# The challenge for operational radars networks: To provide accurate rainfall rates with quantified errors.

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(acknowledgements to Rob Thompson (Reading),
Malcolm Kitchen, Tim Darlington (Met Office,
Pierre Tabary (MeteoFrance).

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## Rain rates must be accompanied by errors if they are to be used in NWP and flood forecasting.

Most important for the heavy rainfall events.

Need $1km^2$ resolution and quantified errors +/- x mm/hr.

WILL CONSIDER:

C-band radars (mostly)

Europe - small countries: $1^\circ$ beam: max range ≈100km

Fairly flat terrain - no big mountains.

Hourly or daily rainfall accumulations.

WON’T CONSIDER:

Snow at the ground. Tornado

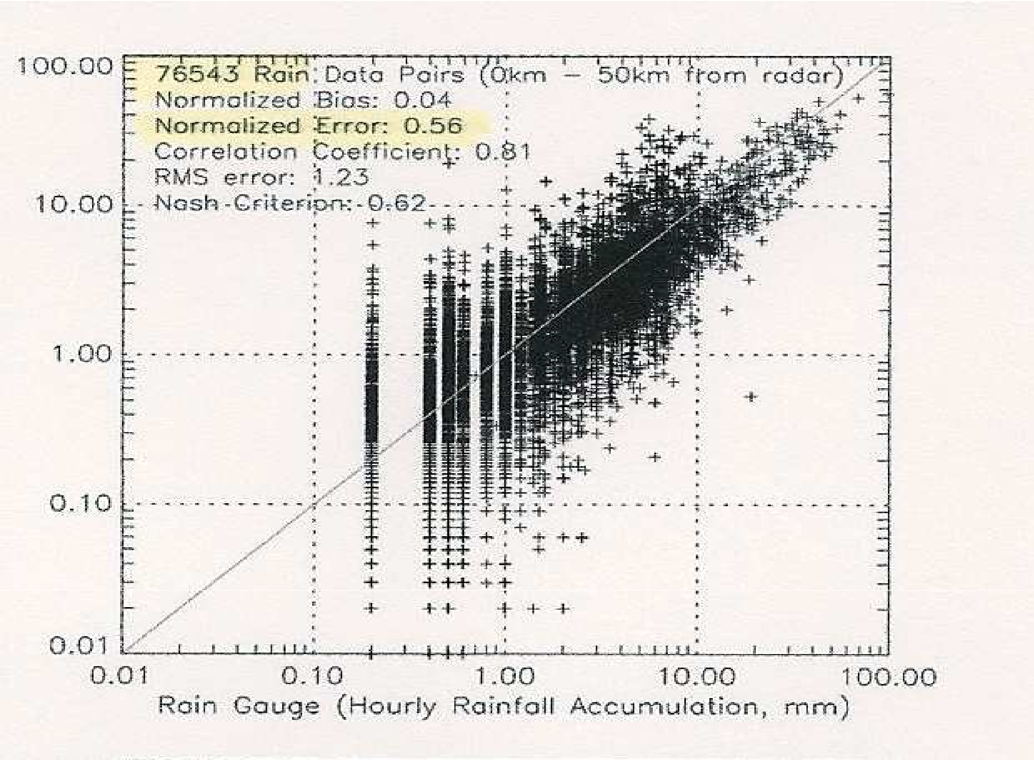
Low level orographic seeder-feeder growth - use LWC from NWP.

# ERROR SOURCES ARE WELL KNOWN.

**CLUTTER**
Z-R
**BEAM BLOCKING**
**VPR** - Vertical Profile of Reflectivity
ATTENUATION by heavy rain and radome
(C-band and especially X-band)
HAIL (Beamfilling?)

Comparison with gauges:
Gauge representativity?
Gauges well maintained?
Wind drift?

# S-band: Recent Measure of Performance: comparison with gauges




**France** - (Tabary et al, 2007)
- S-band, 300m gate.

NO ATTENUATION

27 wet days, hourly totals.
Gauges < 50km, (76,543 pairs.)
Freezing level - >1km:
BEAM IN RAIN
BELOW ANY BRIGHT BAND

FRACTIONAL ERROR: 56%
BIAS 4%

**So do we always quote a 56% error with hourly totals?**
**Where does 56% error come from???. Z-R variability???**
**'Adjust' Z every few hours/days 'for different Z-R'?**
**Is there a real physical reason for this?**

# C-band:  comparison with gauges

**France:  Figueras et al,  2012,  No bright band, Correct for attenuation using $\phi_{DP}$  removes heavy rain bias,  rms  errors still about 60%**

**Switzerland** - (German et al, 2006)    -  DAILY TOTALS >0.3mm.
SHORT 83m GATE
2004:   19 gauges (range <75km)  -  scatter in summer  ≈ 1.9dB
68% of days within a factor of 1.6        32% of days > factor of 1.6
40% of Switzerland - beam above 3.4km
for the whole country error 2.3dB (factor of 1.7)
2000:    error was 4dB   - factor of 2.5
Improvement due to improved clutter recognition, beam shielding, & VPR.
- Reduced the number of rejected clutter pixels by a factor of three.

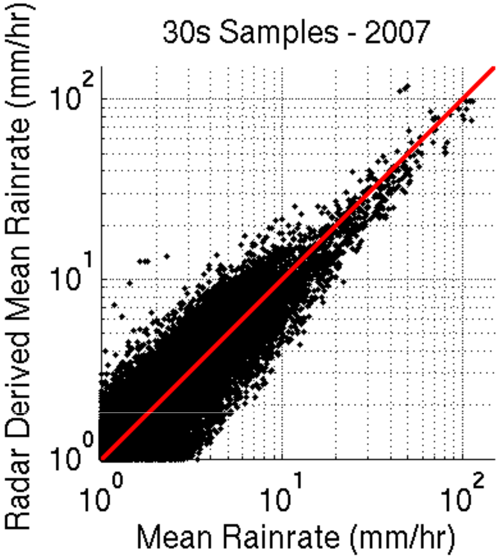
**USE A SHORT PULSE – more chance of finding clutter-free  gates**
**e.g.  75m pulse  not 300m   - sensitivity down by 16   (12dB)**
**Use polarisation to better separate clutter from precipitation.**

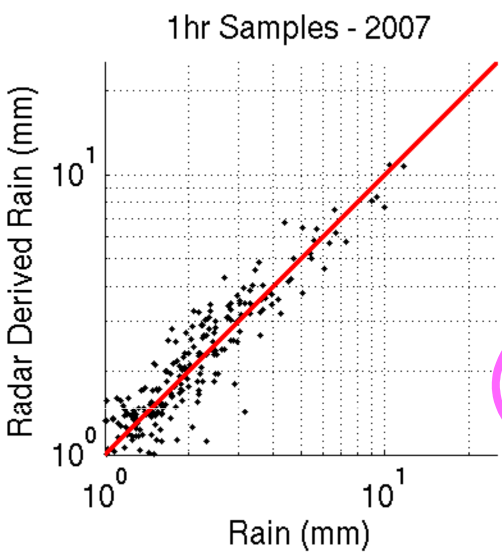
# Z-R errors – due to changes in drop size spectra?

## One year's disdrometer data – calculate Z and R from 30sec raindrop spectra

**30SEC RATE**

**MEAN FRAC ERROR 45%**



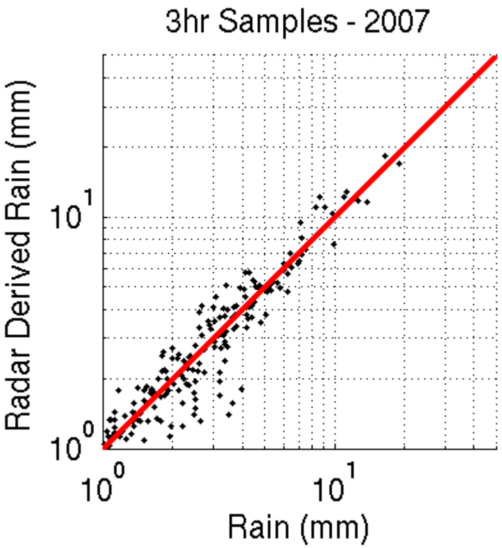



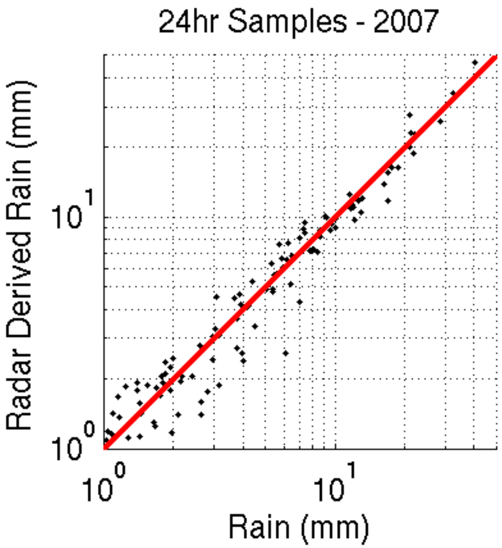

**HOURLY TOTAL**

**MEAN FRAC ERROR 25%**

**3 –HOURLY TOTAL**

**MEAN FRAC ERROR 25%**




**DAILY TOTAL**

**MEAN FRAC ERROR 23%**

# COMPUTE R, Z AND $Z_{DR}$ FROM DROP SPECTRA; FIND R OF EXPONENTIAL SPECTRUM WITH THAT Z & $Z_{DR}$ COMPARE WITH R DIRECTLY FROM THE SPECTRA.

**30SEC RATE**

**MEAN FRAC ERROR 30%**

**HOURLY RATE**

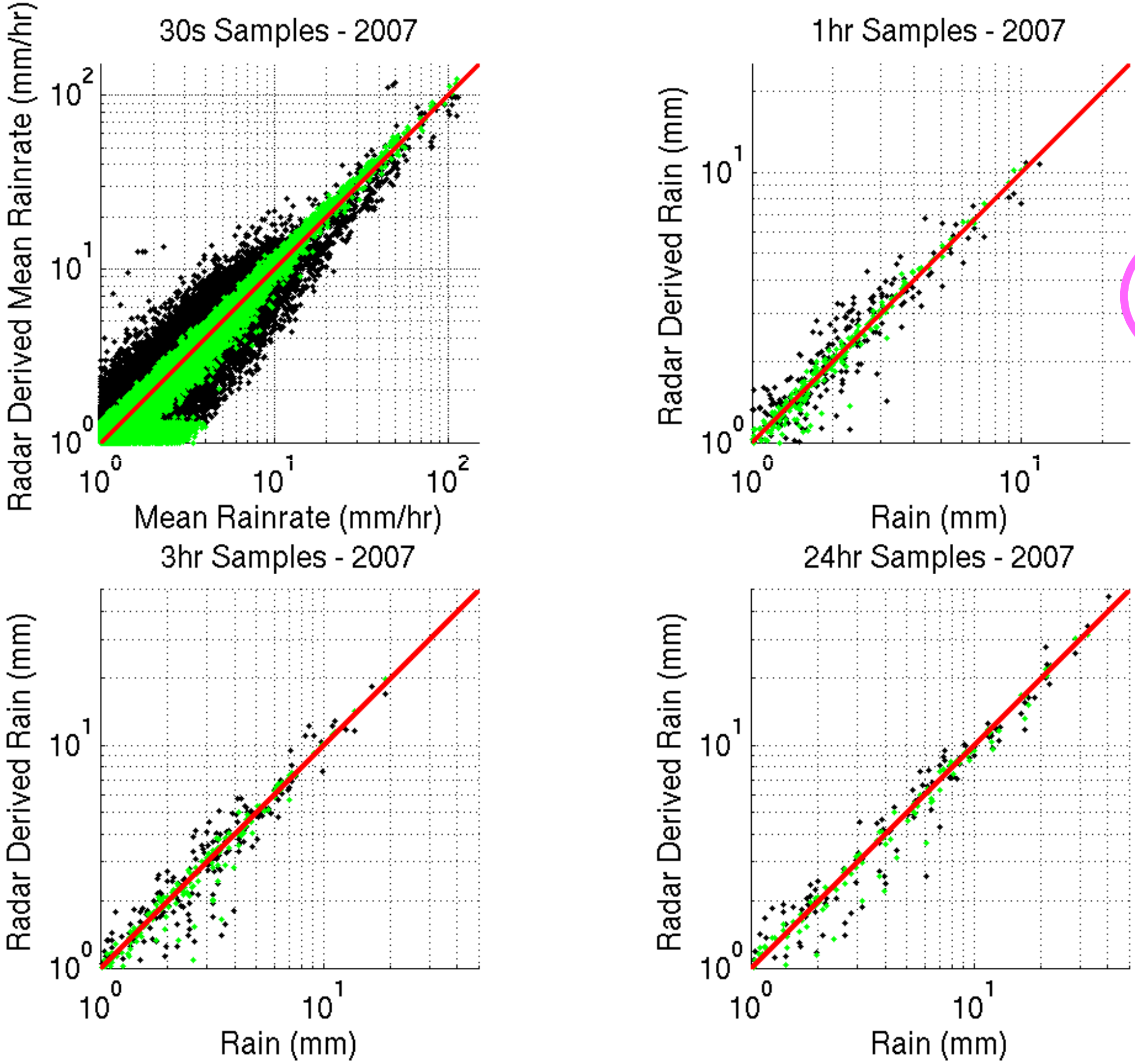
**MEAN FRAC ERROR 13%**

**3 HOURLY RATE**

**MEAN FRAC ERROR 15%**

**DAILY RATE**

**MEAN FRAC ERROR 13%**






13% error remains : spectra not a pure exponential or gamma function with $\mu = 3$

**From disdrometer computations we conclude that**

**a) Z-R:**

**Rainfall totals 30 seconds typical error 45%.**

**1 hour and daily typical error 25%**

**(Lee and Zawadski, 2005: 41% and 28%)**

**(The 60% hourly/daily error > than 25% Z-R error)**

**b) If we know the 'a' in Z-R from Z and $Z_{DR}$ then**

**30 seconds typical error 30%**

**1 hour and daily typical error 13%**

**But it seems we have 60% error from another source …**

**To use $Z_{DR}$ for better rain need it accurate to 0.2dB.**

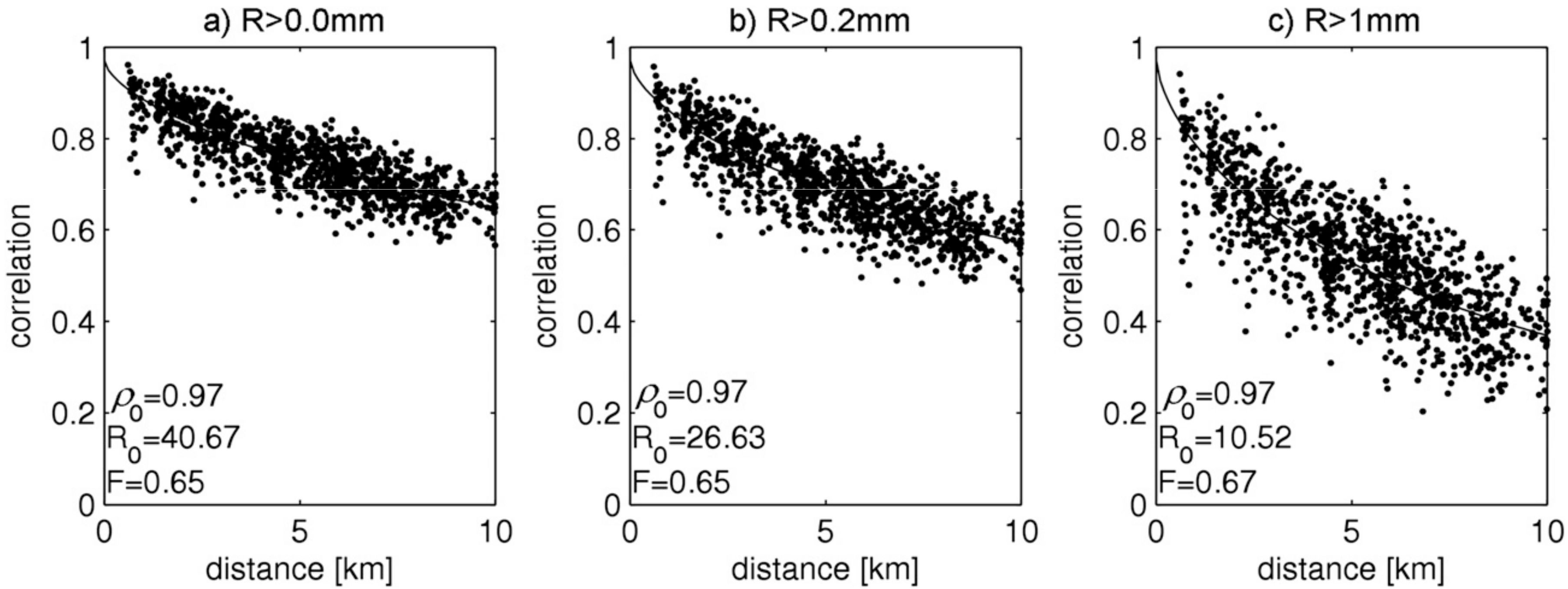
**Differential attenuation In heavy rain: $Z_{DR}$ several dB negative**

**–do we have a sufficiently accurate correction algorithm?**

# RAIN GAUGE REPRESENTATIVITY?

**Summary in Bringi et al (J of Hydromet, 2011)**
**HYREX - UK 1993-1997 49 tipping bucket gauges.**
**Two areas each of size 2km by 2km with eight gauges**

**SPATIAL CORRELATION OF HOURLY TOTALS**

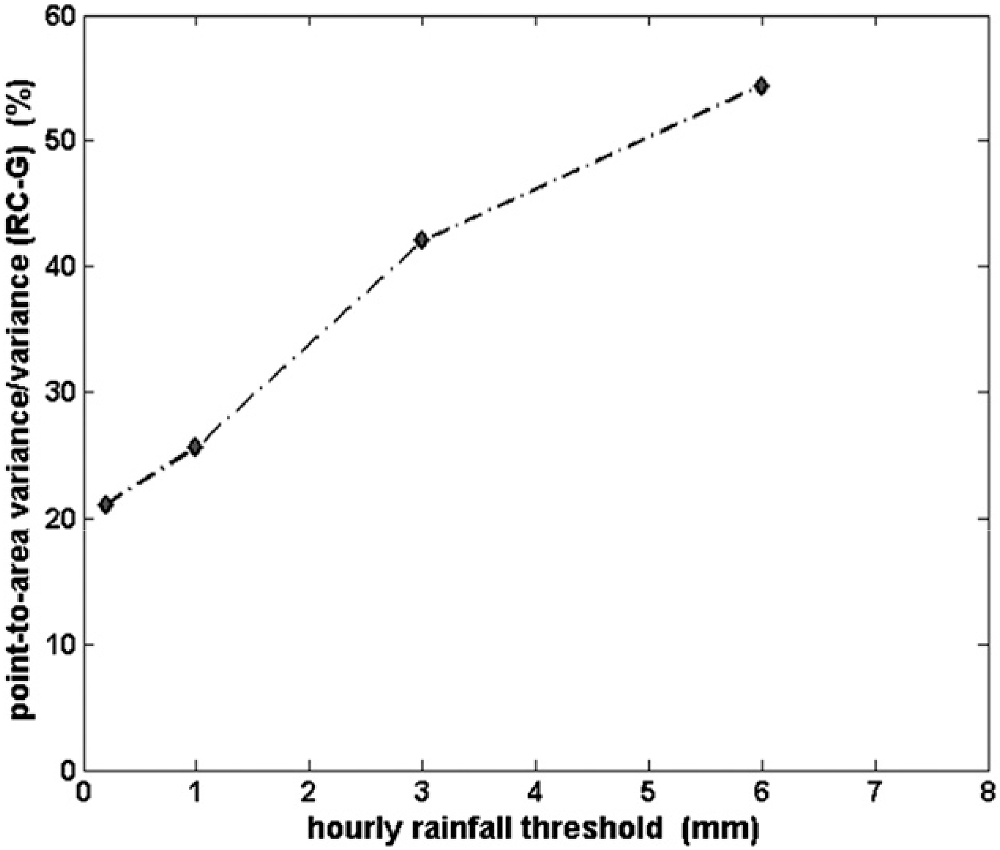



VARIES WITH THRESHOLD –
SHORTER CORRELATION DISTANCE FOR HEAVIER RAIN

FOR TOTALS >1MM DISTANCE OF 5KM CORRELATION ABOUT 0.5

# RAIN GAUGE REPRESENTATIVITY?

FOR AN AREA OF
2km by 2km




Plot: Ratio of the
point to area variance
to the
radar to gauge variance.
against rain threshold

For 1mm threshold
20% of
Radar/gauge variance
Is due to representativity

Rising to 55%
for 6mm/hr threshold

Le Bouar et al (2001) suggested that for a 4km by 4km area,
70% of the radar-gauge variance was due to gauge representativity!

# Does this suggest that gauge comparisons are virtually useless?

"55% gauge representativity errors for >6mm/hr for 2 by 2km area"

At 50km range beamwidth is 1km, so area should be < 2km by 2km?

But rather than sorting correlation distances by rain threshold, wouldn't it be more sensible to do it by the observed variability of Z, and establish a link between Z texture and gauge representativity error?

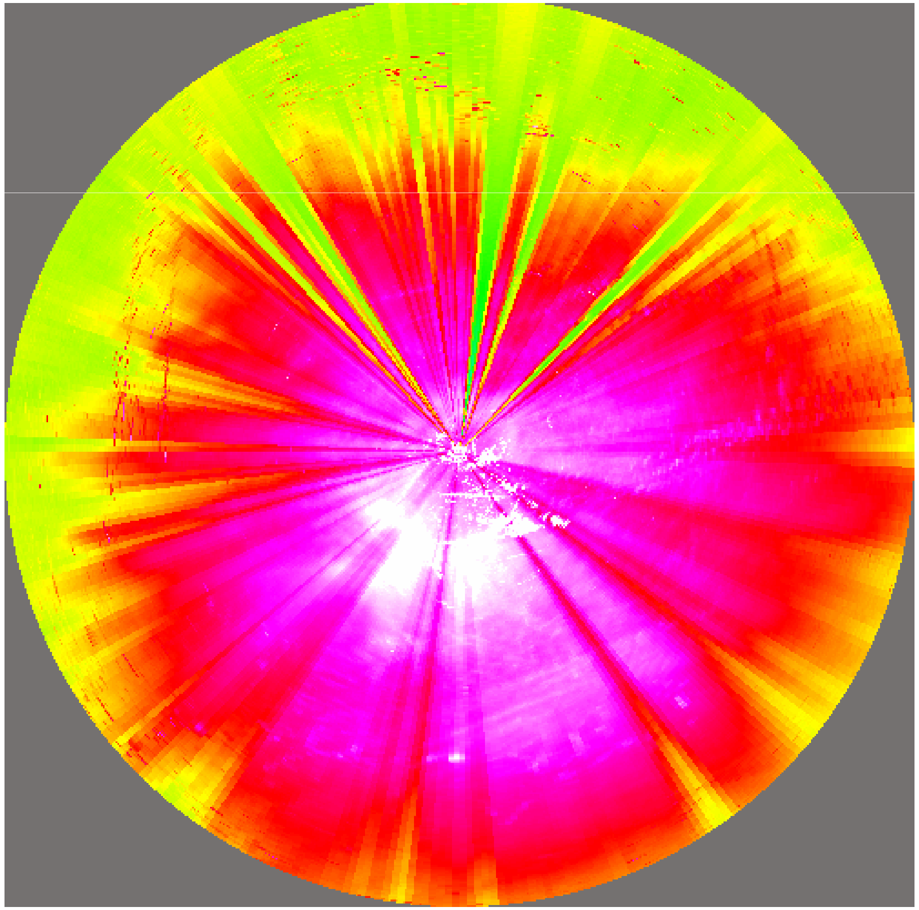
Sort the 75,643 S-band radar-gauge pairs by Z texture:
Is there a link with the size of the radar to gauge errors.
{Wind speed – for wind drift errors…}

**But it does suggest we have to be careful in interpreting radar errors from gauge comparisons.**

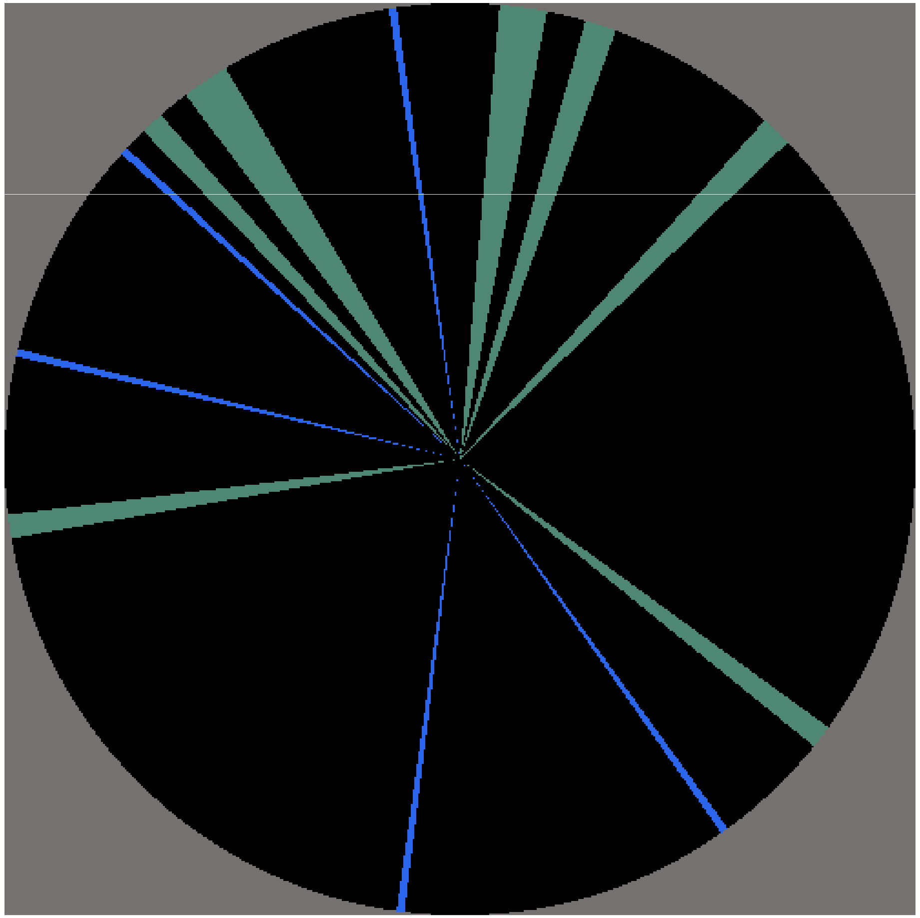
**What about another metric…..**

# BEAM BLOCKING:
# STATISTICS WHICH ARE RARELY SHOWN

**Integrated raw Z from lowest beam**
**10 days November 2010**
**Cluttered gates removed**



**Beam blockage derived from digital terrain map**



**Suggest: examine statistics of these integrated Z plots:**

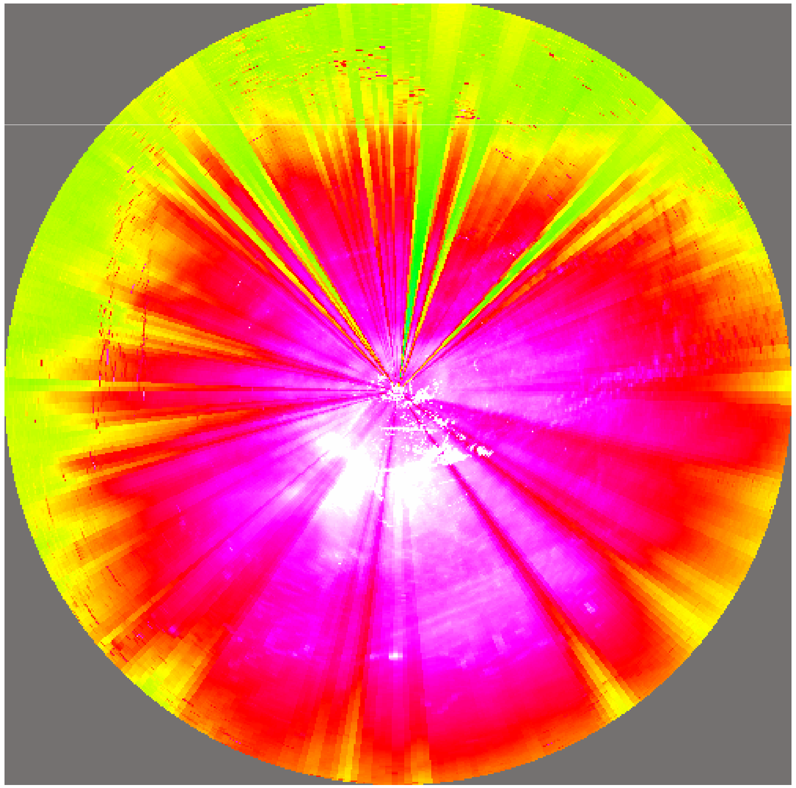
**The rain doesn't know where the radar is.**

**Spatial correlation of integrated Z totals should be isotropic.**

**Find azimuthal Z correction so correlations are isotropic.**

**Are these factors consistent? Do they change in time?**

**WILL THIS HELP TO QUANTIFY BEAM BLOCKING ERRORS?**



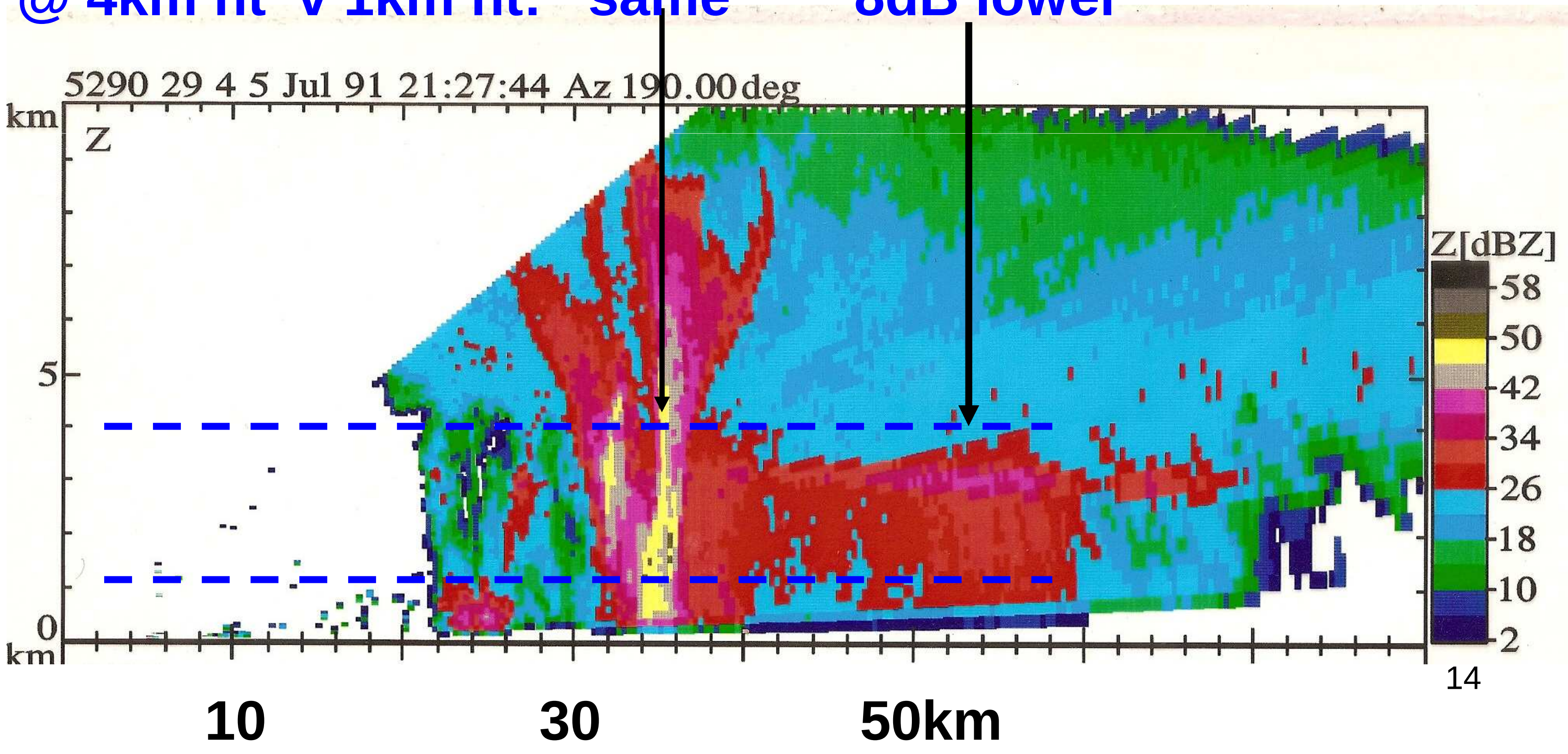
## VPR BRIGHT BAND: is variable in space and time.

**ONLY OBVIOUS FROM** High resolution RHI's :

The VPR is very variable in space and time and,

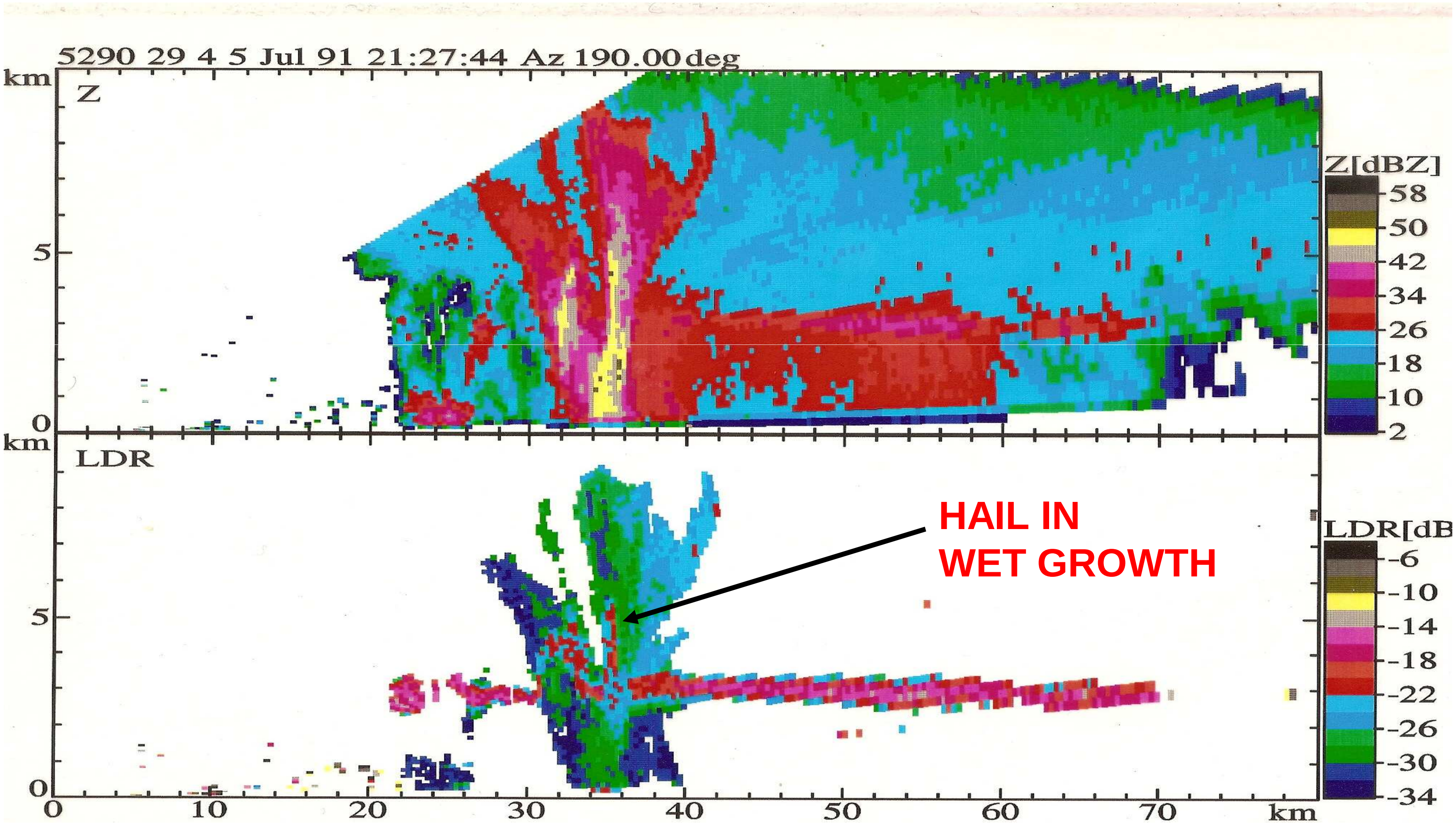
a mean profile OVER LARGE AREA AND TIME is not representative

**Z @ 4km ht v 1km ht: same 8dB lower**



# EMBEDDED CONVECTION: DIFFERENT VPR

RECOGNISE AND CORRECT FOR BRIGHT BAND USING HIGH LDR
EMBEDDED CONVECTION – LOW LDR – NO BRIGHT BAND.



# ATTENUATION.

**IDENTIFY RAYS ATTENUATED BY RAIN FROM THE HIGH VALUE OF $\phi_{DP}$.**

- Theory suggests that uncertainty over link between $\phi_{DP}$ and attenuation leads to errors of about factor of two in simple correction schemes.

- Just how variable is this coefficient in reality?

**Smyth and Illingworth (1998) suggested that total differential attenuation of a storm could be measured from the negative value of ZDR in the stratiform region behind the storm**

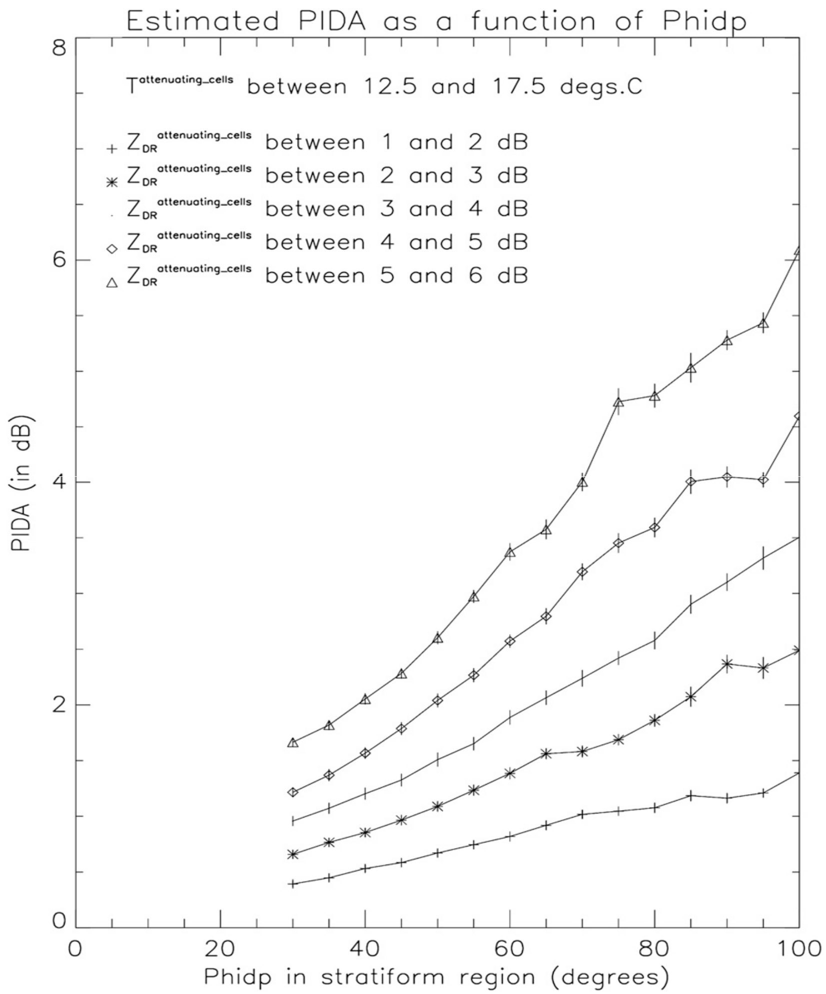
**- if no attenuation ZDR should be zero.**

**In fact this is a rare occurrence so of no use operationally, but the negative ZDR gives us information on the path integrated differential attenuation.**

**Differential attenuation should be about 0.3 of total attenuation.**

# PATH INTEGRATED DIFFERENTIAL ATTENUATION AGAINST $\phi_{DP}$ AS A FUNCTION OF ZDR (Tabary et al, JAMC, 2009)

**PIDA FROM -VE ZDR**




$\phi_{DP}$

**ZDR 5-6dB**
**6dB/100DEGS**
**Melting hail??**

**Vary by factor 4**

**ZDR 1-2dB**
**1.5dB/100DEGS**

**So wet hail has a KDP.**

# ATTENUATION

**ADDITIONAL CONSTRAINT TO FIX THE COEFFICIENT LINKING ATTENUATION TO $\phi_{DP}$.**

- Use emission as a constraint for total attenuation along the ray.
  Absorbers are emitters - attenuating rays will ‘glow’ at microwave frequency.
  From increase in noise on that ray - estimate total attenuation to <1dB.

- Choose coefficient linking $\phi_{DP}$ with attenuation so that the total attenuation agrees with the emission.

- CAN ALSO ESTIMATE RADOME ATTENUATION.

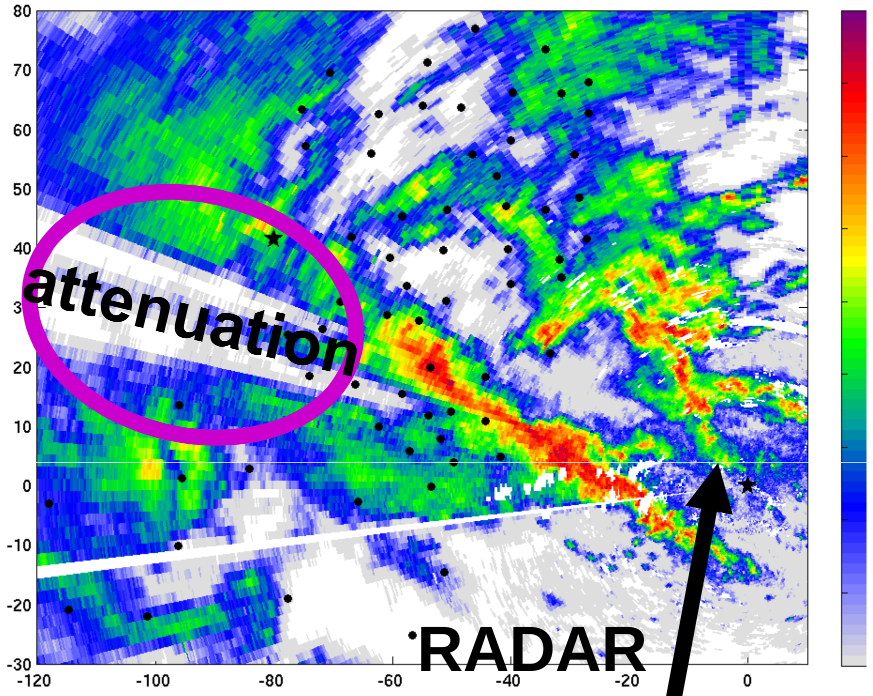
- ALSO CAN ESTIMATE DIFFERENTIAL ATTENUATION TO CORRECT ZDR USING THE BRIGHTNESS TEMPERATURES DIFFERENCE AT H AND V.

(TALK 8-A5, THOMPSON, WEDNESDAY 10AM)

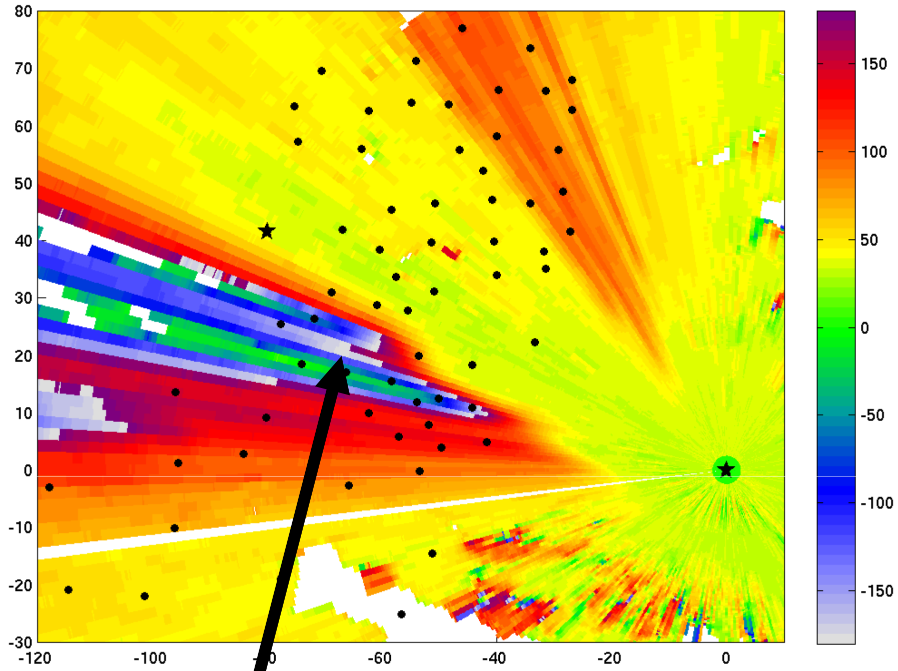
# BEAMFILLING PROBLEMS?

## Floods over London: 20 July 2007

**Z at 1043.**




**$\phi_{DP}$ at 1043**



200 degs phase shift: but how convert into an attenuation?

14 °/dB : 14dB of attenuation?

10°/ dB (Mie) 20dB of attenuation?

$Z_{DR}$ will be -5 or -7dB: Don't think we can correct to 0.2dB!

**Note: >** 50° change in phase shift from one ray to the next:
BEAM FILLING PROBLEM

## Dual polarisation radar - now being installed operationally in many European countries.

1. HAIL; Low $\rho_{HV}$ etc for hail 'hot spot' recognition. (Tabary et al, 2009)

2. ATTENUATION - recognition and correction using $\phi_{DP}$

3. VPR: LDR - much neglected, excellent for recognising the bright band.

4. BEAM BLOCKAGE- no direct help, apart from better clutter recognistion

5. CLUTTER(+anaprop) identification -best parameter -spatial texture of $\phi_{DP}$.

6. Z-R. a) Absolute calibration of Z to <1dB, every time there is moderate rain using redundancy of polarisation parameters .
   (Gourley, Illingworth and Tabary, 2009).
   b) Drop shapes now well established. (Brandes et al, 2002)
   (confirmed recent work by Bringi and Thurai).

7. Z/$Z_{DR}$-R: Need $Z_{DR}$ accurate to 0.2 dB to improve Z-R relationship
   - calibrate $Z_{DR}$ with vertical dwells every 15 mins
   - monitor azimuthal correction of $Z_{DR}$ using light (20-22dBZ) rain.

# HAIL

IDENTIFY AND FLAG USING POLARISATION (Tabary et al, 2009)

- $\rho_{HV}$ LOW (<0.94), $Z_{DR}$ high (>4dB) , $K_{DP}$ high (> 4°/km) – NOT ZERO.
- Z HIGH (>55dBZ). 'HOT SPOTS'

Too many free variables to characterise from the polarisation parameters:

a) Variable size spectrum of the hailstones.

b) Variable shape of the hailstones.

c) Variable fall mode of the hailstones.

d) Wet or dry growth. e) build up and shedding of water from hailstone.

+ partial beamfilling artefacts

SUGGEST - flag hail pixels as having VERY HIGH ERROR.

In most of Europe the amount of rain falling from hail affected pixels is a small fraction of the total rainfall.

(This may not be true in other climates - e.g. Colorado)

Cap Z at a certain value?

Quantify by interpolation over space and time?

Transient – so comparisons with gauges impractical

# POLARISATION PARAMETERS.

1. Need very high correlation coefficient for good data – antenna beam pattern matched in H and V.   Must have good data – no clutter.

2. Adachi and Yamauchi achieve 0.998 in rain with an FM/CW system. They shape of the transmitted pulses in H and V matched very closely. High $\rho_{HV}$ means more accurate ZDR and $\phi_{DP}$.

3. KDP in rain, unaffected by beam blocking,  but needs filtering over several km to smooth the noisy phase signal…..

How do you identify and correct for differential phase shift on backscatter from large drops? Especially at X-band this can be several degrees.

(Papers on this  backscatter problem in Session 6 – Tuesday).

Beam filling problems in severe weather.  Hail swaths often <1km wide.

X-band:    What are the economics of a 0.5degree beam?

4. USE A SHORT 75M PULSE.

Pick out many more uncluttered gates, with good phase, ZDR and $\phi_{DP}$.



Better spatial resolution for KDP rain rates.

# PRIORITIES FOR IMPROVED RAIN RATES + ERRORS

1. Improved ground clutter recognition
   Use short gates - more chances of finding an uncluttered gate.
   More $\phi_{DP}$ samples to estimate Z texture and KDP

2. Beam shielding - PPI scans which overlap in elevation. (+integrated Z maps)
   e.g. 0°, 0.4° , 0.8° and 1.2°

3. VPR - also need PPIs overlapping in elevation.
   Bright band recognition/correction insert LDR scan after each PPI.

3. How accurately do we need polarisation parameters?
   LDR - for bright band OK to 2dB? Can have a fast LDR scan.
   $\phi_{\mathbf{DP}}$ - for attenuation/clutter recognition - OK to a few degrees - but KDP?
   $Z_{DR}$ - to find 'a' in $Z = a R^{1.5}$ need to 0.1 or 0.2dB - difficult.
   only reduces errors from 25% to 15%, but we are not yet at 25%.

4. Scan sequence. Suggest 5 minute sequence (+ interpolation for advection) and LDR for VPR correction, better than 2.5mins and poorer VPR scheme.



5. Gauge representativity errors?

# 3. NEED LOCAL VPR CORRECTION SCHEME?

Current method - UK Met Office: <u>Use ‘standard Chilbolton VPR profile’</u>:

a) Fixed bright band depth.

b) Enhancement increases with Z of the rain.

c) Bright band height at 0ºC from NWP

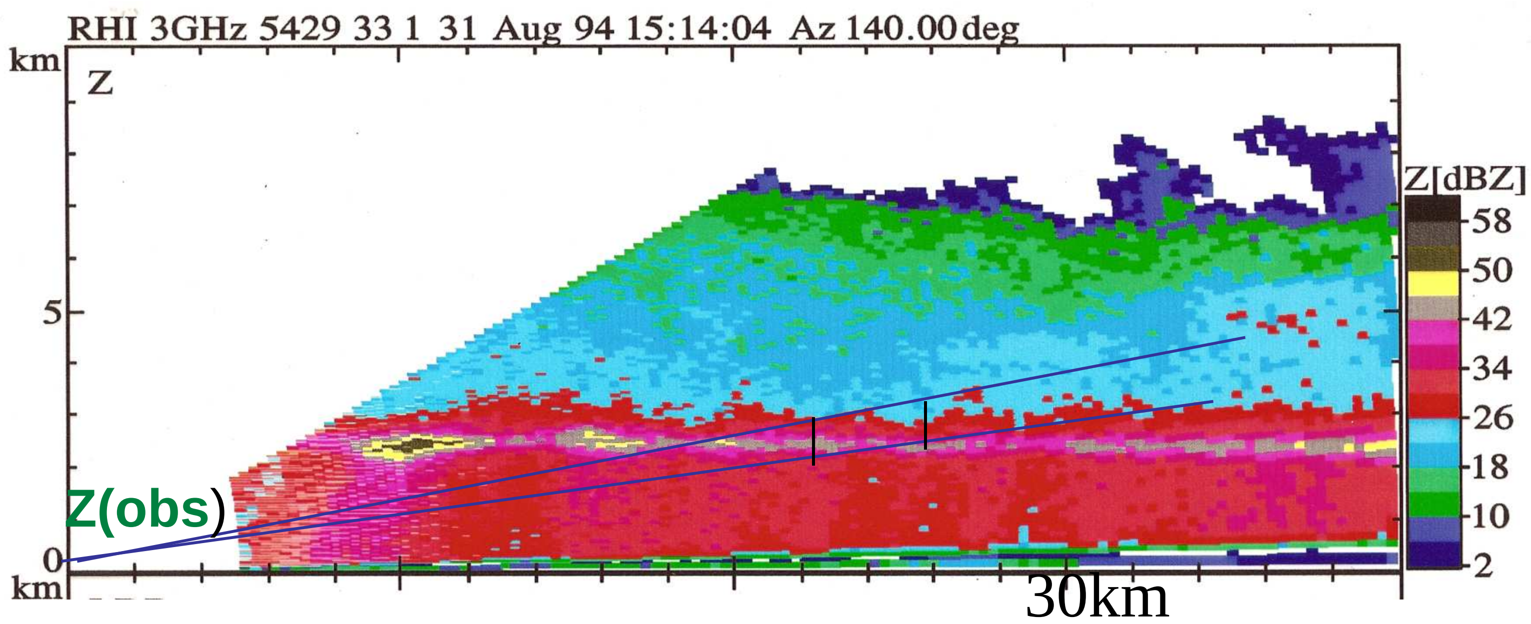
(error in bright band height < 150m: Mittermaier et al, QJ, 2004)

d) Z(obs) from lowest usable beam - assume standard profile

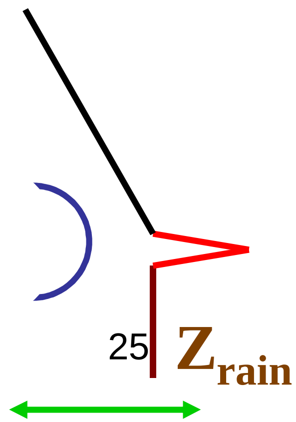
- multiply lowest beam tilt by beam pattern at appropriate range

←→**scale profile to get Z(obs)**. Read of **Z** in the rain which gives Z(obs)

IMPACT? Quite good - but no advantage using higher beams.

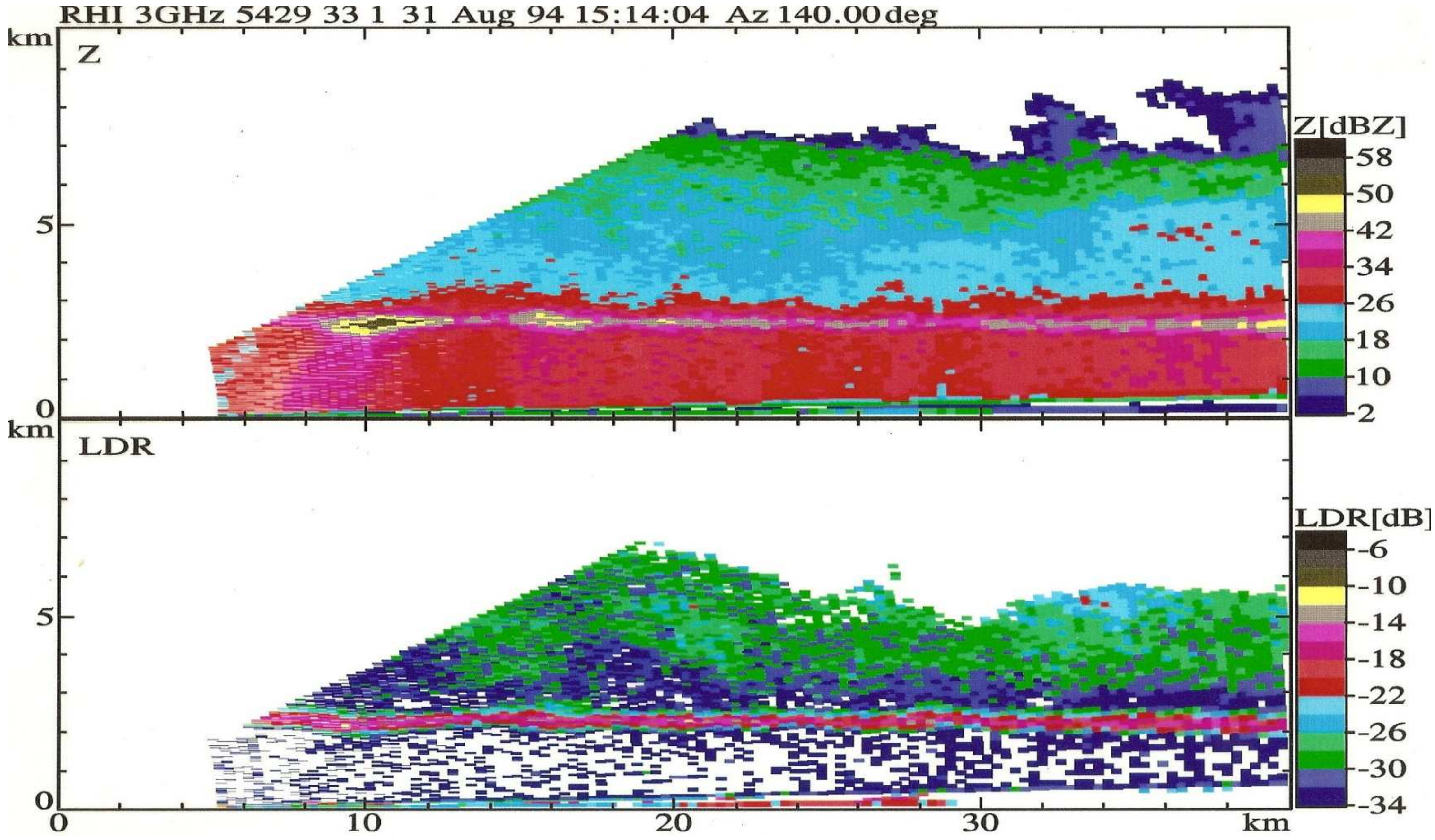



Standard Profile



# 3. LDR - FOR LOCAL VPR CORRECTION SCHEME

POLARISATION - IDENTIFY THE MELTING LAYER BY THE HIGH VALUE OF LDR TYPICALLY BETWEEN -14 AND -18dB

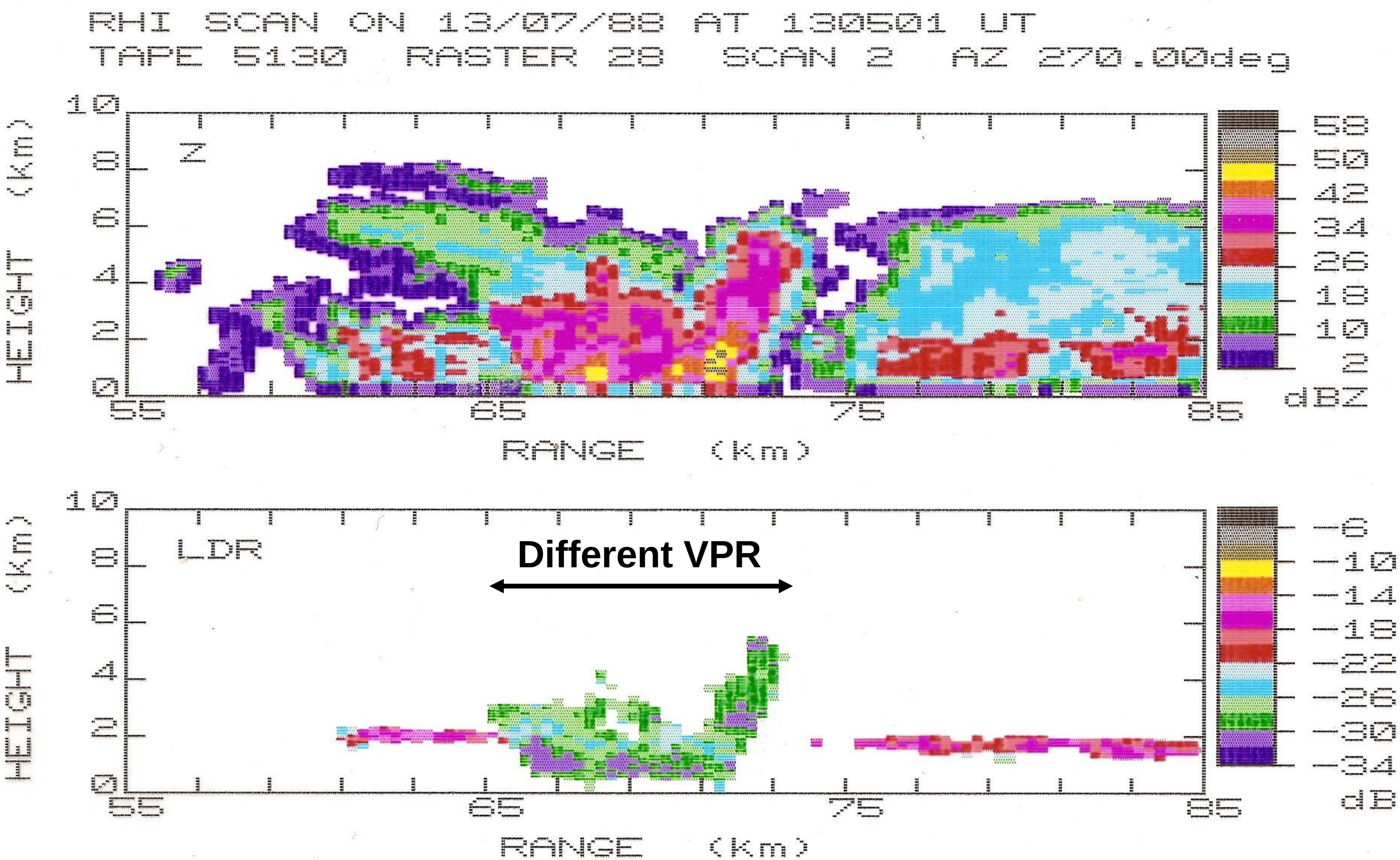



CLUTTER: CAN HAVE HIGH LDR - RECONGISE AND REJECT

NOTE: CONSTANT Z PROFILE BELOW BRIGHT BAND

RECONGIZE DIFFERENT VPR FOR EMBEDDED CONVECTION

- NO BRIGHT BAND LDR OF MELTING GRAUPEL -26 TO -30dB



# 3. LDR - FOR LOCAL VPR CORRECTION SCHEME

STATISTIC OF LDR VERSUS
BRIGHT BAND ENHANCEMENT
(Caylor et al, 1989, COST report
high resolution,Chilbolton RHIs)

LDR ABOVE -18dB
large enhancement of Z
typically 10dB

LDR below -18dB:
typically no enhancement of Z

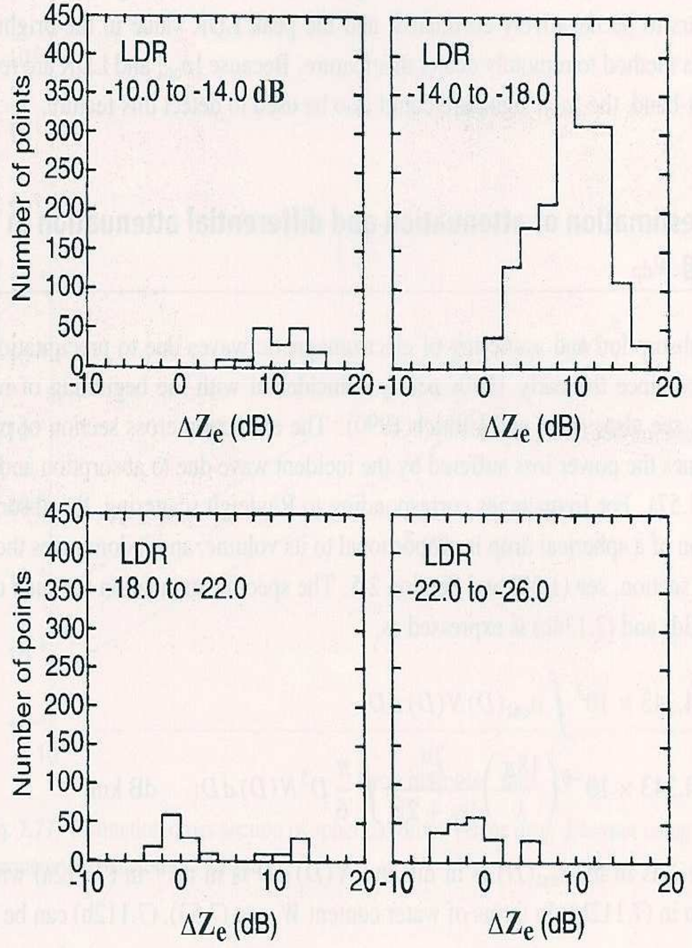



Fig. 7.76. Histograms of the enhancement of reflectivity in the bright-band ($\Delta Z_e$, dB) relative to the rain below as a function of LDR in the bright-band. Data from the S-band RAL/Chilbolton radar, UK. From Caylor et al. (1989).

## 3. LDR - CONCLUSION FOR LOCAL VPR CORRECTION

**B) IF THERE ARE BEAMS BELOW BRIGHT BAND:**
**ASSUME CONST Z PROFILE ?(usually OK in summer)**

CONCLUSION: Need to study statistics of high resolution RHI data set on the Z vertical profile below the bright band.

(or use profiles from vertical $Z_{DR}$ calibration dwell every 15 minutes)

to establish fractional error F(VPR)

i) Is it best to use the lowest clean beam?

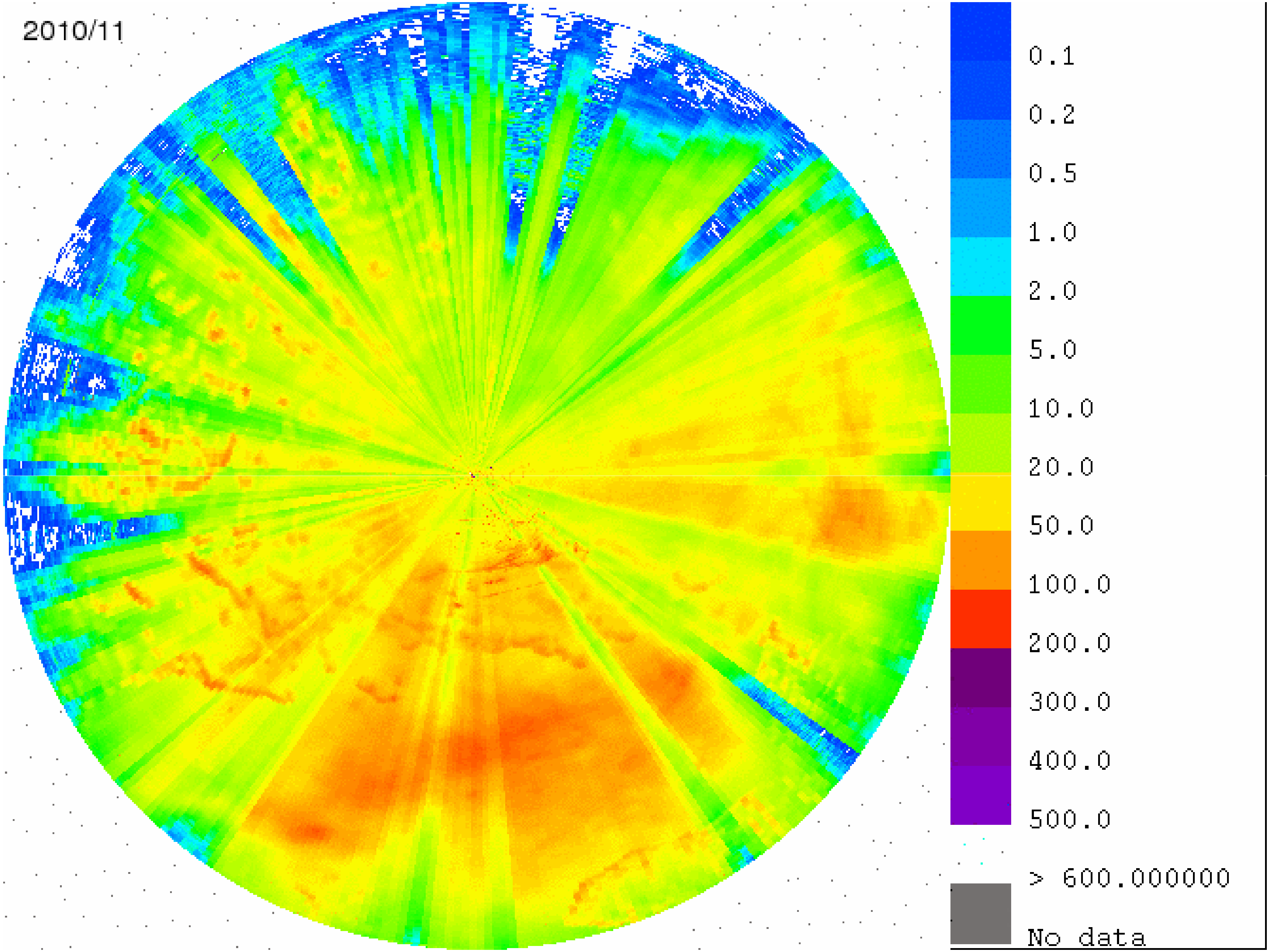
ii) Better to use Z weighted with height?

Tabary et al, 2007: Empirical suggestion:

Weighting varies as exp(-(height in km))

so beam at 2km has 13% the weight of beam at 0km.

- need to establish the form of this weighting with height.



2010/11
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
100.0
200.0
300.0
400.0
500.0
> 600.000000
No data

## 4. BEAM SHIELDING:

Currently compute using a digital terrain map

| | 20% | 50% | up to 70% blockage; |
|---|---|---|---|
| increase R by factor | 1.15, | 1.54, | & 2.12, |
| with weighting: | 0.87, | 0.65, | 0.47 |

Uncertainty arises from changes in beam refraction - difficult to model/predict.

Polarisation can't help.

Suggest: monitor Z of clutter (providing > Z of the rain)

- Z of clutter causing blockage changes, affects shielding, increases error.
- but maybe Z changes when clutter becomes wet?

## CHOOSE IDEAL RAIN EVENTS.

Uniform rainfall - Horizontal gradients of Z below a threshold.

Low wind . High melting layer. No attenuation. No hail.

**F(shield):** Look at lower three beams - lowest one shielded.

Compare lowering of Z in lower beam with shielding computations.

Look at variability of shielding for various events (via refractivity changes)

- derive error: F(shield) in the rain estimate.
- is it explicable by changes in Z of gate causing shielding?
- does monitoring the Z of the shielding gate reduce F(shield)?

# 5. CLUTTER:

Currently mostly use pulse to pulse variation in Z return

(Don't use zero mean Doppler - will reject rain moving perp to the beam).

Gates deemed to be cluttered are rejected.

(Use dynamic clutter map as last resort? Yes CH; No UK).

Finally use speckle filter to remove isolated gates with bird/aircraft…

Polarisation

High RMS of $\phi_{DP}$ of neighbouring gates (75m gates for better resolution?)

- suppress when attenuation leads to radial gradients in $\phi_{DP}$.

**CHOOSE IDEAL RAIN EVENTS.**

Uniform rainfall - Horizontal gradients of Z below a threshold.

Low wind shear. High melting layer. No attenuation. No hail.

**CLUTTER:** Look at lower three beams - lowest one cluttered.

By comparing Z of lowest cluttered beam with those unaffected,

objectively set the thresholds (pulse to pulse variation, $\phi_{DP}$ texture,…)

for a pixel to be rejected as cluttered.

# Implications for radar design

1. 330Hz (450km range) staggered prf for:
   a) Multiple Doppler 3-D winds. b) lots of empty gates emission/attenuation

2. Short 0.5μsec pulse (75m gate - 12 gates/km) - clutter identification.

3. Intersperse longer 2μsec pulses - extra 12dB sensitivity – insects.

4. PPI in 30secs: 1deg/88msecs; elevation: 0.0°, 0.4°, 0.8°, 1.2°
   Target: 0.5m/s Doppler width, time to independence =16msec
   6 independent samples, 12 gates = 72 samples per km/per azimuth.
   Accuracy of Z estimate to 12% or 0.5dB
   (if only 3 of the 12 gates are uncluttered - then Z to 1dB).
   $\phi_{DP}$ OK to 5° or so, $Z_{DR}$ good enough for calibration.

5. VPR very important need LDR to 2dB: Extra PPI in 15 secs?

6. Scan sequence: 0.0°, 0.4°, 0.8°, 1.2°: 4 * 45 secs = 3mins.
   leaves 2 mins for higher elevation scans.
   Repeat cycle 5 minutes.