Advanced uses of weather radar

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Dual-Wavelength Radar

- Rainfall and hail detection
- Backscattering cross-sectional area σ depends upon diameter relative to wavelength

	Wavelength (cm)		
Diameter (mm)	**3**	**5**	**10**
0.1 (drizzle)	Rayleigh	Rayleigh	Rayleigh
1 (rain)	Rayleigh	Rayleigh	Rayleigh
10 (v. large rain, small hail)	Mie	Mie	Rayleigh
100 (large hail)	Mie	Mie	Mie

Rainfall Measurement Using Dual-Wavelength Radar

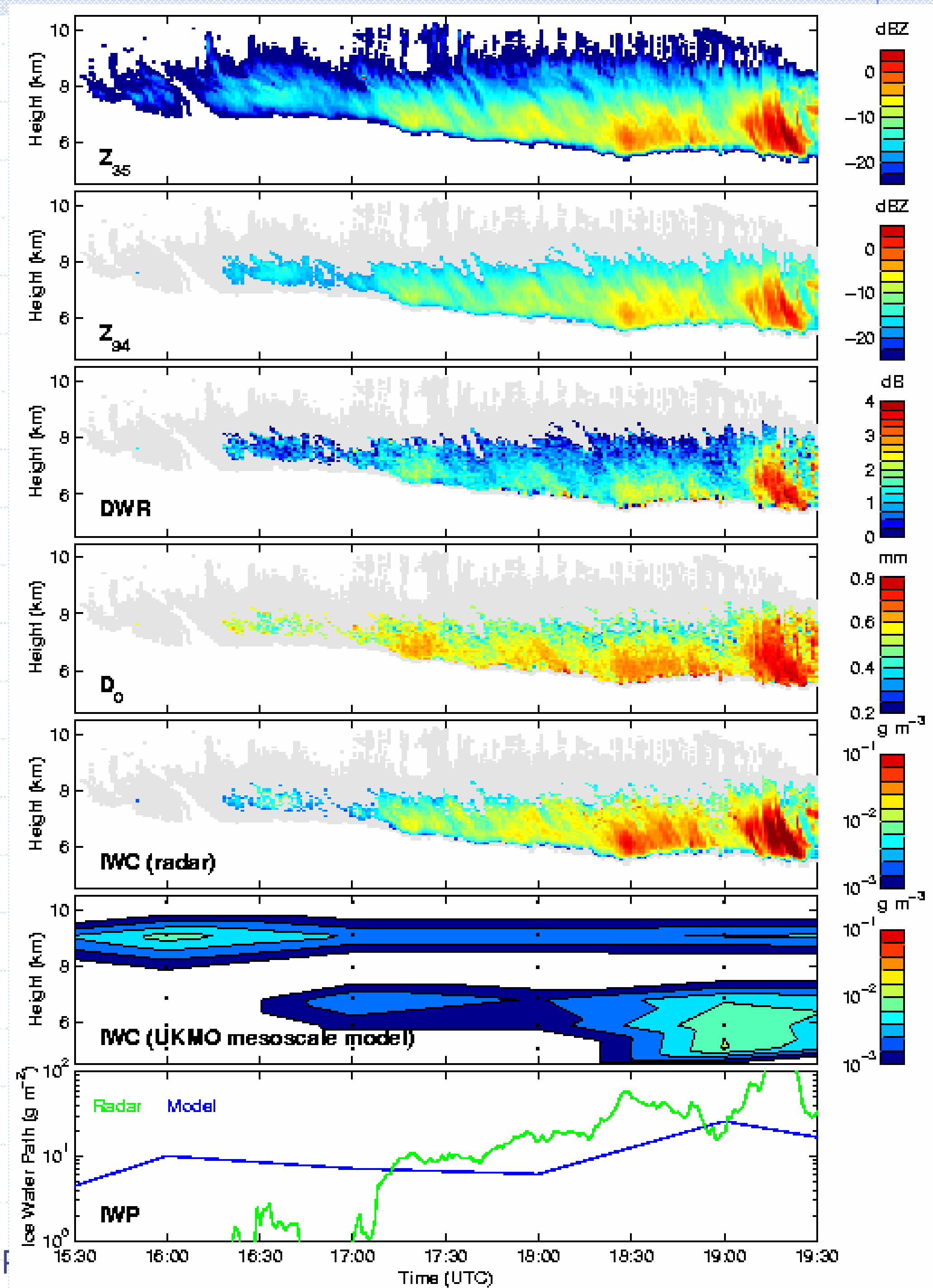
- Japanese are using K- and X-band radars for rainfall measurements.
- Raindrops are Rayleigh scatterers at X-band but in the Mie region for K-band.
- Can also get attenuation from K-band compared to X-band and use attenuation-rainfall relationships.
  - i.e., $R = A\,I^{b}$
  - Studies by Atlas, Ulbrich, and others show that rainfall is almost exactly linearly proportional to attenuation for 1-cm wavelength radar signals.

Dual-Wavelength Hail Detection

- Ludlam and Atlas first proposed that using two wavelengths might be useful for hail detection.
- Hail signal $H = 10\ log\ (z_s/z_x)$, where z is radar reflectivity factor at S- and X-band, respectively. H is measured in dB.
- H is usually positive (i.e., $z_s > z_x$)
- For some sizes of small hail, H can be negative.

Dual wavelength radar measurement of cirrus microphysical properties

Robin Hogan Anthony Illingworth and Henri Sauvageot



- The figure shows a case study from 22 June 1996 in which thick cirrus was observed by the colocated 35 GHz Rabelais and 94 GHz Galileo radars.
- www.met.rdg.ac.uk/radar/research/dualfreq/iwc.html

Polarization

- Polarization is one of the fundamental characteristics of electromagnetic radiation
  - Amplitude
  - Frequency/wavelength
  - Polarization
  - Direction of propagation

Why is polarization important?

- If all targets were perfect spheres, polarization wouldn't help.
- Most hydrometeors are ***NOT*** spheres!
  - Ice crystals are very irregular
  - Hail is seldom spherical
  - Raindrops are oblate
  - Cloud droplets *are* spheres, however.

Uses of Polarization with Radar

- Linear depolarization ratio
- Circular depolarization ratio
- Reflectivity depolarization ratio

Linear Depolarization Ratio

- Radar transmits linear polarization (typically, horizontal)
- Radar detects both horizontal and vertical polarizations

$$LDR = 10 \cdot \log_{10}\left(\frac{z_{horizontal}}{z_{vertical}}\right)$$

- LDR = 1 for perfect spheres
- LDR = ∞ for long, thin scatterers

Circular Depolarization

- Radar transmits circular polarization (typically, right-hand circular, e.g., RHC)
- Radar detects both RHC and LHC polarizations

$$CDR = 10 \cdot \log_{10}\left(\frac{z_{parallel}}{z_{orthogonal}}\right)$$

- CDR = 0 for infinitely long, thin scatterers
- CDR = - ∞ for perfect spheres

Reflectivity Depolarization Ratio

(Seliga and Bringi, 1976)

- Radar transmits alternate pulses of horizontal and vertical polarization
- Separate averages of z_h and z_v are determined

$$Z_{DR} = 10 \log(z_h/z_v)$$

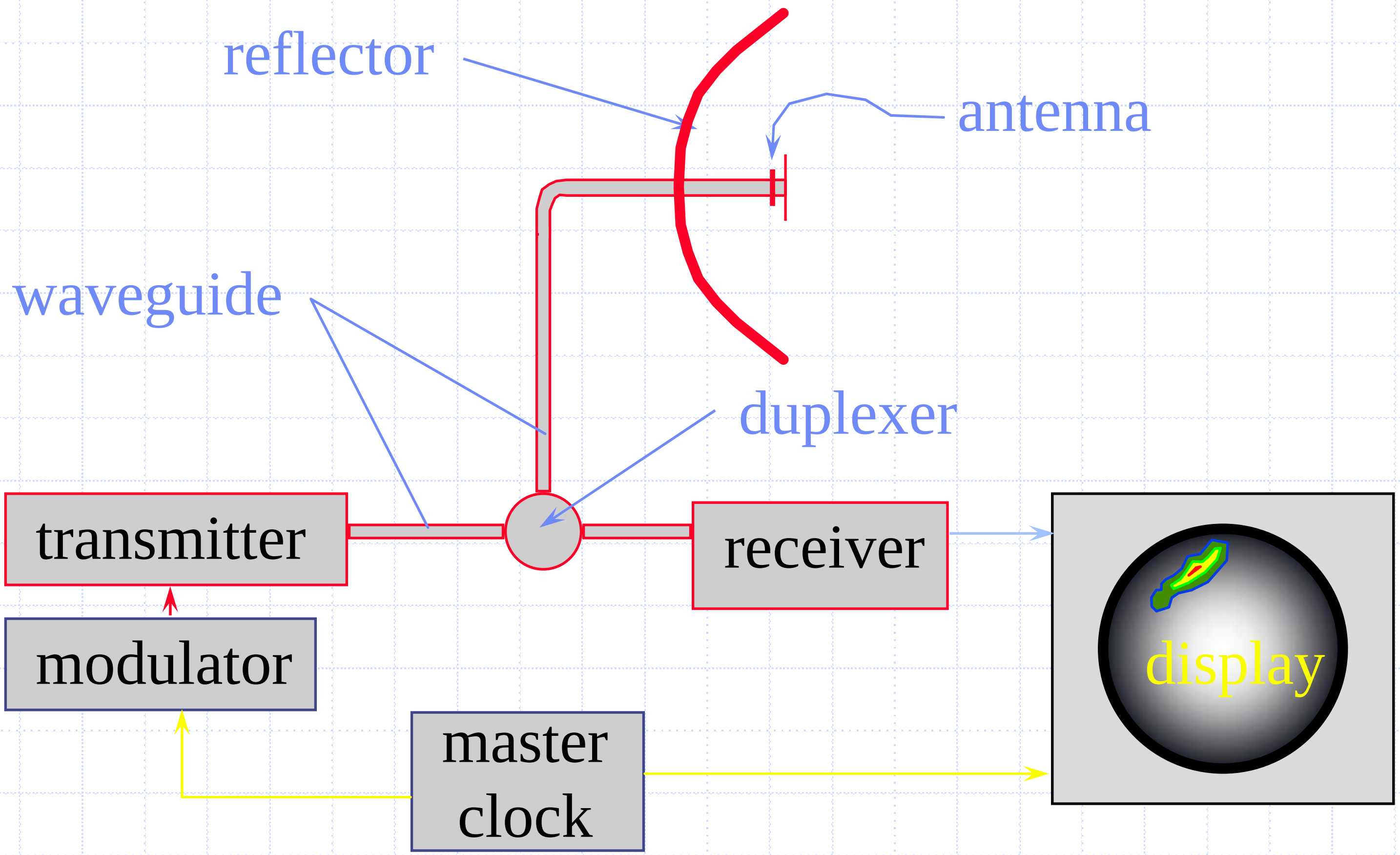
- Z_{DR} also written as ZDR
- $Z_{DR} = 0$ for perfect spheres
- $Z_{DR} > 0$ for nonspherical hydrometeors

Z_{DR} for various situations

Source	Z_{DR} (dB)
Drizzle	0
Light rain	0-1
Moderate rain	~3
Heavy rain	up to 5
Graupel	slightly negative
Hail	0

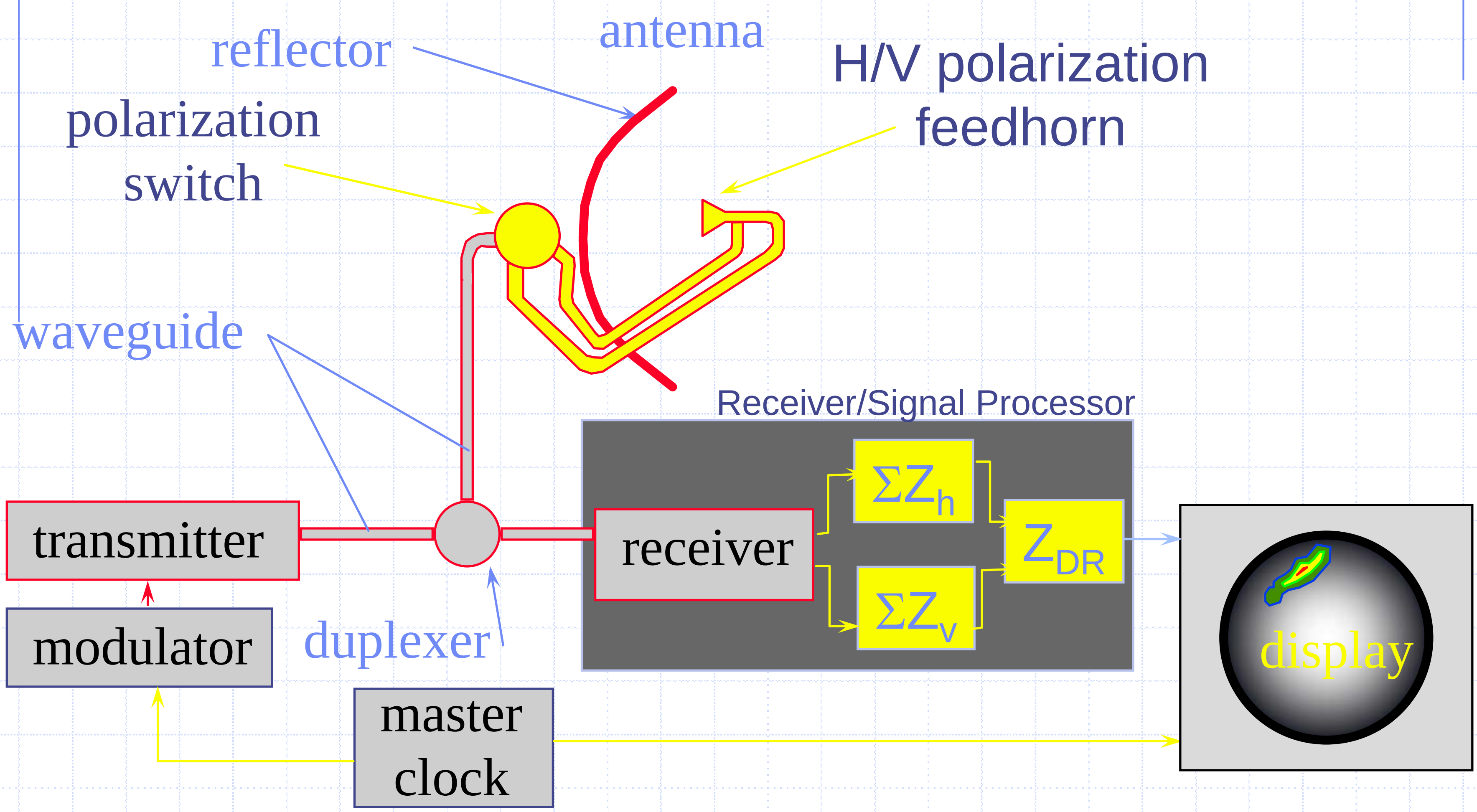
Block diagram of radar

(as used in real radars)

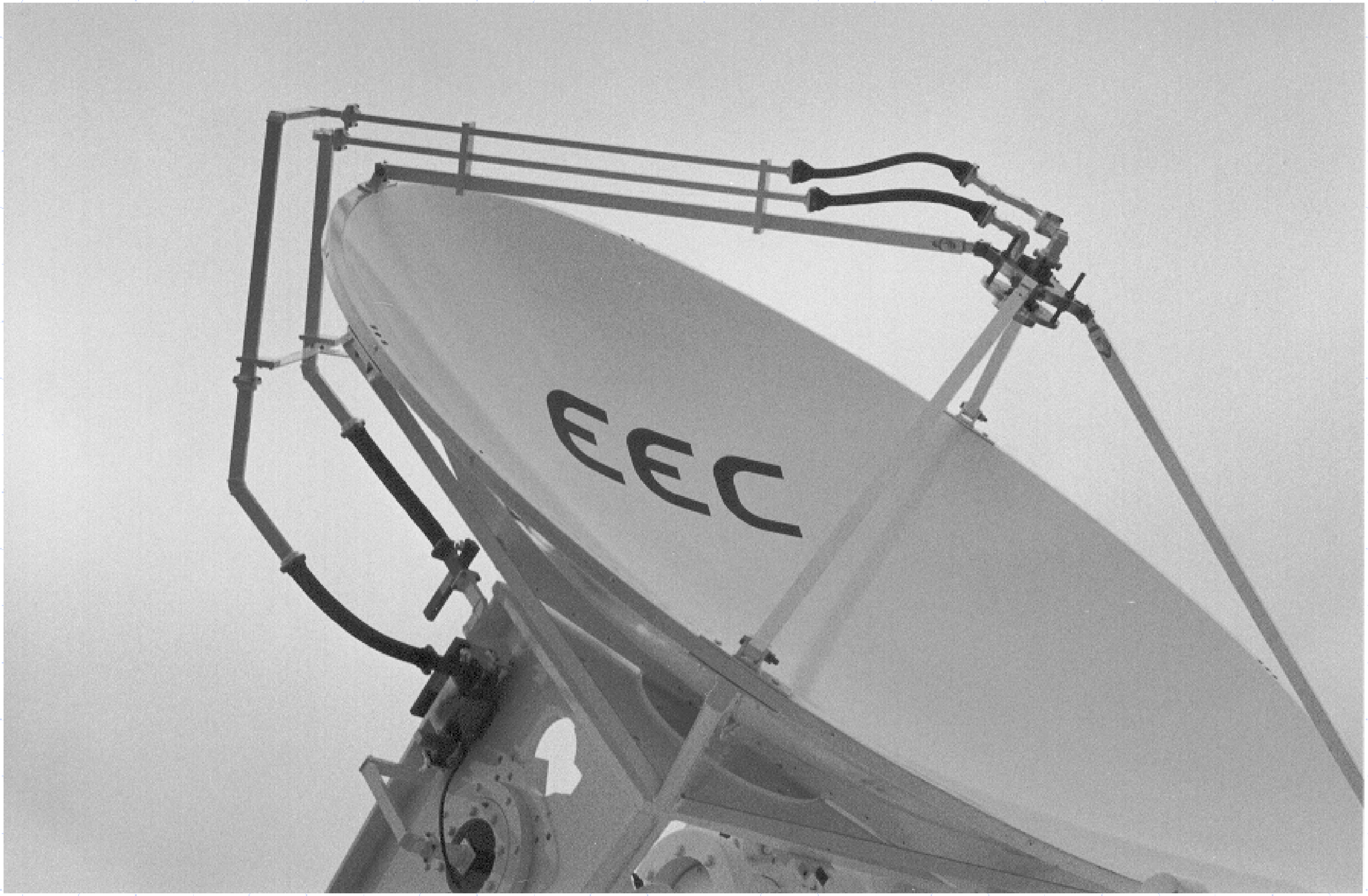


Block diagram of radar

(as used in Z_{DR} radars)



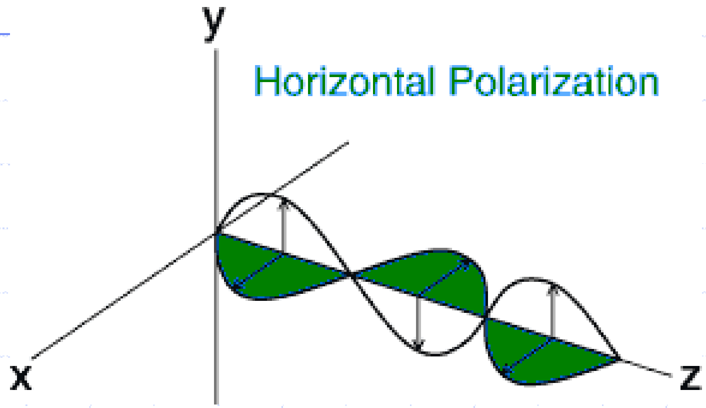
Dual-polarization feed on Antenna

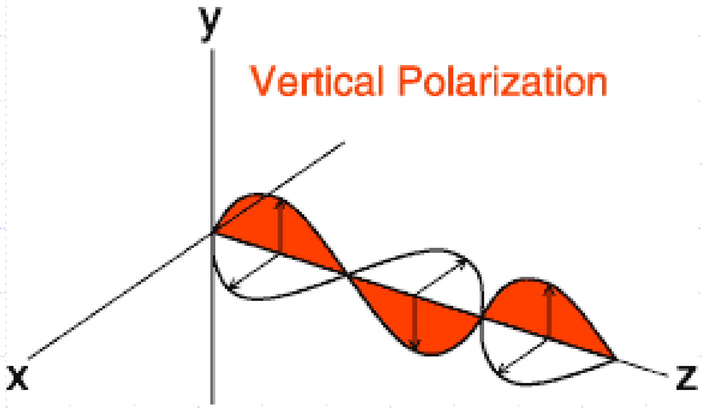


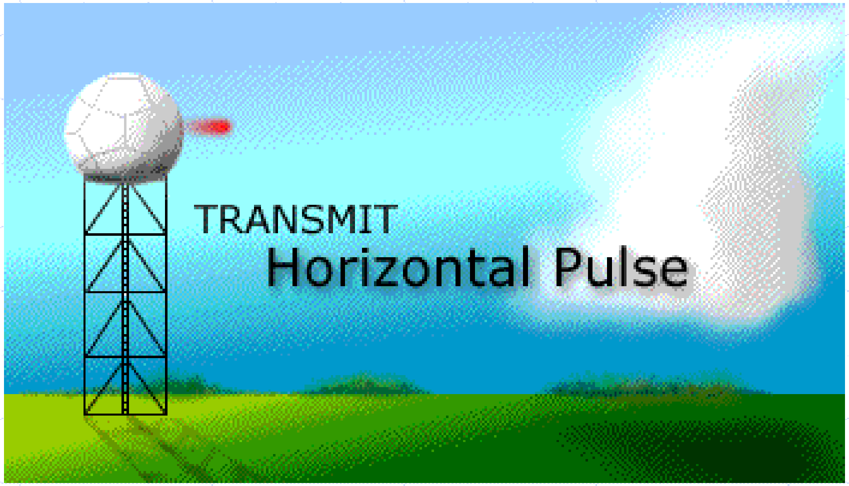
Dual-polarization feedhorn and antenna (CSU-CHILL)

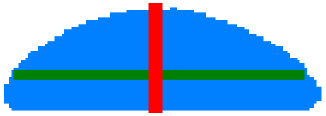
http://radarmet.atmos.colostate.edu/CHILL/Pix.html

Dual-Linear, Switching Polarimetric Radar









Large Raindrop

Reflectivity Factor at Horizontal Polarization, Zh (dBZ)

$$Z_h = Z_h^{\text{int}} - \alpha_h(r) + OES$$

- Z_h is measured
- Z_h^{int} is the intrinsic Z_h due to the hydrometeors
- $\alpha_h(r)$ is the two-way attenuation
- OES stands for Other Error Sources
  - system noise
  - calibration errors
  - sidelobe contamination
  - statistical uncertainty of estimate

$$Z_h^{\text{int}} = 10\log\left[\frac{\lambda^4}{\pi^5|K|^2}\int_{D_{eh}=D_{eh,\min}}^{D_{eh}=D_{eh,\max}} \sigma(D_{eh})N(D_{eh})dD_{eh}\right]$$

Measures amount

Differential Reflectivity, ZDR (dB)

$$Z_{DR} = Z_{DR}^{\text{int}} - \alpha_{dp}(r) + OES$$

$$Z_{DR} = Z_h - Z_v$$

- Z_{DR} is measured
- Z_{DR}^{int} is the intrinsic Z_{DR} due to the hydrometeors

Measures shape

- $\alpha_{dp}(r)$ is the two way differential attenuation
- OES stands for Other Error Sources
  - system noise
  - mismatched main-lobe power patterns
  - mismatched sidelobe power patterns
  - statistical uncertainty of estimate

Correlation Coefficient, $|\rho_{hv}(0)|$

$$|\rho_{hv}(0)| = |\rho_{hv}(0)|^{\text{int}} + ES$$

- $|\rho_{hv}(0)|$ is the measured magnitude of the correlation coefficient at zero time lag between horizontally and vertically polarized signals
- $|\rho_{hv}(0)|^{\text{int}}$ is the intrinsic $|\rho_{hv}(0)|$ due to the hydrometeors
- ES stands for Error Sources
  - Sidelobe contamination
  - Low SNRs (system noise)
  - Spectral shape (non-Gaussian spectra)
  - Phase noise (of transmitter)
  - Spatial phase pattern of transmitted signal

Measures hydrometeor diversity

Resonant (δ) scattering

Phase Variables
ϕ_{DP} (°), K_{DP} (° km^{-1}), and δ (°)

$$\phi_{DP} = \phi_{DP}^{\text{sys}} + \phi_{DP}^{m} + \delta + ES$$

- ϕ_{DP} is the measured two-way differential propagational phase shift
- ϕ_{DP}^{sys} is the system, or initial (r = 0), ϕ_{DP}
- ϕ_{DP}^{m} is the ϕ_{DP} owing to the propagation medium
- δ is the backscatter differential phase
- ES stands for Error Sources
  - System noise
  - Nonuniform beamfilling
  - Sidelobe contamination
  - Statistical uncertainty of estimate

$$K_{DP}^{\text{int}} = \frac{1}{2}\frac{\partial \phi_{DP}^{m}}{\partial r}$$

Measures amount and shape

Good for *R*

ρ_{hv} and LDR_{hv}

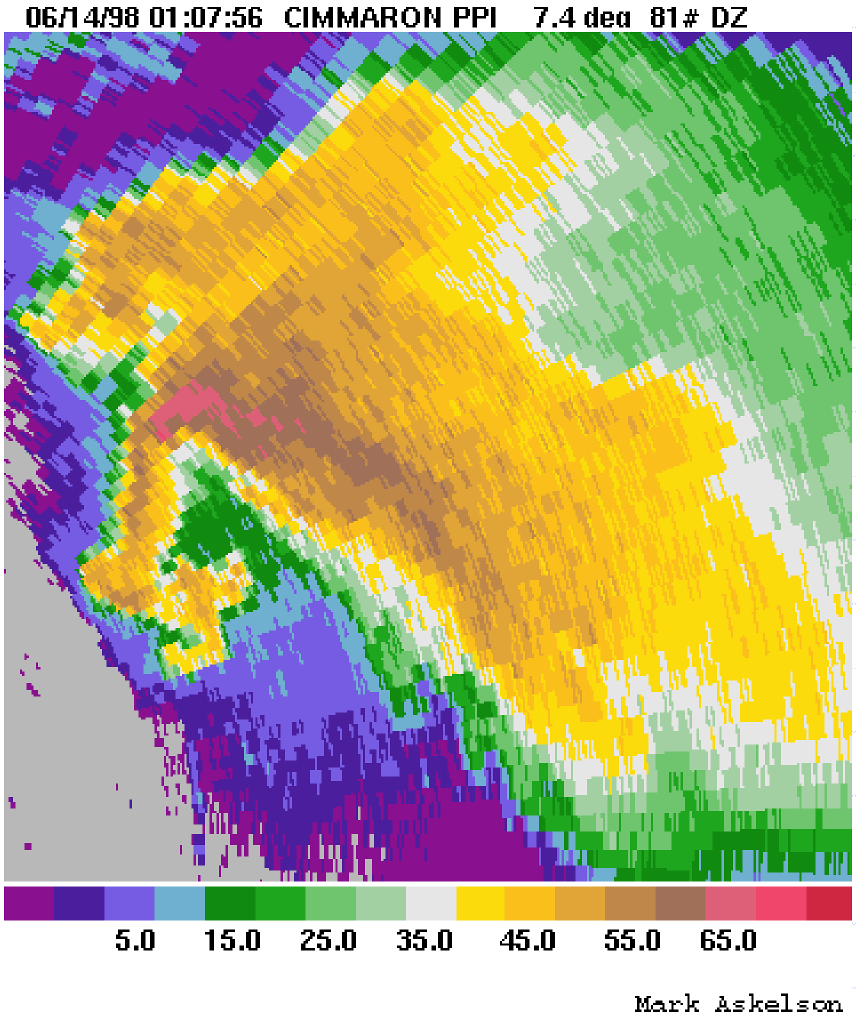
- ρ_{hv} is the correlation of horizontally- and vertically-polarized powers. It is decreased by wide distributions of
  - hydrometeor eccentricities
  - canting angles
  - irregular hydrometeor shapes

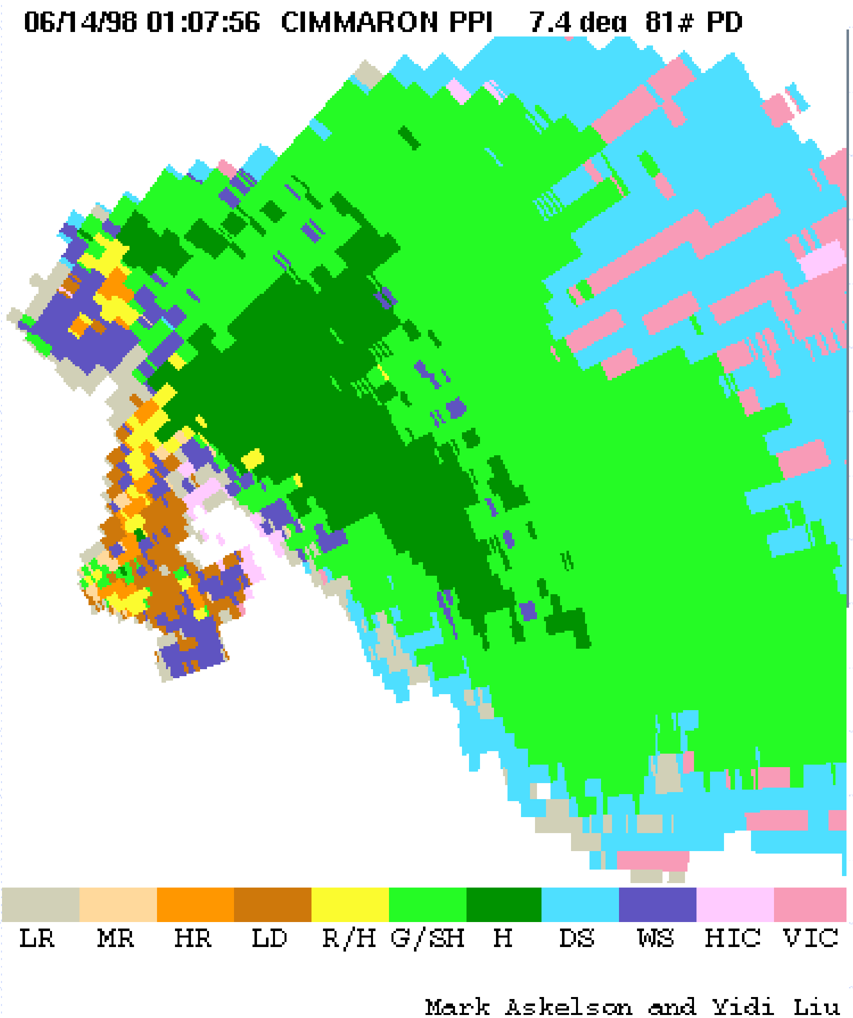
and by
  - Mie scattering
  - mixtures of hydrometeor types

LDR_{hv} is the horizontally-polarized power received from a vertically-polarized transmitted wave normalized by the concomitantly received vertically-polarized power. Significant depolarization occurs in
  - mixed phase precipitation
  - wet snow
  - hail

Hydrometeors & Downdrafts: RFD (cont.)

Hook in Tornadic Supercell

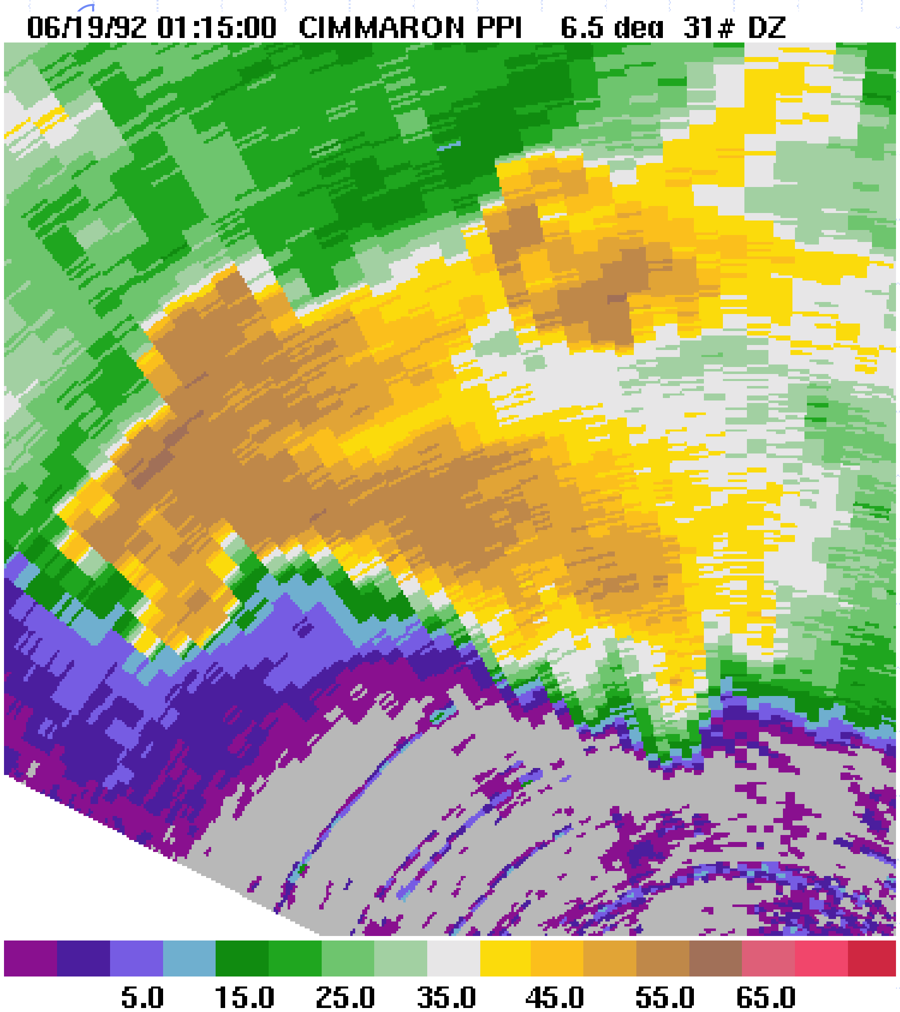


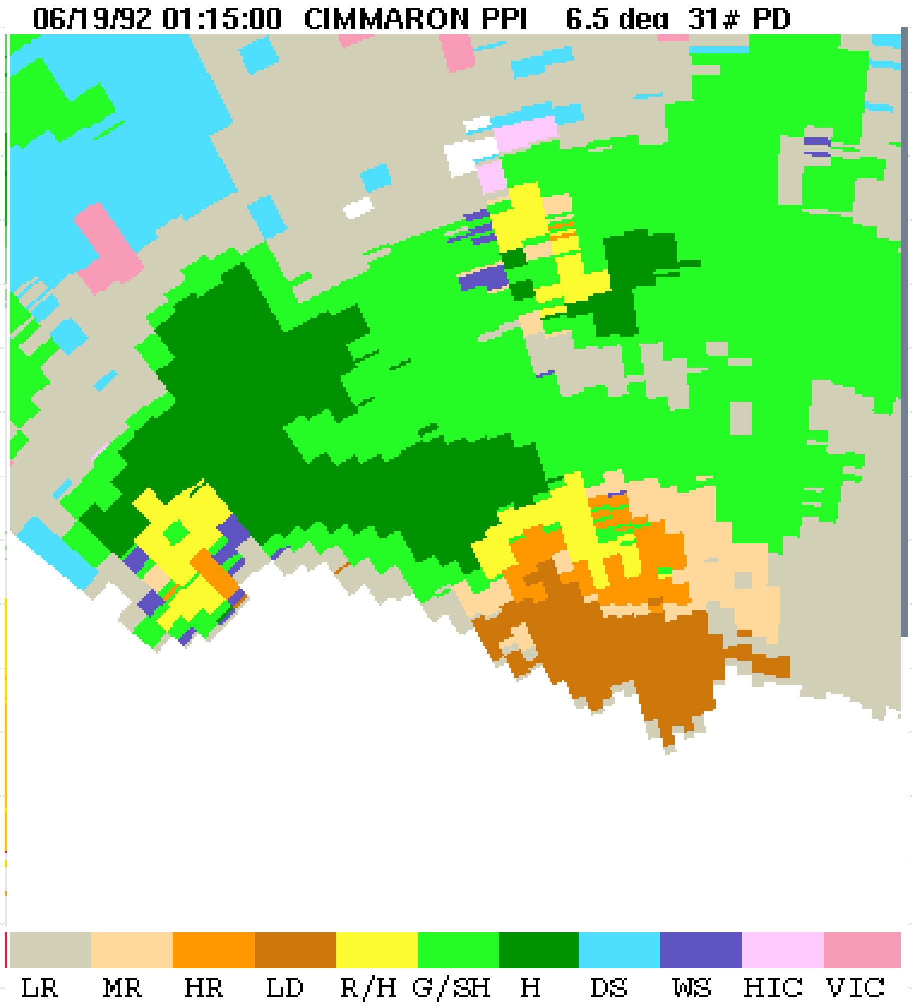


Hook altitude ~3.9 km agl

Hydrometeors & Downdrafts: RFD (cont.)

Hook in Nontornadic Supercell

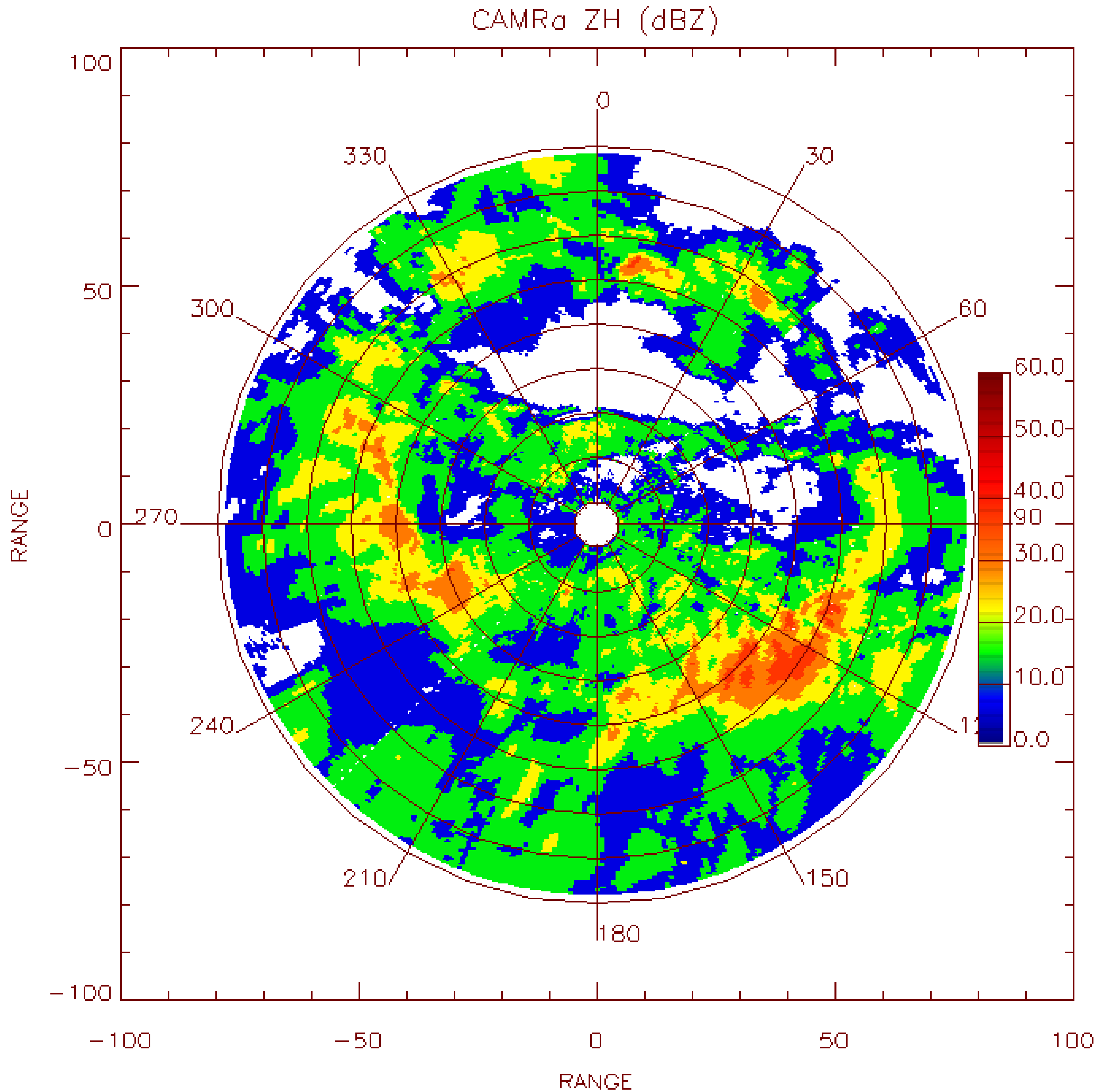


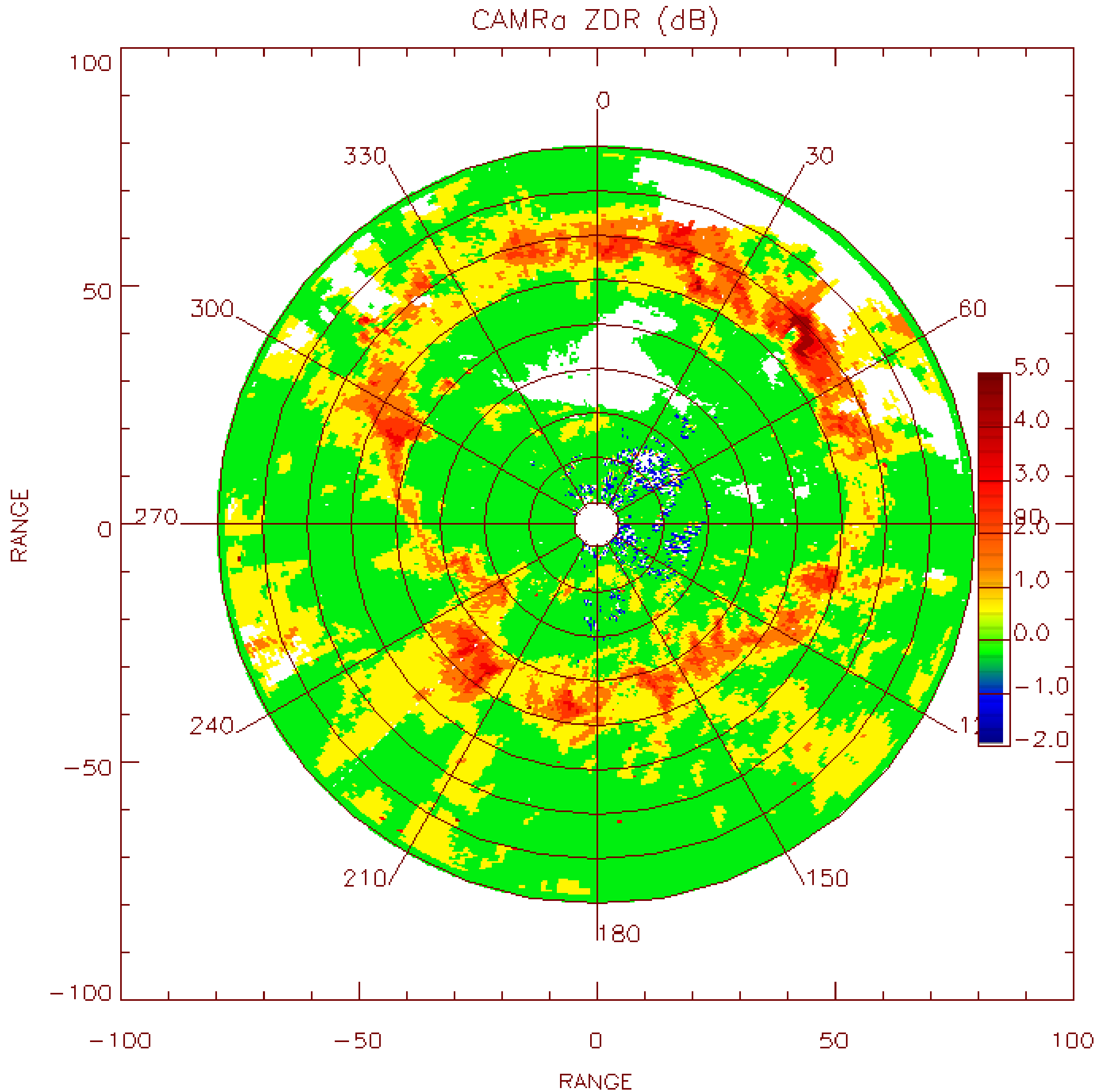


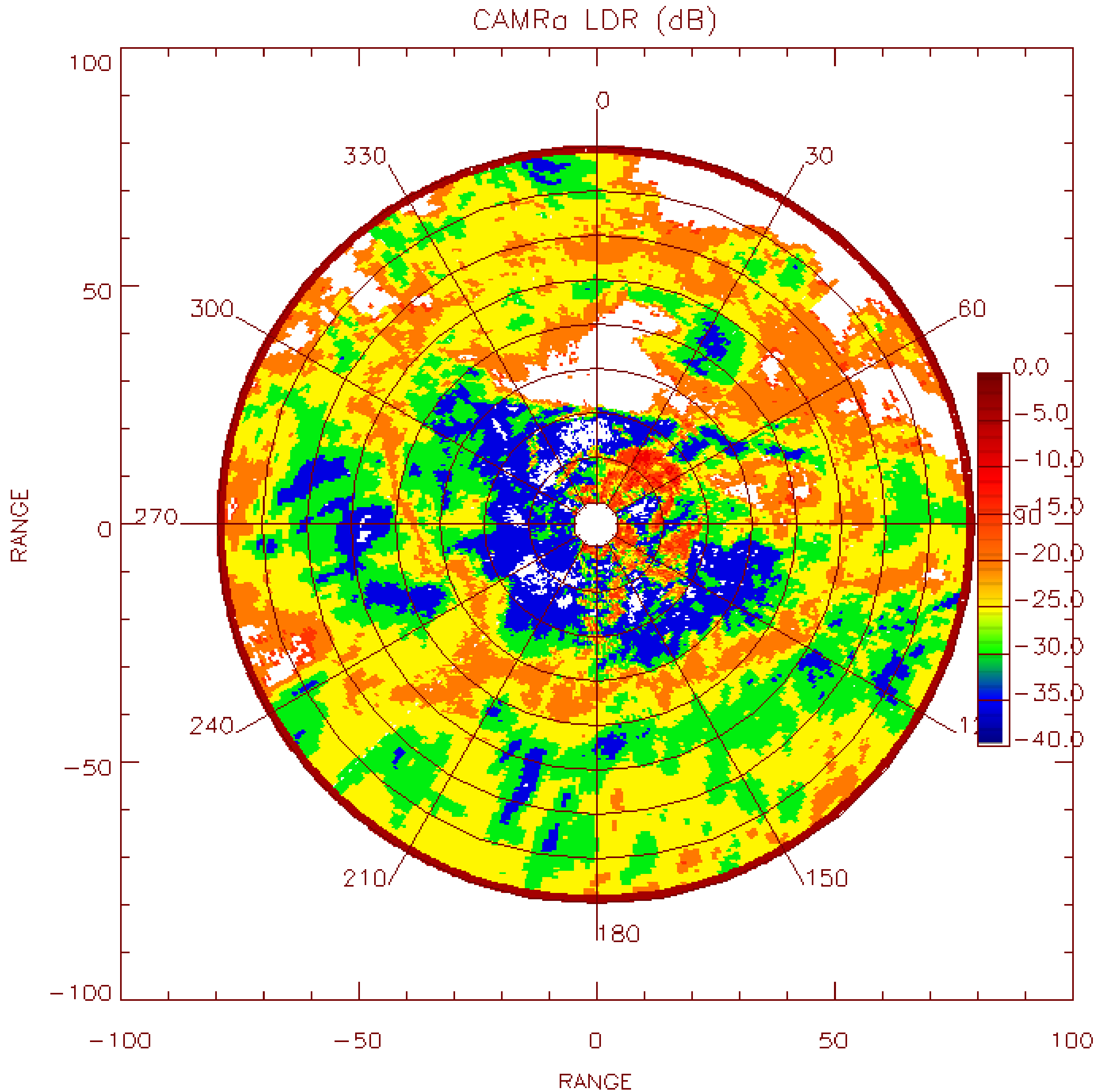
Hook altitude ~3.8 km agl

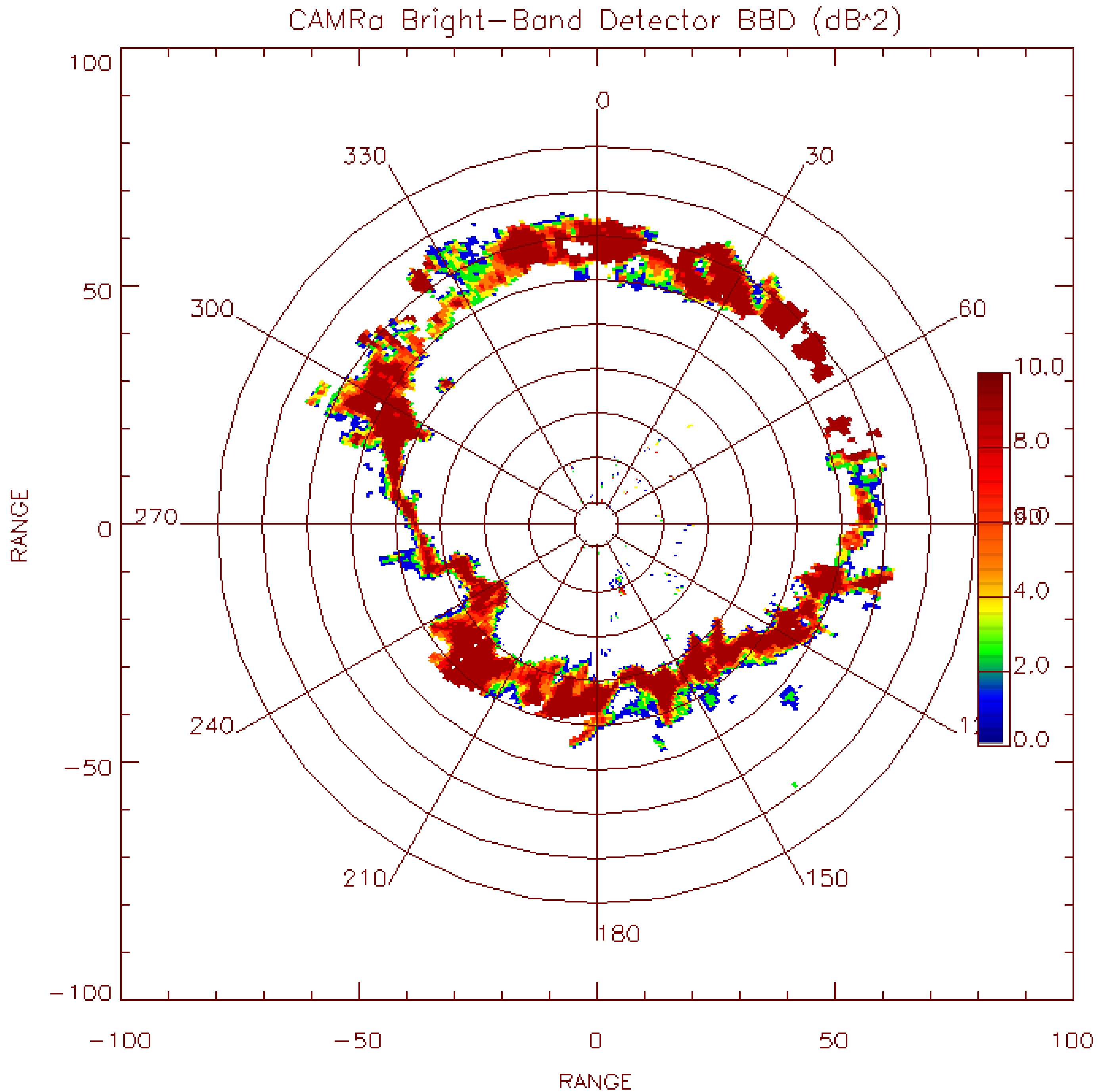
Example of using ZDR data

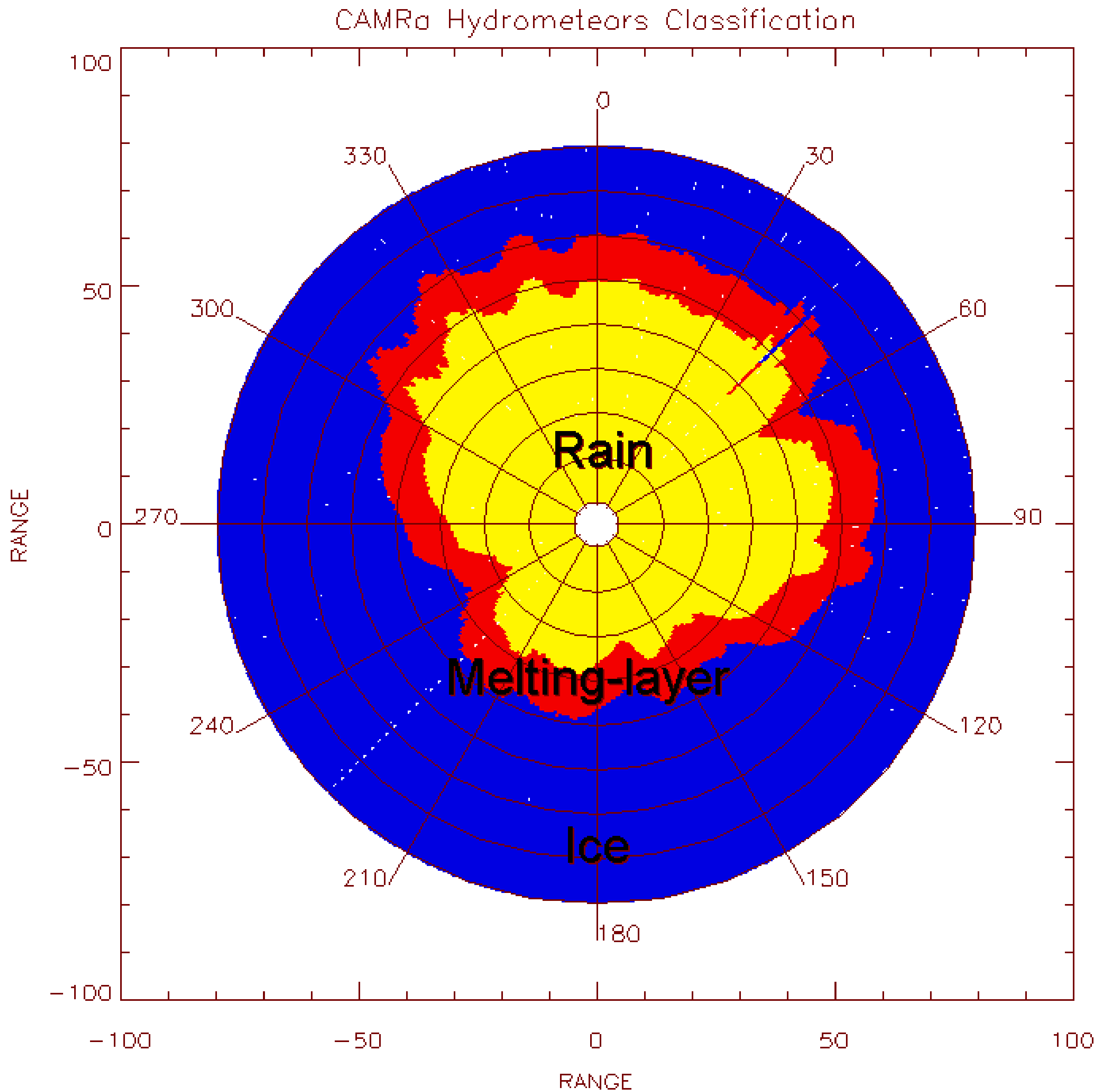
- Case study of bright-band situation around a radar
  - Radar reflectivity factor
  - Z_{DR}
  - L_{DR}
  - Bright-band detection
  - Hydrometeor classification
  - Rainfall


CAMRa ZH (dBZ)
100
50
0
−50
−100
−100
−50
0
50
100
RANGE
RANGE
0
30
60
330
300
270
240
210
180
150
60.0
50.0
40.0
30.0
20.0
10.0
0.0

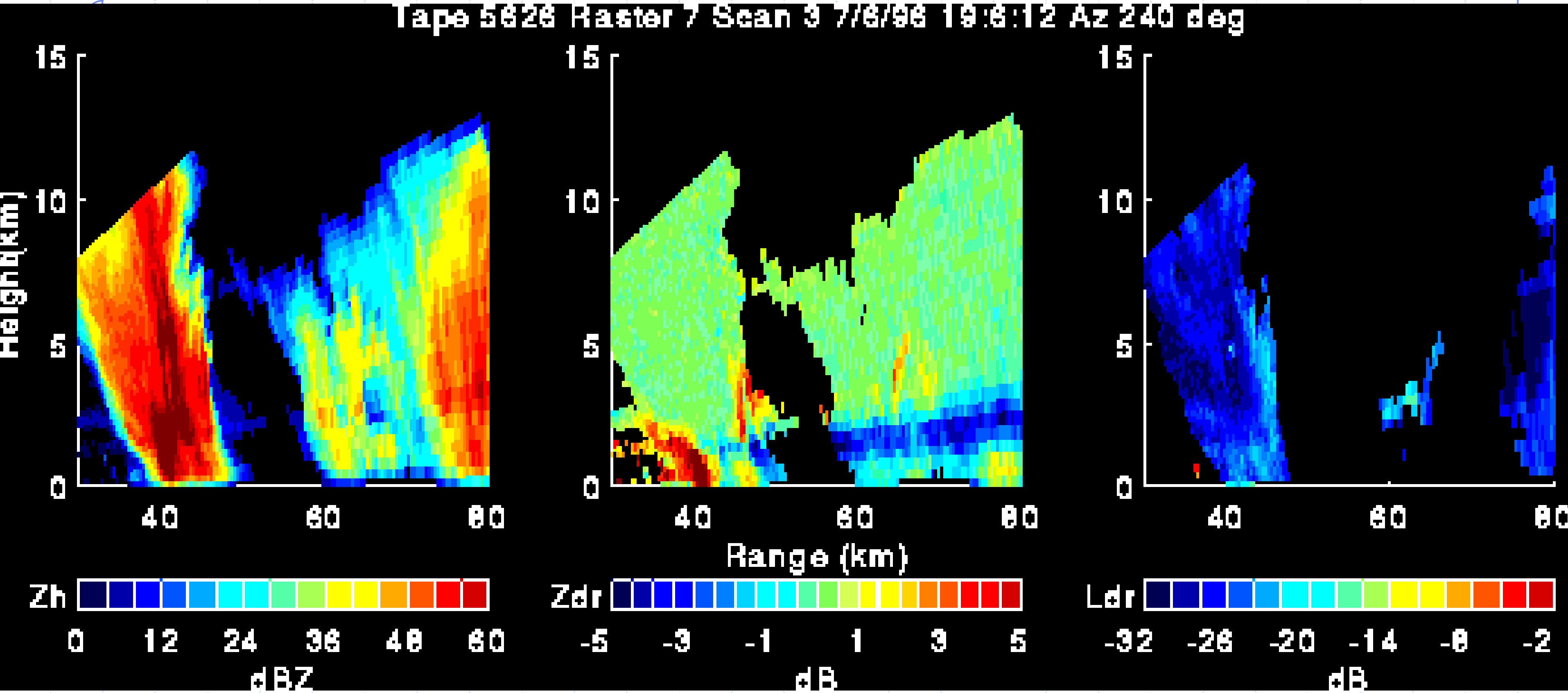

CAMRa ZDR (dB)
100
50
0
−50
−100
RANGE
−100
−50
0
50
100
RANGE
0
30
60
150
180
210
240
270
300
330
5.0
4.0
3.0
2.0
1.0
0.0
−1.0
−2.0


CAMRa LDR (dB)
100
50
0
−50
−100
−100
−50
0
50
100
RANGE
RANGE
0
30
60
90
150
180
210
240
270
300
330
0.0
−5.0
−10.0
−15.0
−20.0
−25.0
−30.0
−35.0
−40.0


CAMRa Bright-Band Detector BBD (dB^2)
100
50
0
−50
−100
RANGE
−100
−50
0
50
100
RANGE
0
30
60
120
150
180
210
240
270
300
330
10.0
8.0
6.0
4.0
2.0
0.0


CAMRa Hydrometeors Classification
Rain
Melting-layer
Ice
RANGE
RANGE
100
50
0
−50
−100
0
30
60
90
120
150
180
210
240
270
300
330

Another example in RHI format



Future Radars

- Rapid scan antennas
  - Courtesy of Bob Blasewitz
    - Lockheed-Martin

Limitations of Mechanical Scanning Radars

- Positioning Antenna is SLOW
- Reduced reaction times
- Blind Sided!
- Mechanical error

Electronic Scanning

- Increased Data Rates
- Instantaneous Beam Positioning
- Elimination of Mechanical Errors
- Multi-mode Operation
- Multi-target capability

Phased-Array Radar System: Background

- Directive antenna made up of a number of individual antennas, or radiating elements
- Radiation pattern is determined by the amplitude & phase of the current at each element
- Electronically steered beams are accomplished by changing phase of current at each element
- Array of elements can be stationary or rotating
- Initial Phased Array Radars were developed by the DOD for surveillance,tracking & guidance functions

WHY Phased Array Radar Systems ?

- Agile, rapid beam steering capability
- Supports multifunctional capability
  - Tracking multiple targets
  - Surveillance of specified volume
  - Weather processing
- Can accommodate large power transmitters for long range applications
- Electronic beam forming and steering eliminate mechanical challenges
- Capability can add to complexity and cost

WHY Phased Array Radar Systems ?

- Simultaneous functions can be implemented
  - Surveillance: user-defined volumes of interest
  - Tracking: 3D, no transponder is necessary
  - Weather: measure reflectivity, velocity, spectrum width, wind shear
- Cost trends are making this a viable choice for the future
  - Electronics are following Moore's Law
  - Commercial competition
  - High technology insertion
  - Invention

Phased Array Radar Capabilities

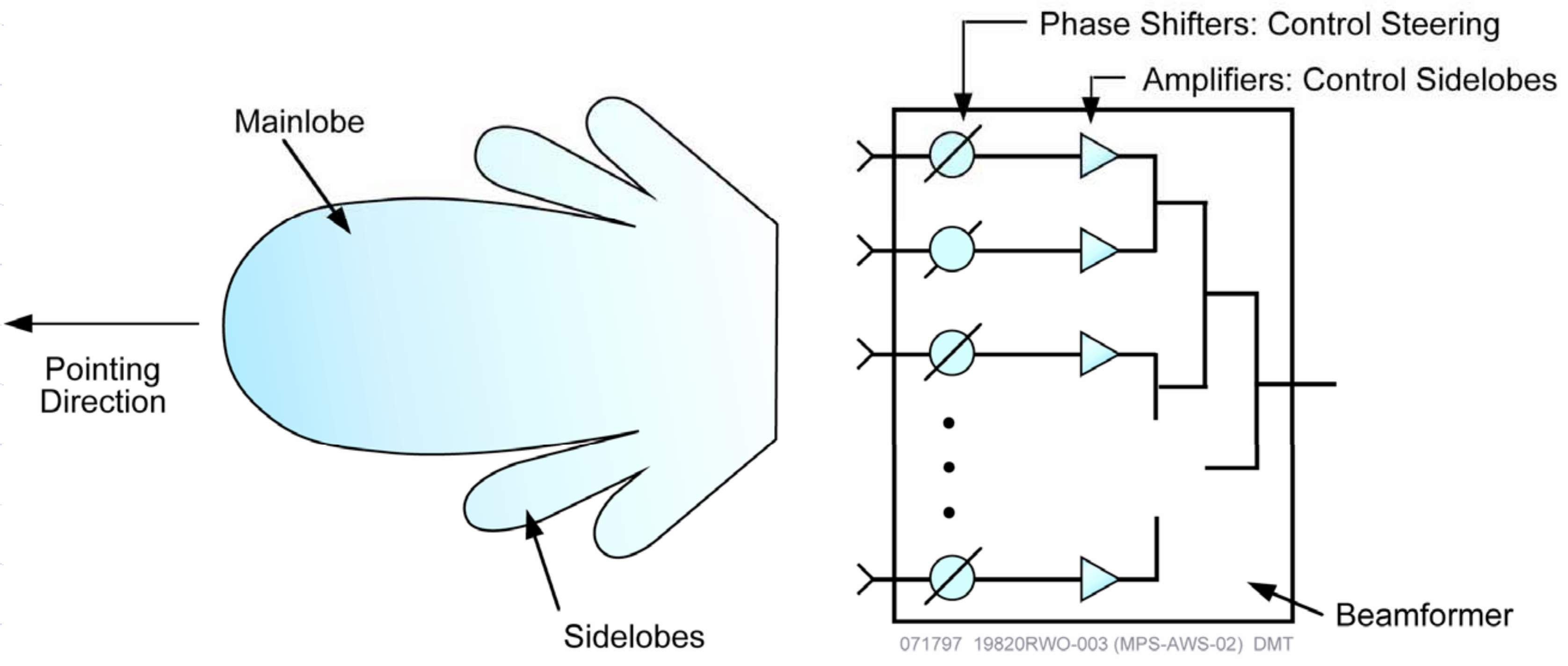
- Surveillance
  - Generates sequence of beam positions to search a given volume
  - Radar commands dictate specified volume of space at a specified scan rate
  - Users can define surveillance dwells by waveform and dwell period for special needs
- Tracking
  - Detections are stored in a track processor
  - Dwell sequences are initiated on detections to establish track rates
  - Data on tracks is smoothed and used to estimate future position & velocity
  - Track files are maintained in track processor
  - Track maintenance is software intensive

Phased Array Radar Capabilities

- Weather
  - Reflectivity measures can be processed through an environmental processor
  - Rain,snow,hail,sleet are good targets for meteorologists
  - Wind shear, velocity can be obtained
  - Cloud bases & tops can be identified
  - Hazardous weather can be located and tracked
- Wake Vortex
  - Capability to detect and measure are being studied
  - Frequency for this challenge is a major driver

What is Beamforming?

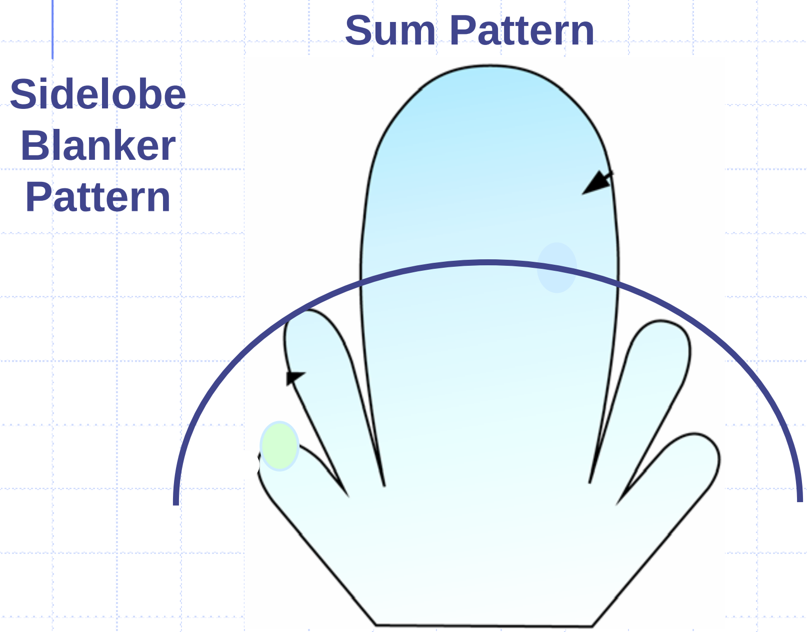
- The combination of energy from the elements of a phased array antenna by which the properties of that antenna beam are established

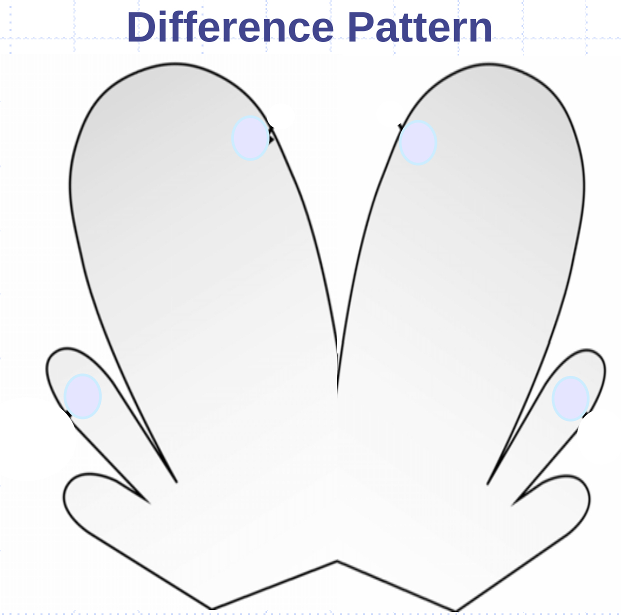


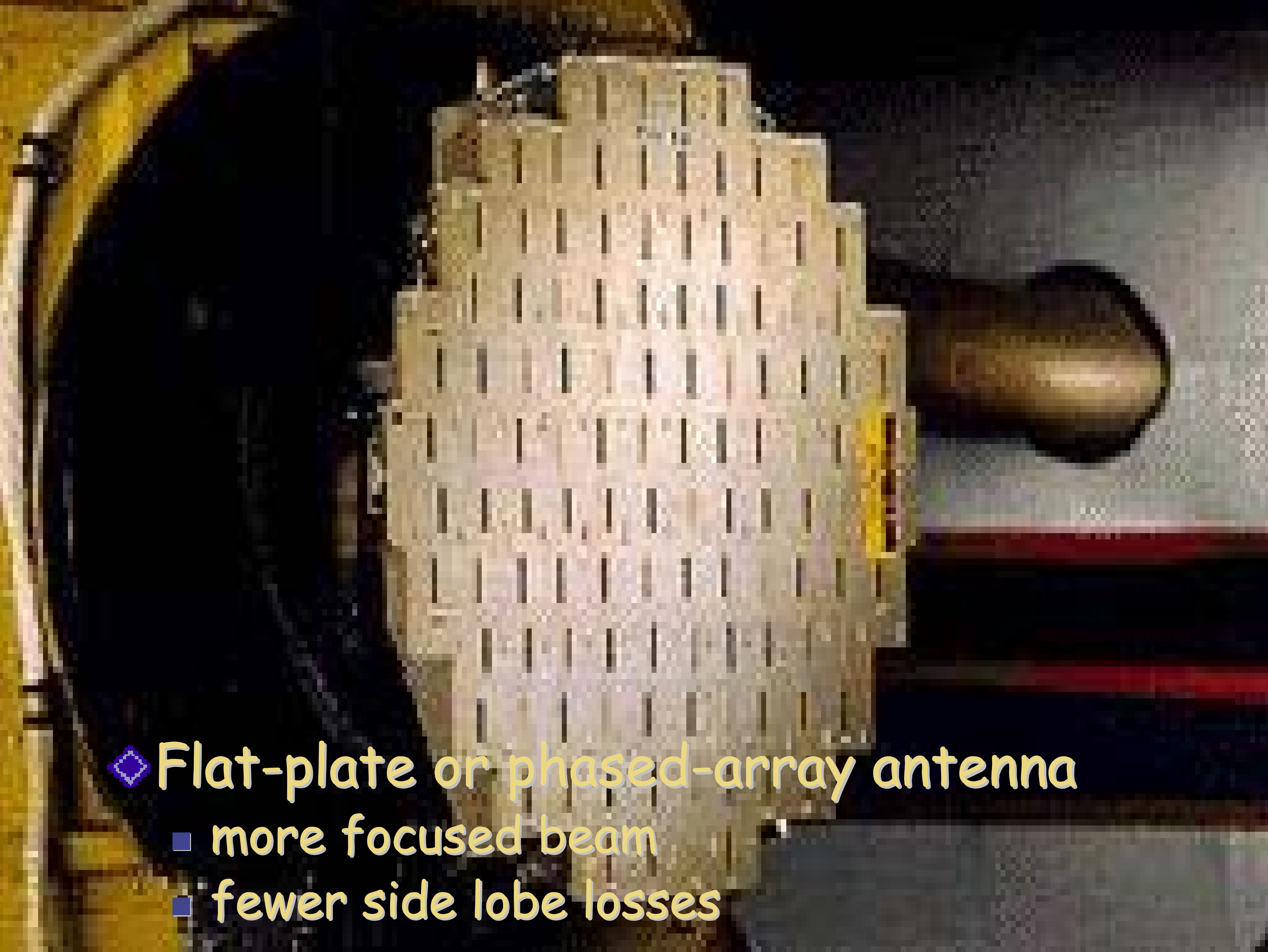
The Antenna Beamformer Sets the Direction of the Radar Beam and the Detailed Properties of its Shape

Antenna Beamforming

- Multifunction radars usually generate multiple beam patterns simultaneously to support the different radar functions
- Typically a multifunction radar has the following beams:
  - Sum patterns: Full power focused beams used on transmit and receive for target detection and tracking
  - Difference patterns: Patterns used on receive to aid in tracking
  - Sidelobe blanking patterns: Used in automatic detection systems to prevent tracking of targets in the antenna sidelobes

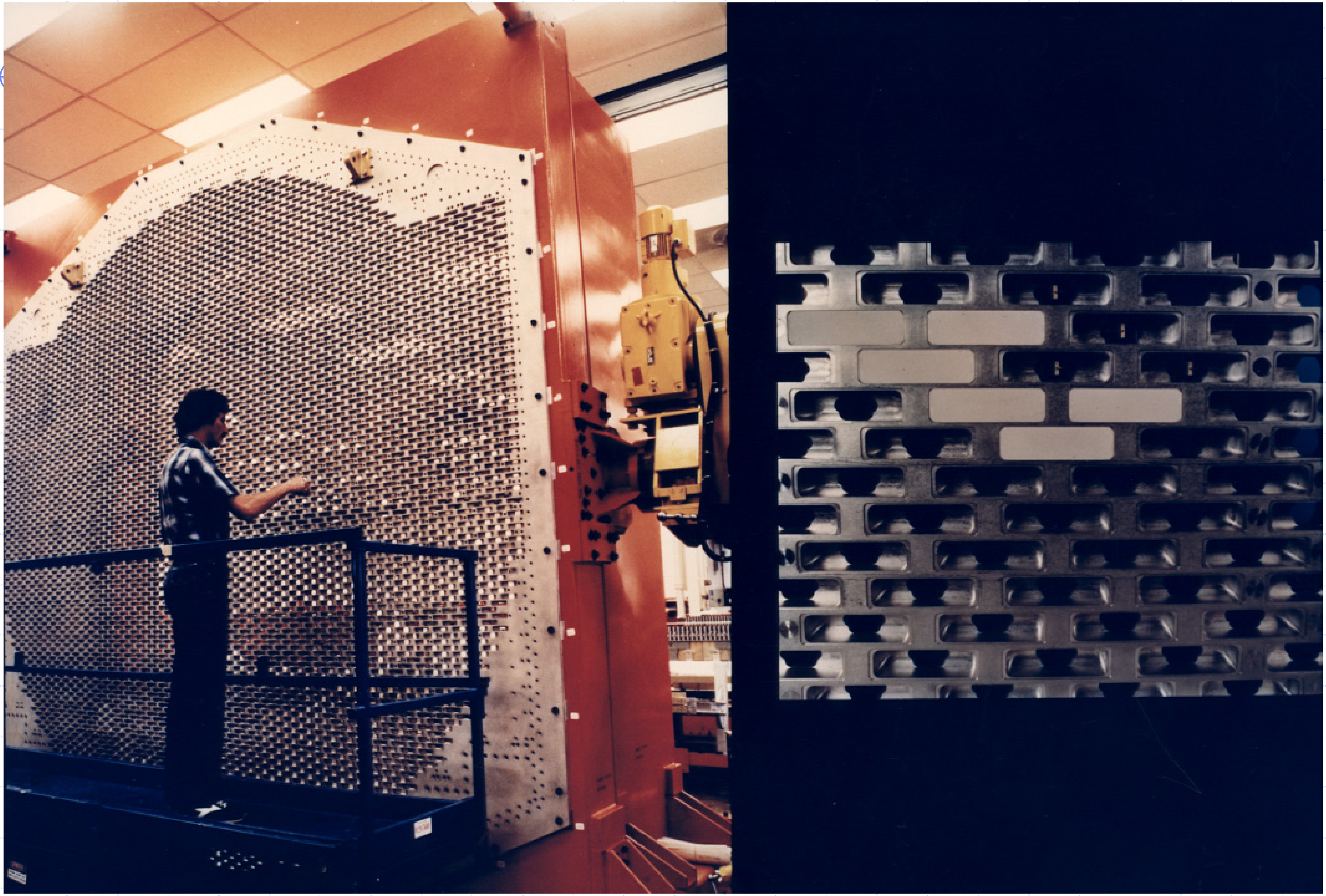




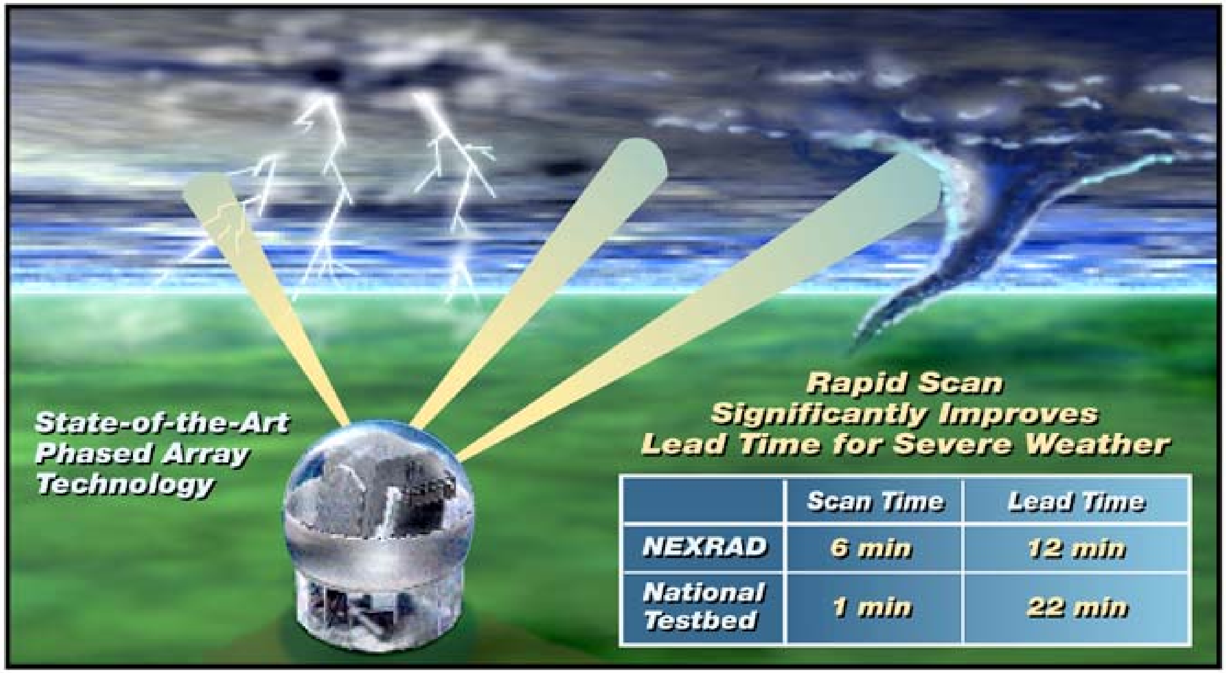


- Flat-plate or phased-array antenna
  - more focused beam
  - fewer side lobe losses

AN/SPY-1D Antenna



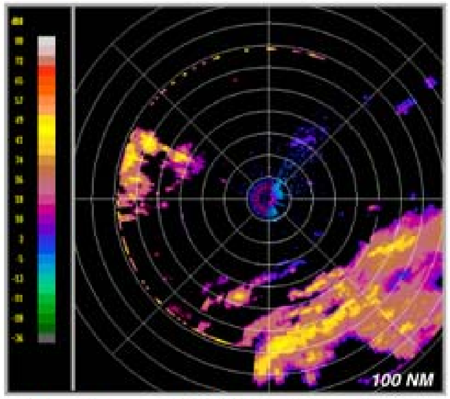
National Testbed for Phased Array Weather Radar



	Scan Time	Lead Time
NEXRAD	6 min	12 min
National Testbed	1 min	22 min

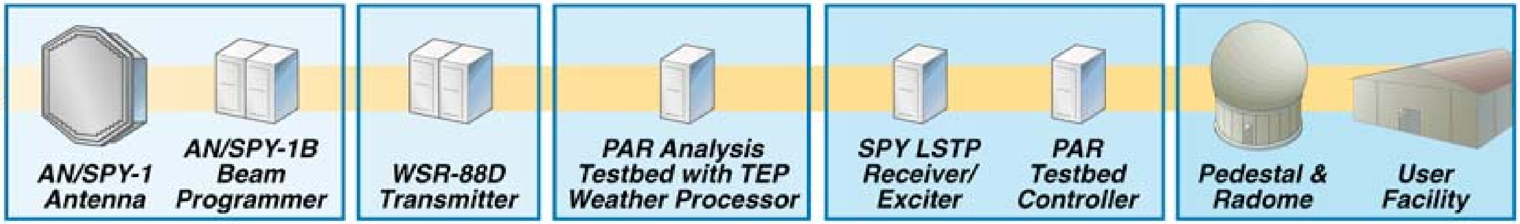
AN/SPY-1 with TEP Weather Processor

- Electronically Steered Beam
- Rapid Volume Scan
- High Resolution
- Maximum Flexibility



Hurricane DENNIS taken from USS O'KANE DDG 77, located off Wallops Island Aug. 30, 1999

Testbed Equipment



Phased Array Weather Radar Technology Provides Increased Lead Time to Save Lives and Property

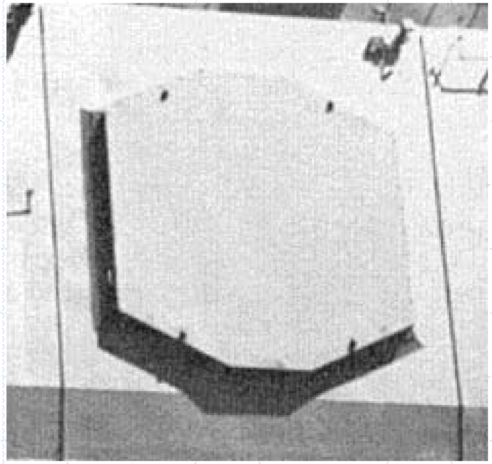
22214JFH-007
032299 / A / 21758TJM-001 (V1-092199)

Radar Evolution

R76

1970

SPY-1A



2000

COBRA

Reflector Antenna

- Tube Transmitter
- Slow Search rates
- Low Tracking rates
- Few Targets

Passive Phased Array Antenna

- Tube Transmitter
- Fast Search rates
- Fast Tracking rates
- Many Targets
- Heavy

Active Phased Array Antenna

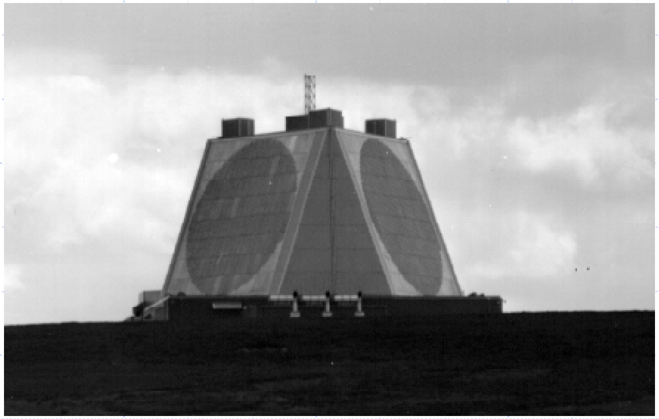
- Solid-State T/R Modules
- Very Fast Search rates
- Fast Tracking rates
- Many Targets
- Lower Weight
- Increased Capability

Vision

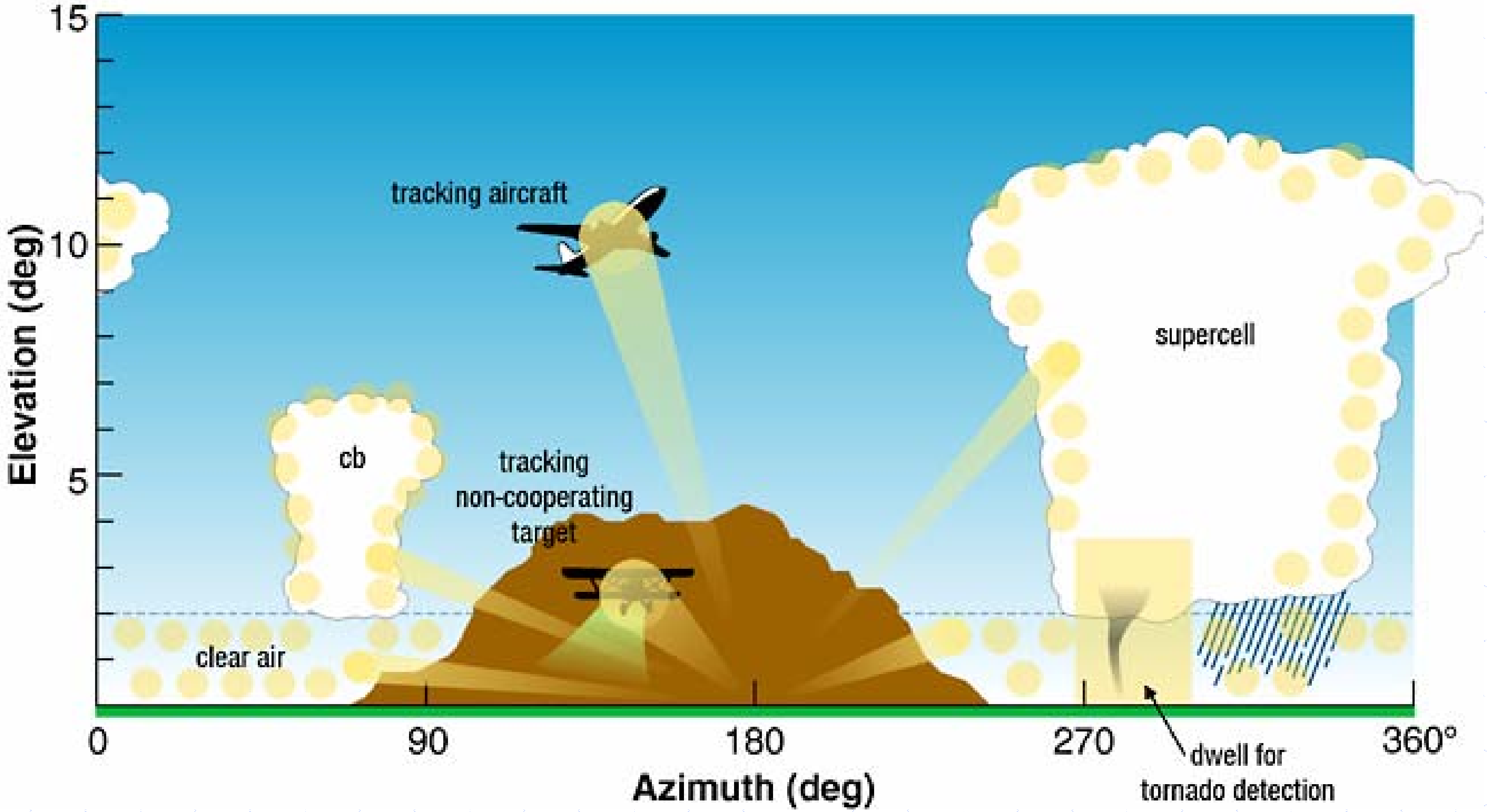
- From Aerospace, Inc. Study
- Multi Purpose Radar
- Integrated Radar Network including CASA radars
- Using Radar Data to Initialize Forecast Models

Vision from Aerospace, Inc. Study

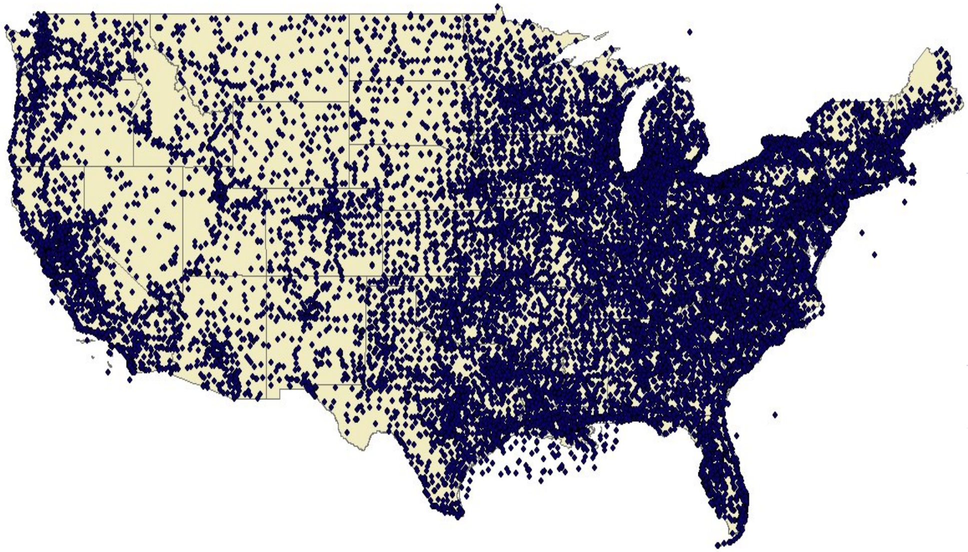
Given this price breakthrough, it is now possible to envision a four-faced radar system (four antennae mounted as in a pyramid) that would yield a weather radar with no moving parts. This would greatly reduce lifecycle cost and yield a volume scanning rate of approximately 20 seconds. The current NEXRAD volume scanning rates are between 5 and 6 minutes.



Multi Purpose Vision



Integrated Radar Network Vision

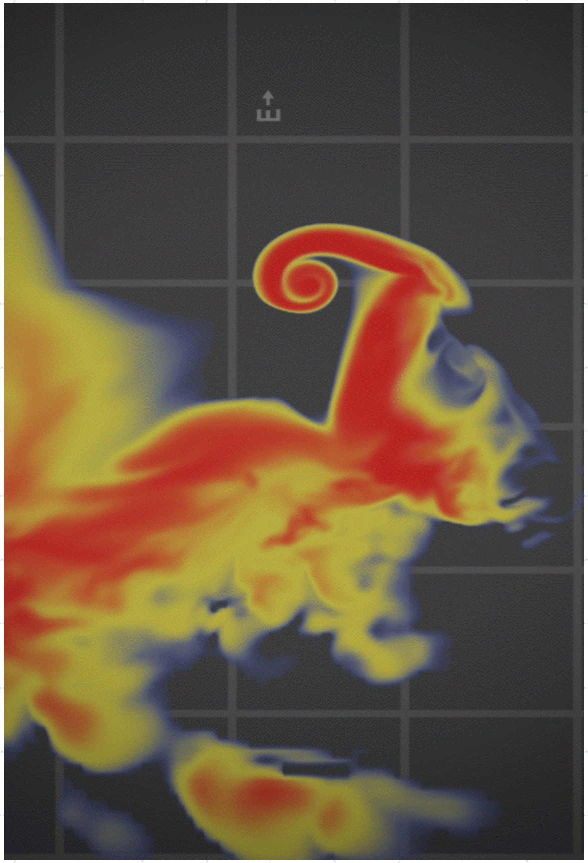


Big (NOAA, FAA), little (CASA) radars, other (HLS, DOT,?) radars, built real-time accessible data bases.

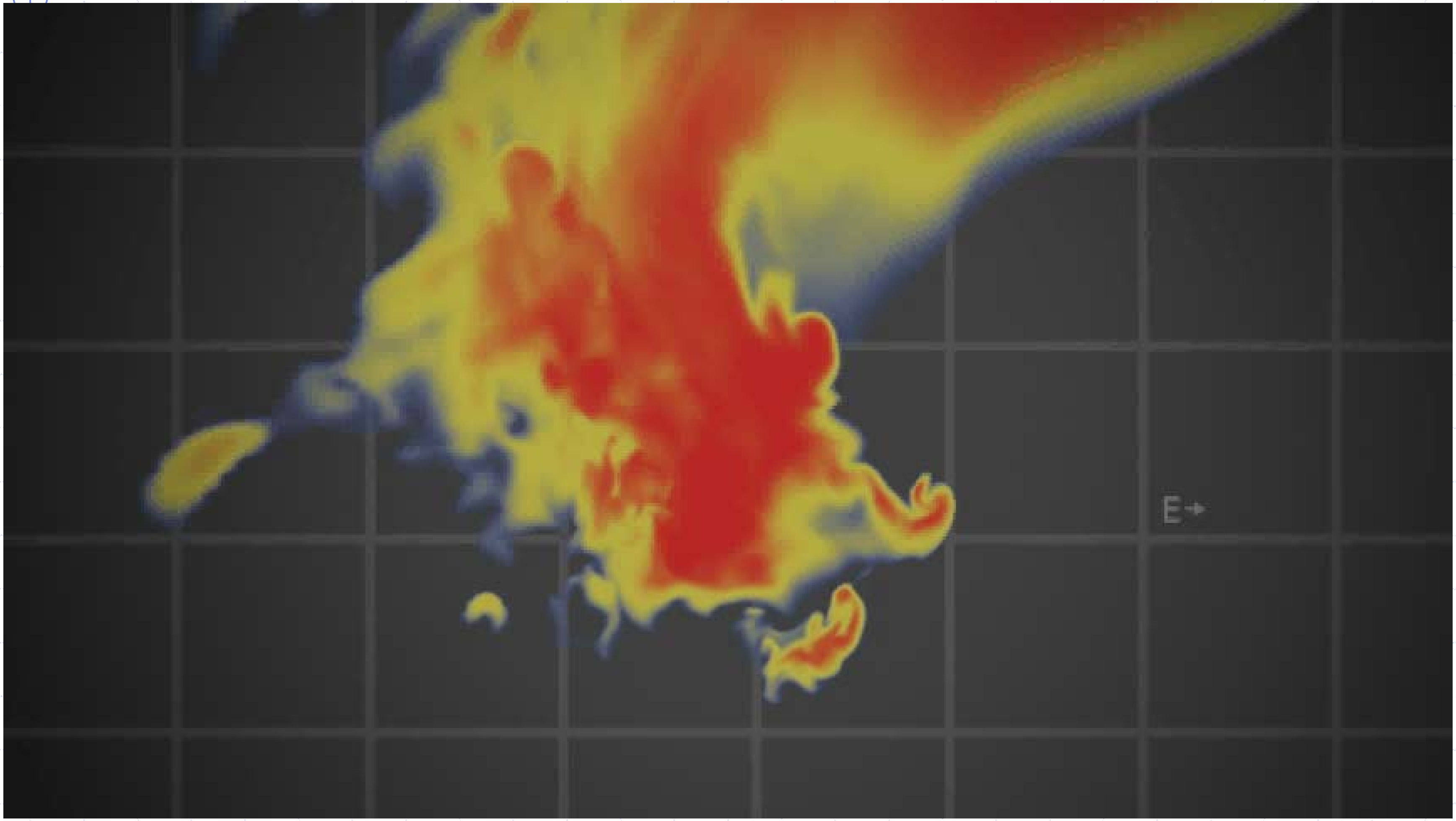
- Deployment of scalable radar systems
- Local, regional, national accessible databases
- Heavy involvement of state and local governments
- Potential commercial involvement
- Media involvement

Using Radar Data to Initialize Forecast Models

- Radar is the only technology that “measures” the atmosphere on the space and time scales of the phenomena one wants to forecast.
- Assimilation of radar data can retrieve wind, temperature, and “pressure” observations.

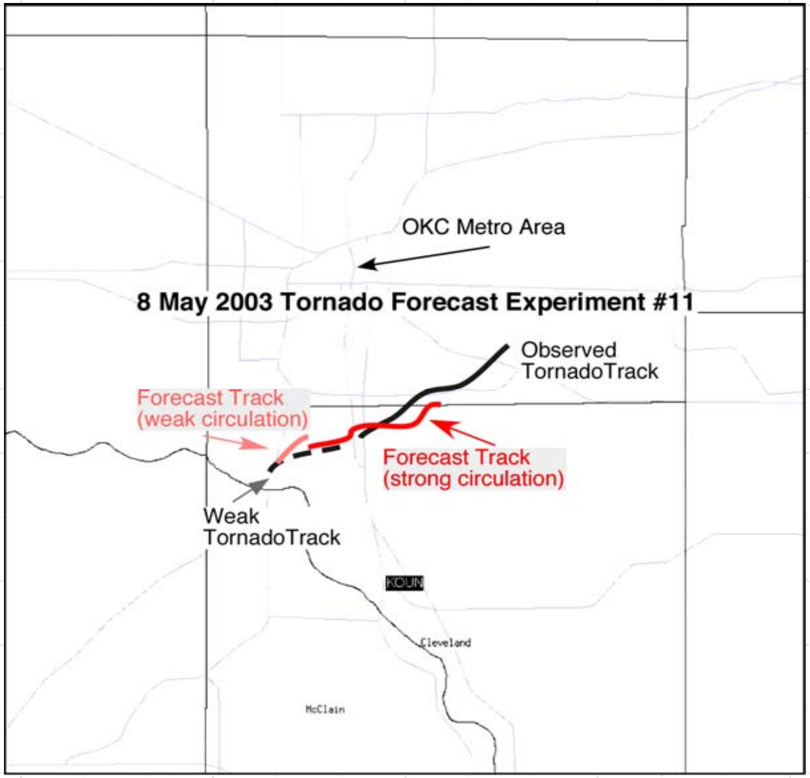


Using Radar Data to Initialize Forecast Models (2)

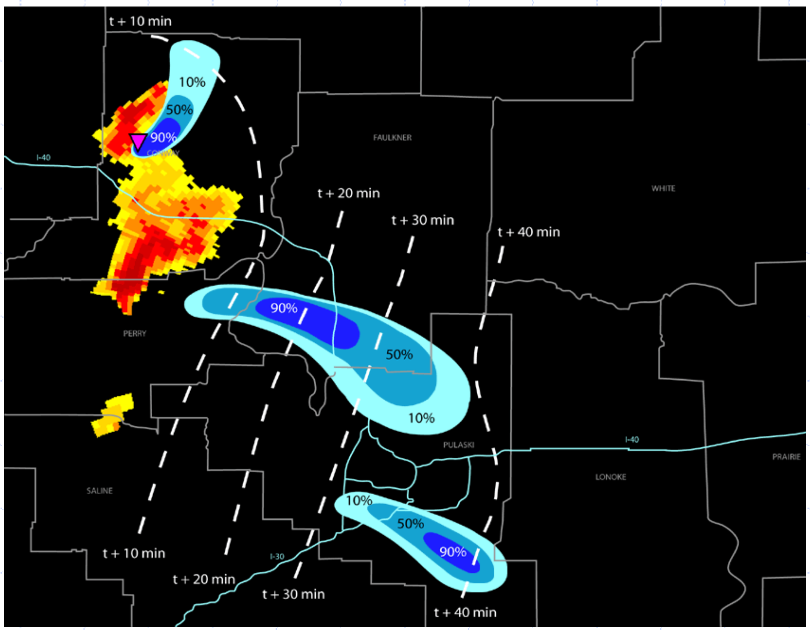


Using Radar Data to Initialize Forecast Models (3)

- Run very short term, very high resolution, ensemble based forecast models to get probabilistic forecasts of severe weather events.
- Move from "warn on detection" to "warn on forecast".
- Extend tornado lead times from 12 minutes to 45 minutes.



Using Radar Data to Initialize Forecast Models (4)



- WFUS54 KOUN 032330
- TOROKC
- OKC151-040000-

- BULLETIN - EAS ACTIVATION REQUESTED
- TORNADO WARNING
- NATIONAL WEATHER SERVICE NORMAN OK
- 630 PM CDT THU OCT 3 2002

- THE NATIONAL WEATHER SERVICE IN NORMAN HAS ISSUED A

- * TORNADO WARNING FOR...
- WOODS COUNTY IN NORTHWEST OKLAHOMA

- * UNTIL 700 PM CDT

- * AT 630 PM CDT...DOPPLER RADAR DETECTED A SEVERE THUNDERSTORM
- CAPABLE OF PRODUCING A TORNADO 13 MILES WEST OF CAPRON...MOVING
- EAST-NORTHEAST AT 30 MPH.

- * LOCATIONS IN THE WARNING INCLUDE CAPRON

- IN ADDITION TO THE TORNADO THREAT... A LINE OF SEVERE THUNDERSTORMS
- EXTENDS FROM THE KANSAS STATE LINE NORTHWEST OF ALVA TO 9 MILES WEST
- OF AVARD. THESE THUNDERSTORMS WILL BE CAPABLE OF PRODUCING DAMAGING
- WINDS AND HAIL TO THE SIZE OF HALF DOLLARS IN THE AVARD...CORA...
- AVARD...HOPETON AND ALVA AREAS.

- TAKE COVER NOW. LEAVE MOBILE HOMES AND VEHICLES. IF POSSIBLE...MOVE
- TO A BASEMENT OR STORM SHELTER. OTHERWISE MOVE TO AN INTERIOR ROOM OR
- HALLWAY ON THE LOWEST FLOOR. STAY AWAY FROM WINDOWS AND OUTSIDE
- WALLS.

- LAT...LON 3698 9895 3682 9884 3688 9854 3700 9854

- ...SPEG.

Summary

- PAR technology will become cheap.
- Multi-purpose radars are feasible:
  - Weather surveillance
  - Radar data assimilation into very high resolution, very short term, ensemble based forecast models
  - Aircraft tracking
  - Non-cooperative aircraft tracking
  - 4D measurements for dispersion winds
  - Chem/bio detection
- Polarization diversity, multi-frequency, active PAR T/R elements already exist.
- Can government agencies collaborate on a multi-purpose project of this magnitude?

Conclusions

- Radar is a very powerful tool for learning about the world.
- Now it is up to YOU to add to the knowledge by your own research!
- Good luck!