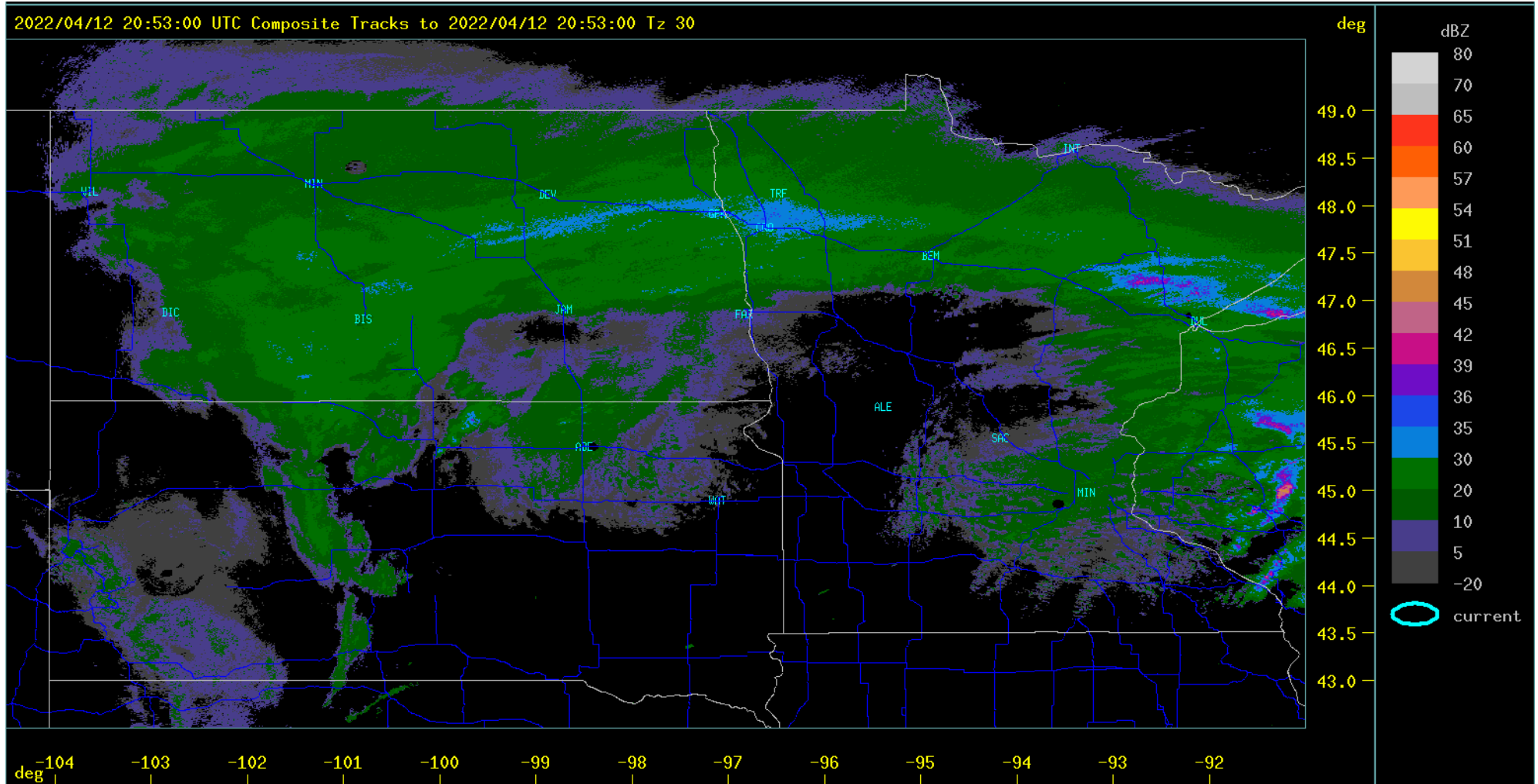


# Radar for Weather Modification



# Radio Detection And Ranging (RADAR)

- Radar Uses
  - Military
  - Weather
  - Aviation
  - Traffic Control (police)
  - Shipping
  - Research
  - Agriculture



# Weather Detection

- Precipitation Measurements
- Storm Detection & Tracking
- Snow Detection
- Cloud Detection
- Weather Modification
- Wind Measurements



# Pulsed Radars

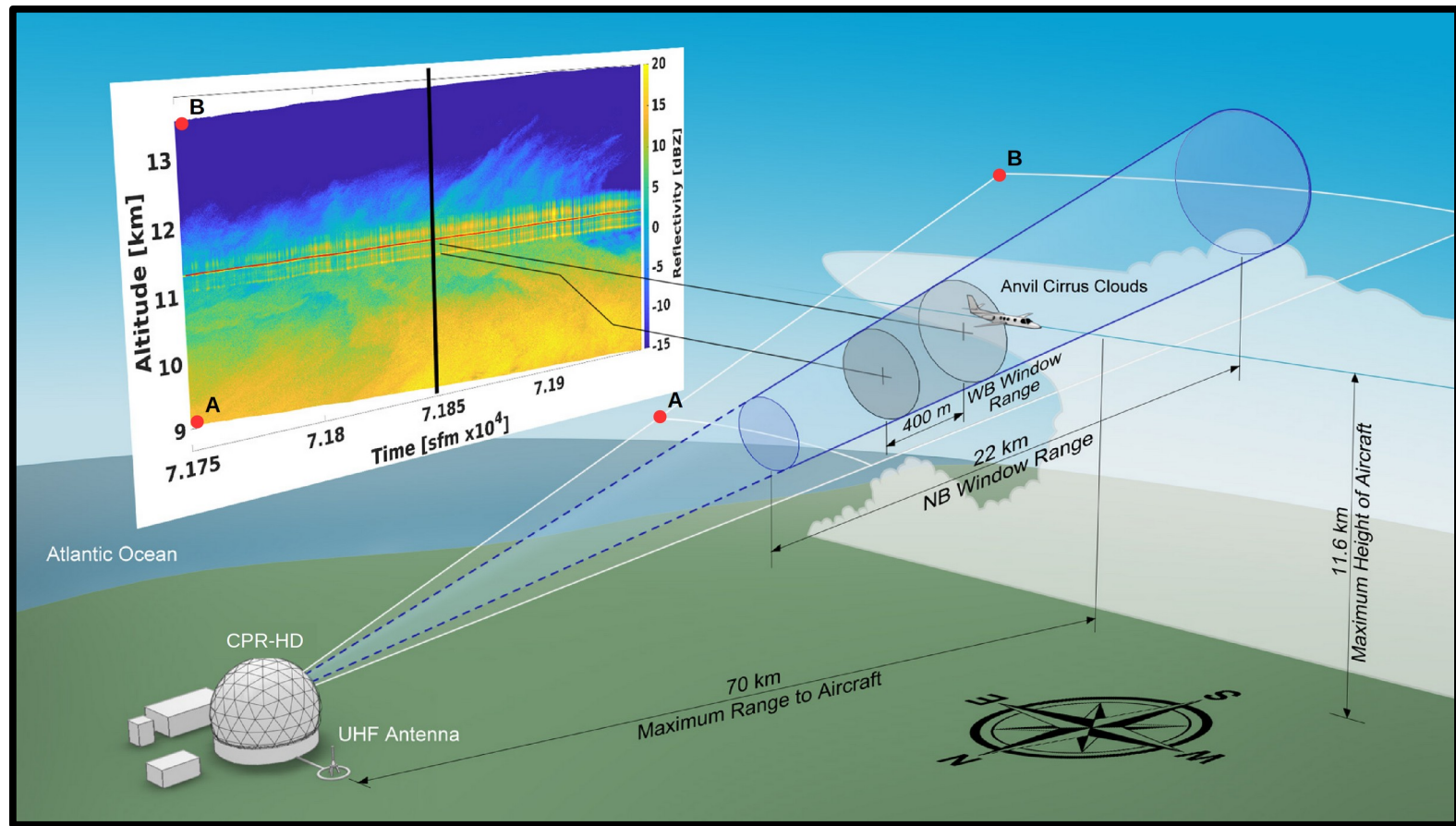
- Pulsed radars transmit short pulses of energy and wait for returned signals.
- Can detect and resolve individual echoes.
- Most weather and aircraft radars are pulsed radars.





# Measurements Conducted with Radar

- Distance
- Position
- Time
- Power
- Velocity
- Frequency Change



Gapp, Nicholas, David J. Delene, Jerome Schmidt, and Paul Harasti, 2025: Comparison of Concurrent Radar and Aircraft Measurements of Cirrus Clouds, *Journal of Atmospheric Sciences*, 82, 15-176, <https://doi.org/10.1175/JAS-D-24-0014.1>.

# Radar Measurement of Distance

- Range - Radar's Middle Name
- Distance = Rate • Time
- Distance is "Range"
- Rate is speed of light (c)
  - 299,792,458 m/s
  - $6.702 \times 10^8$  miles/hr

**Radar**



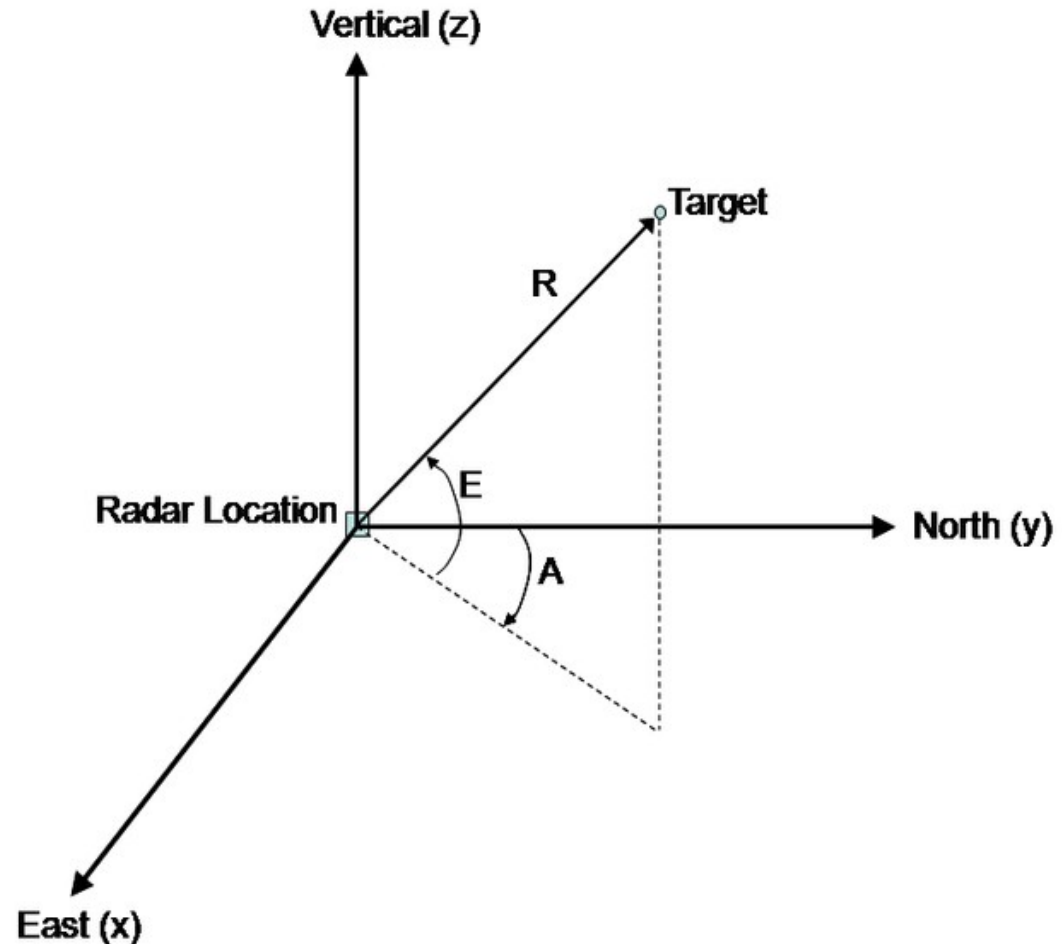
**Target**

<https://www.weather.gov/mkx/using-radar>

- What does a radar measures easily and accuracy?

# Position Radar Measurement Parameters

- Range ( $R$ )
- Azimuth ( $A$ )
  - Requires a horizontally scanning antenna.
- Elevation ( $E$ )
  - Requires a vertically scanning antenna.



# Received Power (Echo Strength)

- Used to calculate radar Reflectivity (Z)
- Z is used to estimate Rain Rate (R)

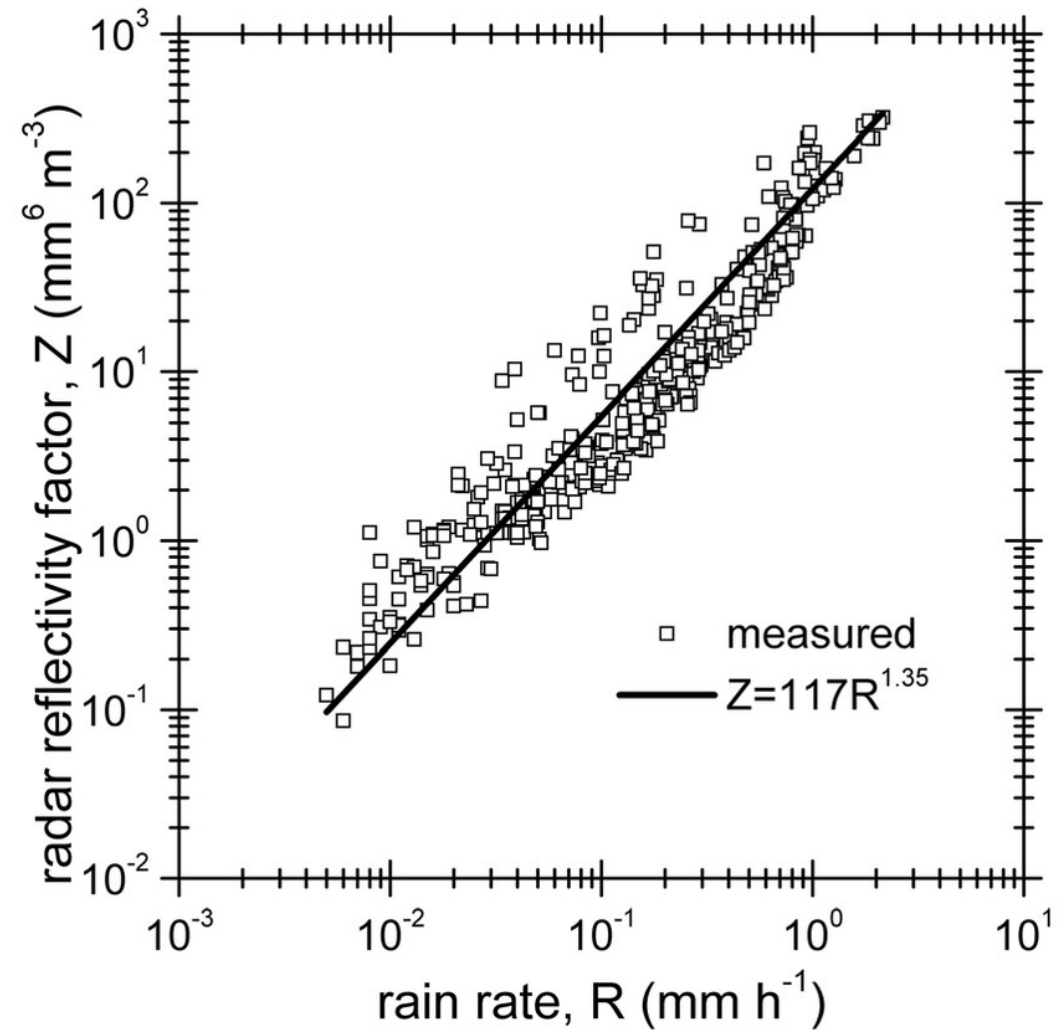
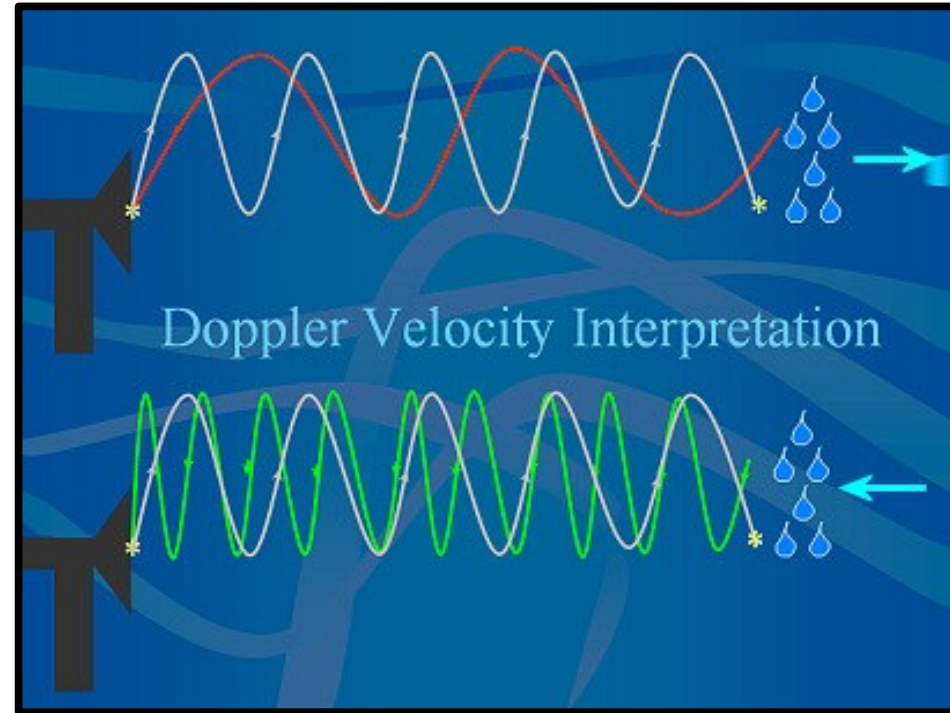


Figure 12 from [Baojun Chen](#), Characteristics of the raindrop size distribution for freezing precipitation observed in Southern China, Journal of Geophysical Research Atmospheres 116(D6), 2011, DOI:10.1029/2010JD015305



# Velocity Radar Measurements

- Obtained by tracking echoes and knowing the time between measurements.
- Doppler Shift - Moving targets change the frequency of the returned signal.
- Transmit known frequency and measure the frequency shift of returned signal.

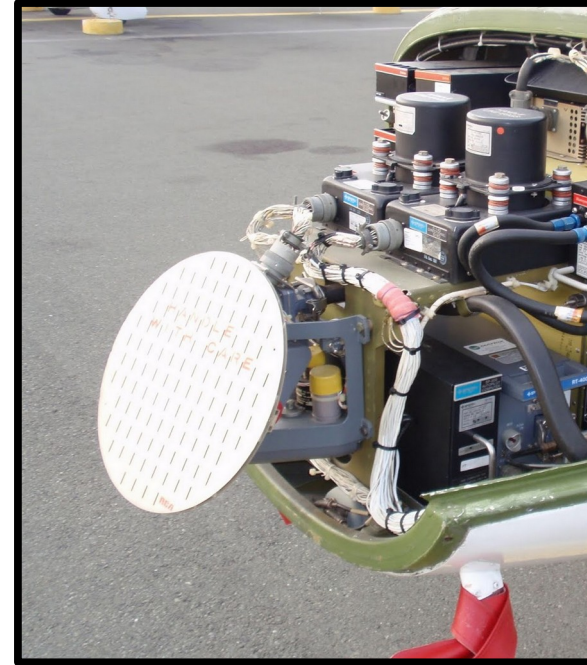


Grey line is the transmitted signal. The returned energy changes its wavelength when it hits a target moving away (red line) or toward the radar (green line)

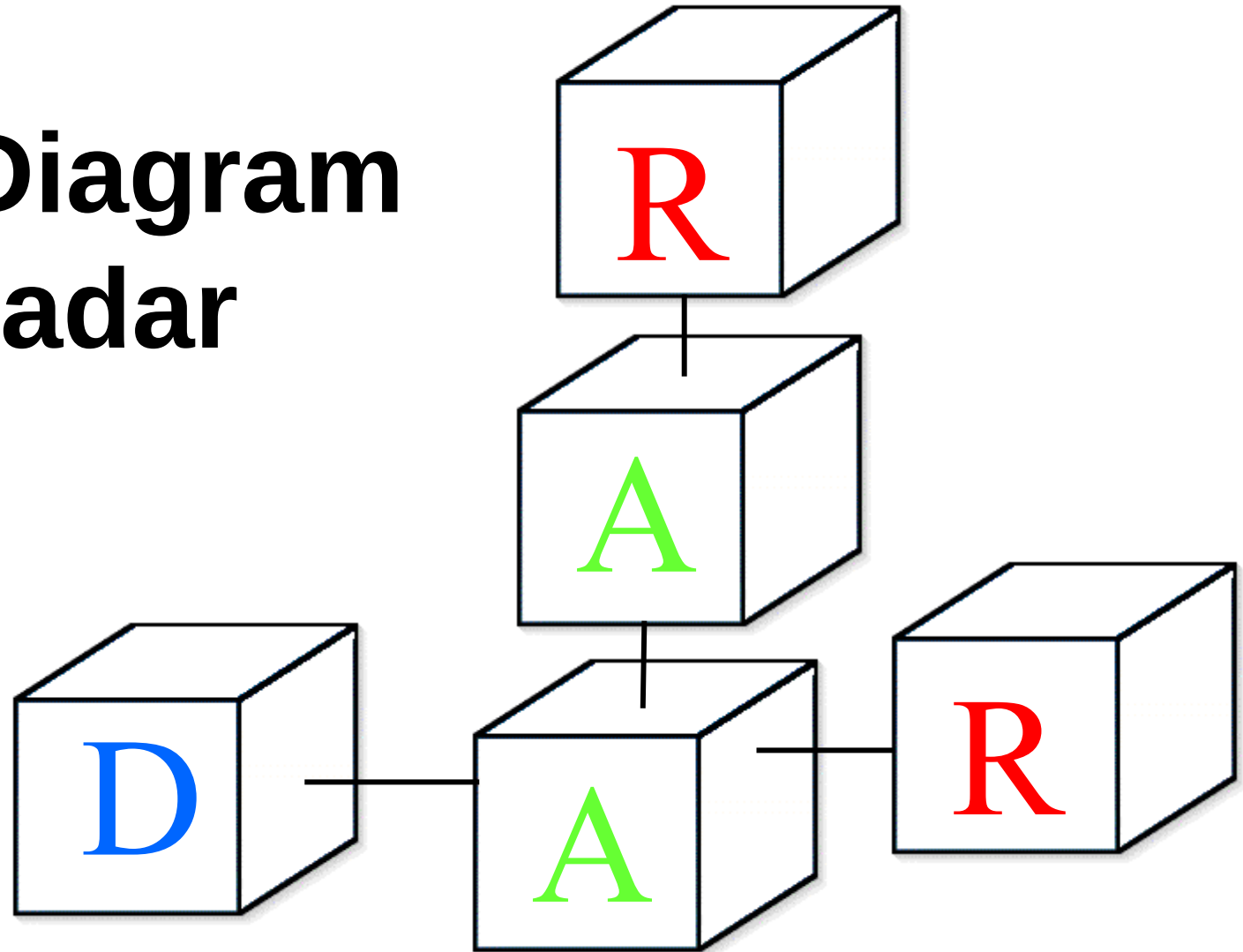
<https://www.weather.gov/mkx/using-radar>

# Radar Measurements from Aircraft

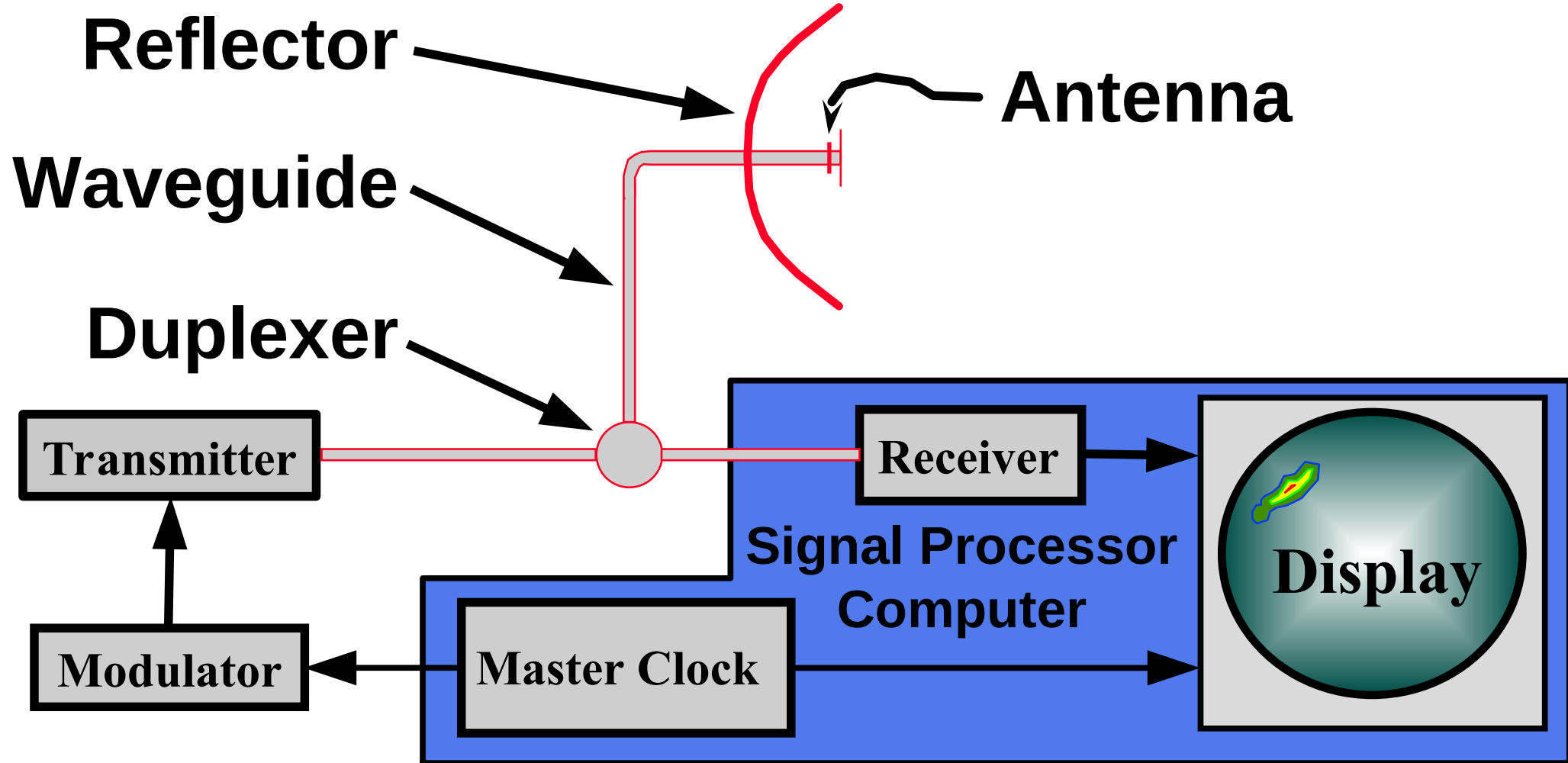
- Must be small, light weight & low power.
- Scan ahead of aircraft ( $\pm 60^\circ$  or  $\pm 90^\circ$ ).
- Limited vertical tilt capability.
- Size dictates use of short wavelength.
  - Short wavelength radar is attenuated!
  - **Cannot always see storms through storms.**
- Used for storm avoidance, not penetration.



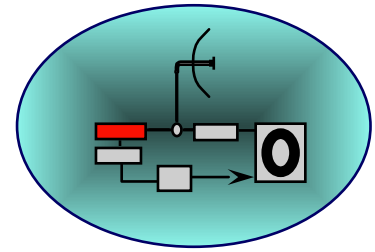
# Block Diagram of Radar



# Block Diagram of Radar



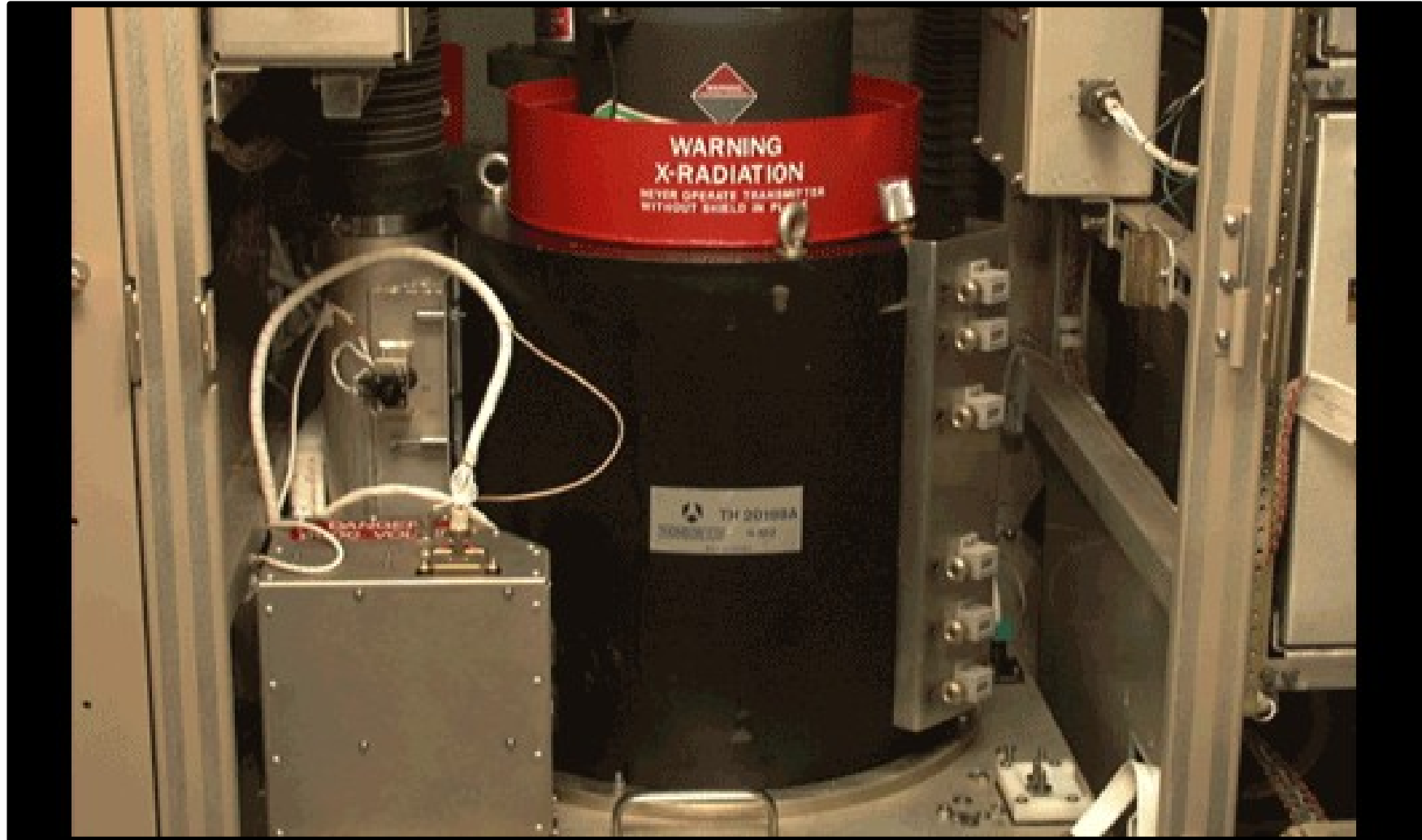
# Radar Transmitter



- Generates the microwave signal.
- Transmits a short burst of power at some frequency.
- Typical power from a few watts (W) to a couple of megawatts (mW).
  - UND Radar Transmits 250,000 W or 250 kW.
  - CPR-HD Radar Transmits 3 mW
- Frequency from 30 MHz to 300 GHz
- UND / CPR-HD Radars use 5550 MHz = 5.55 GHz

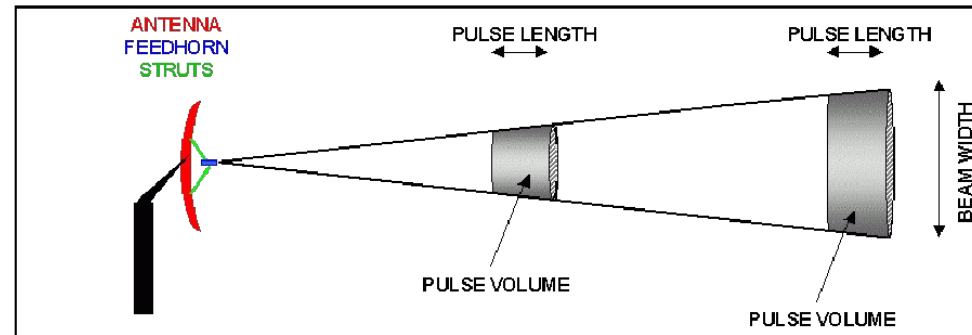


# WSR 88D Radar Transmitter



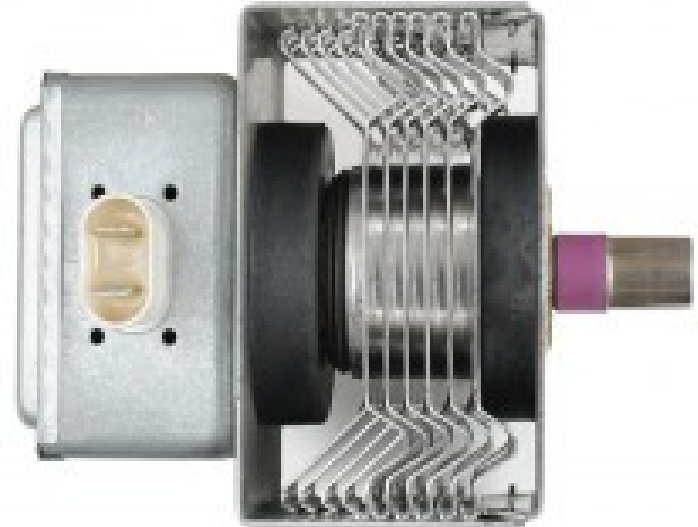
# Transmitter Pulse Parameters

- Duration of transmitted pulse is called pulse duration (t) or pulse length (h)
  - Typically  $0.25\ \mu\text{s}$  to  $10\ \mu\text{s}$  or longer
  - $1\ \mu\text{s} = 10^{-6}\ \text{s}$  ( $\sim 150\ \text{m}$  effective length)
- Transmitted pulse is repeated many times, called pulse repetition frequency (PRF)
- Typically, 150 to 5000 Hz
- UND upper limit - 1200 Hz



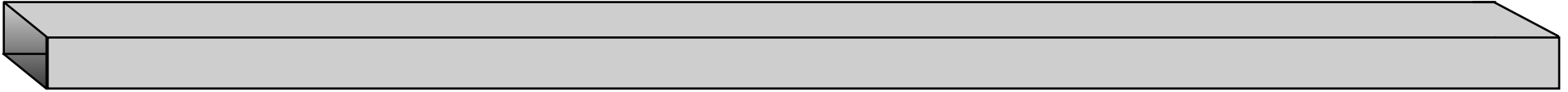
# Radar Transmitter Types

- Magnetron
  - Invented in 1939 by the British
  - Generate power up to 250 kW
  - Small and light weight
- Klystrons
  - Generate up to 2 MW
  - Larger/bigger than magnetrons
  - Very stable frequency output
- Solid-state Transmitters



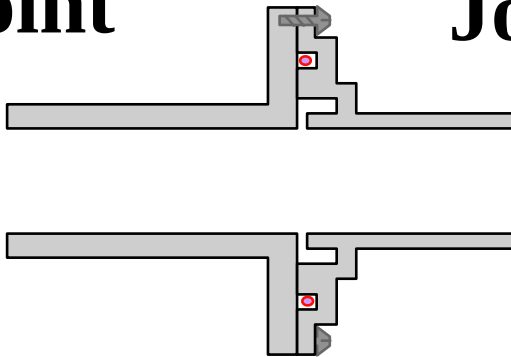
# Waveguide for Radar

## Rectangular Piece of Hollow Waveguide



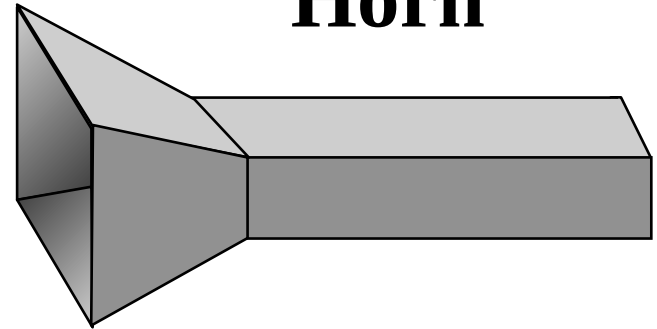
**Flange  
Joint**

**Choke  
Joint**

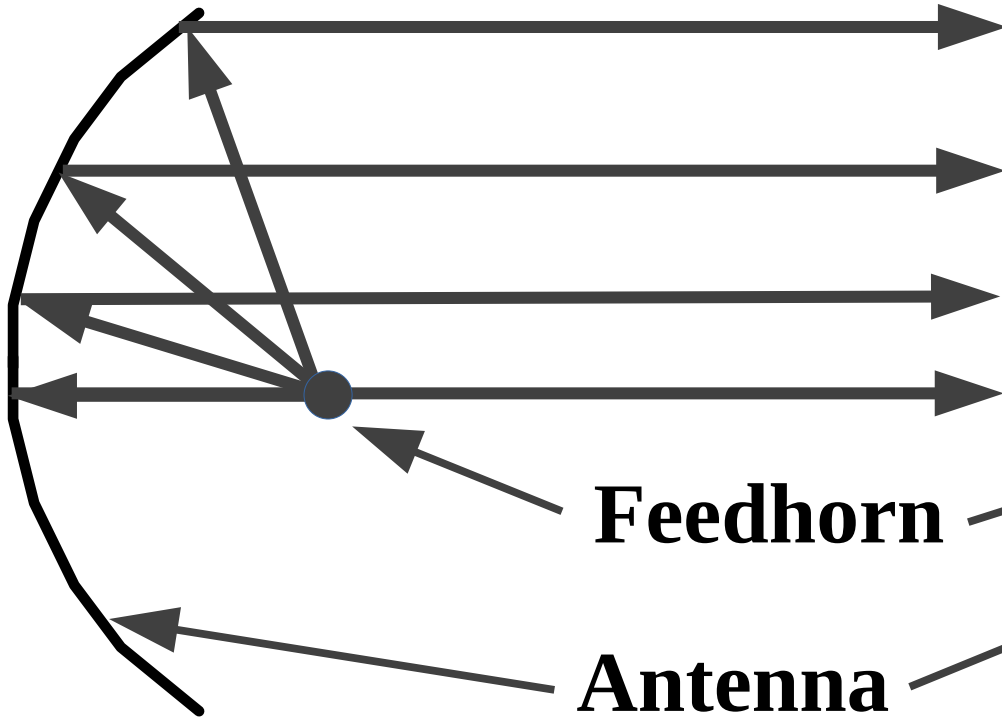


**(cross-section)**

**Horn**



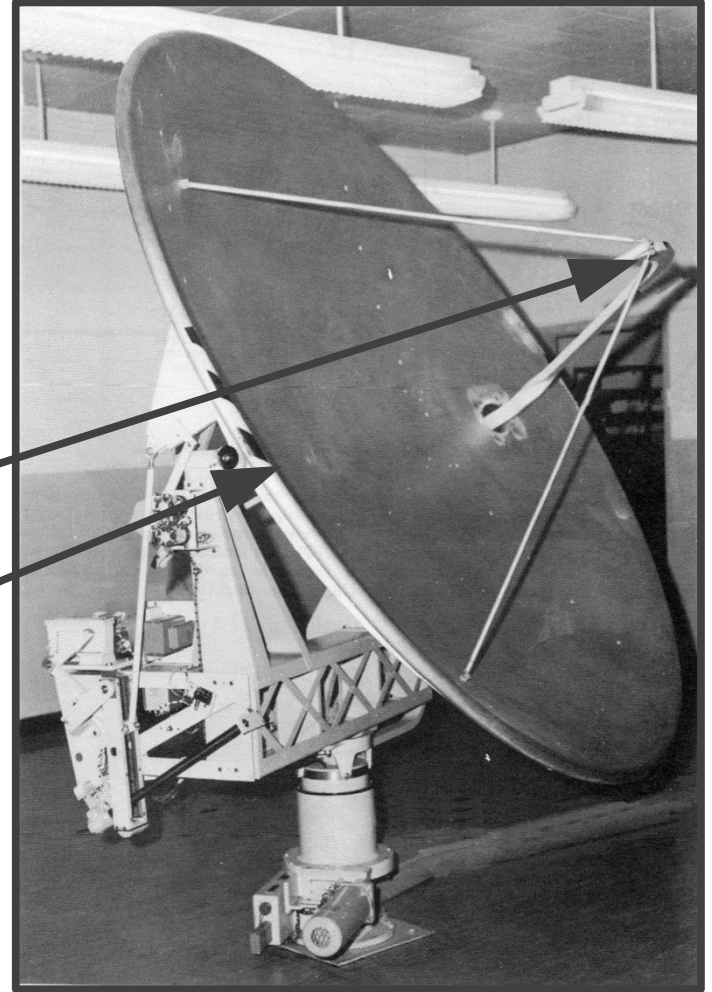
# Cross-Section of Parabolic Reflector



**Feedhorn**

**Antenna**

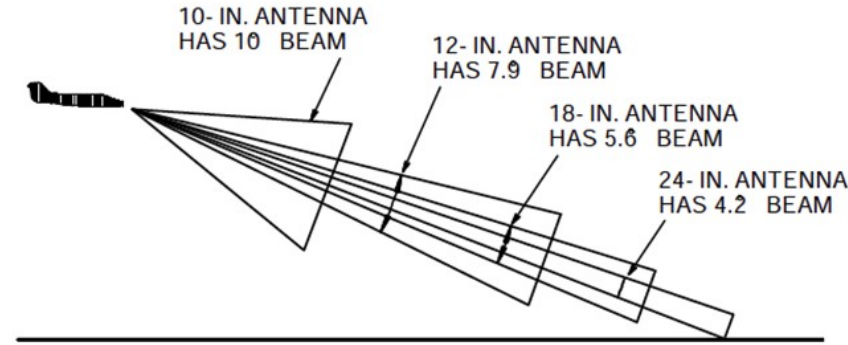
**Rays from focus are  
reflected parallel into space.**





# Radar Reflector Functions

- Directs signal into space.
  - Focuses it.
- Generally parabolic in shape.
- Larger antennas give smaller beam widths for the same wavelength signal.
- Higher frequencies (shorter wavelengths) require smaller antennas for the same beam width.
  - Aircraft usually use X or C band.
  - Ground-based radars usually use S or C band.



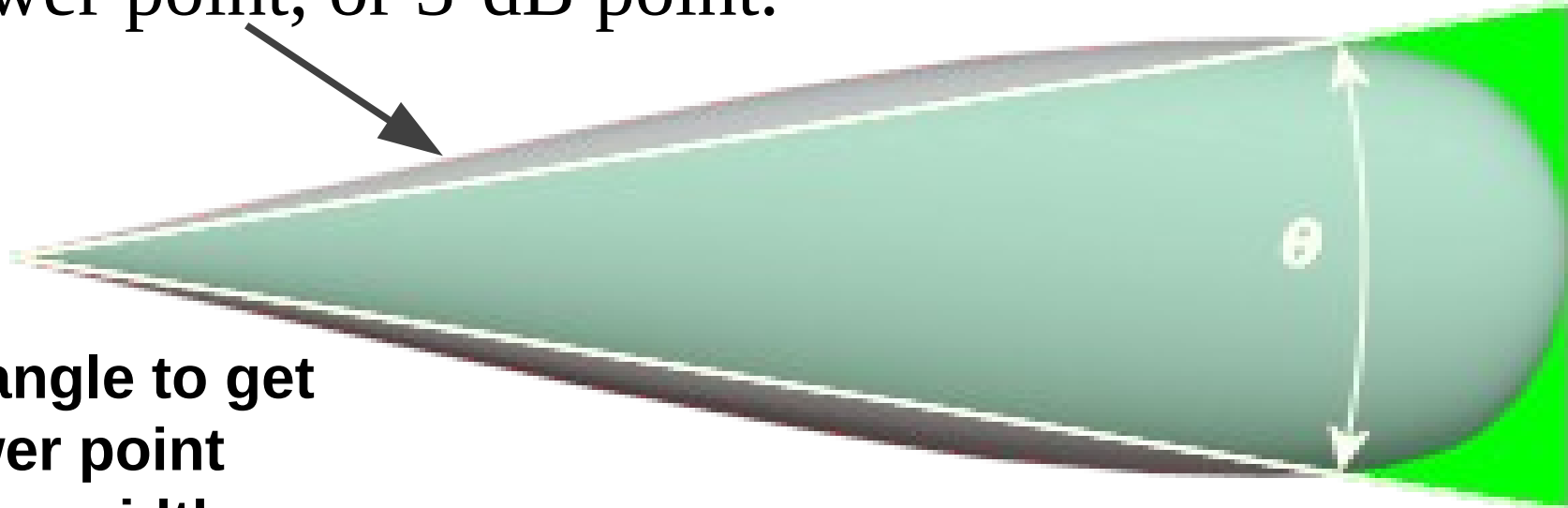
# Advantages of using Radar Reflector

- Reflectors focus energy into a particular direction.
- Reflectors make the energy at some point stronger than it would have been otherwise.
- Reflectors allow us to determine direction to a target.



# Antenna Beam Width

- The angular width of an antenna pattern.
- The angular width where the power density is one half that on the axis of the beam.
- Half-power point, or 3-dB point.



**Double the angle to get the half-power point antenna beam width.**

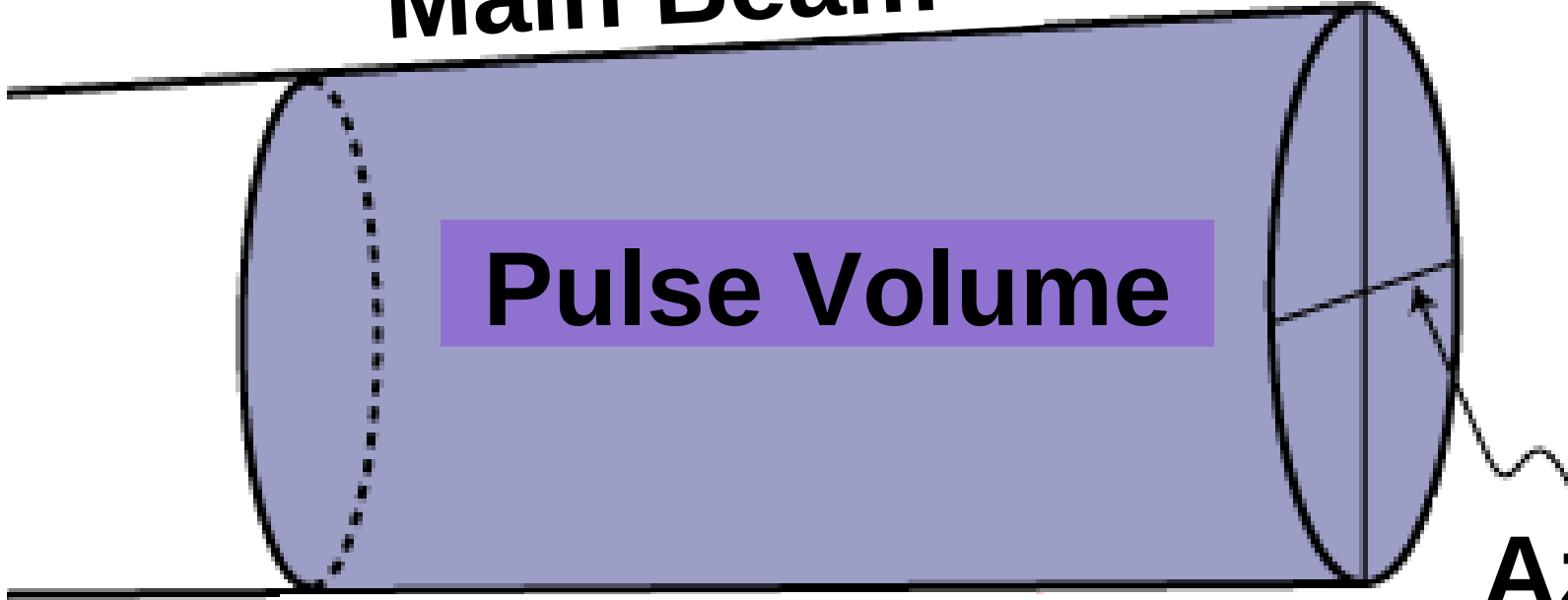
# Radar Pulse Volume

**Main Beam**

**Pulse Volume**

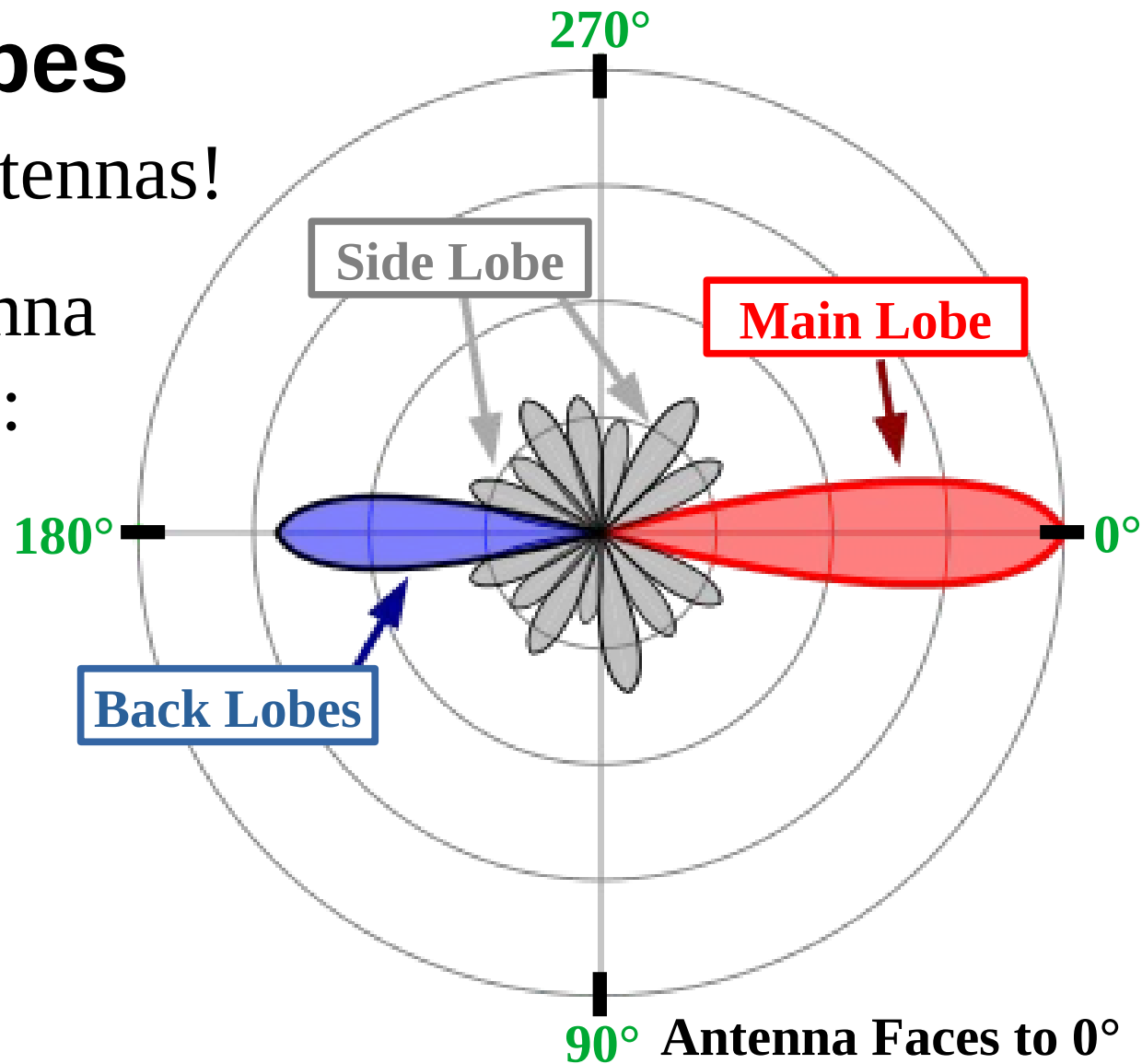
**Radial Dimension**

**Azimuthal  
Dimension**



# Antenna Sidelobes

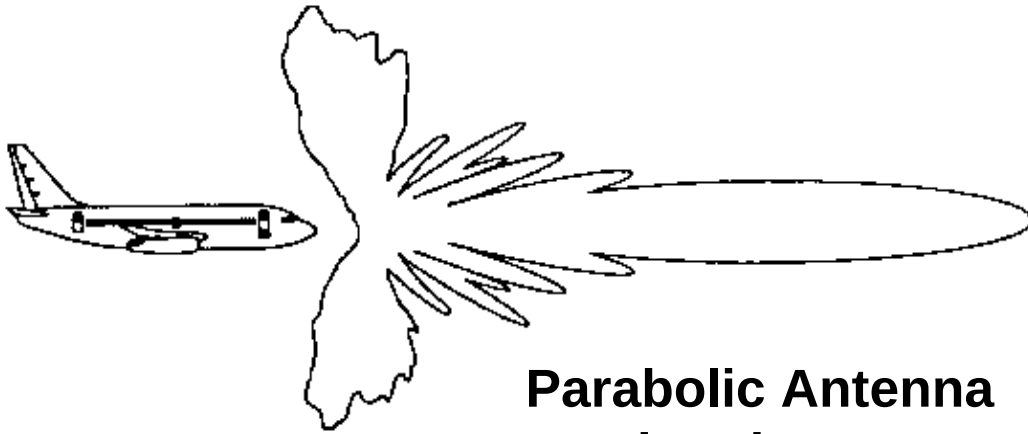
- There are no perfect antennas!
- All antennas have antenna patterns, which include:
  - Main lobe
  - Side lobes
  - Back lobes



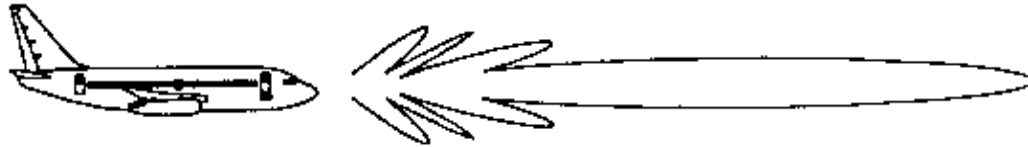


# Flat-plate or Phased-array Antenna

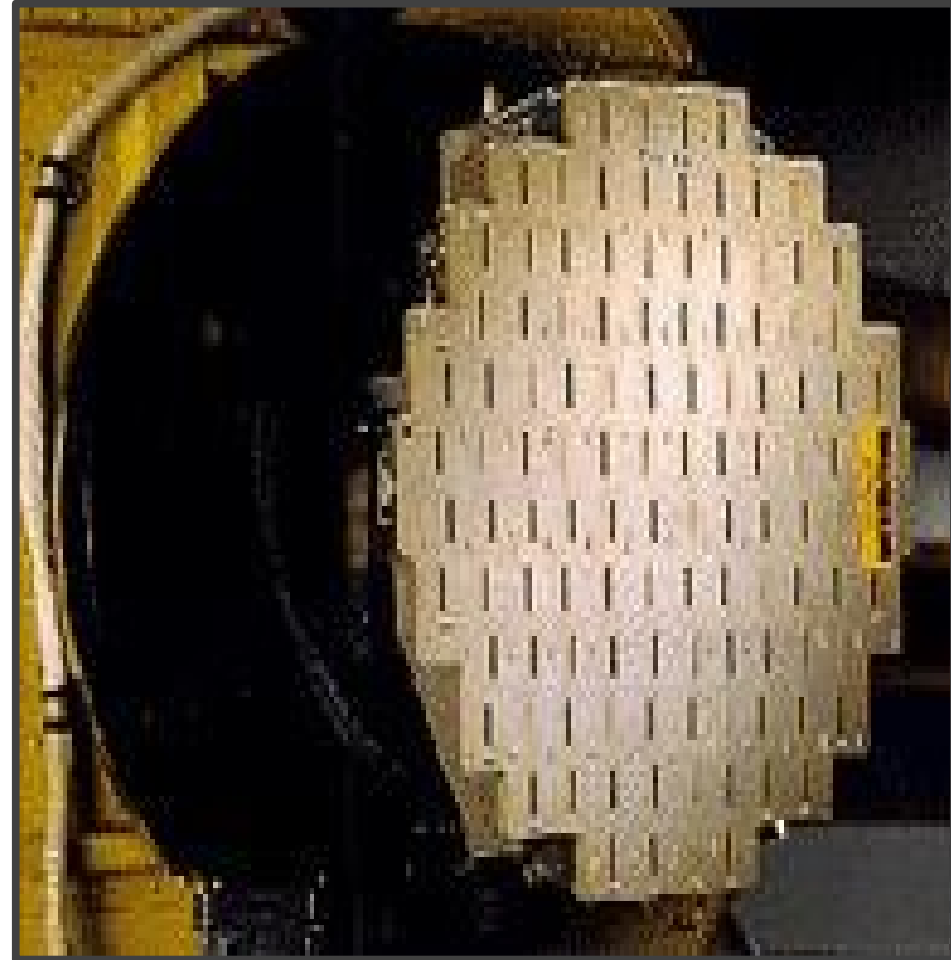
- More focused beam.
- Fewer side lobe losses.



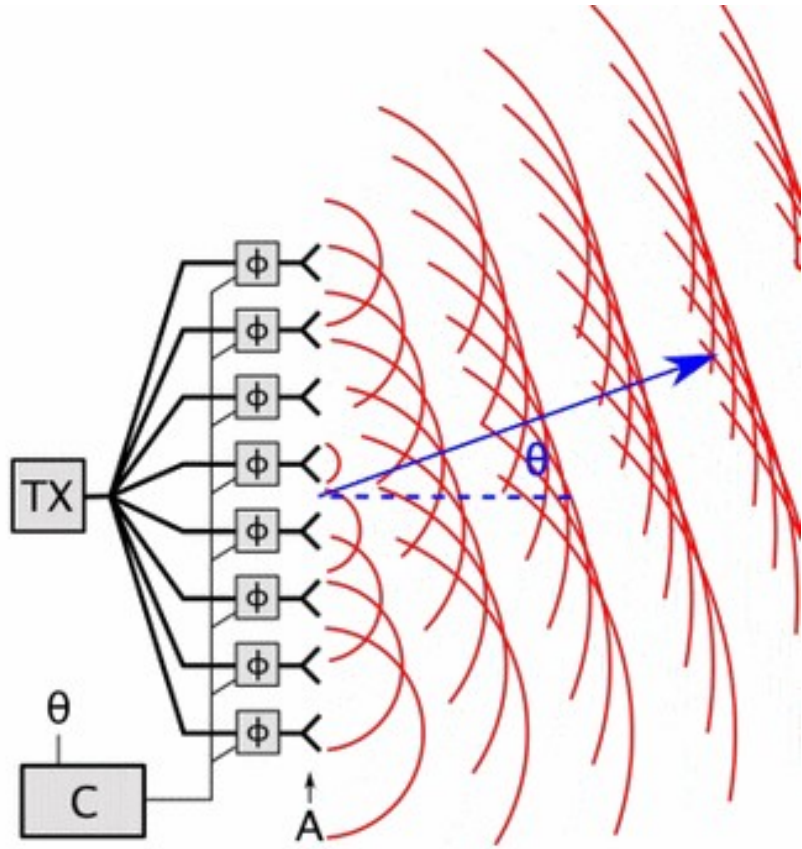
**Parabolic Antenna  
Azimuth Patter**



**Flat-plate Antenna  
Azimuth Patter**



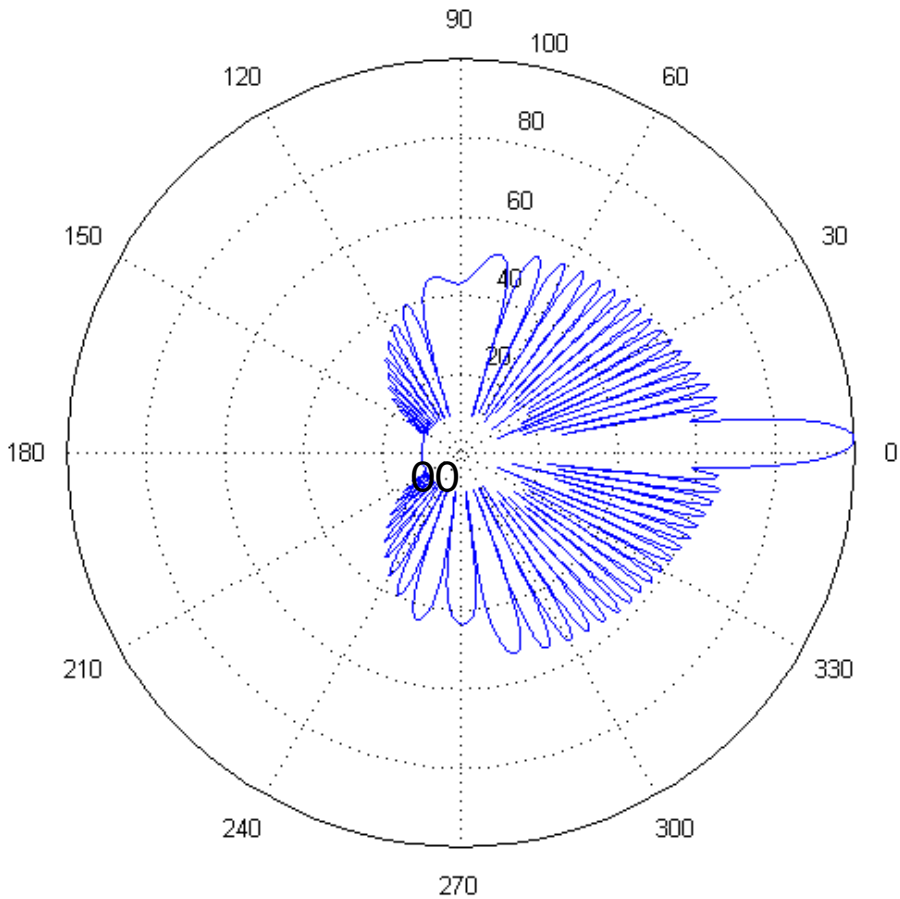
# Principles of Phased Array Radar



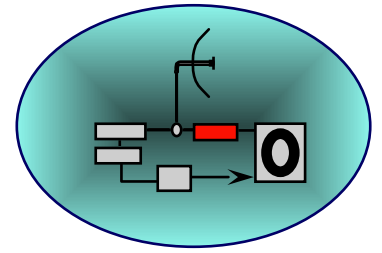
[https://en.wikipedia.org/wiki/Phased\\_array](https://en.wikipedia.org/wiki/Phased_array)

# Side Lobes During Electronic Scanning

- Phased-array Scanning.
- There are higher-order main lobes when scan is performed wide range.



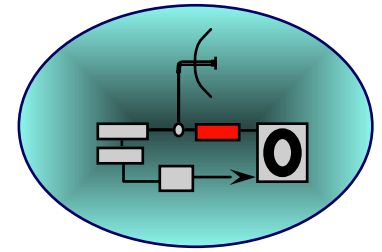
# Radar Receiver Function



- Detect and amplify the tiny signal received by the antenna.
- Must be very sensitive.
  - Typically, radar receivers can detect powers of 0.000 000 000 000 02 W.
    - This power is more conveniently expressed logarithmically as -107 dBm.
    - $P \text{ (dBm)} = 10 \cdot \log_{10}(P \text{ (linear power)} / 1 \text{ mW})$

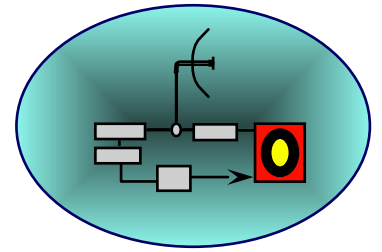
# Radar Receivers Operations

- Operate initially at radio frequencies (RF) using low-noise amplifiers.
- Signal converted to intermediate frequencies for easier amplification (IF amplifier).
- Output is a voltage.





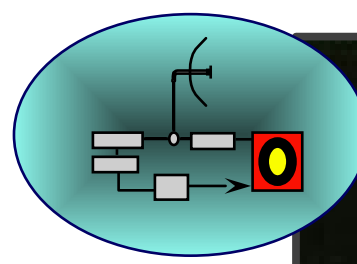
# A-scope Radar Display System



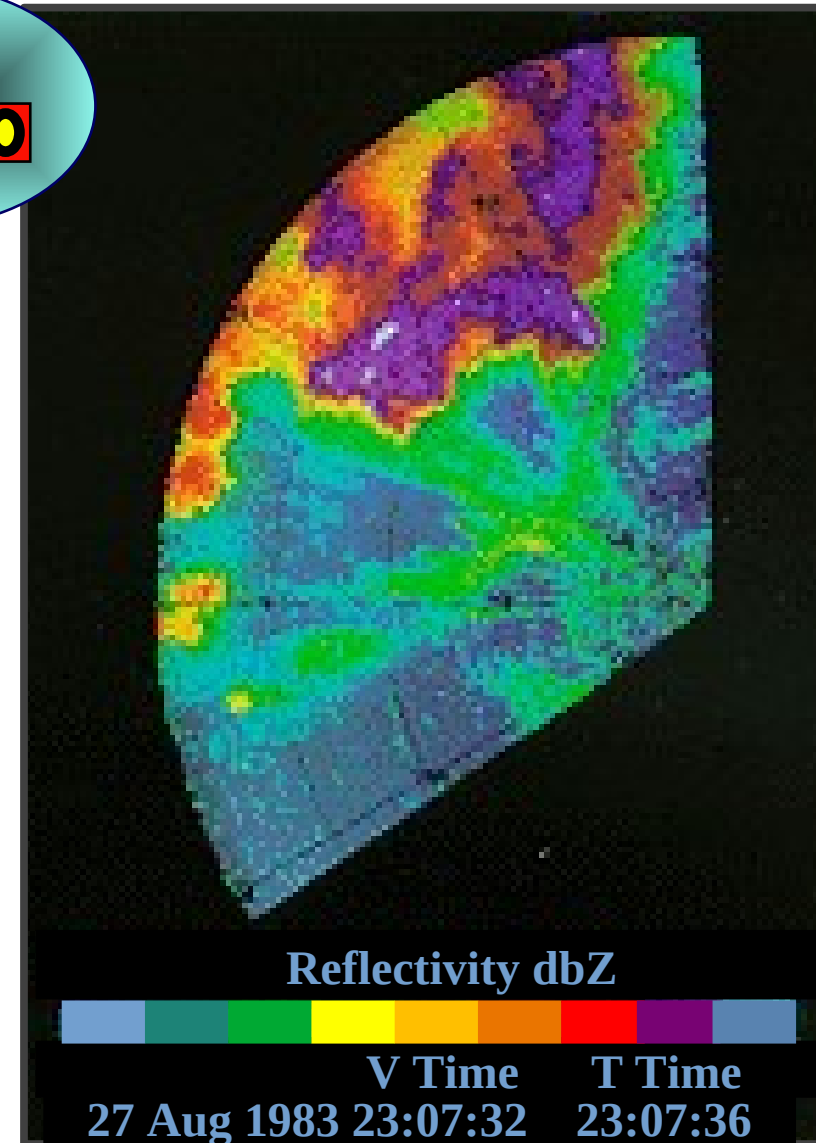
- The original radar display, an oscilloscope.
- Time is x-axis, voltage or power is y axis.
- Each pulse is shown individually.



# Plan Position Indicator (PPI) Radar Display

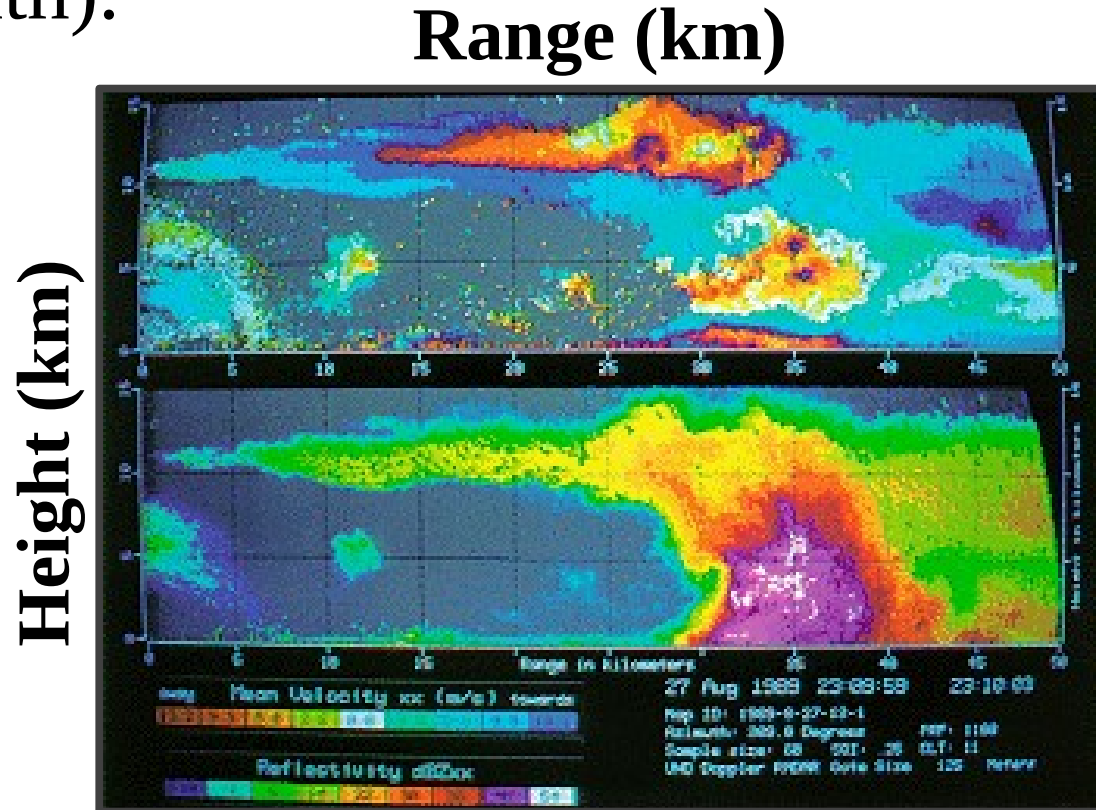


- Map-like display with radar (usually) at center, north to top, east to right.
- Range rings give distance.
- Intensity shown by brightness (monochrome displays) or color (modern displays).



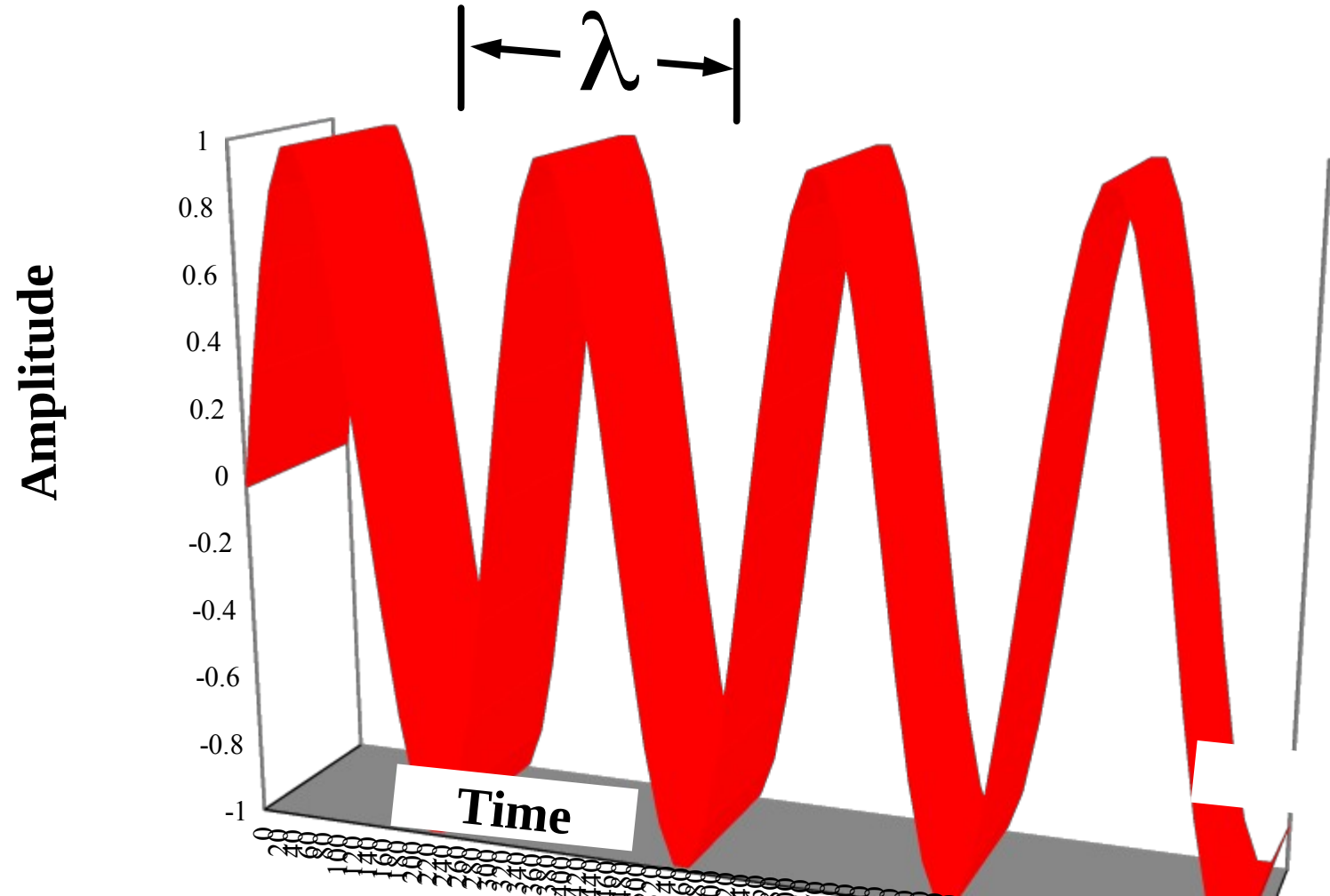
# Range-height Indicator (RHI) Displays

- Shows a vertical profile along a particular direction (azimuth).
- Scans up and down.
- Display shows range in x direction and height in y direction.
- Intensity shown by brightness or color.

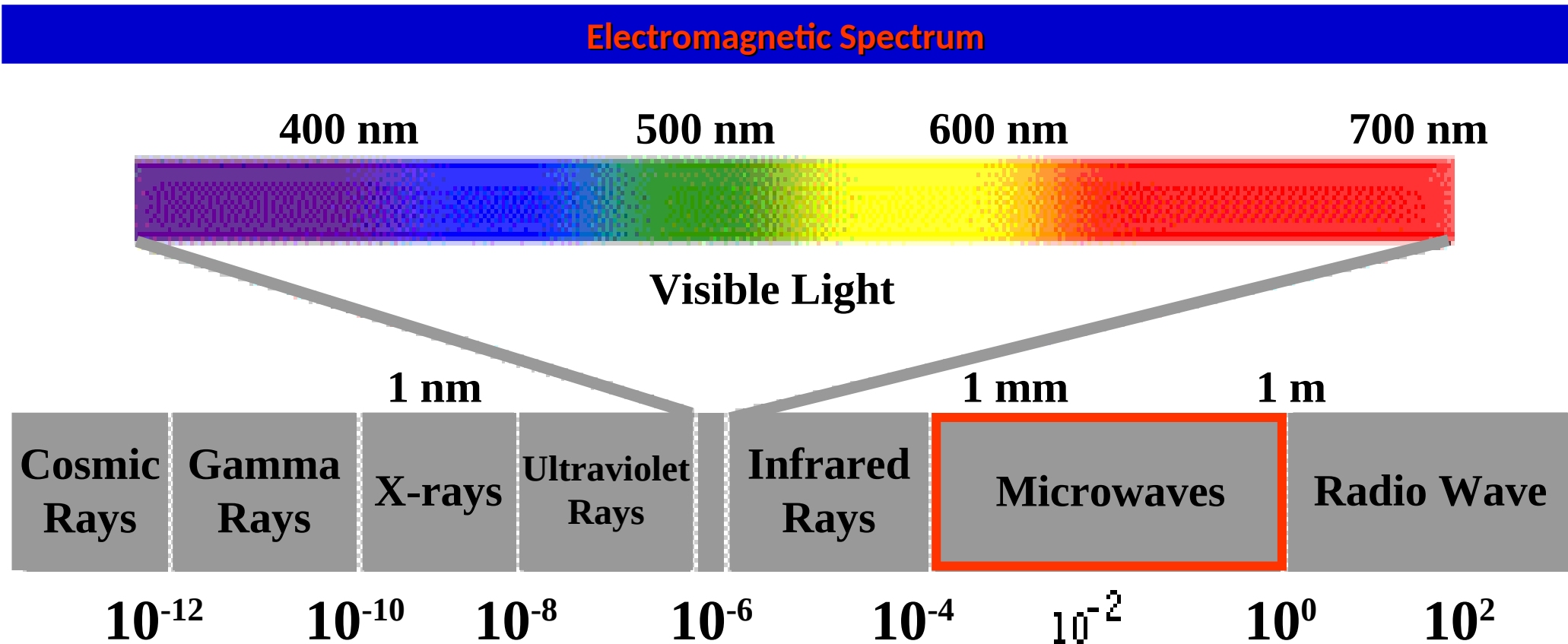


# Electromagnetic Radiation Characteristics

- Wavelength
- Frequency
- Amplitude
- Polarization



# Radars Transmits at Microwave Wavelengths

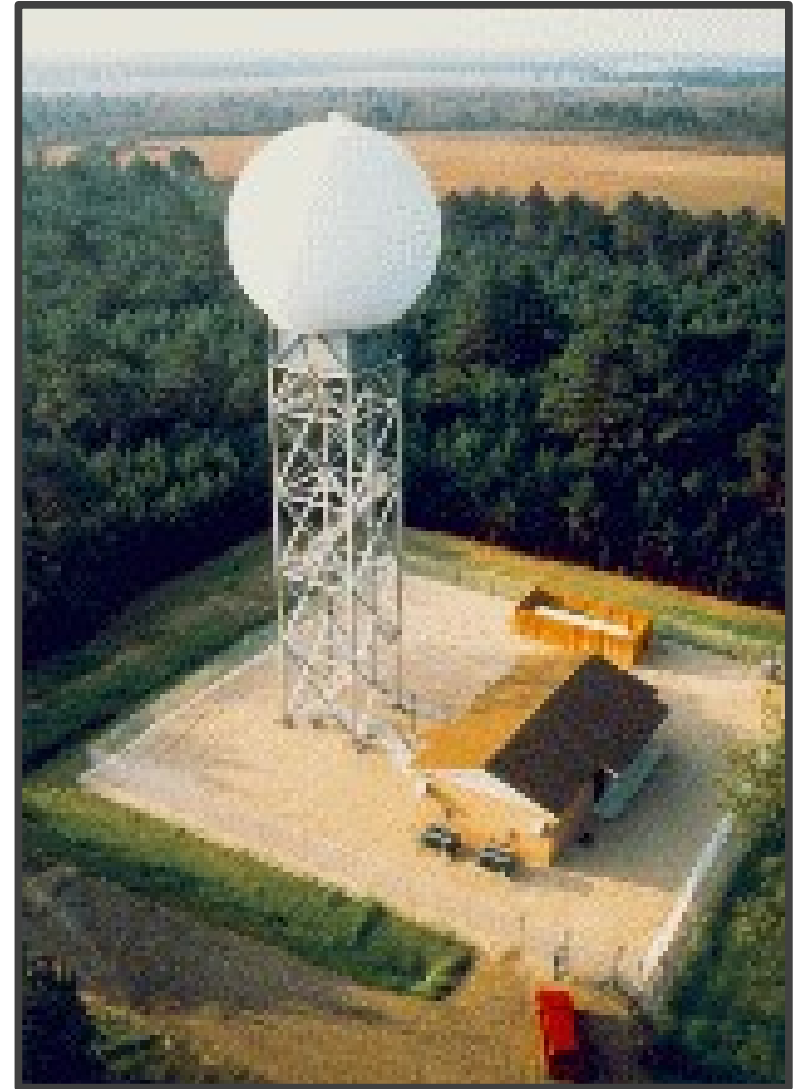


# Radar Wavelength Band Types

<u>Band Designation</u>	<u>Frequency</u>	<u>Wavelength</u>
HF	3-30 MHz	100-10 m
VHF	30-300 MHz	10-1 m
UHF	300-1000 MHz	1-0.3 m
<b>L</b>	<b>1-2 GHz</b>	<b>30-15 cm (20 cm)</b>
<b>S</b>	<b>2-4 GHz</b>	<b>15-8 cm (10 cm)</b>
<b>C</b>	<b>4-8 GHz</b>	<b>8-4 cm (5 cm)</b>
<b>X</b>	<b>8-12 GHz</b>	<b>4-2.5 cm (3 cm)</b>
K <sub>u</sub>	12-18 GHz	2.5-1.7 cm
K	18-27 GHz	1.7-1.2 cm
K <sub>a</sub>	27-40 GHz	1.2-0.75 cm

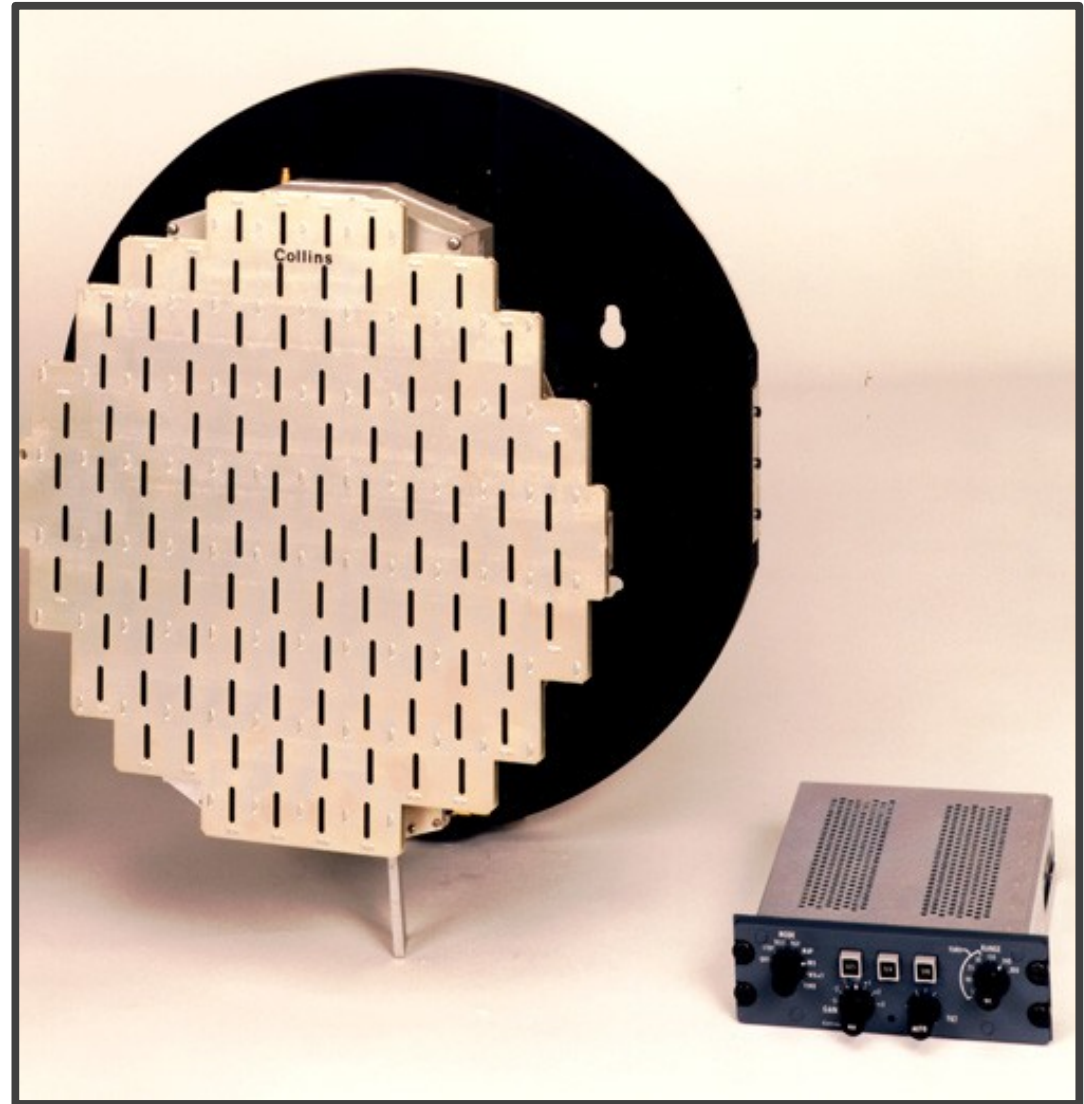
# S and C Band Radar (10 / 5 cm Wavelength)

- Ground Based Weather Radar
- WSR-88D or TDWR



# X Band Radar (3 cm Wavelength)

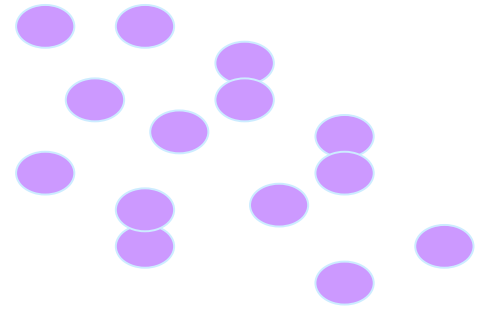
- Airborne Weather Radar



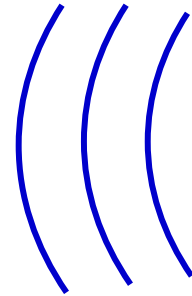


# Some Radar Terminology

- Target
  - Object (or group of objects) that reflect radar energy.
- Echo
  - Reflected radar energy.



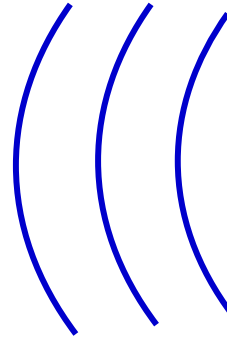
**Target**



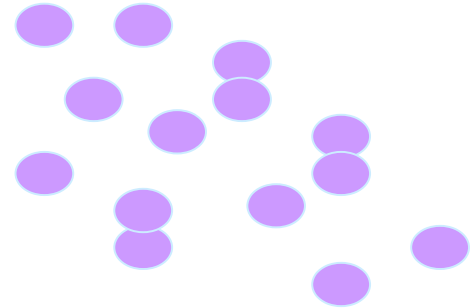
**Echo**

# Amount of Energy (Echo) Reflected

- Size of Targets
- Number of Targets
- Composition of Targets
- Distance to Targets

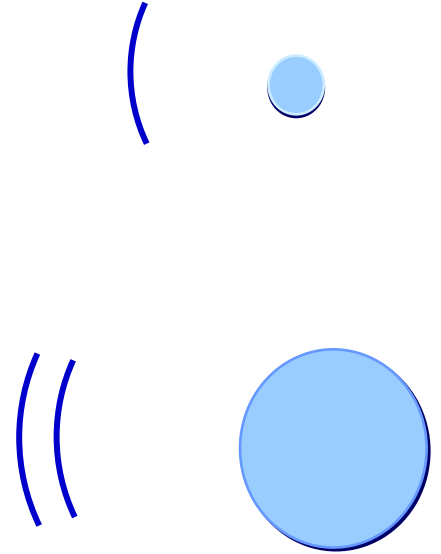
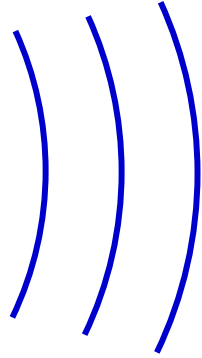
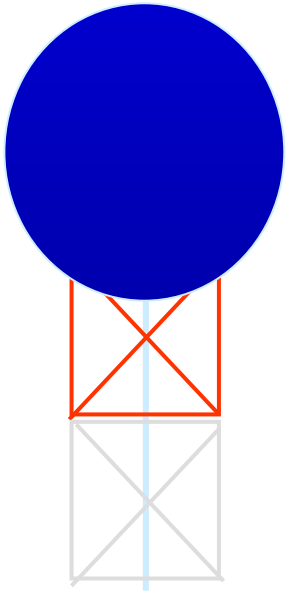


**Echo**

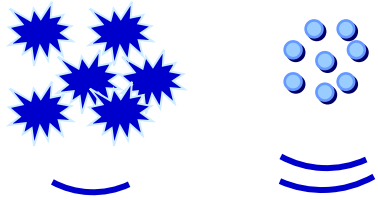


**Target**

**Size - Bigger Reflects More,  $\sim D^6$**



# Depends on Composition of Targets

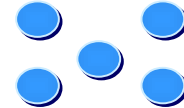


**Most  
Reflective**

**Wet Hail**



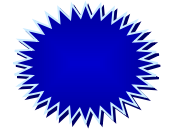
**Rain**



**Wet Snow**



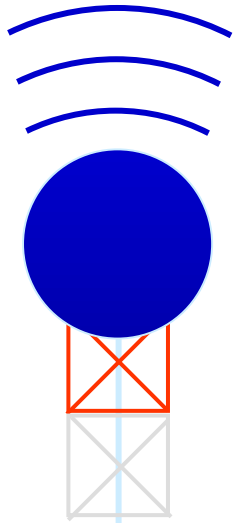
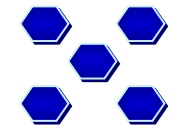
**Dry Hail**



**Dry Snow**

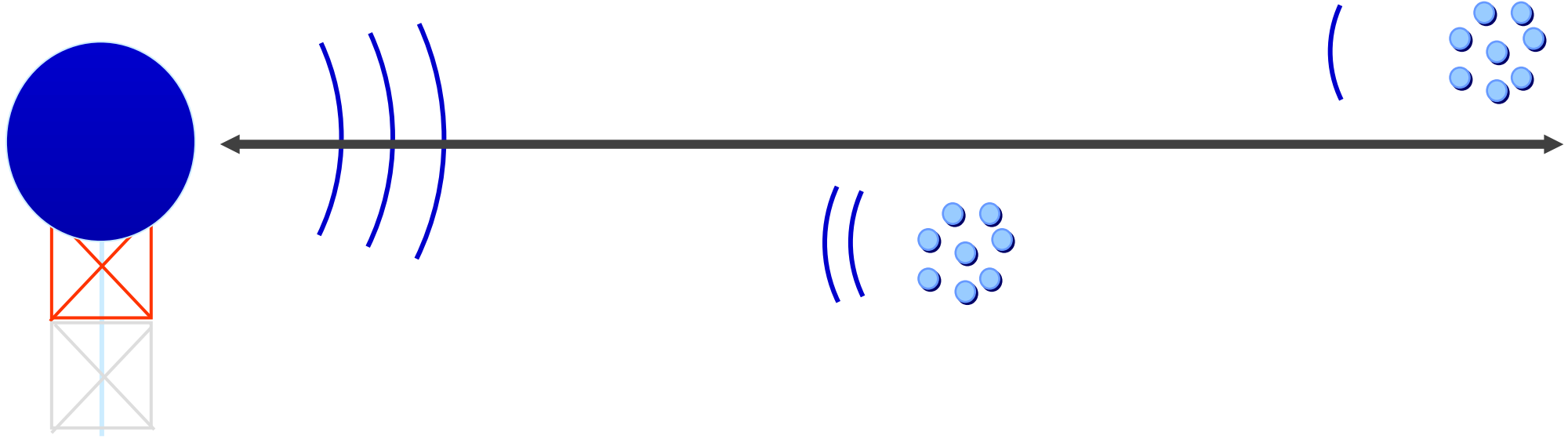


**Ice Crystals**



**Least  
Reflective**

# Depends on Distance to Targets



# Overall: Radar Reflectivity

- Function of amount of energy reflected.
- Measured in dBZ.
- Can be considered echo intensity or strength.
- Related to rainfall rate.
- Categorized into six levels.
  - Digital Video Integrated Processor (DVIP)

# Digital Video Integrated Processor (DVIP)

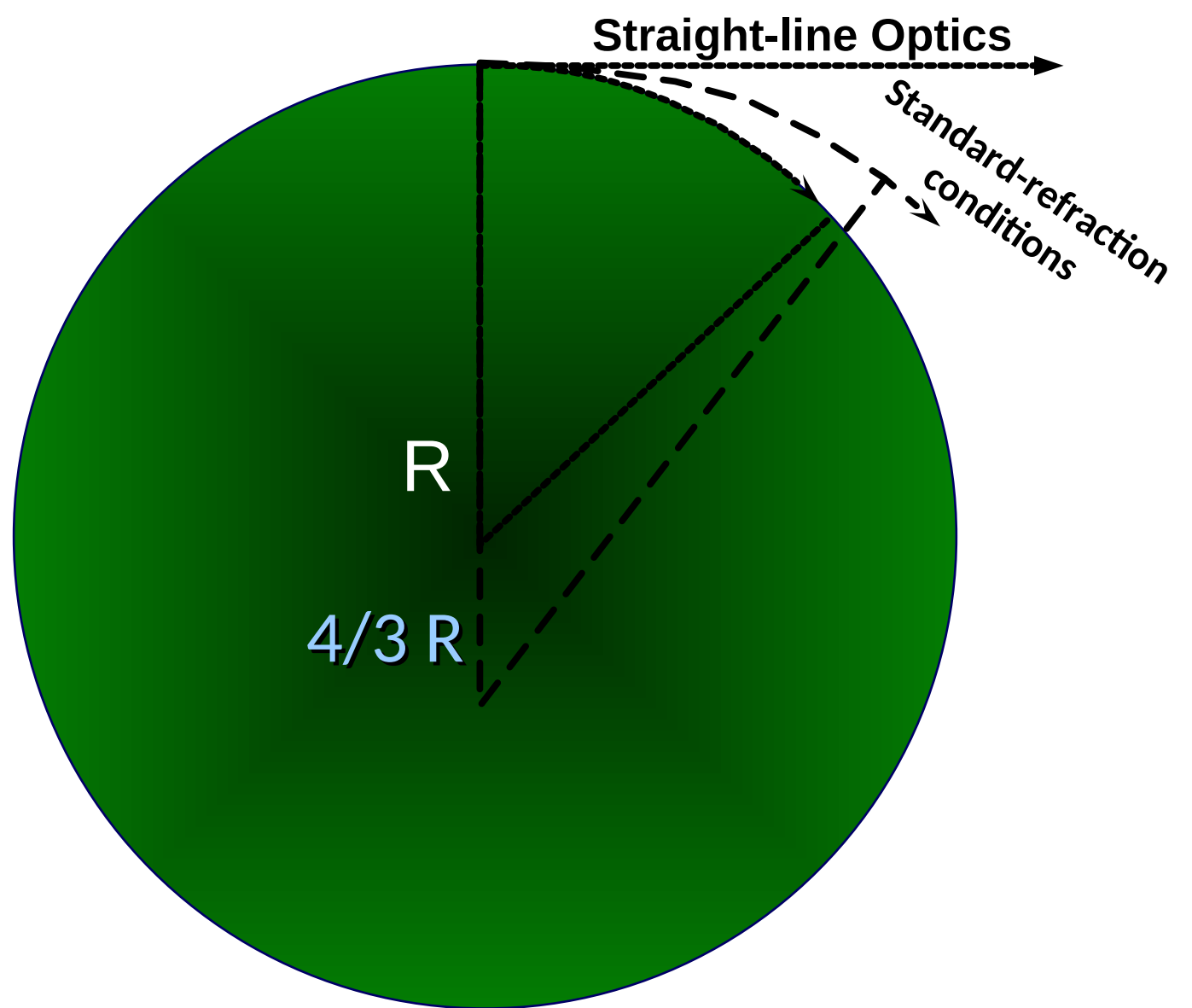
<u>DVIP Level</u>	<u>Rainfall Rate</u>	<u>Reflectivity</u>
1	<0.10"/hr	29.5 dBZ
2	0.25"/hr	35.9 dBZ
3	0.50"/hr	40.7 dBZ
4	1.25"/hr	47.0 dBZ
5	2.50"/hr	51.9 dBZ
6	>4.00"/hr	55.1 dBZ

What value of reflectivity would you typically need to indicate hail in a storm?

# Speed of Light (Radar Wave)

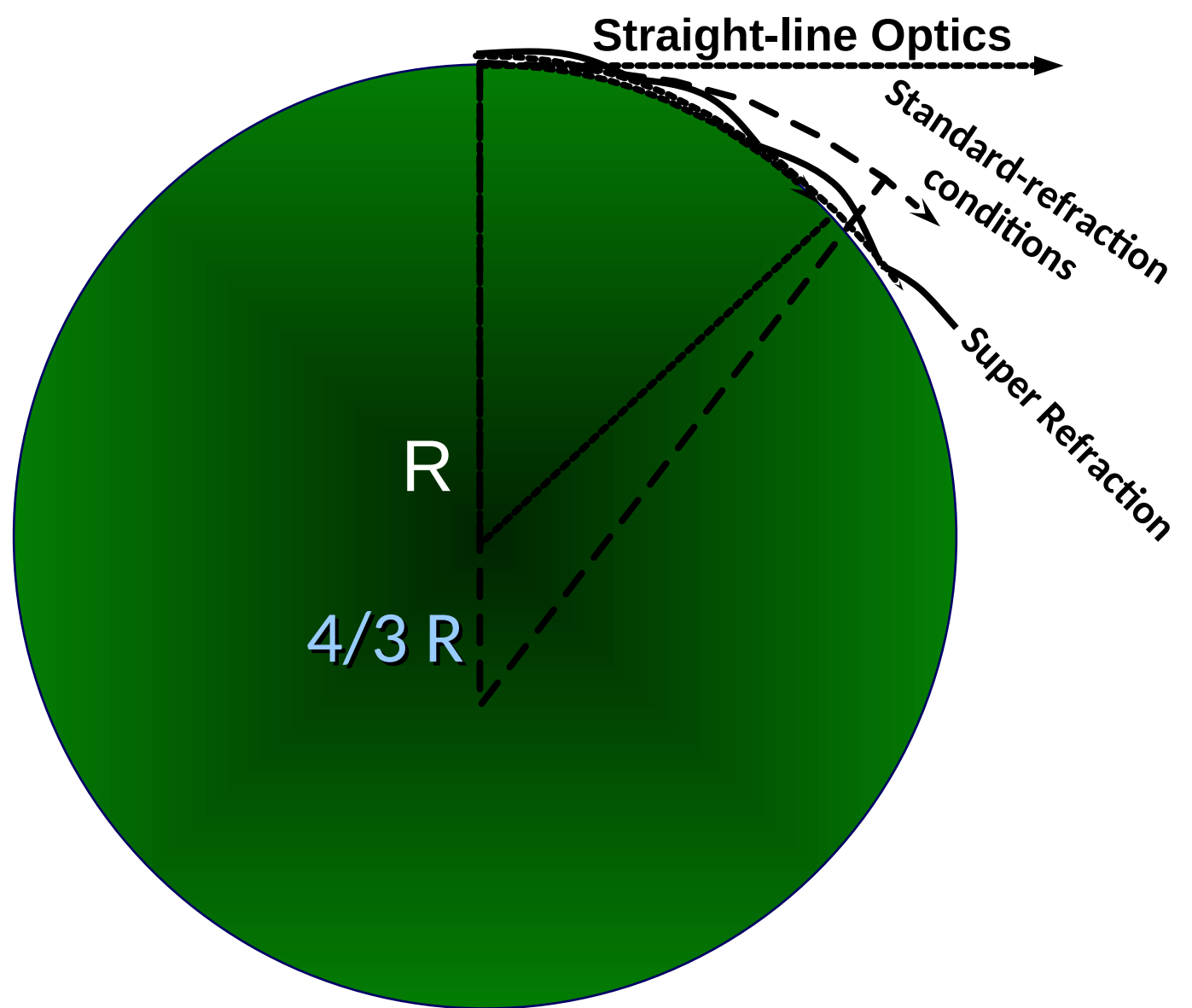
- The speed of light in a vacuum is
$$c = 299,792,458 \pm 10 \text{ m/s} \approx 3 \cdot 10^8 \text{ m/s}$$
- In the atmosphere, the speed ( $u$ ) is slower!
- We can calculate  $u$  from the pressure, temperature and vapor pressures.
- From the surface to outer space,  $u$  varies from 0.9997 to 1.0000 of  $c$ .

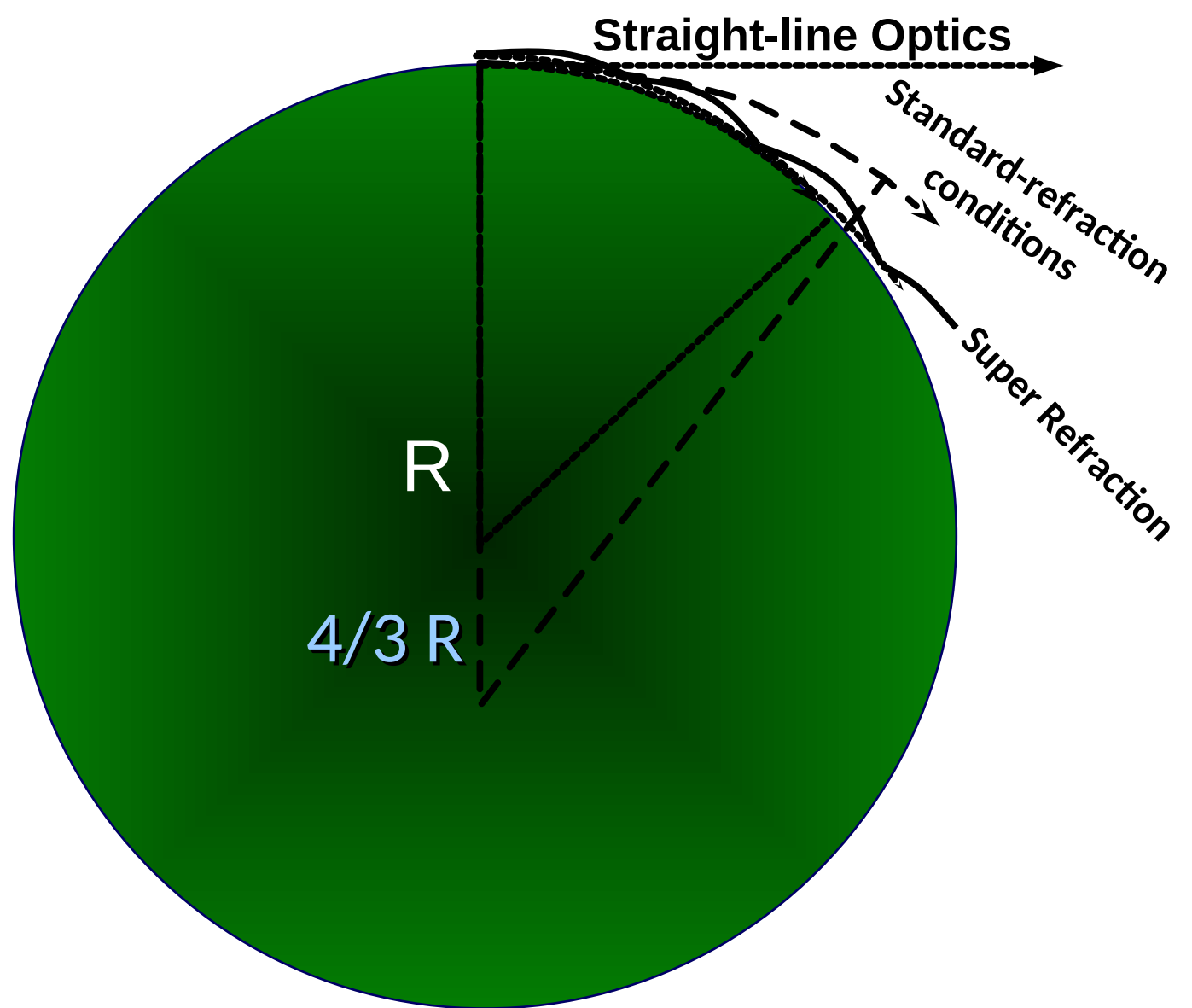




# Actual Conditions

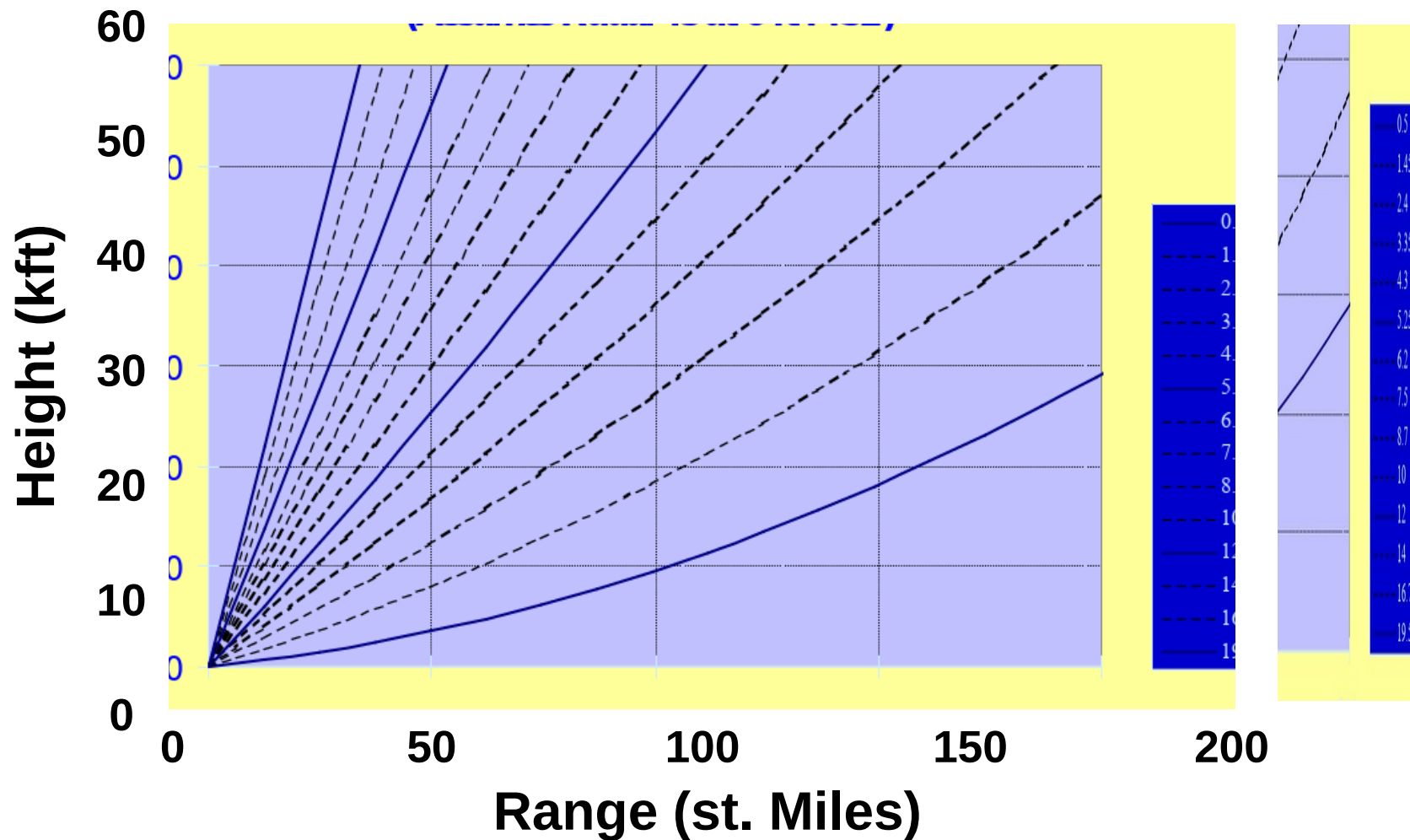
- The actual value of the gradient of refractivity under any given set of temperature, pressure, and humidity conditions can be calculated from sounding information.
- Be aware, however, that the assumption of standard refraction is only an approximation and errors will be made if it is applied blindly to all conditions.





# Height of Radar Beam as Function of Distance

## NEXRAD Tilt Sequence (Assumes 0 ft MSL Radar)



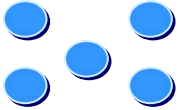
# Meteorological Targets

- Clouds
- Rain
  - Size Distributions
  - Z-R Relationships
  - DVIP Levels
- Snow
- Hail
- Attenuation

**Wet Hail**



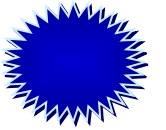
**Rain**



**Wet Snow**



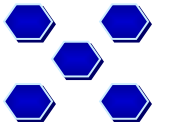
**Dry Hail**



**Dry Snow**



**Ice Crystals**



# Z-R Relationship

- To convert radar measurable  $Z$  to hydrologically useful parameter  $R$ , we need a relationship to convert between these.
- Convenient, empirical relationship is a power-law relationship:

$$Z = AR^b$$

# DVIP Intensity Levels

- DVIP: Digital Video Integrator Processor
- Use Marshall-Palmer (MP) relationship of  $Z = 200 R^{1.6}$

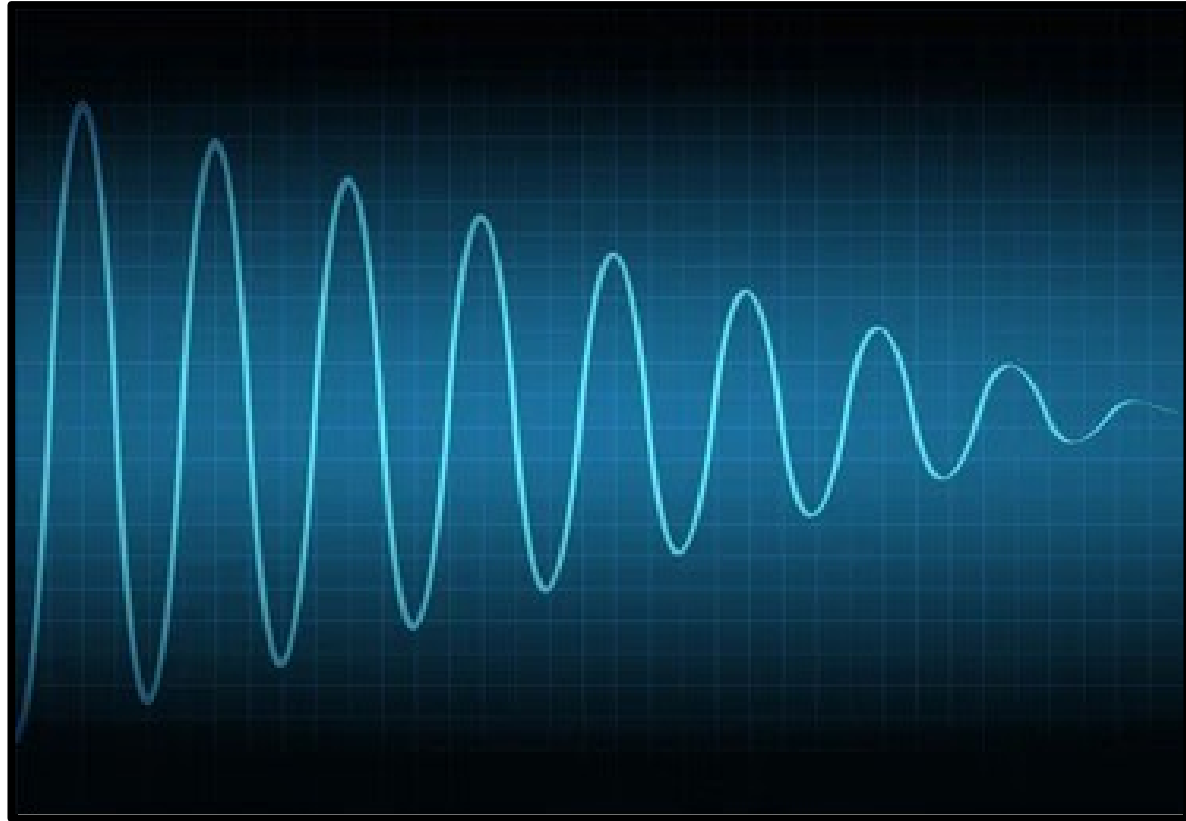
<u>DVIP Level</u>	<u>Rainfall Rate</u>	<u>Reflectivity</u>
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3	0.50"/hr	40.7 dBZ
4	1.25"/hr	47.0 dBZ
5	2.50"/hr	51.9 dBZ
6	>4.00"/hr	55.1 dBZ

**DVIP levels 1, 2, 3, and 5 are shown on aircraft radars.**



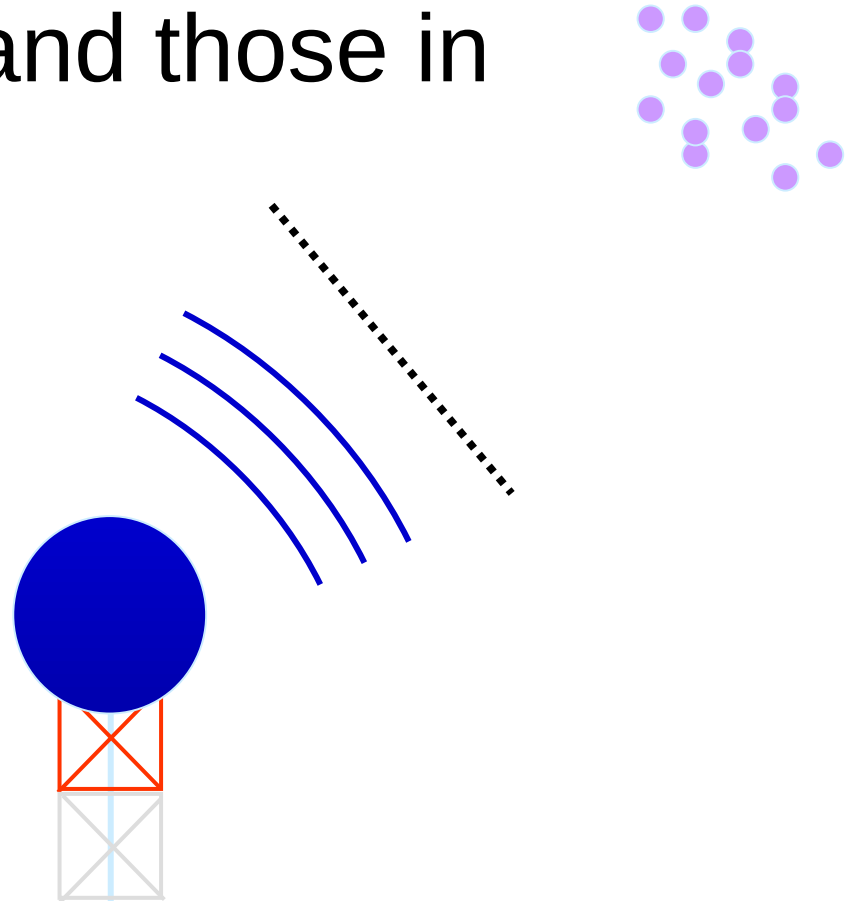
# Attenuation of Transmitted Signal (Energy)

- Atmospheric Attenuation
- Cloud Attenuation
- Rain Attenuation
- Snow Attenuation
- Hail Attenuation
- Hardware Attenuation

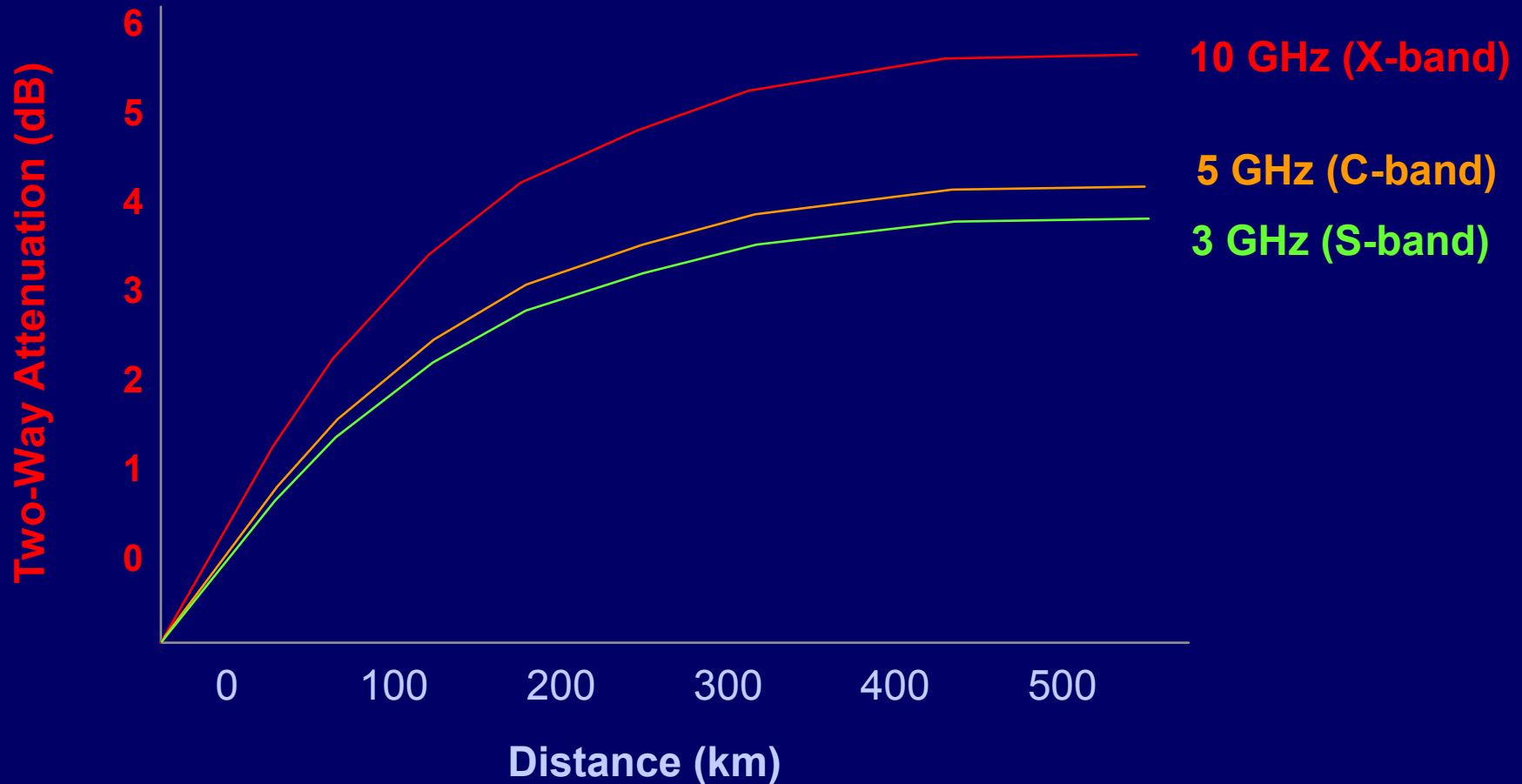


# Atmospheric Attenuation

- Some gases cause no attenuation.
- Nitrogen, carbon dioxide, and those in very small concentrations
- Attenuating Gases:
  - Oxygen
    - Constant Concentration
  - Water Vapor
    - Variable Concentration



# Two-way Atmospheric Attenuation

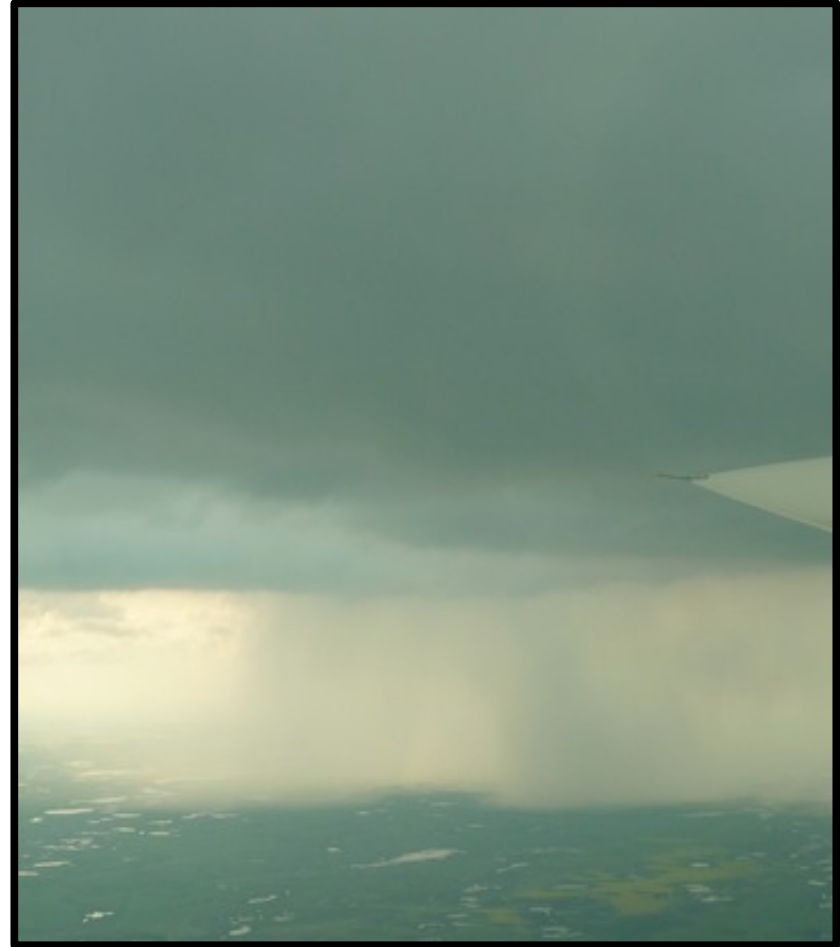
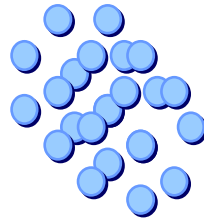
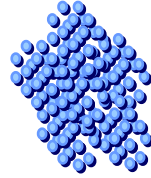


# Cloud Attenuation

- Clouds can be water or ice.
- Clouds range from very thin to very dense.
- Attenuation in clouds depends upon:
  - Temperature
  - Wavelength
  - Whether it is water or ice.

# Rain Attenuation

- Raindrops are much larger than cloud droplets, so rain attenuation is also larger than cloud attenuation.



# Hail Attenuation

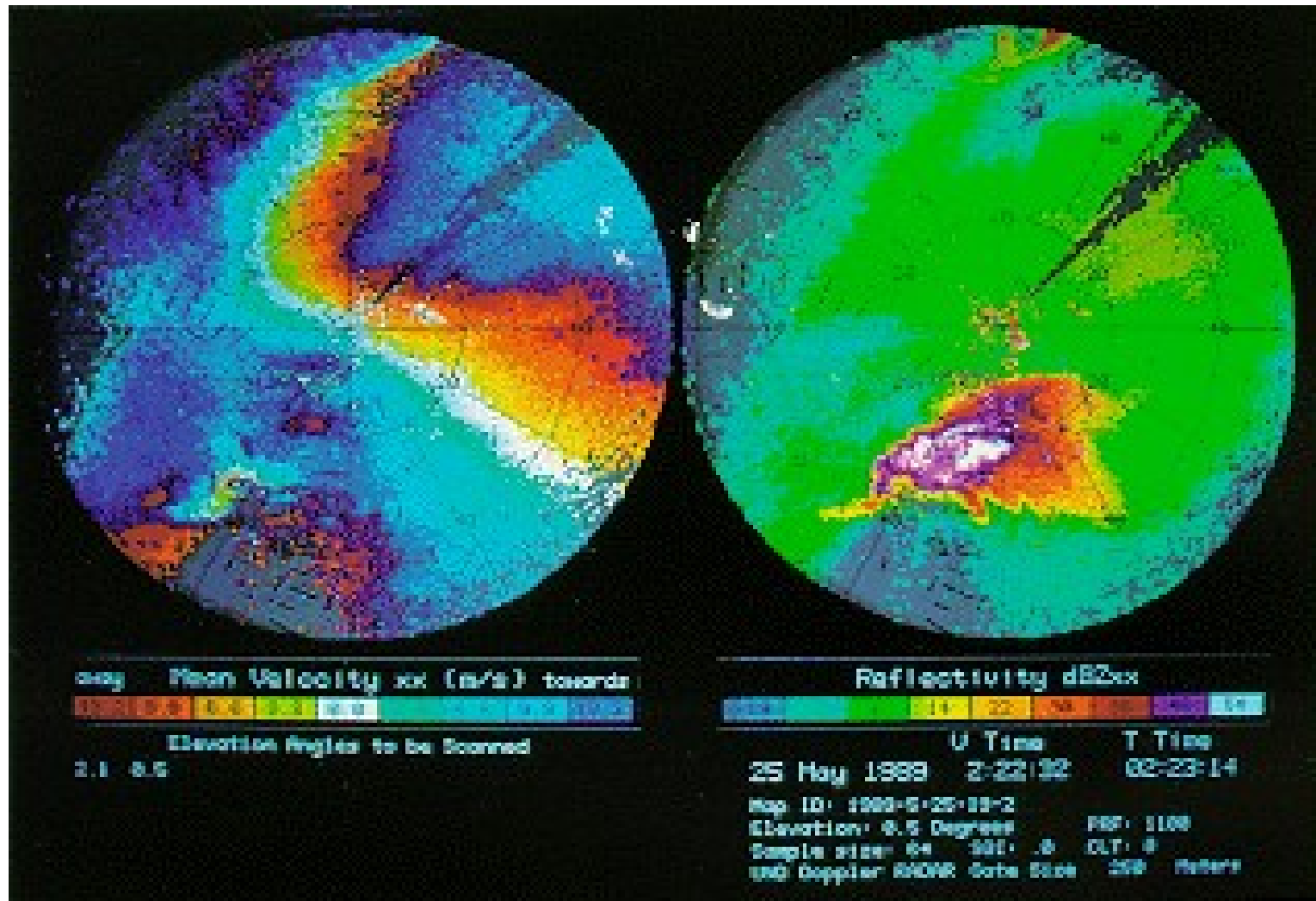
- Hail undoubtedly causes heavy attenuation, but...
- Hail is a rare phenomena.
- Hail often falls with very heavy rain.
- Nobody has ever determined attenuation rates for hail.
- Even if they did, how would you know where and how hard it was hailing?
- **Conclusion: When it hails, there is attenuation, but we probably never know how much.**

# Attenuation Shadows

- Attenuation shadows sometimes indicate the presence of attenuation.
- Airborne radars frequently have attenuation.
  - Since most are X- or occasionally C-band radars, attenuation shadows are common on aircraft radars.

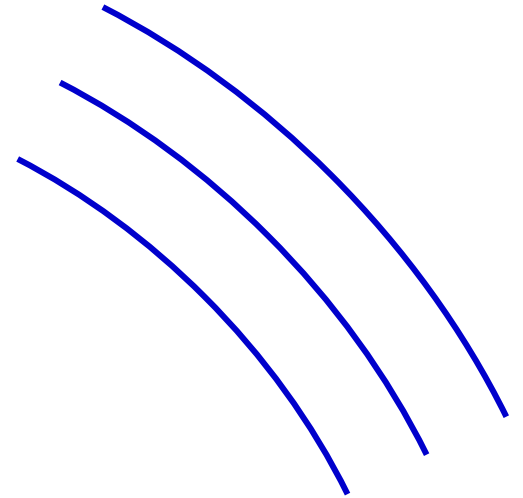


# Example of Attenuation Shadow

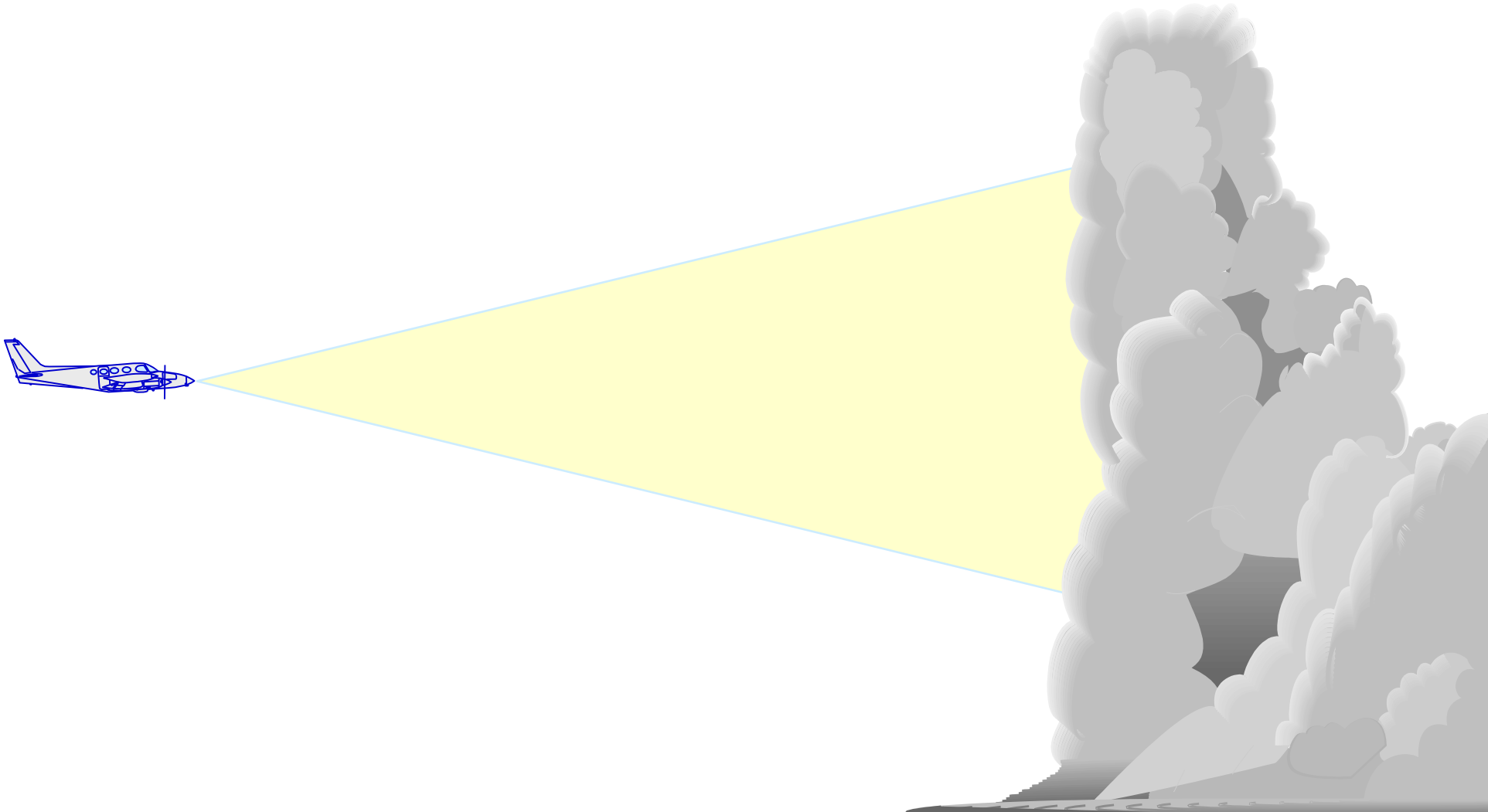


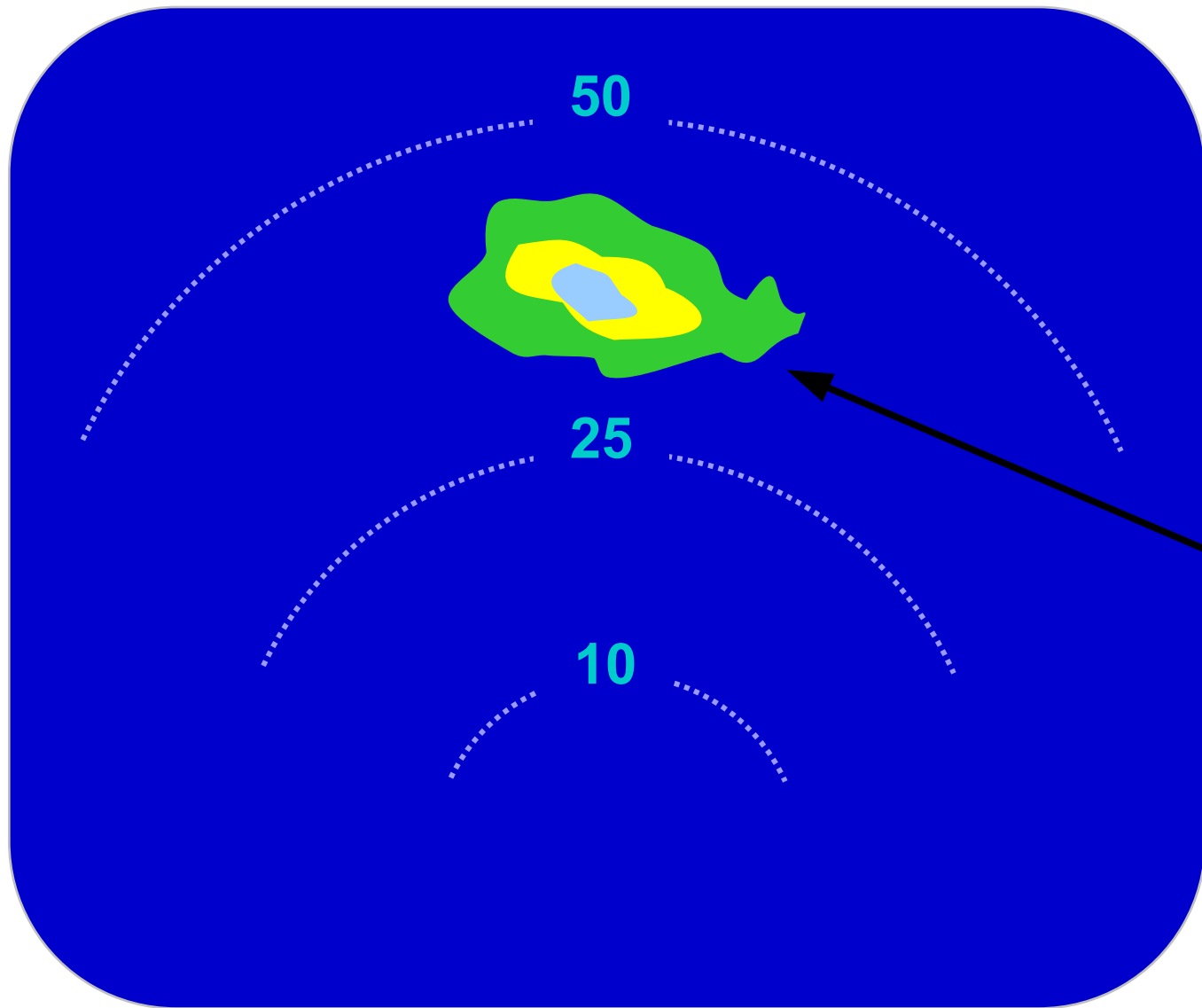
# Beam Characteristics

- A target that fill the entire beam will be “painted” more strongly and accurately than one that does not.
- **Narrow Beam** versus **Wide Beam**
- **Long Range** versus **Short Range**



# Narrow Beam





**Narrow Beam**

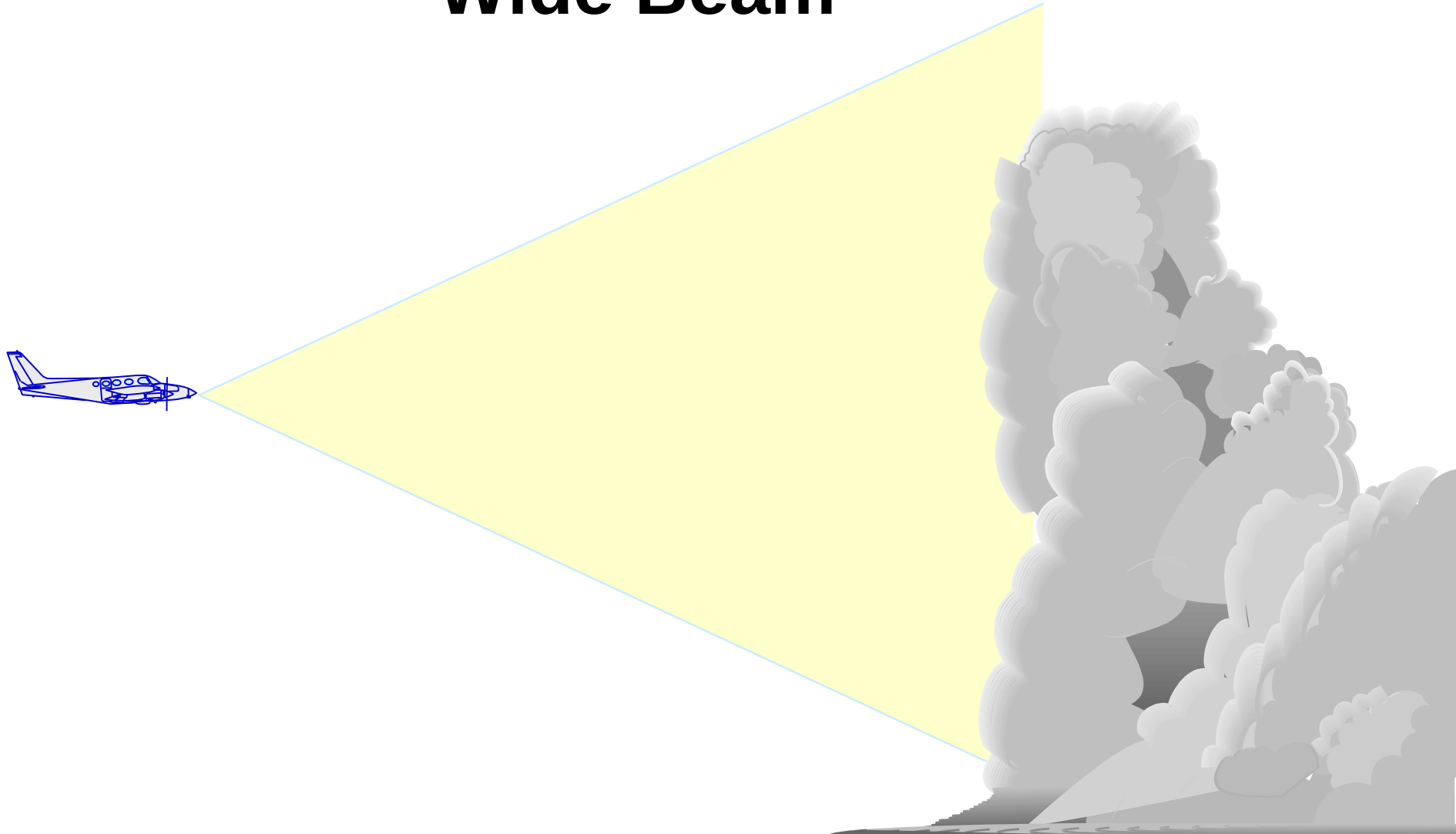


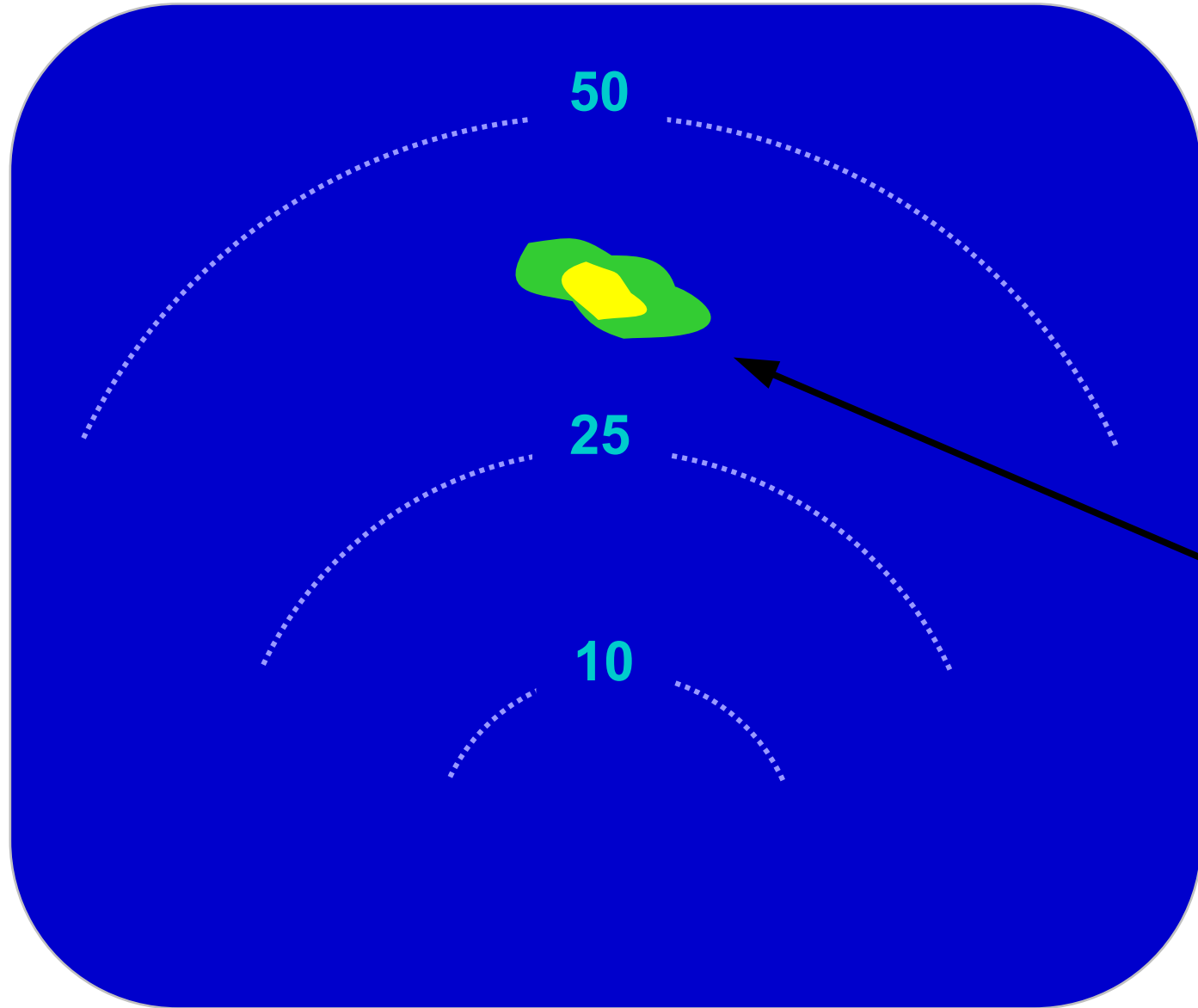
**Fill Beam**



**Strong**

# Wide Beam





**Wide Beam**

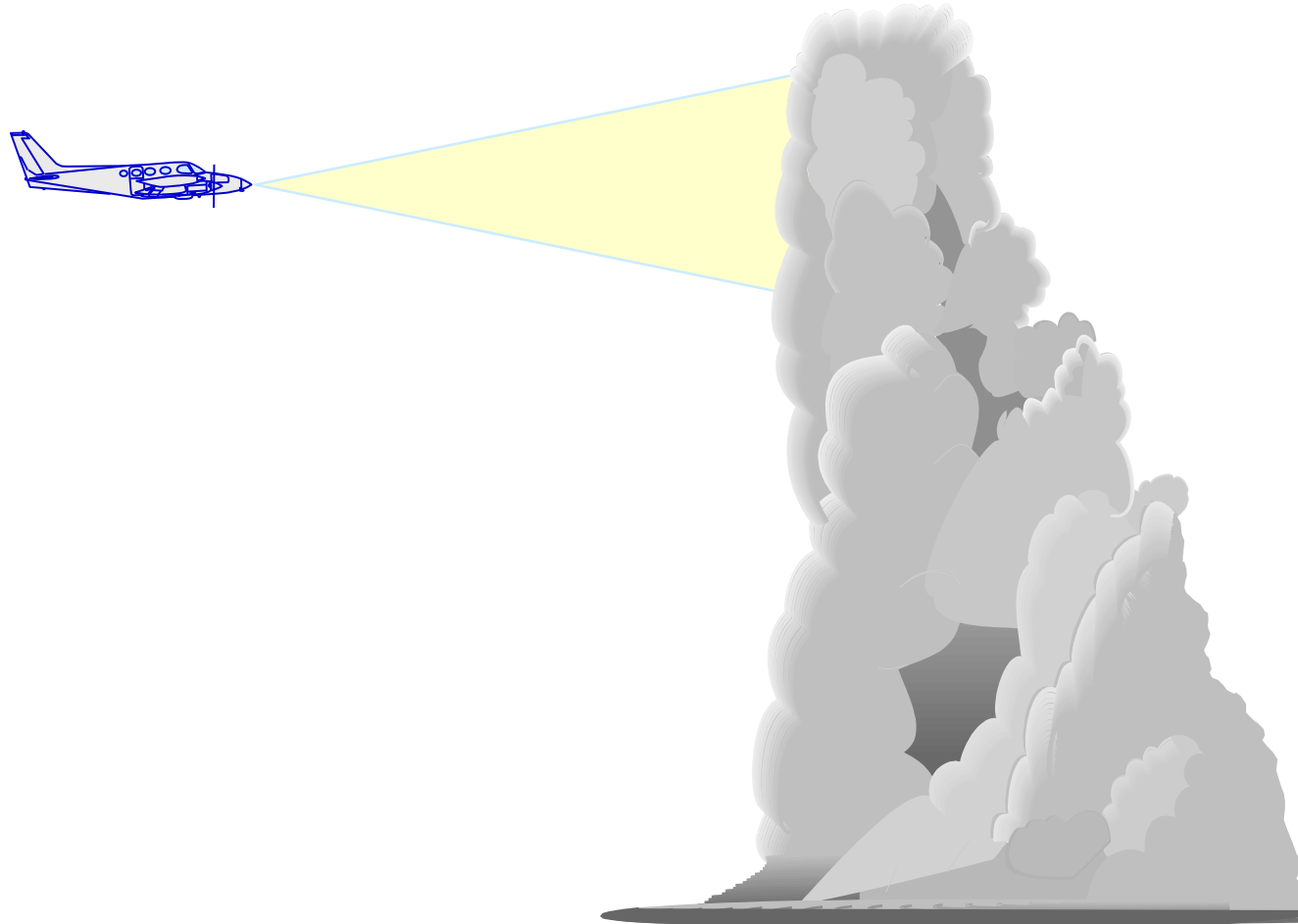


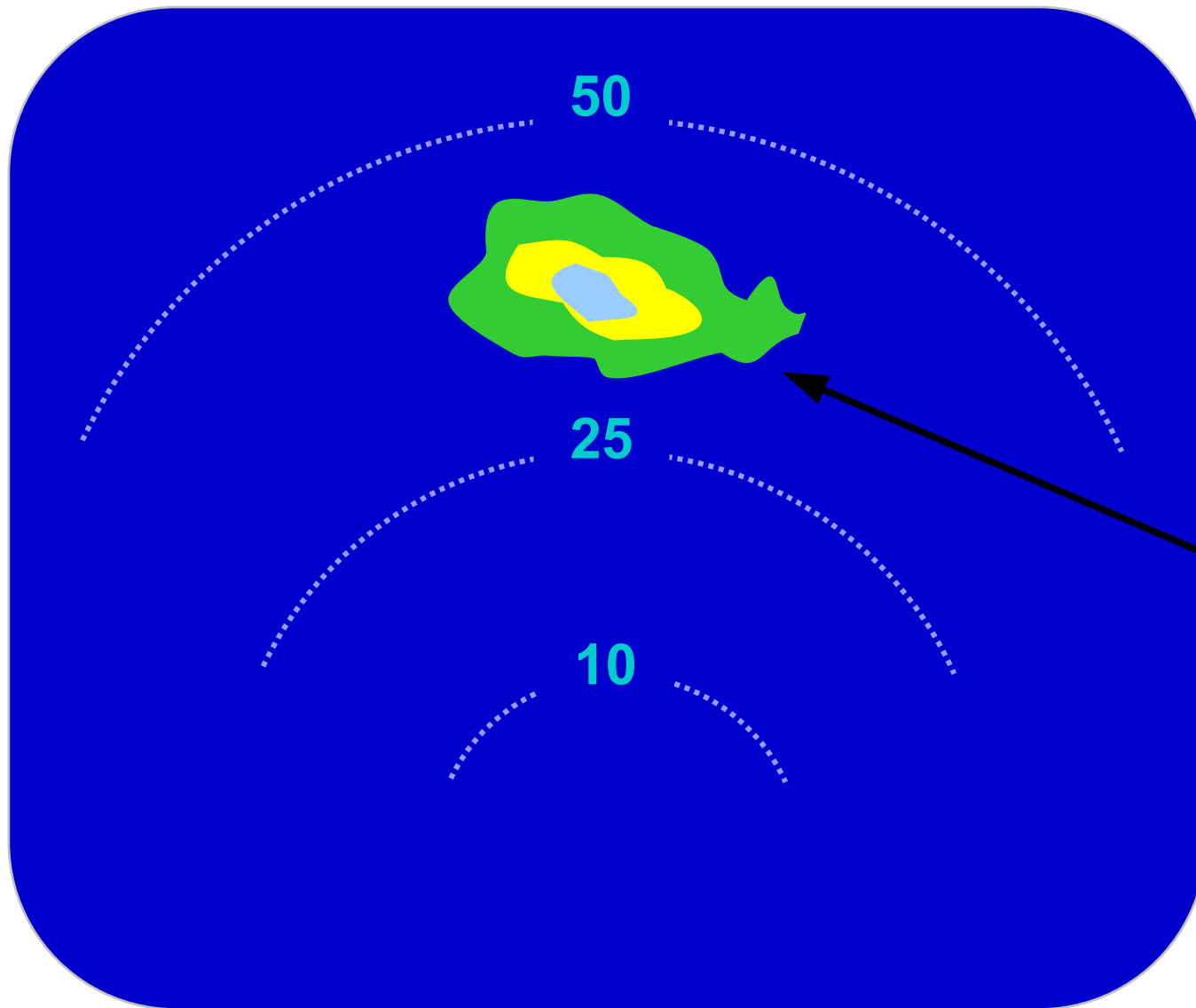
**Not Filled Beam**



**Weaker**

# Short Range





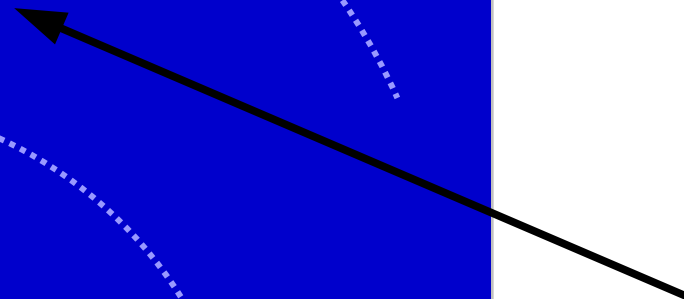
**Short Range**



**Fill Beam**

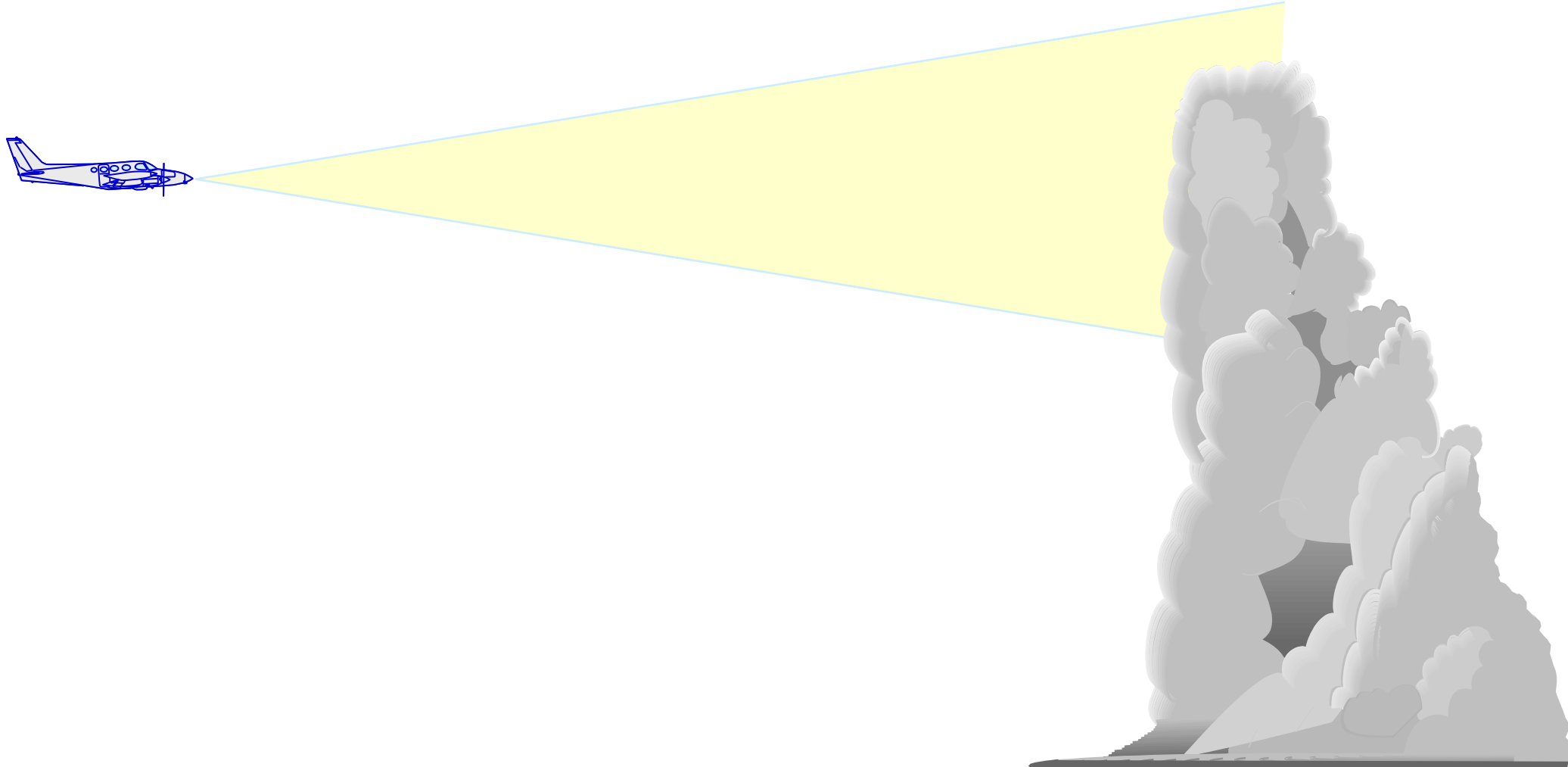


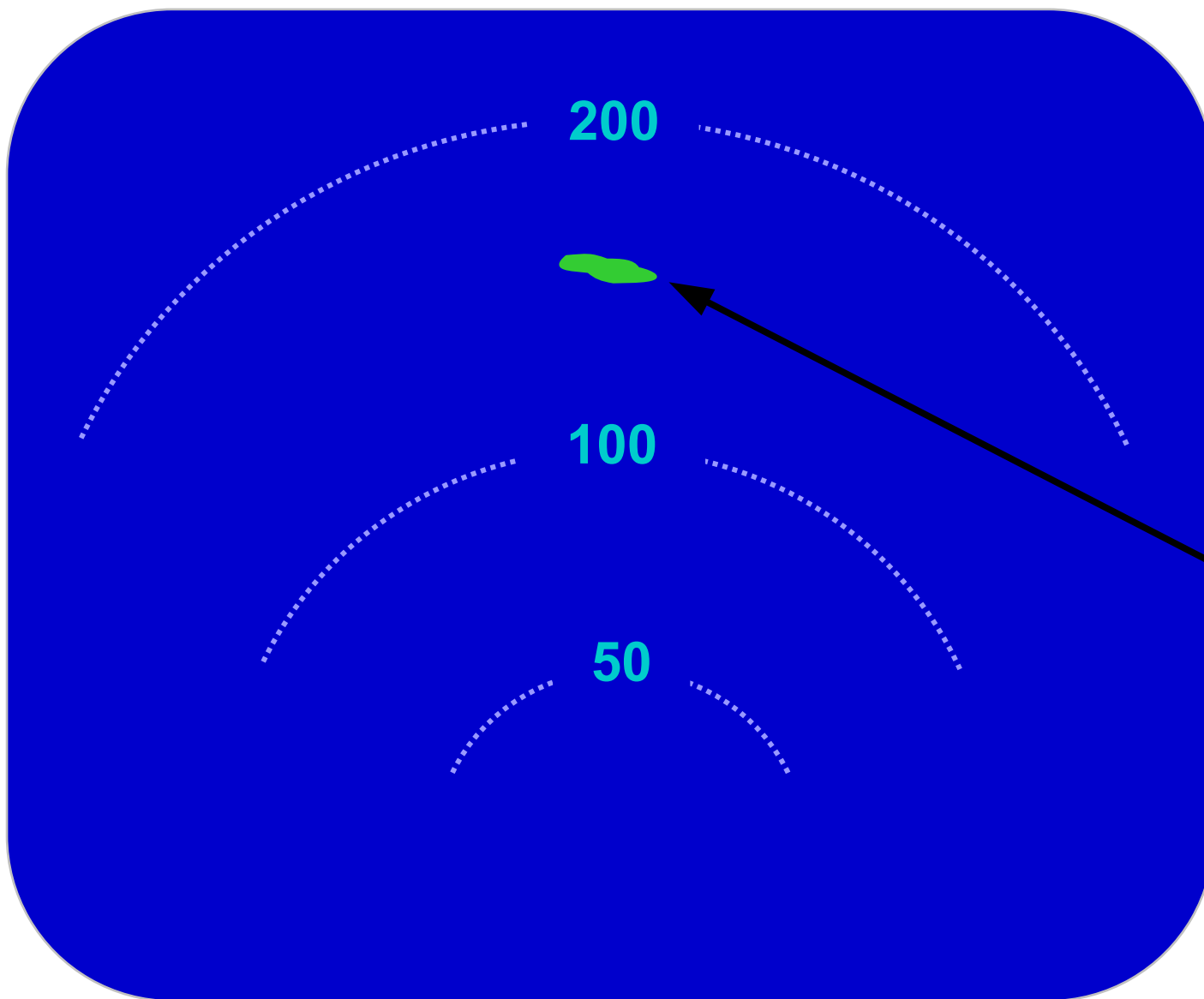
**Strong**





# Long Range





**Long Range**



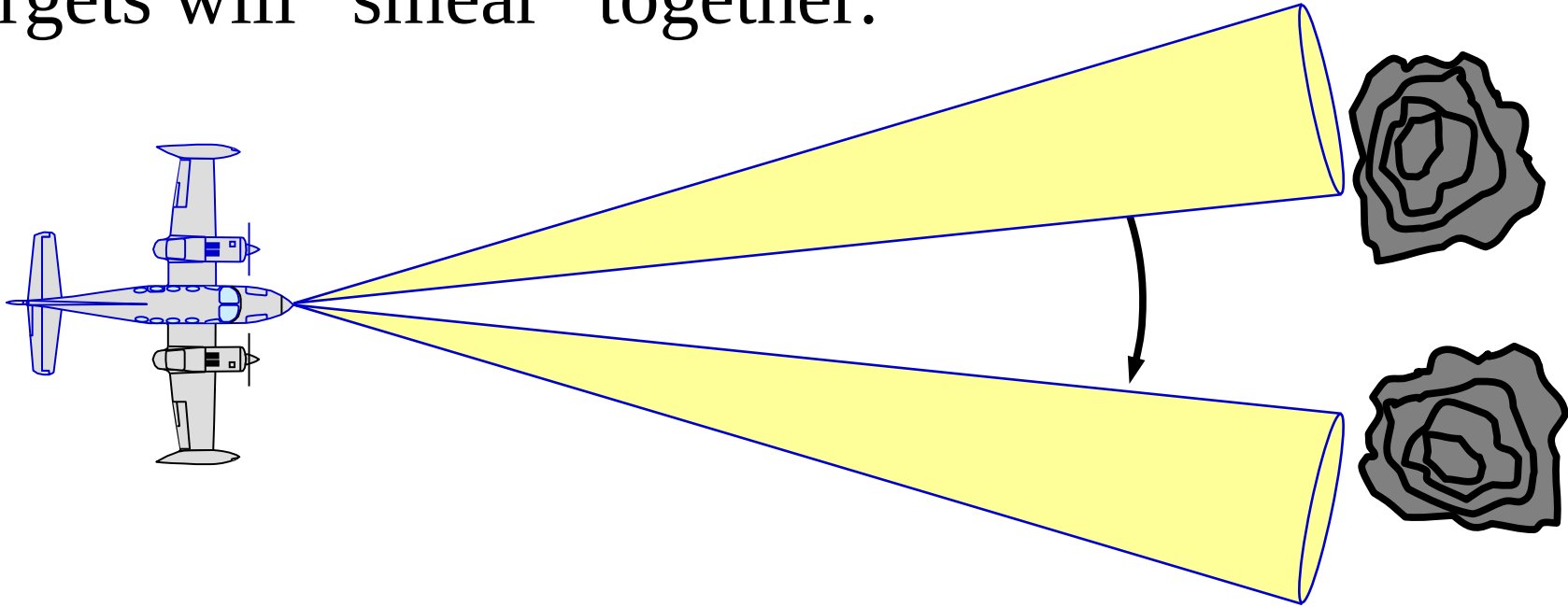
**Not Filled Beam**



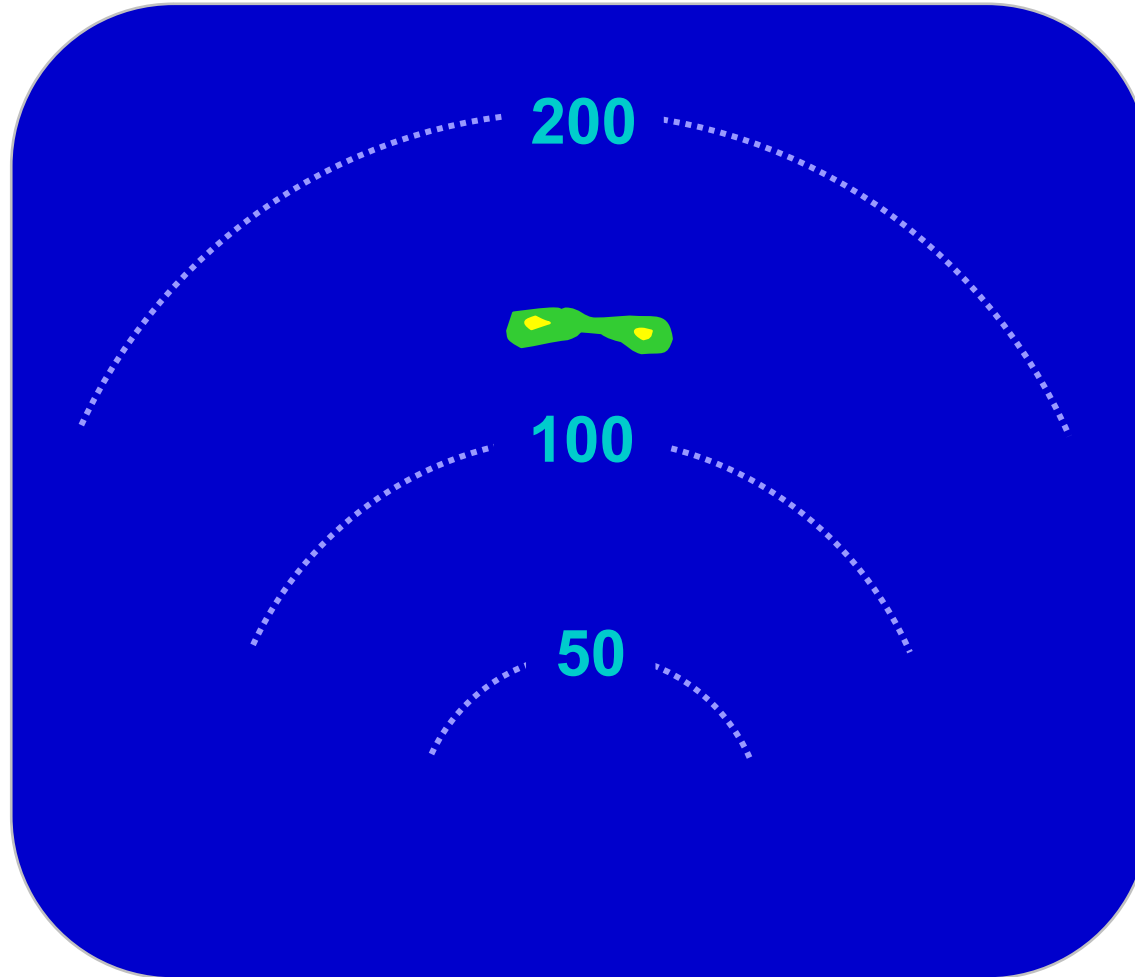
**Weaker**

# Beam Width Smearing

- Problem at long ranges.
- Two targets are located so that each is on one edge of the beam at the same time.
- Targets will “smear” together.

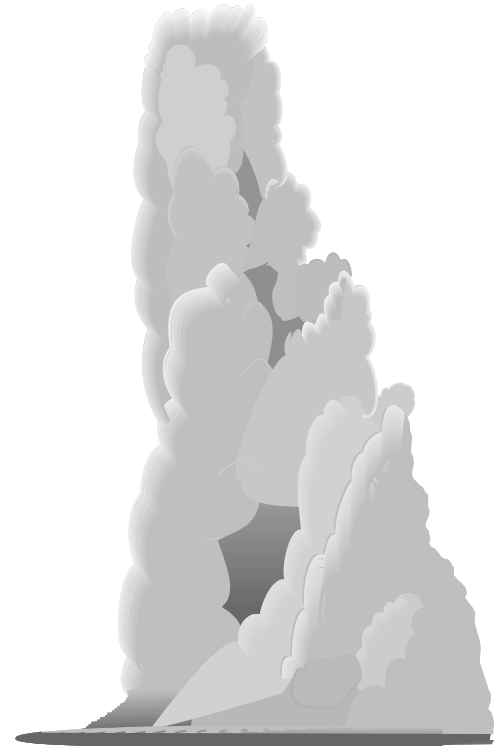
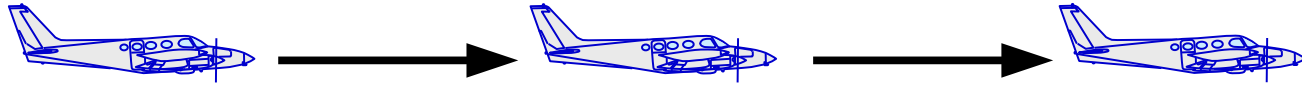


# Beam Width Smearing Results (Far Away)

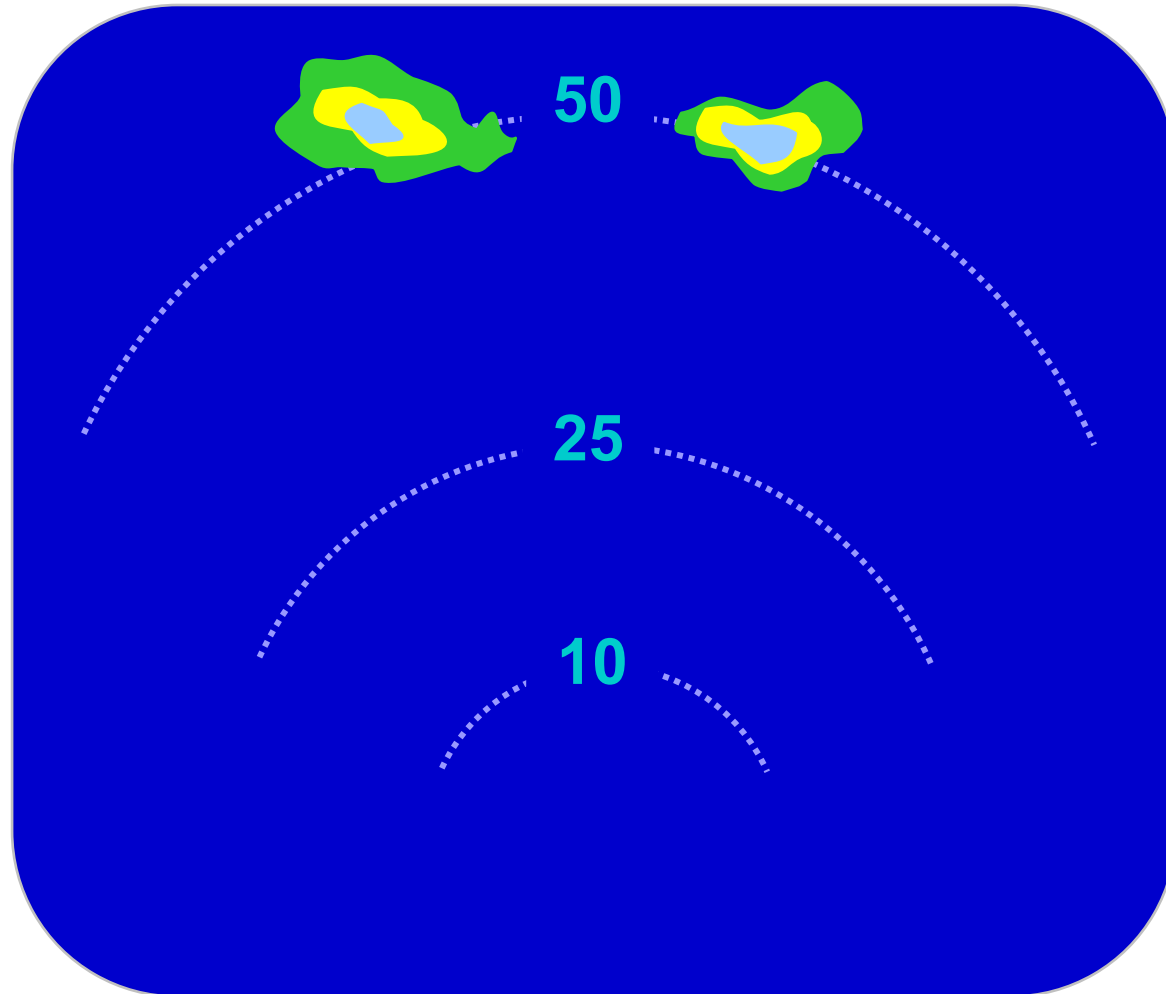


# Beam Width Smearing

- As aircraft gets closer, targets will take on their actual shape.



# Beam Width Smearing Results (Closer)

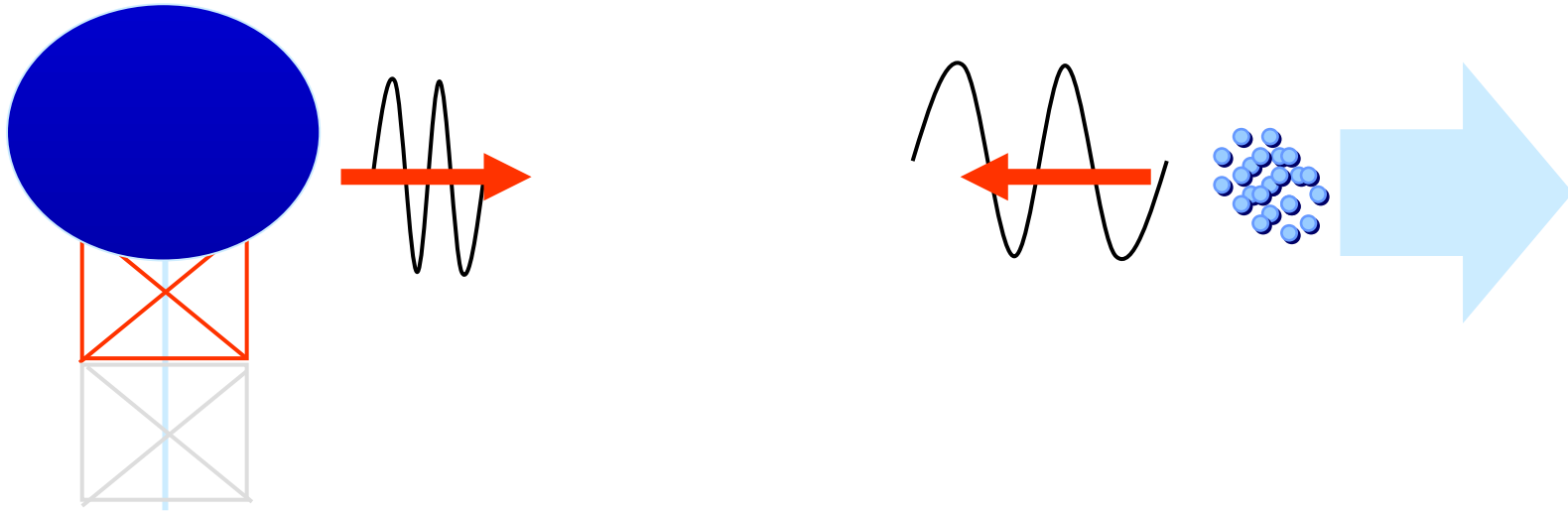


# Doppler (or Coherent) Radar

- Able to determine the frequency shift of the transmitted wave.
- How does Doppler Radar Works?

# Spectrum Width

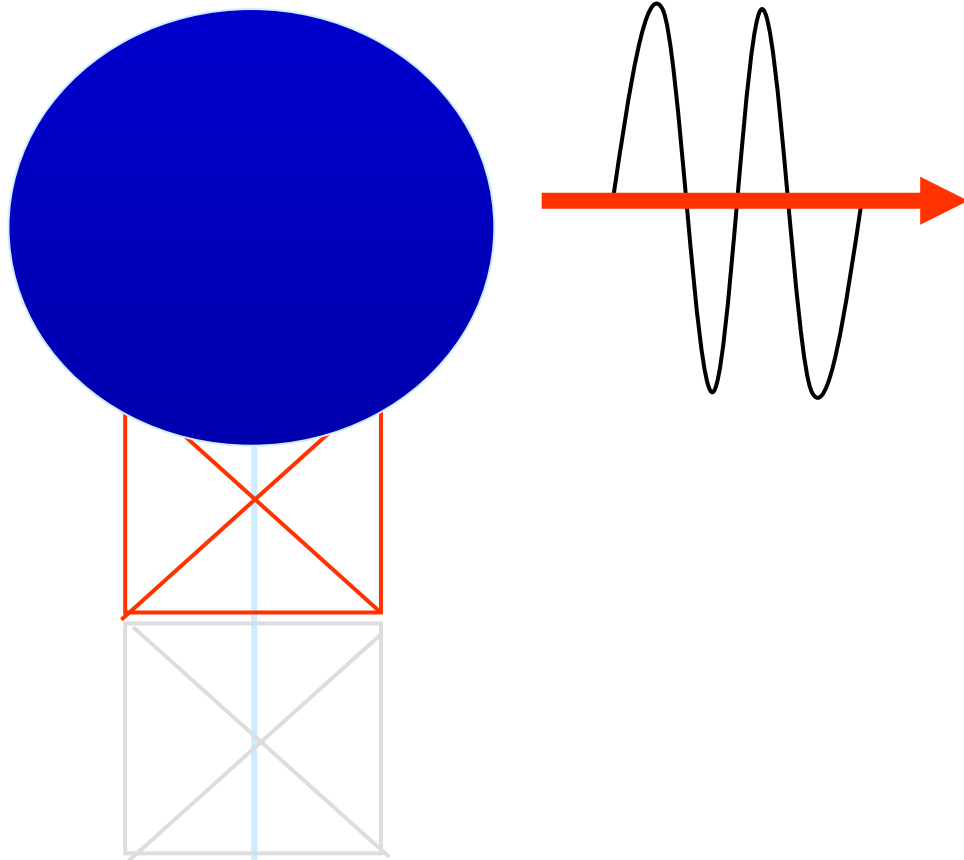
- Due to motion of targets
- Actually measures frequency distribution called spectrum width



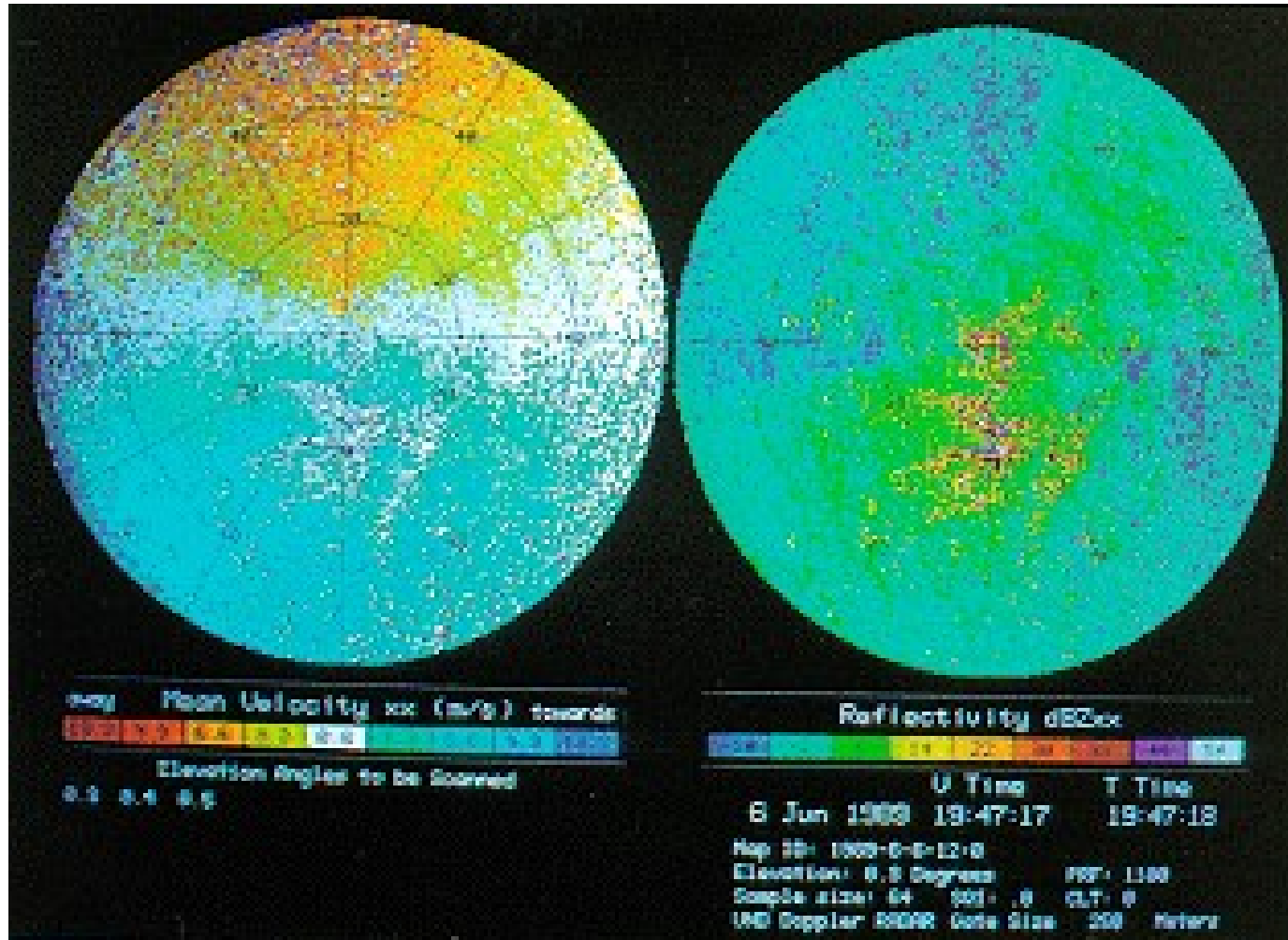


# Radar Echoes

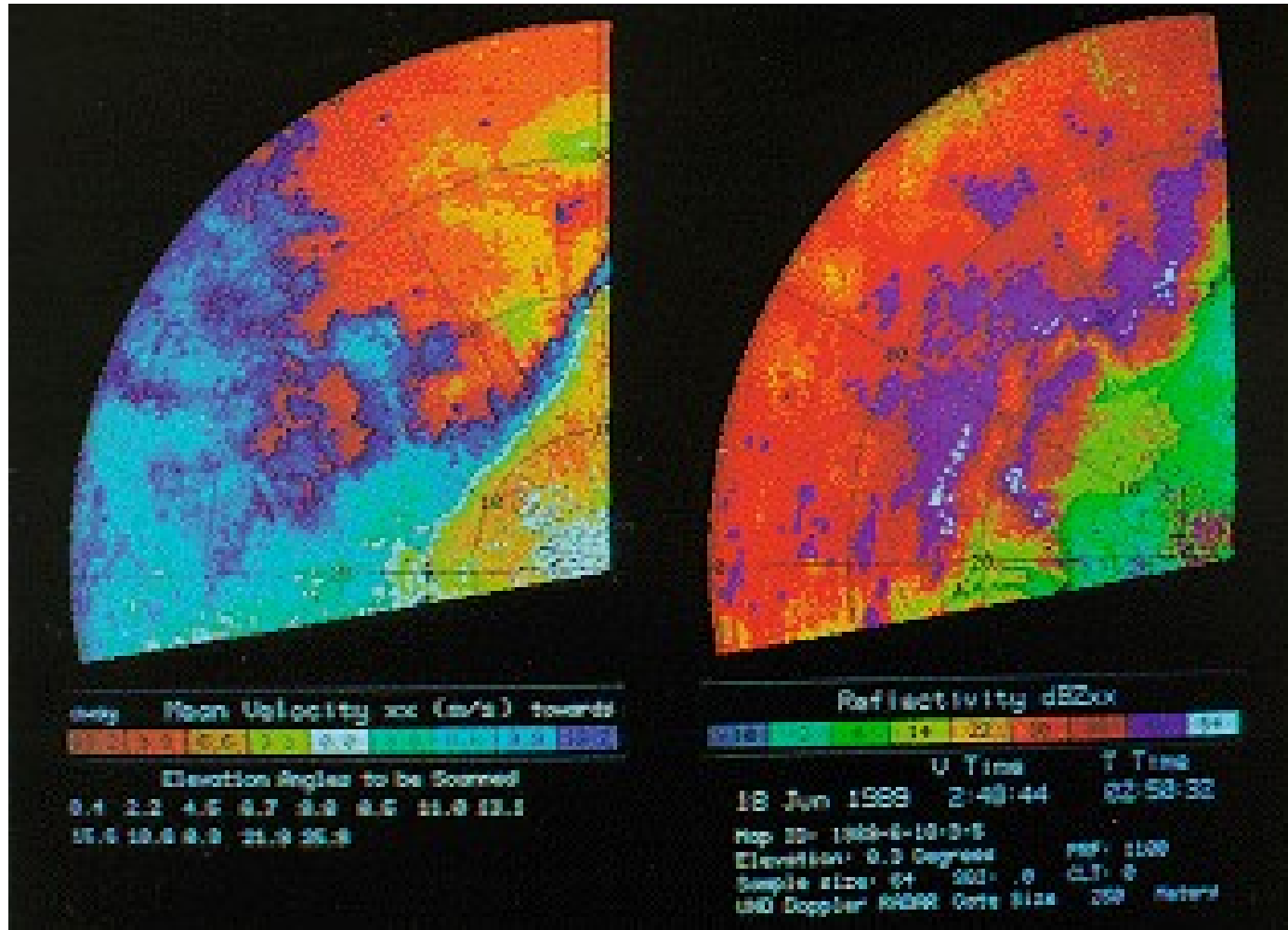
## Examples from Various Sources



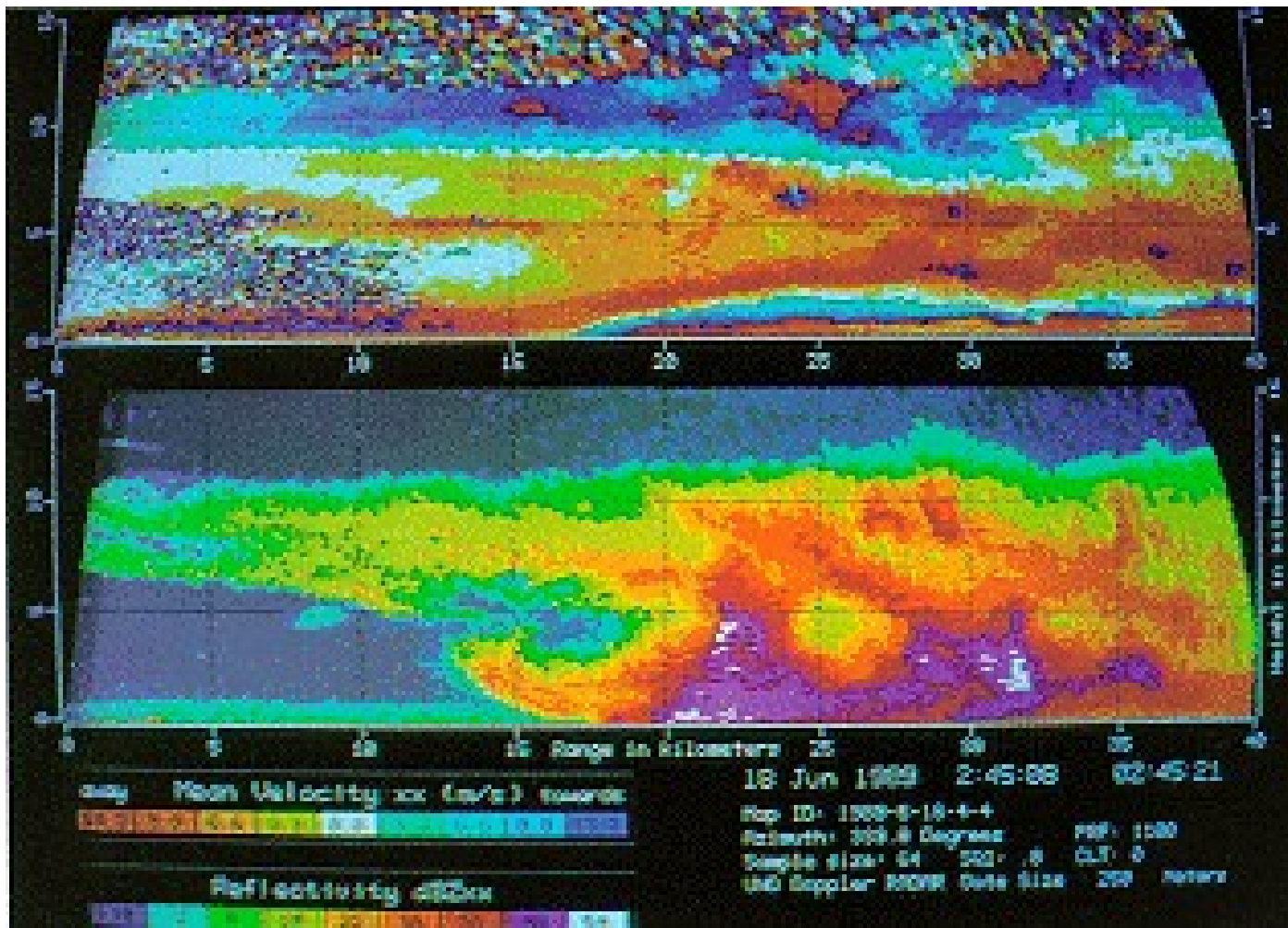
# Environmental Winds



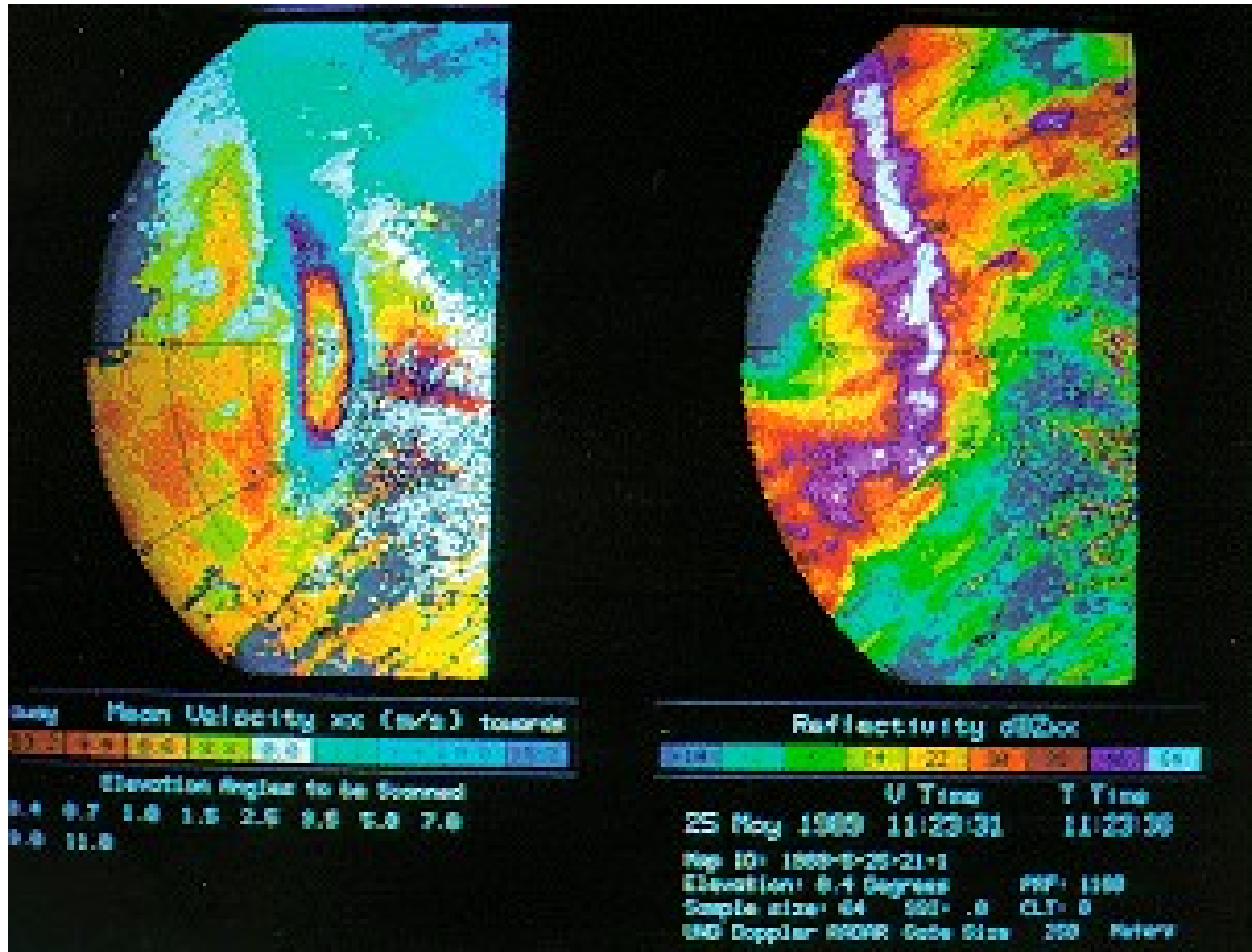
# Gust Fronts – Best in Velocity Observation



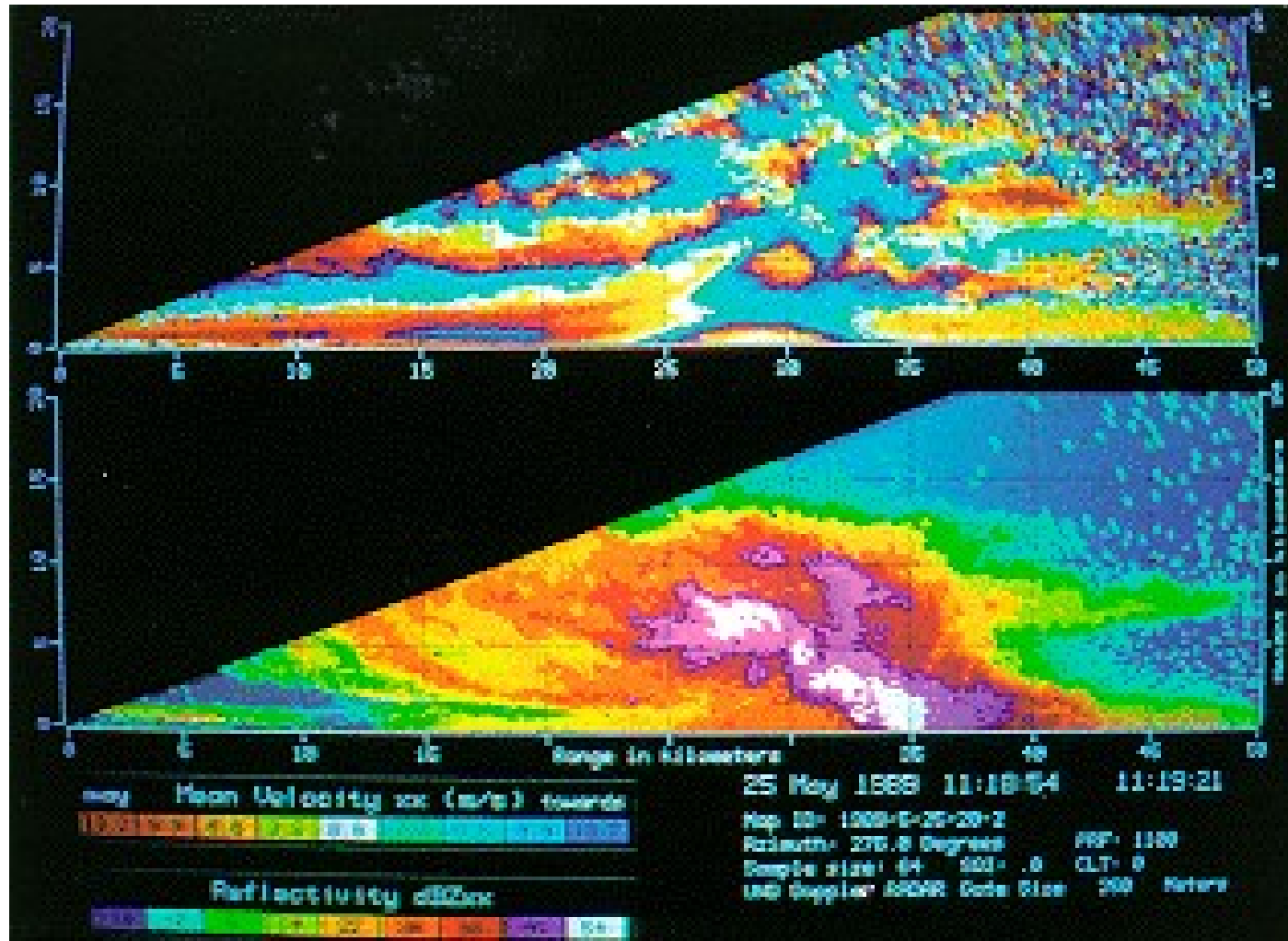
# Gust Fronts – RH View



# Straight-line Winds ... a Bow Echo

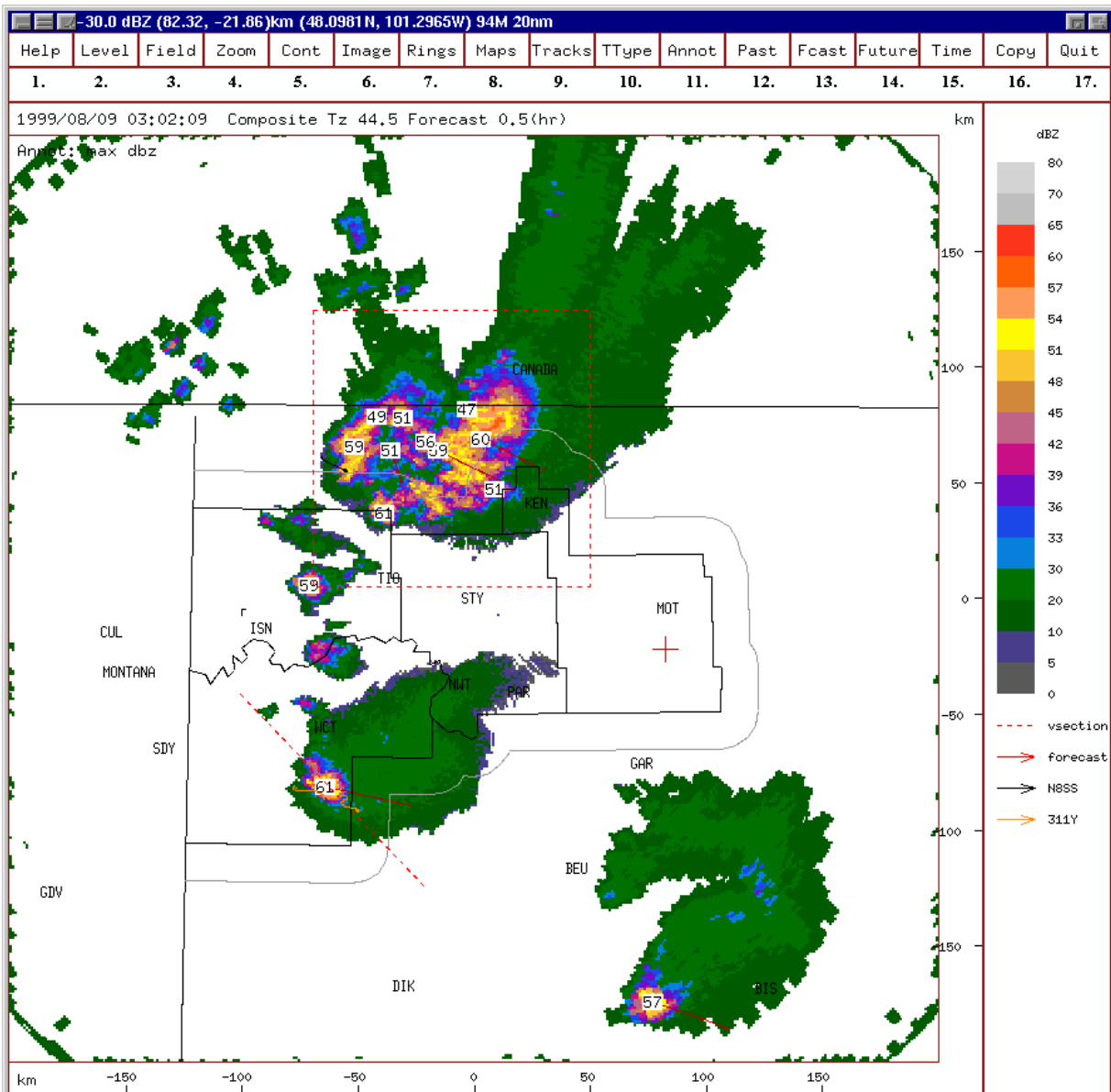


# Bow Echo – RHI View



# Microburst

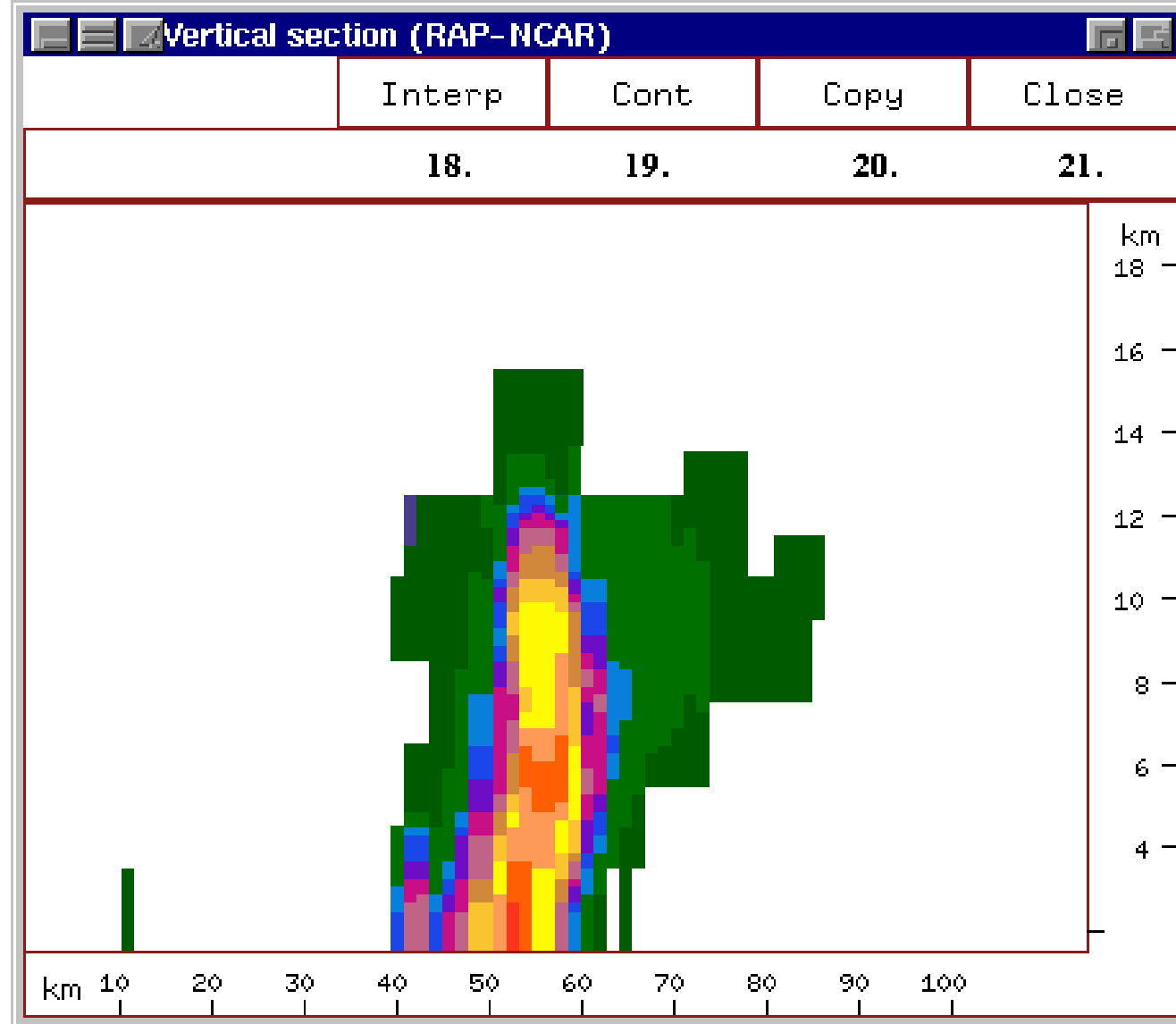
# TITAN-LROSE Displays - PPI





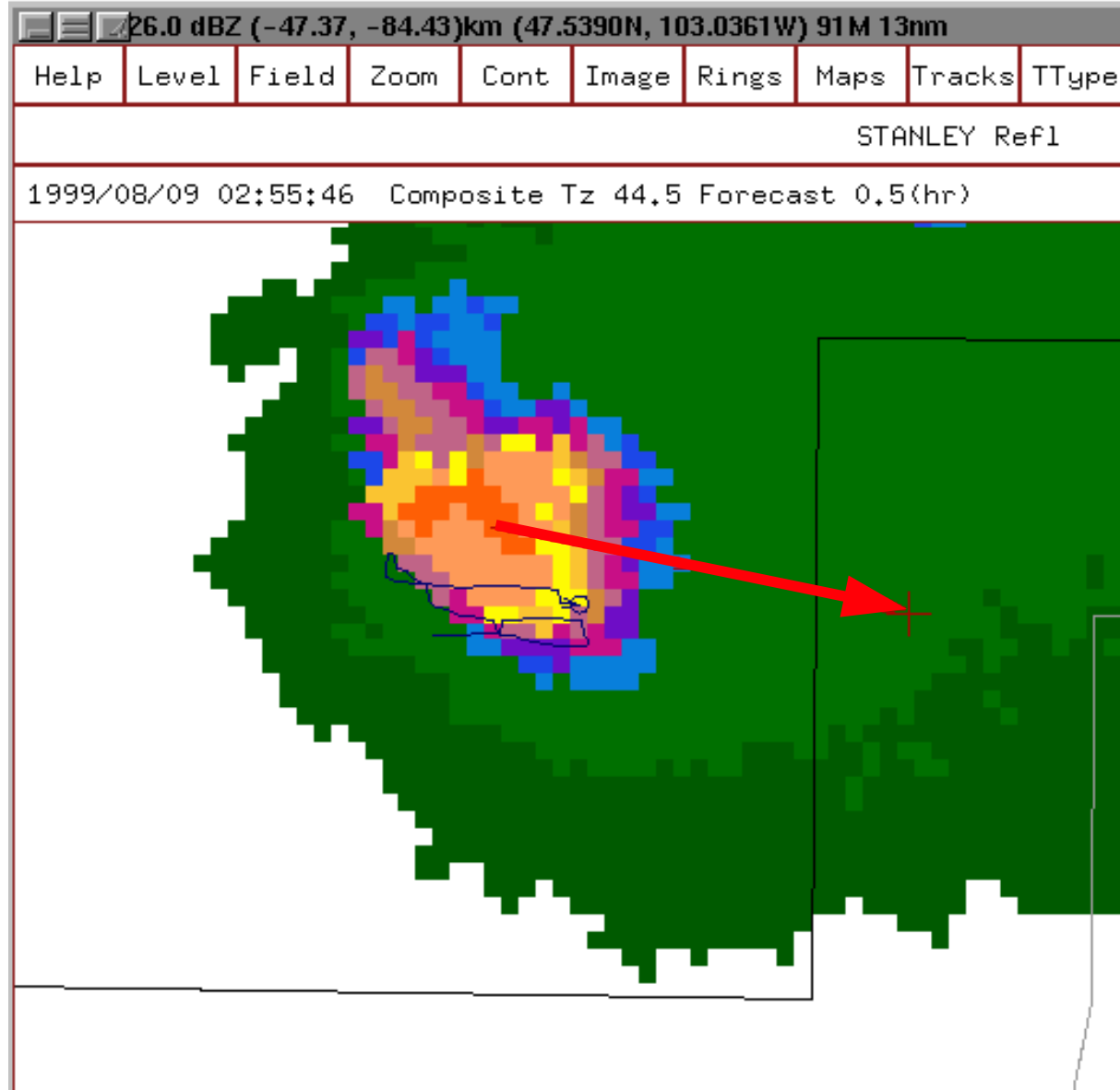
# TITAN-LROSE

## Displays - RHI



# TITAN-LROSE

## Displays Composite Forecast

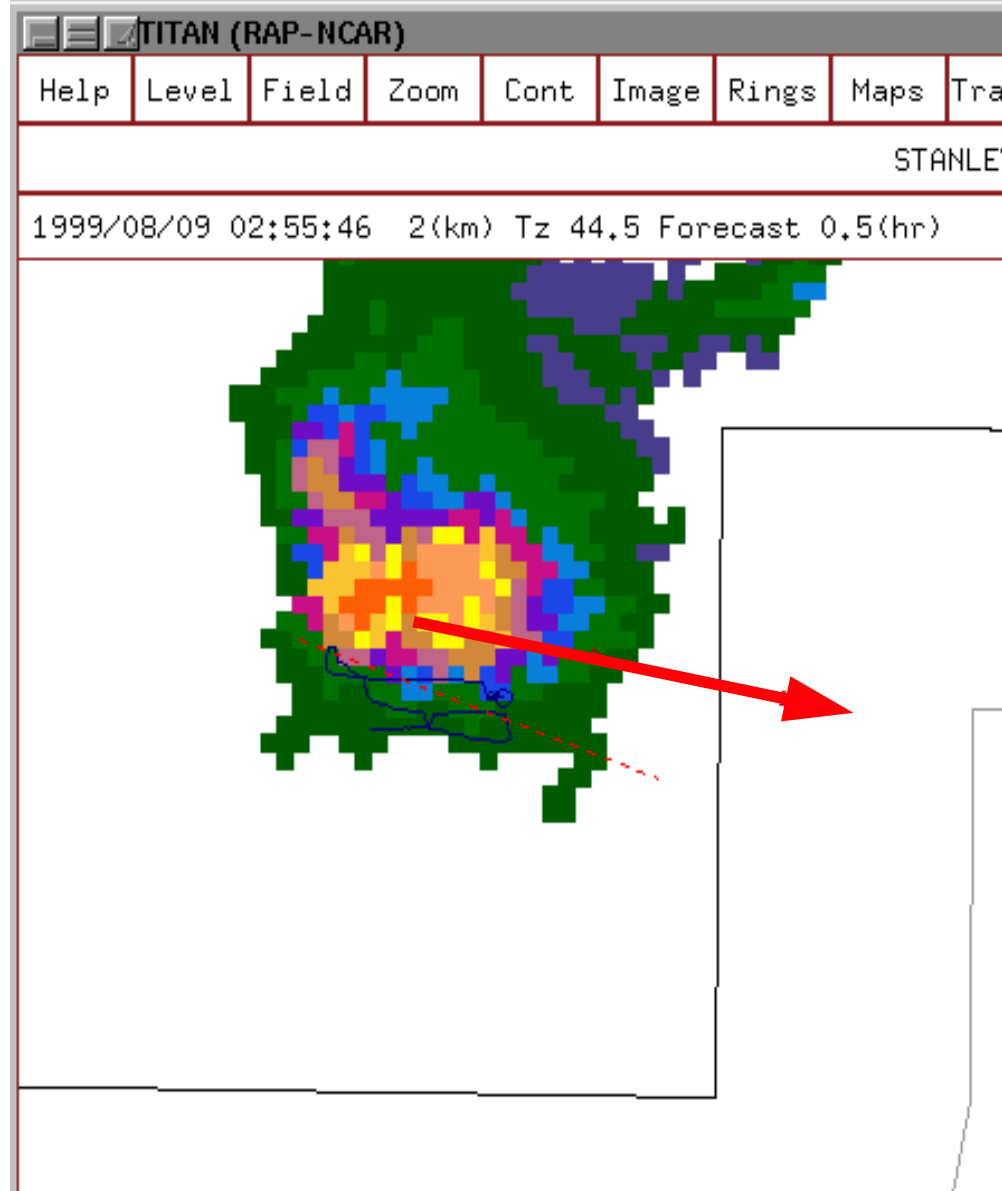


# TITAN-LROSE

## Displays

## CAPPI

## Forecast



Donut Hole

