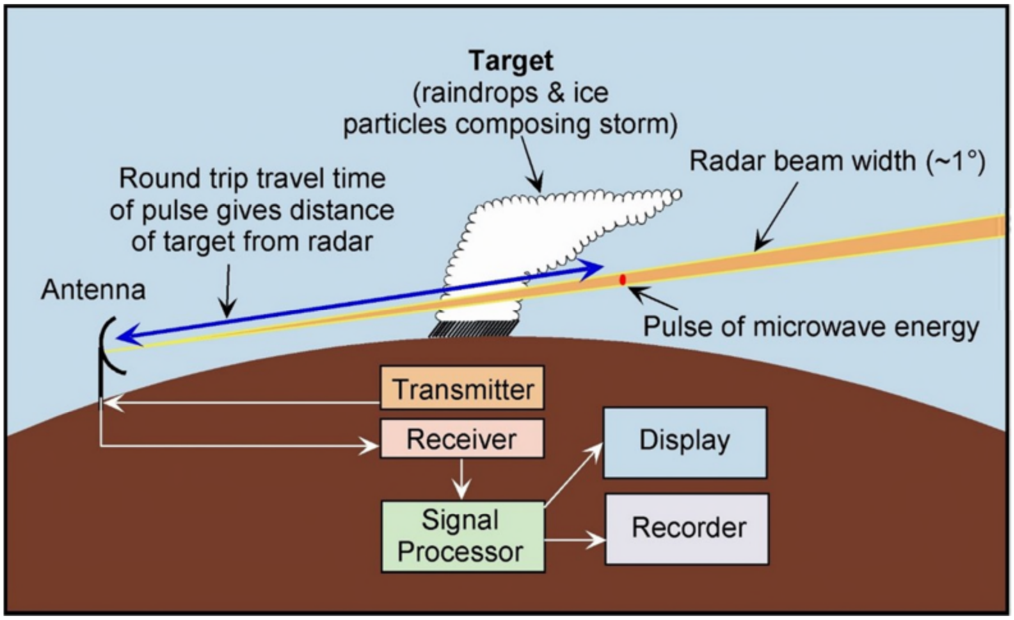
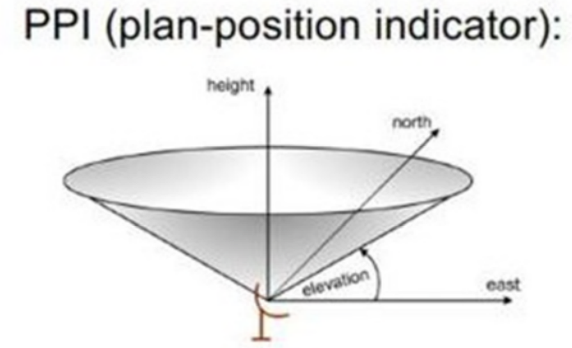
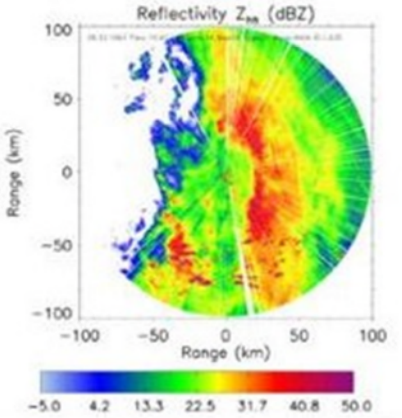
Chapter Eight
Weather Radar

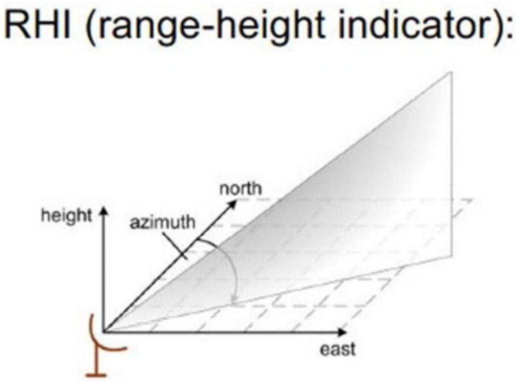
Radar Principles

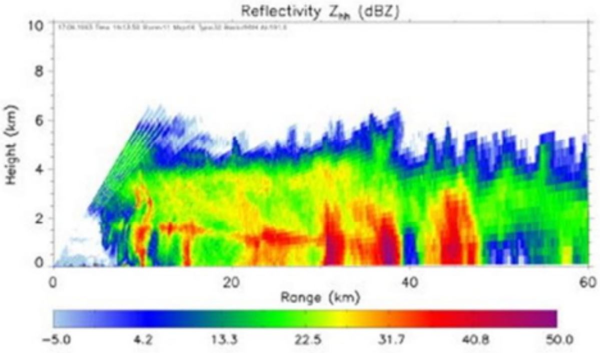
- The components of a radar system are:
  - ✓ **Transmitter:** The transmitter generates pulses of radio frequency (RF) radiation.
  - ✓ **Receiver:** The receiver detects the returned energy.
  - ✓ **Antenna:** The antenna focuses the outgoing beam and the incoming radiation.
  - ✓ **Radar Display Systems:**
    - ▪ **Plan Position Indicator (PPI):** maps the received signals on polar coordinates in plain view.
    - ▪ **Range Height Indicator (RHI):** shows the vertical structure of echoes which is generated when the antenna scans in elevation with azimuth fixed.
    - ▪ Microprocessors are used to convert the signals to reflectivity Z or rainfall rate.











- The radar measures the distance to the target by measuring the time between the transmission of a pulse and the detection of the return pulse.

- The total distance traveled by the pulse is $2r$, where r is the distance to the target.

- The time of travel is the total distance divided by the speed of the radiation, c,

$$t = 2r / c \tag{8.1}$$

Therefore, if the travel time is known the distance to the target can be deduced by

$$r = ct / 2 \tag{8.2}$$

Radar Parameters

- **Pulse Width:** Denoted as τ, the pulse width is the transmission duration of the pulse (usually measured in microseconds). Also called pulse duration.
  - The pulse width determines the range resolution of the radar. If two targets are separated by distance Δr that is less than $c\tau$, they will appear as a single target.
  - The pulse width also determines the minimum range of the radar. Since the radar cannot detect incoming pulses while it is transmitting, the minimum range of a radar is

$$r_{\min} = c\tau / 2 \tag{8.3}$$

- **Pulse Repetition Frequency:** Abbreviated as PRF, and denoted as f_r, this is the number of pulses per second transmitted by the radar.
  - The maximum unambiguous range of a radar is

$$r_{\max} = \frac{c}{2f_r} \tag{8.4}$$

- **Peak Power:** The maximum power of the pulse, denoted as P_t. Usually measured in Watts.

- **Wavelength:** Denoted by λ, this is the wavelength of the radiofrequency wave transmitted by the radar. For weather radars this is in the microwave part of the spectrum. Wavelengths of 3-10 cm are commonly used.

- **Beamwidth:** Denoted as θ, this is the angular width of the radar beam.

- **Antenna Area:** Denoted as A_e, this is the area of the aperture of the antenna.
  - For a given beamwidth, as the wavelength increases a larger antenna area is required. Thus, a radar operating at a wavelength of 10 cm will have a larger antenna than one operating at 3 cm.

- **Antenna Gain:** The gain, G, describes the focusing of the radar beam.
  - If the antenna transmitted isotropically (evenly in all directions of a sphere) the power incident on a small target of cross-section A_t at a distance r would be

$$P_{iso} = P_t \frac{\omega}{4\pi} \tag{8.5}$$

where ω is the solid angle of the target with respect to the radar.

- If the target is small, such that we can use the small-angle approximation, then the solid angle of the target is $\omega = A_t / r^2$ and the power incident on the target from (8.5) is

$$P_{iso} = \frac{P_t A_t}{4\pi r^2} \tag{8.6}$$

- The gain is the power intercepted by the target divided by what the power would be if the antenna transmitted isotropically,

$$G = P_\sigma / P_{iso} \tag{8.7}$$

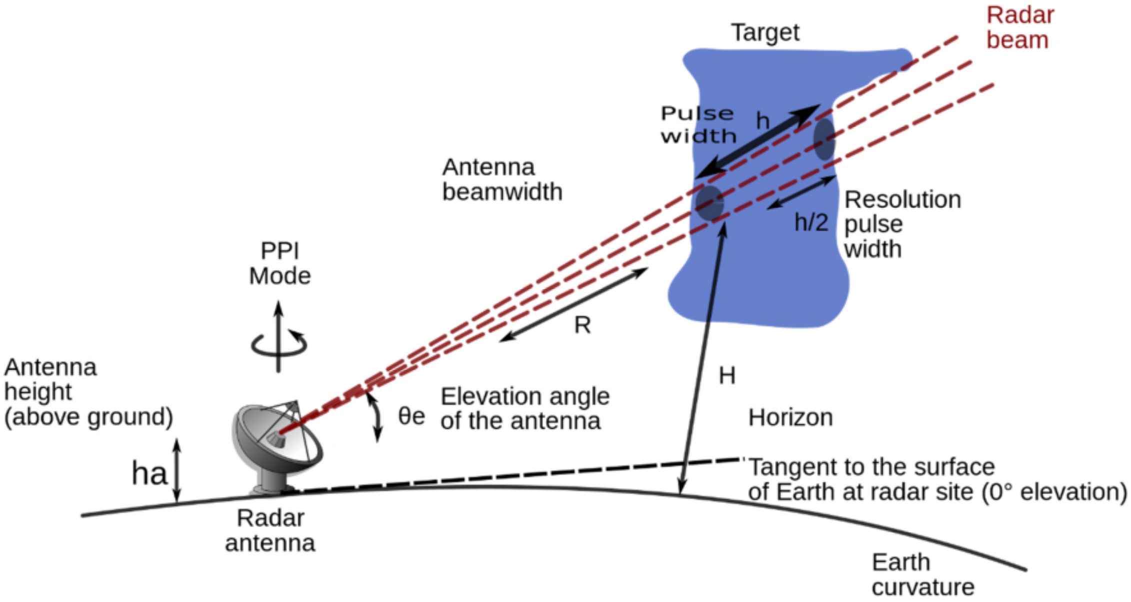
- Therefore, the power intercepted by a target is

$$P_\sigma = G \frac{P_t A_t}{4\pi r^2} \tag{8.8}$$

- The gain is a dimensionless number that is greater than one.

- Gain is related to the wavelength of the radar, and the antenna aperture, by

$$G = \frac{4\pi A_e}{\lambda^2} \tag{8.9}$$



The Radar Equation for a Single Target

- A target of cross-sectional area A_t at a distance r from the radar intercepts an amount of power given by (8.8), repeated here,

$$P_\sigma = G\frac{P_t A_t}{4\pi r^2}$$

- If the target reflects (or reradiates) this same amount of energy isotropically, the amount of power received by the radar would be

$$P_r = P_\sigma \frac{\omega_e}{4\pi} \tag{8.10}$$

where ω_e is the solid angle of the antenna with respect to the target.

- ω_e is given by

$$\omega_e = \frac{A_e}{r^2} \tag{8.11}$$

and using (8.11) and (8.8) in (8.10) results

$$P_r = P_t \frac{G A_t A_e}{16\pi^2 r^4} \tag{8.12}$$

- From (8.9) we know

$$A_e = \frac{G\lambda^2}{4\pi}$$

and substituting this into (8.12) results in the radar equation for an isotropically reflecting target of cross-sectional area A_t

$$P_r = P_t \frac{G^2\lambda^2}{64\pi^3 r^4} A_t \tag{8.13}$$

- The cross-sectional area A_t in (8.13) is usually replaced with the *backscattering cross section*, which is also called the *effective cross section*, or *radar cross section*, σ.
    - ➢ The effective cross section is the cross section that the target appears to have, and may either be larger or smaller than the actual physical cross section of the target.
    - ➢ A target that is very absorptive will reflect and return a small amount of the radar power that hits the target. Thus, the target will appear to be much smaller to the radar, and therefore have a smaller radar cross section. This is the basis of stealth technology to hide aircraft and ships from radar detection.

  - The effective cross section takes into account the shape and composition of the target.

- In terms of effective cross section, the radar equation becomes

$$P_r = P_t \frac{G^2\lambda^2}{64\pi^3 r^4}\sigma \tag{8.14}$$

Radar Equation for Hydrometeors

- Rain drops are much, much smaller than the wavelength of the radar radiation, and therefore scatter like Rayleigh scatters where Rayleigh scatters applies to particles that are small compared to the wavelength (λ) of the radar (remember why the sky is blue?).

- Rayleigh scattering theory gives the backscattering cross section of a spherical droplet of diameter D as

$$\sigma = \frac{\pi^5}{\lambda^4}|K|^2 D^6 \tag{8.15}$$

where K is the complex index of refraction of sphere K= $(m^2-1)/(m^2+2)$ and m = n-ik with n is refractive index and k is absorption coefficient.

  - Substituting (8.15) into (8.14) gives

$$P_r = P_t \frac{G^2}{64r^4}\frac{\pi^2}{\lambda^2}|K|^2 D^6 \tag{8.16}$$

- If the radar signal scatters off of multiple droplets within the volume of the radar pulse, the returned power is the sum of the powers from all the droplets,

$$\bar{P}_r = P_t \frac{G^2}{64r^4}\frac{\pi^2}{\lambda^2}|K|^2 \sum D^6 \tag{8.17}$$

  - We have included an overbar over the P_r to indicate we are really dealing with an average return power.

- Radar *reflectivity* is defined as

$$Z = \frac{\sum D^6}{V} \tag{8.18}$$

where V is the volume sampled by the radar pulse.

  - Reflectivity has MKS units of m^3, but is usually reported in units of $mm^6\ m^{-3}$.

  - Reflectivity is essentially backscattering cross section per volume.

- The geometric volume sampled by the radar beam is

$$V = \pi\left(\frac{r\theta}{2}\right)^2 \frac{c\tau}{2} \qquad (8.19)$$

However, the radar beam is not really uniform over this volume, and the volume doesn't really have 'sharp' edges or boundaries. The radar energy is strongest in the center of the volume, and tapers off toward the edges. Therefore, it is more appropriate to use an *effective radar volume* given by

$$V_{eff} = \frac{\pi}{2\ln 2}\left(\frac{r\theta}{2}\right)^2 \frac{c\tau}{2} \qquad (8.20)$$

- Using (8.20) in (8.18), and then rearranging, gives us

$$\sum D^6 = \frac{\pi}{16\ln 2}(r\theta)^2 c\tau Z \qquad (8.21)$$

and using (8.21) in (8.17) result in the *radar equation for hydrometeors*,

$$\bar{P}_r = \frac{\pi^3 c}{1024\ln 2}\underbrace{\left(\frac{P_t\tau G^2\theta^2}{\lambda^2}\right)}_{\text{Term A}}\underbrace{\left(|K|^2\frac{Z}{r^2}\right)}_{\text{Term B}} \qquad (8.22)$$

Reflectivity and Rainfall Rate

- The definition of reflectivity given in (8.18) is for a discrete raindrop distribution. For a continuous distribution of raindrops, the reflectivity is

$$Z = \int_0^\infty D^6 n_d(D)dD \qquad (8.23)$$

- Using the Marshall-Palmer distribution in (8.23) yields

$$z = \frac{720n_o}{\Lambda^7} \qquad (8.24)$$

or

$$\Lambda = \left(\frac{720n_o}{Z}\right)^{1/7} \qquad (8.25)$$

- In a prior lesson we found that the slope factor of the Marshall-Palmer distribution is related to rainfall rate via

$$\Lambda = \left(\frac{\pi n_o \bar{u}}{R} \right)^{1/4} \tag{8.26}$$

- Equating (8.25) and (8.26) solving for Z yields the theoretical Z-R relation

$$Z = \frac{720}{(\pi \bar{u})^{7/4} n_o^{3/4}} R^{7/4} \tag{8.27}$$

- In practice Z-R relations are found empirically, with an often used relation of

$$Z = 200 R^{1.6} \tag{8.28}$$

where R is in mm hr^{-1}, and Z is in mm^6 m^{-3}

Decibels of Reflectivity

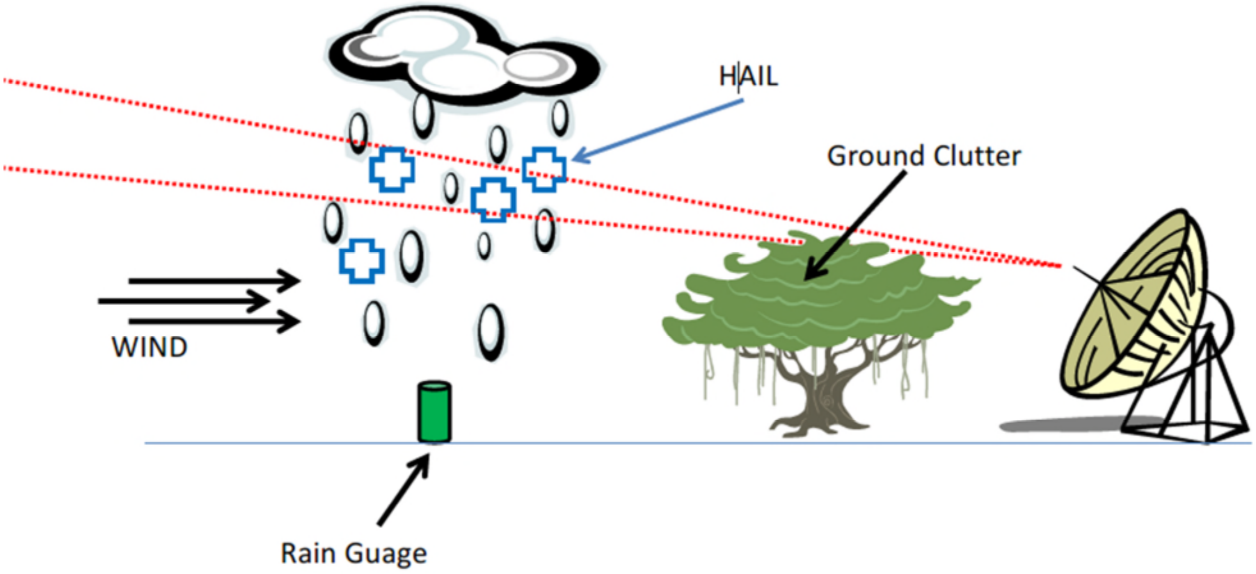
- Since Z can vary by a wide range it is convenient to use a logarithmic form for reflectivity. We define decibels of reflectivity, or $\boldsymbol{dBZ}$, as

$$dBZ = 10 \log_{10} \left(\frac{Z}{mm^6 m^{-3}} \right) \tag{8.29}$$

- Typical values of dBZ are 50 or greater in the core of a thunderstorm, and around 30 for light rain.

Radar Errors

- Ground clutter
- Attenuation
- Bright band
- Strong winds
- Evaporation below beam
- Mixed precipitation (ice and liquid)



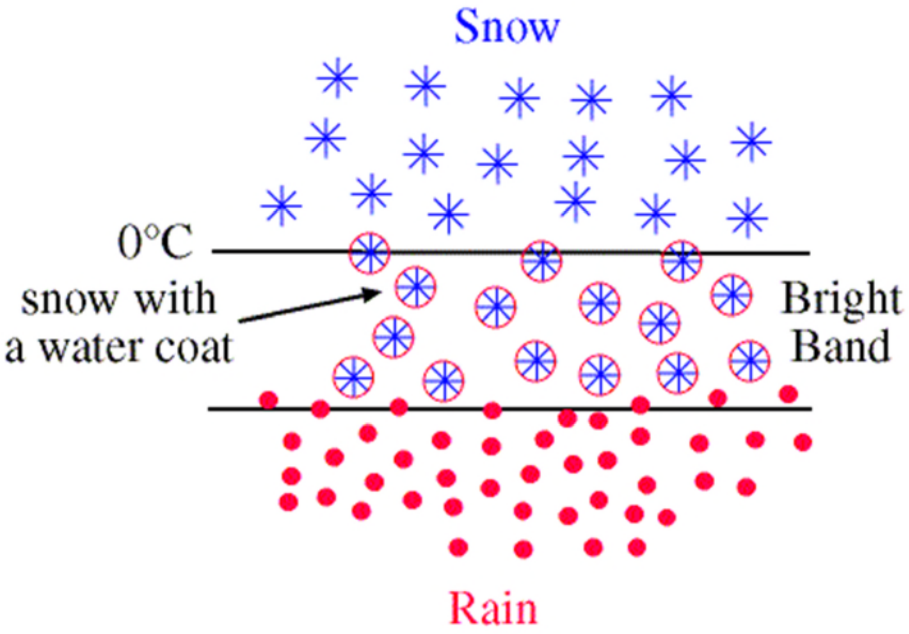
Bright Band

- Snow and frozen precipitation will usually have a smaller value of reflectivity because it is made of ice, which has a lower index of refraction than liquid water.

- When frozen precipitation falls to a level where the temperature is above freezing it begins to melt.

- The water surface on the outside will cause an increase in reflectivity, which results in a bright band on the radar image at the height near the freezing level.

- The bright band does not extend to the surface because once the snowflake completely melts it falls faster. Therefore, the droplet concentration decreases as altitude decreases, resulting in lower reflectivity.



Radar Beam Height and Elevation Angle

- As the radar beam gets further from the radar the altitude of the beam above the ground gets larger. This is due to two effects:
  - Curvature of the Earth.
  - Refraction of the beam upwards.
- The altitude of the beam $h(r)$ with distance from the radar r is given by

$$h(r) = h_o - ka + \sqrt{r^2 + k^2 a^2 + 2rka\sin\varphi} \tag{8.30}$$

  where φ is the elevation angle, k is a standard refraction coefficient, a is the radius of the Earth, and h_O is the height of the radar antenna.
- Figure 1 shows beam height versus altitude for various elevation angles.
- Because the beam rises off the ground with distance, shallow precipitation at large distances may be completely missed by the radar.
- The lowest elevation angle is usually 0.5°.

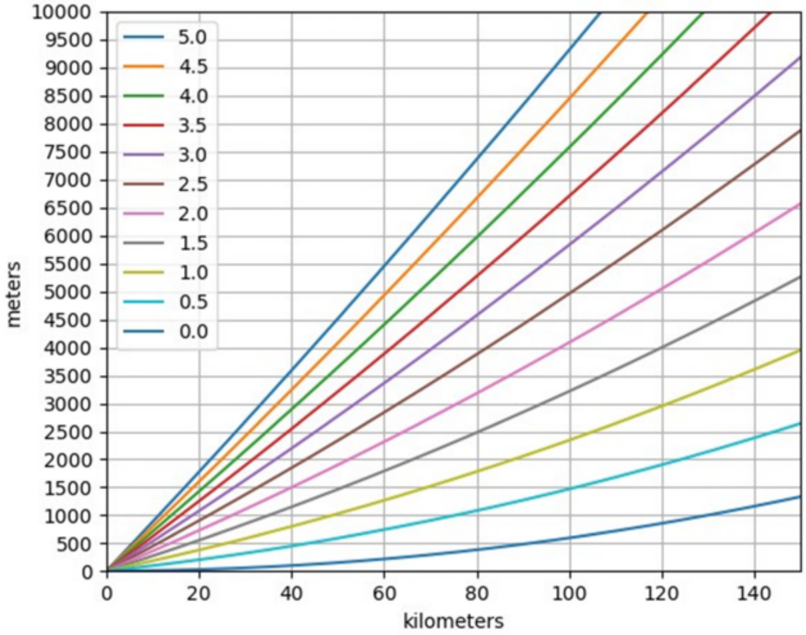
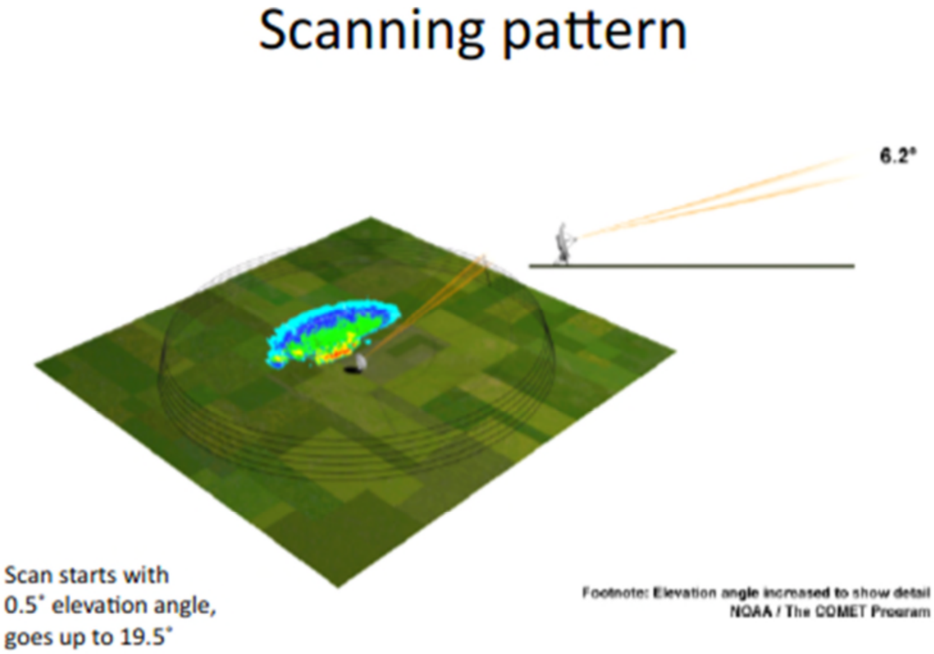


Figure 1: Beam height versus range for various elevation angles. Values used in (8.30) are $h_O = 10$ m and $k = 4/3$.



Scanning pattern

Scan starts with
0.5˚ elevation angle,
goes up to 19.5˚

Footnote: Elevation angle increased to show detail
NOAA / The COMET Program

Advanced Weather Radar Systems

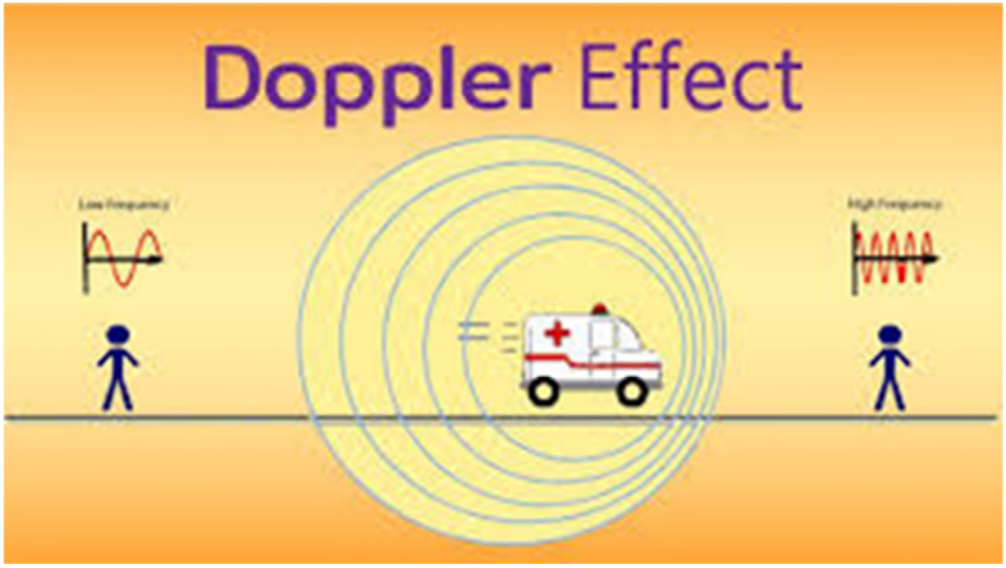
Doppler Weather Radar

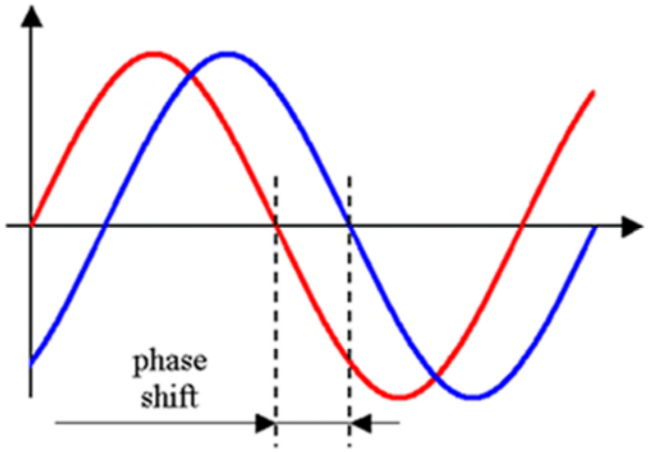
- Most meteorological radars are non-coherent and are used to observe the location and pattern of echoes and to measure the intensity of the background signal.
- The radar can also detect the pulse-to-pulse change in signal strength and therefore the relative motion of the scatters can be estimated.
- Pulsed Doppler weather radar operation is based on Doppler Effect
- **Doppler effect**: an increase (or decrease) in the frequency of sound, light, or other waves as the source and observer move towards (or away from) each other

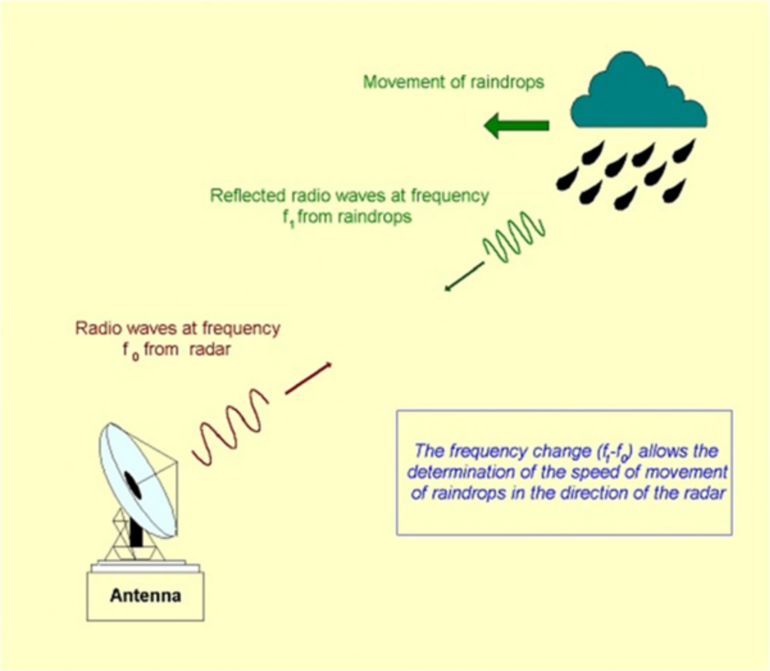
- In addition to radar reflectivity, Doppler weather radar can detect the relative motion of the targets.
- In other words, it can measure how fast rain or hail is moving toward or away from the radar.
- Doppler weather radar can measure the change in the phase of the returned pulses

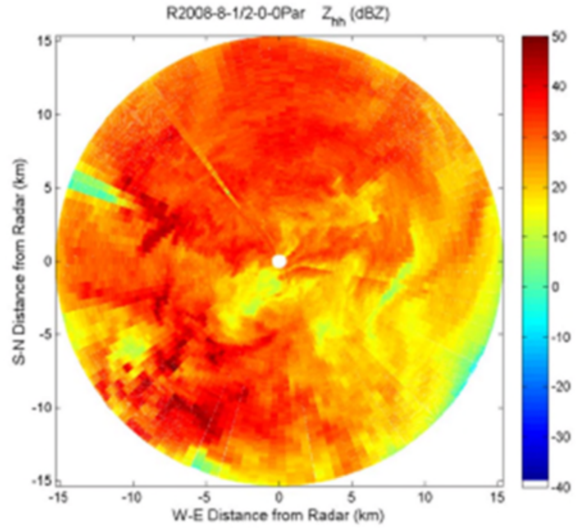
- The calculate Doppler velocity is by: $v = \Delta f \lambda / 2$

- Most modern radars have Doppler capability

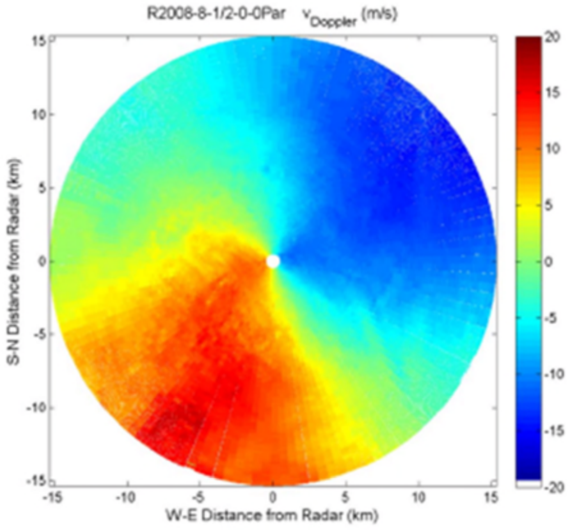








Reflectivity (dBZ)



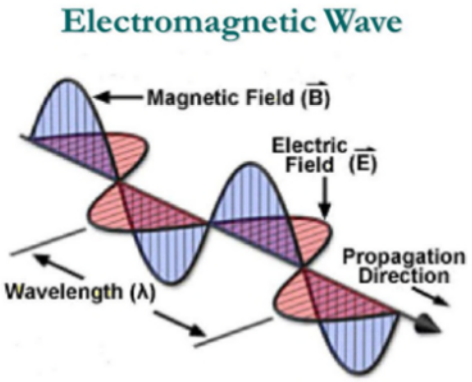
Doppler velocity (ms^{-1})

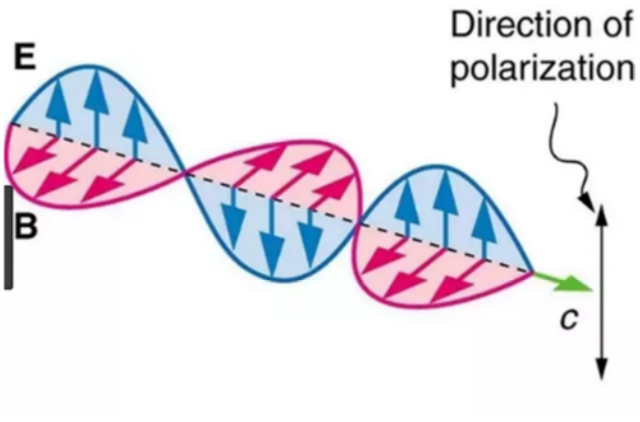
- Tornado Detection

Dual Polarization Weather Radar

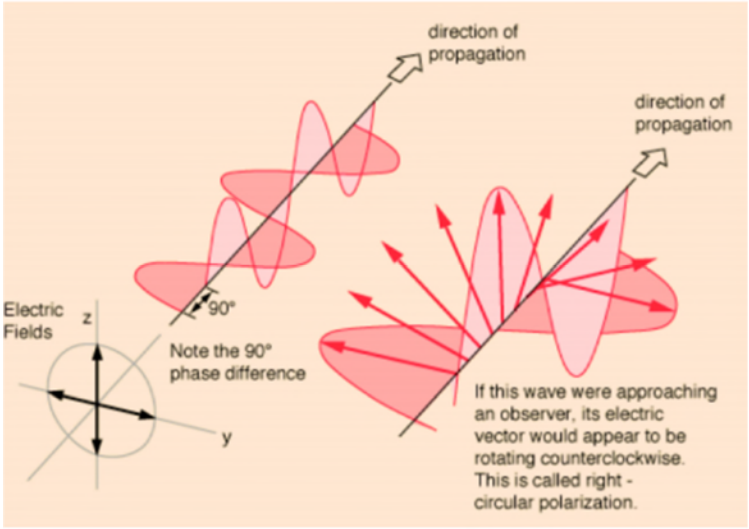
➢ Polarization of EM waves

- An electromagnetic wave such as light consists of a coupled oscillating electric field and magnetic field, which are always perpendicular to each other and to the direction of propagation.
- By convention, the "polarization" of electromagnetic waves refers to the direction of the *electric field* **E**.
- In *linear polarization*, the fields oscillate in a single direction (*horizontal or vertical*)

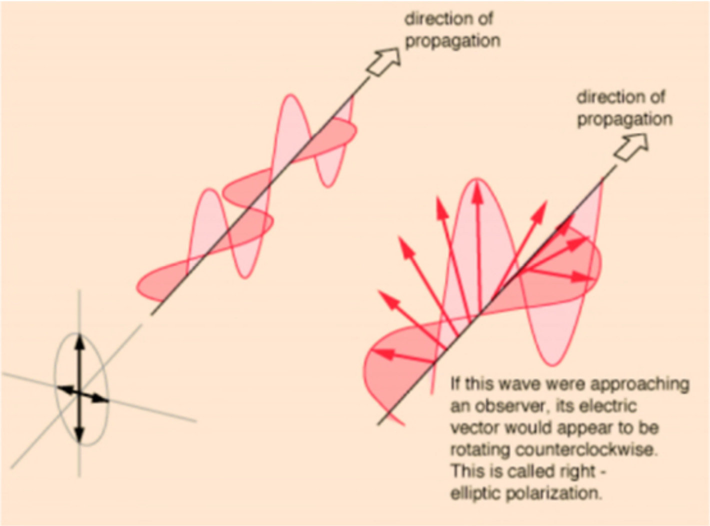




- *Circularly polarized* light consists of two perpendicular EM plane waves of equal amplitude and 90° difference in phase.
- (either right- or left-hand circular (clockwise/anti-clockwise respectively)
- The light illustrated is right-hand circularly polarized

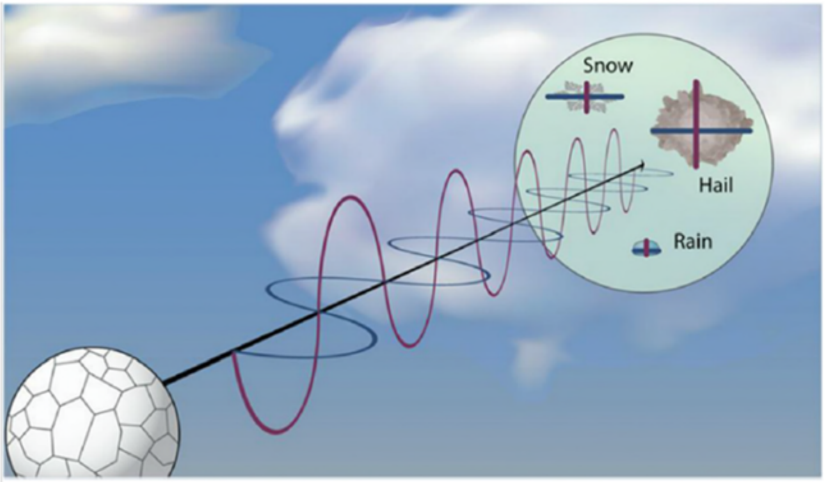


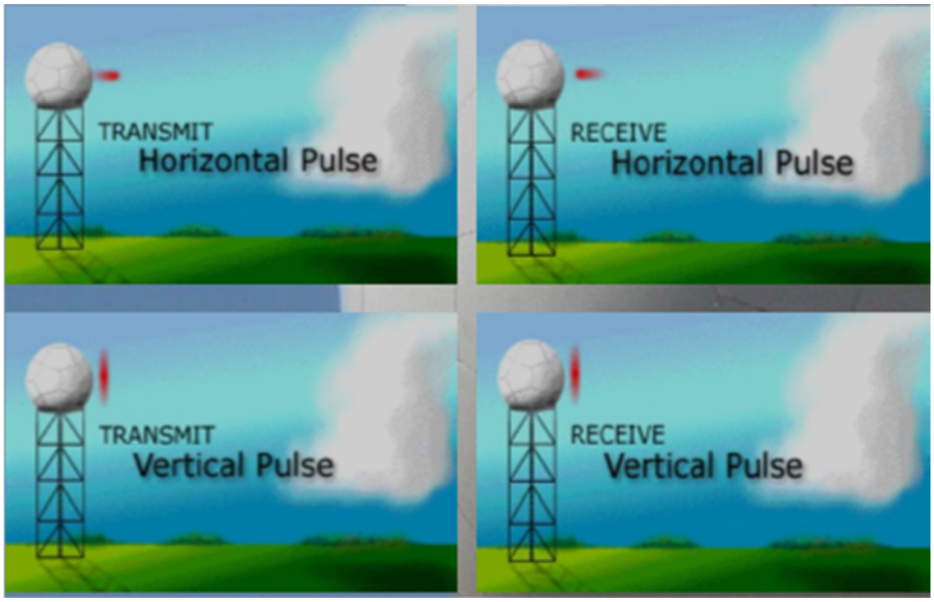
- *Elliptically polarized* light consists of two perpendicular waves of unequal amplitude which differ in phase by 90°.
- The illustration shows right-hand elliptically polarized light.



What is Dual-Polarization & How Is It Different from conventional Radar?

- Many radars transmit and receive radio waves with a single horizontal polarization
- Polarimetric radars transmit and receive both horizontal and vertical polarizations
- Can determine:
  - SIZE
  - SHAPE
  - VARIETY



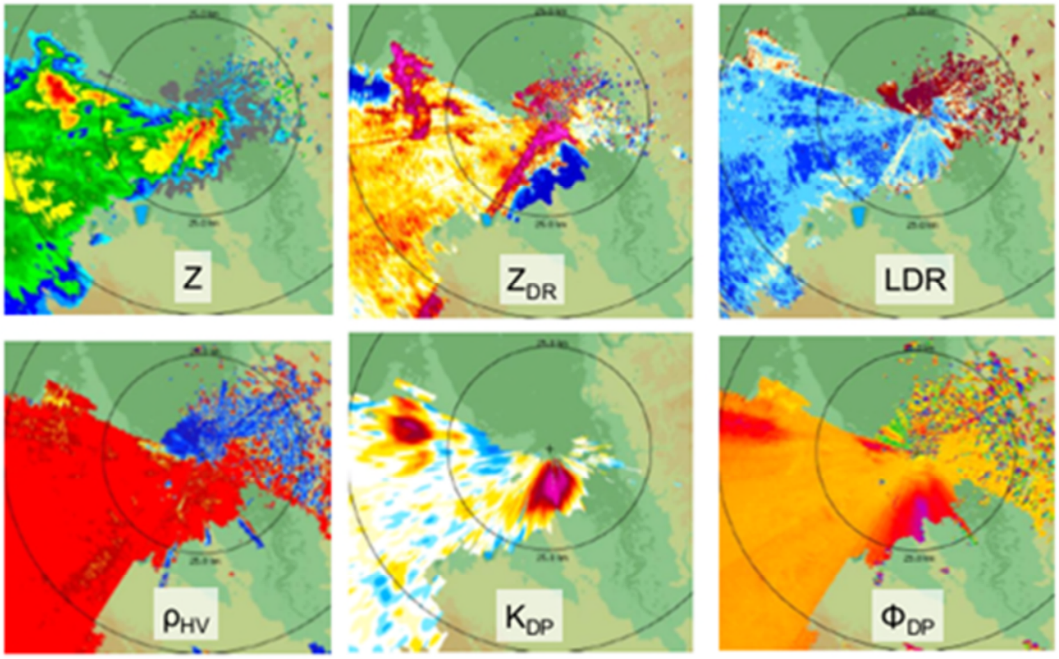


Still gets

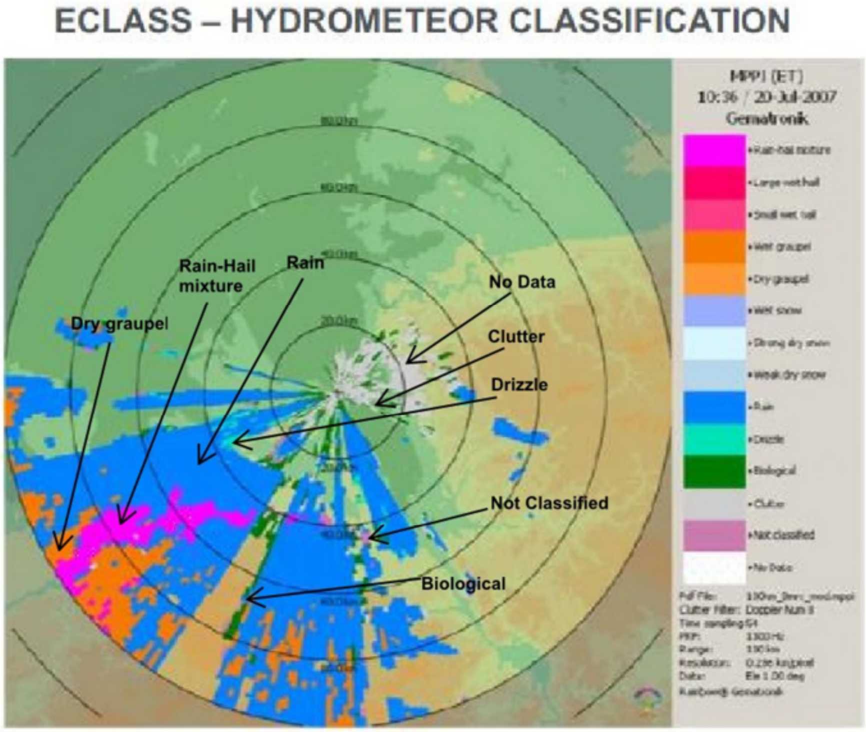
- Reflectivity (**Z**)
- Velocity (**V**)

+

- Differential Reflectivity (**Z_{DR}**)
- Linear Depolarization Ratio (**LDR**)
- Correlation Coefficient (**ρ_{HV}**)
- Specific Differential Phase (**K_{DP}**)
- Differential Phase Shift (**Φ_{DP}**)



- Based on the values of the radar parameters a classification system is used to identified different types of hydrometeors

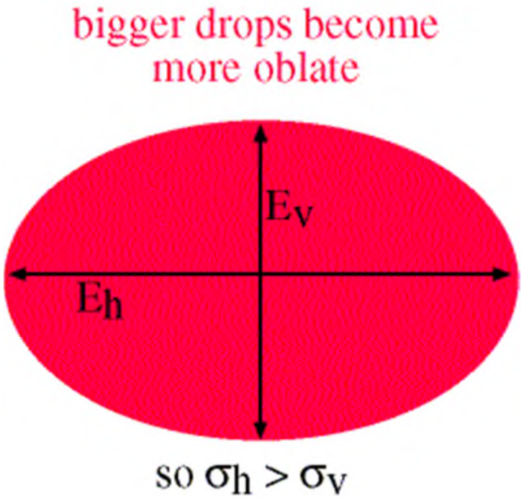


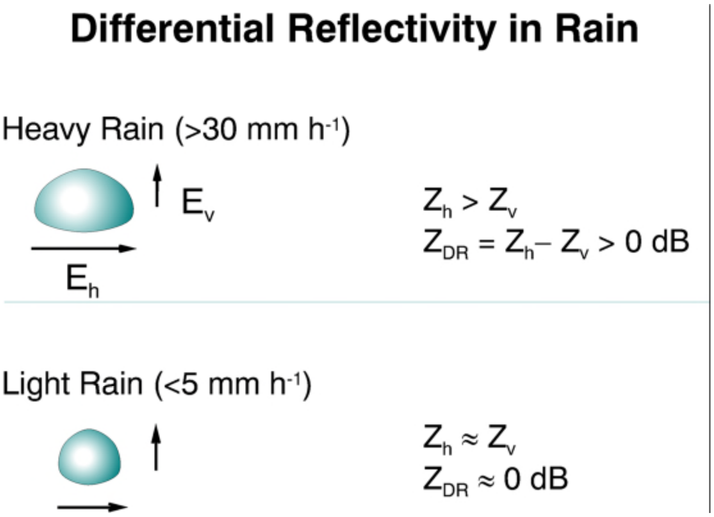
Differential Reflectivity

- Raindrops are not always spherical when they fall - especially the larger drops
- They tend to become more oblate
- So, the reflectivity would be larger if the wave were horizontally polarized, or $Z_h > Z_v$
- Define differential reflectivity (Z_{DR})

$$Z_{DR} = 10 \log (Z_h/Z_v)$$

- Z_{DR} is great for discriminating large drops from hail - hail tumbles randomly, looks like a spherical particle.
  - So, Z_{DR} for hail is about 0.
  - Z_{DR} for ice is about 0 as well





Differential Reflectivity in Rain

Heavy Rain (>30 mm h^{-1})

$Z_h > Z_v$

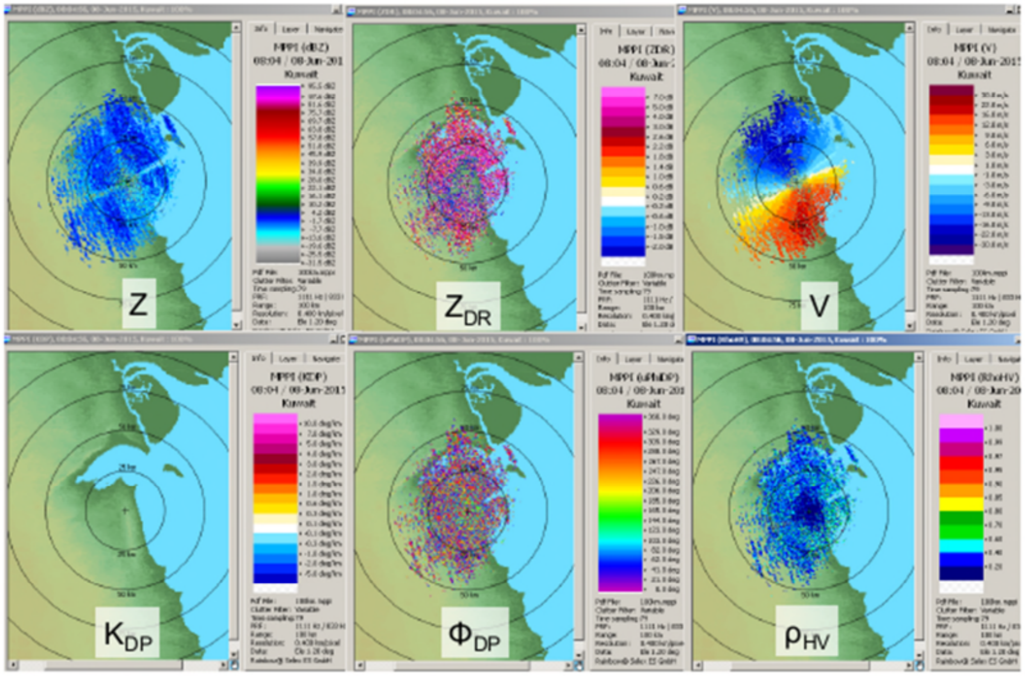
$Z_{DR} = Z_h - Z_v > 0$ dB

Light Rain (<5 mm h^{-1})

$Z_h \approx Z_v$

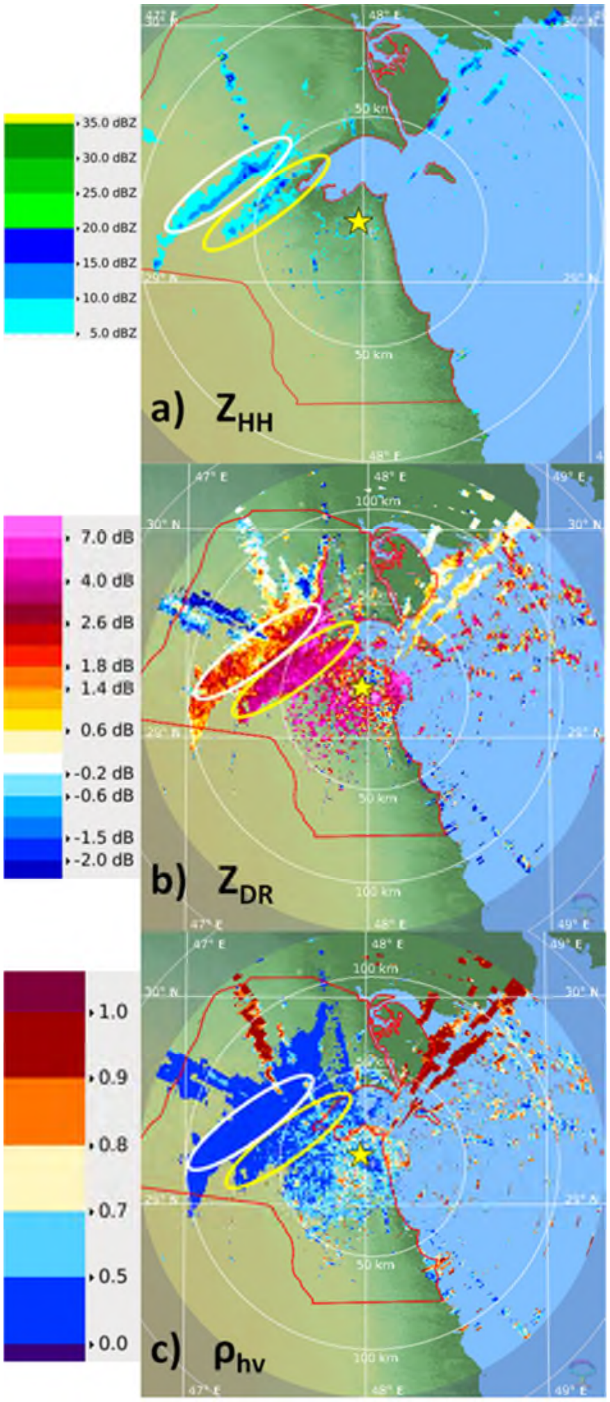
$Z_{DR} \approx 0$ dB

Kuwait Radar



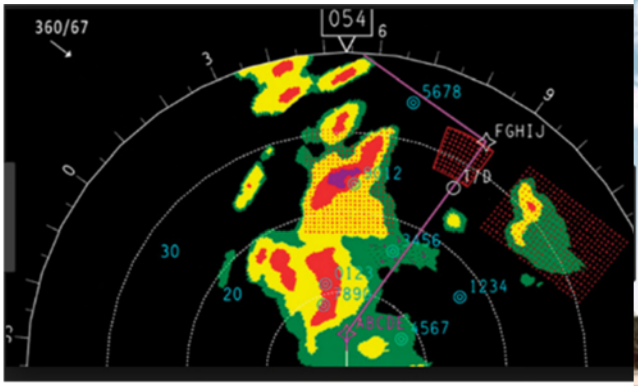
Dust Storm Detection

- Kuwait (C-band) example of dust storm observations at 1319 UTC 20 February 2015
- White ellipse indicates dust storm.
- Yellow ellipse indicates area of likely biological scatters
- Yellow star is location of Kuwait International Airport (radar site)
- Spikes extending down-radial to the northwest and northeast likely are clutter



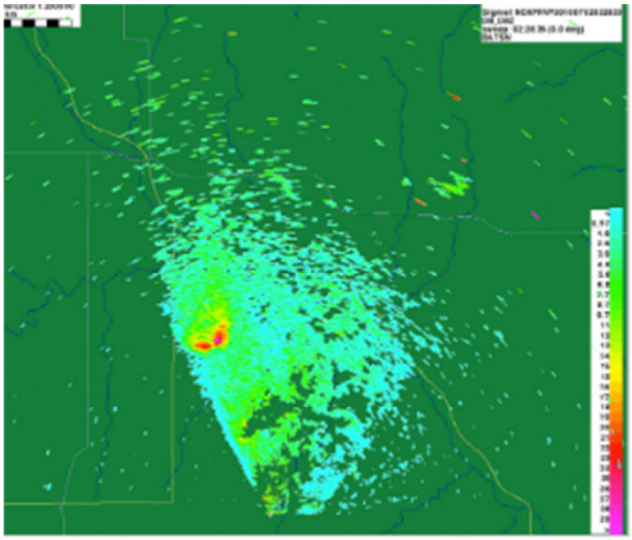
Air Born Weather Radar

Air born weather radars are used for research missions and for detection of hazardous weather events ahead of flight route (military and commercial aviation)



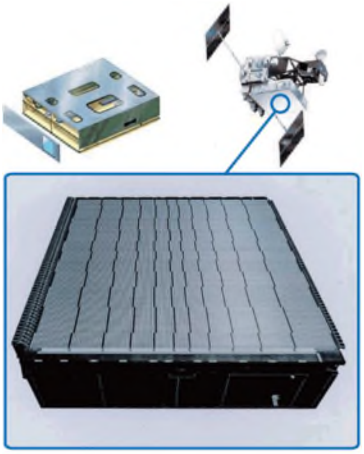
Mobile Weather Radar

Mobile radars can be driven into position as a storm is developing to rapidly scan the atmosphere at low levels, below the beam of WSR-88D radars



Space Born Weather Radar

Used for detecting clouds and measuring precipitation like TRMM satellite born radar and GPM satellite born radar.



Some of the Uses of Radar in Meteorology

- Precipitation measurements
- Wind measurements
- Turbulence and wind shear detection
- Nowcasting
- Hail and aircraft icing detection
- Location of melting level in stratiform precipitation
- Mesocyclone and tornado vortex guide (TVS) detection
- Wind soundings in stratiform precipitation
- Hurricane structure
- Wind data assimilation in numerical weather prediction models
- Extrapolation forecasting of severe weather