

Absolute calibration of 94/95-GHz radars using rain

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ABSTRACT

Absolute calibration of cloud radars is very difficult. A new method is proposed for 94/95-GHz radars which exploits the fact that at this frequency, the radar reflectivity factor of rain measured at a range of 250 m is approximately constant at 19 dBZ for rain rates between 3 and 10 mm h⁻¹, due to the combined effects of extinction and non-Rayleigh scattering. The standard deviation of around 1.5 dB is due to natural variations in the number concentration of drops, and is consistent with the variation predicted from theory, but averaging over a number of different rain events over a month or more should be sufficient to reduce the calibration error to less than 1 dB. A thin layer of rainwater on the radomes of the 94-GHz radar at Chilbolton, Southern England, was found to cause a two-way attenuation of between 9 and 14 dB, but we show that the technique may be successfully implemented by operating the radar at a low elevation angle and employing a shelter to keep it dry. Most 94-GHz cloud radars world-wide use the same amplifier, and monitoring the calibration of this radar over a two-year period of continuous use reveals a loss of power of around 1 dB in the first year and 10 dB in the second. Frequent calibration is therefore recommended.

1. Introduction

Radars at 94 and 95 GHz have been used in cloud research now for more than a decade (Lhermitte 1987; Pazmany et al. 1994; Clothiaux et al. 1995; Sekelsky and McIntosh 1996), and NASA plan to launch a spaceborne cloud radar in 2004 at this frequency (Austin and Stephens 2001), but in order to use them quantitatively to derive cloud properties they must be well calibrated. The usual approach to calibrating meteorological radars is to use a calibration target of known backscatter cross-section, but this is logistically difficult (see Joe and Smith 2001), and the full beam pattern should be measured for an accurate calibration. It is our experience that 'system calibrations' based on a link budget calculation are often wrong by more than a factor of two due to the difficulty in accurately characterizing every component of the radar hardware.

Goddard et al. (1994) proposed a technique for absolute calibration of polarimetric centimeter-wavelength radars to 0.5 dB which utilizes the fact that the radar parameters reflectivity factor (Z), differential reflectivity and differential phase shift are not independent in heavy rain. The method cannot be used at millimeter wavelengths because the combined effects of non-Rayleigh scattering by large raindrops and extinction make the Z of rain much more difficult to interpret. However, we find empirically that at 94 GHz these two effects are large enough to cause the Z of rain measured at a short range from the radar to vary little with rain rate. This property offers the potential for easy calibration of a 94/95-GHz

radar every time it rains, requiring only a basic rain gauge to be available at the same location.

In section 2, Mie-scattering calculations are performed to determine the theoretical reflectivity of rain, and to find the optimum range from the radar where the intervening extinction is such that the measured reflectivity varies least with rain rate. In section 3 results are presented from two years of data taken by rain gauge and vertically pointing radar. These data demonstrate the potential accuracy of the technique, but also highlight the problem of strong attenuation that occurs as soon as the rain wets the surface of the radomes covering the two antennas of the radar. In section 4 we overcome this problem by operating the instrument at a lower elevation and sheltering it from the rain.

2. Theory

We define the effective reflectivity factor of liquid water drops measured by a radar at frequency f as

$$Z_f = \frac{|K_f(T)|^2}{|K_f(0)|^2} \int_0^\infty n(D) D^6 \gamma_f(D) dD, \quad (1)$$

where $|K_f(T)|^2$ is the dielectric factor of liquid water at temperature T , $|K_f(0)|^2$ is the dielectric factor of liquid water at 0°C, $n(D)$ represents the size distribution (where $n(D) dD$ is the number concentration of drops in the diameter range D to $D + dD$) and γ_f is the Mie/Rayleigh backscatter ratio. The ratio of dielectric factors in (1) ensures that, after correction for attenuation, different frequency radars will all measure the same Z in a 0°C cloud containing targets small enough to Rayleigh scatter at all

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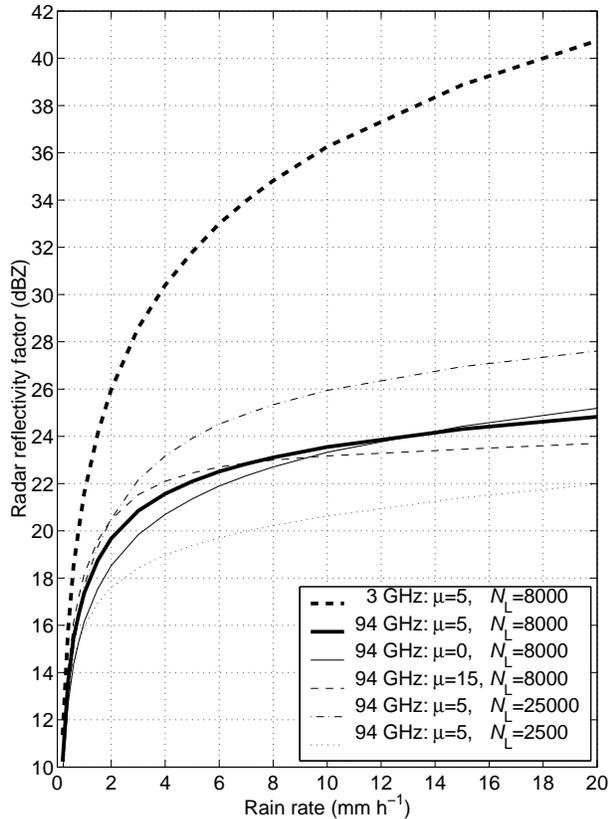


FIG. 1: Z versus rain rate at 3 and 94 GHz. The size distribution has been represented by a normalized gamma distribution, and at 94-GHz various values of the shape parameter μ and the number concentration parameter N_L have been used. The temperature is 10°C and extinction has been neglected.

frequencies. At 3 GHz the dielectric factor is 0.93 and is independent of temperature, while at 94 GHz it varies with temperature, increasing from 0.67 at 0°C to 0.81 at 20°C . Hence, in this convention, the 94-GHz effective reflectivity factor of a Rayleigh-scattering cloud at 20°C is 0.82 dB more than the reflectivity factor of the same cloud but either (a) at 0°C , or (b) measured at 3 GHz. Formulas for the dielectric constants of ice and liquid water were given by Liebe et al. (1989).

Mie theory is adequate for representing the scattering of raindrops at 94-GHz; T-matrix scattering calculations for realistic raindrop distributions viewed at vertical incidence, 45° elevation and horizontal incidence show that the effects due to the oblateness of real raindrops are only significant for rain rates greater than around 50 mm h^{-1} . Below 20 mm h^{-1} (corresponding to a median volume diameter of less than 2.2 mm in Eq. 2) the error in assuming spherical drops is invariably less than 0.5 dB.

We represent the raindrop size distribution by the ‘normalized gamma distribution’ of Illingworth and Black-

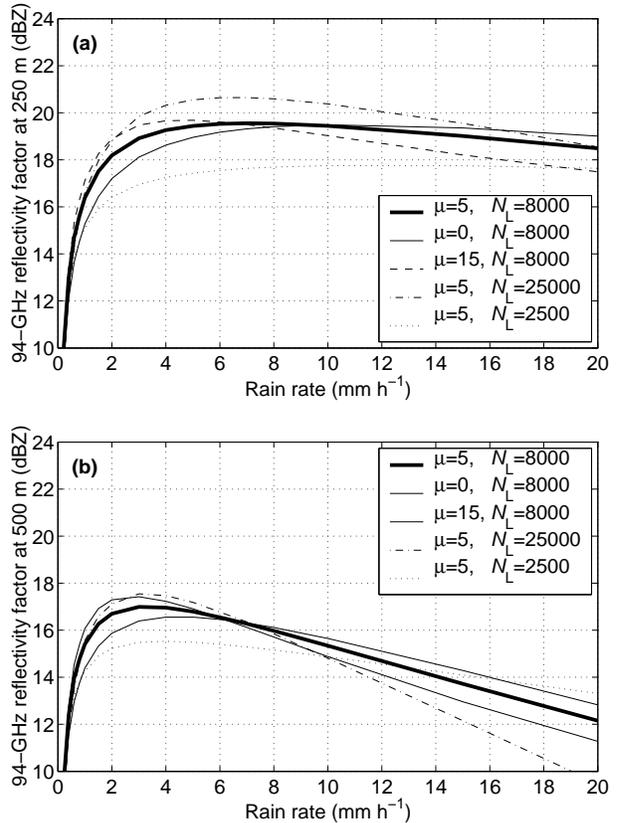


FIG. 2: 94-GHz Z versus rain rate, including the two-way extinction by the rain and atmospheric gases at saturation. Panel a corresponds to the values measured at 250 m from the radar, and panel b to the values at 500 m from the radar. Both are at a temperature of 10°C .

man (2002):

$$n(D) = \frac{N_L 0.03 D_0^4 \Lambda^{\mu+4}}{\Gamma(\mu+4)} D^\mu \exp(-\Lambda D), \quad (2)$$

where $\Lambda = (3.67 + \mu)/D_0$. The size distribution is characterized by three parameters, the median volume diameter D_0 , the concentration parameter N_L and the shape parameter μ . This formulation has several advantages over the simpler expression of Ulbrich (1983), the most important being that the three parameters are independent of each other in natural rain (Illingworth and Johnson 1999), enabling the full variability of rain to be easily simulated. The factor $0.03 D_0^4$ ensures that in the case of $\mu = 0$, this expression reduces to the familiar inverse-exponential distribution of Marshall and Palmer (1948), with N_L equal to their concentration parameter ‘ N_0 ’.

We calculate Z versus rain rate by varying D_0 in (2) while keeping N_L and μ constant. The main distribution we consider has $\mu = 5$ (similar to the mean values found by Tokay and Short 1996, Wilson et al. 1997 and Illingworth and Johnson 1999) and $N_L = 8000 \text{ mm}^{-1} \text{ m}^{-3}$ (the value used by Marshall and Palmer 1948, and close to the mean value found by Illingworth and Johnson 1999).

The thick lines in Fig. 1 show the curves for 3- and 94-GHz radars at 10°C; the large difference is due to non-Rayleigh scattering at 94 GHz. Illingworth and Johnson (1999) reported the standard deviation of μ to be around 5 (although the distribution was distinctly skewed), and that of N_L to be around half an order of magnitude. The thin lines in Fig. 1 show the 94-GHz curves for μ values of 0 and 15 and N_L values of 2500 and 25 000 $\text{mm}^{-1} \text{m}^{-3}$, and indicate the range to be expected in natural rain. There seems to be little dependence of Z on μ , although these values of N_L change Z by 0.5–2.5 dB. It should be noted that for constant rain rate an increase in N_L results in a higher value of 94-GHz Z , whereas the converse is true at 3 GHz. The reason is that non-Rayleigh scattering effectively renders Z a lower moment of the size distribution than rain-rate. This is seen in Fig. 1 by the fact that an increase in rain rate from 2 to 20 mm h^{-1} (i.e. 10 dB) causes an increase in Z at 94-GHz of only 6 dB.

In practice the reflectivity of rain would be measured at some distance from the radar, so extinction should be taken into account. Figure 2 shows the same 94-GHz curves as in Fig. 1 but with adjustment for the two-way extinction (both attenuation and scattering) by the rain to 250 m and 500 m, assuming the properties of the rain to be constant over this distance. The stronger extinction at higher rain rates has the effect of removing the small dependence of Z on rain rate that was observed in Fig. 1, with the result that for rain rates above 3 mm h^{-1} the reflectivity measured at a range of 250 m is approximately constant at 19 dBZ. The dependence of extinction on number concentration is such that attenuated Z is somewhat less sensitive to N_L than unattenuated Z , especially at high rain rates. Nonetheless, the standard deviation of the Z that would be measured in rain is still likely to be around 1.5 dB. The much smaller attenuation by atmospheric gases has also been included in Fig. 2, assuming saturated air and a pressure of 1013 hPa.

It should be noted that these curves are slightly temperature dependent: the radar backscatter cross-section increases with temperature due to the change in the dielectric factor $|K|^2$ discussed earlier, but this is largely offset by the increased attenuation due to the greater vapor content at higher temperatures. It turns out that, assuming saturated air, the difference between the 250-m curves at 10°C and 20°C is negligible, while the 0°C curve is just 0.3 dB lower.

At 500 m from the radar the extinction is much stronger and there is a significant decrease of Z with rain rate. This is a concern for radars with antennas larger than 0.63 m for which 250 m is strictly within the near field. However, given that the extinction might also be varying over scales of 500 m, it would probably be better for such radars to still use rain observed at 250 m but to make a correction for the near-field effect (e.g. Sekelsky 2002).

3. Results with unsheltered radomes

We now apply the technique to data taken by the dual-antenna 94-GHz *Galileo* radar, which operates near-continuously at Chilbolton, Southern England in a vertically pointing configuration. The radar has an antenna diameter of 0.46 m, so the far-field approximation is valid beyond around 130 m. Between March 1999 and October 2000 it was mounted on the side of the 25-m dish of the 3-GHz radar at Chilbolton to enable coaxial scanning, and an independent cross-calibration of the 94-GHz radar was possible. Of course, this arrangement would not be possible for the majority of 94-GHz radars around the world, but it should be stressed that an external calibration source such as this is not necessary for the operation of the rain calibration technique.

The 3-GHz radar is calibrated to better than 0.5 dB by the method of Goddard et al. (1994). Cross-calibration of the 94-GHz radar was performed in non-precipitating, Rayleigh-scattering cloud, and care was taken in the analysis to correct the 94-GHz signal for attenuation by atmospheric gases and to make the small correction for the near-field effect at 3-GHz (Sekelsky 2002). The resulting 94-GHz radar calibration is believed to be accurate to around 1.5 dB.

At this point we should consider the possibility of range-dependent errors due to the separation and possible misalignment of the transmit and receive antennas. Sekelsky and Clothiaux (2002) compared the Pennsylvania State University dual-antenna 94-GHz radar and the University of Massachusetts single-antenna 95-GHz radar in low-level liquid water cloud and found a significant range-dependent offset between the two systems in the lowest 800 m, which they attributed to incomplete beam overlap of the Penn State radar, as well as a 0.06° misalignment of its two antennas. We have performed some calculations and found that beyond the near-field zone, the error in dB for perfectly aligned antennas is proportional to the square of the antenna diameter multiplied by the square of the separation of the antenna axes. The *Galileo* antennas are half the diameter of the Penn State antennas, and the antenna axes are around two-thirds as far apart. Therefore the overlap error in dB is nine times smaller, and at 250 m amounts to only 0.6 dB. A misalignment of 0.06° could increase this to 1.1 dB, although if the sign of the misalignment were reversed (i.e. if one beam was leaning slightly into the other) then the error would actually be reduced. It should be noted that dual-frequency retrievals of stratocumulus liquid water content using 35- and 94-GHz radars (Hogan et al. 1999), which are very sensitive to range-dependent biases in either radar, have been possible down to ranges of only 400 m. This would have been impossible if the overlap problem was as described by Sekelsky and Clothiaux (2002) for the geometry of the Penn State radar.

Figure 3a shows 5 hrs of data measured by the

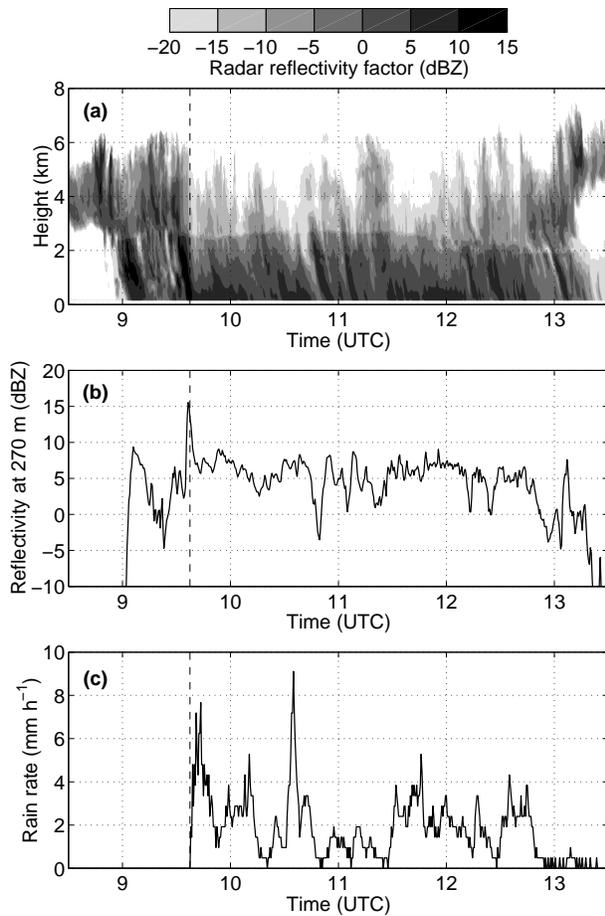


FIG. 3: (a) Time-height section of Z measured by the 94-GHz *Galileo* radar on 24 September 2000; (b) Z at an altitude of 270 m; (c) surface rain rate. The horizontal dashed line on each panel indicates when rain was first measured at the ground.

Galileo at vertical incidence during a stratiform rain event. Panel b depicts Z at a height of 270 m (the nearest range-gate to 250 m), while the rain rate measured at Chilbolton by a drop-counting rain gauge is shown in panel c. Just before 09:38 UTC, when rain was first detected at the surface, the reflectivity factor at 270 m reached 15 dBZ, corresponding to a rain rate at this altitude of around 0.8 mm h^{-1} (Fig. 2a). As soon as the rain reached the ground, however, Z at 270 m dropped back to the range 0–8 dBZ, where it remained for the 3-h duration of the rain. This was due to the strong attenuation caused by the radomes as soon as they obtained a covering of rain water. The effect is clearly visible in Fig. 3a, where Z can be seen to suddenly drop at all altitudes immediately after the rain reached the ground (indicated by the vertical dashed line). The problem of radome attenuation for cloud radars was also noted by Sekelsky et al. (1998).

Figure 4 depicts Z at 270 m versus rain rate, measured during April 2000. Each circle represents a 30-s average,

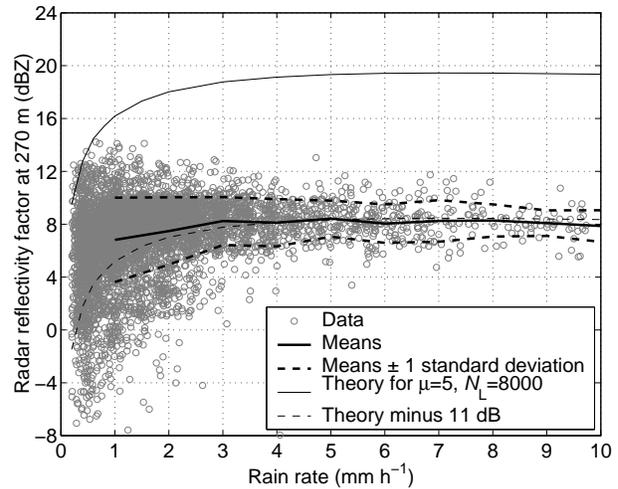


FIG. 4: Observed Z at 270 m versus rain rate for the month of April 2000, and the theoretical curve for a normalized gamma distribution with $\mu = 5$ and $N_L = 8000 \text{ mm}^{-1} \text{ m}^{-3}$ (as in Fig. 2a). The difference implies a mean two-way attenuation of 11 dB by the wet radomes. The radar was calibrated by comparison with the 3-GHz radar at Chilbolton in non-precipitating cloud, and the 1 dB sensitivity drift during April 2000 evident in Fig. 5 has been removed.

and the thick lines show the means and standard deviations of Z in each 1-mm-h^{-1} rain-rate interval. For rain rates between 3 and 10 mm h^{-1} the means are constant at 8 dBZ, with the scatter decreasing from around $\pm 2 \text{ dB}$ at 3 mm h^{-1} to $\pm 1 \text{ dB}$ at 10 mm h^{-1} . These variations are consistent with the 1.5 dB predicted from theory. Averaging over a number of different rain events (i.e. a range of values of N_L and μ) over a month or longer would be expected to improve the accuracy of the mean to considerably better than 1 dB, provided that the radomes could be kept dry. The means are 11 dB lower than the theoretical curve, indicating the magnitude of the two-way radome attenuation. An attenuation of 11 dB could have been caused by a uniform film of water 0.7 mm thick (Mead et al. 1998).

Regular cross-calibration events with the 3-GHz radar in non-precipitating cloud indicated that the *Galileo* was losing power in the 18 months that it was mounted on the 3-GHz dish, amounting to a total loss in this period of around 11 dB. The solid curve in Fig. 5 shows the ‘noise-equivalent reflectivity’ at 1 km between October 1998 and September 2000. Noise-equivalent Z may be regarded as the minimum detectable signal at 1 km for a single radar pulse (note that by averaging many pulses the actual minimum detectable signal is at least an order of magnitude smaller). The error bars indicate the 3-GHz cross-calibration events and their estimated accuracy. Measurements over this period show that the 1–2 dB increase in the level of the background noise during periods of rain does not change (i.e. with the receiver acting as a radiometer; see Fabry 2001), suggesting that the sensitivity of the

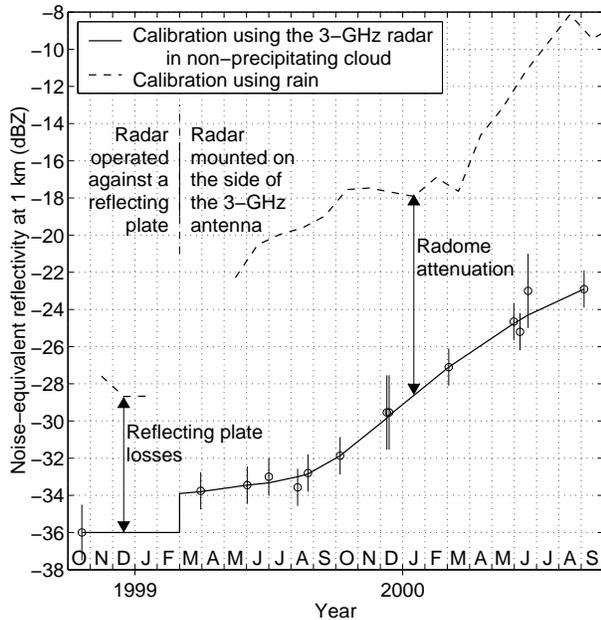


FIG. 5: The change in the calibration of the 94-GHz radar as determined by comparisons with the 3-GHz radar in non-precipitating Rayleigh-scattering cloud (error bars and solid line), and using the new technique of assuming the Z of rain at 270 m to be 19 dBZ (dashed line). Before March 1999, the difference is due to losses associated with rain water on the reflecting plate, while afterwards it is due to attenuation by rain water on the radomes.

receiver is constant and that the problem lies with a loss of power in the 94-GHz power amplifier.

Before March 1999 the *Galileo* was operated from inside one of the buildings at Chilbolton, with the beam directed through a covered window against a reflecting plate at 45° . The calibration figure obtained during the CLARE'98 experiment in October 1998 by comparison with the 3-GHz radar (Hogan and Goddard 1999) suggests a further 2 dB loss of sensitivity between October and March. However, given the fact that only 1 dB of sensitivity was lost in the first 6 months that the radar was mounted on the 3-GHz dish (i.e. March–September 1999), it seems more likely that the power produced by the tube was constant and the initial 2 dB drop in sensitivity occurred in March 1999 when the operating environment of the radar was changed. This is indicated in Fig. 5 as an unchanging sensitivity before March 1999. So the main deterioration of the system seems to have occurred after September 1999, when a steady decrease in sensitivity with time (amounting to 10 dB in a year) was recorded. It should be stressed that the calibration by comparison with the 3-GHz radar is unaffected by radome attenuation and beam-overlap effects as it is performed strictly in non-precipitating clouds more than 2 km from the radars. It is encouraging to find that the -36 dBZ noise-equivalent reflectivity at 1 km for the new radar tube in October 1998 in Fig. 5 agrees well with the theoretical



FIG. 6: Photograph of the *Galileo* radar on 14 March 2002. The elevation angle was 30° and the scaffold provided shelter from the rain. The radar was pointed to the west and the wind direction in the two days that it was inclined at this angle was weak easterly.

sensitivity calculated from a specified transmitted power of 1.5 kW, a pulse length of $0.5 \mu\text{s}$, an antenna gain of 50 dB (beamwidth 0.5°) and a receiver noise figure of 9.5 dB (including losses).

The dashed line in Fig. 5 indicates the calibration resulting from the new calibration method in rain, but without accounting for any losses due to standing water on the reflecting plate or the radomes. Between November 1998 and January 1999 the difference between the two lines is around 7 dB, indicating the losses associated with rain water on the reflecting plate. After March 1999, when any losses were due to water on the radomes, the difference ranges between 9 and 14 dB and appears to be at its lowest in the winter months. This could be due to the fact that stratiform rain in winter tends to be lighter than the more convective rain in summer, resulting in thinner coatings of water on the radomes.

4. Results with sheltered radomes

Clearly the 5-dB variation in radome attenuation means that the calibration using rain cannot be implemented reliably at vertical incidence. While the problem of standing water is most severe for radars that use radomes because of the strong attenuation of the beam as it passes through the water layer, our results with a reflecting plate suggest that the performance of an antenna open to the environment is also likely to suffer when it gets wet because the droplets on the surface scatter the radiation in all directions. A better approach is to keep the instrument completely dry while measuring rain. In this section results are presented from two days of data taken in March

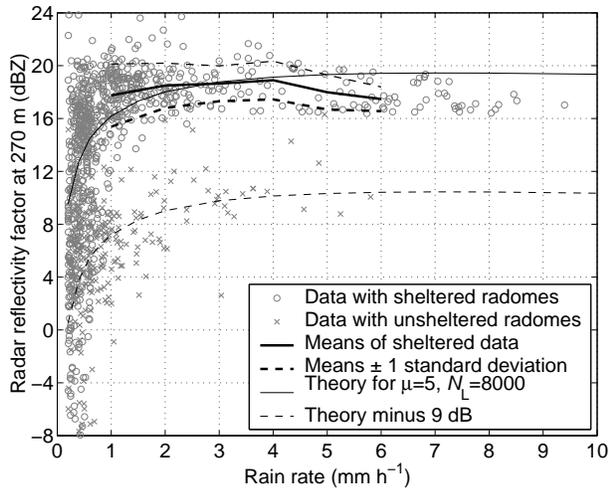


FIG. 7: Z at 270 m versus rain rate for the 14 hrs on 14–15 March 2002 when the radar was operating at 30° elevation sheltered from the rain (circles) and the 3 hrs of 15 March after it was returned to an unsheltered vertically pointing configuration (crosses). The difference implies a wet-radome attenuation of approximately 9 dB.

2002 with the *Galileo* operating at an elevation of 30° beneath a makeshift shelter that protected it from the rain (Fig. 6). Visual inspection confirmed that the radomes remained dry.

The circles in Fig. 7 show 30-s-averaged data taken between 11 UTC on 14 March and 14 UTC on 15 March (during which it rained for around 14 hrs) when the radar was inclined at 30° from the horizontal. Unfortunately no 3-GHz data were available for independent calibration, so the calibration used here is intended to maximize agreement with the theoretical curve (shown by the thin solid line). The shapes of the theoretical curve and the means of the data do not match up as well as in Fig. 4, although of course far less data is being used. The scatter of the points is around ± 2 dB. The crosses show data taken after 14 UTC on 15 March when the radar was returned to vertical incidence and the radomes were no longer protected from the rain. Although the rain rate was generally lower at this time, the immediate drop in reflectivity of approximately 9-dB due to radome attenuation is clear, and is consistent with the 9–14 dB radome attenuation found in section 3. This gives us more confidence in the theoretical figure of 19 dBZ used in the new calibration technique. It is regrettable that only a small amount of data were taken, explaining the poor statistics evident in Fig. 7, but two days after the sheltered observations were taken the power amplifier failed completely and had to be returned to the vendor. A new tube for the radar is currently on order.

5. Conclusions

A simple technique for calibration of 94/95-GHz radars to better than 1 dB has been demonstrated, which

utilizes the fact that rain between 3 and 10 mm h^{-1} measured at a range of 250 m has a reflectivity factor that is approximately constant at 19 dBZ. The technique could be used with both ground-based and low-altitude airborne instruments in rainfall, provided that they can be kept dry.

From space this calibration technique would be much more difficult to apply due to the strong attenuation by the melting layer (the extinction due to ice and atmospheric gases is small in comparison). Even for rain generated entirely at temperatures warmer than 0°C , the rainfall rate will increase to 3 mm h^{-1} over a finite but unknown vertical distance from the top of the cloud, so it would be very difficult to disentangle the effects of an increasing rainfall rate and an increasing attenuation. At lower frequencies such as 35 GHz, attenuation and non-Rayleigh effects are much weaker, so Z always has a strong dependence on rain rate and the method cannot be used.

Independent monitoring of the calibration of the Chilbolton 94-GHz radar reveals a loss of power of 11 dB over a two-year period of continuous operation, which is a concern given that the 94-GHz cloud radars operating in various laboratories world-wide use the same tube as the one in this study. Recent design modifications by the vendor are believed to have alleviated this problem. This loss of power could pose a serious problem in data interpretation, although many radars employ a coupler to monitor the transmit power and correct the data accordingly. The same trend is evident when the new calibration technique is applied to data taken at vertical incidence, but a difference of 9–14 dB is found due to attenuation by the wet radomes. The variation in this effect means that one cannot simply apply a correction factor to the data when it rains. However, the technique may be successfully implemented by operating at lower elevation angles beneath a shelter, and we are currently building a manually operated rotating mount that will allow calibration data to be easily obtained whenever it rains.

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