The measurement of rainfall - why it is not so simple

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The problem

More data, more data

Right now and not later.

Our storms are distressing,

Our problems are pressing.

We can brook no delay

For theorists to play.

Let us repair

To the principle sublime

Measure everything, everywhere ← **Impossible!**

All of the time.

Aaron Fleisher, 1957 (**Theme song of the Sixth Weather Radar Conference)**

This talk

- Reviews the principal methods of measuring (estimating) rainfall
- Demonstrates the problems faced by each instrument
- Suggests points where statisticians may be able to help: *“Statistical Challenges”*

Five methods for deducing rainfall

1. Rain Gauges (400BC, or earlier)
2. Radar (1950s)
3. Disdrometers (1970s)
4. Vertical pointing Doppler radar (Early 1990s)
5. Microwave Links (Late 1990s)

Rain gauges

An incomplete history

- ***400 BC in India***
  - Bowl of known shape --- used by farmers to aid crop planting
- ***Romans in Asia Minor***
  - Known to have made measurements
- ***1250 AD in China***
  - Bamboo raingauges and snow gauges (in use until 20th century)
- ***1442 AD in Korea***
  - King Sejo required daily records of the amounts collected in a brass tube to be recorded

Statistical challenge 1 (SC1)

How relevant is the point measurement of a rain gauge to the region surrounding the gauge?

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We have a “continuous” time series of measurements., but a very discontinuous spatial series of measurements.

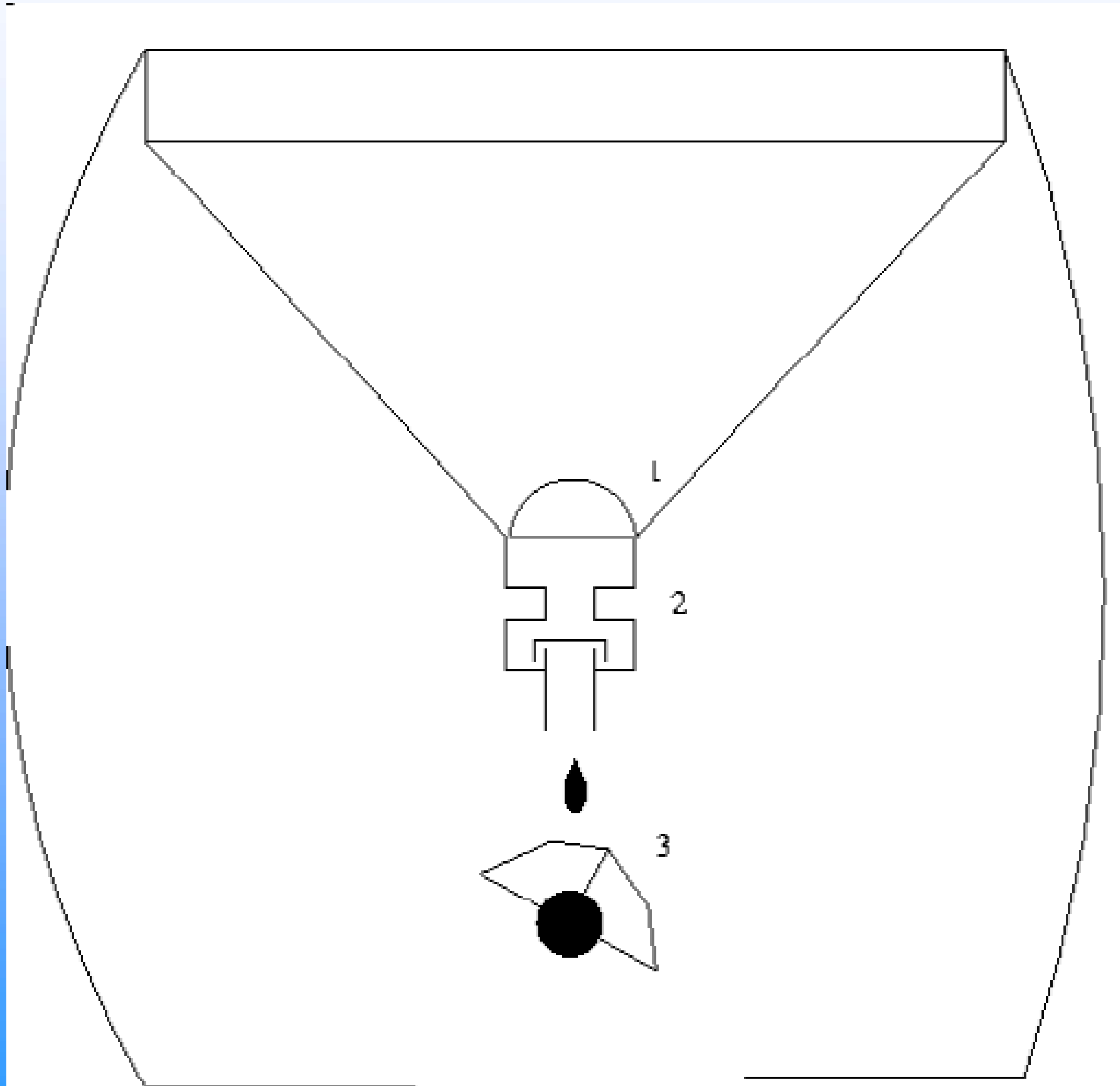
Can we use Taylor’s frozen-field hypothesis to make inferences about spatial correlation from observed temporal correlation?

Some facts about rain gauges

- In 2002 there were about 40,000 gauges worldwide.
- About half were tipping-bucket gauges

Tipping-bucket gauges

The tipping-bucket gauge



The time of each tip is recorded --- potentially to the second

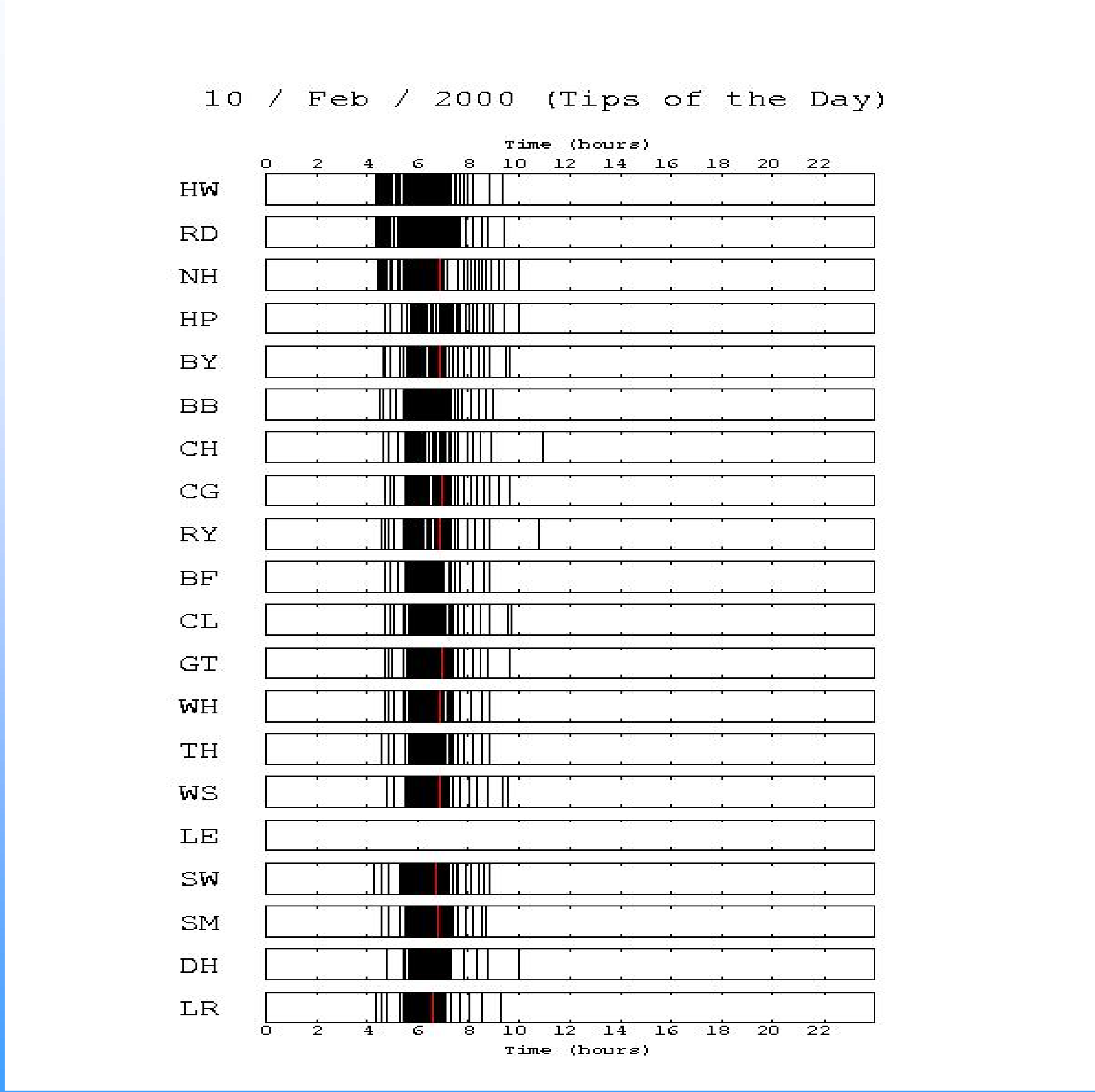
1660 Sir Christopher Wren

The inspiration?

A modern tipping-bucket gauge brand new and ready to tip

The tipping buckets

Typical data



Each vertical line represents a minute containing a tip.

SC2:

In the absence of radar information can one use tipping-bucket gauges to track rainstorms?

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My approach --- Upton, (2002), *J. Hydrol*, **261**, 60-73 was:

1. Estimate the lags between gauges in the times of storm onset by maximising cross-correlation of 1-minute rainfalls

2. Eliminate gauges having low cross-correlations

3. Fit a planar regression

4. Remove outlier gauges

Why tipping-bucket rain gauges may under-record

- Turbulence can cause exposed gauges to under-report by as much as 10%
- Wetting loss about 0.05mm per event
- Evaporation loss about .004 mm/hr
- Unavailability between buckets

  (it takes up to 0.5 sec for a tip)
- Shelter by buildings, trees, etc

Well sited?
(It *is* safe from vandals!)

A mid-20th century rain gauge installation

The modern equivalent

Other reasons why rain gauges may give false readings

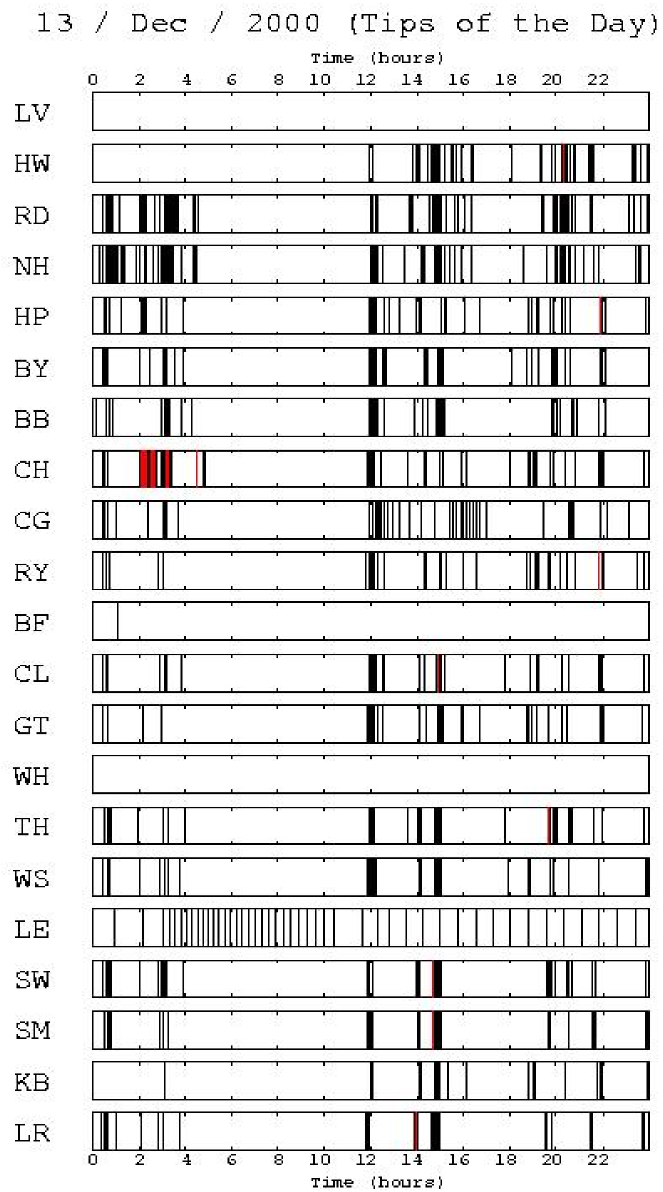
- Insects in gauge
- Animal interference
- Snow not recorded
- Snow melting long after it fell

Not blocked!

Very probably blocked!

Definitely blocked!

A bad day for tipping-buckets!



HW has no morning records.

CH has many multiple tips

BF has only a single tip

LE is partially blocked

KB is up the wall!

Quality control

SC3: **Can we devise effective algorithms that will detect a malfunctioning gauge?**

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Possibilities discussed in Upton & Rahimi, (2003) *J. Hydrol,* **278**, 197-212

include

- Unusual numbers of tips in an event
- Unusual median inter-tip times in an event
- Unusually short inter-tip times
- Cusums of ever-increasing inter-tip times

SC4: What is meant by rainrate?

Quoted rainrates are meaningless unless we know the integration time.

For tipping bucket gauges the integration times are the (variable) times between tips.

Radar

A big beast: The Chilbolton radar

The Met Office radar at Hameldon Hill

The new Met Office Doppler radar at Thurnham

The radar cycle

1. Radar sends out pulse.
2. Receives echoes. (Time lag indicates distance; echoes are collected into about 440 distance bins).
3. Rotates through about 0.9 degrees. Repeats the above.
4. (A complete revolution typically takes about a minute)
5. Changes elevation and repeats the above

A complete cycle takes from 5 to 15 minutes --- slower cycles give better information (but less frequently)

Consequences of the radar cycle

- Data are collected from several elevations over a circular region of some 200km in radius
- Data from the same location are collected only at 5-15 minute intervals
- At any elevation the data from the (neighbouring) initial and final directions will be separated in time by more than a minute.

What the radar measures

- Measures (inter alia) the strength of an echo --- backscatter reflectivity, *z*.

- Modern radars may measure reflectivity in two polarizations, and other features such as the radial velocity components of the raindrops

From reflectivity to rainrate

- $z \propto D^{6}$ (*D* = drop diameter)
- $Z = 10\log_{10}(z)$ (Units are now decibels)
- First approximation:

$$Z = 200R^{1.6}$$

(R = rainrate)

SC5: **Can we improve on the first approximation: $Z=200R^{1.6}$?**

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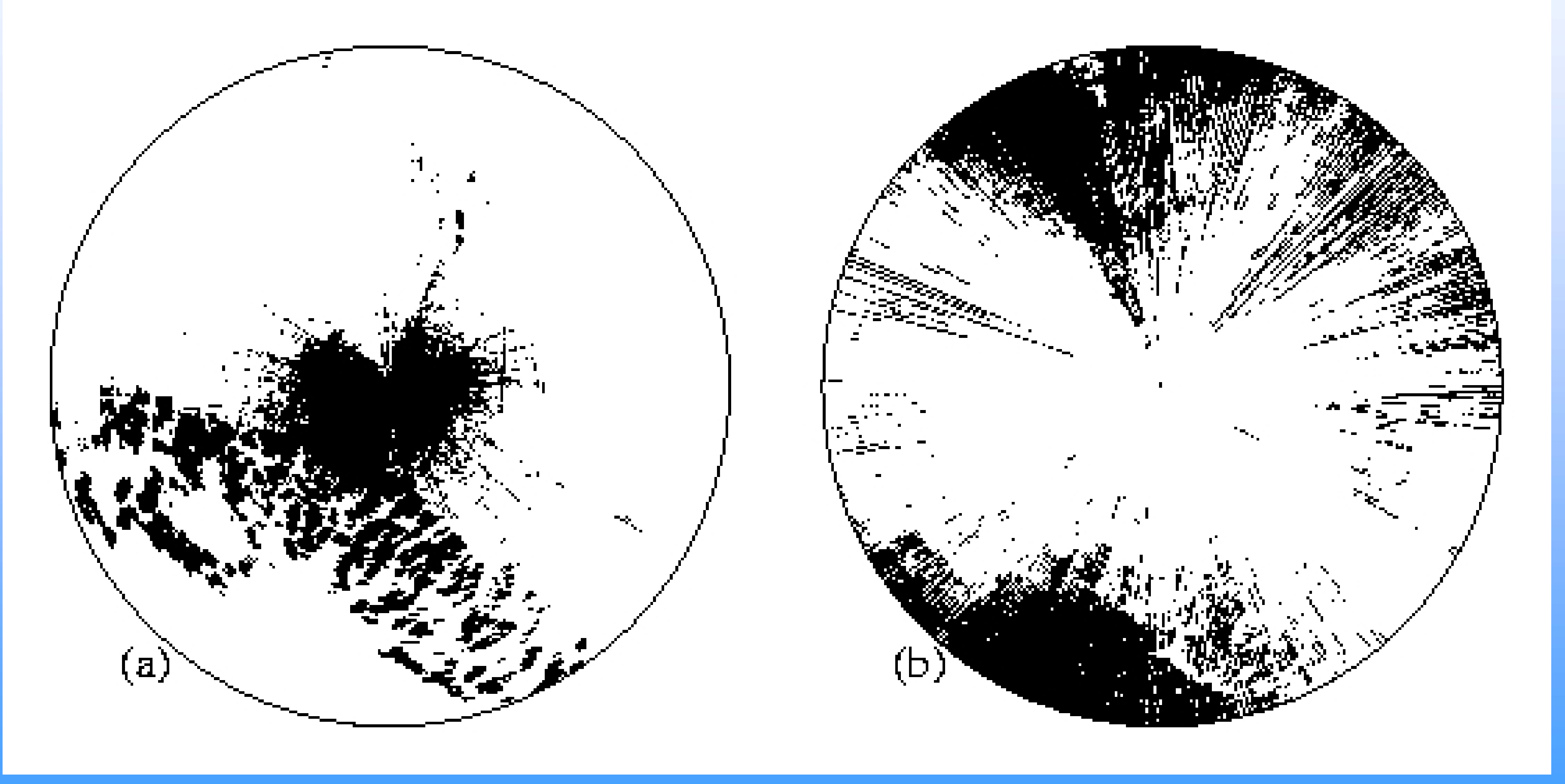
- Heavy summer rain is associated with big drops
- Big drops mean very large Z
- Stratiform rain generally consists of smaller drops and hence the same volume of water will give a much smaller Z
- The relation between Z and R depends on the dropsize distribution (dsd)

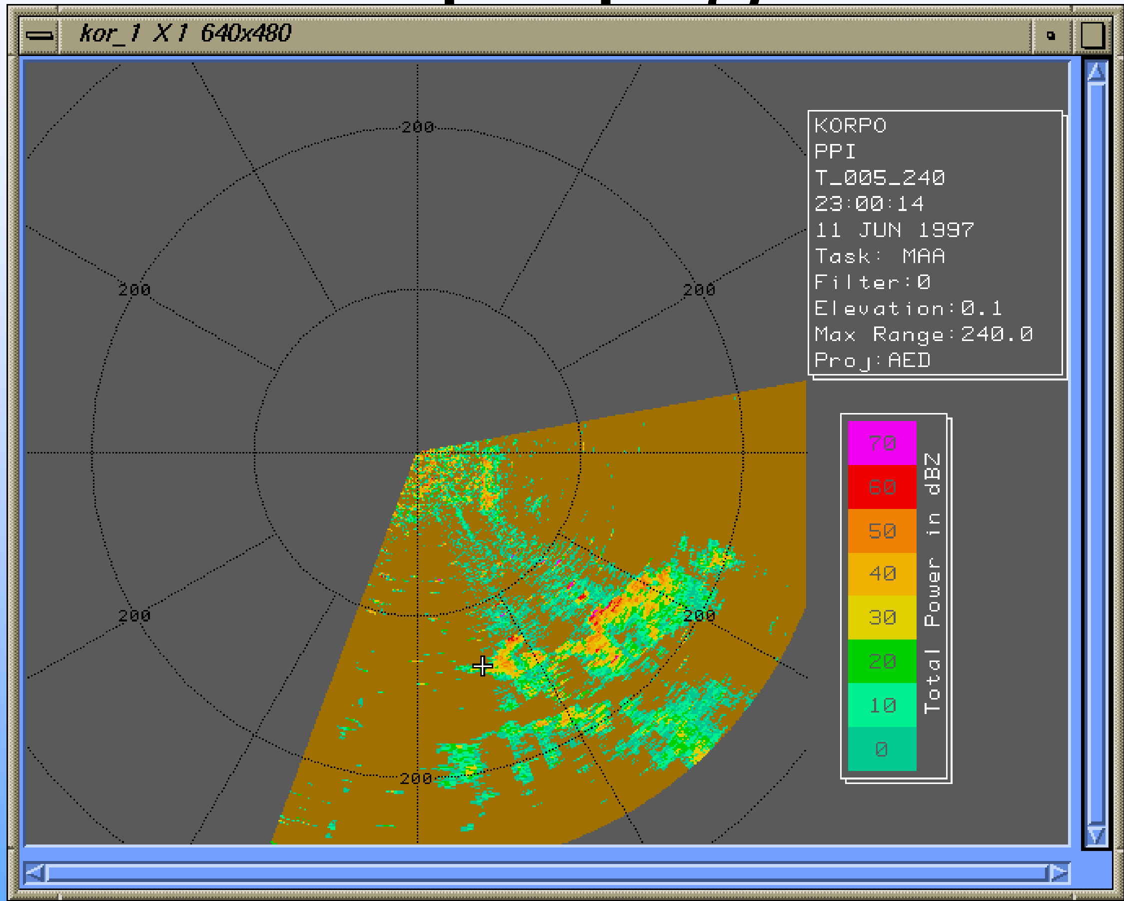
Clutter (a) and obscuration (b)



SC6: Can we devise an algorithm that distinguishes clutter from rainfall?

- Clutter maps are currently used to identify “at risk” pixels.
- But the echo from rain can dominate the clutter echo, so that the measured value is reliable and need not be discarded.

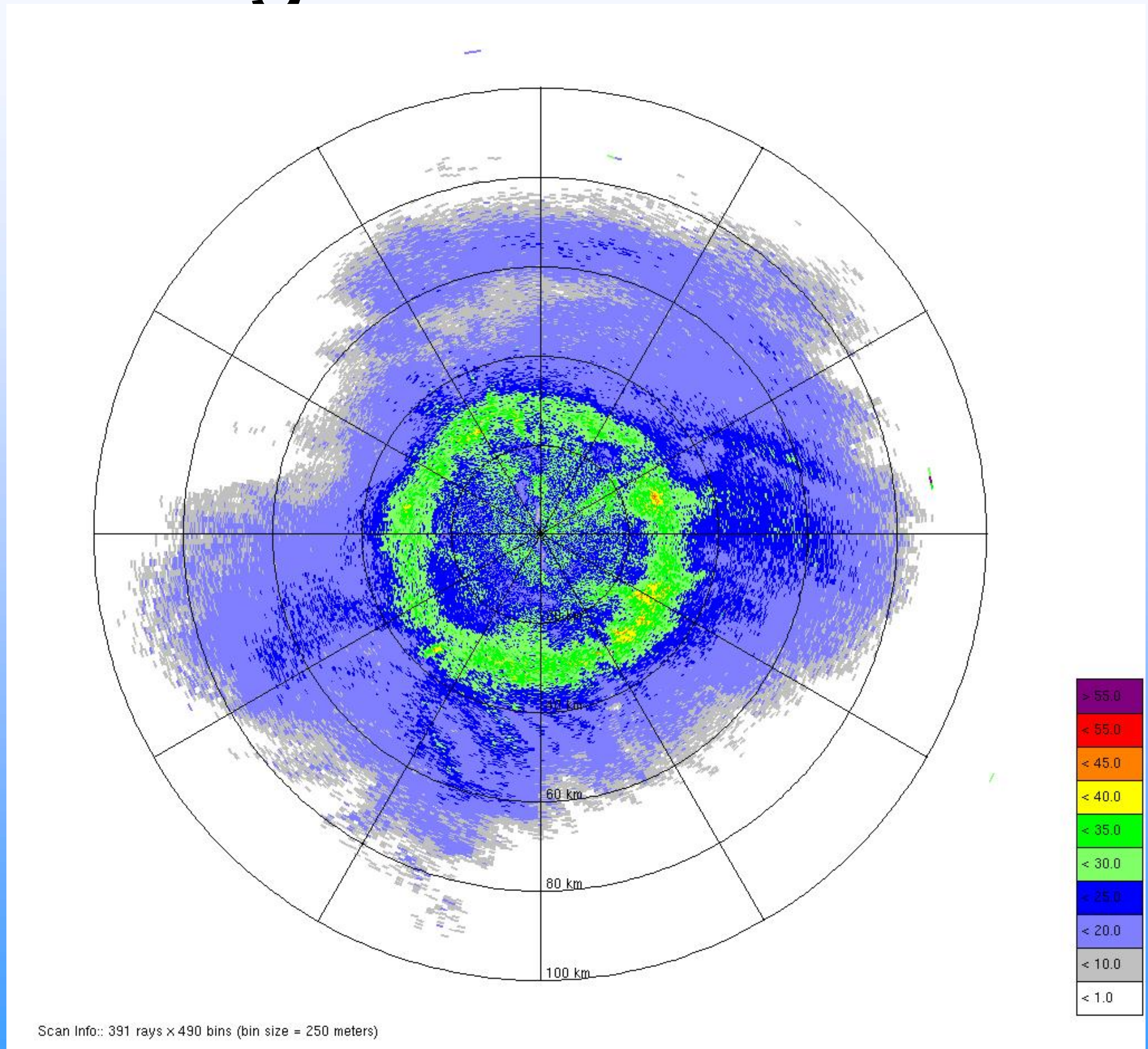
Anomalous propagation



From http://www.smhi.se/sgn0106/if/meteorologi/radar/seaclut.html

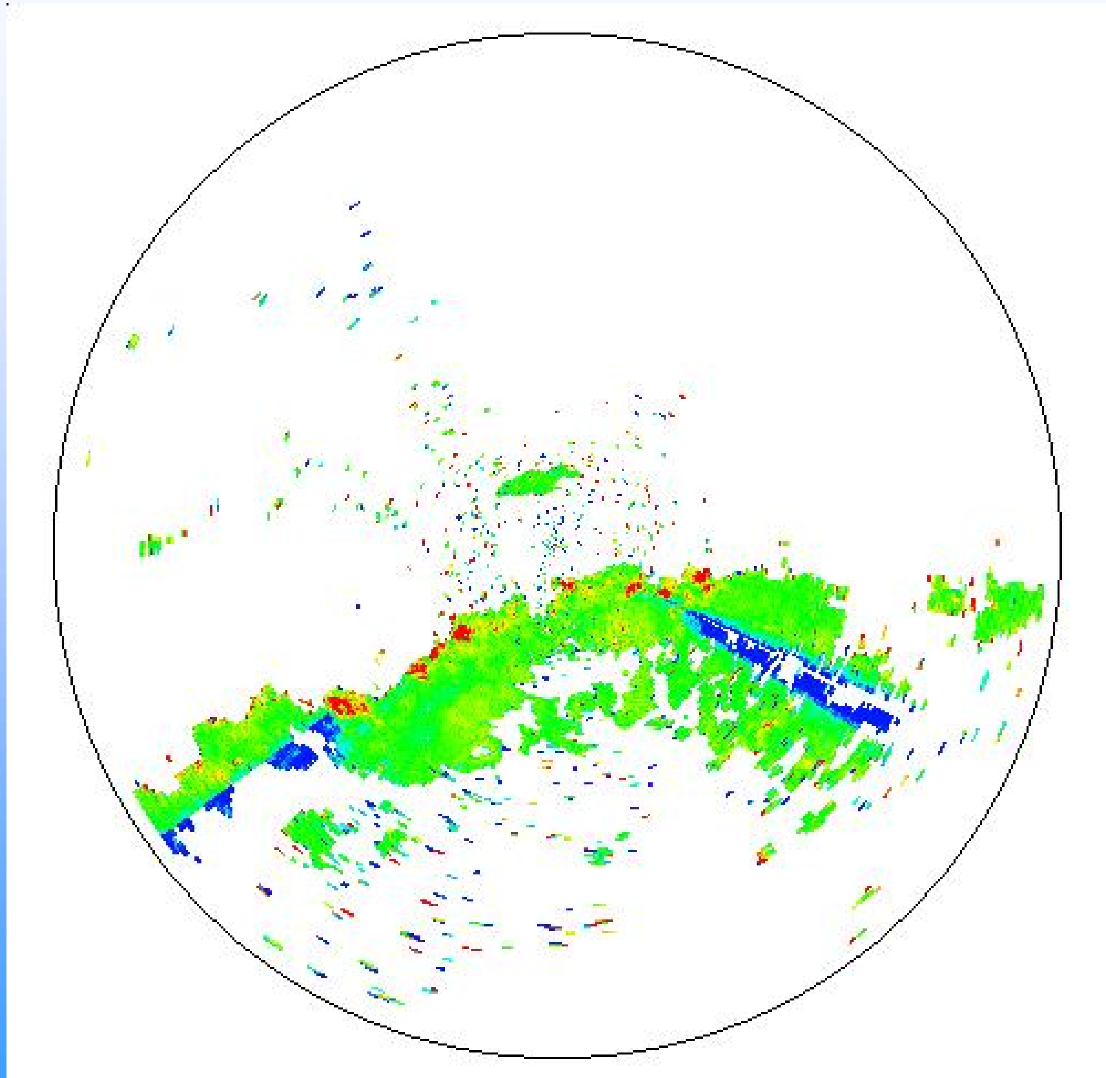
SC7: **Can we improve on existing algorithms for the detection of anaprop?**

The bright band



SC8: **Are bright band detection algorithms effective?**

Attenuation

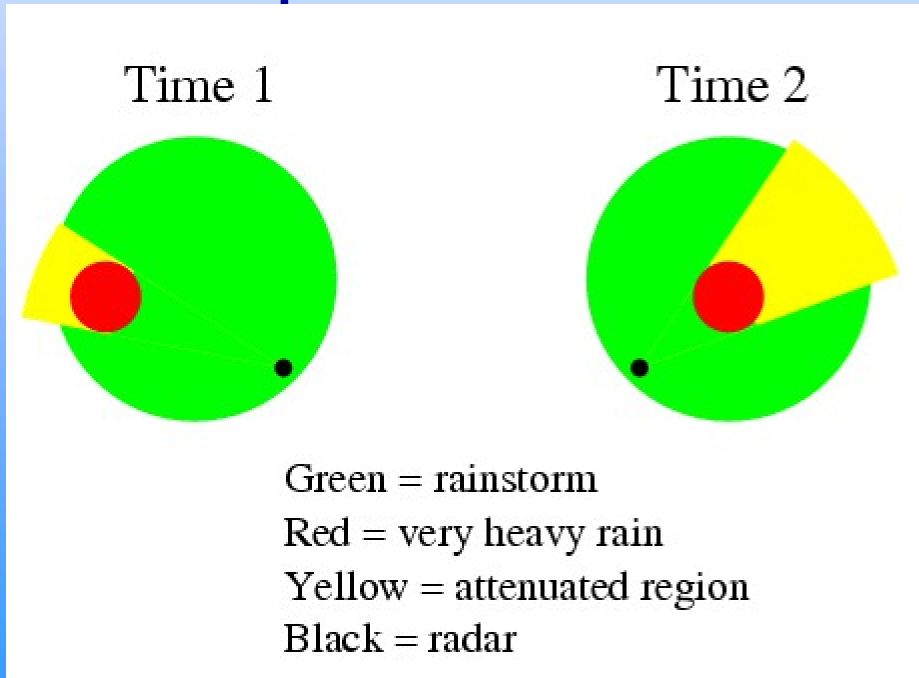


SC10: Can we devise an algorithm that identifies seriously attenuated regions?

SC11: Can we use past information to "repair" attenuated areas?

Storms both move and evolve.

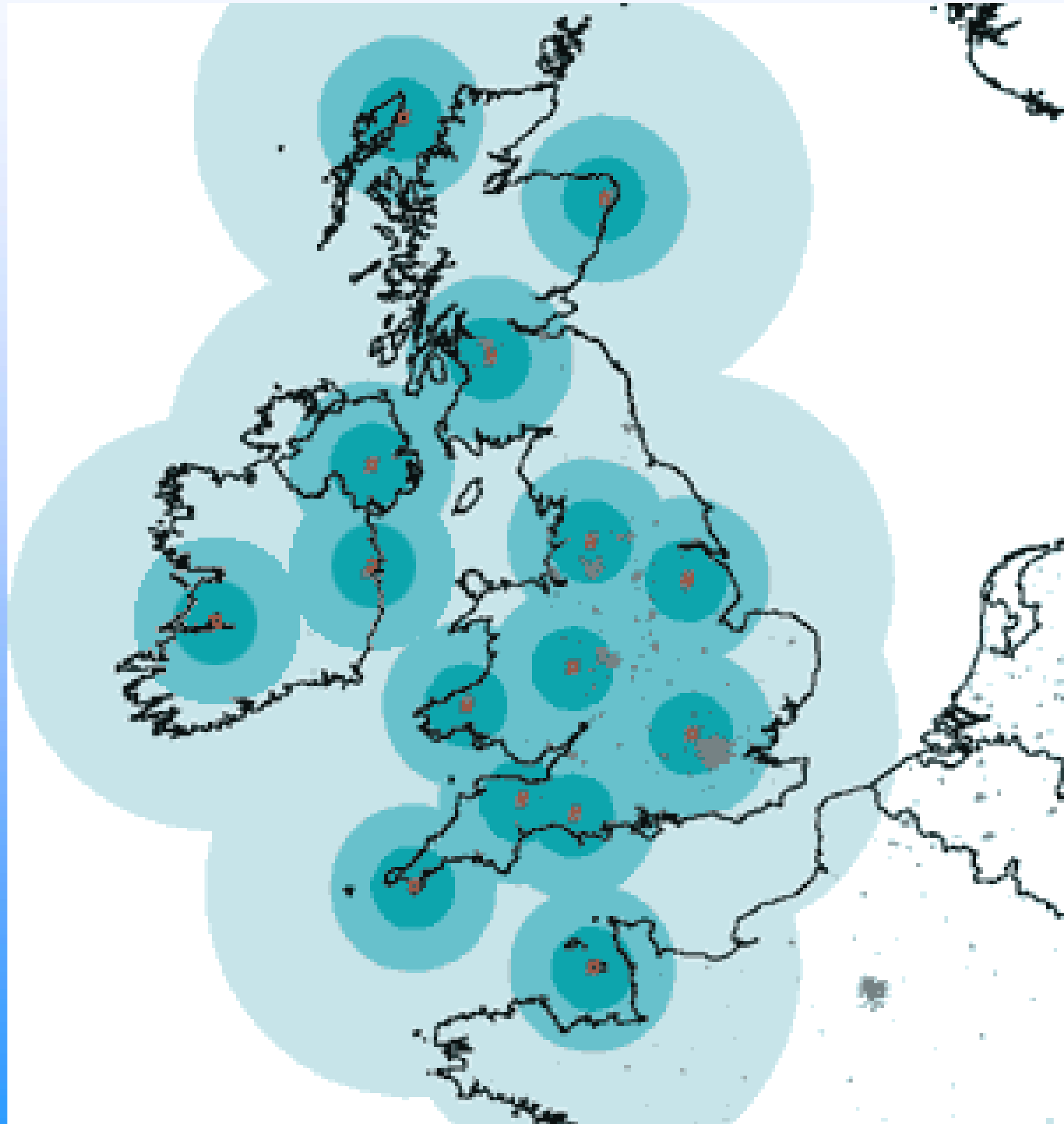
The extent of the attenuation will depend on the relative position of storm and radar



One approach to tracking a rainstorm using radar data is to be found in

Upton (2000) *Physics and Chemistry of the Earth, B*, **25**, 1117-1121.

SC12: How do we best combine information from overlapping radars?



http://www.metoffice.co.uk/

SC13: How do we best describe the uncertainty inherent in radar information?

In general, the more distant radar bins:

- are likely to be more affected by attenuation
- report values from larger spatial volumes (so have generally smaller values because of averaging)
- have larger footprints, so that spatial precision is reduced
- refer to volumes that are more distant from the earth's surface (rain affected by wind shear will not fall vertically).

Microwave links

Transmitters and receivers

The basic idea...

- Signal is emitted at a constant strength
- Signal is attenuated/scattered by intervening rain
- Estimate attenuation
- Estimate on-path rainfall from amount of attenuation

Potential problems

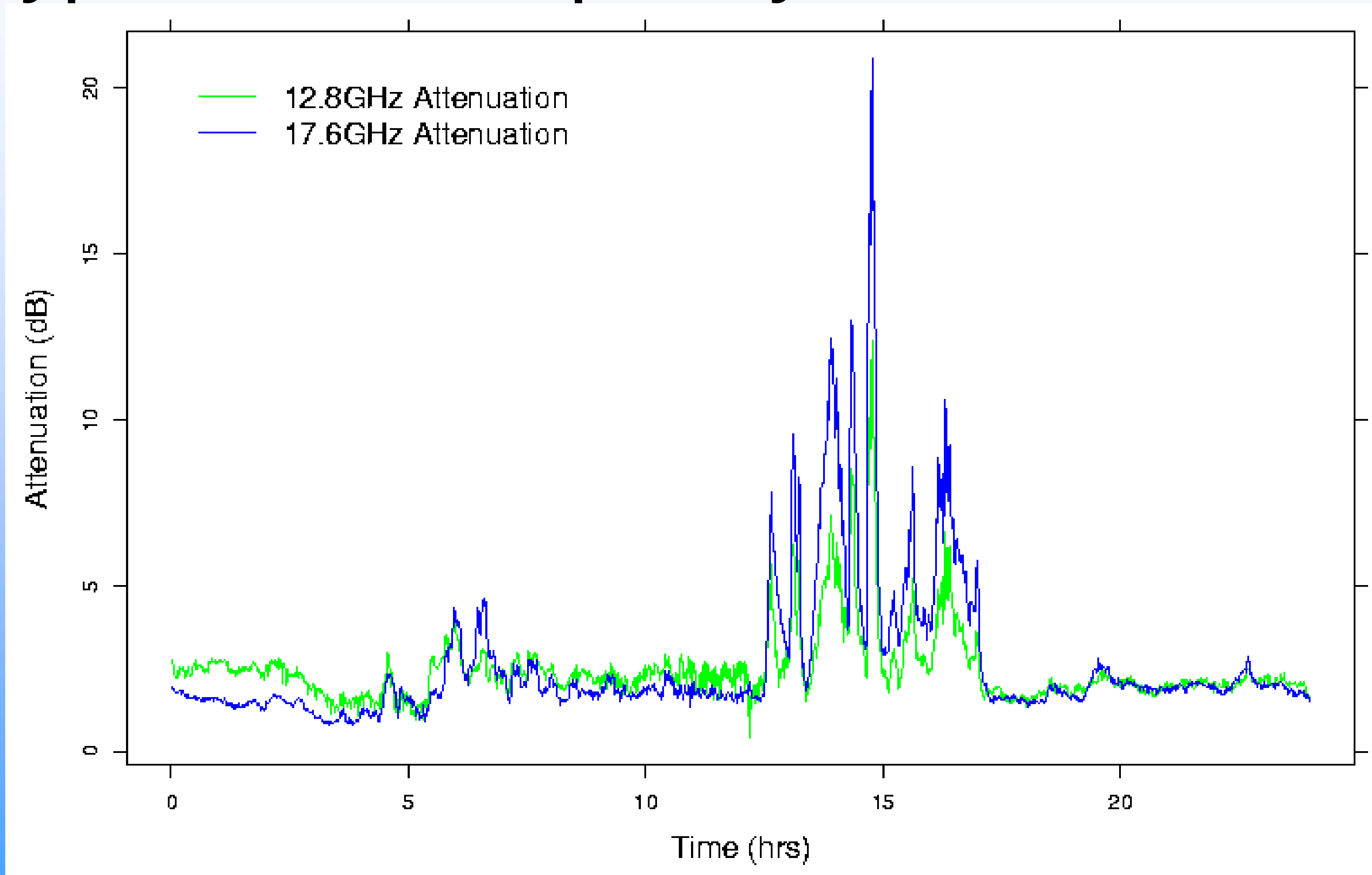
- Amount of attenuation depends on drop size distribution (dsd)
- Non-linear relation: Doubling rainrate does not double attenuation

Potential solutions

1. Choose wavelength for which relation is near linear and unaffected by dsd

2. Choose pair of wavelengths for which *difference* in attenuations has near-linear relation to rainrate and is unaffected by dsd

A typical dual-frequency trace



SC14: How do we best determine the baseline during an event (so as to determine the amount of rain-induced attenuation)?

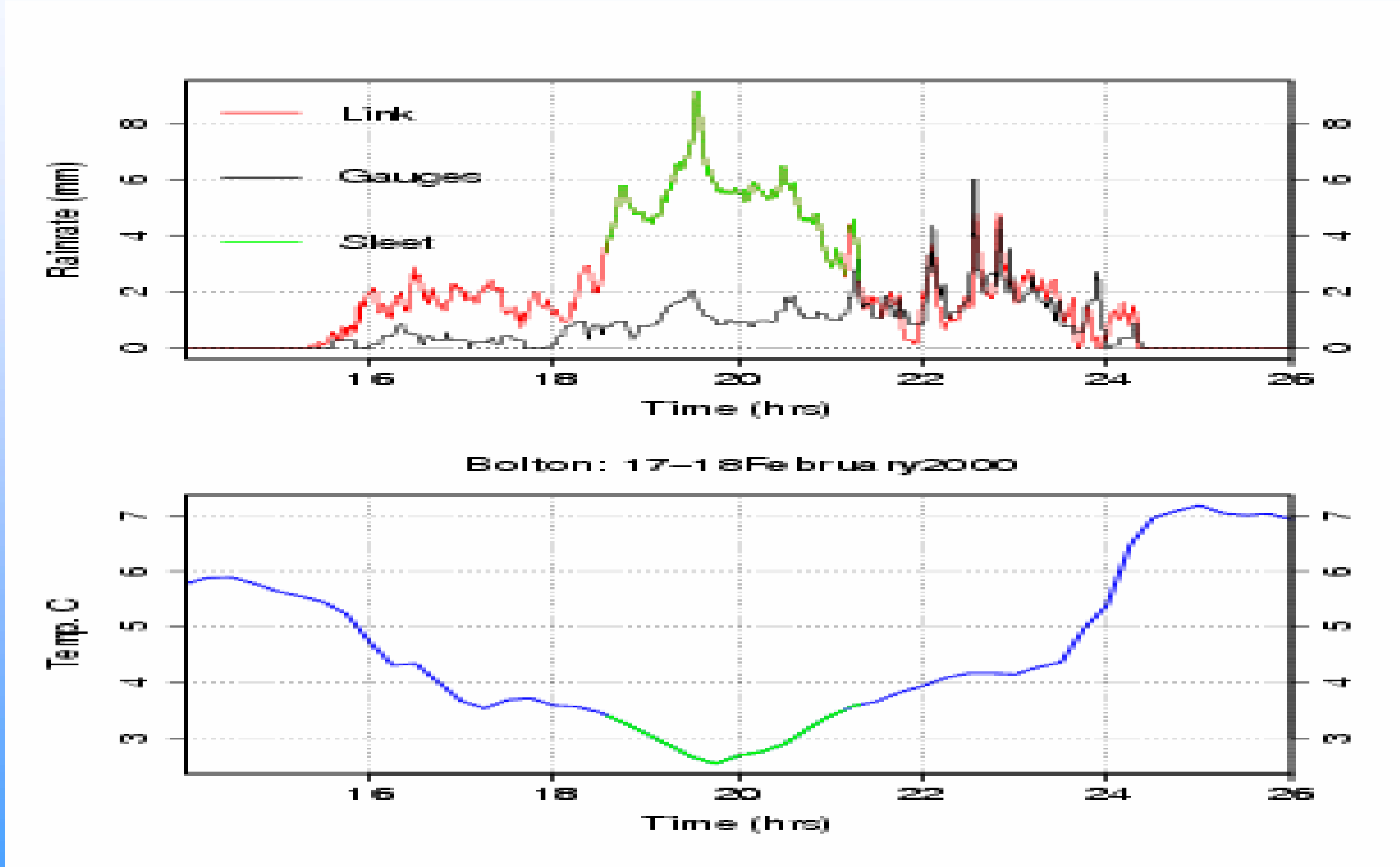
The signal spreads out as it leaves the transmitter.

It may reflect off the ground or hillsides.

In still conditions the signal may be refracted or ducted to give very variable received signal strengths

SC15: How do we distinguish between rain-induced variation and other variation?

The effect of sleet…



SC16: Without resorting to thermometers, can we deduce that there is sleet on the path?

A microwave link may give a good estimate of the on-path rainfall,
but

SC17: How relevant is that on-path estimate to locations off the path?

Coverage provided by a link

Space/time Integration		Approximate coverage area for given percentage error $100\frac{\lvert I_1 - I_2 \rvert}{(I_1 + I_2)/2}$		
Time interval	Link length	<5%	<15%	<25%
5 min	10 km	0.5 km^2	1 km^2	5 km^2
	20 km	2 km^2	5 km^2	15 km^2
1 hour	10 km	2.5 km^2	20 km^2	40 km^2
	20 km	10 km^2	60 km^2	120 km^2
5 hour	10 km	5 km^2	40 km^2	90 km^2
	20 km	20 km^2	120 km^2	240 km^2

The World is criss-crossed by commercial links, each of which may be being attenuated

SC18: How do we best accomplish a tomographic reconstruction of the rainstorms present?

Rain drops keep falling...

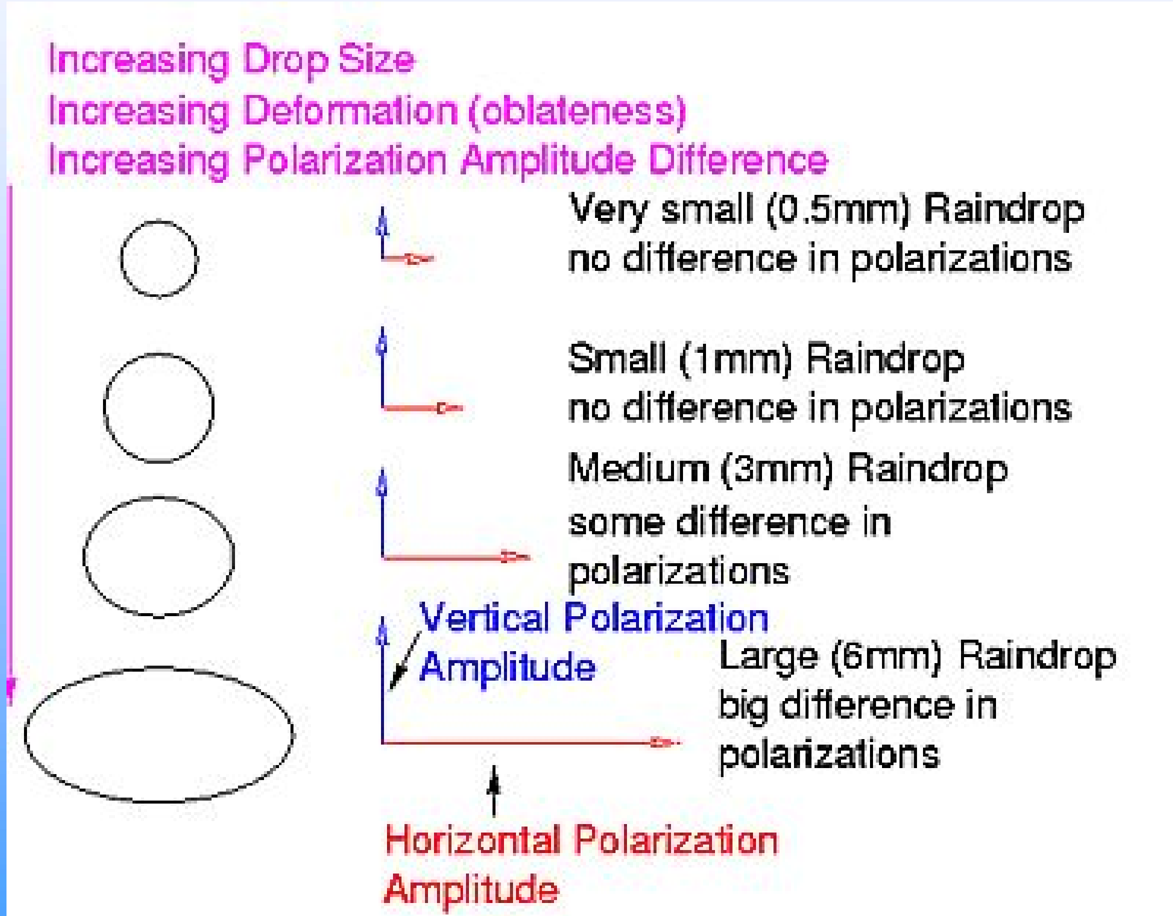
But what do they look like?

Missed it!

From http://soilerosion.net/doc/water_erosion.html

What we imagine...

But actually...



www.chilbolton.rl.ac.uk/images/raindrop.jpg

The shapes of rain drops

- Diameters up to about 7mm
- Small rain drops (D < 1 mm) are spherical
- Medium-sized rain drops are oblate spheroids: ***"A shape more like that of a hamburger bun."***
- Larger drops become distorted into a shape ***"rather like a parachute with a tube of water around the base."***
- They then break up into smaller drops.

Differential reflectivity

- Since drops are non-spherical, it matters whether the electromagnetic wave is transmitted in the horizontal or vertical plane.
- The difference in reflectivities gives an indication of the (average) drop shape.
- This helps to distinguish between rain, sleet, and hail, and potentially gives information about the dsd.

Methods for the determination of rain drop size distributions (DSDs)

- Wiesner (1895) filter paper
- Fine flour
- Pan of castor oil
- Disdrometer --- optical
- Disdrometer --- audio
- Vertical Doppler radar

An impact disdrometer

Problems with impact disdrometers

Drop size is determined by “noise” of impact, but:

- The impact of a big drop masks the impacts of near-simultaneous small drops
- The smallest drops cannot be sensed at all

SC19: **Can we improve on the current algorithm for adjusting for under-reporting of small drops?**

An optical disdrometer

http://www.thiesclima.com/disdrometer.jpg

Problems with optical disdrometers

Drop size and speed are determined by interruption of laser beam(s)

- The large drops can mask small drops
- The smallest drops cannot be sensed at all

SC20: **Can we exploit the relation between fall speed and size to get better estimates of drop sizes?**

What do DSDs look like?

They are usually regarded as being well approximated by gamma distributions.

Estimation of a truncated gamma distribution

Atmospheric scientists usually ignore the low-end truncation and use high-order sample moments to estimate parameters

SC21: **Do better!**

One approach is given in

Brawn and Upton (2007),*Environmetrics*, to appear

What is a dropsize distribution?

- Large drops fall faster than small drops.
- Thus the DSD sensed by a radar in a volume of space, will not be the DSD observed at that time by the ground-based disdrometer.

SC22: Develop a relation between these two DSDs

An array of optical disdrometers in Iowa

Radar-disdrometer (uses Doppler)

http://www.metek.de/produkte.htm

The big challenge (I)

All these measuring instruments are measuring different aspects of rainfall in different ways, in different regions of space and with different integration times

SC23: How do we best reconcile them?

The big challenge(II)

SC24: How do we quantify the uncertainty?

(in our reconciliation of these measurements)