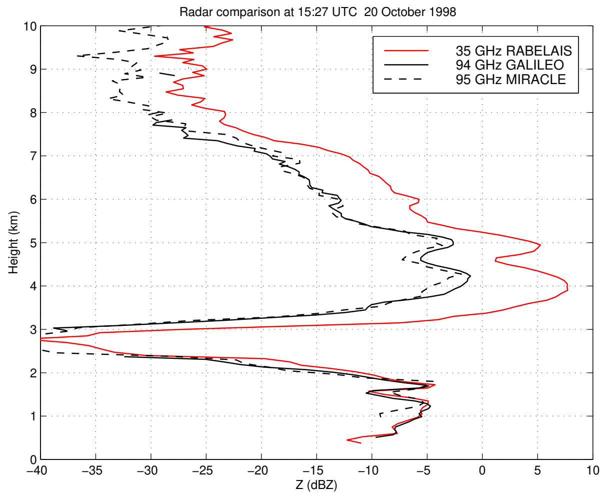

Fig. 7: A comparison of vertical profiles of reflectivity from the Rabelais, Galileo and Miracle radars during CLARE'98.

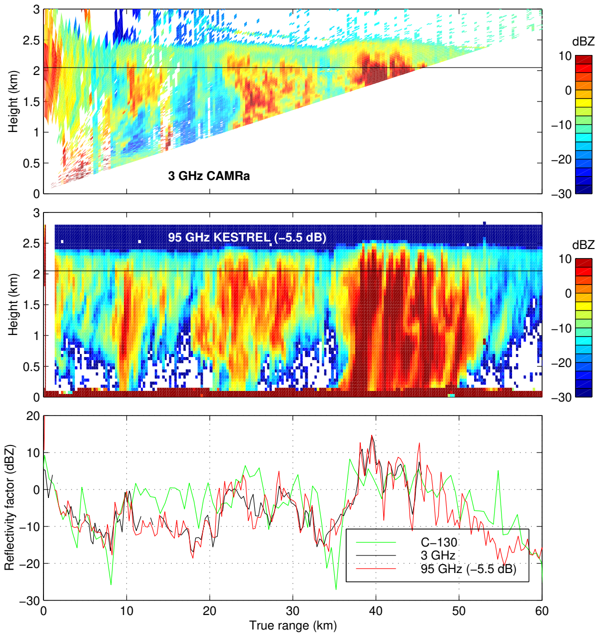

Fig. 8: Comparison between Kestrel and CAMRa reflectivities at an altitude of 2.05 km on 7 October 1998, for the outbound leg of the aircraft starting at 14:00 UTC. The CAMRa has been calibrated using the standard calibration figure of +5 dB, and 5.5 dB has been subtracted from the Kestrel reflectivity to maximise the agreement between the two instruments. Also show is the reflectivity calculated from the microphysical probes on the C-130 aircraft.

0.8 (in logarithmic units), reintroducing the range correction, and adding a calibration figure:

$$Z_{\text{true}} = 0.8\,[Z_{\text{raw}} - 20\log_{10}(r)] + 20\log_{10}(r) + C$$

where Z is in dBZ, r is the range is in km, and C is the calibration figure in dB. By recovering the data in this way we can also calibrate the 35 GHz radar against the 3 GHz using events during CLARE'98. Figure 5 shows a ray through drizzle taken on 20 October 1998, from which a value for C of $-$**1.5 dB** is obtained. After this calibration figure is applied, the noise-equivalent reflectivity at 1 km (as derived from the cloud-free gates at the end of the ray) is -25.2 dBZ, the same as that for the vertically-pointing data after calibration. This confirms nicely that the problems with the instrument can be overcome and a consistent calibration can be derived.

Because of the rescaling that is necessary for the scanning 35 GHz data during CLARE'98, it has not been put on the FTP site. In any case the fact that the 3 GHz radar is over 10 dB more sensitive than the 35 GHz radar means that for most scanning applications the 3 GHz radar is more useful.

94 GHZ GALILEO AND 95 GHZ MIRACLE

The two W-band radars have been calibrated by comparison with the Rabelais from a number of vertically-pointing observations of low stratiform clouds during CLARE'98. The comparison must be performed at short range to minimise atmospheric attenuation at the higher frequency, but far enough away that the far-field approximation is reasonably good. Calibration cannot be performed using ice clouds because the two-way atmospheric attenuation at W-band can easily exceed 5 dB at cirrus altitudes, and Mie scattering by large ice crystals can introduce a further 5 dB difference. Because the scattering behaviour at 94 and 95 GHz is virtually the same, it was found that reflectivity profiles from the Galileo and Miracle matched up very well in cirrus.

The agreement in low clouds was less good because such clouds are intrinsically less homogeneous in the horizontal, and the Galileo was around 100 m from the other two radars. The fact that the near-field zone of the Miracle extends to 900 m meant that better calibration from the Rabelais could be achieved with the Galileo. An example profile through low cloud and cirrus from 20 October 1998 for the three cloud radars after calibration is shown in Fig. 7. The Rabelais and Galileo data has been averaged over 10 seconds and the Miracle data over 6.6 seconds. The agreement between the two W-band radars in cirrus is very good given their separation. The Rabelais signal is between 7 and 10 dB higher in the cirrus due to the combined effects of differential attenuation at low levels and Mie scattering at the higher frequencies by large ice crystals, although it matches up well with the Galileo in the low cloud.

The result of these comparisons is that **16 dB** should be added to raw Galileo reflectivities during CLARE'98 and **2 dB** should be added to Miracle reflectivities in order for them both to be calibrated in agreement with the Rabelais and therefore CAMRa. **The Galileo and Miracle data on the CLARE'98 FTP site are currently calibrated using the old calibration values. Therefore 2 dB needs to be added to them.** The corresponding noise-equivalent reflectivity at 1 km after calibration is **−36 dBZ for both radars**. This figure tends to vary in time more than the equivalent figures at lower frequencies because of the stronger contribution from atmospheric thermal noise, which varies as low clouds pass overhead.

95 GHZ KESTREL

Comparisons of the airborne 95 GHz 'Kestrel' radar with the ground-based Miracle radar by Anne Guyot seem to indicate that the Kestrel consistently reports reflectivities between 8 and 10 dB higher than the Miracle. Recent work to investigate the cause of this discrepancy has identified a non-linear response in the Kestrel's receiver amplifier. The radar was calibrated with a corner reflector, which has a very large backscatter cross-section and therefore the echo from it tends to lie near the top of the dynamic range of the receiver. Clouds on the other hand give a relatively low return, so given that the dynamic range of a radar receiver is typically around 80 dB, it is easy to see how a receiver non-linearity could cause the calibration of meteorological signals to be in error by this magnitude. Unfortunately it means that a simple calibration figure is probably not sufficient to correct the reflectivity values and that at the very least a look-up table is required. One should bear in mind that such a table would correct the raw echo power (i.e. before range correction) rather than the reflectivity, in the same way as the formula given earlier to correct the scanning Rabelais data.

To illustrate that there is a real difference between the CAMRa and the Kestrel, and to circumvent any errors introduced in calibrating the Miracle from the CAMRa, it seems sensible to go directly from CAMRa to Kestrel during CLARE'98 flights in Rayleigh-scattering stratocumulus. The only day for which this is suitable is 7 October 1998, because the stratocumulus contained drizzle and was therefore visible by the two radars at a reasonable range. A crucial additional point is that the CAMRa employed a variable scan-rate so that it could track the C-130 at an altitude of 2 km. This meant that the beams of the two radars were well matched in time and space at the altitude of the C-130 aircraft. Precise matching is necessary because of the extreme inhomogeneity of drizzle.

The outbound leg following the 14:00 UTC overhead has been used, and the comparison is performed at a height of 2.05 km since the variable scan-rate was configured to follow the C-130 at this altitude. It is found that for this leg, the Kestrel measured a 5.5 dB higher reflectivity on average than the CAMRa. Figure 8 shows the excellent agreement between the two radars after this value has been subtracted from the Kestrel reflectivity. However, the Johnson-Williams probe aboard the C-130 aircraft measured liquid water contents of between 0.4 and 0.9 $\mathrm{g\,m^{-3}}$, corresponding to a two-way liquid water attenuation at 95 GHz in the 300 m between the sampling altitude and the top of the cloud of between 1.1 and 2.5 dB. Using the thermodynamic variables of the ECMWF model, the two-way attenuation by atmospheric gases between the sampling altitude and the altitude of the aircraft (3.1 km) was around 0.25 dB. Hence the true Kestrel calibration figure is closer to −7.5 dB, in agreement with the difference found between the Miracle and the Kestrel. Because liquid water content tends to increase with height in stratocumulus, this estimate of liquid water attenuation could be an underestimate and the Kestrel calibration figure could be as much as −8.5 dB. Note that this value may only be valid to correct signals of this strength and at this distance from the antenna. Unfortunately the comparison could not be performed closer to the top of the cloud to reduce the uncertainty in liquid water attenuation, because the features of the reflectivity time series matched up much less well due to the poorer temporal coincidence of the samples.

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