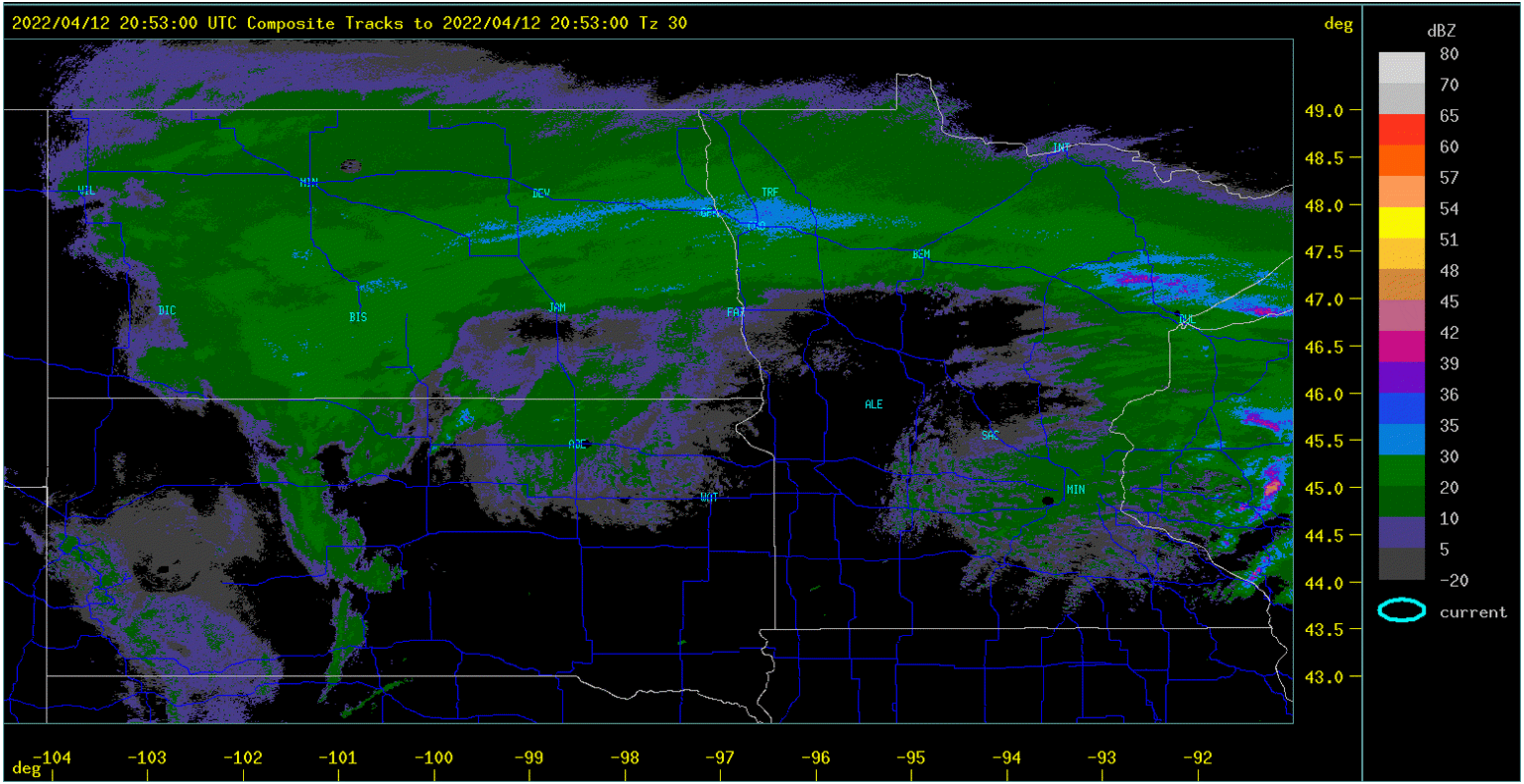
Radar for Weather Modification



Radio Detection And Ranging (RADAR)

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

Weather Detection

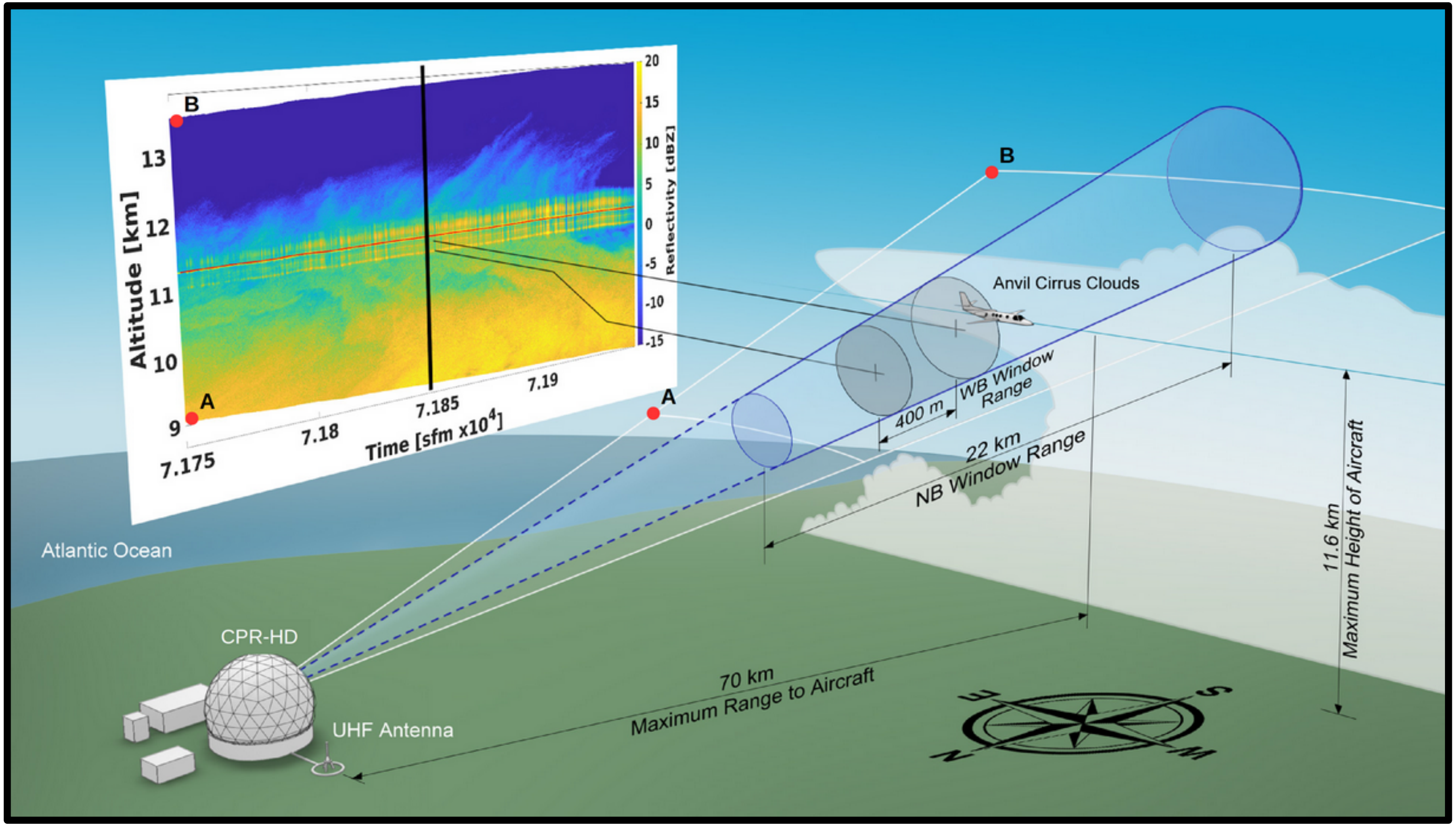
- Precipitation Measurements
- Storm Detection & Tracking
- Snow Detection
- Cloud Detection
- Weather Modification
- Wind Measurements

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

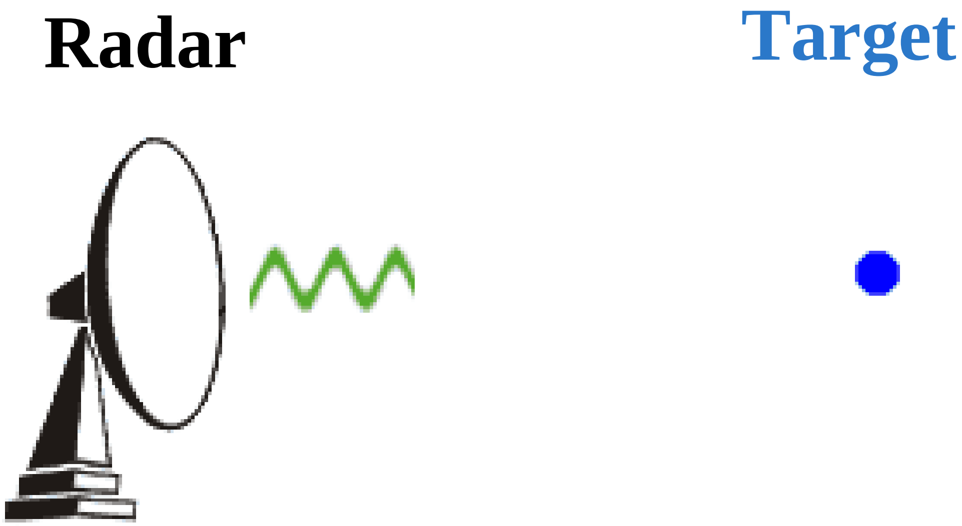
- **Distance**
- **Position**
- **Time**
- **Power**
- **Velocity**
  - **Frequency Change**



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 x 10^8 miles/hr

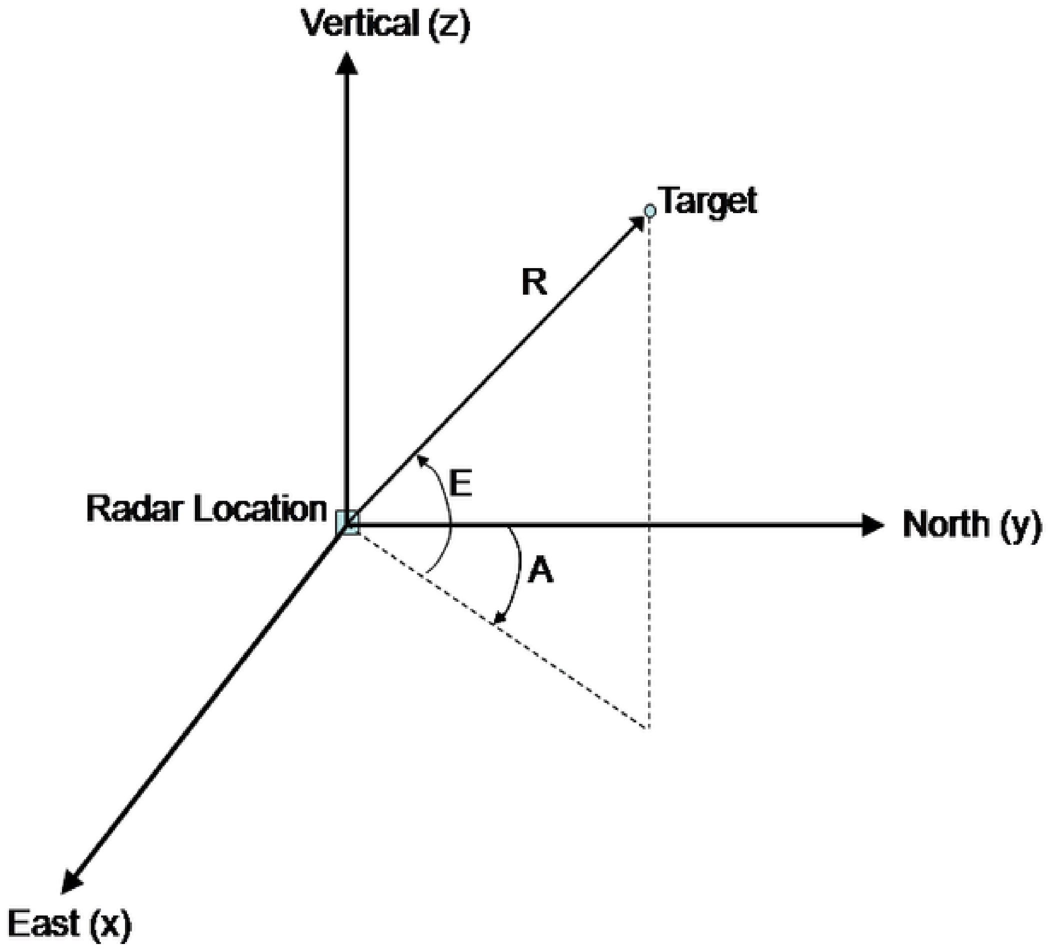


https://www.weather.gov/mkx/using-radar

- 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)

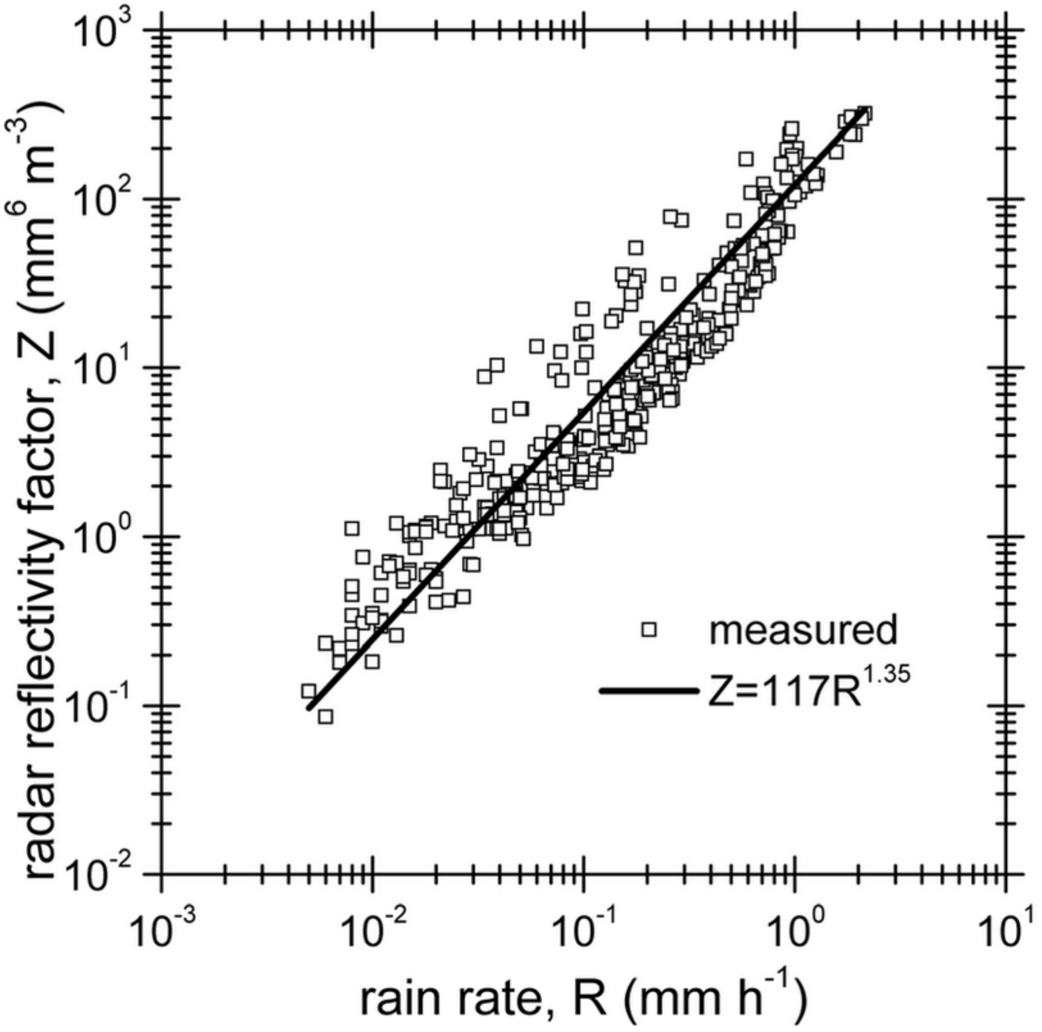
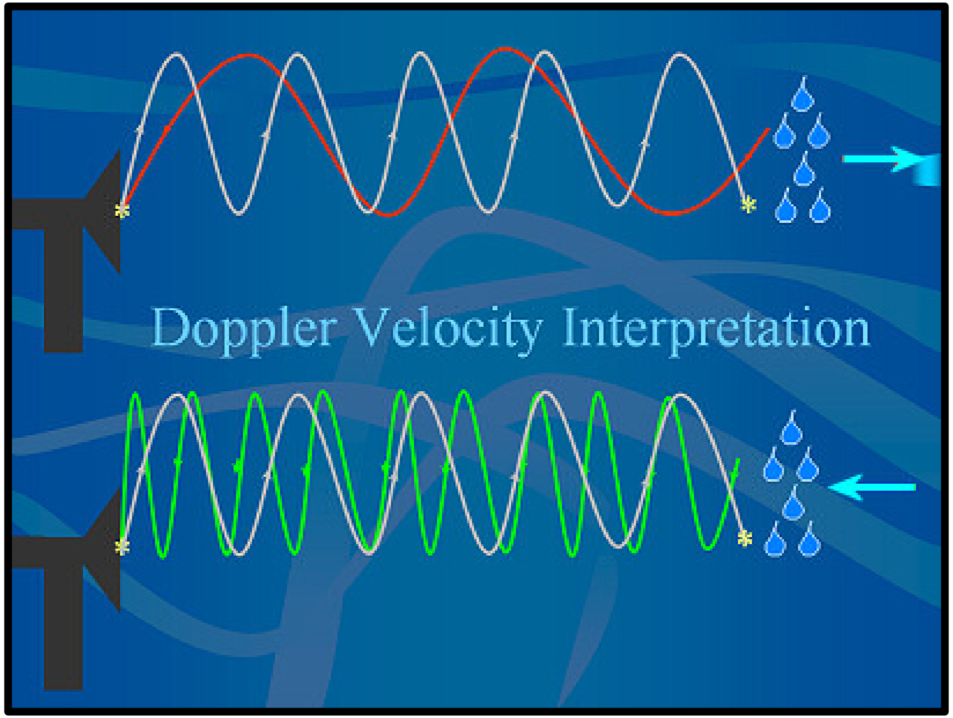


Figure 12 from Baojun Chen, Characteristics of the raindrop size distribution for freezing precipitation observed in Southern China, Journal of Geophysical Research Atmospheres 116(D6), 2011, DOI:10.1029/2010JD015305

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.

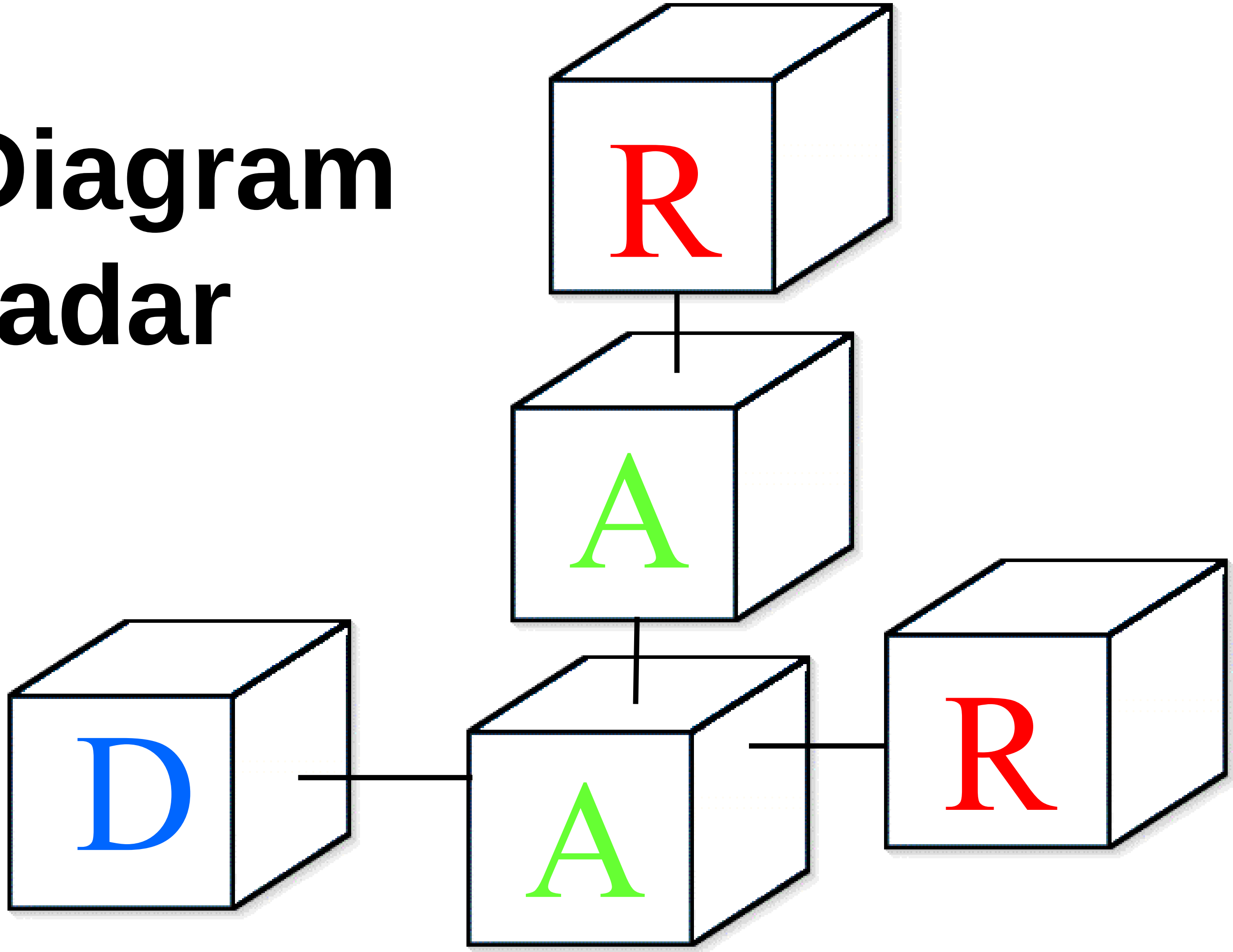


Grey line is the transmitted signal. The returned energy changes its wavelength when it hits a target moving away (red line) or toward the radar (green line)
https://www.weather.gov/mkx/using-radar

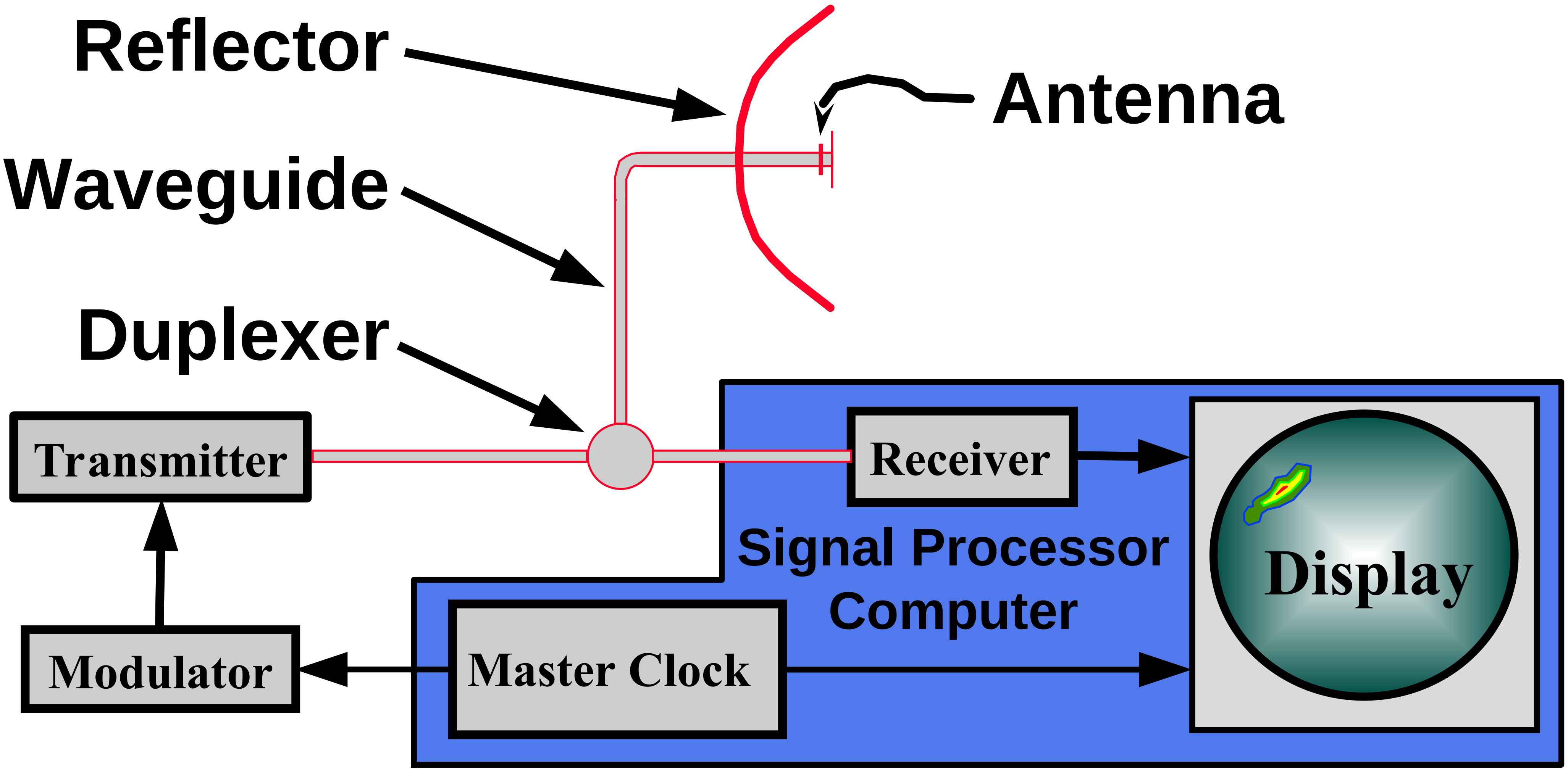
Radar Measurements from Aircraft

- Must be small, light weight & low power.
- Scan ahead of aircraft (±60° or ±90°).
- 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.

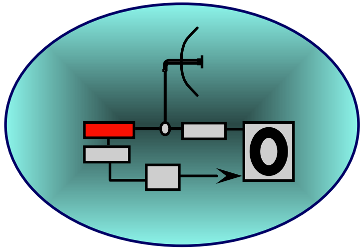
Block Diagram of Radar



Block Diagram of Radar

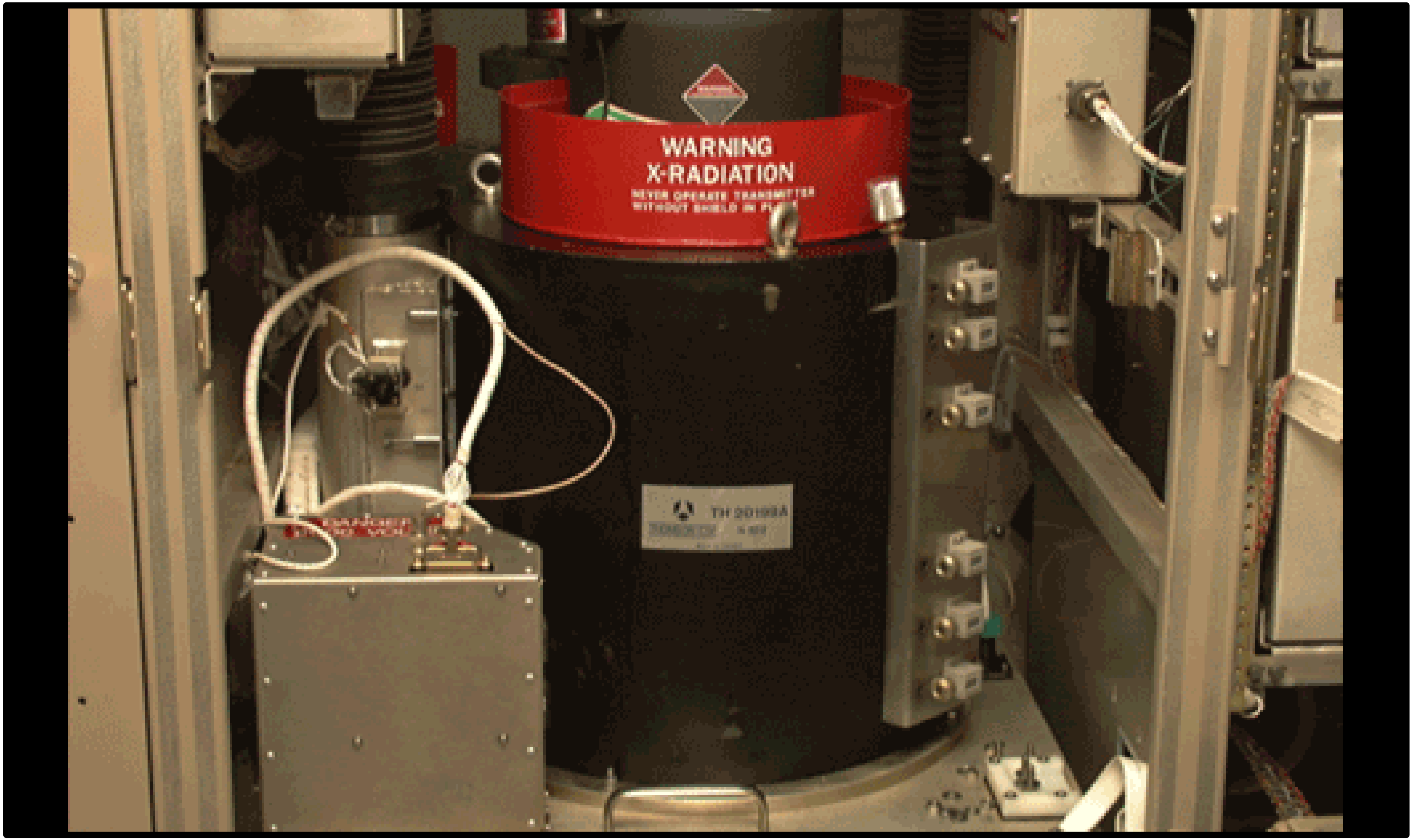


Radar Transmitter



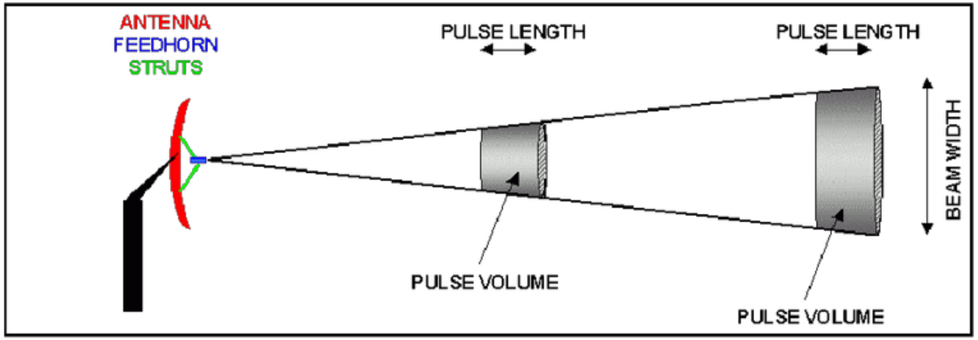
- Generates the microwave signal.
- Transmits a short burst of power at some frequency.
- Typical power from a few watts (W) to a couple of megawatts (mW).
  - UND Radar Transmits 250,000 W or 250 kW.
  - CPR-HD Radar Transmits 3 mW
- Frequency from 30 MHz to 300 GHz
- UND / CPR-HD Radars use 5550 MHz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

WSR 88D Radar Transmitter



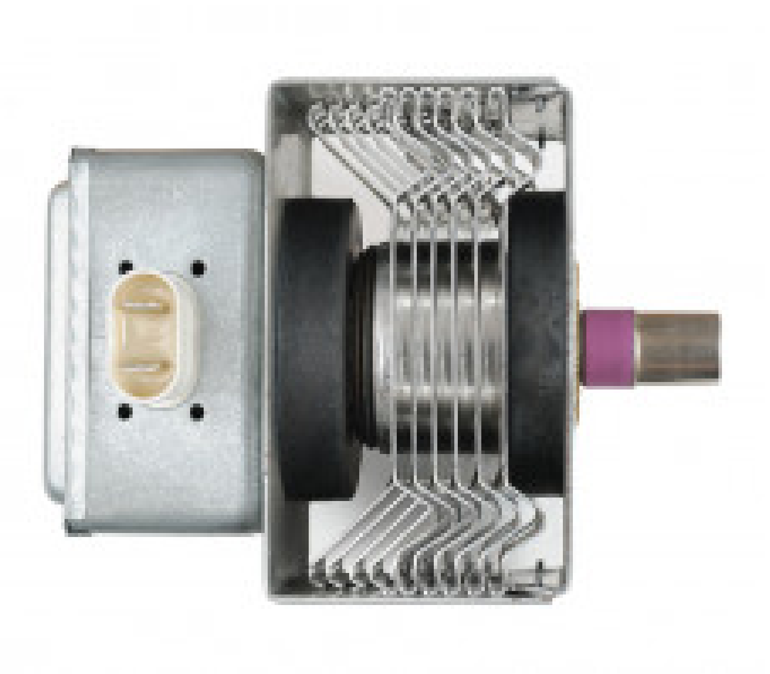
Transmitter Pulse Parameters

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



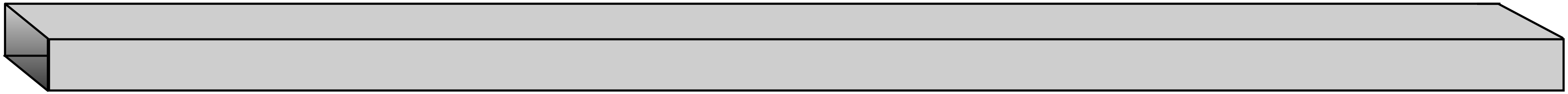
Radar Transmitter Types

- 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



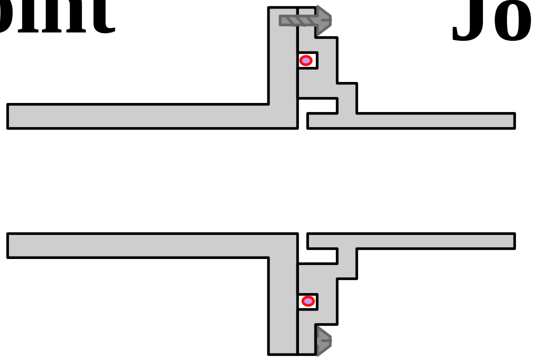
Waveguide for Radar

Rectangular Piece of Hollow Waveguide



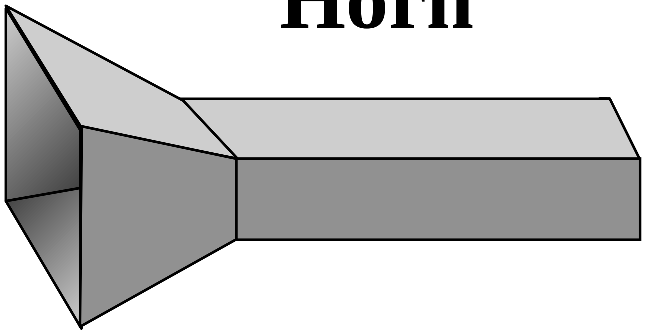
Flange Joint

Choke Joint

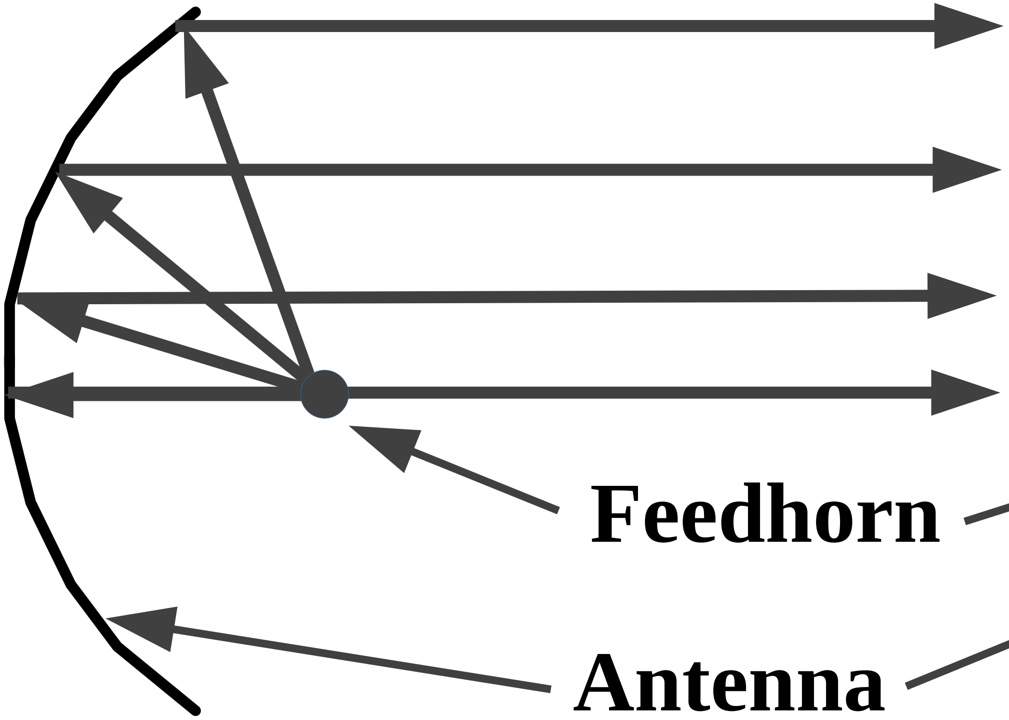


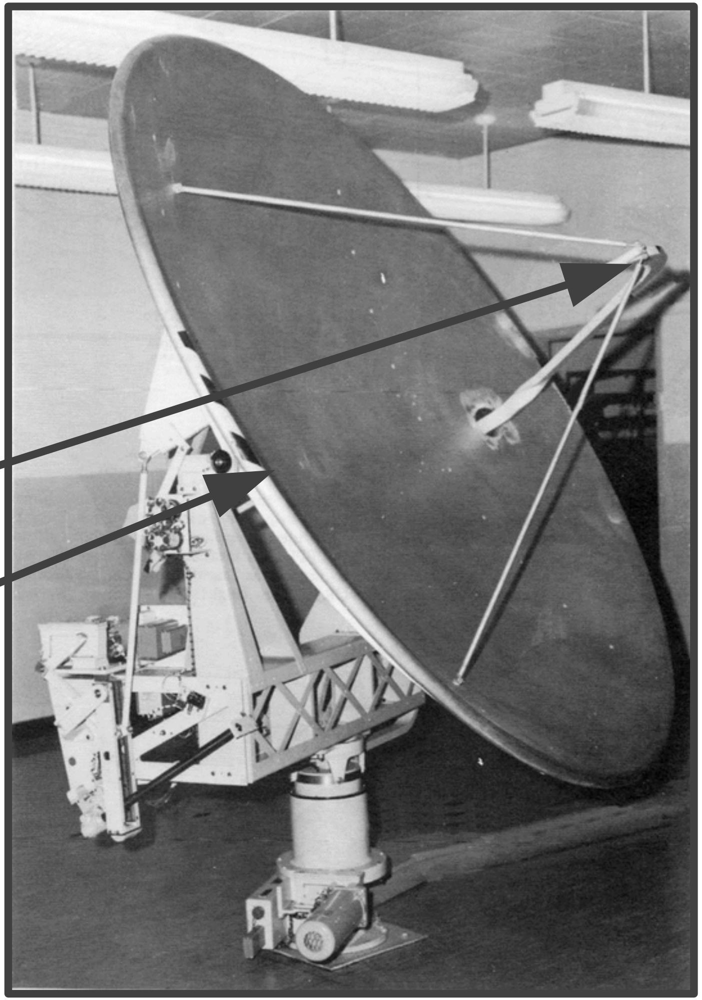
(cross-section)

Horn



Cross-Section of Parabolic Reflector

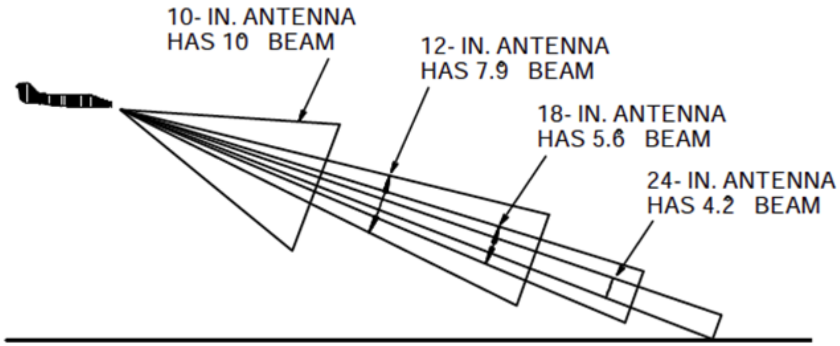




Rays from focus are reflected parallel into space.

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.

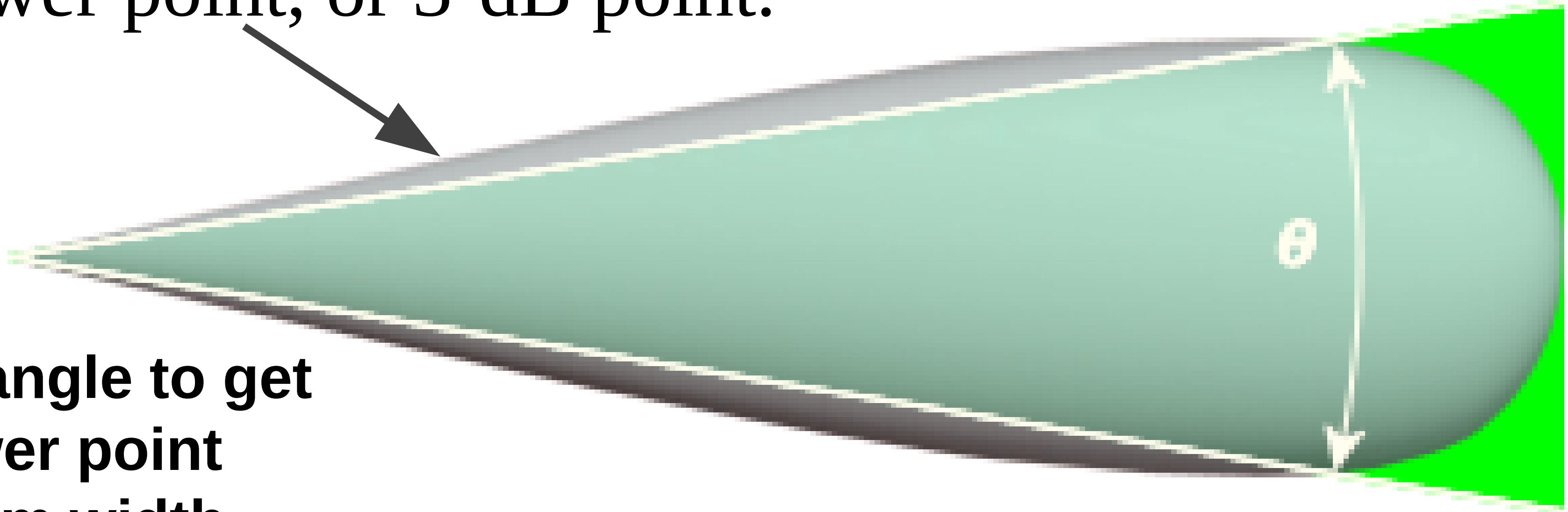


Advantages of using Radar Reflector

- 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.

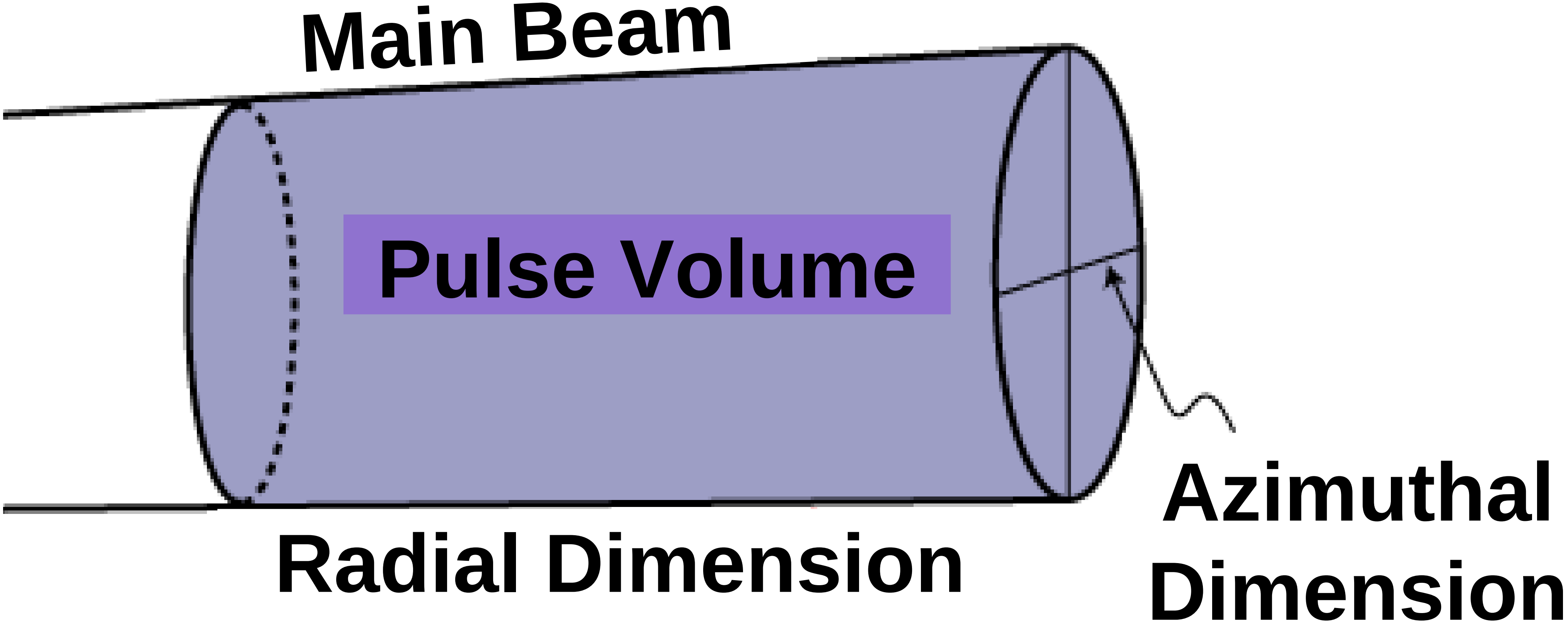
Antenna Beam Width

- 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.



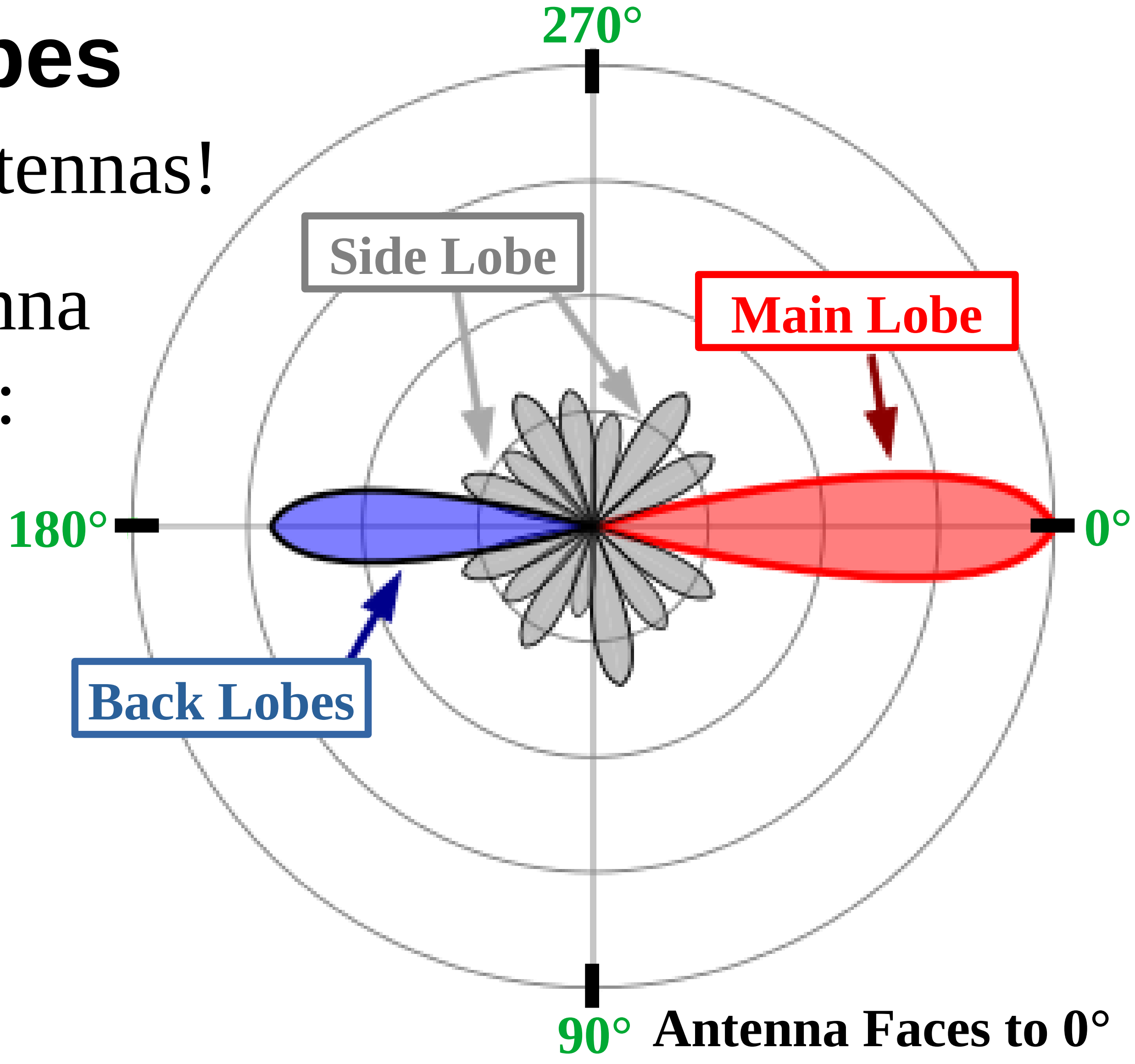
Double the angle to get the half-power point antenna beam width.

Radar Pulse Volume



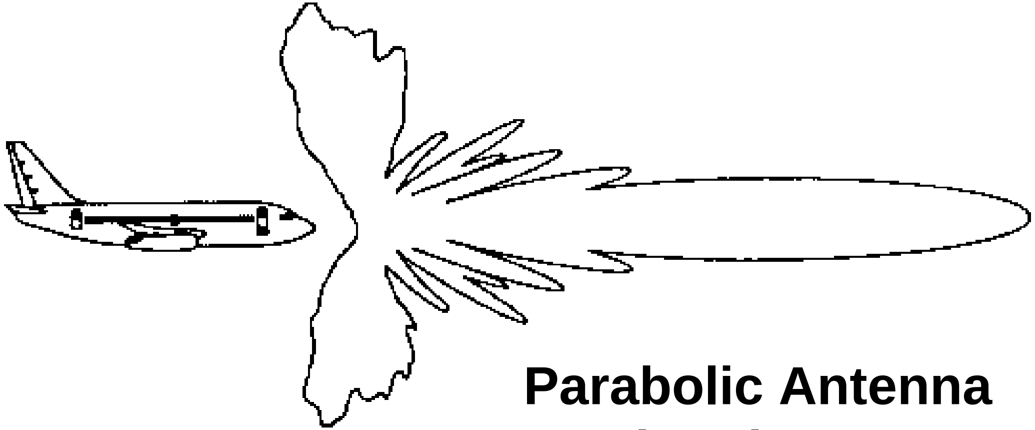
Antenna Sidelobes

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

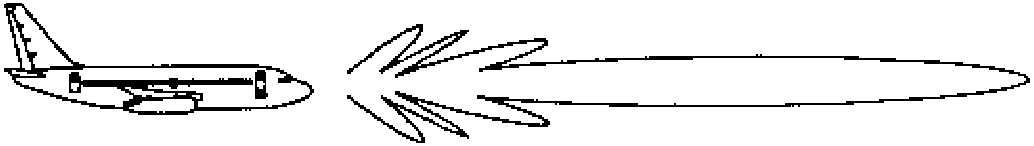


Flat-plate or Phased-array Antenna

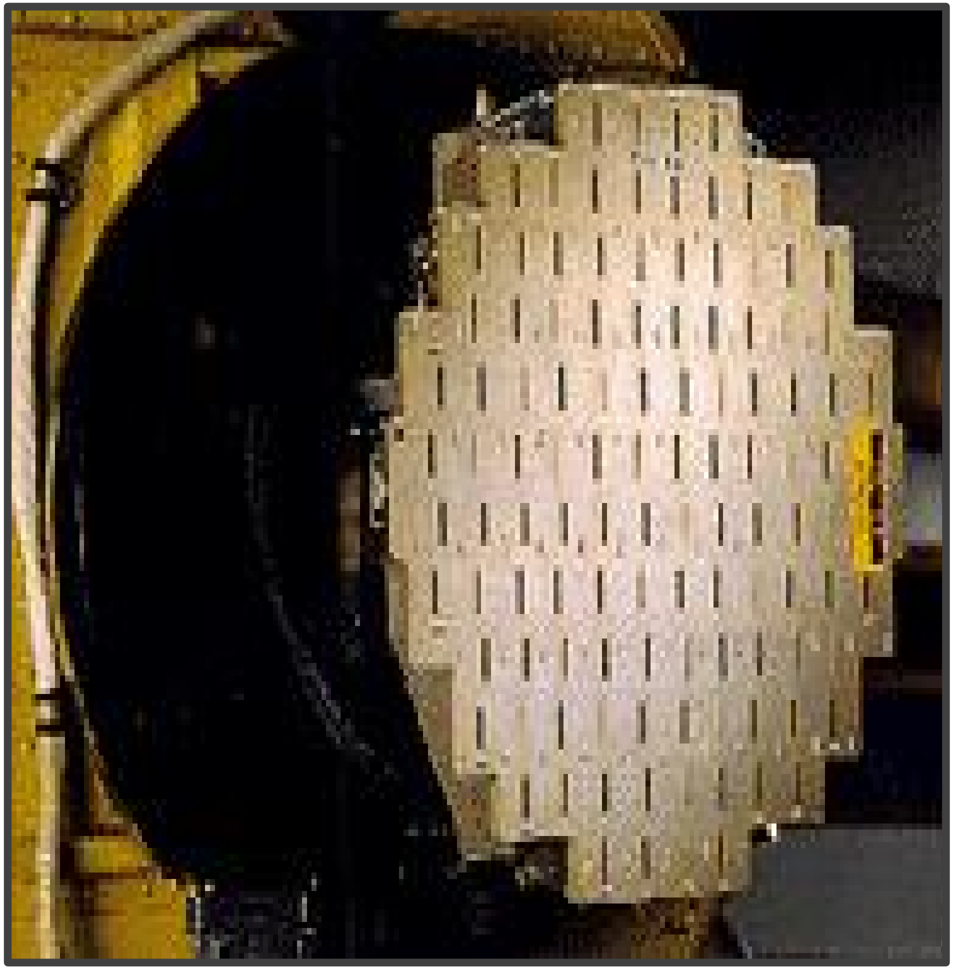
- More focused beam.
- Fewer side lobe losses.



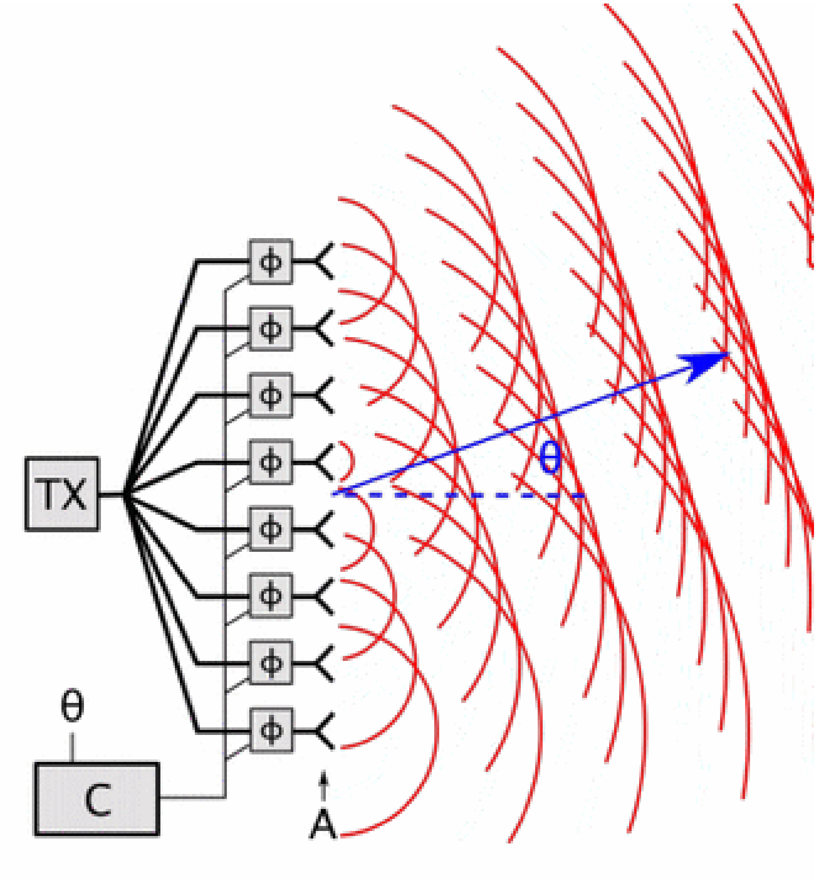
Parabolic Antenna Azimuth Patter



Flat-plate Antenna Azimuth Patter



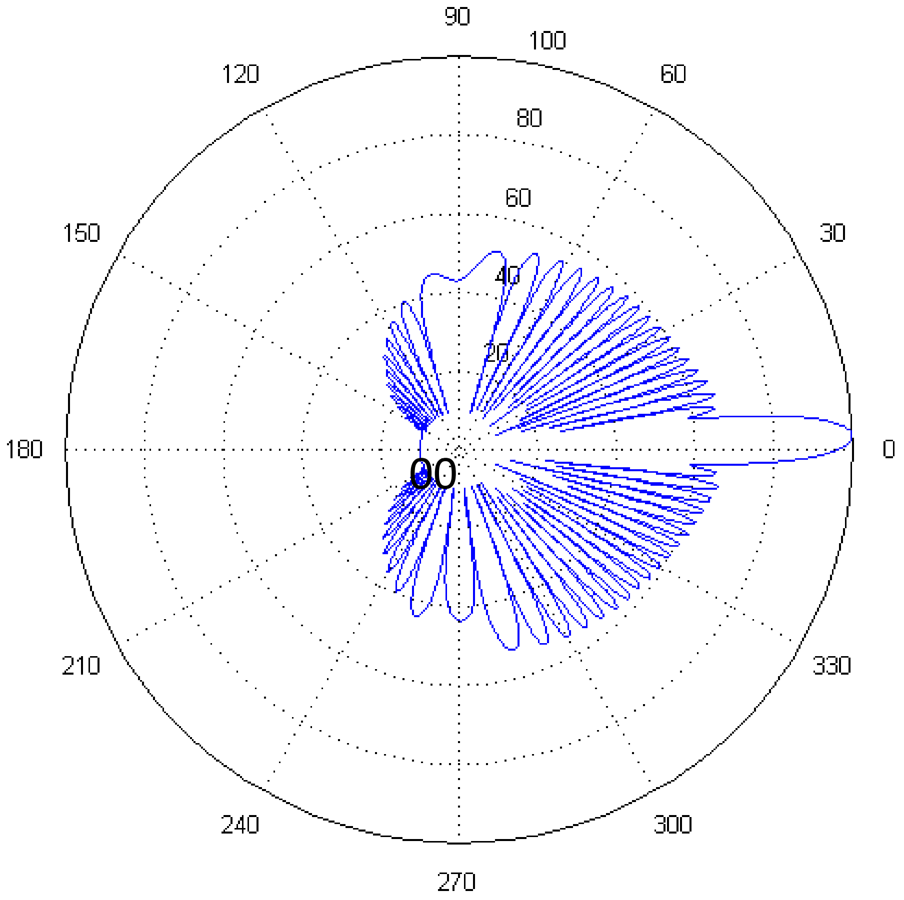
Principles of Phased Array Radar



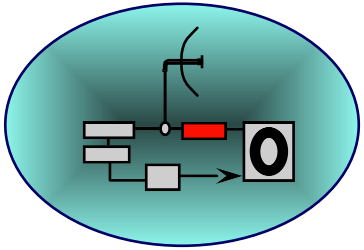
https://en.wikipedia.org/wiki/Phased_array

Side Lobes During Electronic Scanning

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



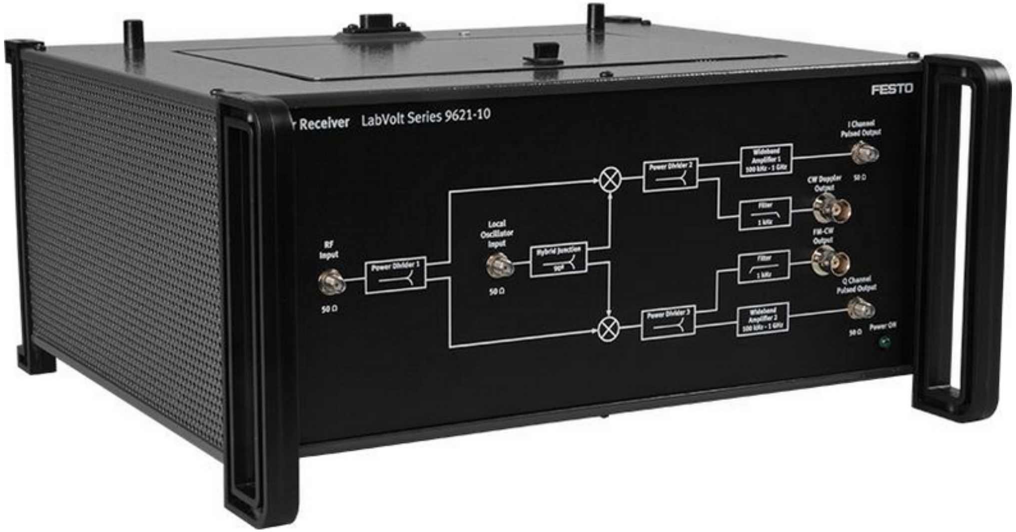
Radar Receiver Function



- 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.
    - $P\ (dBm) = 10 * \log_{10}(P\ (\text{linear power}) / 1\ mW)$

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.

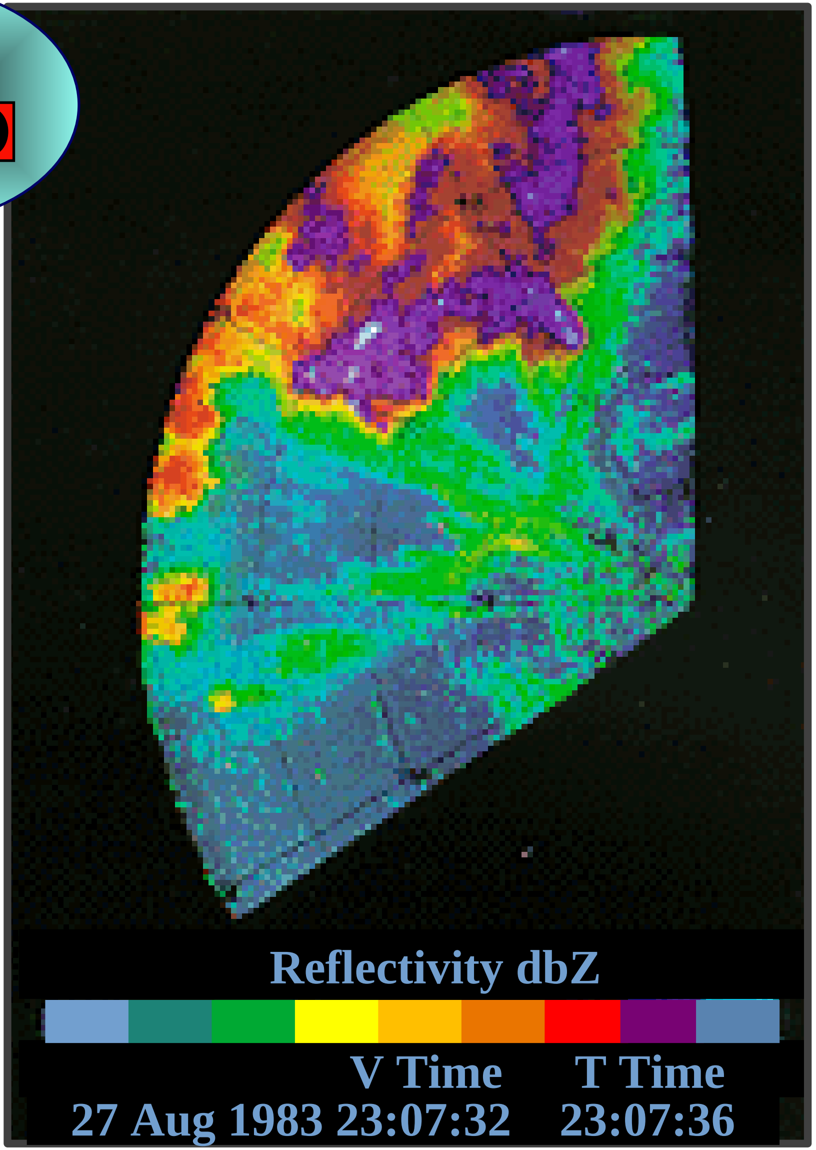


A-scope Radar Display System

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

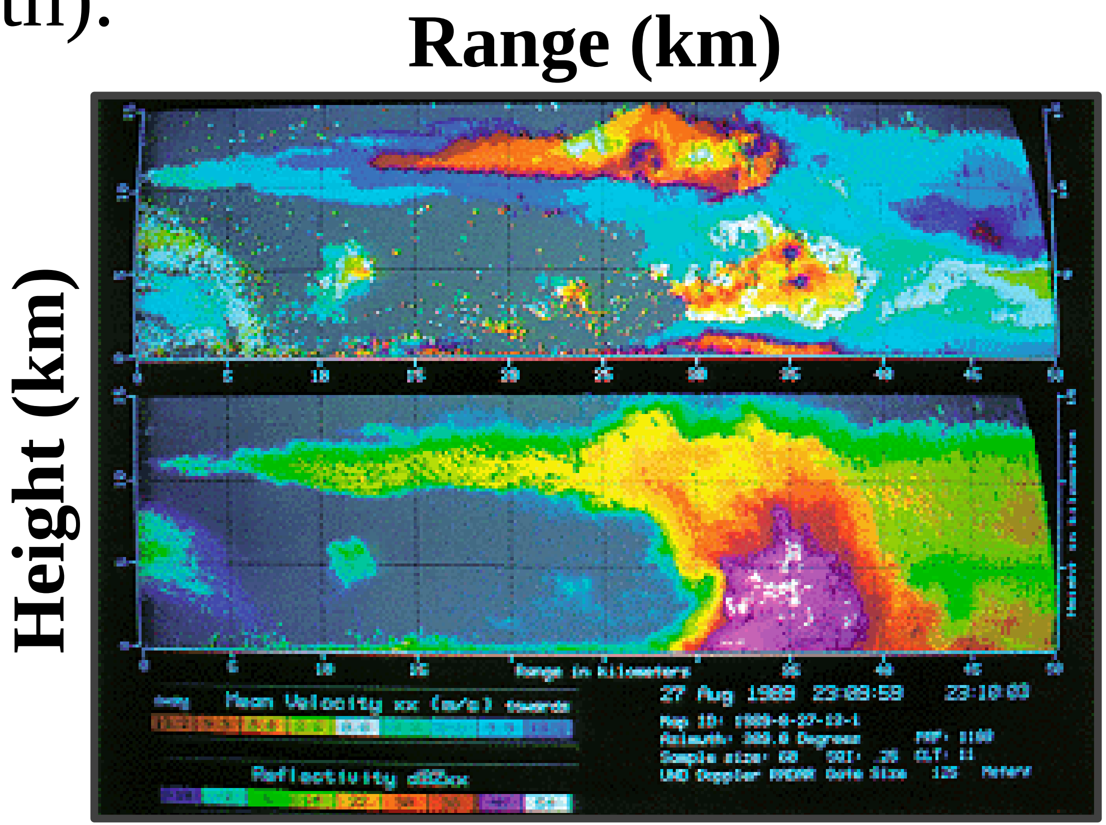
Plan Position Indicator (PPI) Radar Display

- 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).



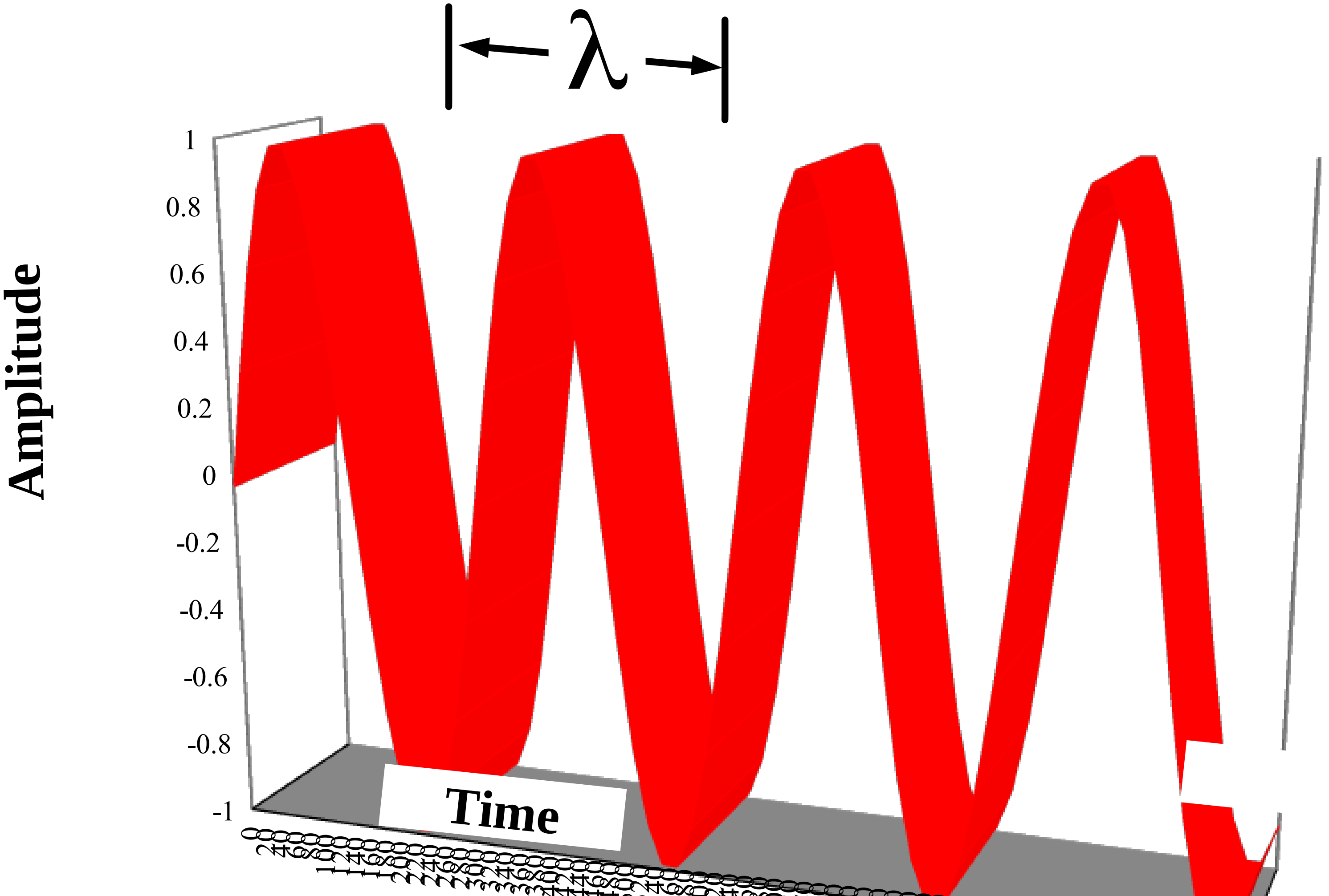
Range-height Indicator (RHI) Displays

- 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.

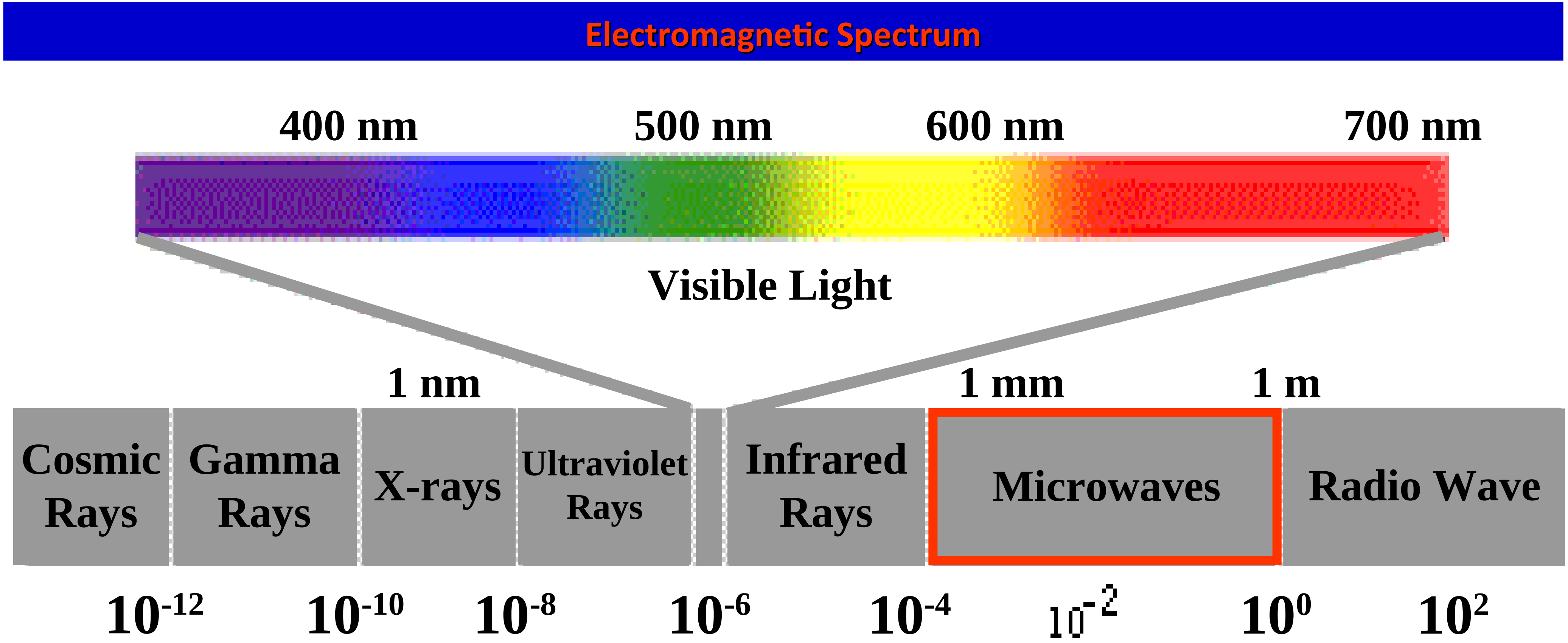


Electromagnetic Radiation Characteristics

- Wavelength
- Frequency
- Amplitude
- Polarization



Radars Transmits at Microwave Wavelengths



Radar Wavelength Band Types

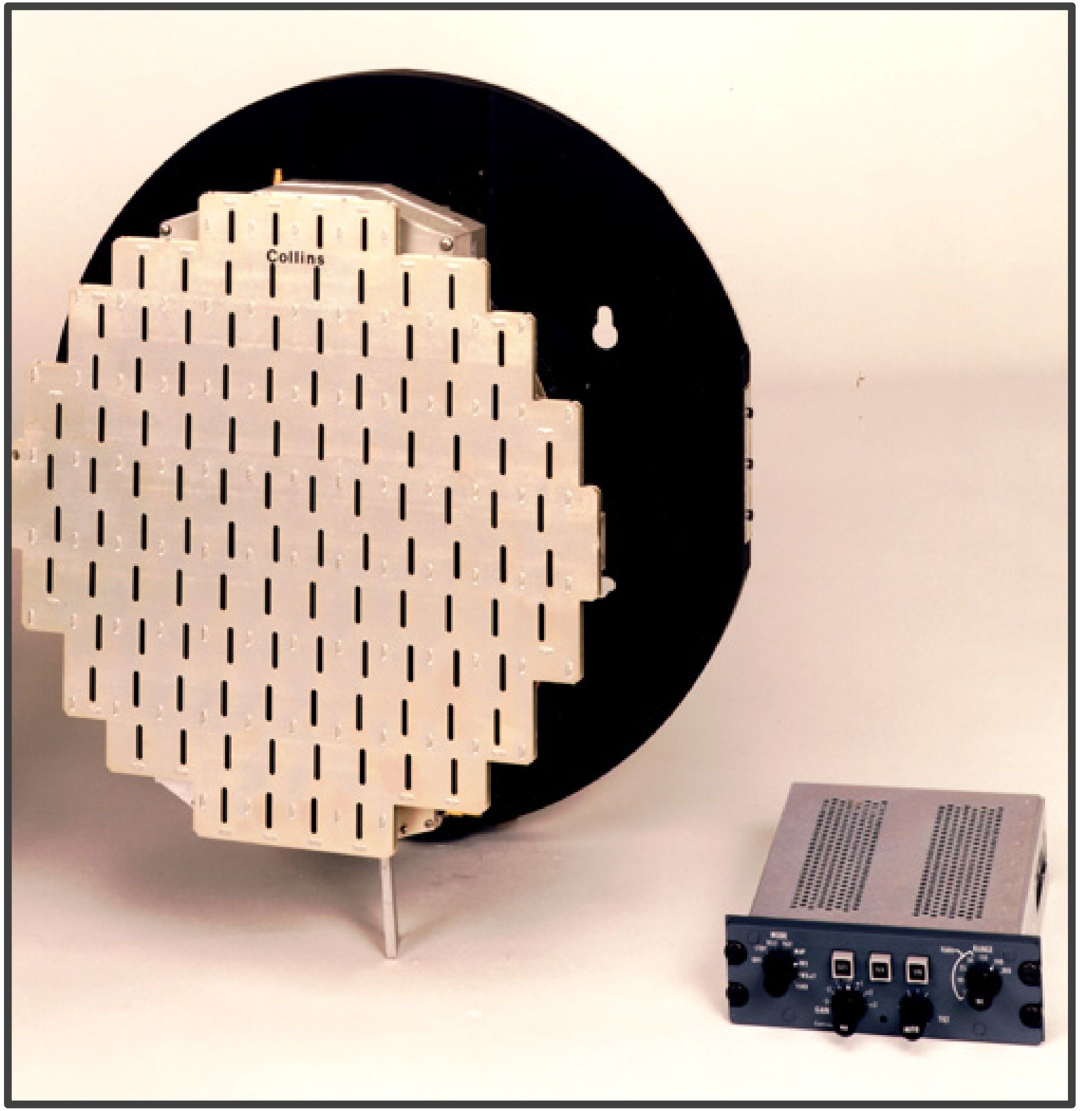
Band Designation	Frequency	Wavelength
HF	3-30 MHz	100-10 m
VHF	30-300 MHz	10-1 m
UHF	300-1000 MHz	1-0.3 m
L	**1-2 GHz**	**30-15 cm (20 cm)**
S	**2-4 GHz**	**15-8 cm (10 cm)**
C	**4-8 GHz**	**8-4 cm (5 cm)**
X	**8-12 GHz**	**4-2.5 cm (3 cm)**
K_u	12-18 GHz	2.5-1.7 cm
K	18-27 GHz	1.7-1.2 cm
K_a	27-40 GHz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

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

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

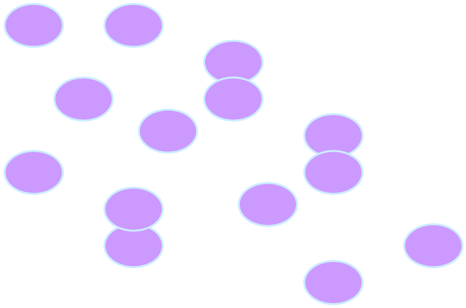
X Band Radar (3 cm Wavelength)

- Airborne Weather Radar

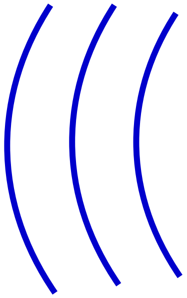


Some Radar Terminology

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



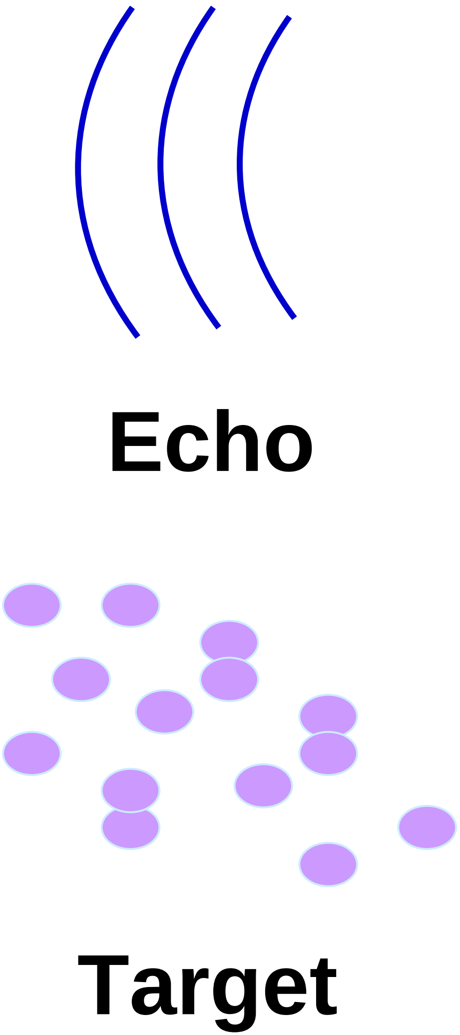
Target



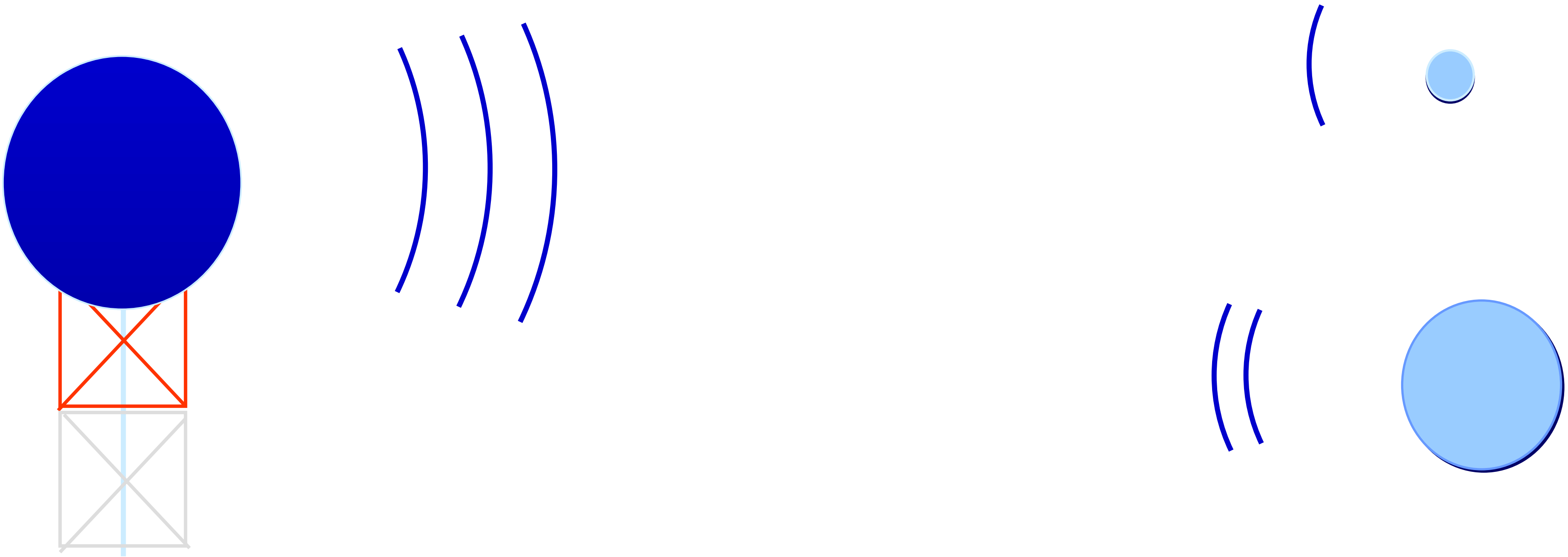
Echo

Amount of Energy (Echo) Reflected

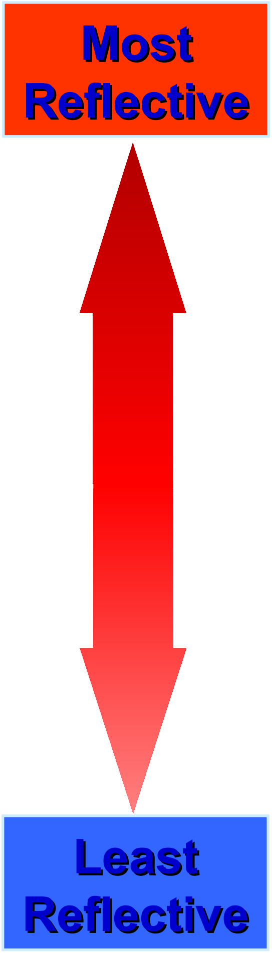
- Size of Targets
- Number of Targets
- Composition of Targets
- Distance to Targets



Size - Bigger Reflects More, ~D^6



Depends on Composition of Targets



Wet Hail

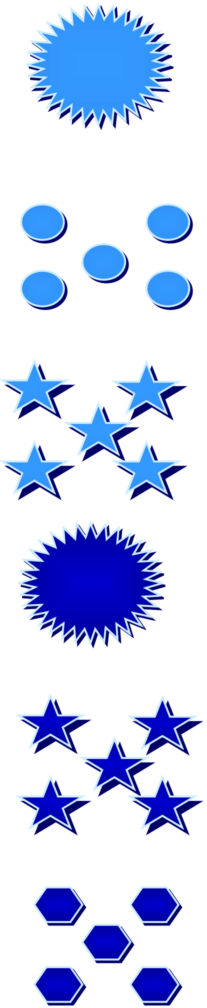
Rain

Wet Snow

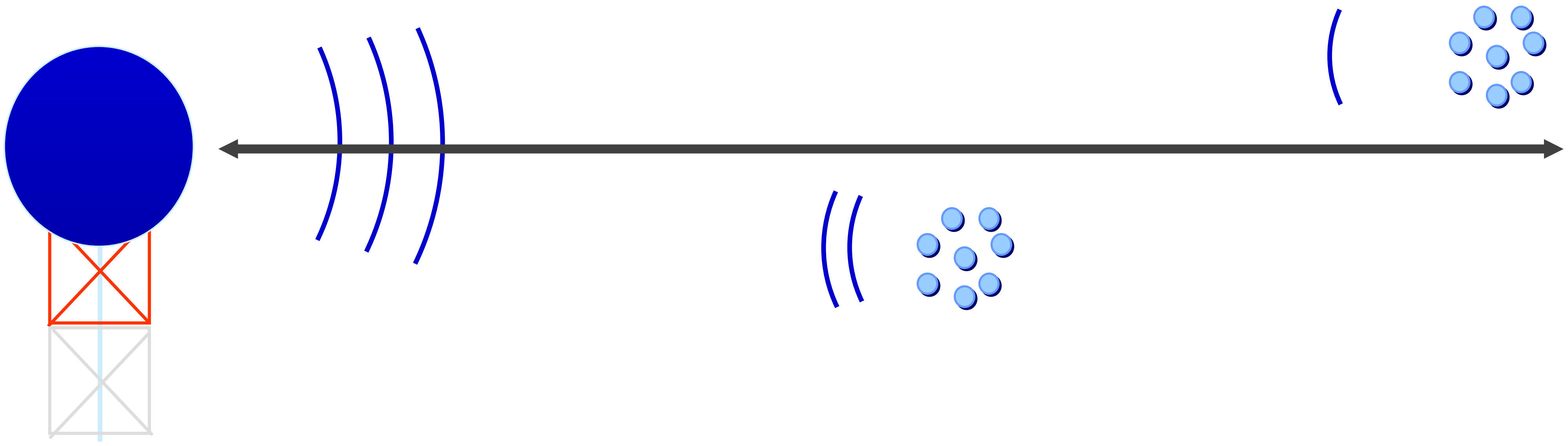
Dry Hail

Dry Snow

Ice Crystals



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)

DVIP Level	Rainfall Rate	Reflectivity
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

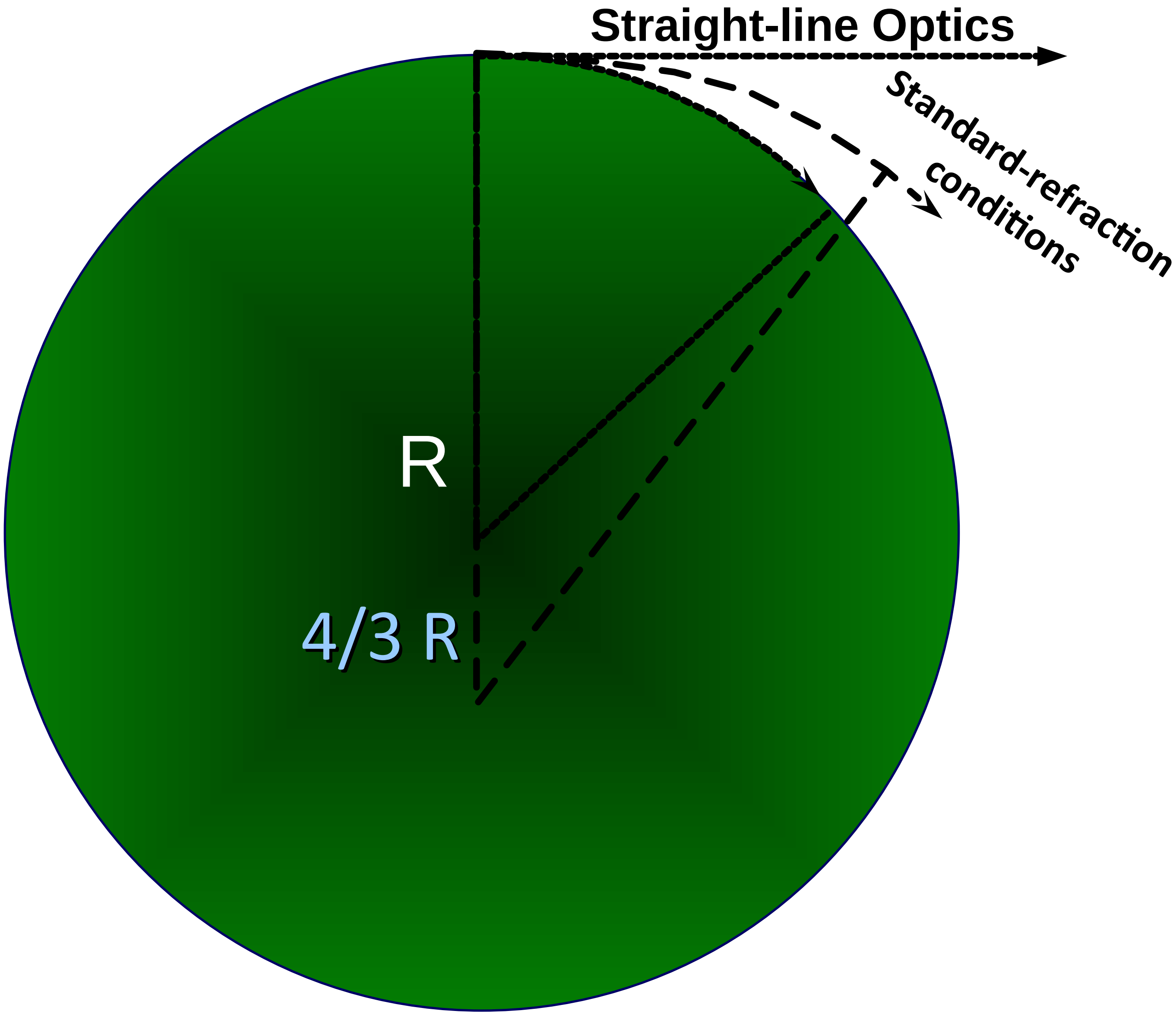
What value of reflectivity would you typically need to indicate hail in a storm?

Speed of Light (Radar Wave)

- The speed of light in a vacuum is

  $c = 299,792,458 \pm 10$ m/s $\approx 3 \cdot 10^8$ m/s

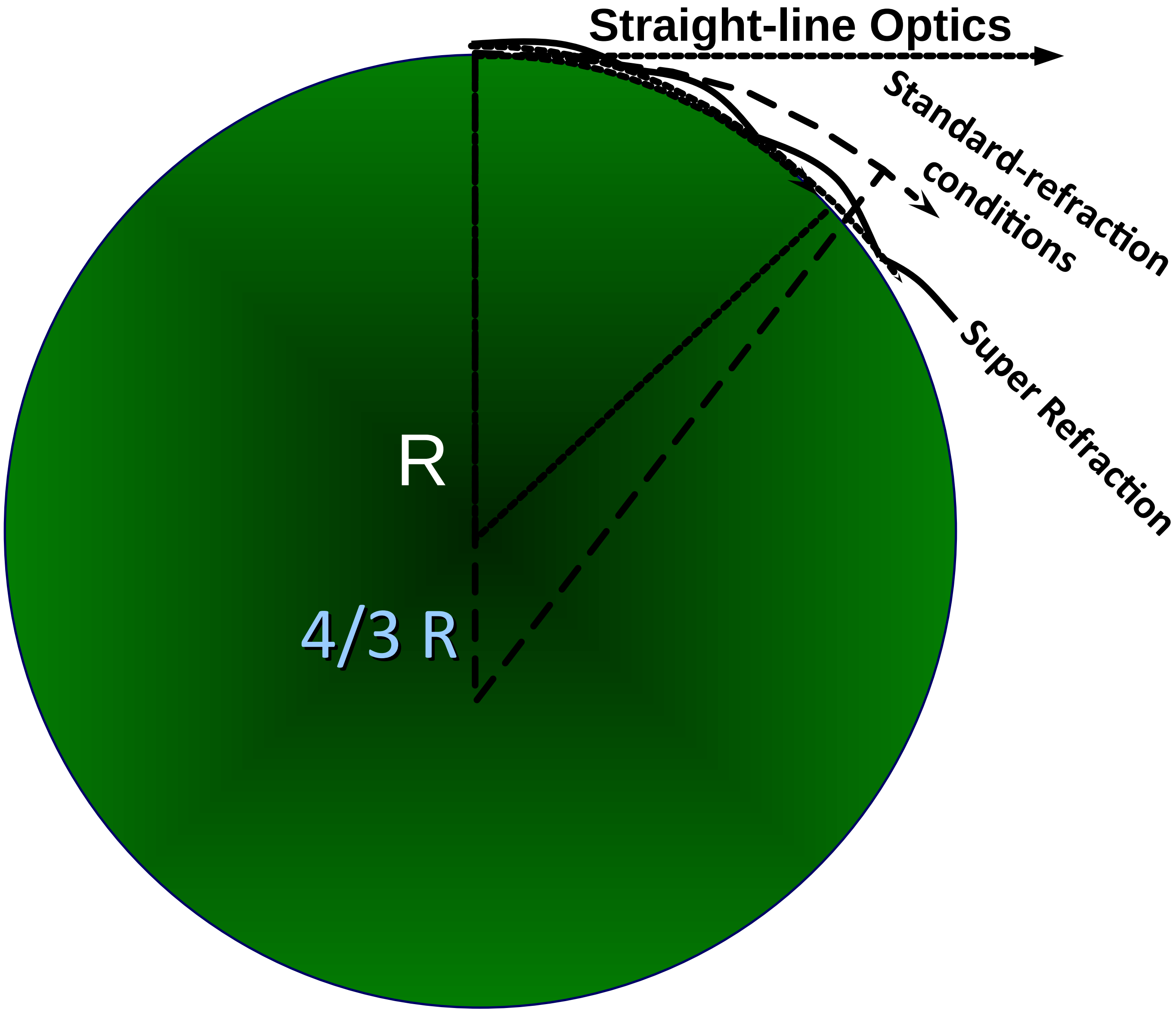
- In the atmosphere, the speed (u) is slower!
- We can calculate u from the pressure, temperature and vapor pressures.
- From the surface to outer space, u varies from 0.9997 to 1.0000 of c.

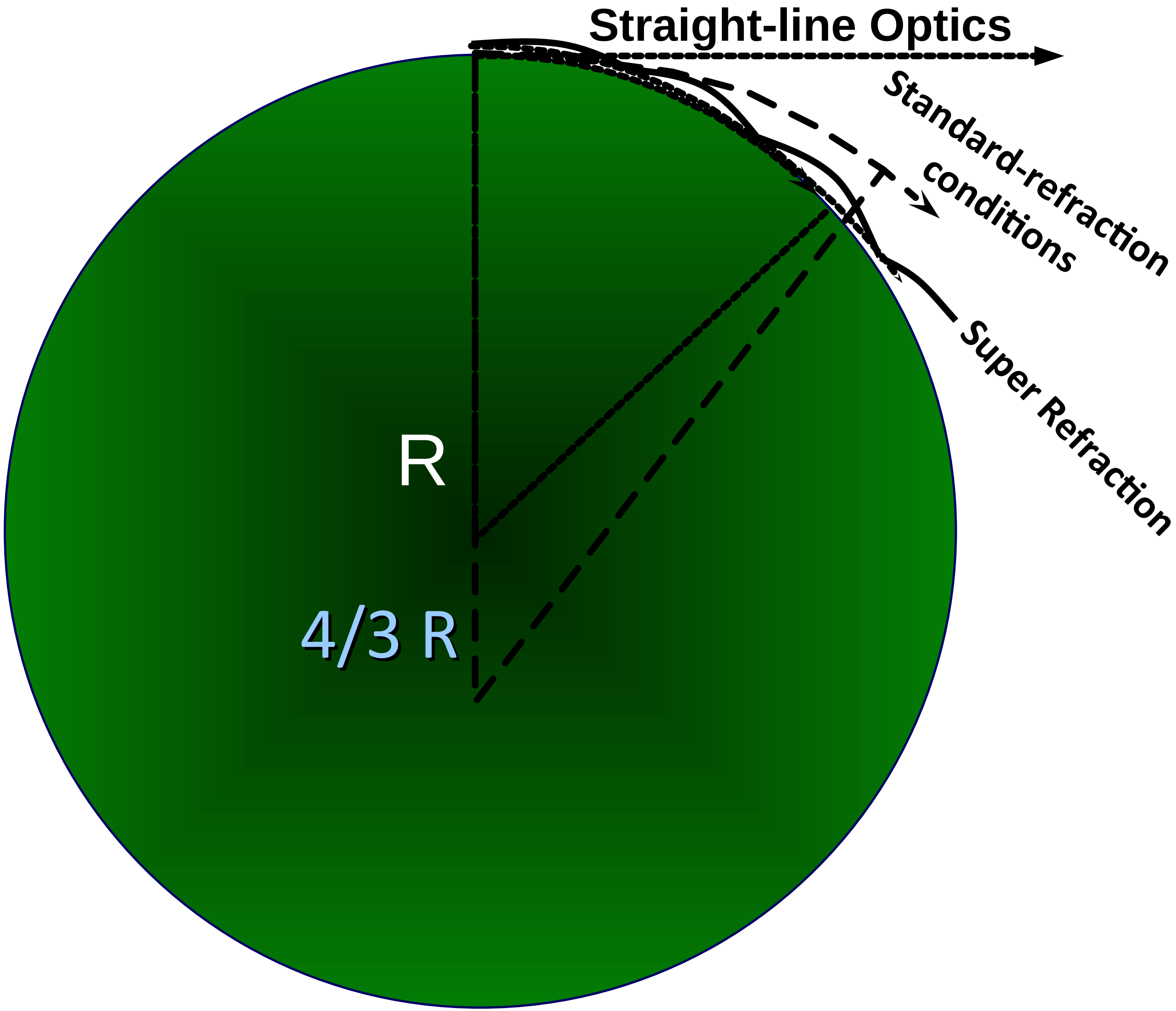


Straight-line Optics
Standard-refraction conditions
R
4/3 R

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.

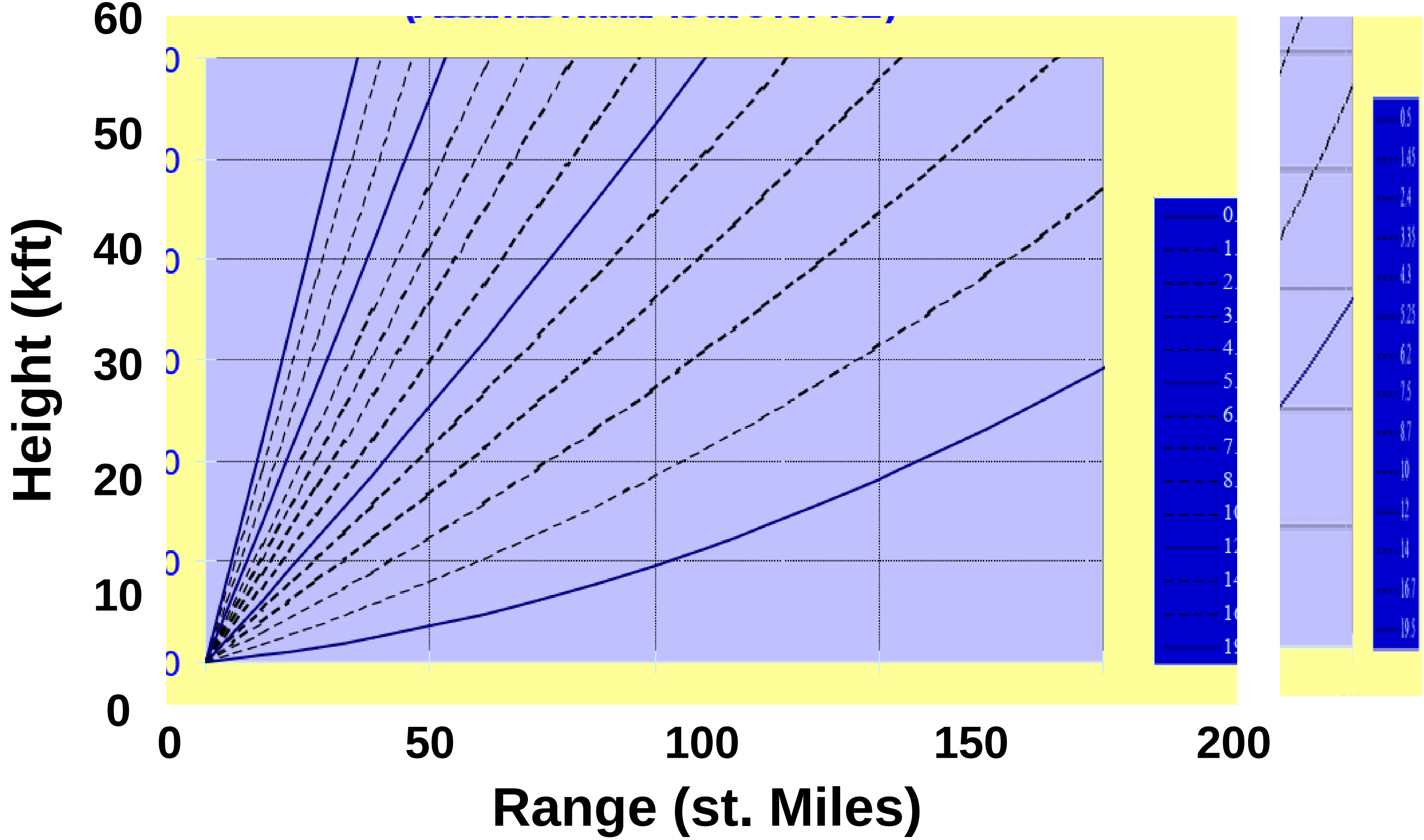

Straight-line Optics
Standard-refraction
conditions
Super Refraction
R
4/3 R



Straight-line Optics
Standard-refraction conditions
Super Refraction
R
4/3 R

Height of Radar Beam as Function of Distance

NEXRAD Tilt Sequence (Assumes 0 ft MSL Radar)



Meteorological Targets

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

Wet Hail

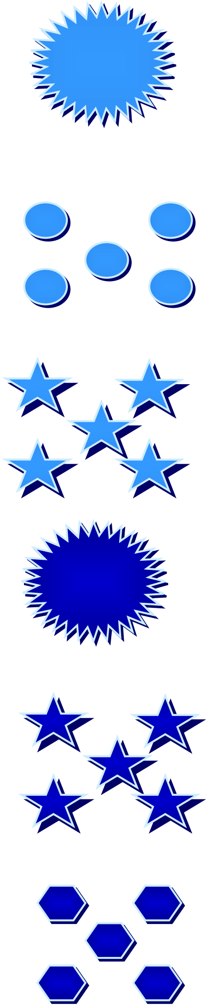
Rain

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

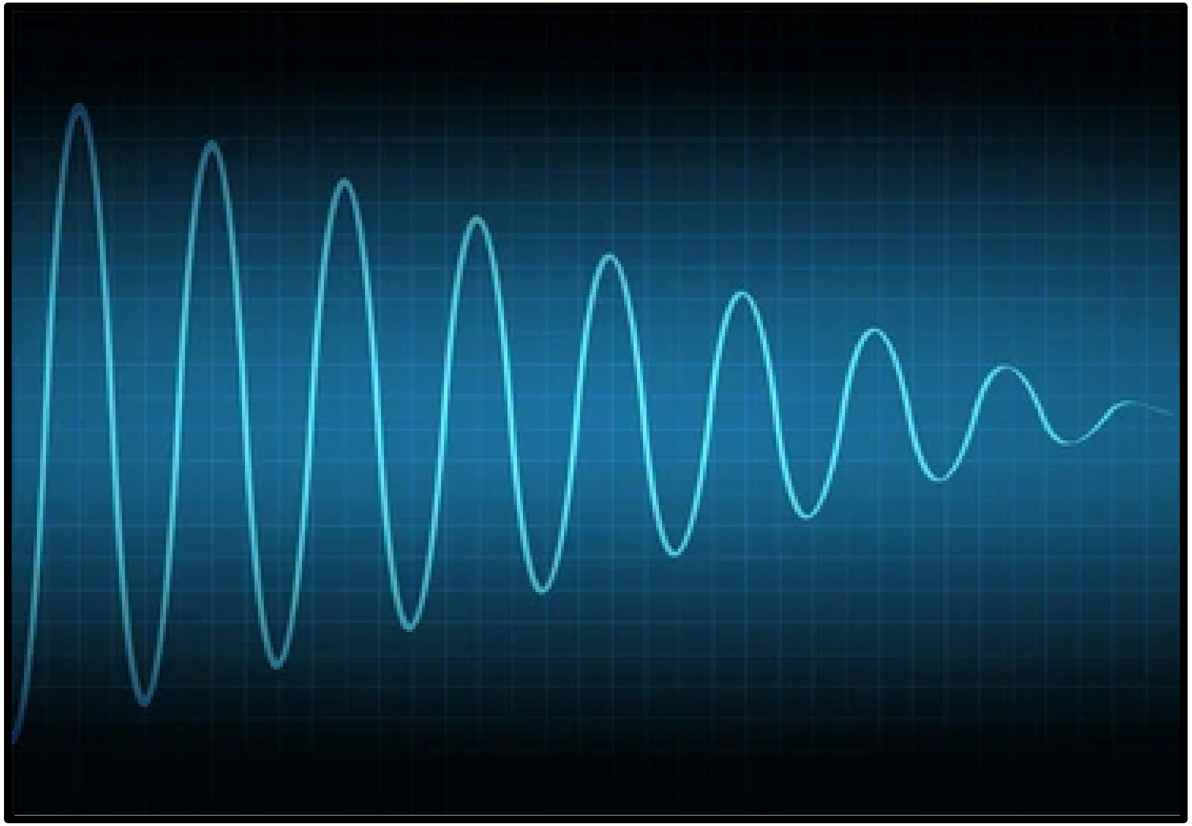
- DVIP: Digital Video Integrator Processor
  - Use Marshall-Palmer (MP) relationship of $Z = 200 R^{1.6}$

DVIP Level	Rainfall Rate	Reflectivity
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

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

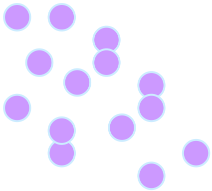
Attenuation of Transmitted Signal (Energy)

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

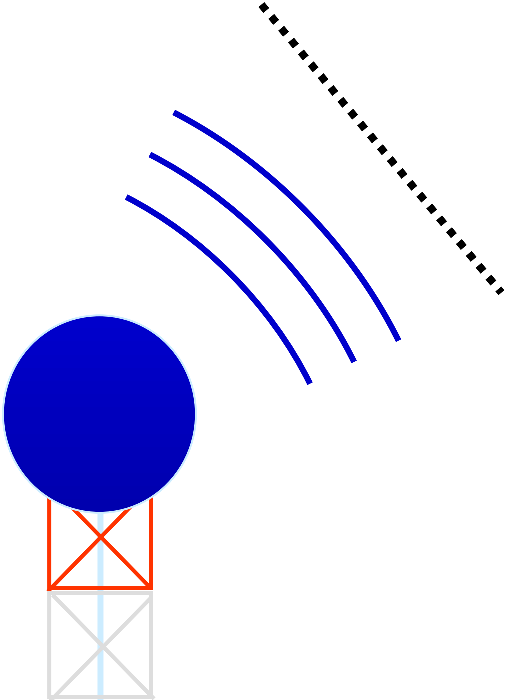


Atmospheric Attenuation

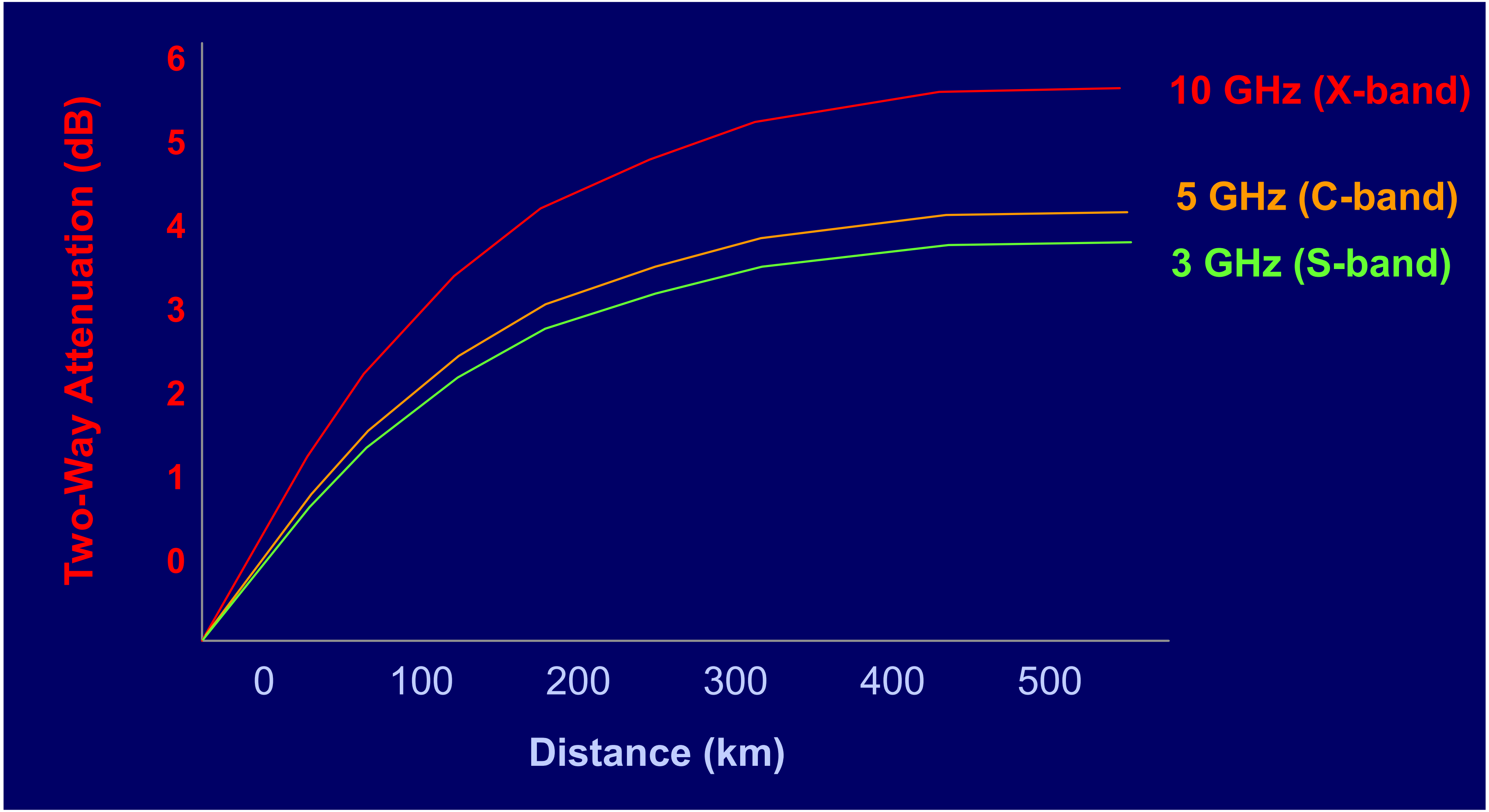
- Some gases cause no attenuation.
- Nitrogen, carbon dioxide, and those in very small concentrations



- 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.

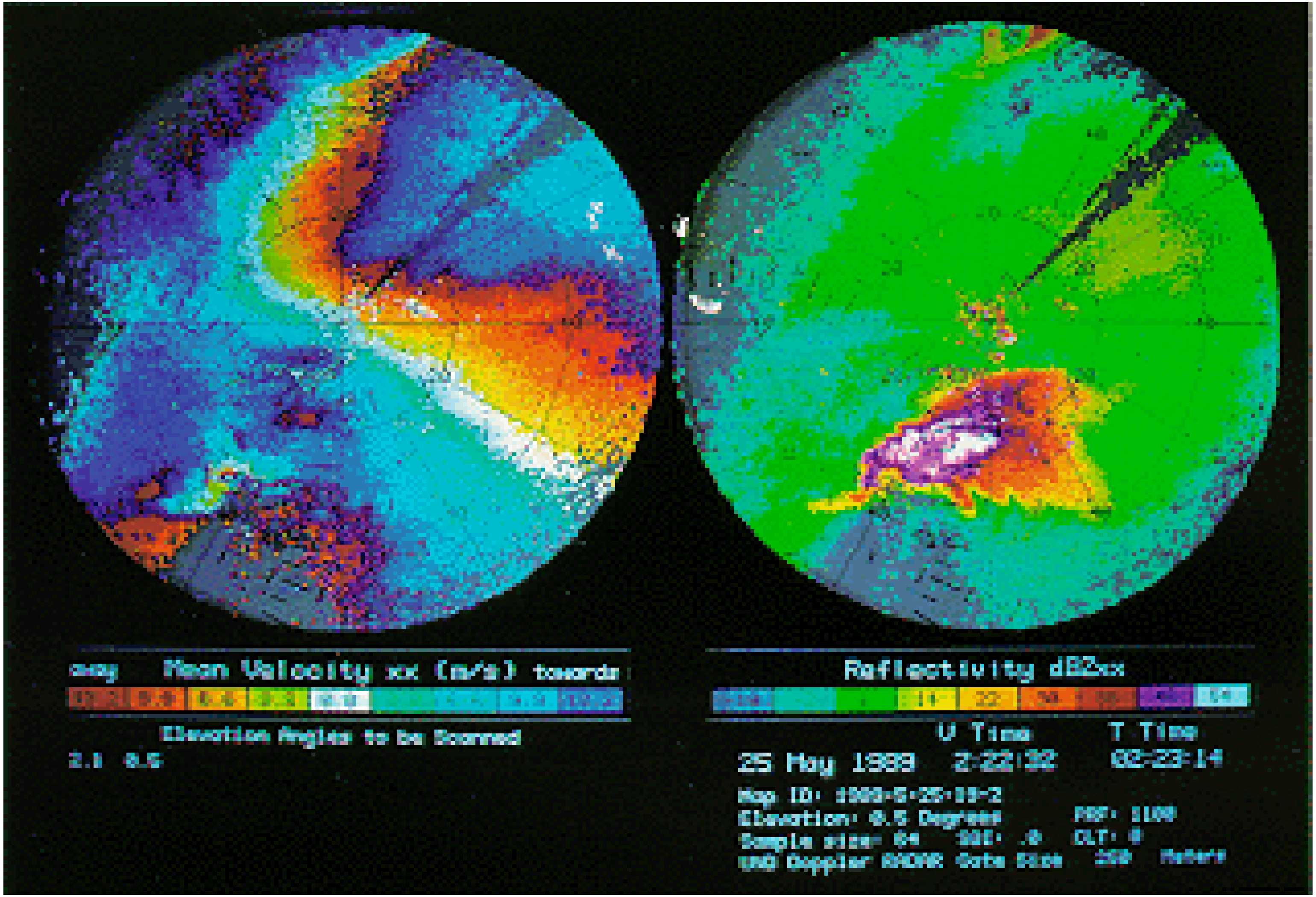
Hail Attenuation

- 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

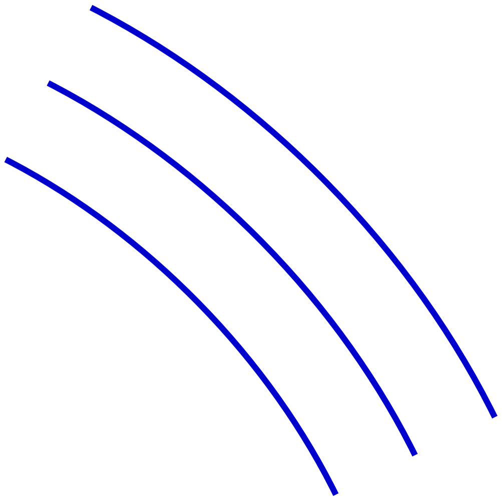
- Attenuation shadows sometimes indicate the presence of attenuation.
- Airborne radars frequently have attenuation.
  - Since most are X- or occasionally C-band radars, attenuation shadows are common on aircraft radars.

Example of Attenuation Shadow

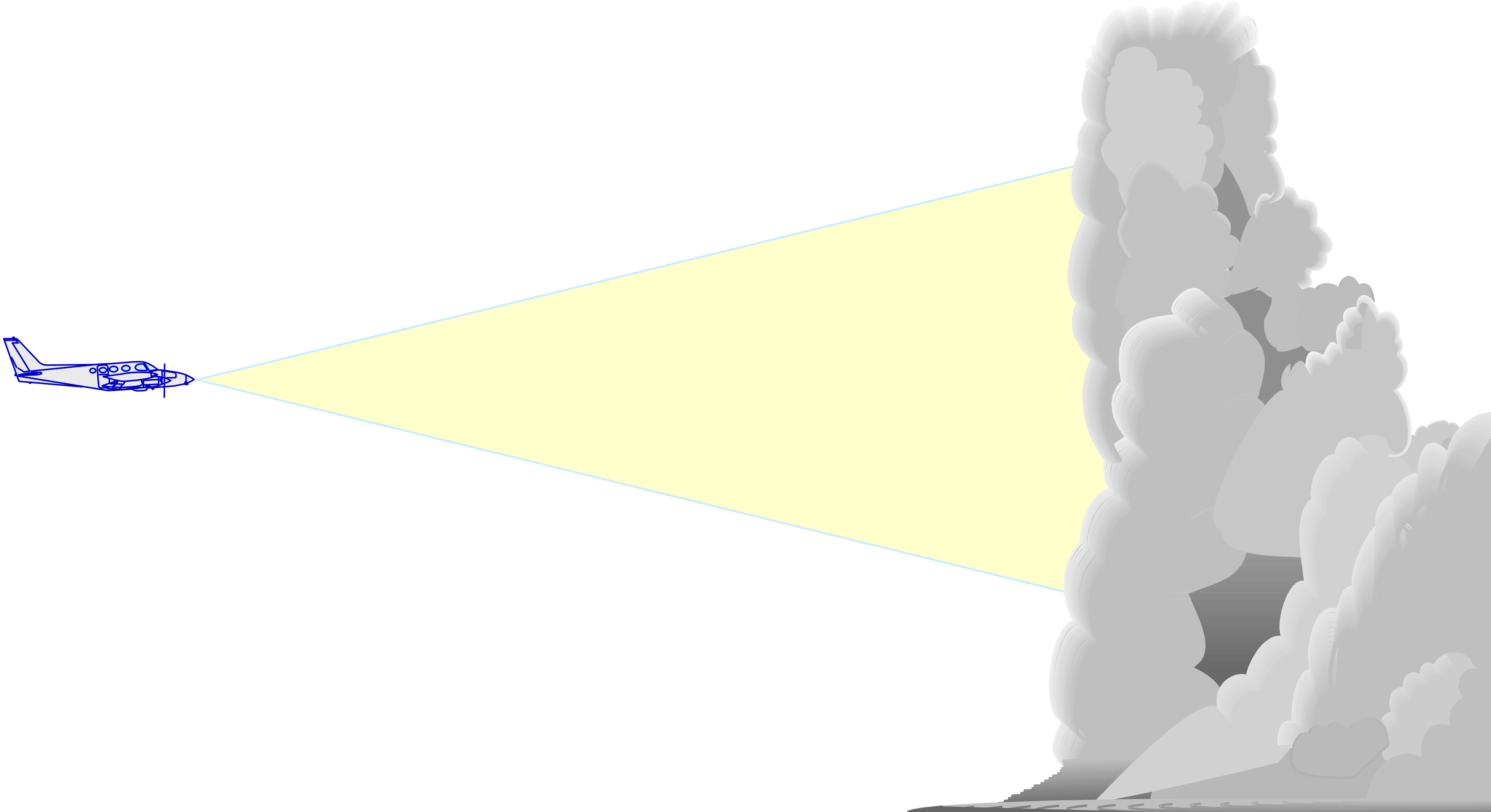


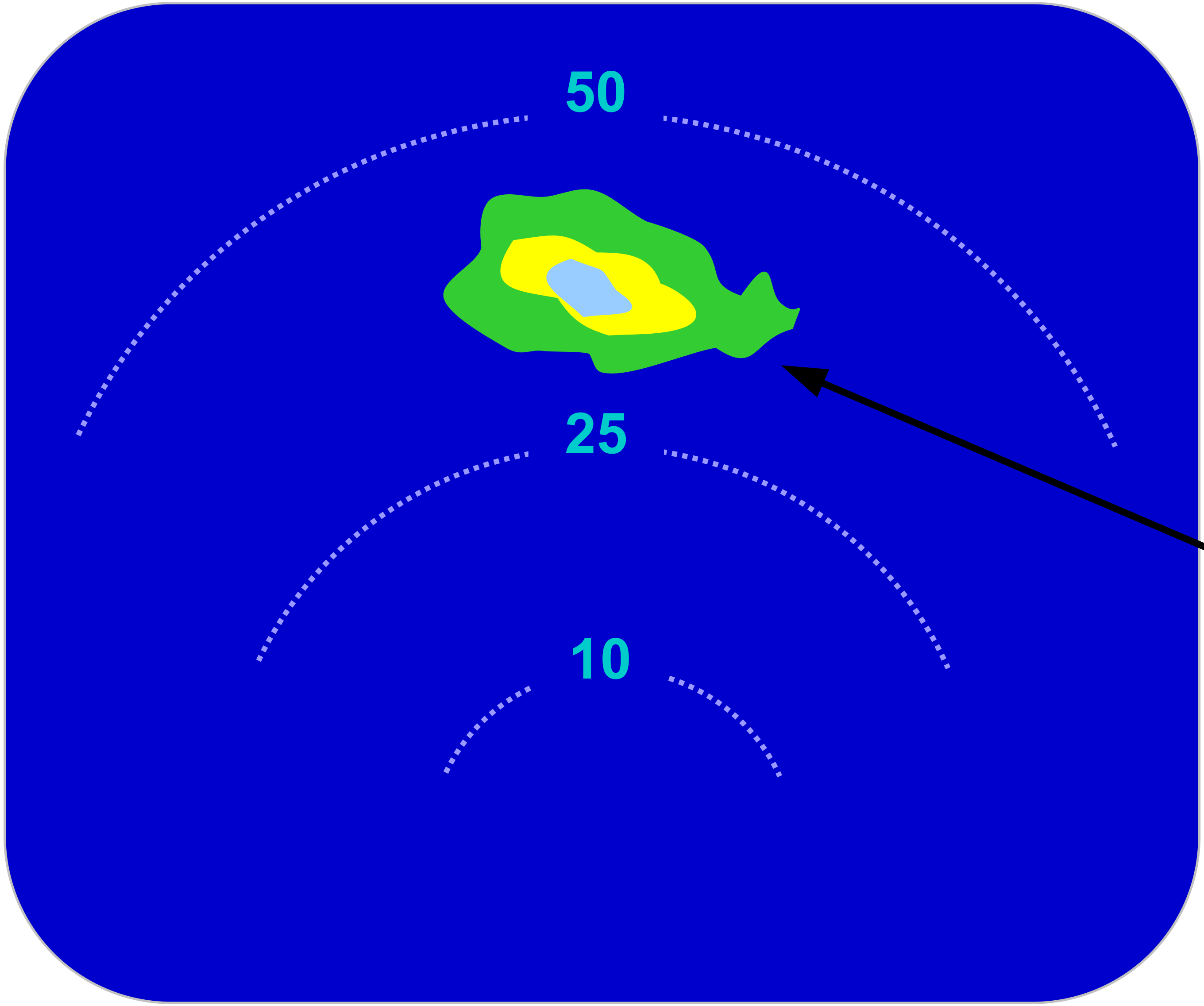
Beam Characteristics

- 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

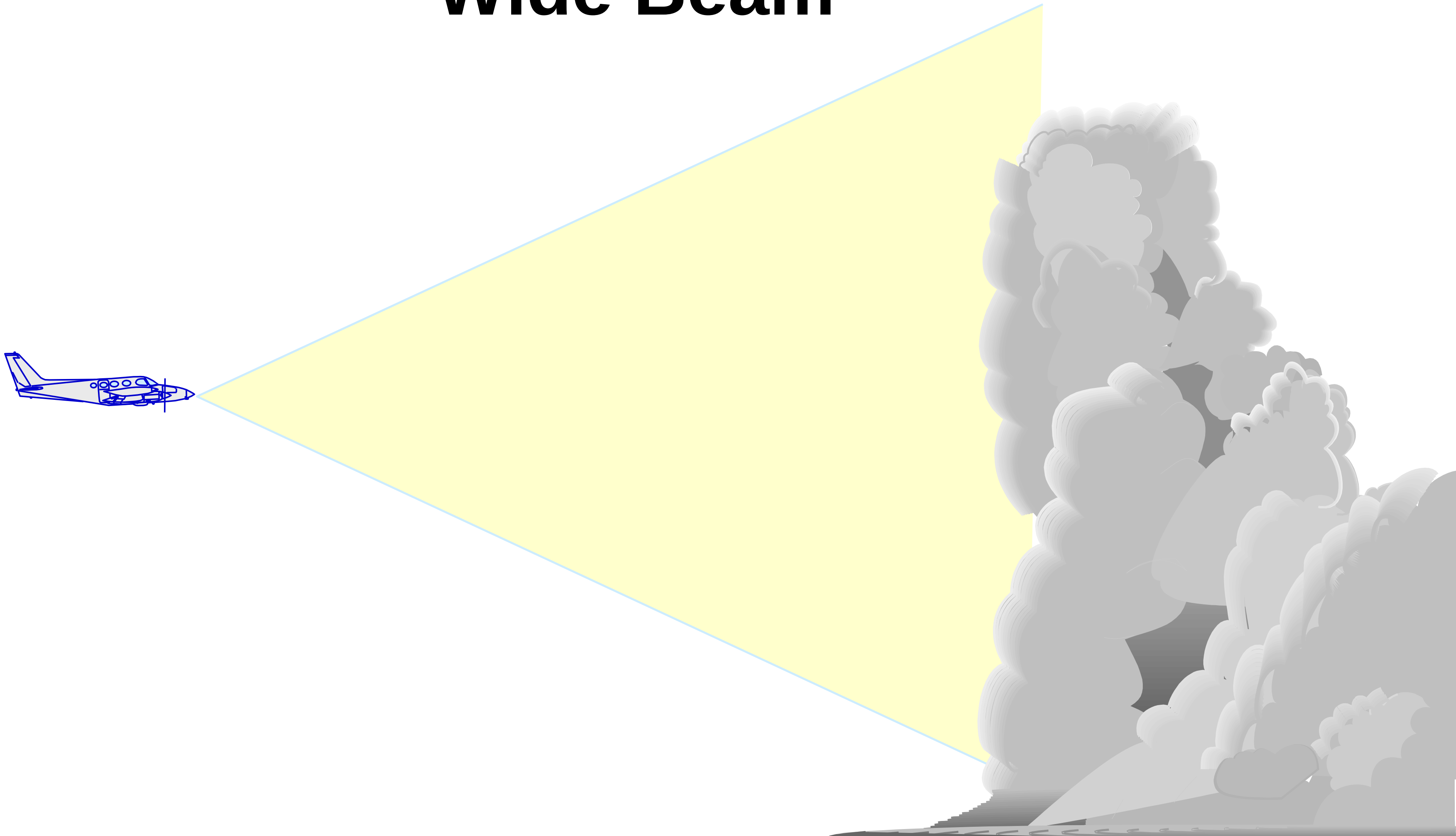
→

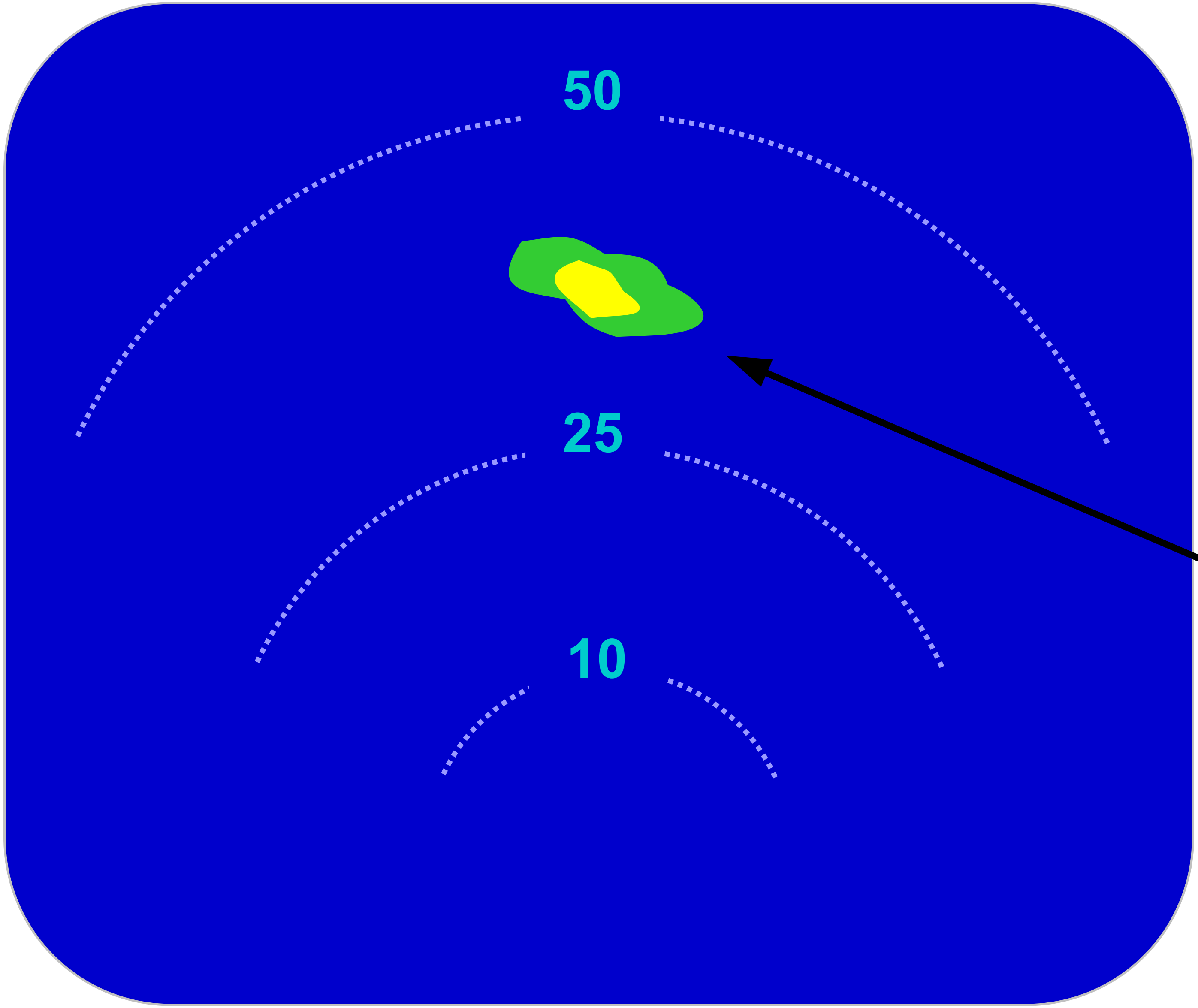
Fill Beam

→

Strong

Wide Beam





Wide Beam

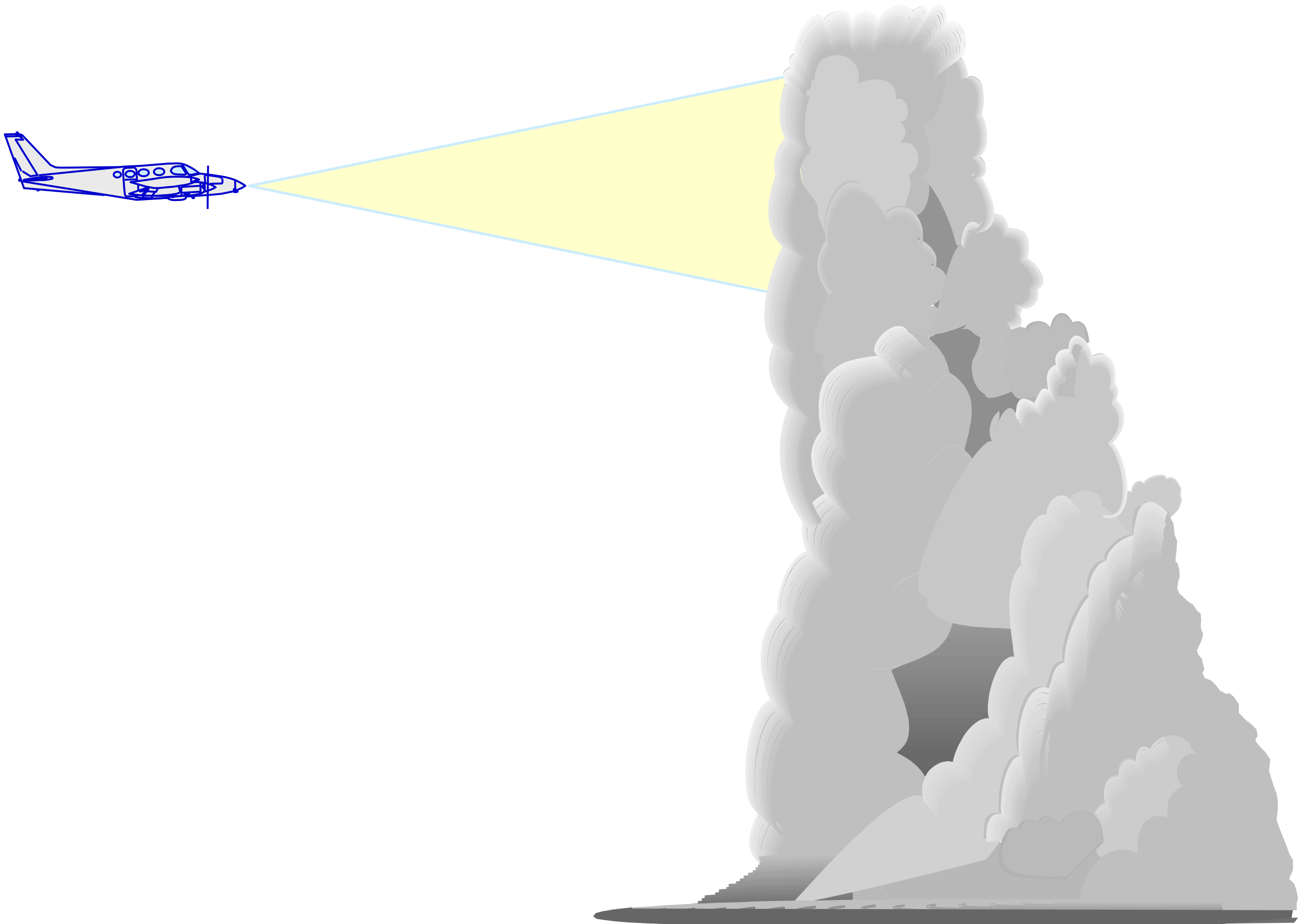
→

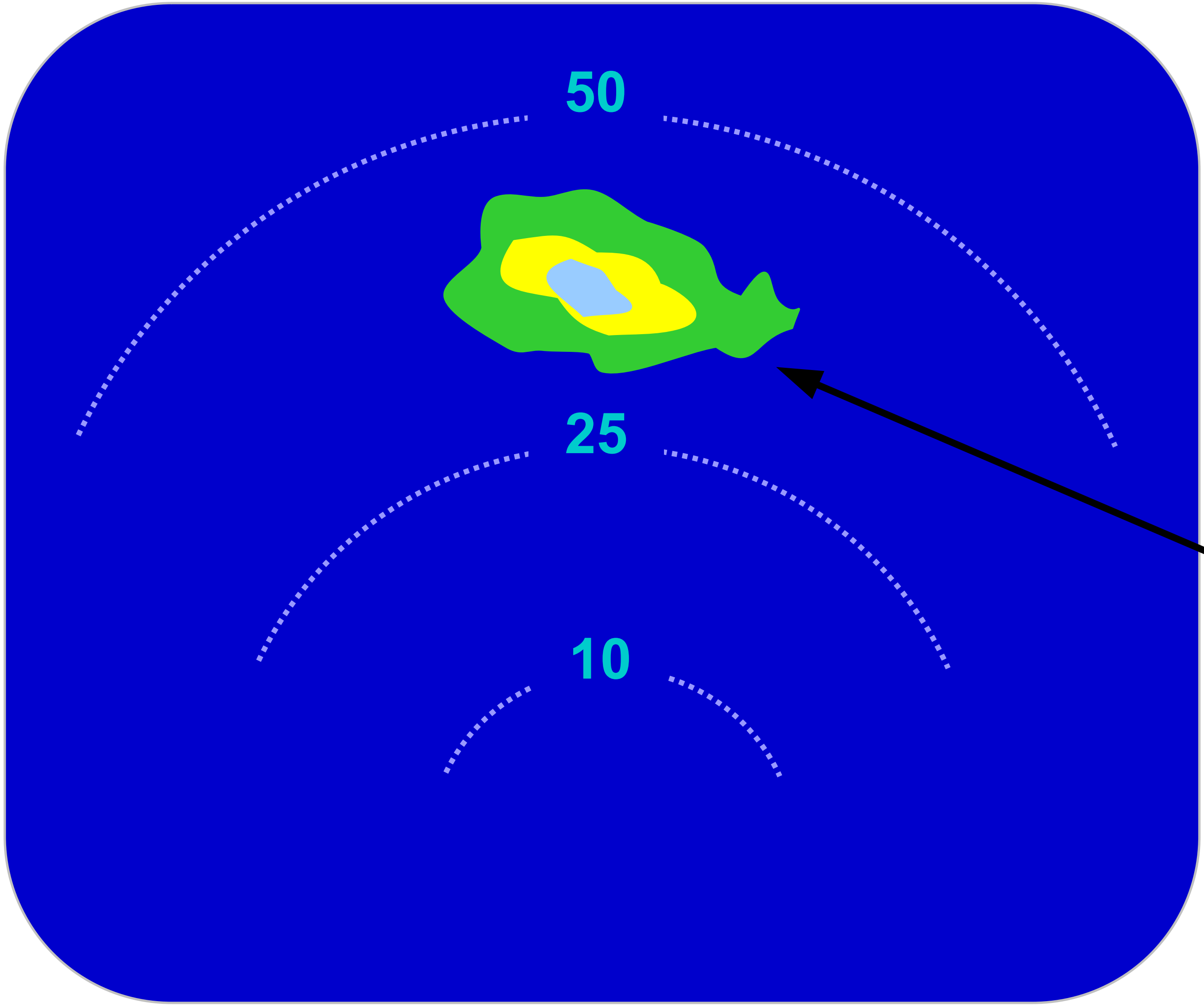
Not Filled Beam

→

Weaker

Short Range





Short Range

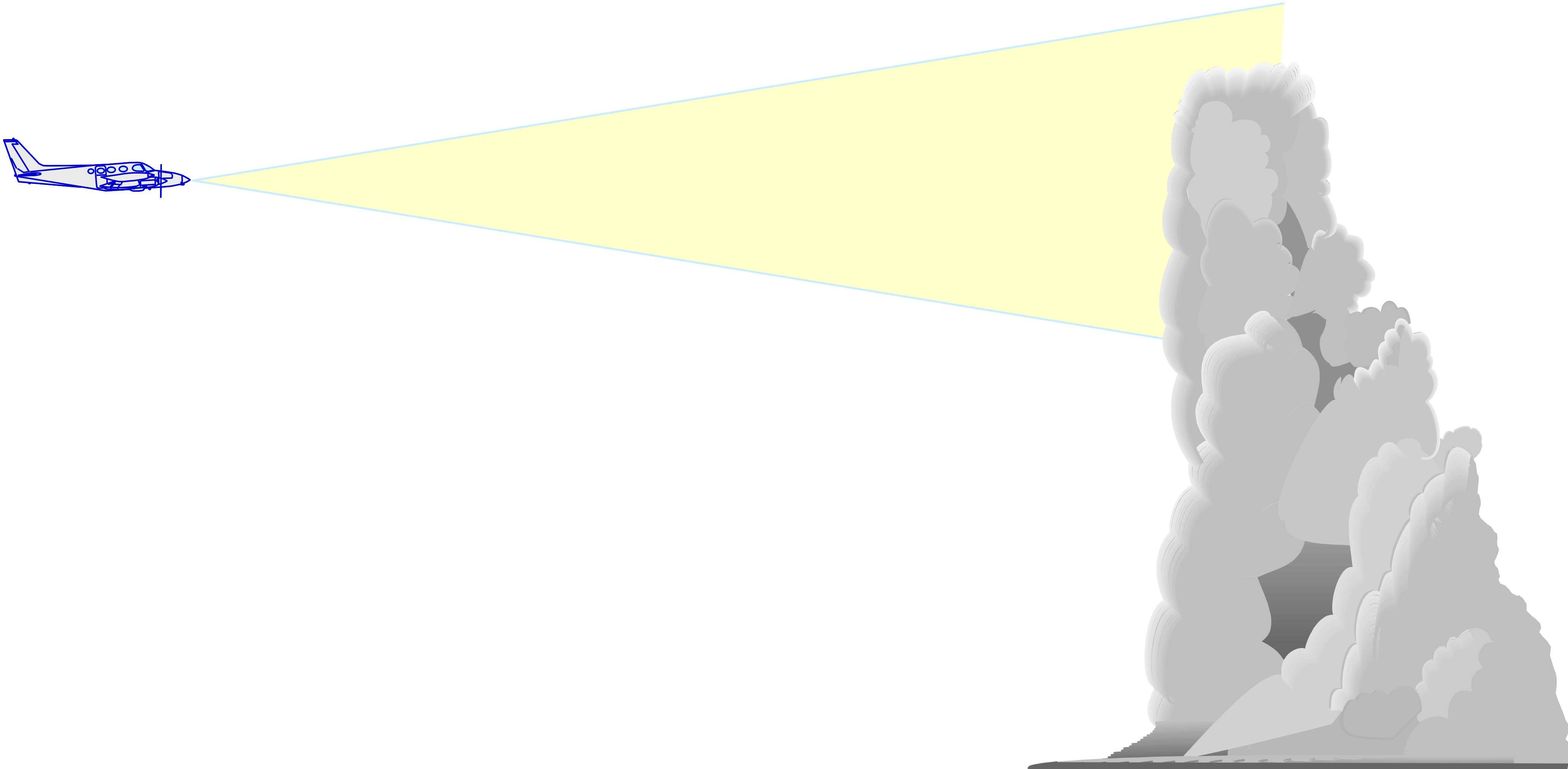
→

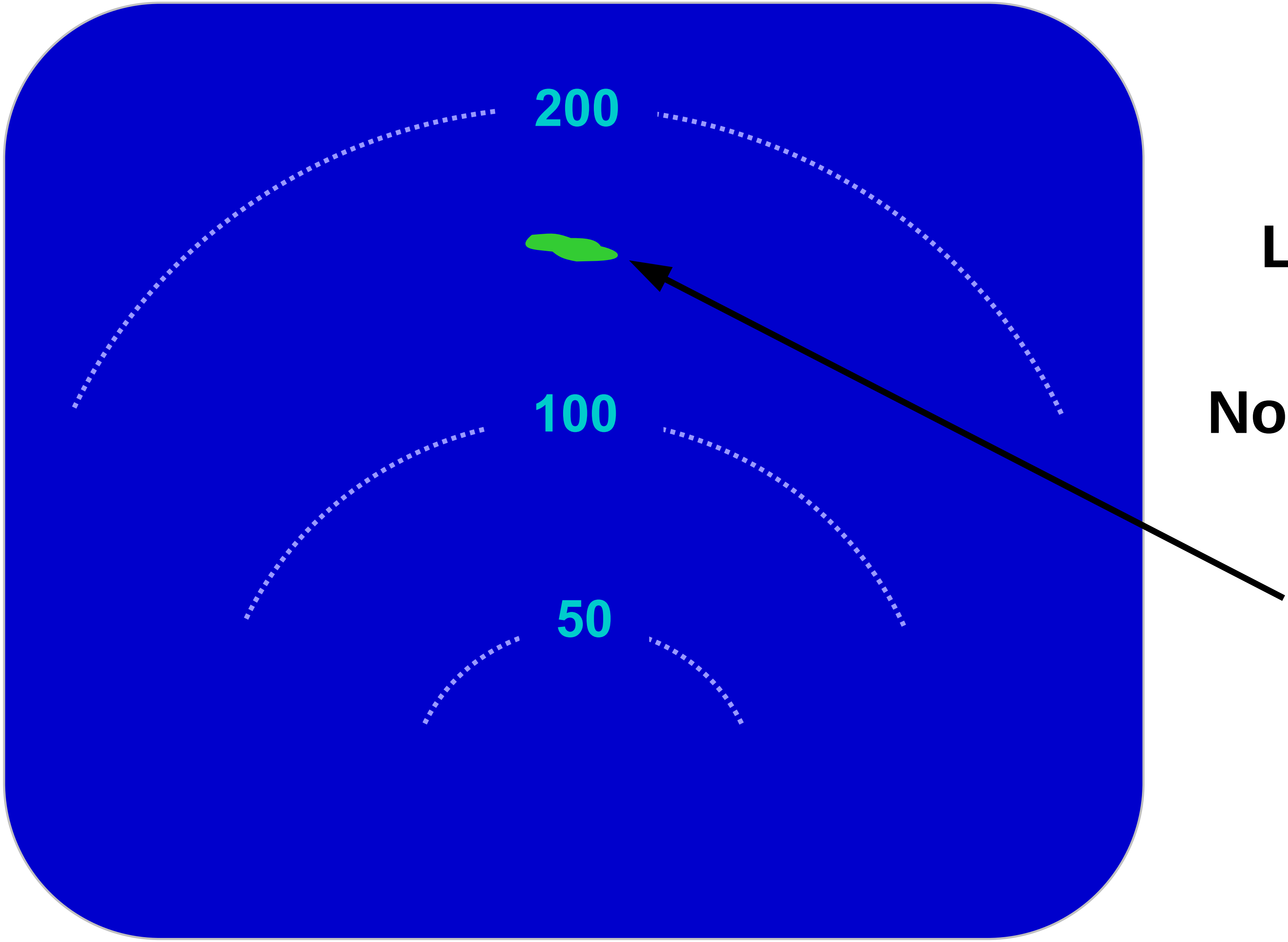
Fill Beam

→

Strong

Long Range





Long Range

→

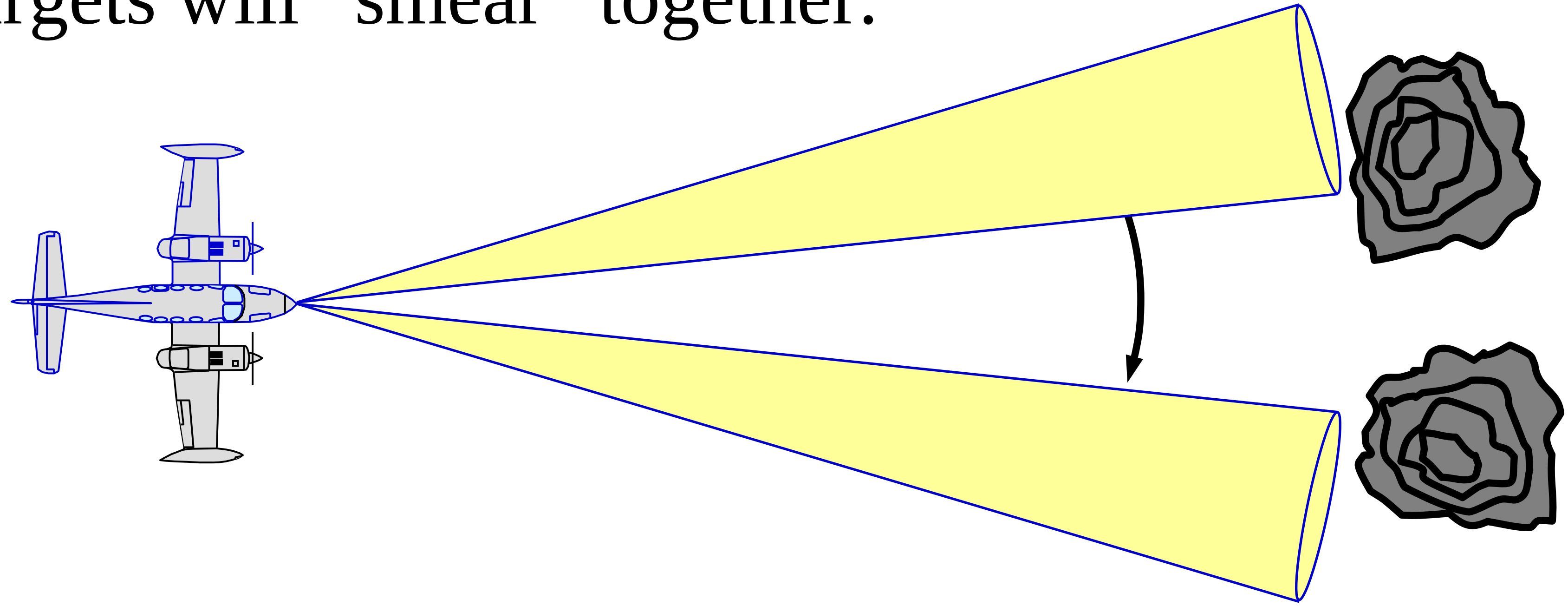
Not Filled Beam

→

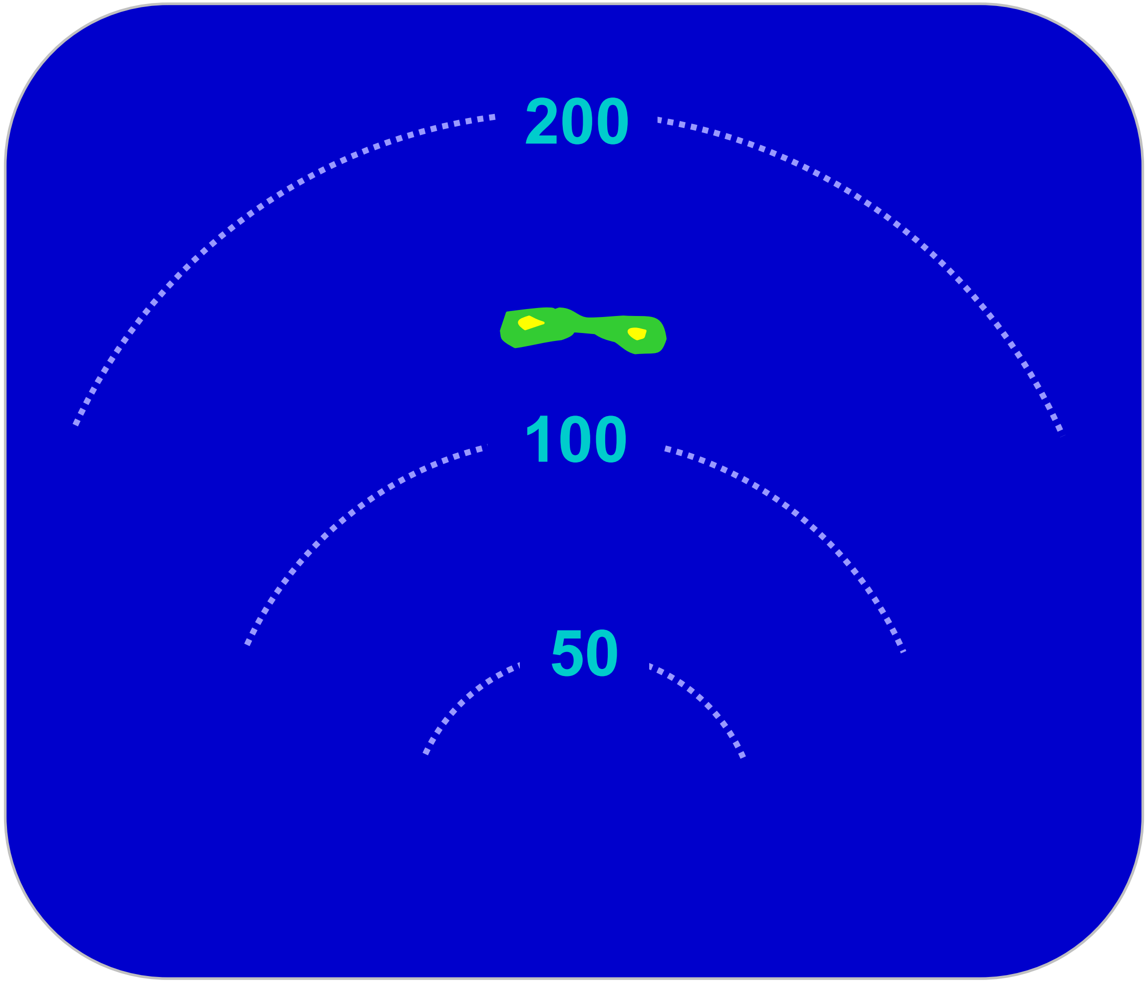
Weaker

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.

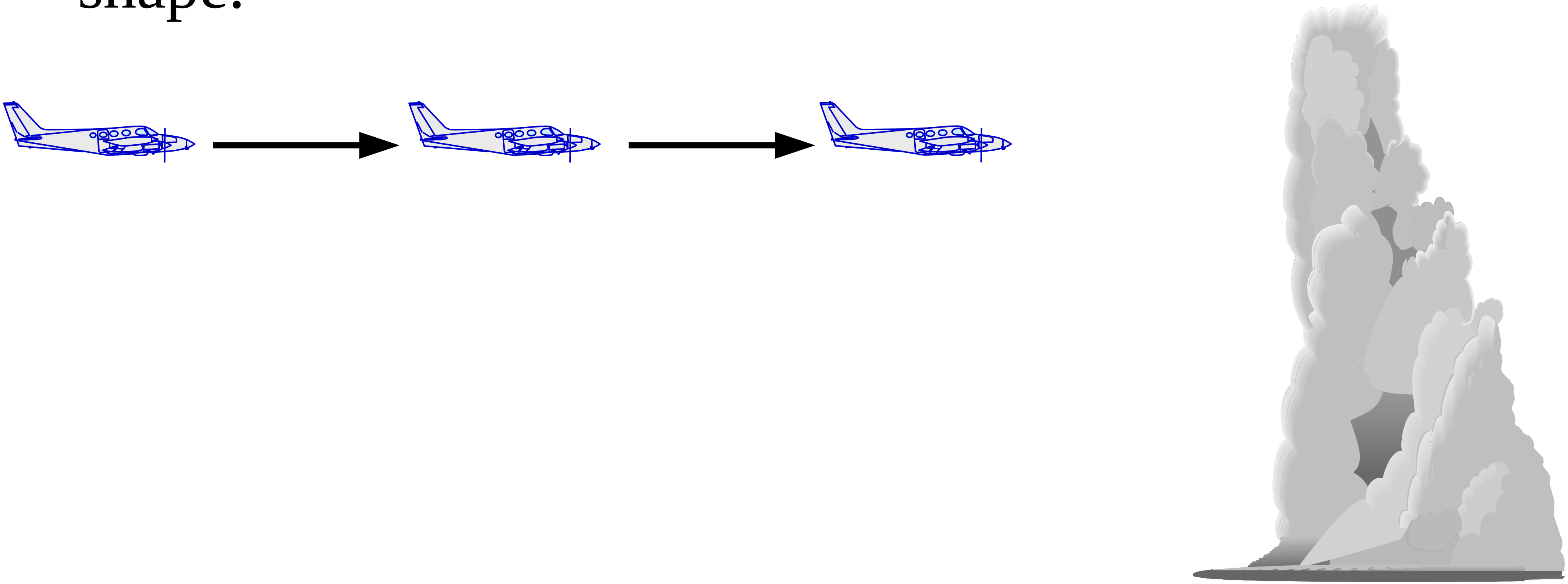


Beam Width Smearing Results (Far Away)

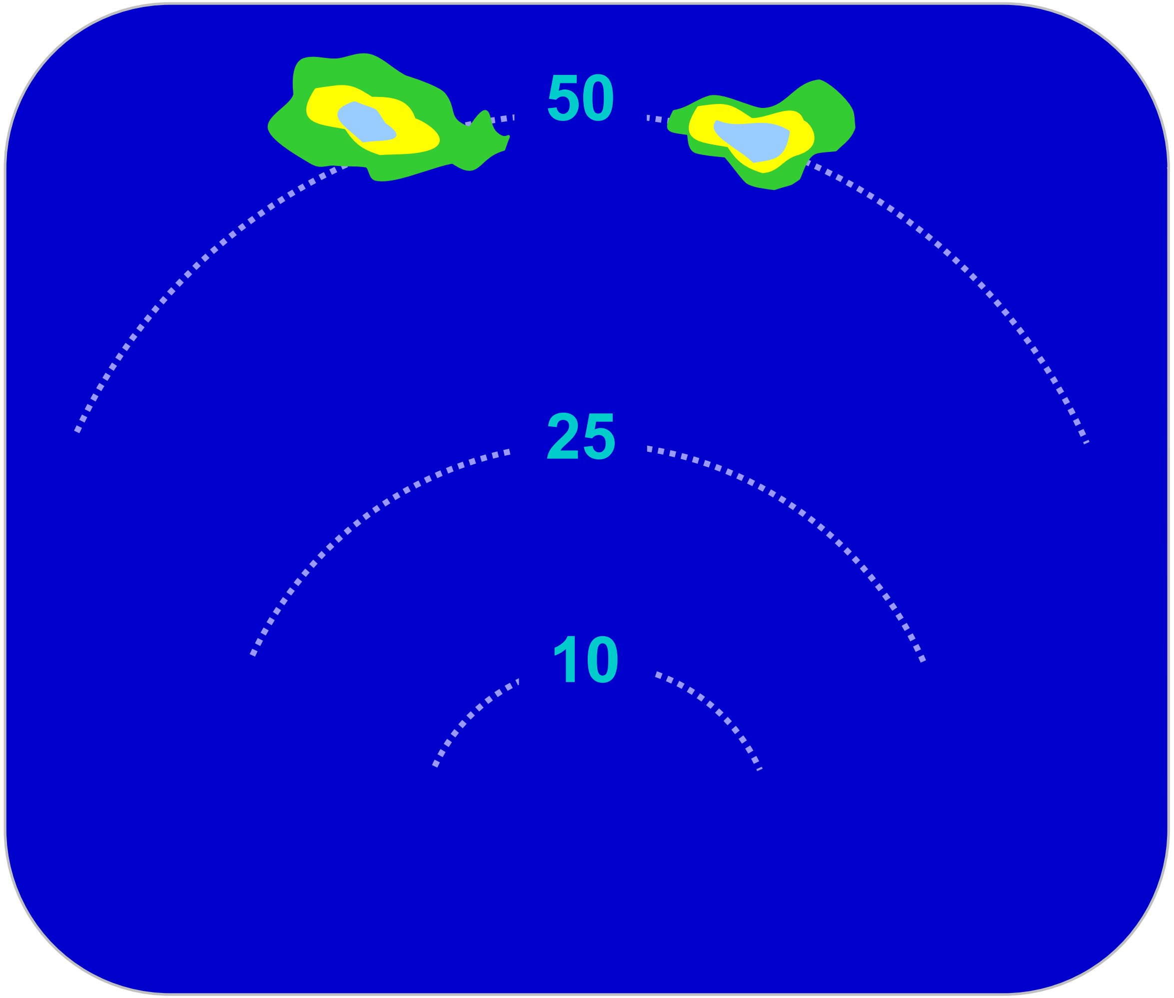


Beam Width Smearing

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



Beam Width Smearing Results (Closer)



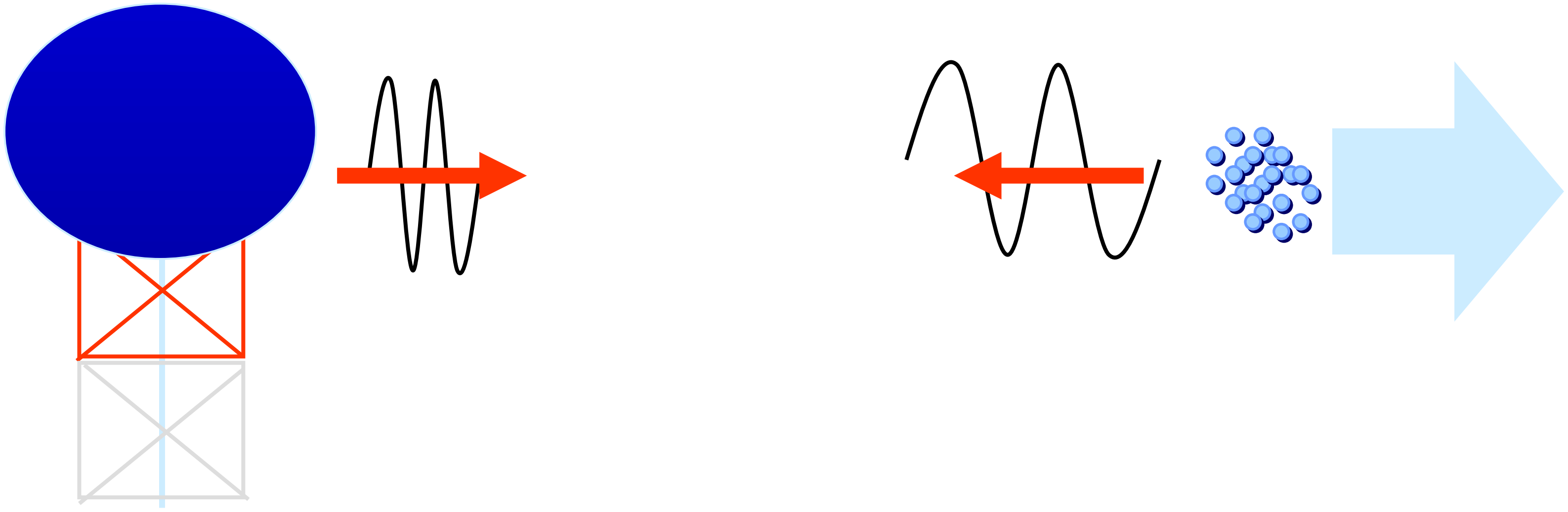
Doppler (or Coherent) Radar

- Able to determine the frequency shift of the transmitted wave.

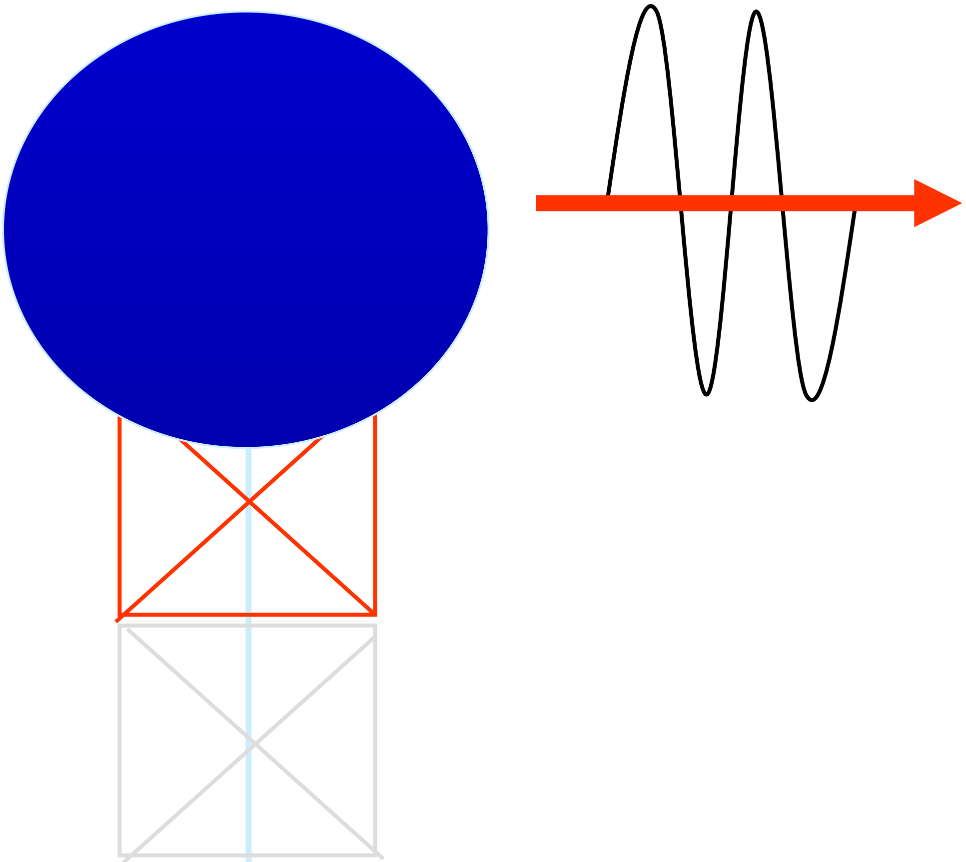
- How does Doppler Radar Works?

Spectrum Width

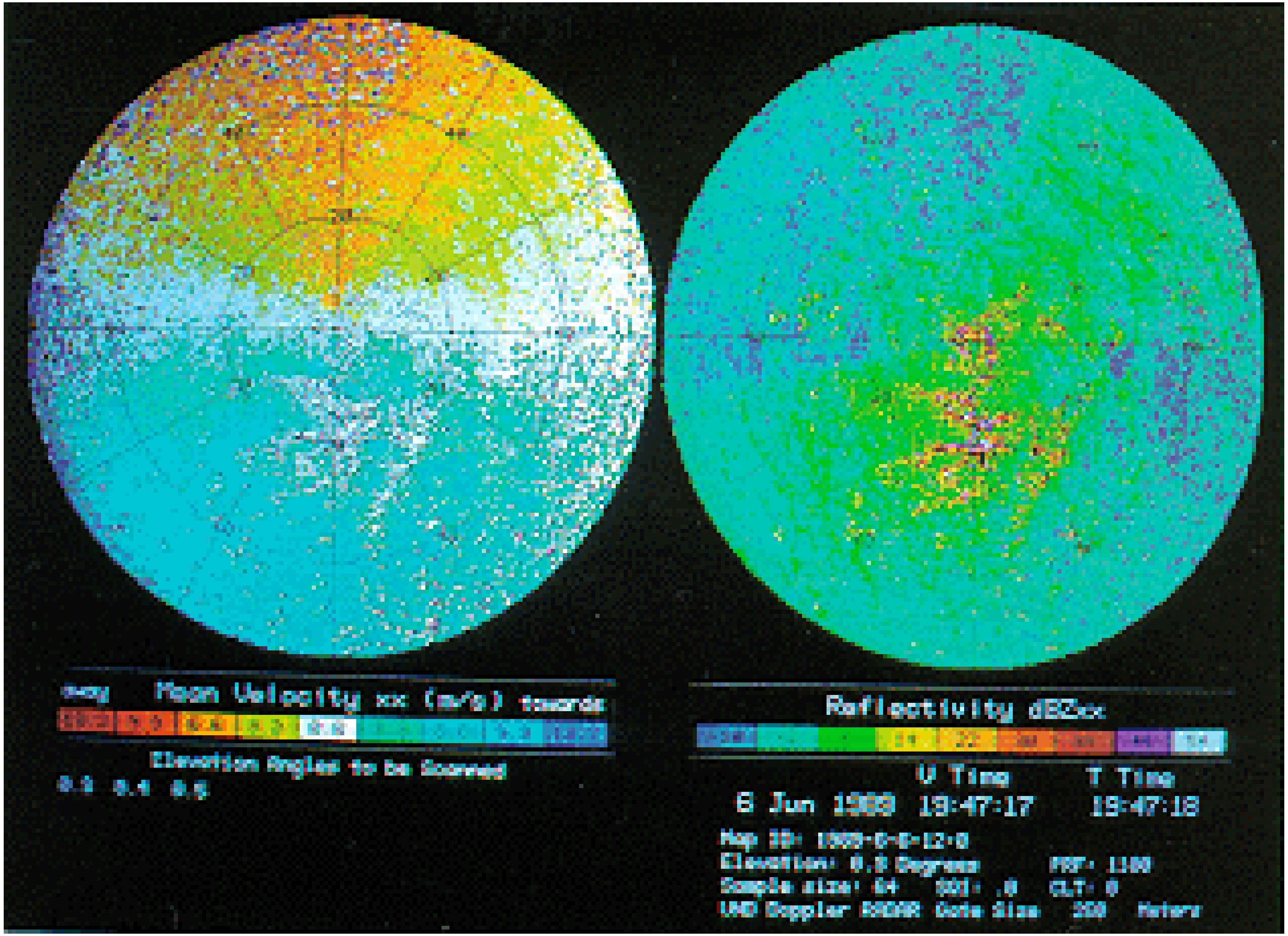
- Due to motion of targets
- Actually measures frequency distribution called spectrum width



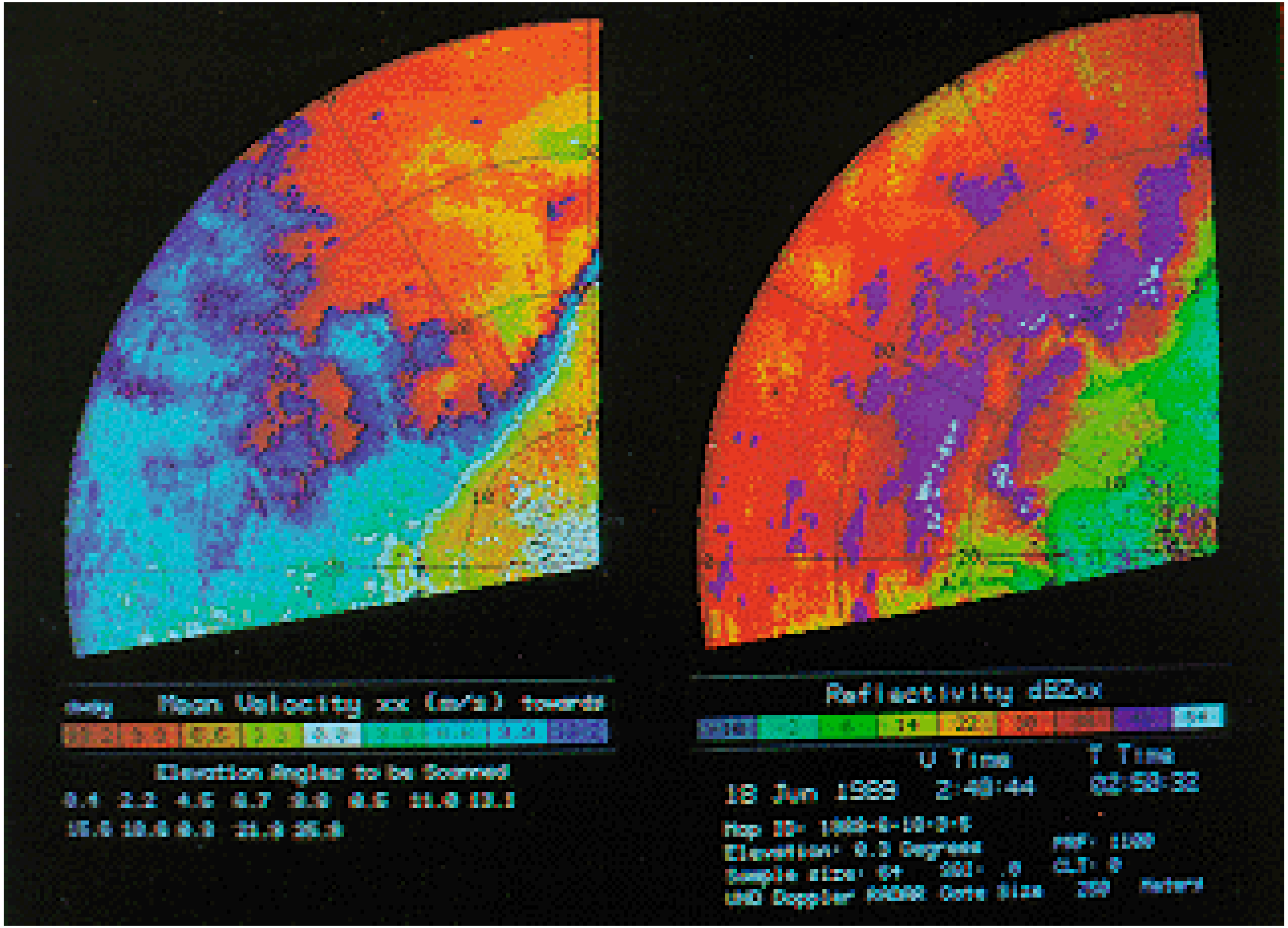
Radar Echoes
Examples from Various Sources



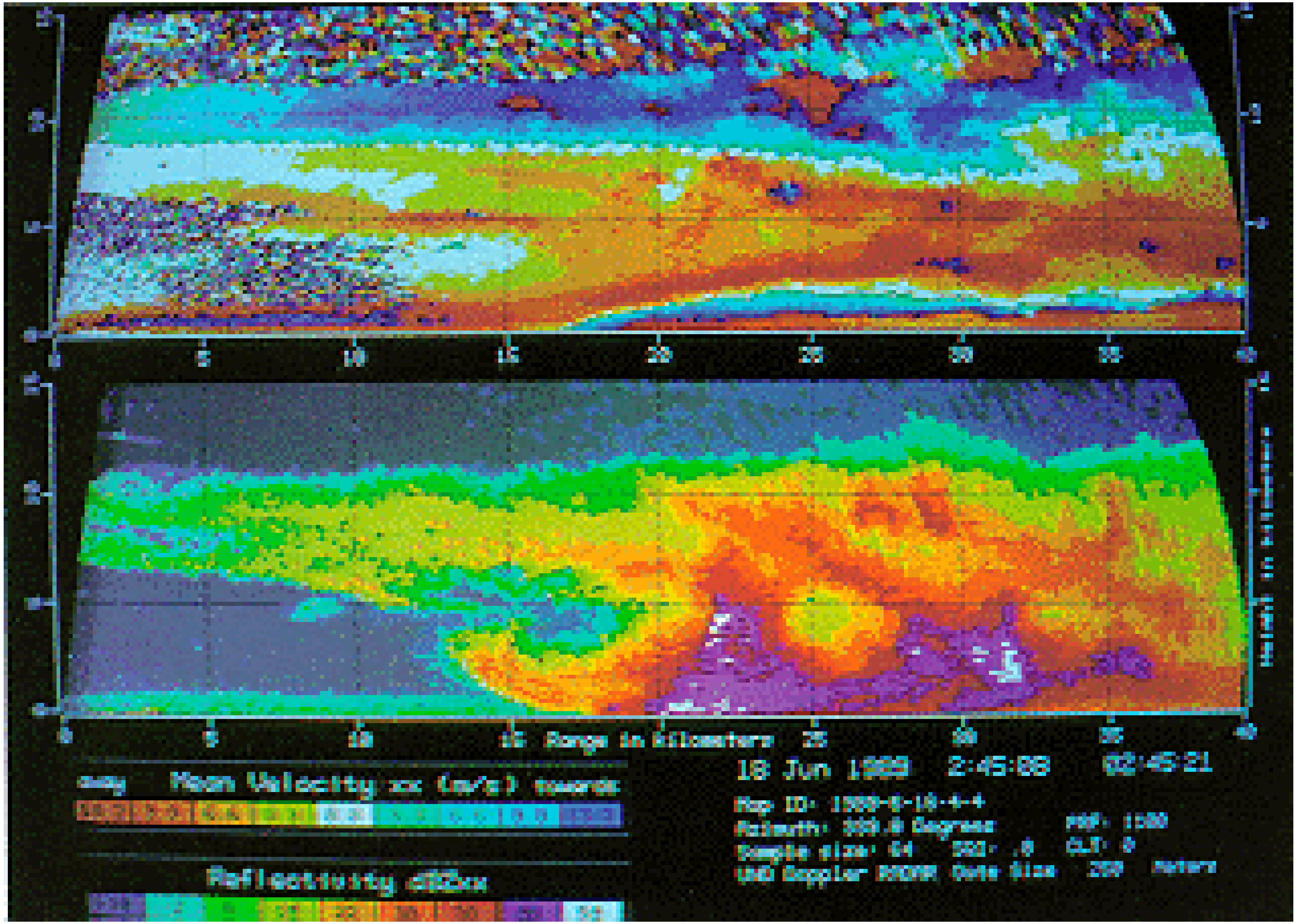
Environmental Winds



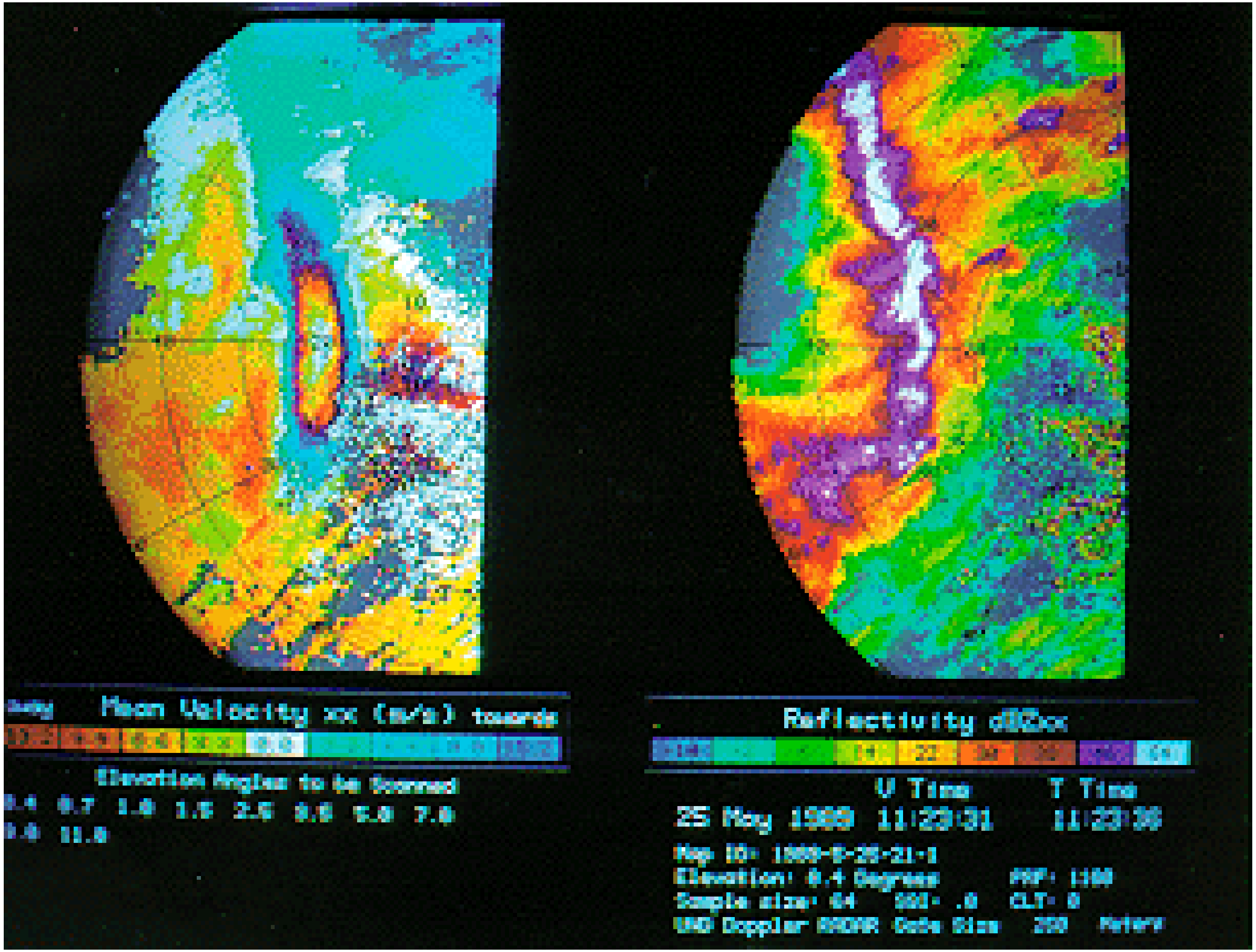
Gust Fronts – Best in Velocity Observation



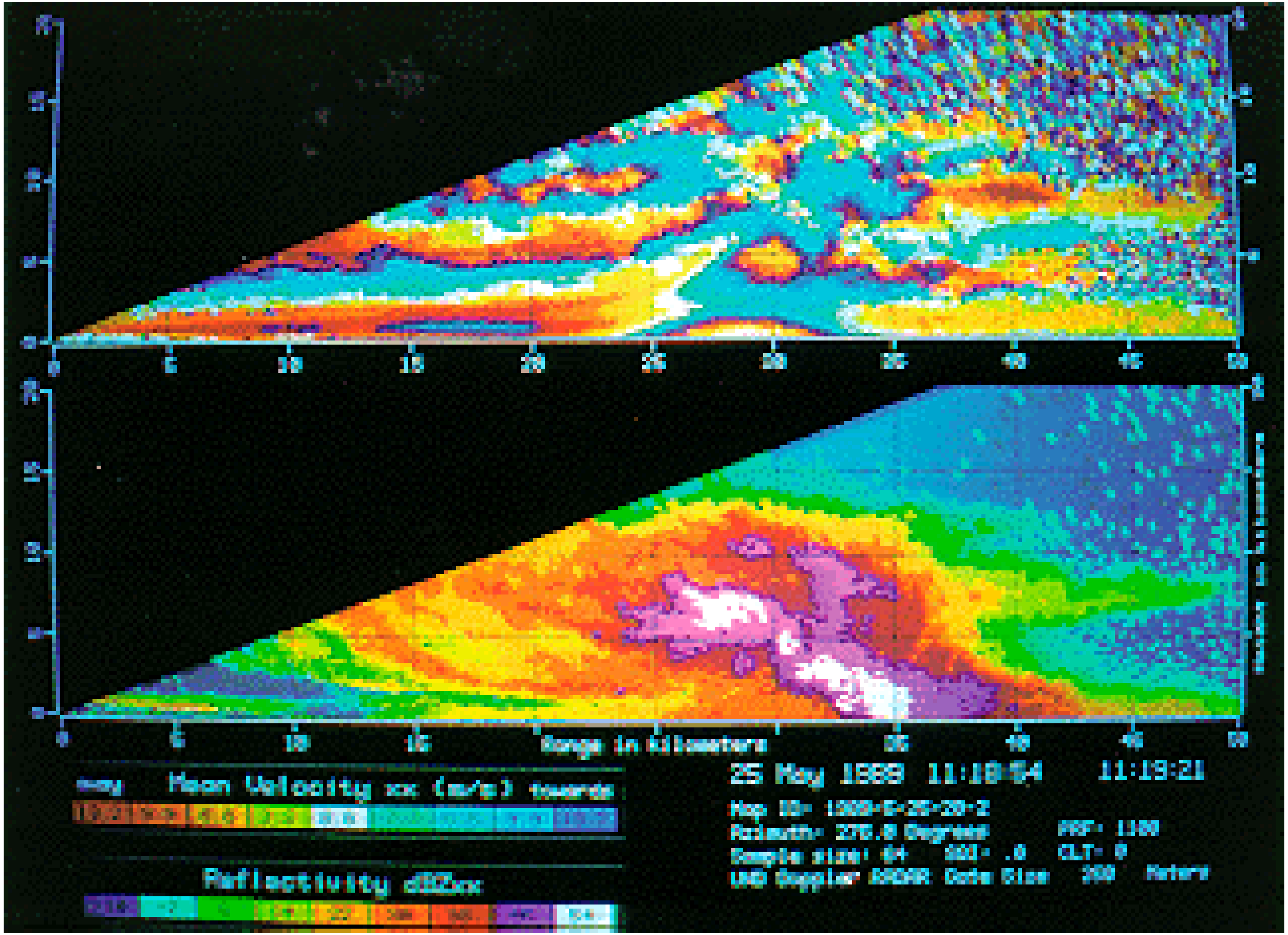
Gust Fronts – RH View



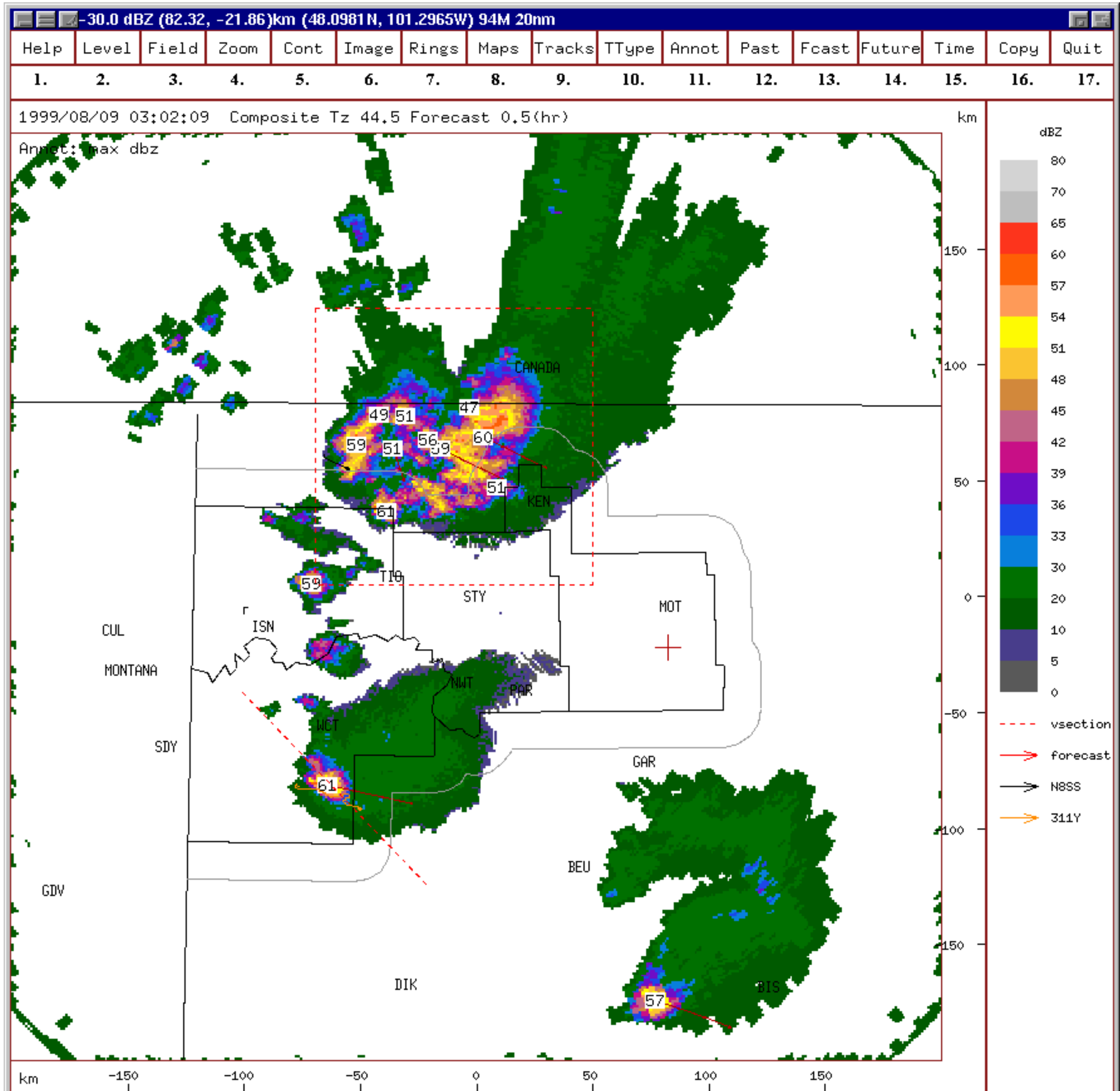
Straight-line Winds … a Bow Echo



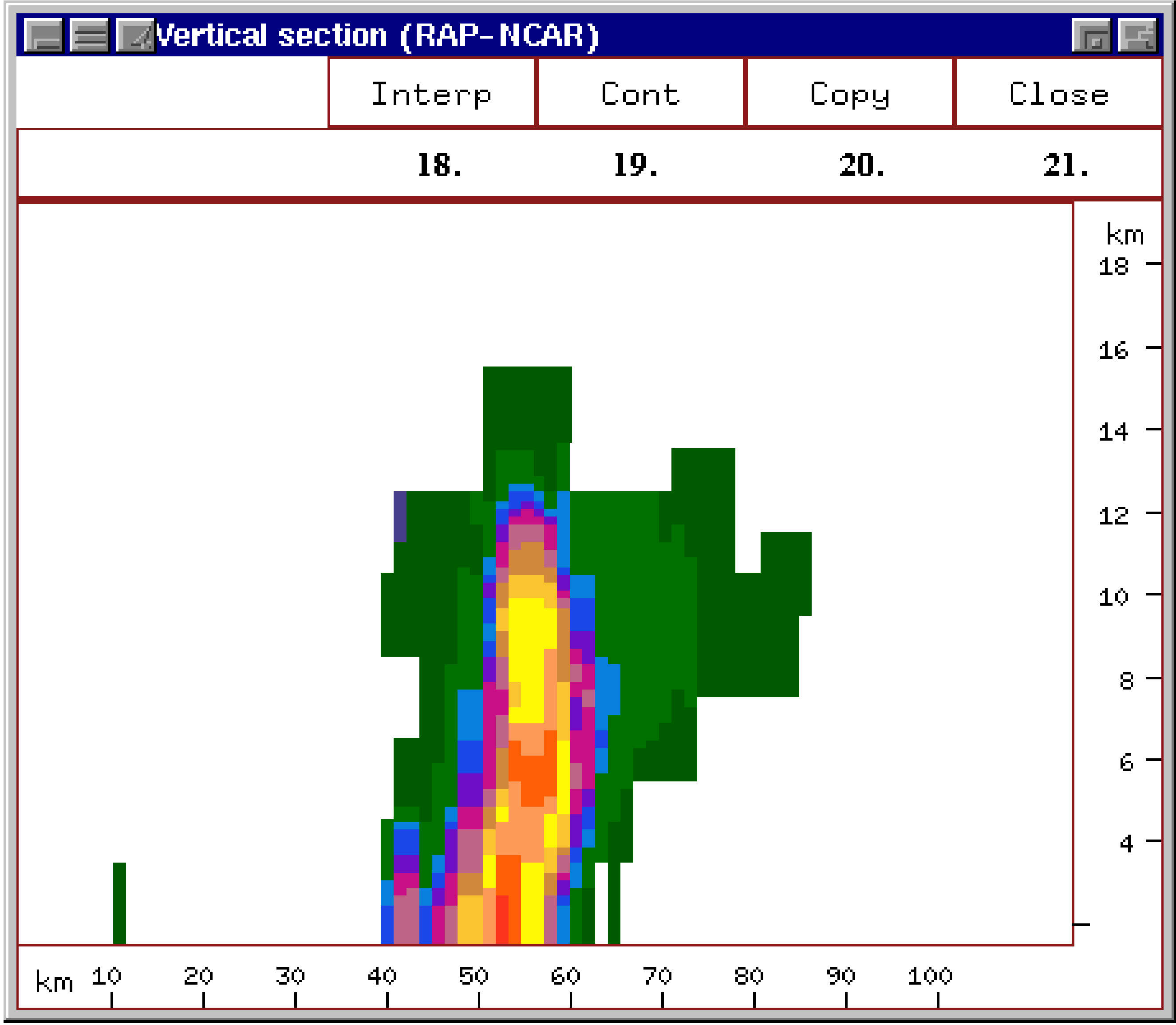
Bow Echo – RHI View



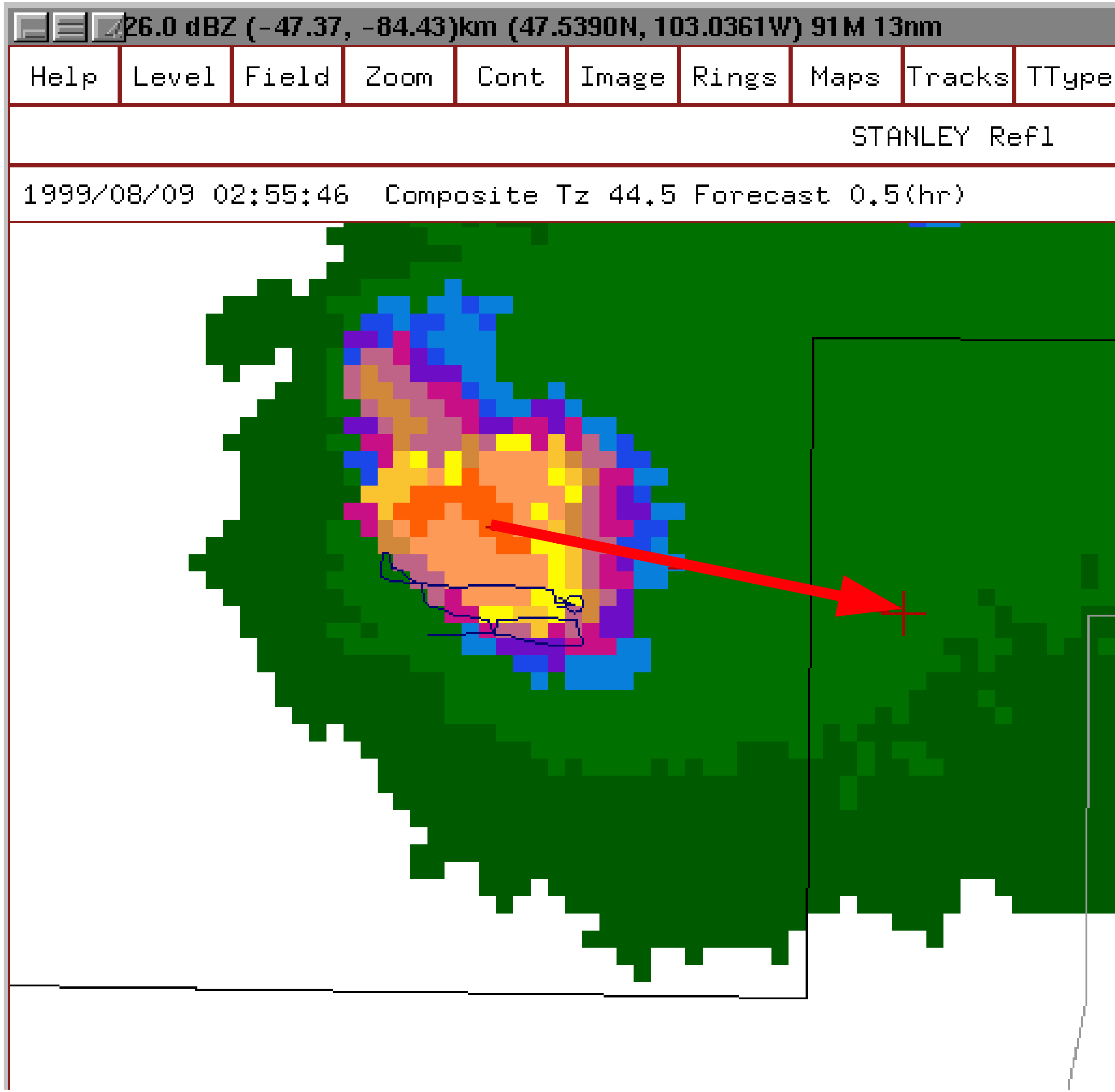
TITAN-LROSE Displays - Plan Position Indicator (PPI)



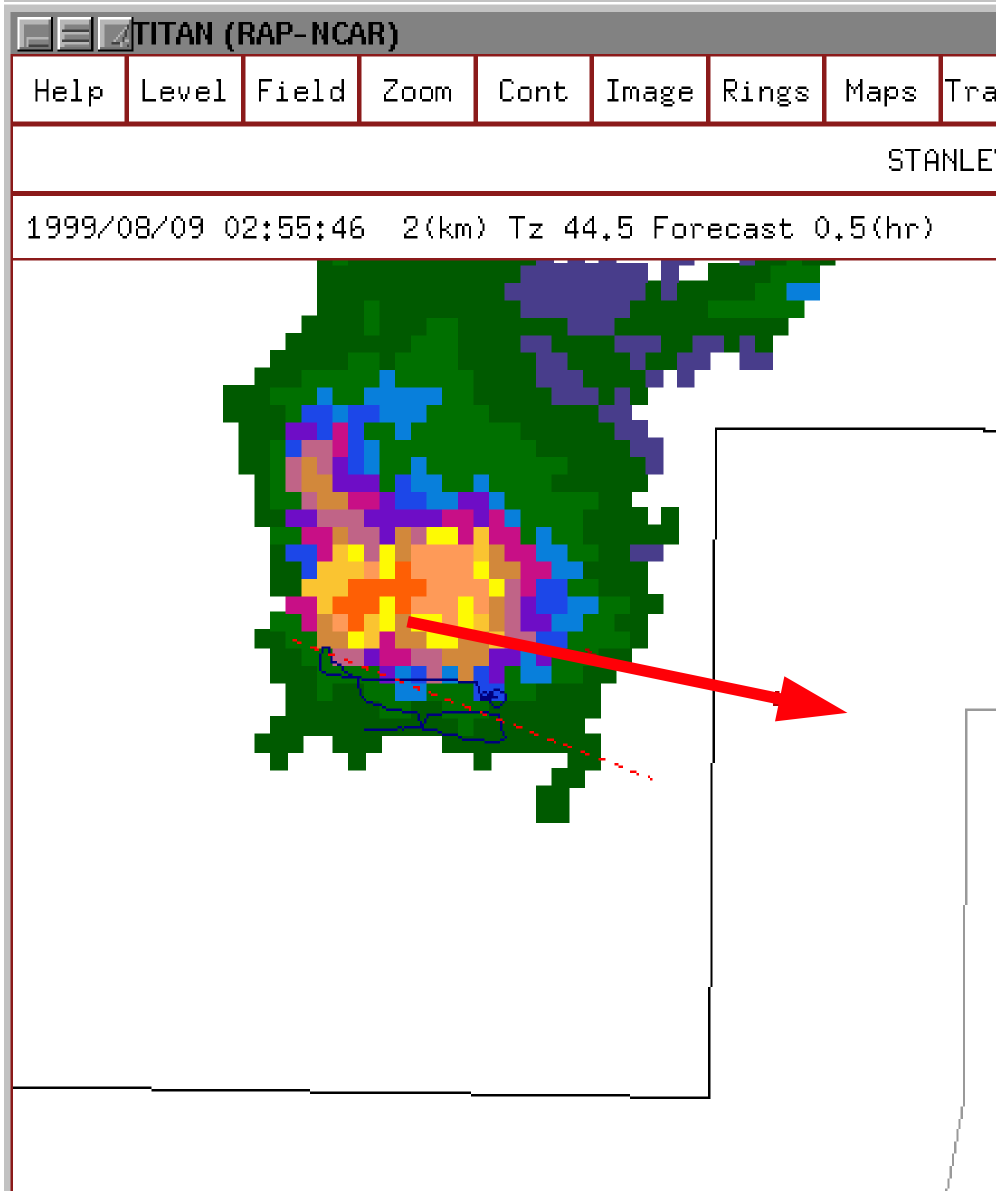
TITAN-LROSE Displays – Range Height Indicator (RHI)



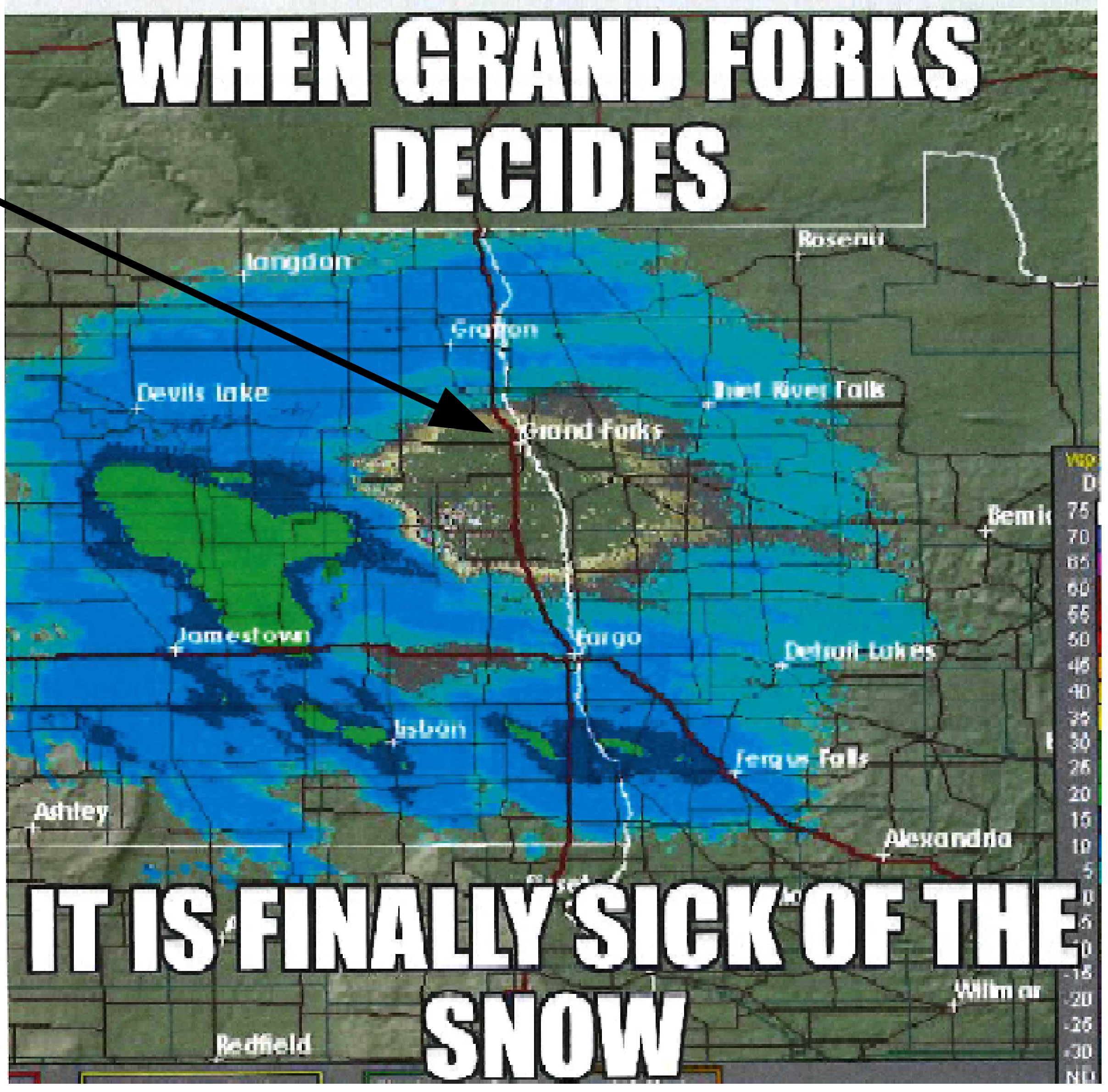
TITAN-LROSE Displays Composite Forecast



TITAN-LROSE Displays Constant Altitude Plan Position Indicator (CAPPI) Forecast



Donut Hole


WHEN GRAND FORKS DECIDES
IT IS FINALLY SICK OF THE SNOW
Langdon
Grafton
Devils Lake
Grand Forks
Jamestown
Fargo
Detroit Lakes
Lisbon
Fergus Falls
Ashley
Alexandria
Redfield