SECOND YEAR: 2604
Intermediate Applied Physics
PLANETARY REMOTE SENSING
Lecture 7: radar basics

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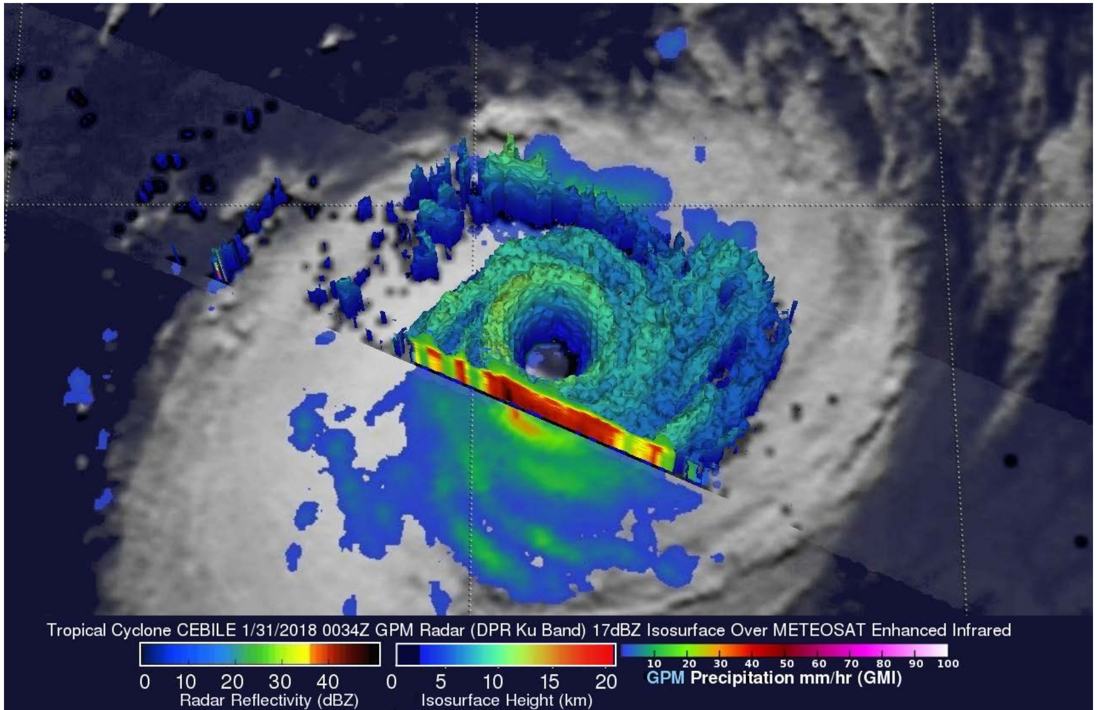
http://www.metoffice.gov.uk/public/weather/observation/rainfall-radar



Purpose of lecture

Radar basics

The purpose of lecture is the following:

- **To explain the basic principle of radars**

- **To introduce the radar equation for single and distributed targets**

Next two radar lectures: we will provide examples for atmospheric radars, altimeters and SARs.

Radio Detection and Ranging

RADAR - RAdio Detection And Ranging
LIDAR - LIght Detection And Ranging
SODAR - SOund Detection And Ranging

Radar is a remote sensing technique: Capable of gathering information about objects located at remote distances from the sensing device.

Two distinguishing characteristics:

1. **Employs EM waves that fall into the microwave portion of the electromagnetic spectrum**

   $(1 \text{ mm} < \lambda < 75 \text{ cm})$

2. **Active technique: radiation is emitted by radar – radiation scattered by objects is detected by radar.**

Radar wavelength

Band	Wavelength	Frequency
HF	10-100 m	3-30 MHz
VHF	1-10 m	30-300 MHz
UHF	0.3-1 m	300-1000 MHz
L	15-30 cm	1-2 GHz
S	8-15 cm	2-4 GHz
C	4-8 cm	4-8 GHz
X	2.5-4 cm	8-12 GHz
K_u	1.7-2.5 cm	12-18 GHz
K	1.2-1.7 cm	18-27 GHz
K_a	0.75-1.2 cm	27-40 GHz
W	2.7 - 4 mm	75-110 GHz

Windprofiler

NEXRAD

MetOffice Radar Network

Wind scatterometers

TRMM PR (13.8 GHz)

Cloud radar

CloudSat CPR (94 GHz)

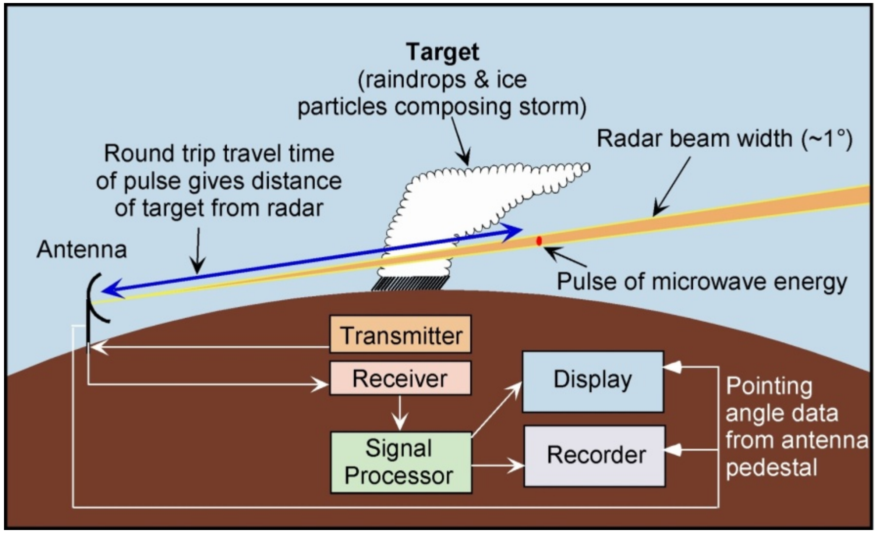
Altimeters

RADARSAT SAR

TERRA-SAR

GPM

How a Pulsed Radar Works

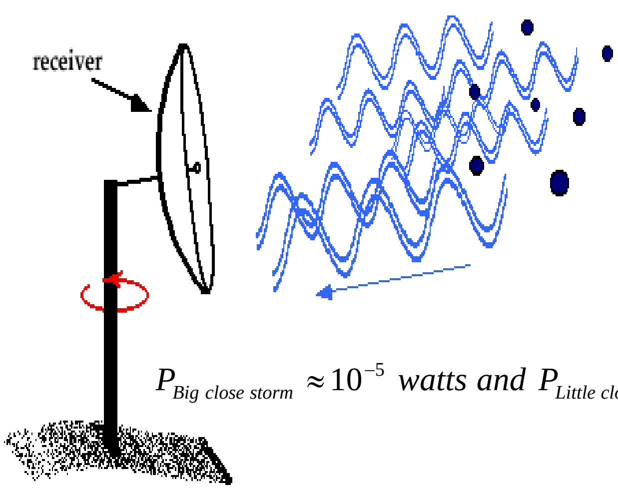


Radar transmits a wave of electromagnetic energy (pulse)

-Energy scatters in all directions

-A ***very*** small portion is reflected back from the target (raindrop)

$P_t \approx kW \text{ or higher}$



Collectively, the energy is scattered back to the radar from millions of droplet to generate the radar reflectivity

$P_{Big\ close\ storm} \approx 10^{-5} \text{ watts and } P_{Little\ cloud\ at\ far\ range} \approx 10^{-13} \text{ watts}$

dB terminology

Common ways to express power (basic unit: watts):

$$dB = 10\log_{10}\left(\frac{P_1}{P_2}\right)$$

decibels
(e.g. SNR is expressed in dB)

$$dBm = 10\log_{10}\left(\frac{P_1}{1\,mW}\right)$$

$$dBW = 10\log_{10}\left(\frac{P_1}{1\,W}\right)$$

How a Pulsed Radar Works

Meteorological radars send out <u>pulses</u> of energy with relatively long periods of “listening” between pulses. Pulses are required, rather than continuous waves, to determine the distance to the target.

Pulse duration (τ_p, μs) and pulse length (h, meters)

Pulse repetition period [msec] and pulse repetition frequency [s^{-1}]

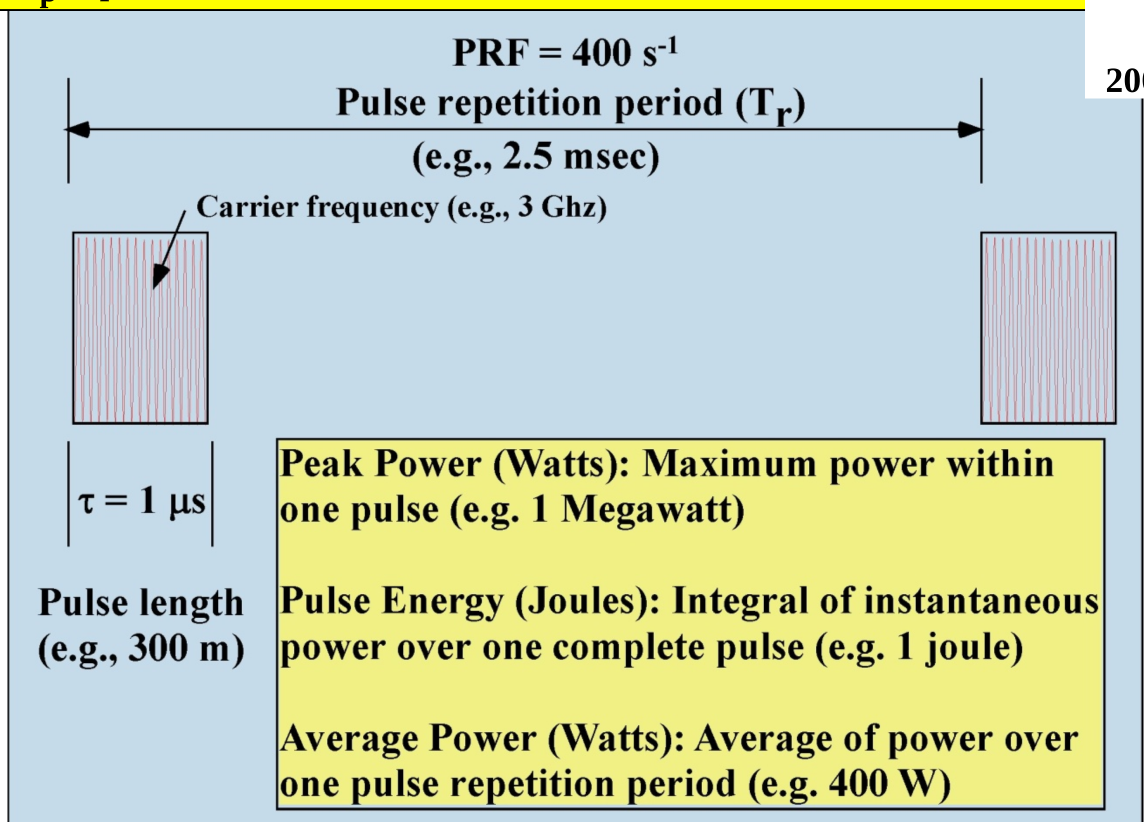
Duty Cycle (= τ_p/T_r)

Typical values

$200\text{Hz} < \text{PRF} < 8000\text{Hz}$

Typical values

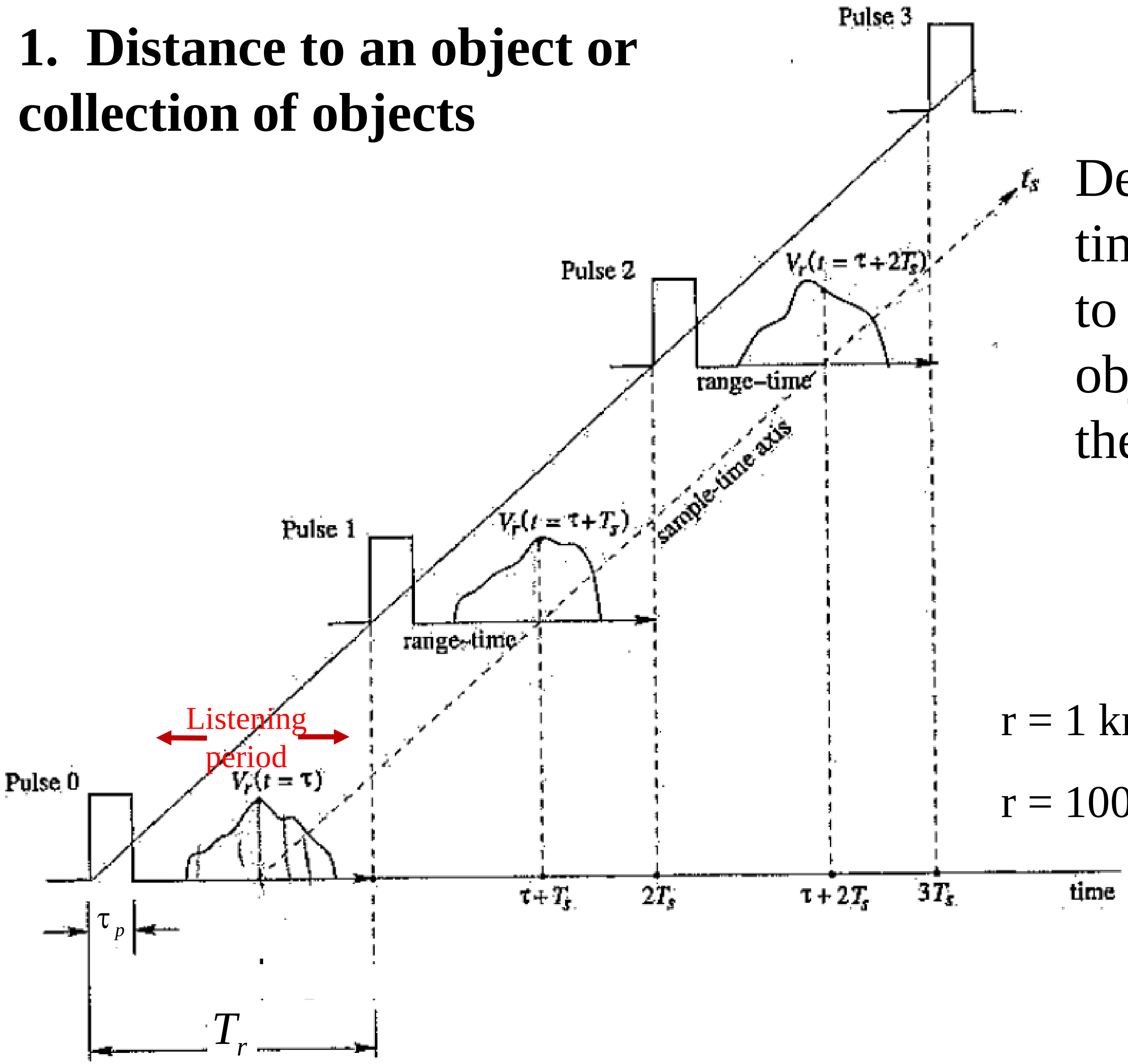
$0.1 < \tau_p < 10$ μs



This sequence is repeated indefinitely

What does a conventional pulsed radar measure?

1. Distance to an object or collection of objects



Determined by the time it takes energy to travel to the objects and return at the speed of light.

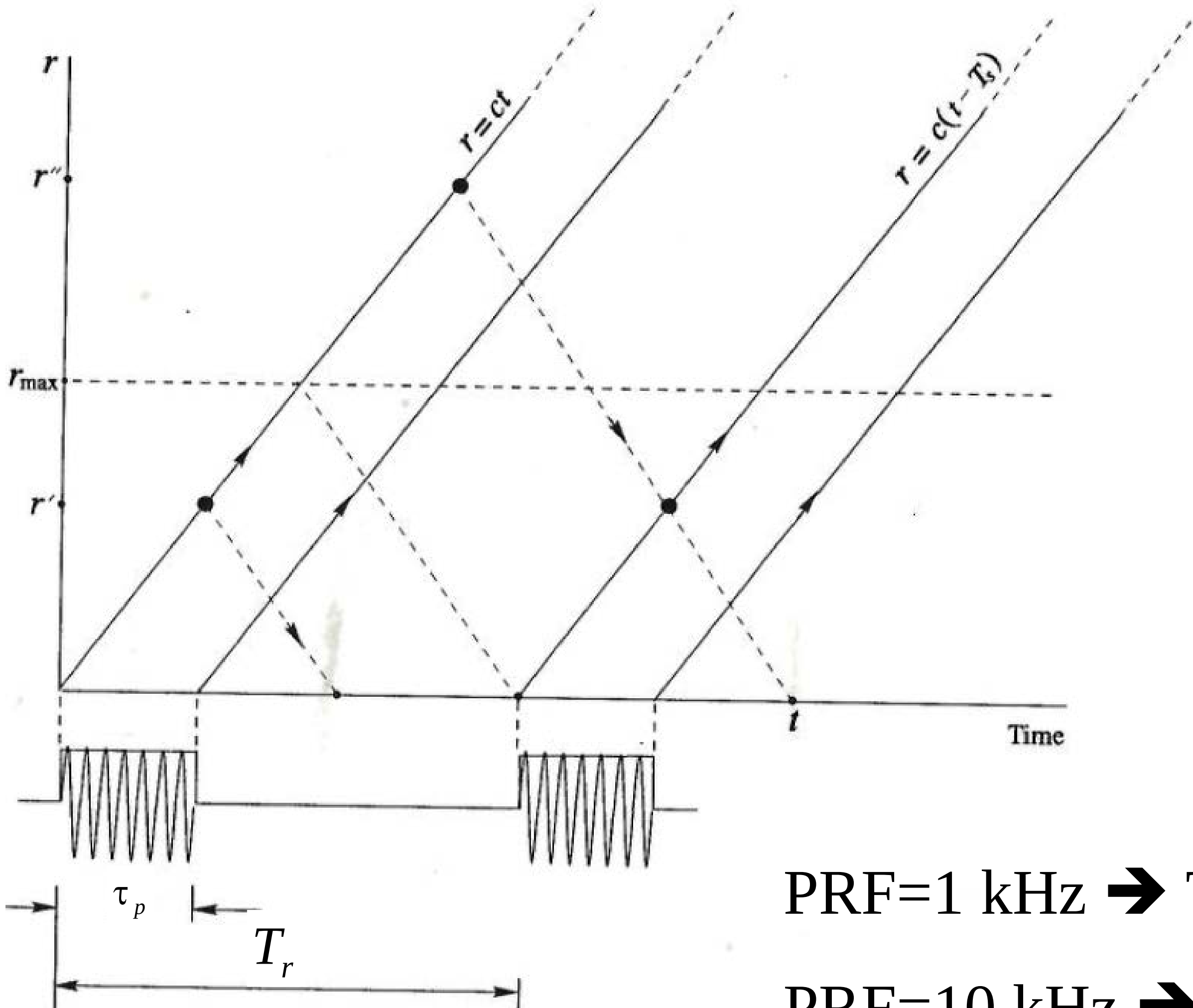
$$r = \frac{c\Delta t}{2}$$

r = 1 km ⇔ Δt = 6.67 μs

r = 100 km ⇔ Δt = 0.667 ms

Maximum unambiguous range

Maximum Unambiguous Range (r_{max}): The maximum distance that an object can be located such that a pulse arriving at the object can return to the radar before another pulse is emitted.



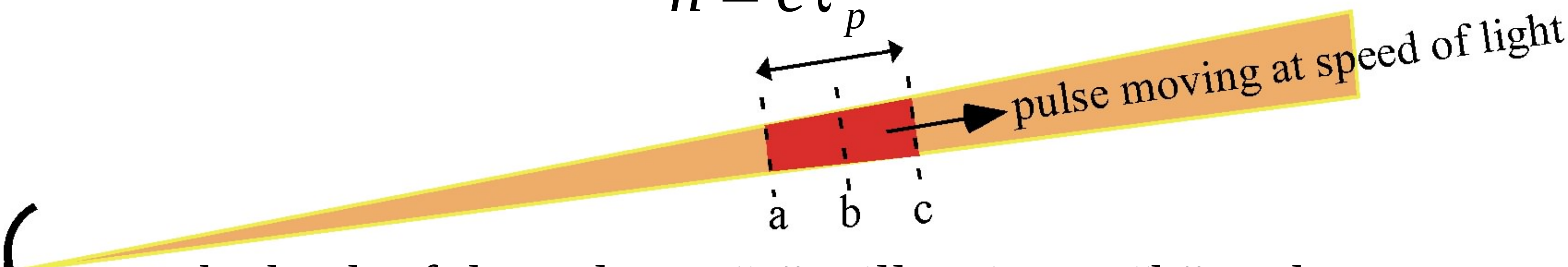
$$r_{\max} = \frac{cT_r}{2} = \frac{c}{2(PRF)}$$

PRF=1 kHz ➔ T_r=1 ms ➔ r_{max}=150 km

PRF=10 kHz ➔ T_r=10 ms ➔ r_{max}=15 km

Resolution along the direction of the beam: distributed targets

$$h = c\tau_p$$



The back of the pulse at “a” will arrive at “b” at the same time that radiation scattered from objects at the front end of the pulse at “c” will arrive back at “b”.

When energy arrives back at the radar, an instantaneous sample will include all radiation scattered between locations b and c: the sample volume is half the pulse length (<u>*h/2*</u>).

$$\boxed{\Delta r = \frac{h}{2} = \frac{c\tau_p}{2}}$$

Examples

τ_p=3.3μs ➔ Δr=500 m

τ_p=0.6μs ➔ Δr=100 m

Radar equation for an isolated target

Measurement of the echo power received from a target provides useful information about it.

The radar equation provides a relationship between the received power, the characteristics of the target, and characteristics of the radar itself.

Steps in deriving the radar equation for an isolated target:

1) **Determine the radiated power per unit area (the power flux density) incident on the target (key quantity= antenna gain)**
2) **Determine the power flux density scattered back toward the radar (key quantity=radar cross section)**
3) **Determine the amount of power collected by the antenna (key quantity=antenna effective area).**

Isotropic antenna

Consider an isotropic antenna = an antenna that transmits radiation equally in all directions

Power flux density (*S*, *watts/m*^{2}) at radius r from an isotropic antenna

$$\boxed{S_{isotropic} = \frac{P_t}{4\pi r^2}} \qquad (1)$$

where P_t is the transmitted power.

In a radar system we want to identify the angular position of the object

➔ antennas that focus radiation in a particular direction are needed

Gain function

The gain is the ratio of the power flux density at radius *r*, azimuth θ, and elevation ϕ for a directional antenna, to the power flux density for an isotropic antenna radiating the same total power.

$$G(\theta,\phi)=\frac{S_{inc}(\theta,\phi)}{S_{isotropic}}$$

So from (1)

$$\boxed{S_{inc}(\theta,\phi)=\frac{G(\theta,\phi)P_t}{4\pi r^2}}$$

Gain-beamwidth-antenna size relationship

The width of the main beam is proportional to wavelength and inversely proportional to the antenna aperture

$$\Theta_{3dB} = \underbrace{1.22\frac{\lambda}{D}}_{in\ radiants} = \underbrace{70^o\frac{\lambda}{D}}_{in\ degrees}$$

(3-dB beamwidth of dish antenna)

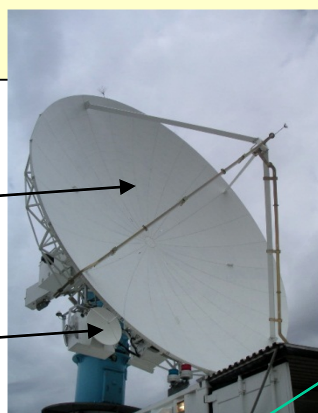
3dB≡ factor 2

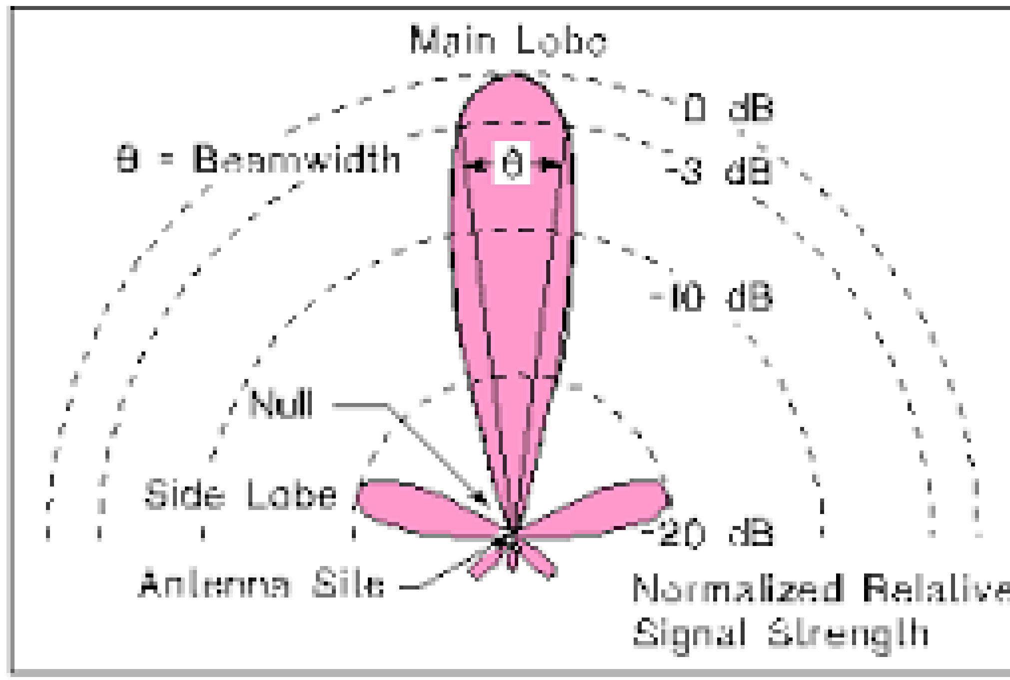
$$\lambda = 10\,cm;\quad D = 3\,m \quad \Rightarrow \Theta_{3dB} = 2.33^0$$

$$\lambda = 10\,cm;\quad D = 6\,m \quad \Rightarrow \Theta_{3dB} = 1.17^0$$

$$\lambda = 8\,mm;\quad D = 0.5\,m \quad \Rightarrow \Theta_{3dB} = 1.12^0$$

Large wavelength radars = big antenna
Small wavelength radars = small antenna for same beam width (i.e. same resolution)





beamwidth

10 cm

0.8 cm

Circular antennas

$$G_{\max} = \frac{16}{(\Theta_{3dB}\Phi_{3dB})} = \frac{16}{(\Theta_{3dB})^2}$$

In radiants!!!!

Example

Compute the incident power density at 100 km range in the direction corresponding to the peak of the main lobe for an antenna with D=3m for a wavelength of 10 cm and for a transmitted power of 10^5Watts

$$\lambda = 10\,cm; \quad D = 3\,m \quad \Rightarrow \Theta_{3dB} = 1.22\frac{\lambda}{D} = 4.07 \times 10^{-2}\,rad$$

$$G_{\max} = \frac{16}{\left(\Theta_{3dB}\right)^2} = 9674.7 = 39.8dB$$

Target is at 100 km range

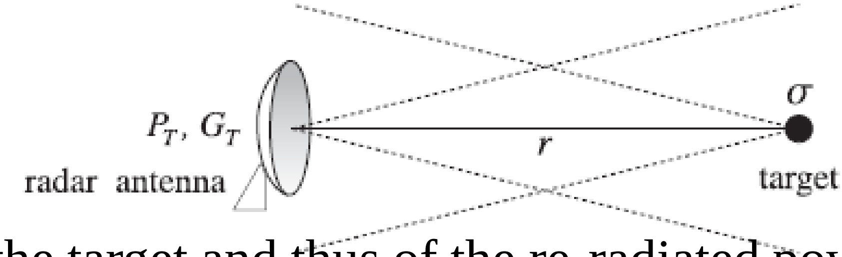
$$S_{inc} = \frac{GP_t}{4\pi r^2} = \frac{9674.7 \times 10^5}{4\pi \times \left(10^5\right)^2} \approx 8 \times 10^{-3} W/m^2$$

Incident Power Flux Density = 8 x 10^{-3} Watts/m^2 ➔E=2.45 V/m ➔ E_{rms}=1.7 V/m

Note that

E_{rms}=6 V/m ⇔ 0.1 W/m^2 suggested value for health in the EU [0.1<f<300 GHz]

Radar cross section



σ provides a measure of the effective area of the target and thus of the re-radiated power as a function of the impinging flux

Fig. 14.11.1 Radar antenna and target.

$$\sigma_{back} \equiv \frac{P_{backscattered\ by\ target}}{S_{inc@target}} = 4\pi r^2 \left(\frac{S_{rec@radar}}{S_{inc@target}} \right)$$

$$S_{inc@target} = \frac{GP_t}{4\pi r^2}$$

Recall from before the power flux density incident on an object

$$S_{rec@radar} = \frac{\sigma_{back}\, G\, P_t}{16\pi^2 r^4}$$

Some typical values:

Gain = 10,000 (40 dB)
Transmitted Power = 100,000 Watts
Target is at 100 km range
Radar cross section = 1 m^2

Power Flux Density
at the antenna = 6.3 x 10^{-14} Watts/m^2!!

Factors affecting radar cross section (RCS)

In general, the radar cross section of an object depends on:

1) Object's shape

2) Size (in relation to the radar wavelength)

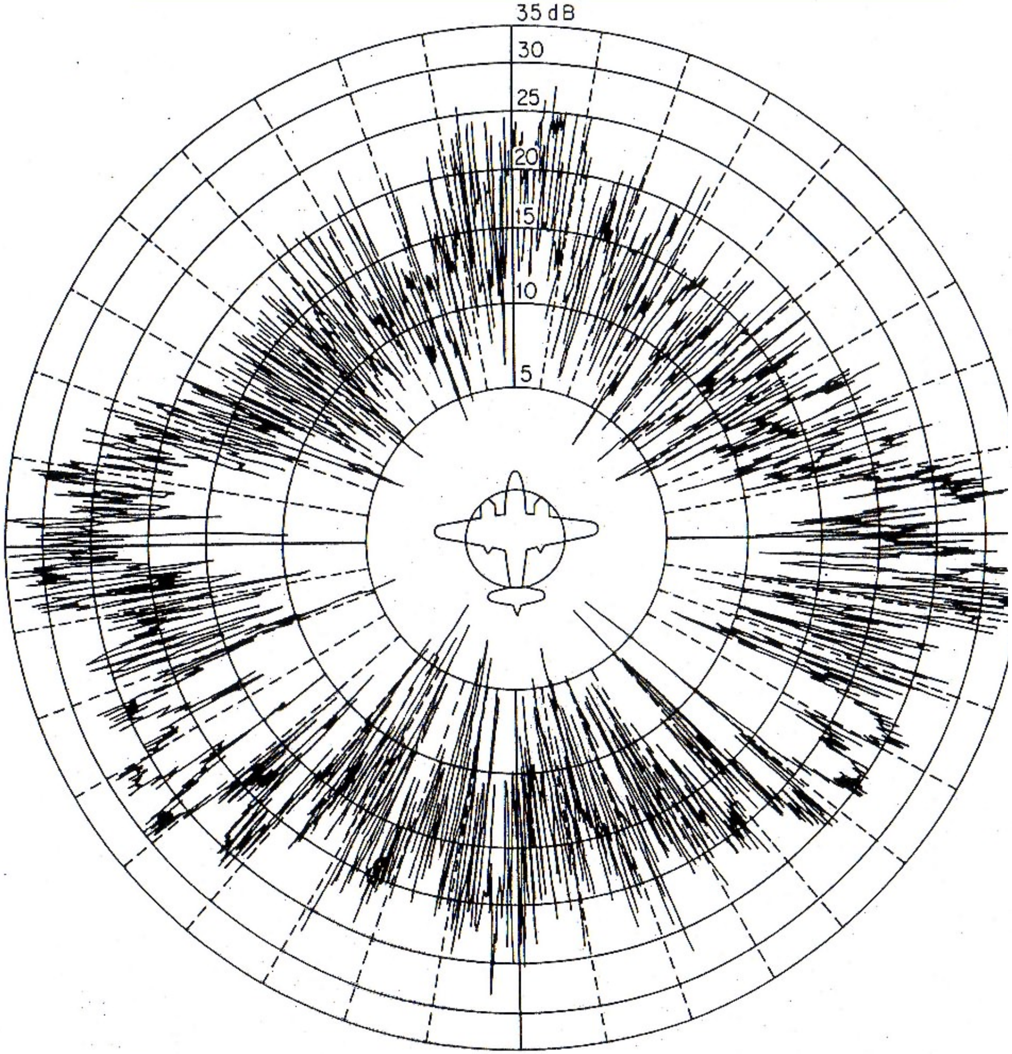
3) Complex dielectric constant and conductivity of the material (related to substances ability to absorb/scatter energy)

4) Viewing geometry

5) Polarization of incident wave

Example: radar cross section (RCS) of an aircraft

RADAR CROSS SECTION OF A B-26 BOMBER



2D Cross section of B-26 aircraft

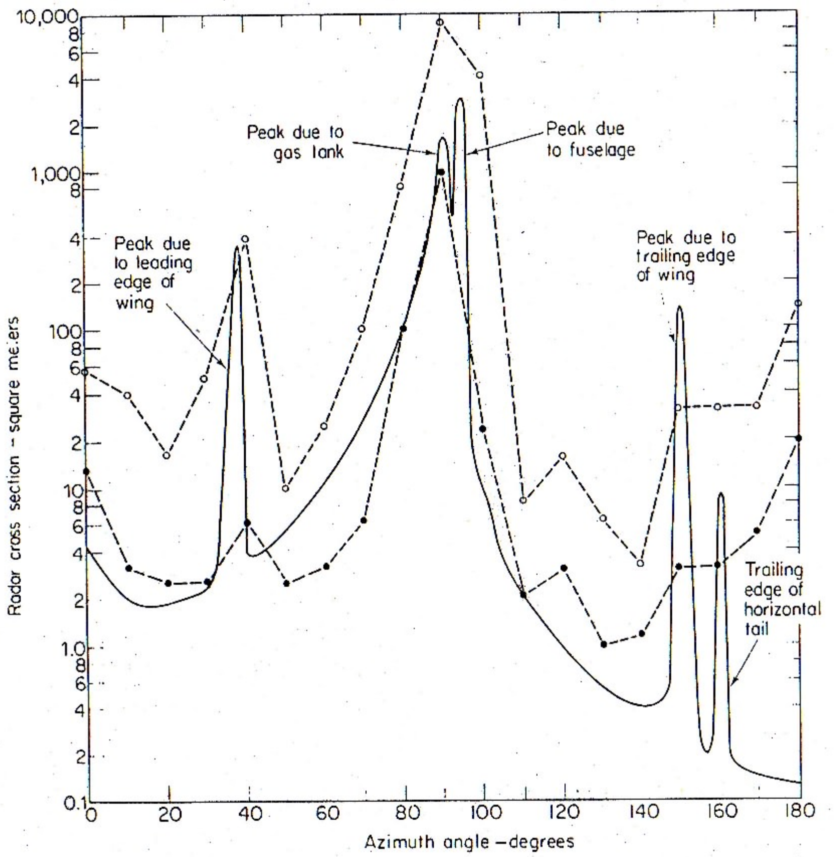


Figure 2.16 Experimental cross section of the B-26 two-engine bomber at 10-cm wavelength as a function of azimuth angle. (*From Ridenour,[28] courtesy McGraw-Hill Book Company, Inc.*)

3 GHz

MIG-21 has a RCS≈3m^2 between 1 and 10 GHz

Antenna effective area

$$S_r = \frac{\sigma_{back} G\ P_t}{16\pi^2 r^4}$$

Power flux density received at the radar

Power received at antenna:

$$P_r = A_e S_r = \frac{\sigma_{back} A_e G P_t}{16\pi^2 r^4}$$

where A_e is the effective area of the antenna

From antenna theory - Relationship between gain and effective area:

(8)

$$G(\theta,\phi) = \frac{4\pi A_e(\theta,\phi)}{\lambda^2} \Rightarrow \quad A_e(\theta,\phi) = \frac{\lambda^2 G(\theta,\phi)}{4\pi}$$

Gain = 10,000 (40 dB)
Power Flux Density
at the antenna = 6.3×10^{-14} Watts/m^2
λ=10 cm
$A_e = 10^2/4\pi$ m^2
$P_r = 0.5 \times 10^{-12}$ Watts

Radar equation for isolated target

Substituting for A_e :

$$P_r = \frac{\sigma_{back}\lambda^2 G^2 P_t}{64\pi^3 r^4}$$

Which we will write as:

$$P_r = \frac{1}{(4\pi)^3} \left[P_t G^2(\theta,\varphi)\lambda^2 \right] \left[\frac{\sigma_{back}}{r^4} \right]$$

constant

radar characteristics

target characteristics

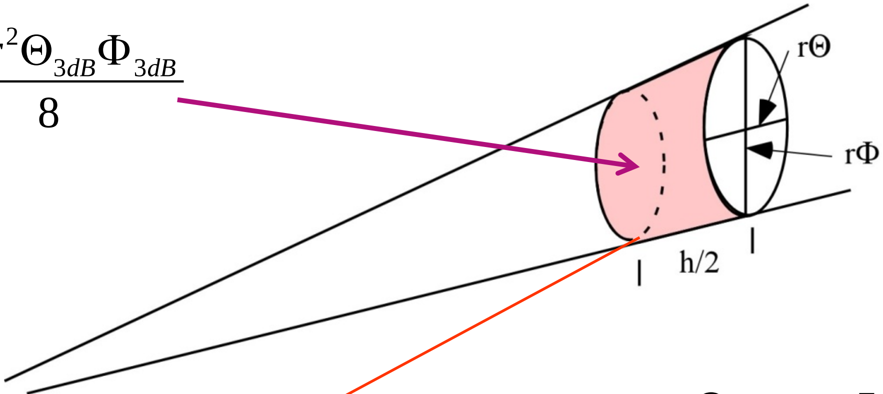
This is the radar equation for a <u>single isolated target</u> (e.g. an airplane, a ship, a bird, one raindrop, …). From a calibrated radar we can get the object backscattering cross section.

What happens for distributed targets?

Atmospheric targets:
There are millions targets inside the scattering volume!!

Contributing volume

$$V_c \approx \pi\left(\frac{h}{2}\right)\left(\frac{r\Theta_{3dB}}{2}\right)\left(\frac{r\Phi_{3dB}}{2}\right) = \frac{\pi h r^2 \Theta_{3dB}\Phi_{3dB}}{8} = \frac{\pi c \tau r^2 \Theta_{3dB}\Phi_{3dB}}{8}$$



Radar equation for distributed targets:

Note that for a circular antenna $\Theta_{3dB} = \Phi_{3dB}$

$$\bar{P}_r = \frac{1}{64\pi^3}\left[P_t G^2 \lambda^2\right]\left[\frac{\sum_j \sigma_{back,j}}{r^4}\right]$$

Sum over the radar scattering volume (which is becoming bigger and bigger with increasing distance)

Radar backscattering coefficient or radar reflectivity

Taking the radar equation :

$$\bar{P}_r = \frac{1}{64\pi^3}\left[P_t G^2\lambda^2\right]\left[\frac{\sum_j \sigma_{back,j}}{r^4}\right] = \frac{1}{64\pi^3}\left[P_t G^2\lambda^2\right]\frac{V_c}{r^4}\underbrace{\left[\frac{\sum_j \sigma_{back,j}}{V_c}\right]}_{\eta} = \frac{c}{512\pi^2}\left[P_t \tau G^2\lambda^2\Phi_{3dB}\Theta_{3dB}\right]\left[\frac{\eta_{avg}}{r^2}\right]$$

where V_c is
the contributing volume

$$V_c = \frac{\pi c \tau r^2 \Theta_{3dB}\Phi_{3dB}}{8}$$

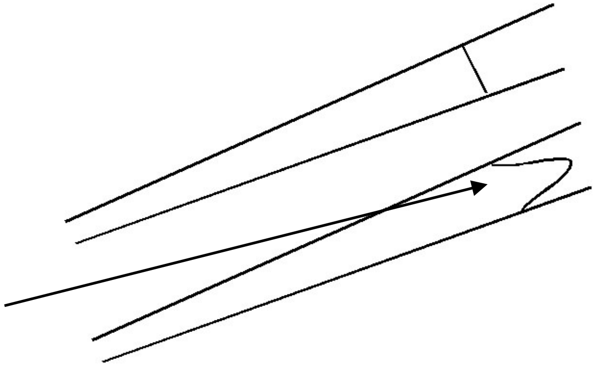
Definition of the "radar backscattering coefficient or radar reflectivity", η

$$\boxed{\eta \equiv \frac{\sum_j \sigma_j}{V_c} \quad \dim ension \quad \frac{m^2}{m^3} = m^{-1} \quad inverse\ length}$$

Radar equation for distributed targets

$$P_r = \frac{c}{512\pi^2} \left[P_t \tau G^2 \lambda^2 \Phi_{3dB} \Theta_{3dB} \right] \left[\frac{\eta}{r^2} \right]$$

The above equation applies for a uniform beam (e.g. with G constant within the 3dB beamwidth). <u>For a Gaussian beam, a correction term 2ln(2) has to be added</u>



$$\boxed{P_r = \frac{c}{\pi^2 1024 \ln(2)} \left[P_t \tau G^2 \lambda^2 \Phi_{3dB} \Theta_{3dB} \right] \left[\frac{\eta}{r^2} \right]}$$

radar characteristics

target characteristics

Isolated vs distributed targets

$$P_r = \frac{1}{64\pi^3} \left[P_t G^2 \lambda^2 \right] \left[\frac{\sigma_{back}}{r^4} \right]$$

The returned power for a single target varies as r^{-4}.

constant

radar characteristics

Target characteristics

$$P_r = \frac{c}{\pi^2 1024 \ln(2)} \left[P_t \tau G^2 \lambda^2 \Phi_{3dB} \Theta_{3dB} \right] \left[\frac{\eta_{avg}}{r^2} \right]$$

The returned power for a distributed target varies as r^{-2}

$$P_r = C_{radar} \; P_t \left[\frac{\eta_{avg}}{r^2} \right]$$

Reason: As contributing volume grows with distance, more targets are added. Number of targets added is proportional to r^2, which reduces the dependence of the returned power from r^{-4} to r^{-2}.

Hydrometeor backscattering cross sections

First Assumption: hydrometeor particles are all spheres (Mie theory)

Small raindrops and cloud droplets: Spherical

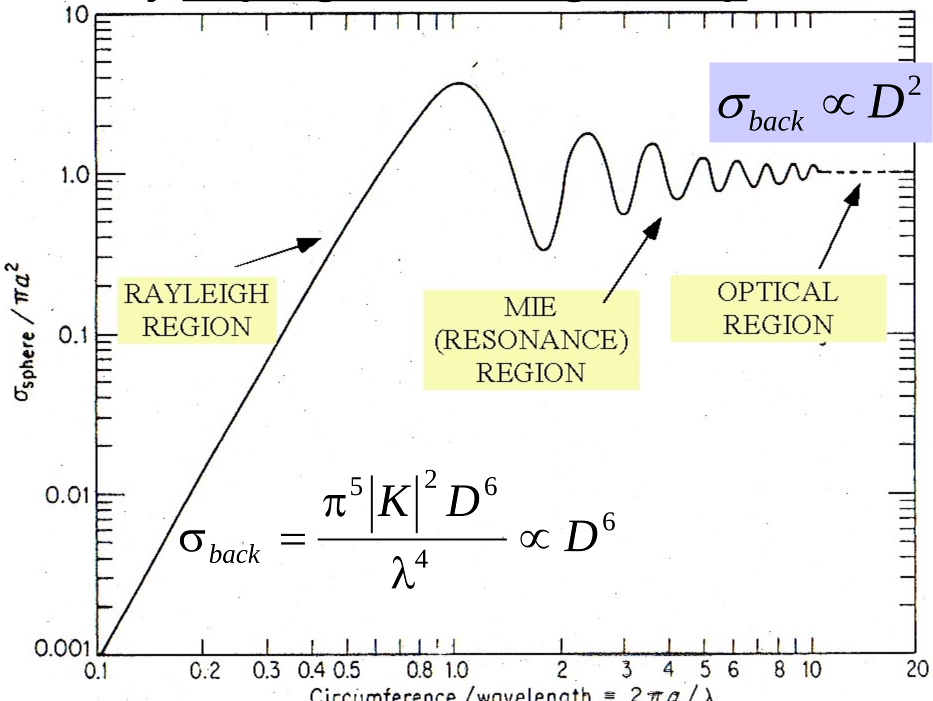
Large raindrops: Ellipsoids

Ice crystals: Different shapes

Graupel and rimed particles: Can be spherical

Hail: May or may not be spheres

Second assumption: The particles are sufficiently small compared to the wavelength of the impinging microwaves that the scattering can be described by <u>Rayleigh Scattering Theory</u>



Note also $1/\lambda^4$ dependence

Related to the dielectric property of the target (water/ice)

$$K = \frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{m^2 - 1}{m^2 + 2}$$

How small is small?

From the figure above, the radius of the particle, a, must be

$$a \le \frac{\lambda}{2\pi}$$

(~ 1/6 of the wavelength)

Validity of the Rayleigh Approximation for weather targets

Valid

λ= 10 cm f=3 GHz	**Raindrops: 0.01 – 0.5 cm (all rain)** **Snowflakes: 0.01– 3 cm (most snowflakes)** **Hailstones: 0.5 – 2.0 cm (small to moderate hail)**
λ= 5 cm f=6 GHz	**Raindrops: 0.01 – 0.5 cm (all rain)** **Snowflakes: 0.01– 1 cm (small snowflakes)** **Hailstones: 0.5 – 0.75 cm (small hail)**
λ= 3 cm f=10 GHz	**Raindrops: 0.01 – 0.5 cm (all rain)** **Ice crystals: 0.01– 0.5 cm (single crystals)** **Graupel: 0.1 -- 0.5 cm (graupel)**
λ= 0.8 cm f=35 GHz	**Raindrops: 0.01 – 0.15 cm (cloud and drizzle drops)** **Ice crystals: 0.01– 0.15 cm (single crystals)**

What is K?

K is a complex number which accounts for the dielectric properties of the medium

$$K = \frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{m^2 - 1}{m^2 + 2}$$ where $$\varepsilon_r = \frac{\varepsilon_1}{\varepsilon_0}$$ $\dfrac{\text{Permittivity of medium}}{\text{Permittivity of vacuum}}$

Refractive index

Values of $|K|^2$

Water

Temperature	λ = 10 cm	λ = 3.21 cm	λ = 1.24 cm	λ = 0.62 cm
20^0C	0.9280	0.9275	0.9193	0.8926
10^0C	0.9340	0.9282	0.9152	0.8726
0^0C	0.9340	0.9300	0.9055	0.8312

$|K|^2 \approx 0.93$ for water particles at low frequencies

Ice

$|K|^2 = 0.176$ for ice particles with no strong dependence on T and frequency

➔ice is producing scattering 5 times smaller for the same size

Radar reflectivity and radar equation for distributed targets

Reflected power

$$P_r = \frac{c}{\pi^2 1024 \ln(2)} \left[P_t \tau G^2 \lambda^2 \Phi_{3dB} \Theta_{3dB} \right] \left[\frac{\eta}{r^2} \right]$$

$$[\sigma_{back}]_j = \frac{\pi^5 |K|^2 D_j^6}{\lambda^4} \propto D_j^6$$

$$\eta \equiv \frac{\sum_j \sigma_{back,j}}{V_c} = \frac{\pi^5 |K|^2}{\lambda^4} \frac{\sum_j D_j^6}{V_c} \equiv \frac{\pi^5 |K|^2}{\lambda^4} Z$$

$$\boxed{Z \equiv \frac{\sum_j D_j^6}{V_c} = \int N(D) D^6 \, dD = \int 64 \, N(r) r^6 \, dr}$$

where the **radar reflectivity factor Z** fully characterize the radar backscattering of the targets within the scattering volume.

Radar constant [W/m]

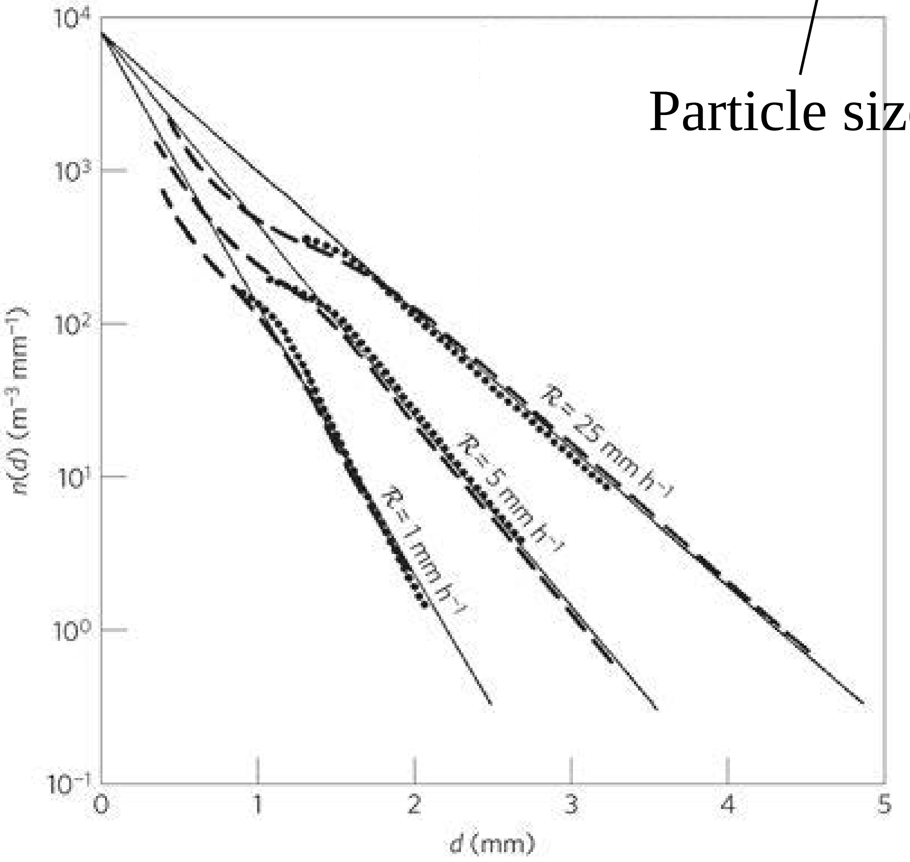
$$\boxed{P_r = \frac{c}{1024 \ln(2)} \frac{\pi^3 |K|^2}{\lambda^2} \left[P_t \tau G^2 \Phi_{3dB} \Theta_{3dB} \right] \frac{Z}{r^2} = C_{radar} \frac{Z}{r^2}}$$

Z can be derived from measurements of P_r

Radar reflectivity factor

$$Z \equiv \frac{\sum_j D_j^6}{V_c} = \int N(D) D^6 \, dD = \int 64 \, N(r) r^6 \, dr$$

Particle size distribution   N [$mm^{-1}m^{-3}$]



The radar reflectivity factor is typically computed in mm^6/m^3 and then converted to logarithmic units

$$Z[dBZ] = 10 \log_{10} \left\{ Z \left[\frac{mm^6}{m^3} \right] \right\}$$

Example: Radar reflectivity of rain

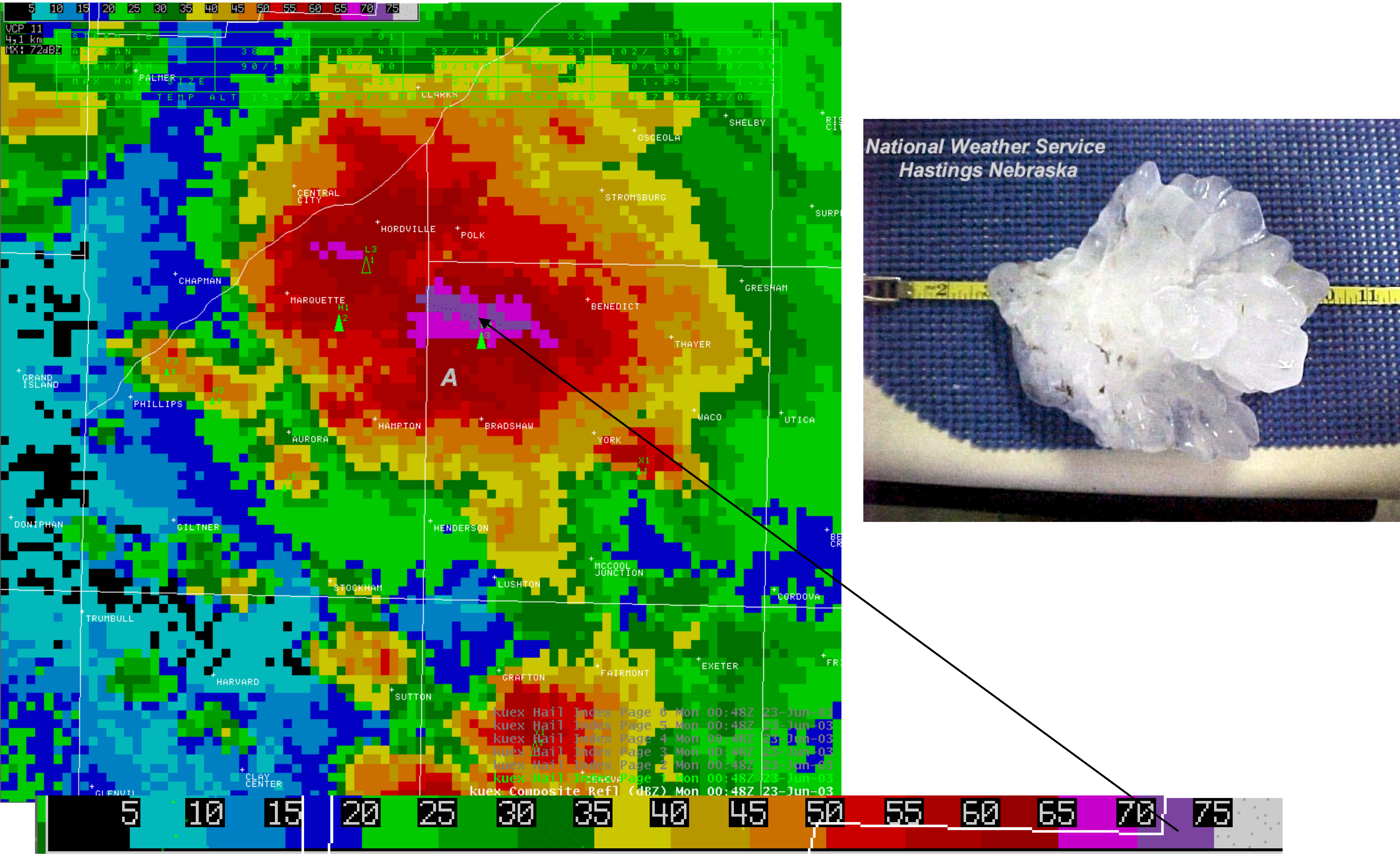
Diameter Range (mm)	Diameter D (at mid-range) (mm)	Measured Drop Concentration N(D) (m^{-3})	D^6 (mm^6)	Contribution to Z, ΔZ (mm^6/m^{-3})
0.5 - 0.7	0.6	6	0.05	--
0.7 - 0.9	0.8	71	0.21	15
0.9 - 1.1	1.0	280	1.0	280
1.1 - 1.3	1.2	488	3.0	1464
1.3 - 1.5	1.4	538	7.5	4030
1.5 - 1.7	1.6	345	16.8	5800
1.7 - 1.9	1.8	212	34	7200
1.9 - 2.1	2.0	159	64	10180
2.1 - 2.3	2.2	129	113	14580
2.3 - 2.5	2.4	79	191	15100
2.5 - 2.7	2.6	54	309	16690
2.7 - 2.9	2.8	33	482	15900
2.9 - 3.1	3.0	19	729	13830
3.1 - 3.3	3.2	21	1073	22570
3.3 - 3.5	3.4	9	1544	13900
3.5 - 3.7	3.6	5	2180	10900
3.7 - 3.9	3.8	8	3010	2480
3.9 - 4.1	4.0	2	4096	8190
4.1 - 4.3	4.2	0	5490	--
4.3 - 4.5	4.4	1	7255	7255
	Totals	2459		170364

These drops contribute most to the radar reflectivity

$Z = 1.7 \times 10^5\ mm^6/m^3 = 52.3\ dBZ$

Range of radar reflectivity factor in weather echoes

Nebraska record hailstorm 2003 75 dBZ



-28 dBZ = haze droplets   25 dBZ = snow   45-50 dBZ = heavy rain   75 dBZ = giant hail

Relationship between the Reflectivity Factor and the Rain Rate

$$Z \equiv \frac{\sum_j D_j^6}{V_c} = \int_0^{D_{\max}} N(D) D^6 \, dD$$

6^{th} moment of the particle size distribution

Precipitation rate (R): The volume of precipitation passing downward through a horizontal surface, per unit area, per unit time.

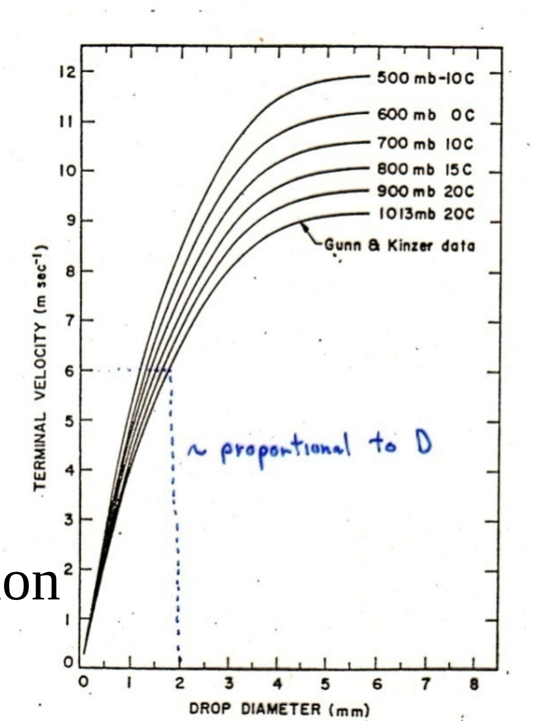
where v_j is the fall velocity of each drop j

$$R = \frac{\sum_j m_j v_j}{V_c} = \int_0^{D_{\max}} \frac{\pi \rho_w}{6} N(D) D^3 v(D) \, dD$$

since v proportional to D

$$R \propto \sum_j D^4$$

4^{th} moment of the particle size distribution



The Z-R conundrum

There have been hundreds of Z-R relationships published – here are just a few between 1947 and 1960 – there have been 4 more decades of new Z-R relationships to add to this table since!

Equation	Reference	Location	Remarks
$320R^{1.44}$	Wexler, R. (1947)	Washington, D.C.	8 rain intensities, each a mean of about 10 storms of same intensity
$214R^{1.58}$	Wexler (1948)	Washington, D.C.	98 storms – original data
$224R^{1.54}$		Ynyslas, Great Britain	5 rainstorms
$630R^{1.45}$		Shoeburyness, England	4 rainstorms
$208R^{1.53}$		Hawaii	50 storms, orographic rain
$190R^{1.72}$	Marshall, Langille, and Palmer (1947)	Various locations	Various types of rain
$220R^{1.60}$	Marshall and Palmer (1948)	Various locations	Various types of rain
$295R^{1.612}$	Hood (1950)	Canada	270 samples, 7 rainstorms; light rain 1–3 mm/hr; heavy thunderstorms 50 mm/hr
$180R^{1.55}$	Boucher (1951)	Cambridge, Mass.	63 rain samples, widespread rain both uniform and variable; showers and thunderstorms
$127R^{2.87}$	Higgs (1952)	Australia	Showers, 8 months of observation
$16.6R^{1.55}$	Blanchard (1953)	Hawaii	Orographic rain within cloud
$31R^{1.71}$			Orographic rain at cloud base
$290R^{1.41}$			Nonorographic rain – thunderstorms
$396R^{1.35}$	Jones (1955)	Central Illinois	1,270 1-minute observations – all rains
$486R^{1.37}$			560 1-minute observations – thunderstorms
$380R^{1.24}$			

$$MetOffice: \quad Z = 200\ R^{1.6} \quad \begin{cases} R = 1mm/h \Rightarrow Z = 200mm^6/m^3 = 23\ dBZ \\ R = 10mm/h \Rightarrow Z = 7962mm^6/m^3 = 39\ dBZ \end{cases}$$

Equation	Reference	Location	Remarks
$215R^{1.34}$	Atlas and Chmela (1957)	Lexington, Mass.	Stratiform rains, 16 April 1954
$350R^{1.42}$			Stratiform rains, 23 April 1954
$310R^{1.34}$			Stratiform rains, 27 April 1954
			Stratiform rains, 28 April 1954
$220R^{1.54}$	Sal'man (1957)	Near Leningrad, USSR	Showers and steady rain
$303R^{1.7}$	Shupiatskii (1957)	Near Moscow, USSR	Various types of rain, $R < 7$ mm/hr
$405R^{1.49}$			Various types of rain, $7 < R < 60$ mm/hr
$289R^{1.59}$			Various types of rain, $R > 60$ mm/hr
$109R^{1.64}$	Ramana Murty and	Kandia, India	Orographic, Monsoon rains

Most of the uncertainties in the retrieval of rain rates comes from this fact.

Equation	Reference	Location	Remarks
			Prewarm frontal rain
$219R^{1.41}$	Sivaramakrishnan (1961)	Poona, India	Thunderstorms
$67.6R^{1.94}$			Steady rains

What do you need to know?

- General principle of a radar system
- Radar equation for single and distributed targets
- Radar backscattering cross section, the reflectivity and the radar reflectivity factor
- Relationship between reflectivity and rain-rate

Questions

- ***Describe the basic principle of a radar system. Indicate the difference between a cloud and a rain radar. What are the key specifics in a radar system?***

- ***Can you relate the antenna size to the antenna gain and to the antenna beamwidth?***

- ***What is the chief factor limiting the accuracy of rainfall rate estimates from radar?***

- ***Compute the radar reflectivity factor for a raindrop size distribution of the form***

$$n(D) = n_0 \exp(-\Lambda D) \qquad\qquad n_0 = 0.08\,cm^{-4} = 8\times10^6\,m^{-4}$$

$$\Lambda[cm^{-1}] = \frac{41}{R^{0.21}}$$

where R is the rain rate in mm/h