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THE INFLUENCE OF VERTICAL AIR VELOCITY ON THE REMOTE MICROWAVE MEASUREMENT OF RAIN

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ABSTRACT

Atlas and Ulbrich showed a close theoretical relation between gauge-measured rain-rate and 1 cm microwave absorption; and other remote techniques for potentially accurate rain estimation have been developed. More recently, Ulbrich cast doubt on the absorption relation, suggesting an important influence by vertical air velocity. This paper uses a mass-continuity argument to show that over flat terrain vertical air velocity has no influence on the relation between gauge-measured rain-rate and rain-rate remotely sensed aloft, although it introduces a discrepancy between the area of the rain sensed aloft and the area of surface rainfall. Thus point rainfall may be correctly estimated, but areal rainfall will be erroneous where rain falls systematically in significant convective updrafts or downdrafts.

This conclusion affects all remote techniques for rain estimation, whether ground or satellite based, although techniques incorporating continuous raingauge calibration may be excepted. Evidence of agreement with gauge measurements cannot be taken as evidence that any technique will estimate rainfall correctly, unless (averaged) vertical air velocity effects can be accounted for.

1. Remote rain measurement techniques

Over the years remote methods of rain measurement have been developed that claim potentially high accuracies, although these often cannot be demonstrated because of practical limitations.

The relation between rain-rate (R) and radar backscatter coefficient (Z) worldwide is uncertain to within an order of magnitude (Battan, 1973; Atlas, Ulbrich and Meneghini, 1984), at least partially because of the variation in rain drop size distribution (DSD). The least inaccurate Z-R radars use long (Rayleigh scattering) wavelengths near 10 cm where atmospheric and rain absorption is small. For carefully calibrated 10 cm radars, using a Z-R relation adjusted locally using raingauges, and with substantial temporal and spatial averaging, Wilson and Brandes (1979) concluded that radar measurements of areal rainfall are accurate to within a factor of two about 75% of the time.

Large rain drops adopt a flattened shape compared to the spherical shape of small droplets, so some DSD information is available for a near-horizontal radar beam from the relative intensities of vertically and horizontally polarised backscatter. This may be used to improve the Z-R relation for the actual rain being observed, so that measurement scatter for rain falling in still air can be reduced. Relative intensities may be measured either as ratios of left- and right-handed circular polarisation backscatter from a left-handed circular transmission (Moninger et al, 1986; Kropfli et al, 1986), or as a direct differential (dB) reflectivity for horizontal and vertical polarisation - the so-called Z_{DR} technique. Goddard and Cherry (1986) compared Z_{DR} measurements with disdrometer and rapid-response rain gauge data for a volume 200 m above the ground-based instruments. If DSDs were assumed to fit the gamma distribution (Atlas and Ulbrich, 1982) which is now generally accepted, their results can be interpreted (Atlas, 1986) as having a bias error equivalent to a 1 dB calibration error - which can be accounted for in future measurements - and a root mean square error of 15%.

Radar systems for satellite-based rain observation cannot use differential backscatter techniques as a nadir pointing instrument cannot observe a raindrop's side section. Furthermore, space payload limitations preclude high-resolution 10 cm antennae, so that shorter and more attenuating wavelengths must be used. Fortunately, the near-vertical path lengths of absorbing precipitation are much shorter than those for ground-based systems, so absorbing wavelengths as short as 0.86 cm are feasible.

Atlas and Ulbrich (1977) - hereafter designated AU - showed that near 1 cm wavelength the relation between microwave Mie attenuation and still-air rainfall-rate was fortuitously constant when averaged over short regions of the important raindrop diameter range 0.02-0.4 cm. Thus the relation between R and microwave attenuation (A) should be reasonably independent of DSD near this wavelength. They used many disdrometer measured DSDs to calculate A-R relations, and fitted power-law curves to the resulting scattergrams. The best fit occurred at 0.86 cm wavelength for a nearly linear relation, with a scatter of 8.8%. AU claim that if 0.86 cm Z data was also available, the improved DSD information reduces A-R scatter to 5%. Useful, although less impressive, results were claimed for longer wavelengths - eg. 20% A-R scatter from a somewhat non-linear curve at the less attenuating 3.22 cm wavelength.

NASA (1987) propose satellite-borne radars, operating at 14 or 16 GHz and 35 GHz (0.86 cm), for low-latitude rain measurement, especially over the ocean, similar to the aircraft measurements by Meneghini Nakamura et al (1986). The techniques include measuring the intensity of radar pulses backscattered at nearly vertical incidence off the ocean surface through the rain. This measures the attenuation through the path-integrated rain-rate, while the rain path-length is ascertained by range-gating. This paper will not discuss the many formidable obstacles to achieving accurate results, but in principle vertically-averaged rain falling in still air is measureable through absorption with a potential accuracy of 5-8.8% as suggested by AU.

An alternative technique for satellite rain estimation over the ocean monitors the microwave sea-surface brightness-temperature. At 10-35 GHz ocean emissivity is approximately 0.4, so the brightness-temperature observed without rain is low. As rain-rate increases the measured radiation is calculated from the radiative transfer equation for the upwelling radiation to the radiometer from the absorbing (and thus emitting) rain, and the upwelling radiation from the ocean surface. The latter now includes a partial reflection of the downwelling radiation to the surface, which itself originates from rain emission in front of a cold space background. At low precipitation (microwave) optical depth the increase in brightness-temperature is proportional to the amount of absorber present. As the optical depth increases, the surface becomes invisible through the absorbing precipitation, and the temperature seen is that of the precipitation itself; at even greater optical depths only the cold precipitation top can be viewed. Thus, as rain-rate is increased from zero the brightness-temperature initially increases linearly with absorber amount, then saturates and starts to fall. Wilheit (1986) suggests that over the oceans passive microwave measurements are essentially attenuation measurements that can be very closely related to the rain rate independently of the details of the drop-size distribution. The many practical problems in passive rain estimation will not be discussed, but on this basis if rain-depth is measured or estimated then in principle we can estimate (still-air) vertically-averaged rain-rate with the low scatter potential of absorption methods.

Thus, provided biases due to radar calibration, beam-filling problems, bright-band and cloud absorption effects can be eliminated, and growth or evaporation effects modelled, then in principle rain can be estimated remotely to 5-15% by absorption or dual-polarisation backscatter techniques. This high potential accuracy fails to take into account the subject of this paper - bias through vertical velocity of the air in which the rain is falling - which may cause factor of two errors in rain estimation for highly structured rain systems.

Section 2 of this paper uses a mass-continuity argument (after Kessler, 1969) to show that over flat terrain vertical air velocity has no influence on the relation between surface-gauge measured rain-rate and rain-rate remotely sensed aloft, although it introduces a discrepancy between the area of the rain sensed aloft and the area of surface rainfall. Thus point surface rainfall may be correctly estimated, but areal rainfall based on the remotely sensed rain area will be erroneous where rain falls systematically in significant updrafts or downdrafts.

This conclusion affects all remote techniques for rain estimation, whether ground or satellite based, although techniques incorporating continuous raingauge calibration may be excepted. A corollary is that evidence of agreement with gauge measurements cannot be taken as evidence that any technique will estimate rainfall correctly, unless (averaged) vertical air velocity effects can be accounted for.

These mass-continuity implications have been overlooked in most of the recent literature. Ulbrich (1986) suggests that vertical air velocities (implicitly at the point of remote measurement) would explain certain experimental discrepancies between gauge and microwave-absorption measured rain. Section 3 examines Ulbrich's argument, and finds no credible evidence to refute the above mass-continuity conclusions. Section 4 highlights the potential magnitude of vertical velocity effects, and Section 5 discusses some comparisons between gauge and remote sensing measurements that may be misleading. Section 6 indicates how continuous gauge calibration can alleviate effects of vertical air velocity.

2. Quantified effects of vertical velocity

a. Introduction

Remote rain measurement is affected by non-zero vertical velocities at the point of sensing, as an updraft retains precipitation aloft for longer. This has been noted by numerous authors, including Battan (1976) who showed that the weighted still-air fall velocity of rain at 9 mm h^{-1} is 5.1-5.5 m s^{-1}, and that vertical velocities comparable with this would have a significant or even substantial effect on rain-rate (aloft). All rain measurements, whether via Z, A, or Z_{DR}, will be affected unless specific account has been taken of vertical velocity effects.

b. Mass-continuity constraints

Kessler (1969) section 14.C.3 discusses the implications of vertical air velocities for radar measurements. He considers a simplified steady-state description of precipitation concentration M kg m^{-3} falling over level terrain in which all drops have the same (negative) vertical velocity V m s^{-1} relative to incompressible air which has an upward vertical velocity w m s^{-1}. By definition, the rainfall rate R kg m^{-2} s^{-1} is given by:

$$R = -M(V + w) \tag{1}$$

Precipitation quickly adopts its nominal velocity relative to the air into which it falls (Kessler, 1969; Appendix A), so that the ratio of rainfall rates for parcels of precipitation at two altitudes in the same vertical column, one susceptible to remote measurement and the other at another level, perhaps the surface (Fig 1), is:

$$R_1/R_0 = (M_1(V_1 + w_1)) / (M_0(V_0 + w_0)) \tag{2}$$

If the precipitation is unaffected by microphysical processes, then $M_1=M_0=M$ and $V_1=V_0=V$:

$$R_1/R_0 = (V + w_1) / (V + w_0) \tag{3}$$

This argument could be refined by having different classes for narrow ranges of drop-sizes, and allowing mechanisms to exchange M between classes to allow for drop coalescence and shattering. Rain generation or evaporation could also be included. These additions are appropriate to a numerical model, but do not add to the present insight.

A remote measuring instrument estimates rainfall rate aloft assuming that $w_1=0$, so over-estimating in the presence of an updraft (Fig 1).

However, if a verifying raingauge is on level ground, then $w_0=0$, and (3) shows that the incorrect estimate of rain rate aloft will agree with the true rain rate when the packet of rain reaches the ground (Fig 1). This paradox exists because the precipitation adopts the convergence field of the air through which it falls, and the ascending (descending) air mass is forced to converge (diverge) horizontally to achieve zero vertical velocity at the surface, so that the embedded surface rain is spread over a smaller (larger) area than the rain observed aloft (Fig 1). Thus, although the point rain-rate estimate is correct, there will be an error in estimated areal rainfall corresponding to the error in measuring rain rate aloft (Kessler, 1969). This error corresponds to the factor $V/(V + w_1)$, as indicated in Fig 1.

In real rain the situation is more complicated, but the same broad conclusions hold. Where $(V + w_1)$ is zero (or positive) for an area of precipitation aloft, that precipitation must be ignored as it does not reach the ground (without first passing through the same level with a negative total velocity). For parcels of non steady-state rain the duration aloft and at the surface may be different, but the relative rainfall is obtained from the integral of (3) as long as the parcel space/time location is identified both aloft and at the surface. The same caveat holds for rain falling out of a sloping updraft. Horizontal wind shear may spread the rain area at all levels, but horizontal spreading maintains the integral of M times area (ignoring areas of positive total velocity), so that as long as representative measurements are available the above conclusions are unaltered.

c. Sloping terrain

Section 2b considered only flat terrain. In sloping terrain we have the further complications of measurement/definition of rainfall, and interpretation of w.

Conventional horizontal orifice raingauges measure "meteorological (point) rainfall". An instrument designed for sloping terrain has an orifice inclined parallel to the slope, and measures "hydrological (point) rainfall": Sharon (1980) discusses the relation between these instruments. If the rain volume collected by the inclined gauge is divided by the area of the gauge orifice projected onto a horizontal surface, the result is the "hydrological (point) rainfall per projected unit area" or HPR.

Consider an air parcel advected up a uniform and extensive upwind slope as depicted in Fig 2. In the absence of convergence, air everywhere within the parcel has zero vertical velocity with respect to the slope, and rain falling at -V with respect to the parcel air will exit the parcel base (onto the slope) to give an HPR calculated by (3) with $w_1 = w_0 = 0$. Poreh and Mechrez (1984) studied the combined effects of wind and topography on rainfall distributions. In the limiting case of terrain having a scale-length large compared with the characteristic scale-length of the rain-response to wind perturbations, then a uniform rain-rate in air with zero vertical velocity well above the hill (ie. no convergence at this level) results in the same uniform HPR on all parts of the hill (at the surface, where there is also no convergence).

The rain itself falls slowly with respect to a horizontal plane (following the rain), because of the vertical component of the upslope wind, as a suitable instrument would detect (Fig 2).

However, to obtain surface rain-rate one must subtract the surface "motion" $\mathbf{v}_0.\nabla\mathbf{h}$ from the w_1 aloft (where $\mathbf{v}_0$ is the surface wind-vector and **h** is the surface), which in the absence of convergence balances w_1. In practice one would need to know the relation between the measurement aloft and the wind/slope characteristics at the point where the rain will fall.

As the terrain and rain-response scale-lengths become comparable, the (smooth) three-dimensional air flow around the hill contains curved streamlines which imply accelerations, and these combine with the still-air fall velocities and inertial mass of (different sized) raindrops to deposit rain in a horizontal distribution which differs from that aloft (Poreh and Mechrez, 1984), so that (single point) raingauge readings may be misleading.

Thus, even if a remote-sensing rain-rate monitor has the capability of measuring vertical velocities, care must be taken in its interpretation near sloping terrain - especially near rugged terrain.

3. Discussion of a recent paper

a. Ulbrich's Argument

Ulbrich (1986) analysed Norbury and White's (1972) measured relation between radar attenuation and raingauge rainfall rate, and that of two other measurements, in the context of their agreement with the AU theoretical curve. Norbury and White's 35.8 GHz absorption measurement was made over a double-pass total path length of only 448 m at a height of only 5 m above the ground. Rain-rate was measured at four rapid-response raingauges evenly spaced at intervals of approximately 45 m. Three of the gauges were placed on top of 3 m poles, while the fourth was situated with its lip 0.5 m above the ground. Agreement between Norbury and White's measurement and AU's theoretical curve is good, although scatter is somewhat greater than AU suggest. Ulbrich (1986) notes that the low altitude of the measurements would inhibit vertical velocities, and that these measurements in UK summer showers were unlikely to be contaminated by large-scale organised vertical motion.

Ulbrich (1986) considered measurements by Anderson et al (1947) (hereafter AA), and Semplak and Turrin (1969) (hereafter ST) measured at 1.25 and 1.62 cm respectively, each of which indicate A-R relationships higher than AU theory by 40-60%. Ulbrich notes that an updraft of 2-4 m s^{-1} would reduce the fall-speed of a gamma-distributed DSD, reducing the rain-rate into agreement with the rain gauges; and that AA's low-scatter measurements were made on the upwind slope of Hawaii near Hilo in orographic rain. ST's measurements exhibited great variation, and the regression fit to most of their data produced an attenuation some 30% less than a theoretical curve based on Mie calculation and a Laws and Parsons DSD. However, the particular subset of ST's data that Ulbrich discusses gave an attenuation so high that no DSD would explain the measured A-R relation. ST and Ulbrich all highlight the fact that this rain occurred over a period associated with the passage of a cold front, and appear to accept the idea that a large scale organised updraft of the order of 1 m s^{-1} along the front reduced the rain-rate, giving the abnormally high attenuation coefficient.

b. Re-examination of the anomalous measurements

AA's measurements involved 9 gauges - 4 having a rapid 30-second integration period - over a 1950 m range, so that spatial resolution of the rain along the path may have been good. However, Ulbrich's (1986) argument that the upslope wind (in the absence of convergence) may have affected a correctly measured rain-rate is not consistent with the arguments of the previous section; in any case this explanation is weakened by AA's comments that winds were light.

Vertical velocities at the gauge sites may have been present through rain falling systematically within orographically initiated convective core updrafts. On flat terrain these updrafts are eliminated at the surface by low-level convergence. However, AA's measurements were made "on a lava flow, parallel to the mean wind-vector" with the receiver at 762 m and the transmitter at 853 m. This might imply siting on a ridge with sufficient exposure to permit convergence below the gauge level.

Orographic rain near Hilo may contain a high proportion of large drops, to 4-5 or even 8 mm diameter (Johnson et al, 1986). AU used power-law approximations to demonstrate attenuation independence of DSD, and these break down for large drops. However, Mie absorption for spherical drops of diameter greater than 5 mm falls below AU's power law, so attenuation coefficients should be reduced rather than enhanced. Large drops adopt a flattened shape, enhancing their attenuation of horizontally polarised radiation (and reducing attenuation for vertical polarisation), but this effect is small for Mie scattering (Oguchi, 1983). AA do not specify microwave polarisation, but it is unlikely that the overall attenuation coefficient will be significantly enhanced by any unusual preponderance of large drops.

Potential weaknesses in AA's experimental technique may have caused overestimation of the absorption coefficient. They describe "rain shelters" housing "funnel and graduate" gauges that were read manually in situ, and may thus have been exposed atop small sheds -

in turn atop a ridge. Heavy convective rain may have been associated with gusting, and horizontal winds generate an upward flow over obstacles that can carry precipitation over a gauge. For correctly exposed gauges 0.3-0.4 m above a flat terrain, Sevruk (1982) suggests that wind-field deformation loss can be up to 10%. For poorly exposed gauges the effect could be larger, although this would be alleviated by the large drops present in tropical rain. An additional 2% loss could be caused by splash-out.

AA's microwave beam-width was 7.5°, giving a 15 m half-width at the transmission path mid-point. Had they chosen a path over a substantially concave terrain to avoid multipath problems, the rain-fall lag between gauge and elevated attenuation measurement may not have been adequately considered. In practice, AA discuss time co-ordination in great detail (without mentioning individual gauge lags), and describe the terrain as having "a gentle slope", so the path slope was probably nearly uniform. Thus, AA may have suffered multipath interference between the direct path and a ground reflection as their antennae were mounted "in a small elevated shack" rather than up masts; indeed slight terrain concavity would enhance ground reflections through focussing.

The lava surface was covered with "saw grass and low brush" which they might have considered adequately rough to absorb incident radiation. However, once this vegetation is flattened and coated with streams of heavy rainfall, microwave energy incident at a grazing angle may have been strongly reflected. If the terrain were less than 2.5 m below the direct transmission, the path-difference between direct and reflected beams would be small over a sizeable portion of the terrain, giving a coherent sum even with diffuse reflection. With vertically polarised radiation, the received signal would be enhanced; but with horizontally polarised radiation the phase reversal on reflection would cause the received beams to interfere destructively, leading to a reduction in received energy and overestimation of absorption coefficient. Alternatively, a longer path-difference could give destructive interference with vertical polarisation. It is surprising that AA do not mention the microwave polarisation, nor discuss multipath precautions, so perhaps they were less than adequately aware of the potential problems. Absence of multipath can only be demonstrated by measuring the maximum received signal (as both transmitter and receiver azimuth and elevations are varied) as a function of transmitter or receiver height (over several meters) above the terrain. This excercise may have been difficult to carry out using 1947 equipment under tropical rain!

Multipath effects are difficult to predict precisely, but with a fixed installation could be fairly systematic and equivalent to a few dB - a 3 dB signal reduction is enough to over-estimate the coefficient by 50% at 25 mm h^{-1}, and by more at lower rain-rates. The rain-coating effect may be less at reduced rain-rates, and could be largely absent for the no-rain calibration. However, it is not clear whether this effect would be sufficiently systematic to produce AA's low scatter.

Section 3.a.'s explanation of the anomalous ST result depends on large-scale wind convergence rather than upslope winds, and merits some discussion.

ST's measurements were made over a 6.4 km path oriented along a north-west/south-east line with four rain gauges distributed along the path, each at a height of 7.6 m above the ground. Weather archives show that a cold front, oriented approximately north/south, and travelling at 9 m s^{-1} due east, occurred near the time that ST report a frontal barometric and wind-velocity pattern associated with their anomalous rain.

Consider the continuity equation for air, considered as an incompressible fluid, near a horizontal surface:

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z} = 0$$

where the symbols have their conventional meanings. Substituting finite differences, over an area where $\Delta x = \Delta y = 6400$ m, $\Delta z = 7.4$ m, $\Delta w = 1$ m s^{-1}, we have $\Delta u + \Delta v = 853$ m s^{-1}. Thus the surface wind speed must change by around 853 m s^{-1} in 6.4 km to account for an average vertical velocity of 1 m s^{-1} over an area of scale-size 6.4 km. Clearly, wind speeds of this magnitude did not occur, so updrafts of 1 m s^{-1} were not generated by large-scale convergence as suggested explicitly by Ulbrich, and implied by ST.

ST's experiment was conducted in New Jersey with the transmitter at Cliffwood, atop a hill 31 m above sea-level, and the receiver to the south-east close to the top of Crawford Hill, at 116 m. Between these sites, the terrain from Cliffwood slopes down to sea-level within 1500 m, and then generally rises, initially gently but increasingly rapidly up the side of the Mount-Pleasant range of hills to the Crawford Hill peak. ST note that the line-of-sight path had "good foreground clearance at both ends" - a desireable condition to avoid microwave multipath interference problems, but one indicating a terrain likely to introduce topographical effects on gauge measurements. During the period ST report a surface wind of up to 7 m s^{-1} from the west to north-west quarter, roughly along the measurement line and up the surface slope. Below the final 1 km of transmission path the surface gradient increases to around 1:11, so that significant local orographic (surface) updrafts could be created here.

It is possible that condensation from this updraft could enhance (feed - Browning et al, 1975) rainfall orographically within the unstable frontal region, so that some rain would be deposited preferentially on the upwind slope of the hill throughout the frontal passage. The last of ST's gauges was situated near the Crawford Hill peak, while the penultimate was located 2 km back along the line-of-sight well away from the steepest slopes. Thus some rain may have been concentrated within the region between these gauges, which would then underestimate the path-integrated rain, leading to an overestimated attenuation coefficient. A view more appropriate to the higher rain-rates would note that ST's path-averaged rain intensity was very high - especially during the five-minute peak during which the raingauges suggested a path-average of 45 mm h^{-1}. High rain intensities of short duration are usually associated with small areas, so the local rain-rate may have been concentrated within a 1 km or so portion of the path, implying rain-rates approaching 250 mm h^{-1}. At the implied intense levels of local convection, orographic enhancement by such a small hill would probably be insignificant, so the rain may have occurred anywhere along the path. A rain pulse of small horizontal dimensions centred anywhere between gauges would produce an overestimated attenuation coefficient, again explaining the disagreement with theory without involving direct effects of vertical velocities on remote measurements. ST themselves note that "From experience with the network, we have learned that the gauge spacing is somewhat too large to permit resolving the distance associated with some of the very heavy rain rates".

Thus both Anderson et al's and Semplak and Turrin's results are inconclusive, especially as the latter are exceptional, providing scant evidence that the AU relation should not hold over flat terrain provided that there is an adequate spatial sampling of accurate gauges. It is probable that many other direct microwave measurements made over long paths could be inconclusive for similar reasons.

4. Magnitude of vertical velocities

For measurement of rain to better than 10%, vertical air velocities must be known to around 0.5 m s^{-1}. Detailed analysis of likely updrafts is outside the scope of this paper, but an indication is given that updrafts may be significant.

Houze (1981a) presents an overview of precipitation structure from various sources. Within mid-latitude cold frontal rainfall, 2-3 m s^{-1} updrafts and downdrafts have been encountered. These are weak compared to the 16 m s^{-1} (or larger) updrafts found during the convective phase of Florida/Ohio summertime thunderstorms. Such intense convection maintains the precipitation aloft (although still measured by remote sensors), until a mature stage when both updrafts and downdrafts co-exist, and precipitation starts to reach the ground. At this stage a cross-section shows updrafts increasing from the ground to 2 m s^{-1} at 2 km, and 12 m s^{-1} at 6 km altitude. Houze (1981b) reviews GATE studies to give insight into tropical precipitation structure. Around 40% of tropical rain falls within broad-area "anvil" cloud with relatively small vertical velocities for this purpose. The remaining 60% is convective rain. Within isolated convective cells 1-3 m s^{-1} updrafts are typical of convective cores within the height-range 700-2500 m. The vertical velocity structure of the convective region of tropical squall lines exhibit intense updrafts - perhaps 10-15 m s^{-1}. These carry precipitation aloft to a region of evaporative downdraft - of perhaps 4 m s^{-1} - behind the squall front.

5. Interpretation examples in remote rain measurements

From Section 2 we see that in the presence of updrafts it is possible to get good agreement between remote measurements of rain-rate and a verifying raingauge on flat terrain under the measured rain aloft, and yet incur dramatic errors from the same type of remote measurement when estimating areal rainfall because the rain area is wrongly estimated by the remote measurement. This has important consequences for the interpretation of accuracy claims for the remote measurement of rain, and for the design of future rain measuring systems.

Wilheit et al (1977) report a comparison between radiometers operating at 19.35 GHz and 37.0 GHz (0.81 cm wavelength) and two types of "conventional" ground-based rain gauge. The radiometers were ground-based, oriented at 45° zenith angle, sensing emission from rain falling below the known freezing-level of 4 km. The results from periods when the rain rate and brightness-temperature measurements were steady for periods of two minutes or more were theoretically re-interpreted in terms of a satellite-based radiometer making nadir passive microwave measurements through constant-temperature rain over the ocean (although the properties of this theoretical ocean would be accurately known). The results showed discrepancies of only 30-40% between the directly measured rain-rate and the theoretically interpreted brightness-temperature "measurements" within the rainfall rates of 1-20 mm h^{-1}.

A ground-based radiometer looking (nearly) upwards makes a small-area "point" measurement comparable with a "point" raingauge measurement, so agreement should be achievable. However, upward- or downward-pointing radiometers deduce a mean rain-rate between the surface and the freezing-level, representative of an altitude where vertical velocities might have developed. Thus, the extent of the areas of rainfall observed by a high spatial resolution satellite-based 10-35 GHz radiometer would not correspond with the areas of surface rainfall if these fall systematically in convective up- or downdrafts, and poor areal rainfall estimates would result. In practice, satellite-based 10-35 GHz radiometers suffer from poor spatial resolution compared with rain-cell dimensions, but the same result would hold - to be compounded with further errors if there was a non-linear relation between high-resolution rain amount and brightness-temperature.

Wilheit et al (1977) also discuss a comparison between the 19.35 GHz Nimbus 5 Electronically Scanning Microwave Radiometer (ESMR) data over the oceans off the west coast of Florida and a ground-based WSM-57 active radar at Miami. Unfortunately agreement here is only within a factor of two because of various practical problems discussed in their paper. However, had it been possible to match active radar and passive radiometer measurements at some altitude representative of the height-averaged vertical velocity, and so perhaps obtain agreement, either measurement would have given a potentially unrealistic representation of the area of the surface rainfall, and so introduced errors in areal rainfall. The same argument would hold for active measurements of path-integrated rain-rate obtained through backscatter off the ocean surface.

In principle active satellite-based rain radars can monitor rain close to the surface by range-gating. This could solve the problem of eliminating vertical velocities, and also eliminate virga effects. In practice there are difficulties in achieving measurements close to the surface, and resolution of the order of 1 km may be all that is achievable. This is a large enough altitude to develop vertical velocities.

Conventional ground-based rain radars usually have practical difficulties in making rain measurements at low altitudes because of the terrain and because of radar side-lobes. Thus measurements are made aloft, and areas of surface rain may be erroneously estimated where rain falls systematically in an updraft or downdraft. This difficulty would also apply to Z_{DR} radars, in spite of their claimed high accuracy, unless systematic vertical velocities are insignificant.

6. Calibration by raingauges

One might anticipate that rain gauge calibration would automatically eliminate bias problems, although the misleading agreement discussed above suggests caution. Consider a hypothetical radar to be calibrated against a rain gauge; assume the radar senses rain only at altitudes above the gauge where significant vertical velocities may have developed, and that the idealised rain of Section 2.c. occurs:

The operator may wait until both radar and gauge show steady readings, and then calibrate. Although this may demonstrate the excellence of the radar's gain and the accuracy of the previously estimated DSD, (3) indicates incorrect calibration for the rain-rate aloft, so that areal rainfall (based on multiplying radar-measured rate, area, and duration) would be erroneously estimated, perhaps by a factor of two for a 4 m s^{-1} updraft.

Alternatively, the calibration might equalise integrations of radar and gauge readings over a time - say one hour - during which an entire rain-cell might cross the gauge and corresponding radar measurement point. If the updraft halves the elevated rain-rate, then the surface rainfall area would be half of that aloft. Each sensor would observe steady rain, but on average the gauge would observe rain for half the radar's duration. On average, equalising the hourly integrations would then calibrate the steady radar reading equivalent to half the steady gauge reading, thus correctly accommodating the updraft. This calibration would be invalid for rain away from the gauge with a more tilted convective structure and rain falling in a downdraft, but provided structures are reasonably homogeneous over the area calibrated by each gauge, and the integration period is appropriately chosen, then updraft effects should be alleviated. Permanent calibrations are inappropriate, and an adequate density of physical raingauges must be available to update the variable calibration as necessary.

In practice "steady reading" calibration techniques are inapplicable, as rain is inhomogeneous, exhibits lag between elevated and surface measurements, and suffers wind-sorting and other problems. Thus long-period averaging (perhaps by filtering rather than by integration) is incorporated by default into systems that include gauges to compensate for orographic effects below the radar beam. The result is that updraft effects are alleviated provided the gauge network is adequately dense (Collier, 1986).

Other remote measurement techniques could be calibrated using gauge data, although they are often aimed at eliminating gauges by their increased complexity, or at wider (ie. satellite) coverage. Satellite measurements could be calibrated against radar "gauges", but these may be accurate - for the reasons stated above - only if they incorporate calibration through a network of physical gauges of adequate density to ensure homogeneous orographic rain structure between gauges. Satellite calibrations would be valid between the radar "gauges" only for synoptically homogeneous rain systems unless the satellite could estimate updraft velocities through direct measurements, or proxy measurements such as image texture.

7. Conclusions

Ulbrich (1986) has recently suggested that vertical air velocities may be important in the measurement of rain rate by microwave absorption techniques, and its comparison with raingauges. This paper suggests that vertical air velocities are important, but not quite in the way that Ulbrich suggested.

In any comparison of rain gauge data and remote measurement of point rain-rate, the vertical velocity of the air near the level where the gauge is situated must be taken into account. For gauges on a flat terrain this is zero, so that on average there should be no effect. For the rare situation of gauges sited aloft, some adjustment may have to be made. In practice it is difficult to make an adequate gauge measurement of rain-rate for comparison with the most accurate remote sensing techniques because of local effects of terrain, the non-uniformity of rain over the remotely sensed area, or instrumental problems.

If we consider rain that maintains a uniform mass concentration and fall-velocity relative to still-air throughout its descent from the remotely sensed point to the surface, then vertical air velocities present at the point where rain is sensed can cause the rain aloft to cover an area different to that covered at the surface. This gives rise to a 10% error in areal rainfall where rain systematically falls in modest convective updrafts or downdrafts of 0.5 m s^{-1} or more. Real rain may suffer complex microphysical changes, and size-sorting through wind-shear, but the above general effect of vertical air velocity is unchanged.

These conclusions impact on all remote rain sensing measurements which implicitly assume that rain falls in still air. This includes both ground-based and satellite-based measurements, even where raingauge data is used to calibrate the remote measurement, although in the latter case an appropriate form of continuous averaging can alleviate the problem.

Satellite-borne rain measurement techniques will have to measure, or model, vertical air velocities if they are to make precise measurements of areal rainfall over flat terrain. Over sloping or rugged terrain the problems are considerably enhanced, and the details of topography and three-dimensional winds would have to be known. A study of the climatology of updrafts associated with rainfall, particularly over the tropical oceans, would be of great value to future remote sensing of rain, especially from satellites.

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FIGURE CAPTIONS

Fig 1. Steady-state rain of uniform density M kg m^3 and still-air fall-rate $-V$ m s^{-1} descends in a sharply-bounded area A m^2 through an updraft w m s^{-1} associated with low-level convergence. By definition, point rain-rate $R = -M(V+w)$. If a remote instrument measures M, V, but assumes $w = 0$, then its measure of point rainfall aloft (R_r) agrees with surface point rainfall (R_0). In the steady-state, $A_1R_1 = A_0R_0$, so $A_1/A_0 = V/(V+w_1)$. Thus the remote instrument over-estimates the rain-area in the presence of an updraft, giving an erroneous area rainfall.

Fig 2. A uniform parcel of air containing rain (density M, still-air fall-rate $-V$) is advected up a (large, uniform) slope by winds with horizontal velocity vector $\mathbf{v_0}$. Rain exits the parcel base - onto the slope - at rate $M(V+0)$, giving a hydrological point rainfall per projected unit area (HPR) of $-M(V+0)$. A remote sensor capable of measuring rain vertical velocity relative to a horizontal surface would erroneously include the upslope wind $\mathbf{v_0}.\nabla\mathbf{h}$, unless it could also measure horizontal velocities and so calculate the upslope wind.

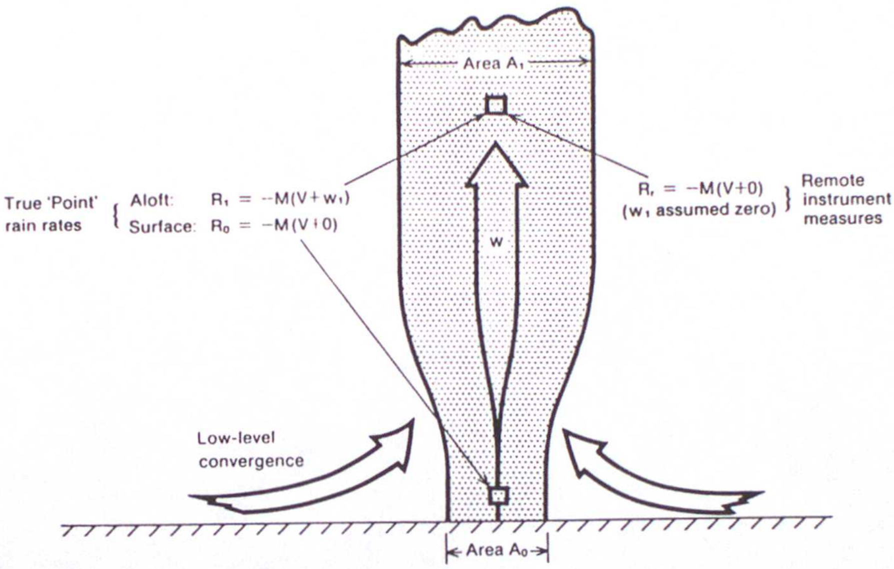

Fig 1. Steady-state rain of uniform density M kg m^3 and still-air fall velocity $-V$ m s^{-1} falls in a sharply-bounded area A m^2 through an updraft w m s^{-1} associated with low-level convergence. By definition, point rain-rate $R = -M(V+w)$. If a remote instrument measures M, V, but assumes $w = 0$, then its measure of point rainfall aloft (R_r) agrees with surface point rainfall (R_0). In the steady-state, $A_1R_1 = A_0R_0$, so $A_1/A_0 = V/(V+w_1)$. Thus the remote instrument over-estimates the rain-area in the presence of an updraft, giving an erroneous area rainfall.

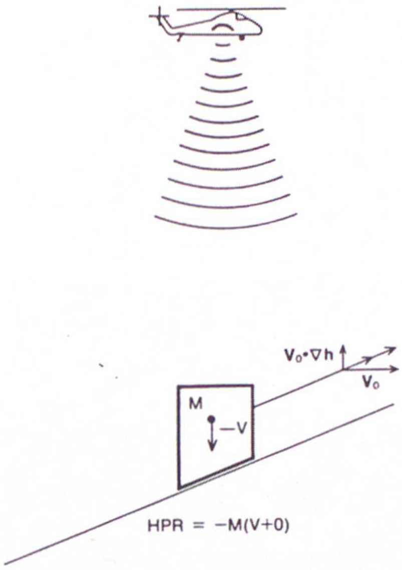

Fig 2. A uniform parcel of air containing rain (density M, still-air fall-rate −V) is advected up a (large, uniform) slope by winds with horizontal velocity vector $\mathbf{v_0}$. Rain exits the parcel base − onto the slope − at rate M(V+0), giving a hydrological point rainfall per projected unit area (HPR) of −M(V+0). A remote sensor capable of measuring rain vertical velocity relative to a horizontal surface would erroneously include the upslope wind $\mathbf{v_0 . \nabla h}$, unless it could also measure horizontal velocities and so calculate the upslope wind.