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CAN WE CALIBRATE RADAR WITH RAINGAUGES

by

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Abstract

The comparison of gauge and radar estimates of rainfall and the use of gauge measurements to correct radar errors have been studied. In radar error verification, the logarithmic ratio of the two rainfall estimates should be used instead of the ordinary ratio. A general formula has been developed to describe the effect of various measurement errors on gauge-radar rainfall comparisons. Based on this scheme, rain gauges only provide a coarse estimate of the mean electrical radar calibration error over time and echo intensity. In real situations other radar measurement errors typically exceed miscalibration. This has been demonstrated by real measurement examples of the effect of microwave attenuation due to rain, and the vertical radar reflectivity profile (bright band and beam overshooting). In practice the electrical calibration of radar by gauges is usually impossible and one should not use the concept »calibration of radar by raingauges».

1. *Introduction*

The calibration of radar means conventionally the determination of the electrical response of the receiver to a known echo intensity. On the other hand we may use rain gauges to calibrate radar-derived rainfall estimates. In this case, based on different techniques a »calibration», »adjustment», »assesment» or »correction» factor is widely used to force the radar estimates of rainfall to agree with gauge values. The latter concept is quite often used in general expressions as »the calibration of radar by raingauges» or »the correction of radar miscalibration by raingauges». These kinds of statements easily lead to the conclusion that the electrical calibration of a radar can be fully performed, or that normal procedures may be skipped over by using raingauges as an independent comparable data source. The purpose of this study is to show that in typical measurement situations raingauges can provide only a coarse way of estimating calibration errors and that raingauges cannot replace an unknown electrical calibration. The correction of radar rainfall estimates by raingauges is also discussed.

2. *Gauge-radar comparison*

When the effect of miscalibration of radar rainfall estimates is studied, a natural way is to compare radar and gauge measurements of rainfall at gauge locations. The logarithmic ratio, hereafter referred to as log ratio (F), of gauge and radar rainfall (G and R respectively),

$$F = \log(G/R), \quad (G \neq 0, R \neq 0), \tag{1}$$

seems to be the best way to compare the two estimates as the distribution of F is approximately normal (CAIN and SMITH, 1976; SMITH and CAIN, 1983). This

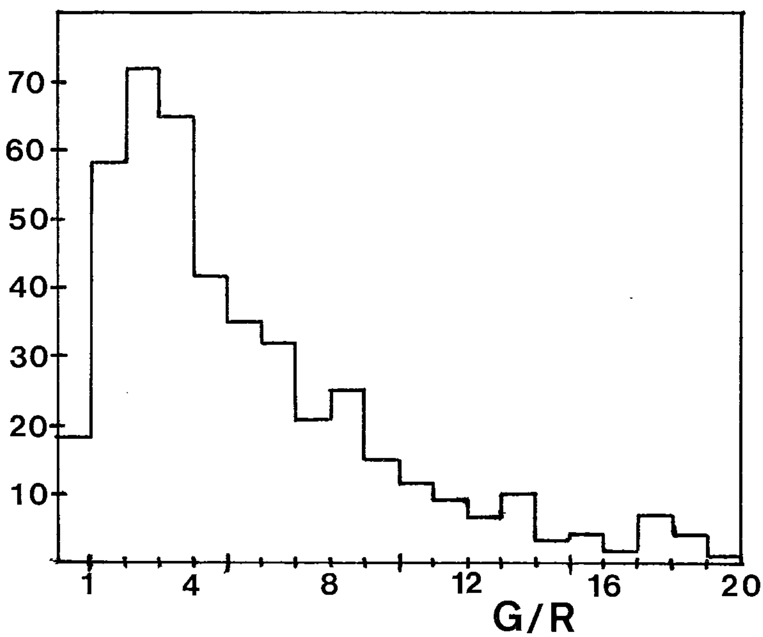

Fig. 1. The distribution of the ratio of daily (24 h) gauge and radar rainfall estimates at gauge locations (G/R, $G > 0$) on 6 measurement days (442 gauge-radar comparisons). Ratios greater than 20 are excluded.

makes objective quality control of the observations possible (KOISTINEN and PUHAKKA, 1981). When the ratio G/R is used, large spurious errors may arise as the distribution of G/R is often skew, fig. 1.

As an example we show two evaluations of radar rainfall error before and after the measurements have been adjusted by

$$P = \langle G/R \rangle \cdot R, \tag{2}$$

where P is the combined gauge and radar rainfall (adjusted or »calibrated» radar estimate), $\langle G/R \rangle$ the mean of all observed ratios at gauge sites and R the radar rainfall at a gauge site. Accordingly the radar bias before and after adjustment by gauges is the mean $\langle \log(G/R) \rangle$ and $\langle \log(G/P) \rangle$ respectively. WILSON and BRANDES (1979) have studied the reduction of radar error by gauge adjustment using G/R-differences at each gauge location,

$$d_R = |1 - R/G|, \tag{3}$$

$$d_P = |1 - \langle G/R \rangle \cdot R/G|, \tag{4}$$

where d_R and d_P represent gauge-radar differences before and after correction by the mean adjustment factor $\langle G/R \rangle$. Table 1 shows the two error verifications for three separate daily rainfall totals.

Table 1. Mean radar rainfall errors before and after gauge adjustment for three daily rainfall periods. The error is measured using both ordinary, see equations (3) and (4), and logarithmic gauge-radar ratios.

Mean error	Aug. 5	Aug. 6	Aug. 31, 1978
$\langle \log(G/R) \rangle$	0.38	0.34	0.53
$\langle d_R \rangle$	53 %	51 %	66 %
$\langle \log(G/P) \rangle$	0.009	−0.007	−0.018
$\langle d_P \rangle$	61 %	32 %	62 %

In spite of the fact that the bias of 3–5 dB has been removed ($\langle \log \langle G/P \rangle \rangle \approx 0$), the mean differences have not reduced because of the skew distribution of G/R values. Hence the radar error evaluation should be based on $\log(G/R)$ rather than G/R. For the same reason the correction of radar rainfall R at a measurement point between gauges should be

$$P = 10^{\widetilde{F}} \cdot R, \tag{5}$$

where $\widetilde{F}$ is the log ratio at the measurement point estimated from surrounding gauges. This will reduce extrapolation errors, see SNELL (1978) and GREENE *et al.* (1980), inherent in some objective analysis methods when the spatial distribution of $\widetilde{F}$ is calculated. The question of the best way to estimate $\widetilde{F}$ is discussed by KOISTINEN and PUHAKKA (1981). It may be noted that the log ratio is also conveniently comparable to electrical radar characteristics which are often expressed on a dB-scale.

3. *The effect of radar miscalibration on gauge-radar comparisons*

If we compare gauge and radar measurements at the same location the result depends on the selected radar reflectivity factor – rainfall intensity (Z_e–R) relationship, which is a function of space and time:

$$Z_e \doteq a(r, \theta, t)\, R^{b(r, \theta, t)} \tag{6}$$

where r is range, θ azimuth angle and t time; a and b depend mainly on drop size distribution. (Vertical coordinate is neglected in this discussion). Taking into account the radar equation

$$\bar{P}_{ro}(r, \theta, t) = \frac{C(t)\,|K|^2 Z_e(r, \theta, t)\, \kappa(r, \theta, t)}{r^2}, \tag{7}$$

where C is the radar constant, $\bar{P}_{ro}$ the observed mean echo power, $|K|^2$ the dielectric factor and κ microwave attenuation, we may write

$$F \equiv \log(G/R) = \log G - \frac{1}{b(r, \theta, t)} [\log \bar{P}_{ro}(r, \theta, t)$$

$$- \log C(t) + 2\log r - \log|K|^2 - \log \kappa(r, \theta, t) - \log a(r, \theta, t)]. \tag{8}$$

If we introduce the calibration of the radar receiver

$$\bar{P}_{ro} = f(\bar{V}, t), \tag{9}$$

where $\bar{V}$ is the signal voltage of the radar receiver averaged over a statistically representative number of pulses and f is an empirically determined function, the »calibration curve», equation (8) becomes

$$F = \log G - \frac{1}{b(r, \theta, t)} [\log f(\bar{V}, t) - \log C(t)$$

$$+ 2\log r - \log|K|^2 - \log \kappa(r, \theta, t) - \log a(r, \theta, t)]. \tag{10}$$

In spite of careful radar hardware monitoring, systematic errors of up to 5 dB are frequently met with in radar measurements (*e.g.* HILDEBRAND *et al.*, 1978; KOISTINEN, 1986). The typical value for calibration errors in modern radars seems to be 2–3 dB (CRANE and GLOVER, 1978). Therefore the calibration should be varied slightly to get the correct received power $\bar{P}_r$:

$$\bar{P}_r = f(\bar{V}, t) \cdot f'(\bar{V}, t), \tag{11}$$

where f' is calibration error factor. The error in the radar constant C can be included in f'.

Other sources of error which have to be included in equation (10) are the gauge error ΔG, the sampling difference between gauge and radar ΔS, the precipitation particle distribution changes while falling from the radar pulse volume to ground ΔD and reflectivity gradients in the pulse volume ΔV. When all these are taken into account, equation (10) becomes

$$F = \log G(r, \theta, t) + \Delta G(r, \theta, t) - \frac{1}{b(r, \theta, t)} [\log f(\bar{V}, t) + \log f'(\bar{V}, t)$$
$$- \log C(t) + 2\log r - \log |K|^2 - \log \kappa (r, \theta, t) - \log a(r, \theta, t)]$$
$$+ \Delta D(r, \theta, t) + \Delta V(r, \theta, t) + \Delta S(r, \theta, t). \tag{12}$$

It can be concluded that in general we have too many unknown variables in equation (12) to solve the calibration by gauge-radar comparisons. In principle we could use a »black box» method in which we suppose that $R = G$ and combine all terms on the right hand side of equation (12) to give

$$R = \sum_{k=0}^{N} A_k(r, \theta, t) \bar{V}^k + \epsilon, \tag{13}$$

where coefficients A_k are determined statistically and ϵ is a residual function depending on the degree of the polynomial (k). Actually we are dealing in the case of eq. (12) with a kind of »behavioral calibration» whereas eq. (13) is related to »arbitrary calibration» using terminology introduced by PIKE and RINEHART (1983). In fact this latter kind of approach has shown to be quite successful even when $k = 0$, *i.e.* $\bar{V}$ is approximated by a yes-no (1–0) function (DONEAUD *et al.*, 1981). However, in this case both the integration time and area have to be large (mean daily accumulation over an area of 30 000 km^2), which means that rainfall variability is lost. It should also be noted that equation (13) is not an electrical calibration of the radar but a statistical estimate of the overall radar-atmosphere measurement system response. In order to improve the result in all circumstances as well as possible, we should first try to estimate all factors on the right hand side of eq. (12) and only after that can we use a »black box» type of solution to convert raw radar rainfall estimates to agree with »calibration» gauges.

In typical operational radar measurements the calibration function f is determined using a signal generator connected to the radar receiver. Again in principle we may set all other errors as insignificant and estimate the calibration error $f'(\bar{V}, t)$ by observed gauge-radar comparisons F. Provided now that a representative number of F-values exist throughout the dynamical range of rainfall echoes and f' does not vary within the integration time of G and R, we can estimate f'. If some reflectivity band is not included in the F-values (*e.g.* light rainfall over land, heavy over sea) the only way to get corrections to this band is extrapolation. This means that at a single radar measurement point the estimated calibration error at the nearby gauge location can be totally unsuitable if f' varies strongly with signal intensity. It can be concluded that in principle we get an estimate of the mean calibration error over time and echo intensity.

In real situations, however, other errors are frequently larger than those of calibration. As a consequence the estimation of calibration error by gauge-radar comparisons even at gauge locations is impossible. Only if the mean calibration error is distinctly larger than other errors can raingauges give a rough estimate of it. This estimate is not necessarily representative at single radar measurement points nor in very light or strong rainfall near the ends of the dynamic range of the receiver. In the following some examples are given to show that the effect of other errors on gauge-radar comparisons easily exceeds that of miscalibration.

4. *The effect of other errors on gauge-radar comparisons*

The most serious error in properly-installed gauges is that due to the aerodynamic deflection of precipitation particles by the wind. According to ALLERUP and MADSEN (1979) the typical wind error for a Hellmann-gauge is 0.5–1 dB if the rainfall intensity is 1 mm/h. In snowfall these errors are much larger. Gauge errors are generally considered to be smaller than radar errors in rainfall, which is a basic requirement for radar rainfall adjustment by gauges. In very light rainfall, gauges and radar estimates frequently show totally different features (HILDEBRAND *et al.*, 1979). The reason for this is that radar detects light rainfall much easier than gauges due to large relative errors due to wetting, evaporation and wind of the latter.

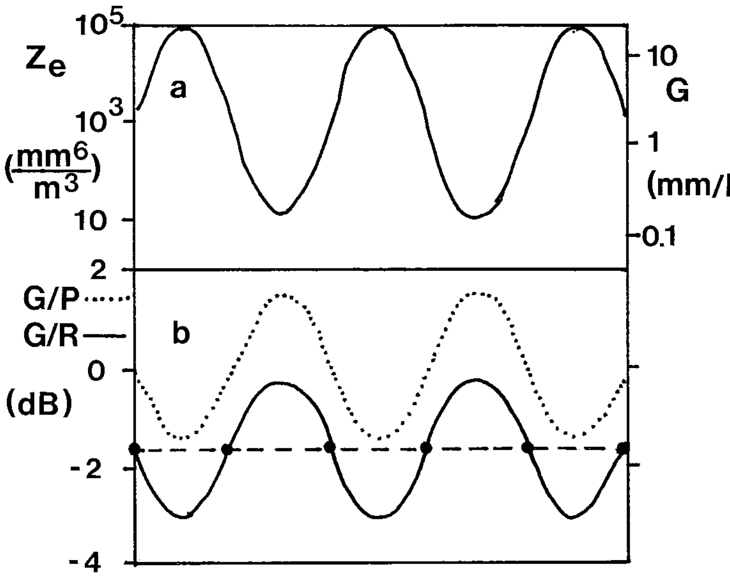

Fig. 2. The effect of gauge adjustment of radar rainfall when an erroneous preselected $Z_e - R$ relationship has been applied.

a. Analytical distribution of Z_e and respective rainfall intensity if $Z_e = 340G^{1.8}$ (showers in Finland) in an arbitrary horizontal direction.

b. Radar rainfall error (dB) before, continuous line, and after, dotted line, adjustment by raingauges if $Z_e = 200R^{1.6}$ (continuous rain) is applied to radar measurements. Large dots show locations and values of gauge-radar comparisons, and the broken line the objectively analyzed value of adjustment factor $\tilde{F}$.

A preselected $Z_e - R$ relationship easily causes errors of up to 2–5 dB (Atlas and Chmela, 1957) if the type of rainfall varies over the measurement area (which is a common situation). Statistically optimized relationships do not diminish radar rainfall error until the integration time is at least one month (Smith and Cain, 1983). Drop size distributions vary rapidly in space and time, increasing the small scale variance of observed F values thus making the representativeness of single gauge-radar comparisons less reliable. Figure 2 demonstrates the effect of a gauge-radar adjustment on an erroneous preselected $Z_e - R$ relationship if all other errors are insignificant. In spite of the bias rejection from radar rainfall measurements, gauge adjustment even causes increased errors, *e.g.* the error at points of the lightest rainfall is 0.2 dB and 1.5 dB before and after the adjustment respectively. It can be concluded that typically the gauge-radar adjustment removes the bias caused by an erroneous average $Z_e - R$ relationship (Brandes, 1974) but at single radar measurement points errors may increase. Only if the decorrelation distance

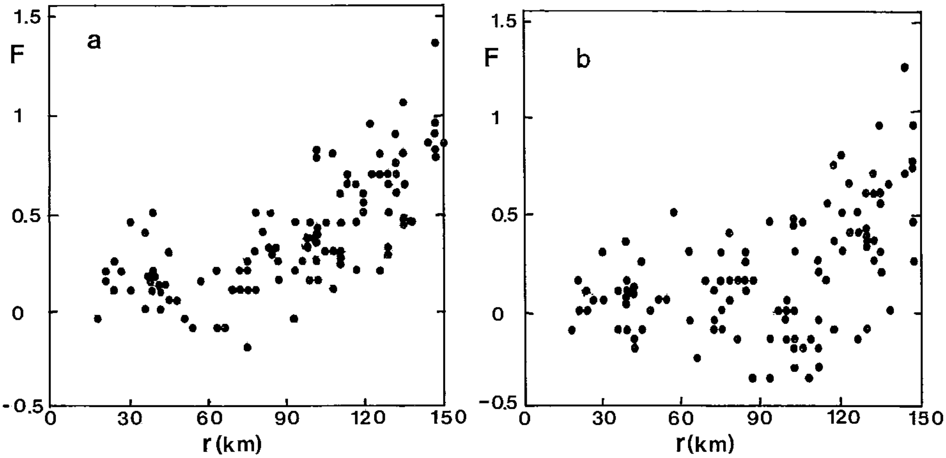

Fig. 3. The effect of rainfall attenuation on log gauge-radar ratio, daily rainfall Aug. 31, 1978, as a function of range (km).
a. Without attenuation correction.
b. With attenuation correction.

of F-values is larger than the gauge spacing (KOISTINEN and PUHAKKA, 1981) or if we have a dynamical justification for spatial F-variations (COLLIER *et al.*, 1983) is it possible to eliminate local radar rainfall errors.

With short wavelengths attenuation (or invalid attenuation corrections) can be a severe source of error (HITSCHFELD and BORDAN, 1954). Figure 3 shows daily log gauge-radar ratios as a function of radar range in a widespread rainfall situation (mean intensity 1–3 mm/h) with and without an attenuation correction. The wavelength is 3.2 cm and the correction has been calculated according to BATTAN (1973). The mean log ratio $\langle F \rangle$ decreased from 3.8 dB to 2.0 dB when the attenuation correction was applied.

The most serious differences between gauges and radar arise from errors ΔD, ΔV and ΔS in equation (12), *i.e.* the fact that the radar sampling volume is considerably larger than that of a gauge and that the radar pulse volume is located above the ground. COLLIER *et al.* (1983) show that low-level orographic enhancement below the radar beam easily leads to differences of 6 dB between gauges and radar. The effect of the bright band can be even stronger (SMITH, 1986). SCHAFFNER *et al.* (1980) have found reflectivity gradients in the radar measurement volume which caused a bias of 3–10 dB (log receiver) in showers and thunderstorms. When strong gradients occur, small variations in choosing the radar measurement bins representing a gauge can lead to 5 dB differences in mean hourly gauge-radar ratios (KLAZURA, 1981). Figures 4 and 5 show the effect of

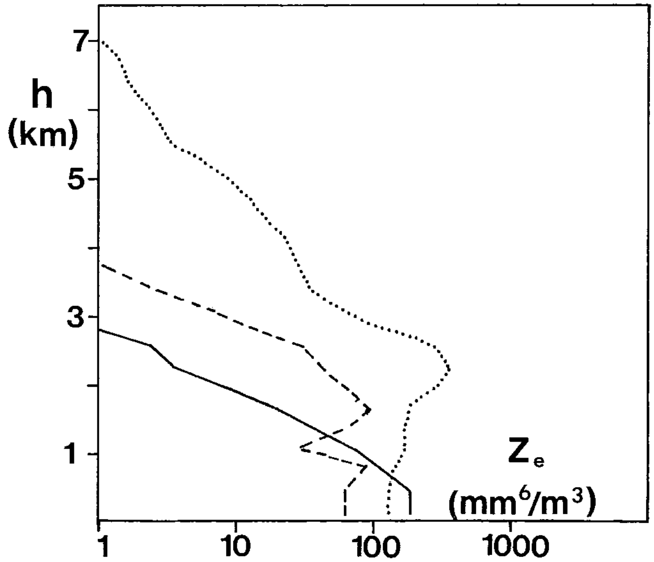

Fig. 4. Mean daily profiles of the radar reflectivity factor Z_e as a function of height *h*. Continuous line 27 Sep. 1978, dashed line 7 Aug. 1978 and dotted line 27 Aug. 1977.

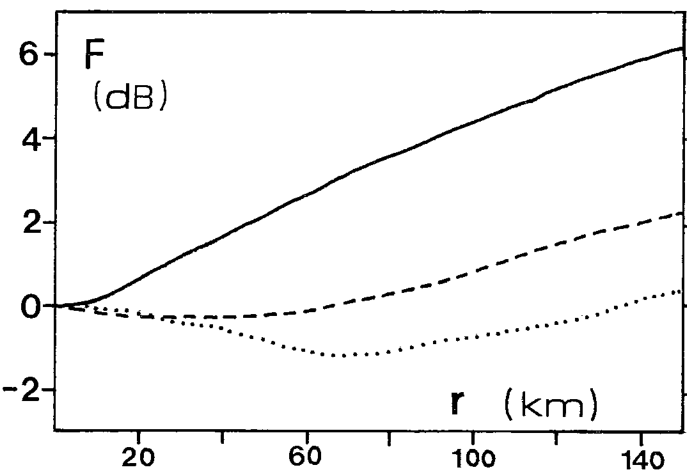

Fig. 5. Gauge-radar rainfall ratio (dB) as a function of radar range based on the vertical (horizontally homogeneous) reflectivity distributions in fig. 4, beamwidth 1.75° and 1° elevation angle.

inhomogeneous beam filling and beam overshooting of scattering particles. Figure 4 presents examples of daily mean vertical radar reflectivity factor distributions. It can be seen that beam overshooting and the bright band cause similar range variations in F as in fig. 3.

5. *Conclusions*

The gauge-radar comparison, which at best is performed using $\log(G/R)$ values, may reflect several errors in radar rainfall measurements. However, in typical measurement situations it is difficult to split an observed gauge-radar ratio into parts having different physical causes. So if we search for a correlation between a precipitation parameter and gauge-radar comparisons (*e.g.* parameter a in disdrometer-measured $Z_e - R$ relationship and F) the lack of such correlation does not prove that such a relationship does not exist. On the other hand one has to be critical when interpreting gauge-radar ratios as the result of one physical reason, *e.g.* calibration error. This follows from the large simultaneous errors caused *e.g.* by the variation of $Z_e - R$ relationship, beam overshooting, rainfall reflectivity gradients and attenuation, which exceed the effect of the calibration error. Consequently rain gauges cannot replace an accurate conventional electrical calibration, which is desirable when meteorological reasons for gauge/radar ratios are being sought after.

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