ELEMENTS of a RADAR SYSTEM

Radar hardware includes what is needed to:

1- **Generate** a strong short microwave pulse ~10^6 W, 1 μsec (**transmitter**)

2- **Focus** it in one direction (**antenna**)

3- **Receive** the very weak echoes ~ 10^{-12} W (**antenna + receiver**)

4- **Amplify** these echoes (**amplifier, mixer and filters**)

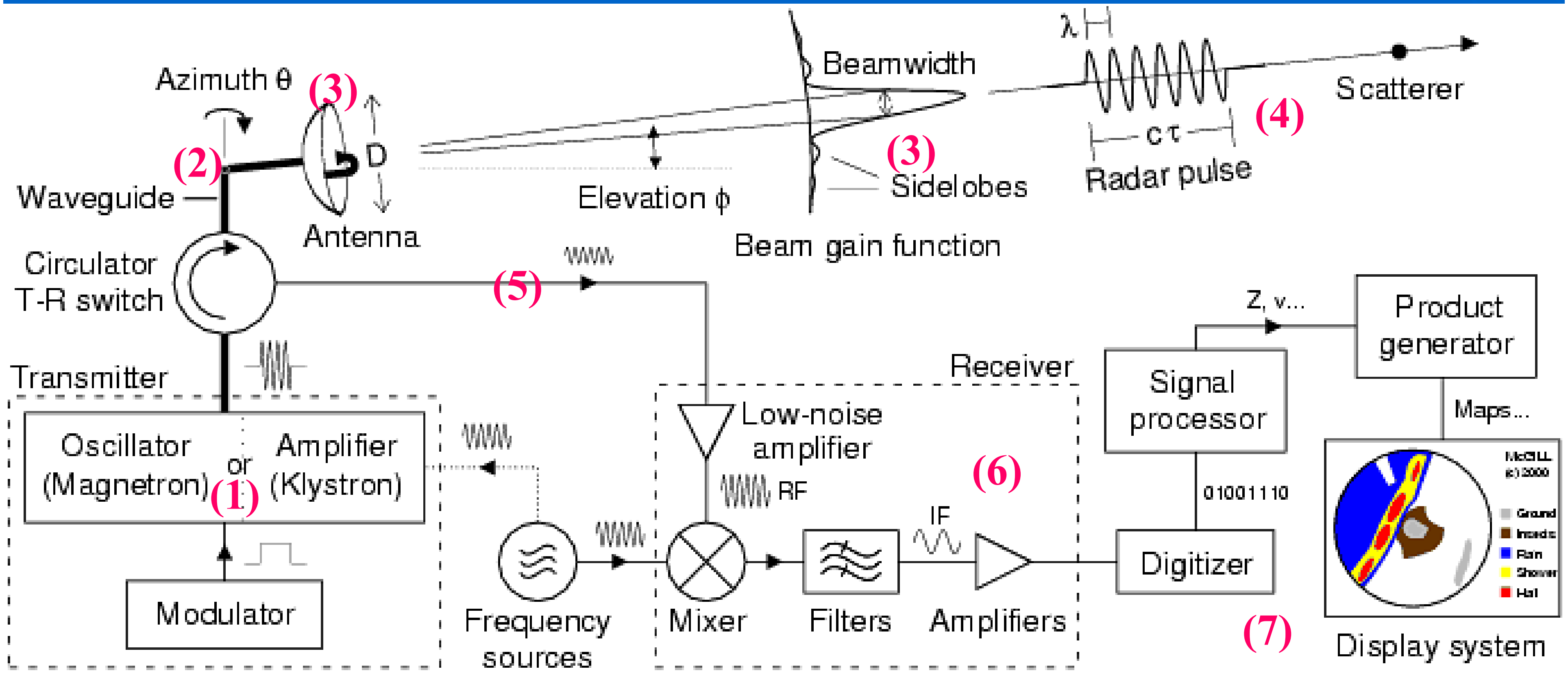
5- **Extract** digital raw data from the signal
(Ex: reflectivity, Doppler velocity) (**digitizer, signal processor**)

Other tasks, usually at a remote site, are also part of a radar system:

6- **Process** the raw data (3-D volume scan) to obtain meteorological maps
(radar product generation **software**, **RAPID**)

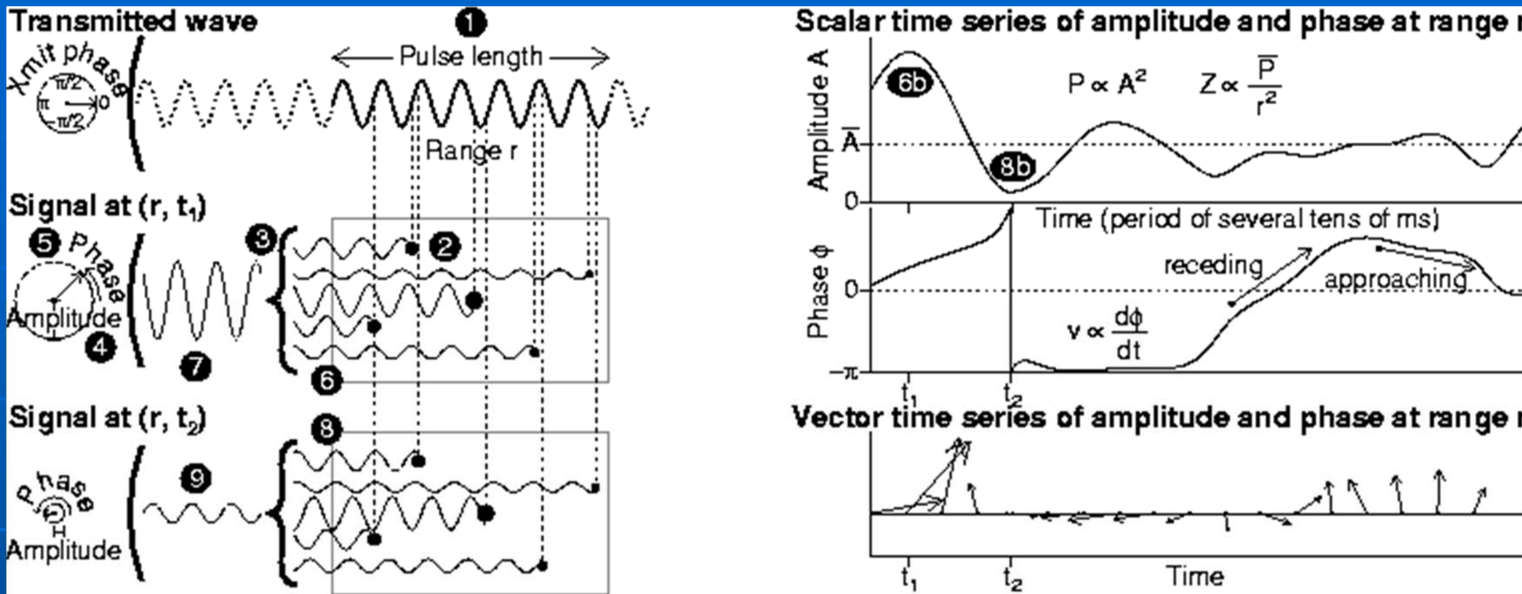
7- **Analyze, interpret, display** the maps and **disseminate** the information

SKETCH of RADAR SYSTEM (Active remote sensor)



1) **Pulse generation and amplification**
2) **Travel to antenna feedhorn in waveguides**
3) **Focus by antenna and gain. Finite beamwidth with sidelobes.** **(Antenna controller)**
4) **Travel to targets and backscattering by these targets**
5) **Reception by the antenna and into receiver via the circulator**
6) **RF (radio frequency) amplification, Mixing (RF-IF) and IF amplification**
7) **Digitization, signal processing, and image display**

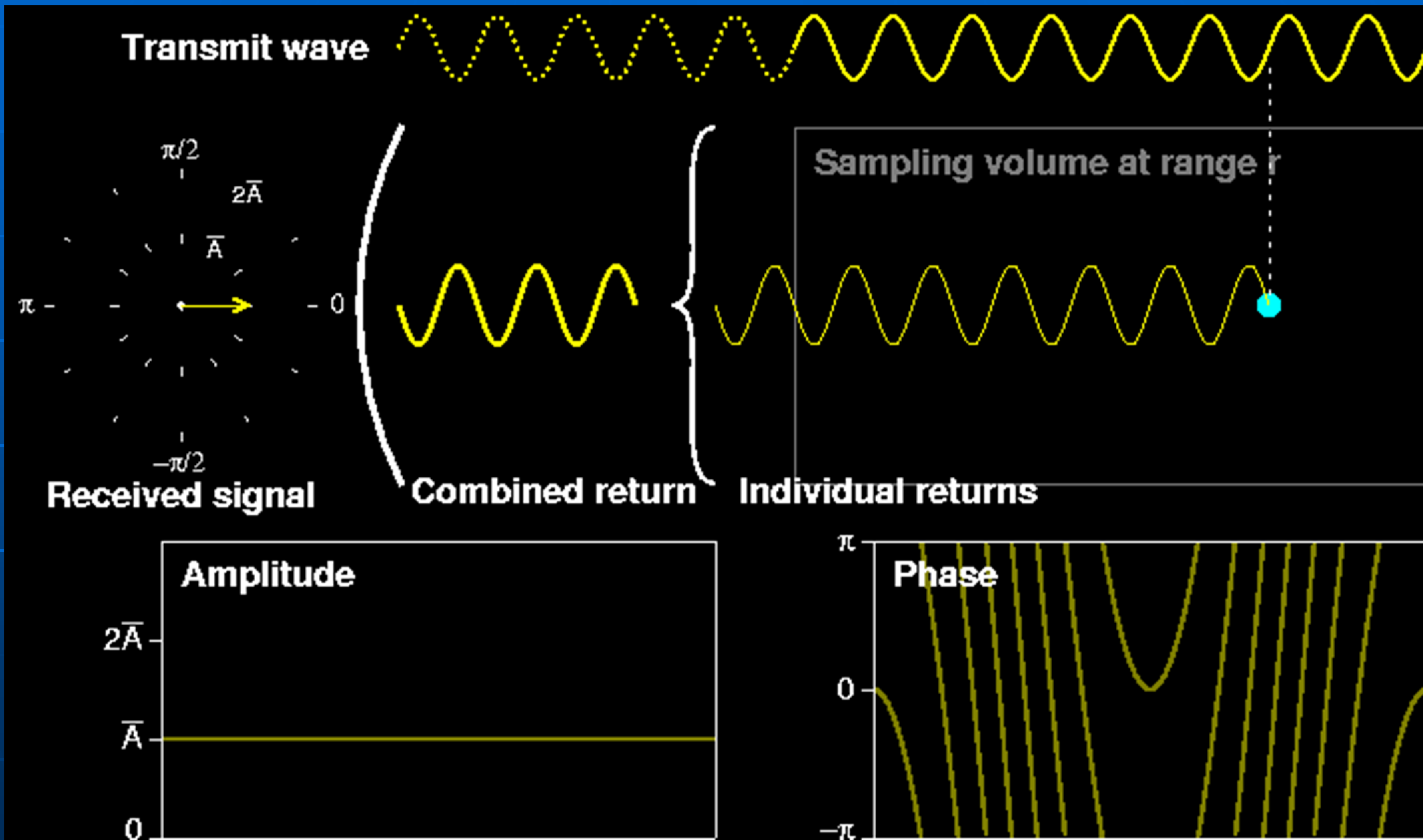
Characteristics of Radar Signal



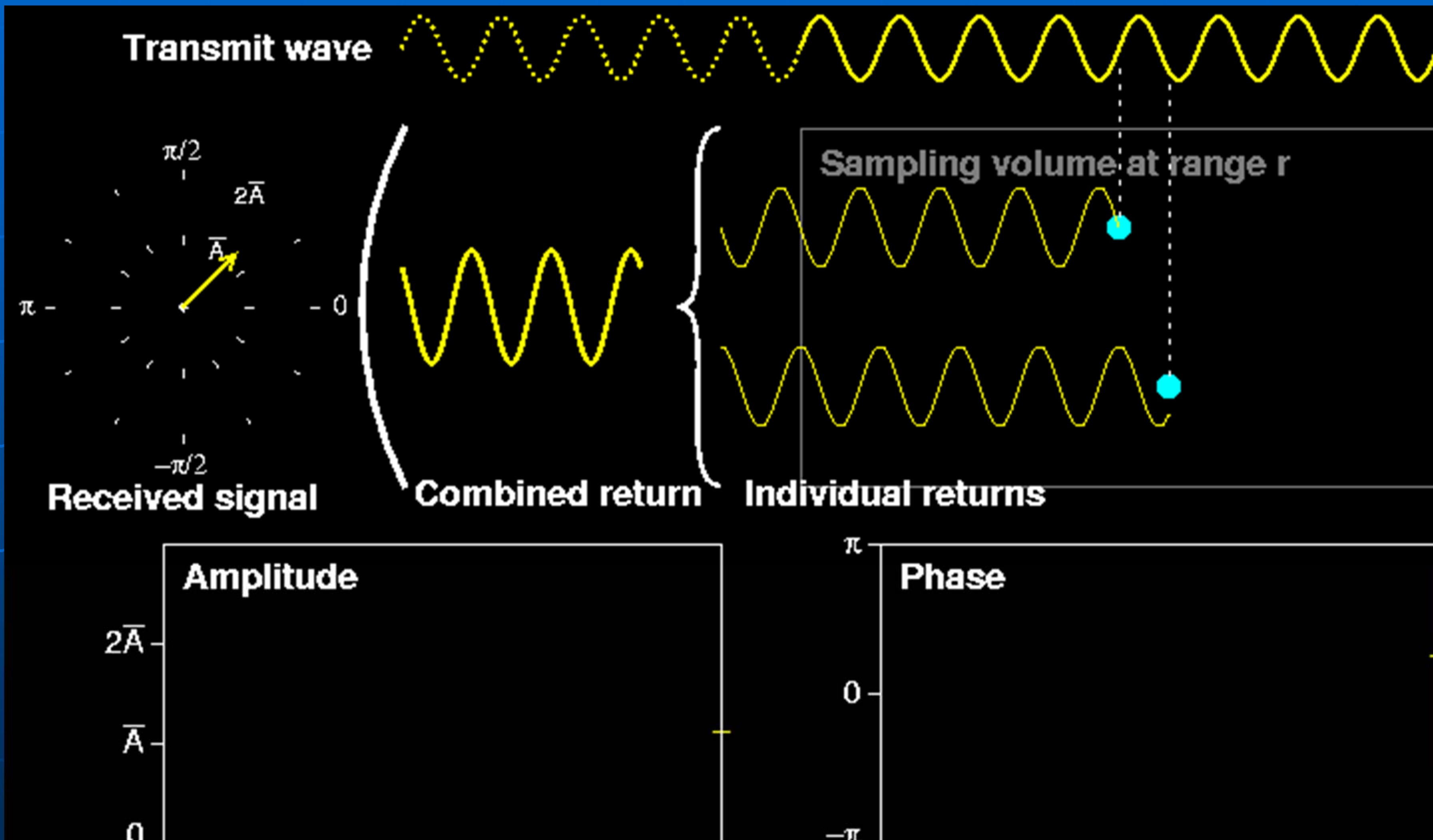
1) Transmitted single-frequency radar pulses illuminate a volume of space
2) Amplitude and phase of backscattered wave depend on size and position of targets
3) Combination of all individual waves into a single return wave back to the receiver
4) Amplitude A of the return wave
5) Phase φ with respect to the transmitted wave
6) Constructive interference results in the strong signal (7)
8) Destructive interference results in the weaker signal (9)

The amplitude fluctuates in time as targets move with respect to each other and in and out of configurations where constructive (6b) and destructive (8b) interference dominate.
Hence, it is necessary to sample echoes for a certain amount of time (at least 30 samples over tens of milliseconds)
This requirement limits the scanning rate of radars to a few rotations per minute.

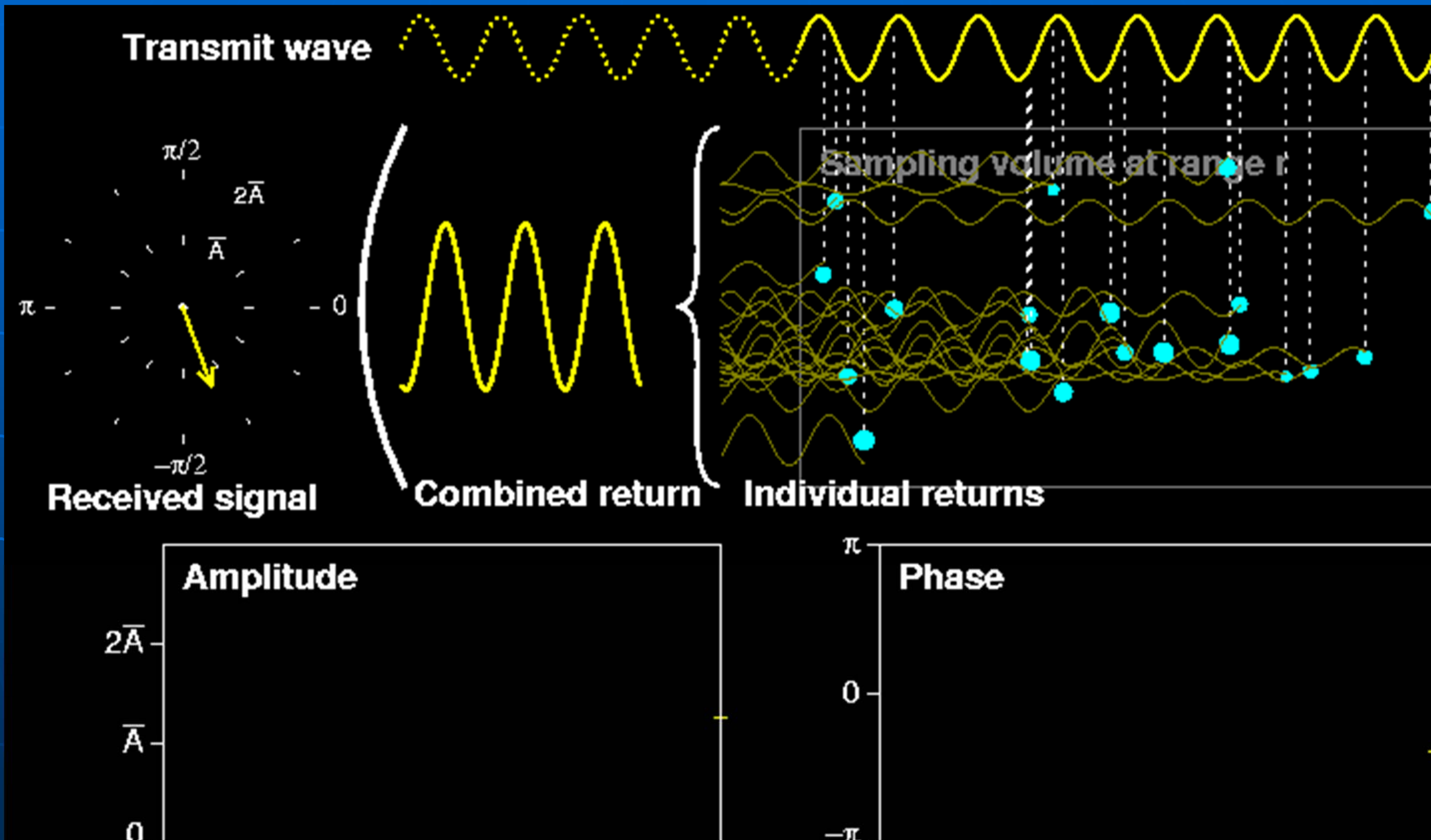
Radar Signal: One Moving Particle



Radar Signal: 2-Particles Situation



Radar Signal: Multiple-Particles Situation



Sampling Considerations: McGill Radar

PRF=1200 Hz Pulse length=1 µsec Scanning rate=6 rpm
Typical polar resolution bin: 1 km by 1° azimuth = 1 archived *datum*

10 sec/rot → 36 deg./sec → 27.8 milliseconds /deg. in azimuth
1200 pulses over 36 degrees, (~33 pulses/deg. of azimuth)

A 1 µsec pulse has a **physical length** of 300 m but an **effective length** of 150 m
(leading edge of the pulse returns to the radar at the same time as the back edge)

1 km sampling is achieved by averaging 7 pulses in range

1 polar datum is the result of averaging (33 x 7) = 231 measurements
(~ 16 x 7) = 112 with a PRF of 600 Hz)

Averaging is first done in azimuth over the 33 pulses of a fixed range.
The 7 resulting averages are then combined into one representative value

RADAR EQUATION

For a volume filled with Rayleigh targets (small compared with wavelength λ)

Radar Equation: $P_r = C\ \{P_t\, t / \theta\varphi\lambda^2\}\ \{L^2\}\ \{|K^2|\, Z / r^2\}$

(1) (2) (3) (4)

1- **Constants**

2- **Radar parameters**: Transmitted Power P_t, (W), pulse duration t, (s), horiz. and vertical angular beam widths $\theta\varphi$, (rad) and wavelength λ, (m)

3- **Path terms**: Two-way attenuation losses

4- **Target properties**: Index of refraction K^2 (**water: 0.93 ice:0.20**), reflectivity factor Z and range r (m)

Radar reflectivity factor Z

$$Z = \sum N(D)\, D^6\, dD \qquad (mm^6/m^3)$$

N(D): # of particles with diameter between D and (D+dD)

REFRACTION of the RADAR SIGNAL

- Refractive index ***n*** at microwave frequencies is dependent on pressure **P**, temperature **T** and water vapor pressure **e**:

  $n = 1 + 10^{-6}(77.6\ \mathbf{P}/\mathbf{T} + 373000\ \mathbf{e}/\mathbf{T}^2)$

  $= (1 + \sim 300\ \text{ppm})$ near sea level

Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Under normal conditions, since ***n*** decreases with height, the path of the radar pulse bends towards the ground, but at a slower rate than Earth's curvature. Near the surface, $dn/dz = \sim -40 \cdot 10^{-6}$/km

4/3 Earth radius approximation used to determine H

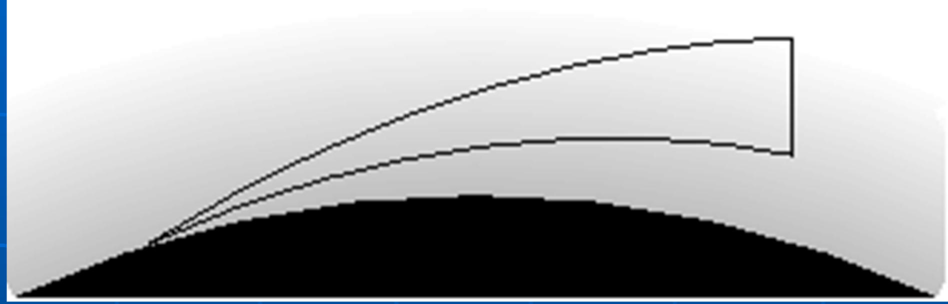
If it is very different, anomalous propagation (AP) will occur.

If superrefraction is very strong ($< -157 \cdot 10^{-6}$/km), the radar beam bends faster than the curvature of the Earth, causing "trapping" in the lowest 100 meters and very large AP echoes.

Normal Refraction

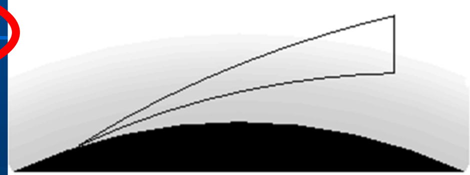
$dn/dh = -40 \cdot 10^{-6}\ km^{-1}$

Bends towards the denser part of the medium



Sub Refraction

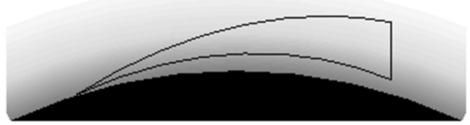
$dn/dh > -40 \cdot 10^{-6}\ km^{-1}$



Unusually warm and/or dry conditions close to the ground, e.g.: Chinooks.

Super Refraction

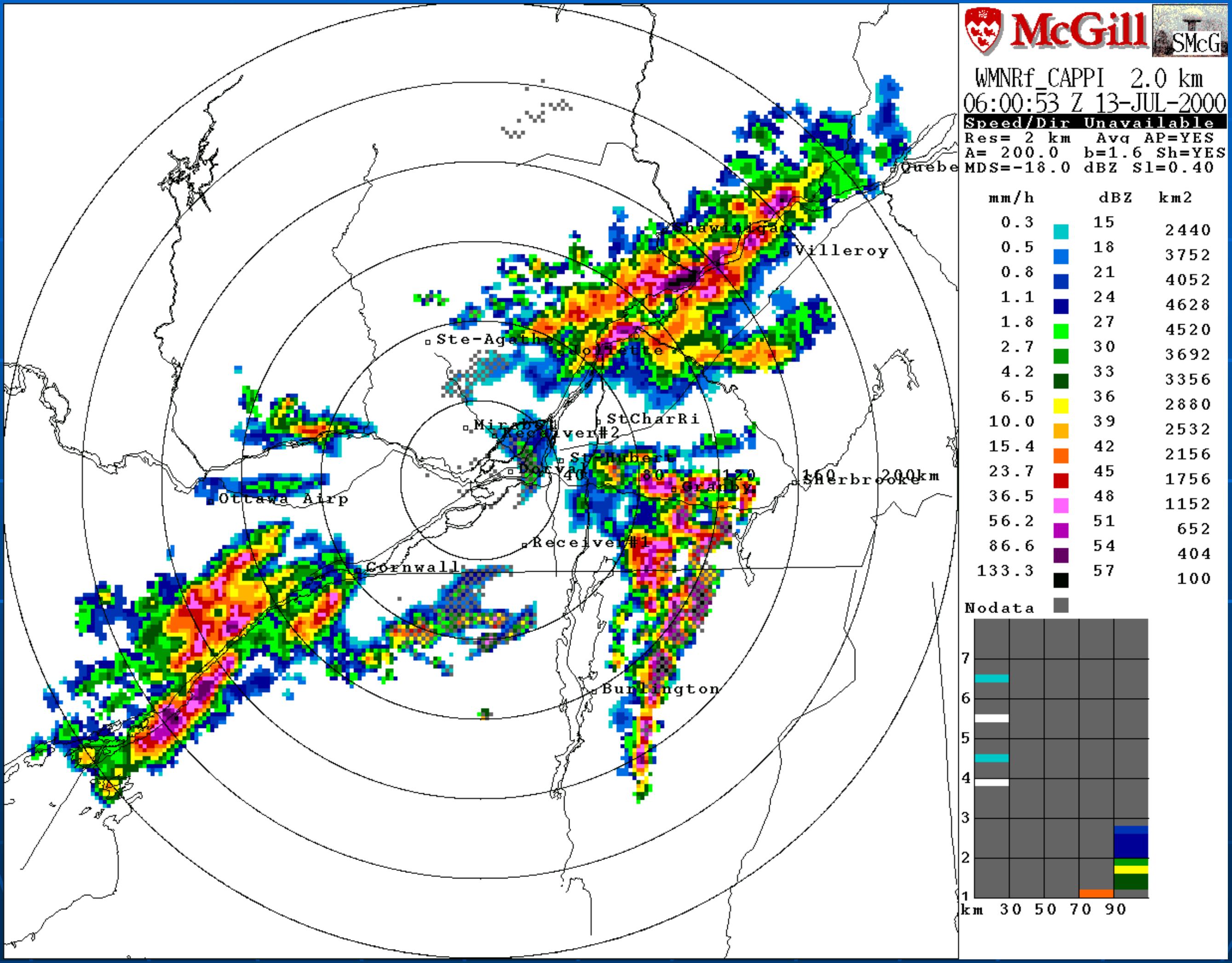
$dn/dh < -40 \cdot 10^{-6}\ km^{-1}$



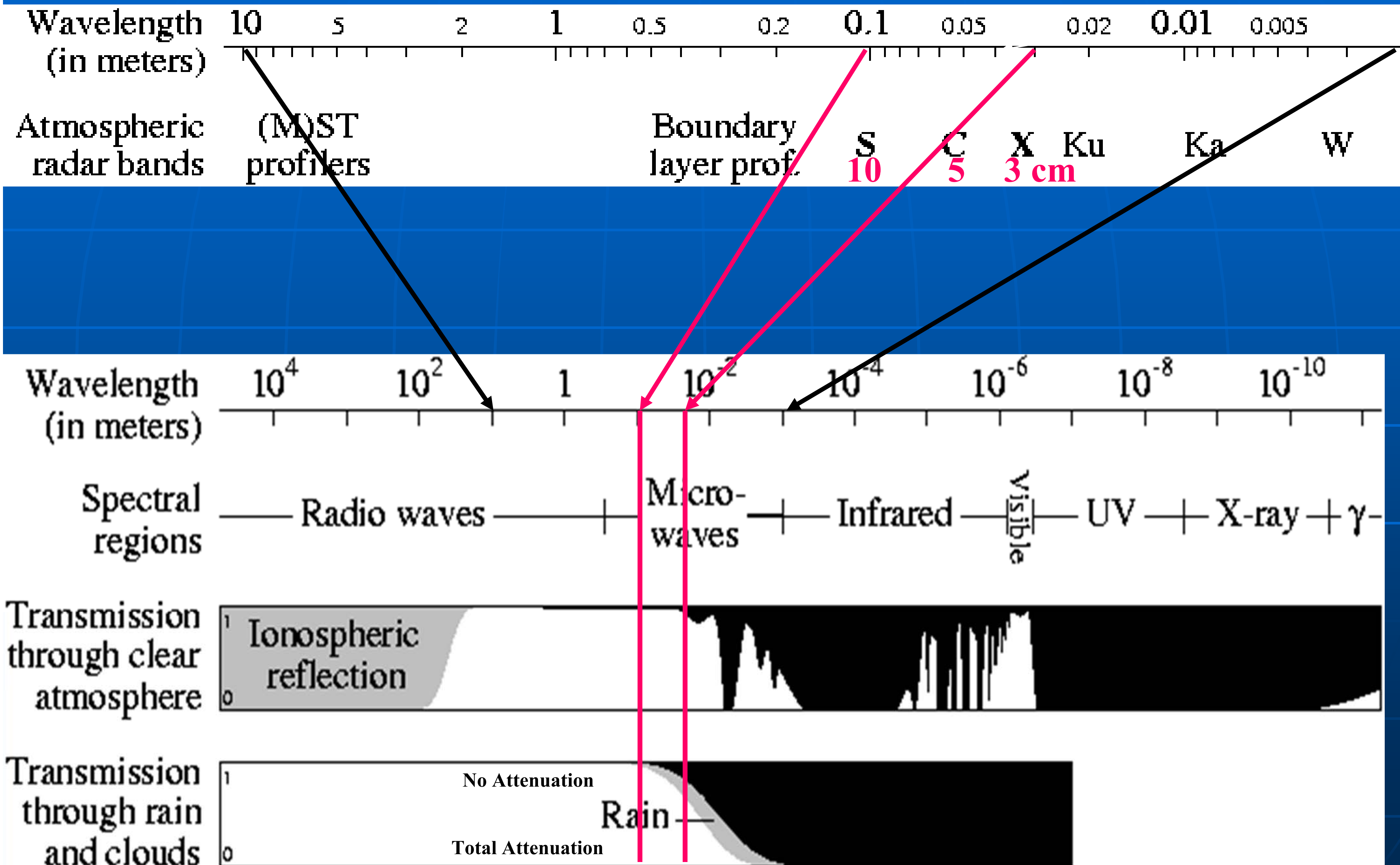
Unusually cold and/or humid conditions close to the ground, e.g.: inversions, storm outflows.

(Prevented detection of bombers during WW-2)

Example of AP



Radar Wavelength: λ



How wavelength affects radar characteristics

1- For a given antenna beam width, antenna size grows with wavelength

2- Resolution (m) =~ 1.4 * Distance to target * wavelength /antenna size

S-Band: 1.4*60*0.104/9 = ~ 1 km 9 m antenna

X-Band: 1.4*60*0.03/2.5 = ~ 1 km 2.5 m antenna

3- Attenuation in rain increases with decreasing wavelength

4- For a given sensitivity to precipitation, system costs generally increase with wavelength

Types of Targets

1- Hydrometeors (Rain, snow, hail, ice pellets)

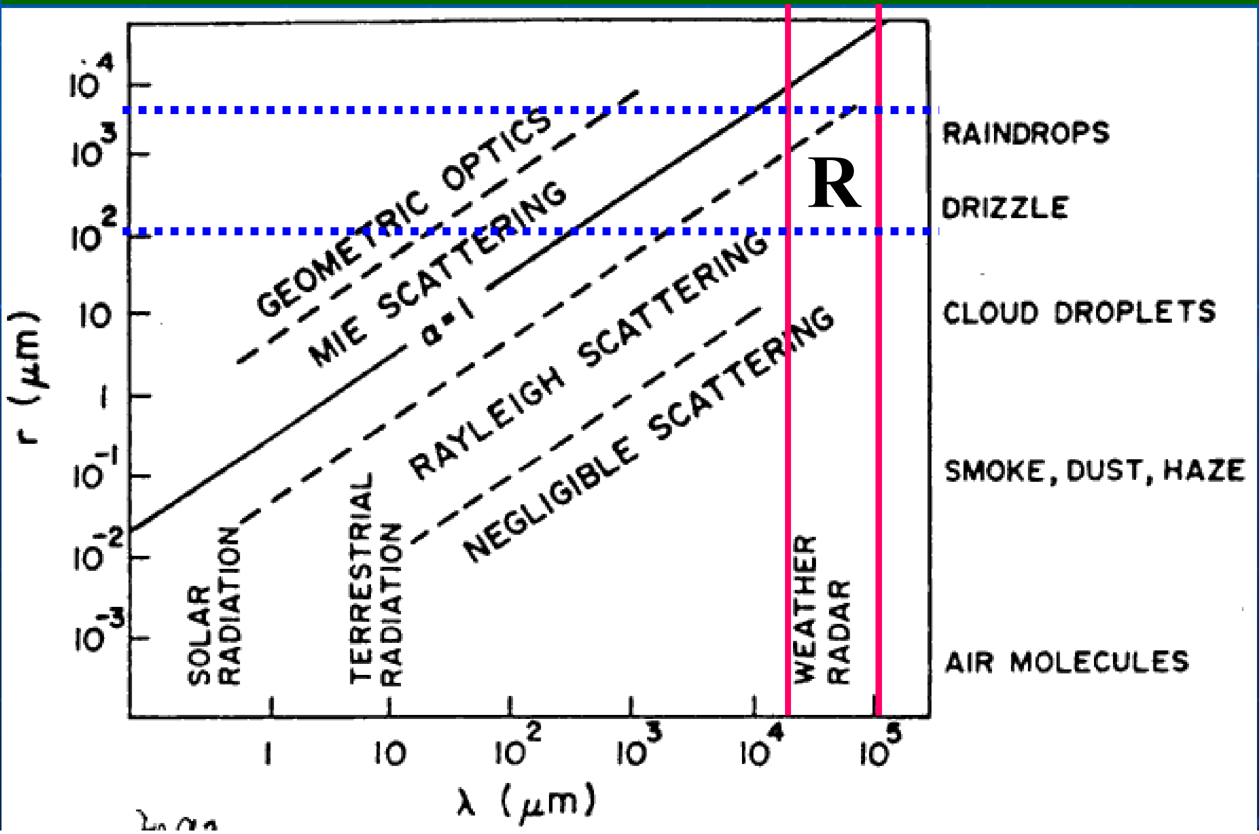
For most radars, they are **Rayleigh** scatterers: $\alpha < 0.2$ where $\alpha = 2\pi a/\lambda$

Scattering is proportional to $\mathbf{D^6 \lambda^{-4}}$

2- Refractive index gradients

Moisture and temperature gradients due to turbulence: prop. to $\mathbf{\lambda^{-1/3}}$

As λ increases, these echoes become stronger wrt hydrometeor echoes

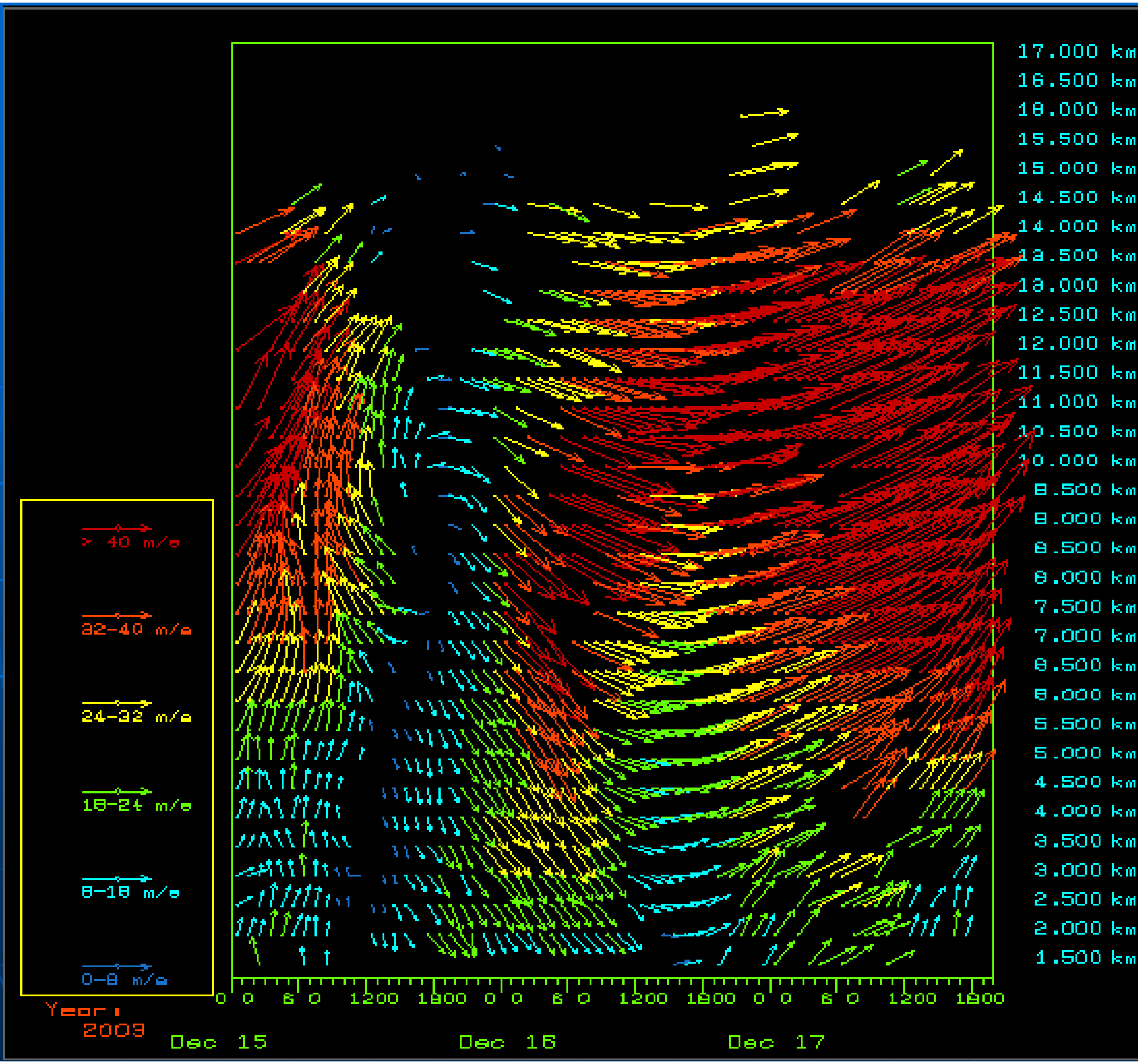


Rayleigh particles:

Band	Diam.
S (10)	< 7 mm
C (5)	< 3.5 mm
X (3)	< 2.1 mm

LONG WAVELENGTH RADARS (several meters)

- **Huge antenna is required and/or poor angular resolution**
- **Radar is sensitive to turbulence, thus getting echoes all the time up to a certain distance/altitude (No need to wait for precipitation)**
- **Thus used for wind profiling**



17.000 km
16.500 km
16.000 km
15.500 km
15.000 km
14.500 km
14.000 km
13.500 km
13.000 km
12.500 km
12.000 km
11.500 km
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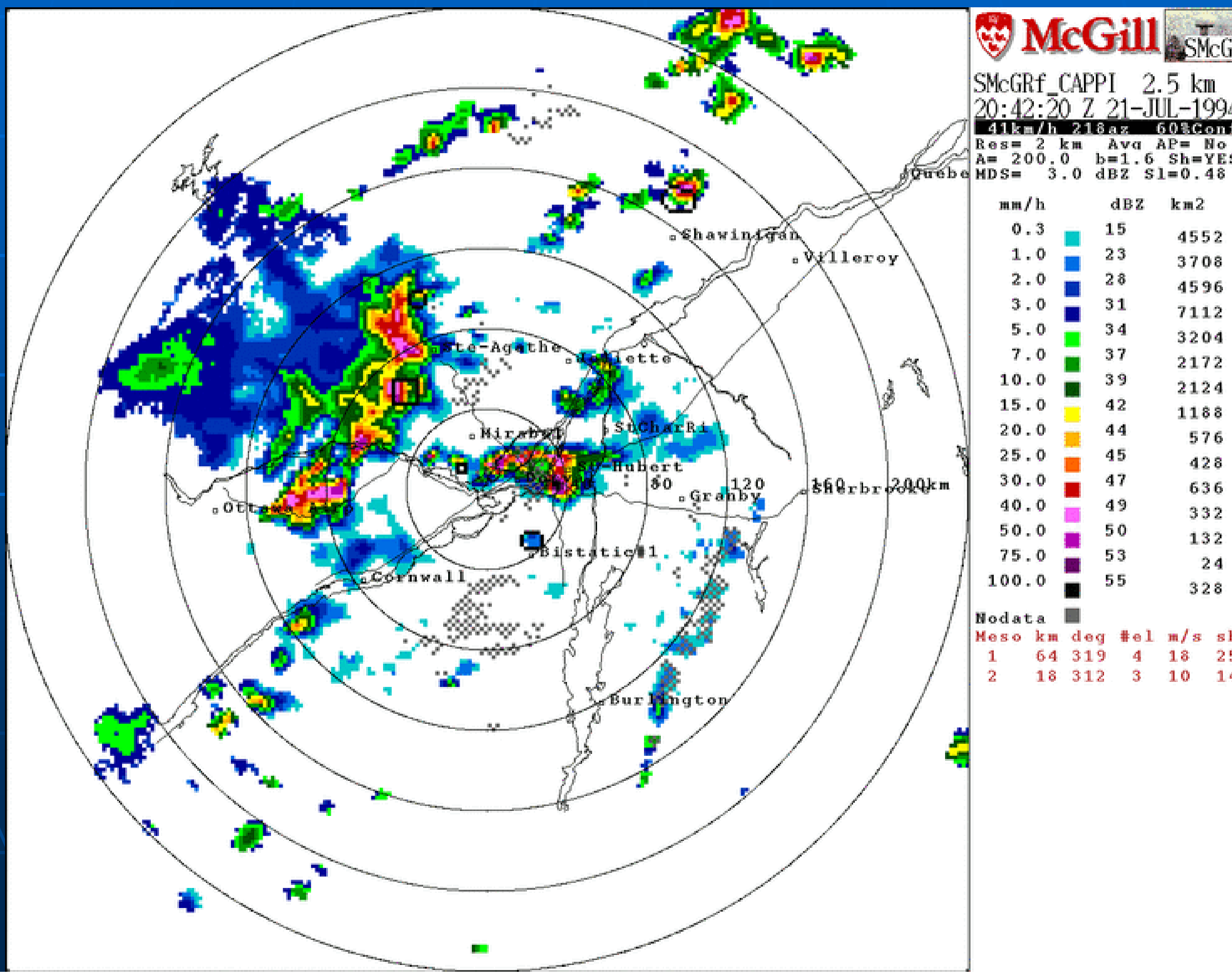
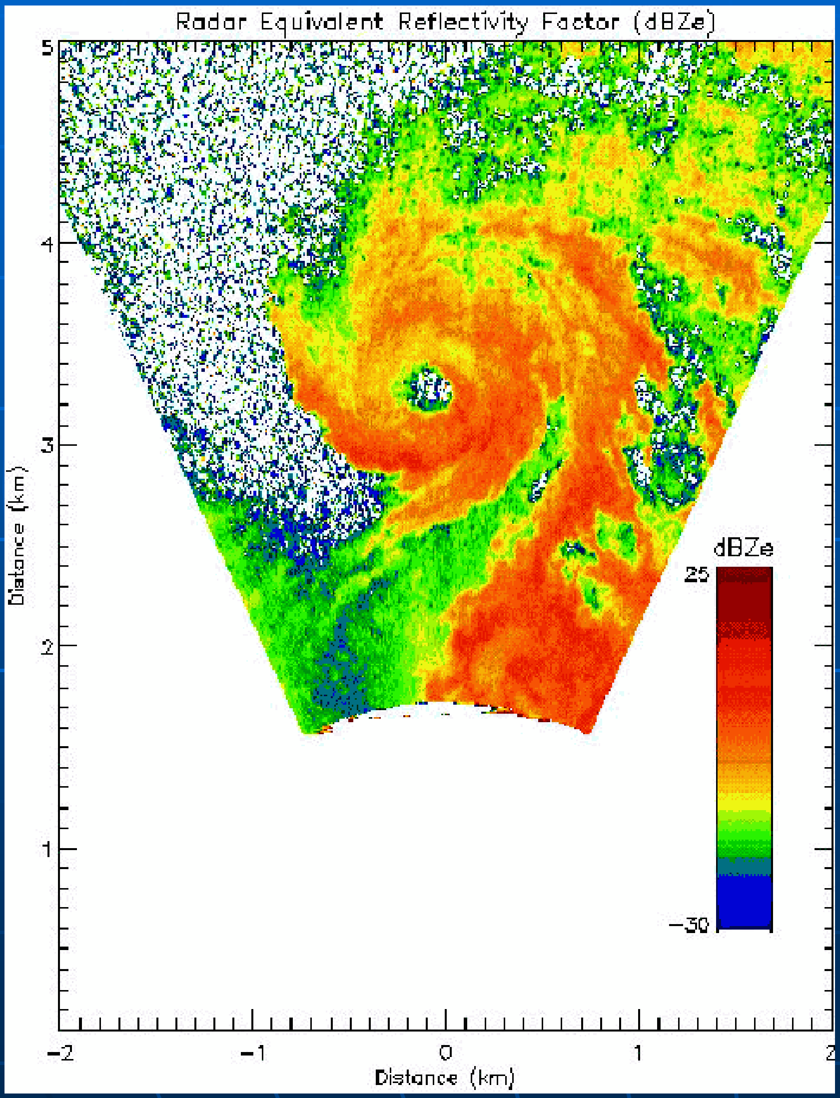
6.000 km
5.500 km
5.000 km
4.500 km
4.000 km
3.500 km
3.000 km
2.500 km
2.000 km
1.500 km
> 40 m/s
32-40 m/s
24-32 m/s
16-24 m/s
8-16 m/s
0-8 m/s
Year:
2003
0 0 6 0 1200 1800 0 0 6 0 1200 1800 0 0 6 0 1200 1800
Dec 15
Dec 16
Dec 17

MEDIUM WAVELENGTH RADARS (3-10 cm)

- A large antenna (several meters) yields a good angular resolution (1° azimuth)
- Radar is sensitive to precipitation of all kinds (rain, drizzle, snow, hail) but also to ground echoes. (3 and 5 cm affected by attenuation).
- Used for weather surveillance and rainfall estimation.



SHORT WAVELENGTH RADARS (~mm)



- Excellent angular resolution and sensitivity to smaller hydrometeors
- Limited penetration through moderate precipitation
- Used for cloud research

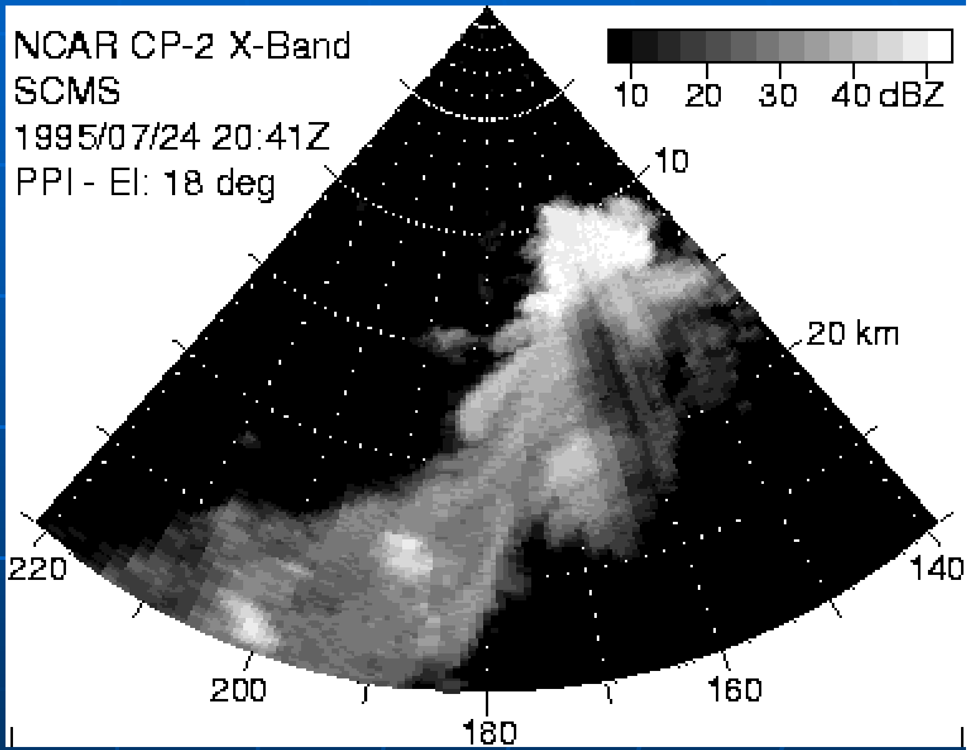
ATTENUATION of Radar Signal

- Gases (oxygen, water vapor) (1.5 db/100 km)
- Hydrometeors (rain, snow, hail)
- Increases rapidly with decreasing wavelength

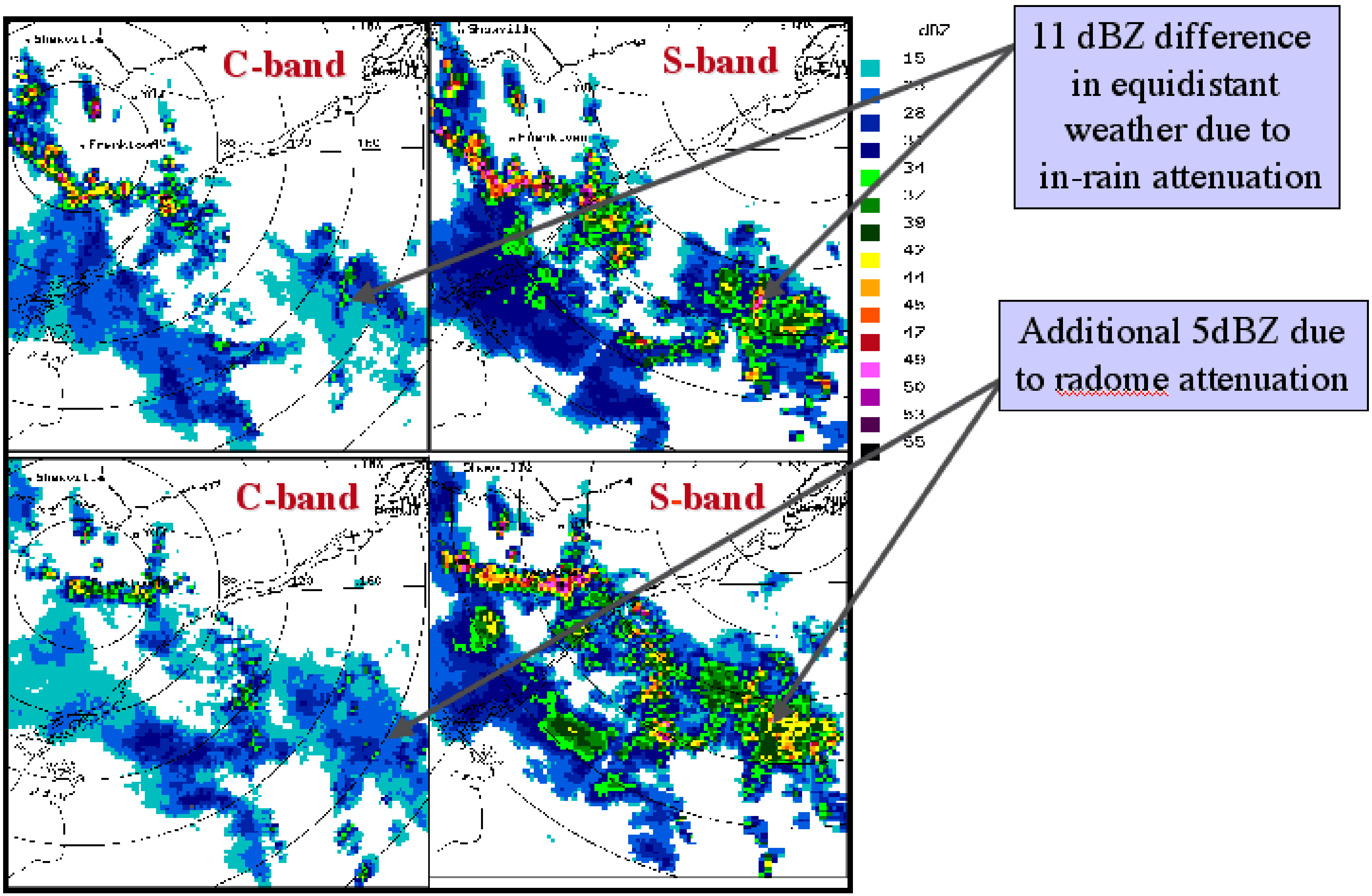
Negligible at S-band (10 cm)
Moderate at C-band (5 cm)

Pronounced at X-band (3 cm)
(nearly proportional to Rainrate)

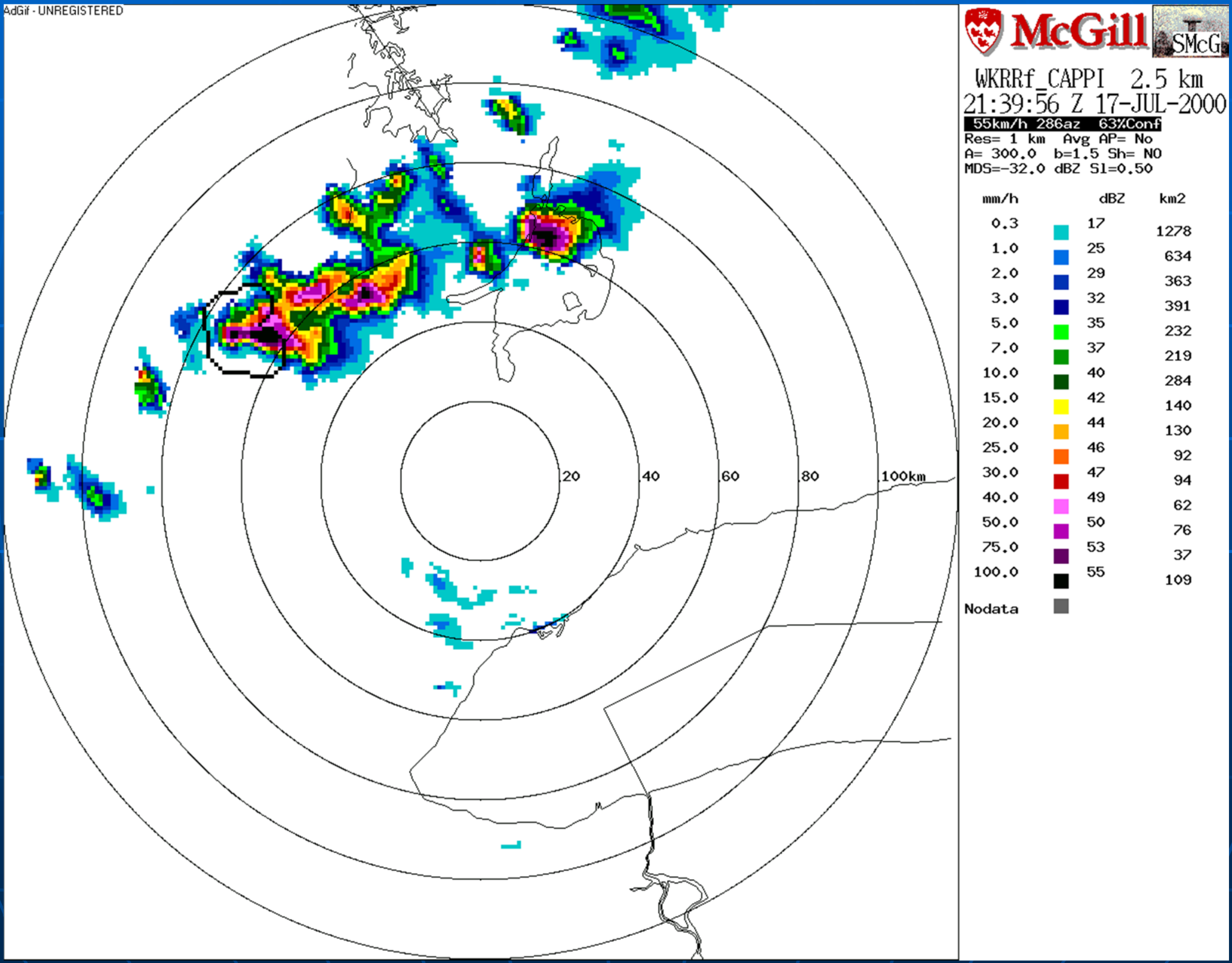
Radome attenuation is an additional problem at C- and X-band.



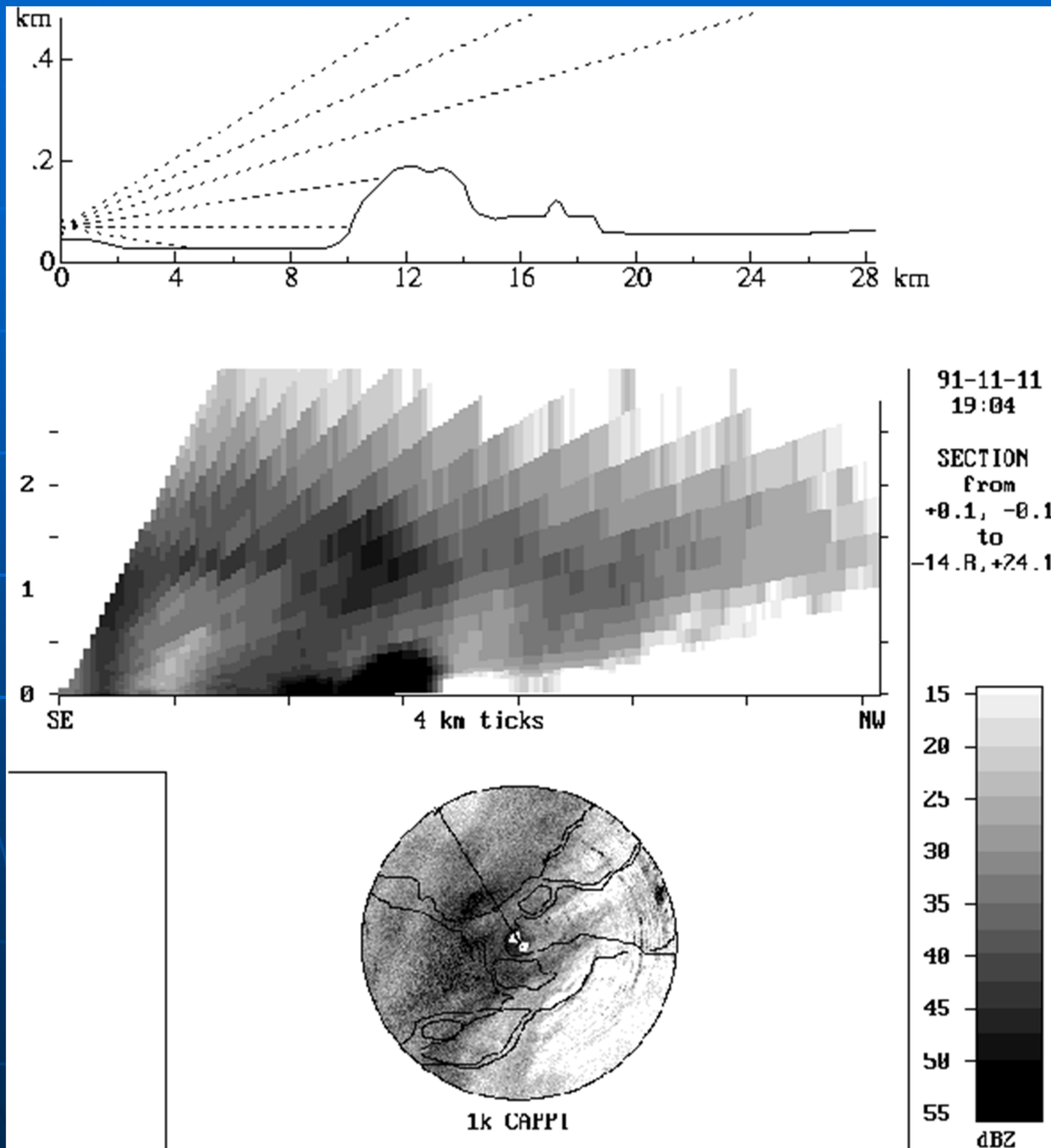
Attenuation at C-band: Franktown example



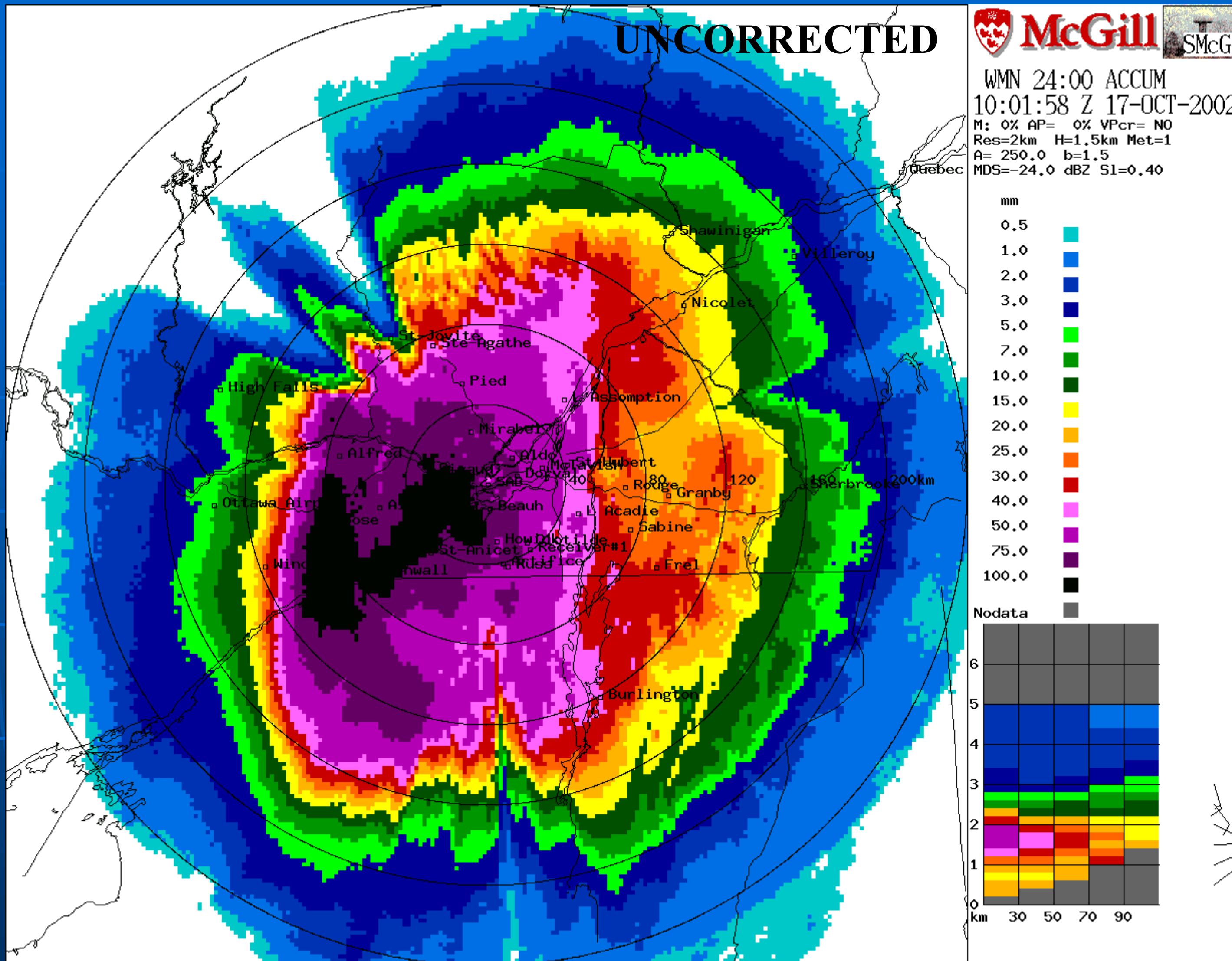
C-Band Attenuation: Toronto Radar



BEAM BLOCKAGE of Radar Signal



Short hills nearby are more of a problem than tall mountains far away.

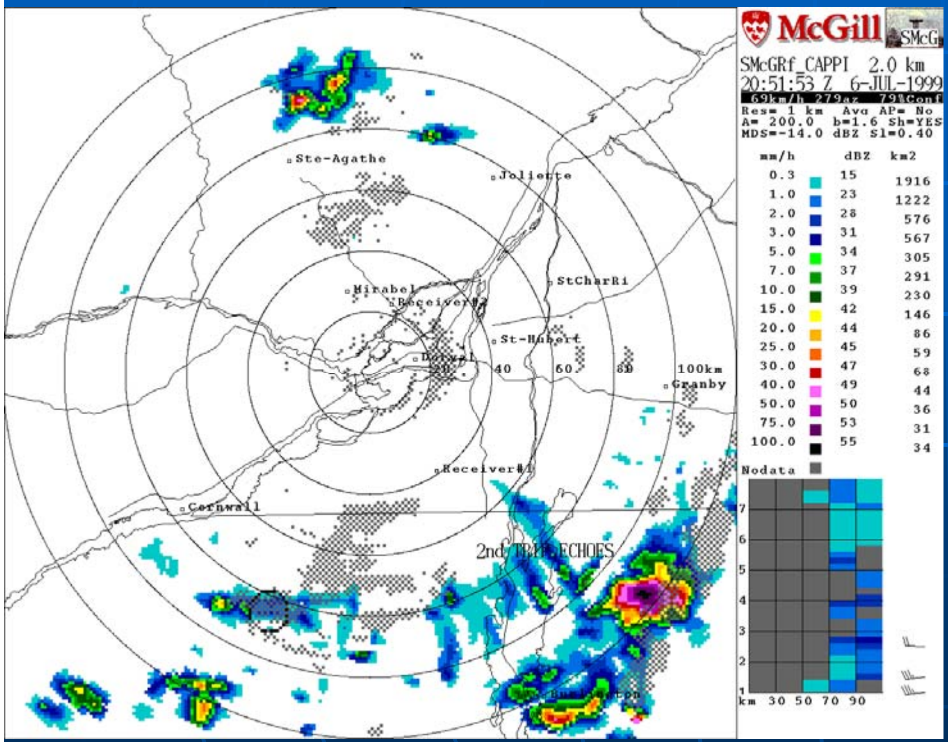


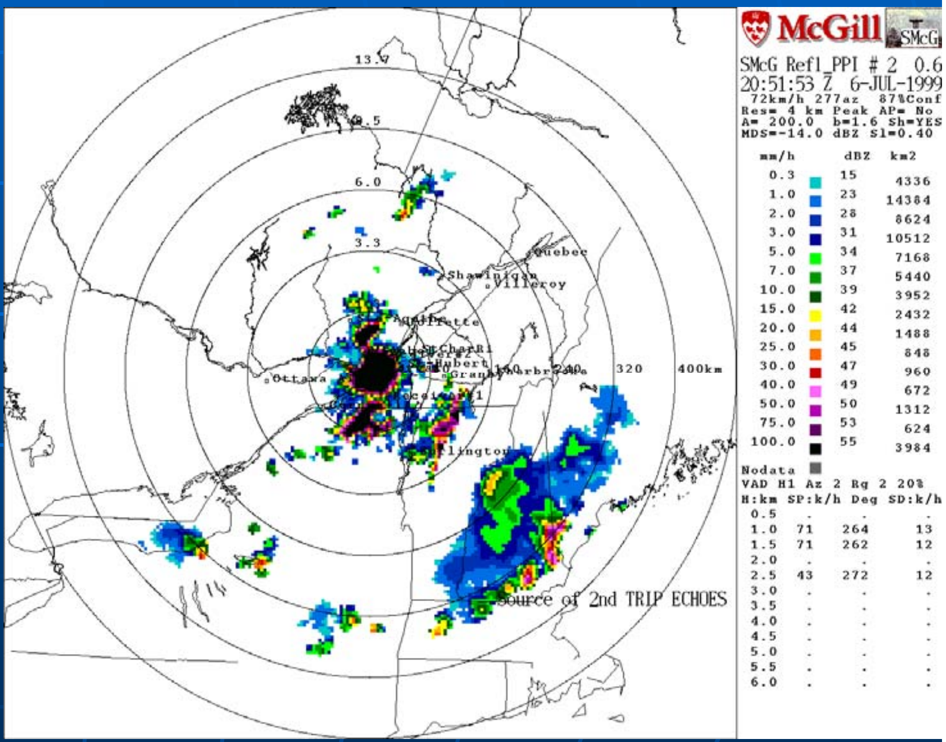
Beam blockage becomes very apparent on a long term accumulation of stratiform precipitation. Observe the distinct shadows in the NW, ESE and South.

Maximum Unambiguous Range

Maximum unambiguous range $R_{max} = ½(c/PRF)$ = 250 km with PRF=600

Ambiguity occurs when echoes from very distant storms (> 250 km) reach the antenna **AFTER** the transmission of the next pulse. (Frequent at low elevation angles)





Strong echoes at Range ~ 340 km are unfolded at range ~(340-250) = ~90 km

REFLECTIVITY FACTOR and RAINFALL RATE

- Reflectivity Factor $Z = \sum N(D)\, D^6\, dD$
- Rainfall Rate $R=(\pi/6)\sum N(D)D^3(v(D)-w)\, dD \;=\; \sim (\pi/6)\sum N(D)D^{3.6}\, dD$

  V(D): raindrop fall speed w = vertical air motion

D	D^6	Z	Volume (D^3)
1 mm	1 x 1 x 1 x 1 x 1 x 1	1	1
2 mm	2 x 2 x 2 x 2 x 2 x 2	64	8
3 mm	3 x 3 x 3 x 3 x 3 x 3	729	27
	TOTAL:	**794**	**36**

No mathematical relationship exists between Z and R, mainly because N(D) varies with rain intensity and precipitation microphysics.

Empirically, from measurements,

$N(D)\ (m^{-3}mm^{-1}) = 8000 \exp(-4.1R^{-0.21}D)$ (Marshall-Palmer 1948)

$\mathbf{Z = 200\, R^{1.6}}$ (stratiform) or $\mathbf{Z=300R^{1.5}}$ (convective)

Radar was transformed from a **qualitative** to a **quantitative** instrument.

Radar meteorology became a **science**

Interpretation of the Radar Reflectivity Scale

Because Z spans several orders of magnitude, it is generally expressed in **dBZ** = 10 log10(Z) Ex: $Z = 200\ mm^6/m^3$ → 23 dBZ

Type and Intensity	Reflectivity
Drizzle or clear air targets (insects)	0 dBZ
Very light rain or snow (A few raindrops or snowflakes)	10 – 15 dBZ
Light rain or snow (Typical spring/fall 1 - 2 mm/hr)	20 – 30 dBZ
Moderate precipitation (3 – 10 mm/hr)	30 – 40 dBZ
Heavy rain (Summer showers: 20 mm/hr)	45 – 50 dBZ
Very heavy rain or hail (Thunderstorm core: 100 mm/hr)	55 - 60 dBZ
Strong ground echoes	> 60 dBZ