



Radar Meteorology

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Weather Radar



Weather radar in Norman, Oklahoma with rainshaft



Weather (WF44) radar dish

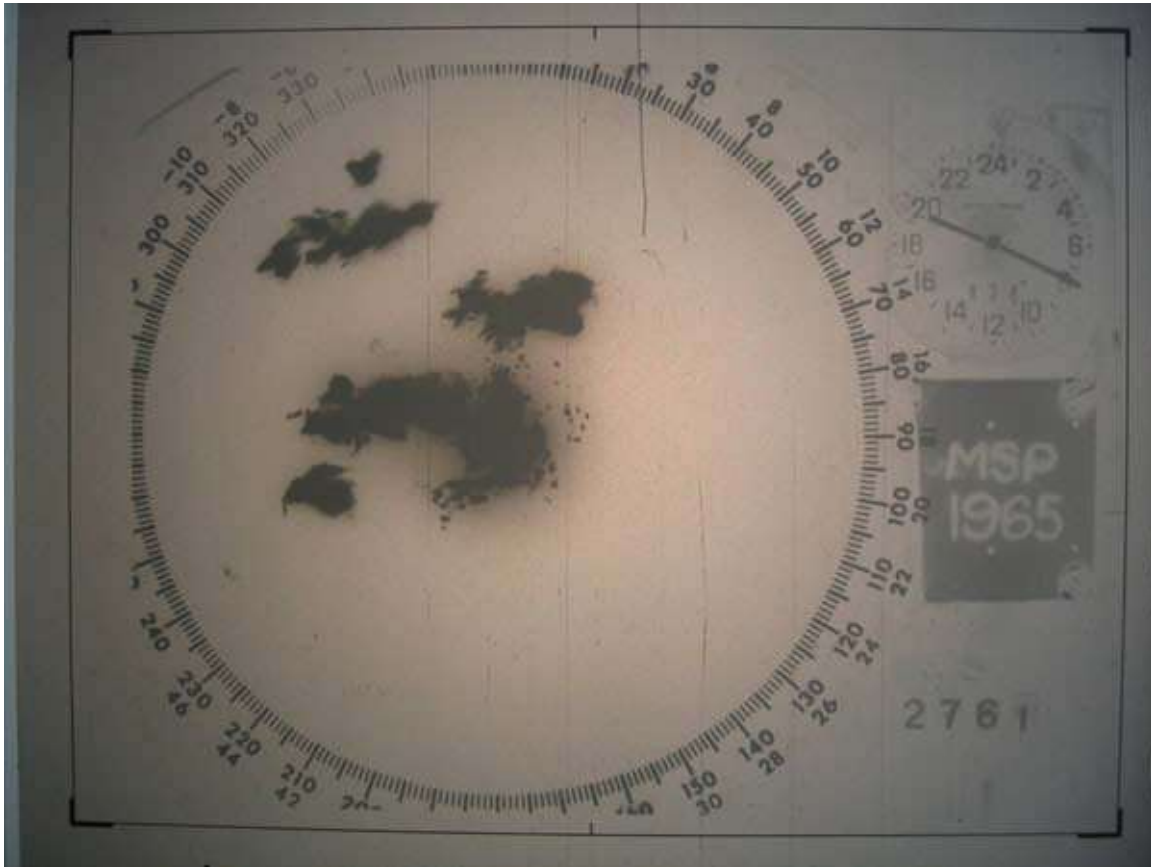


University of Oklahoma OU-PRIME C-band, polarimetric, weather radar during construction

A **weather radar**, or **weather surveillance radar (WSR)**, is a type of radar used to locate precipitation, calculate its motion, estimate its type (rain, snow, hail, etc.), and forecast its future position and intensity.

Modern weather radars are mostly pulse-Doppler radars, capable of detecting the motion of rain droplets in addition to intensity of the precipitation. Both types of data can be analyzed to determine the structure of storms and their potential to cause severe weather.

History



1960s radar technology detected tornado producing supercells over the Twin Cities metropolitan area.

During World War II, military radar operators noticed noise in returned echoes due to weather elements like rain, snow, and sleet. Just after the war, military scientists returned to civilian life or continued in the Armed Forces and pursued their work in developing a use for those echoes. In the United States, David Atlas, for the Air Force group at first, and later for MIT, developed the first operational weather radars. In Canada, J.S. Marshall and R.H. Douglas formed the "Stormy Weather Group" in Montreal. Marshall and his doctoral student Walter Palmer are well known for their work on the drop size distribution in mid-latitude rain that led to understanding of the Z-R relation, which correlates a given radar reflectivity with the rate at which water is falling on the ground. In the United Kingdom, research continued to study the radar echo patterns and weather elements such as stratiform rain and convective clouds, and experiments were done to evaluate the potential of different wavelengths from 1 to 10 centimetres.

In 1953, Donald Staggs, an electrical engineer working for the Illinois State Water Survey, made the first recorded radar observation of a "hook echo" associated with a tornadic thunderstorm.

Between 1950 and 1980, reflectivity radars, which measure position and intensity of precipitation, were built by weather services around the world. The early meteorologists had to watch a cathode ray tube. During the 1970s, radars began to be standardized and organized into networks. The first devices to capture radar images were developed. The number of scanned angles was increased to get a three-dimensional view of the precipitation, so that horizontal cross-sections (CAPPI) and vertical ones could be performed. Studies of the organization of thunderstorms were then possible for the Alberta Hail Project in Canada and National Severe Storms Laboratory (NSSL) in the US in particular.

The NSSL, created in 1964, began experimentation on dual polarization signals and on Doppler effect uses. In May 1973, a tornado devastated Union City, Oklahoma, just west of Oklahoma City. For the first time, a Dopplerized 10-cm wavelength radar from NSSL documented the entire life cycle of the tornado. The researchers discovered a mesoscale rotation in the cloud aloft before the tornado touched the ground : the tornadic vortex signature. NSSL's research helped convince the National Weather Service that Doppler radar was a crucial forecasting tool. The Super Outbreak of tornadoes on April 3–4, 1974 and their devastating destruction might have helped to get funding for further developments.

Between 1980 and 2000, weather radar networks became the norm in North America, Europe, Japan and other developed countries. Conventional radars were replaced by Doppler radars, which in addition to position and intensity of could track the relative velocity of the particles in the air. In the United States, the construction of a network consisting of 10 cm (4 in) wavelength radars, called NEXRAD or WSR-88D (Weather Service Radar 1988 Doppler), was started in 1988 following NSSL's research. In Canada, Environment Canada constructed the King City station, with a five centimeter research Doppler radar, by 1985; McGill University dopplerized its radar (J. S. Marshall Radar Observatory) in 1993. This led to a complete Canadian Doppler network between 1998 and 2004. France and other European countries switched to Doppler network by the end of the 1990s to early 2000s. Meanwhile, rapid advances in computer technology led to algorithms to detect signs of severe weather and a plethora of "products" for media outlets and researchers.

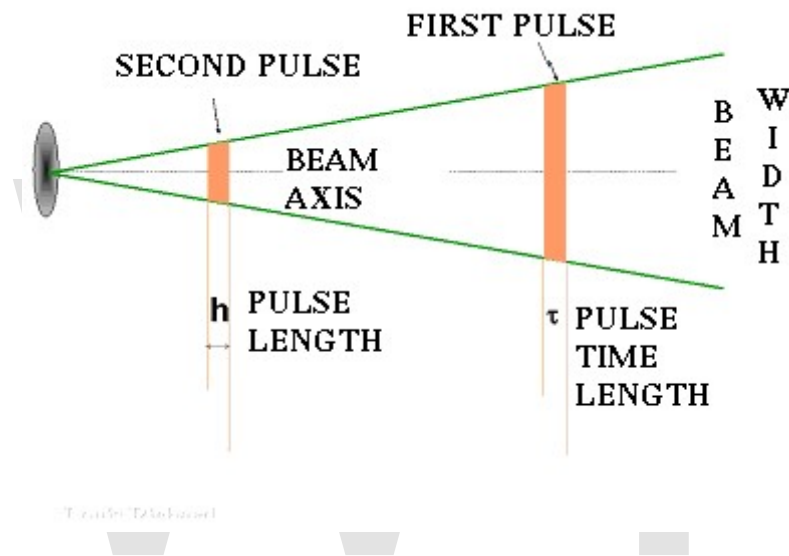
After 2000, research on dual polarization technology has moved into operational use, increasing the amount of information available on precipitation type (e.g. rain vs. snow). "Dual polarization" means that microwave radiation which is polarized both horizontally and vertically (with respect to the ground) is emitted. Wide-scale deployment is expected by the end of the decade in some countries such as the United States, France, and Canada.

Since 2003, the U.S. National Oceanic and Atmospheric Administration has been experimenting with phased-array radar as a replacement for conventional parabolic antenna to provide more time resolution in atmospheric sounding. This would be very important in severe thunderstorms as their evolution can be better evaluated with more timely data.

Also in 2003, the National Science Foundation established the Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere, "CASA", a multidisciplinary, multi-university collaboration of engineers, computer scientists, meteorologists, and sociologists to conduct fundamental research, develop enabling technology, and deploy prototype engineering systems designed to augment existing radar systems by sampling the generally undersampled lower troposphere with inexpensive, fast scanning, dual polarization, mechanically scanned and phased array radars.

How a weather radar works

Sending radar pulses



A radar beam spreads out as it moves away from the radar station, covering an increasingly large volume.

Weather radars send directional pulses of microwave radiation, on the order of a microsecond long, using a cavity magnetron or klystron tube connected by a waveguide to a parabolic antenna. The wavelengths of 1 to 10 cm (4 in) are approximately ten times the diameter of the droplets or ice particles of interest, because Rayleigh scattering occurs at these frequencies. This means that part of the energy of each pulse will bounce off these small particles, back in the direction of the radar station.

Shorter wavelengths are useful for smaller particles, but the signal is more quickly attenuated. Thus 10 cm (4 in) (S-band) radar is preferred but is more expensive than a 5 cm (2 in) C-band system. 3 cm (1 in) X-band radar is used only for very short distance purposes, and 1 cm (0.4 in) Ka-band weather radar is used only for research on small-particle phenomena such as drizzle and fog.

Radar pulses spread out as they move away from the radar station. This means that the region of air any given pulse is moving through is larger for areas farther away from the

station, and smaller for nearby areas, decreasing resolution at far distances. At the end of a 150–200 km sounding range, the volume of air scanned by a single pulse might be on the order of a cubic kilometer. This is called the *pulse volume*

The volume of air that a given pulse takes up at any point in time may be approximately calculated by the formula $v = hr^2\theta^2$, where v is the volume enclosed by the pulse, h is pulse width (in e.g. meters, calculated from the duration in seconds of the pulse times the speed of light), r is the distance from the radar that the pulse has already traveled (in e.g. meters), and θ is the beam width (in radians). This formula assumes the beam is symmetrically circular, " r " is much greater than " h " so " r " taken at the beginning or at the end of the pulse is almost the same, and the shape of the volume is a cone frustum of depth " h ".

Listening for return signals

Between each pulse, the radar station serves as a receiver and listens for return signals from particles in the air. The duration of the "listen" cycle is on the order of a millisecond, which is a thousand times longer than the pulse duration. The length of this phase is determined by the need for the microwave radiation (which travels at the speed of light) to propagate from the detector, to the weather target, and back again, a distance which could be several hundred kilometers. The horizontal distance from station to target is calculated simply from the amount of time that lapses from the initiation of the pulse to the detection of the return signal. (The time is converted into distance by multiplying by the speed of light). If pulses are emitted too frequently, the returns from one pulse will be confused with the returns from previous pulses, resulting in incorrect distance calculations.

Determining height

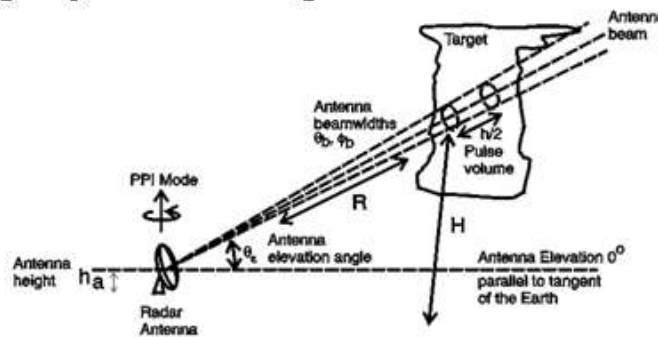
BEAM HEIGHT WITH DISTANCE (AGL)

$$H = \left(\sqrt{r^2 + (k_e a_e)^2 + 2r k_e a_e \sin(\theta_e)} \right) - k_e a_e + h_a$$

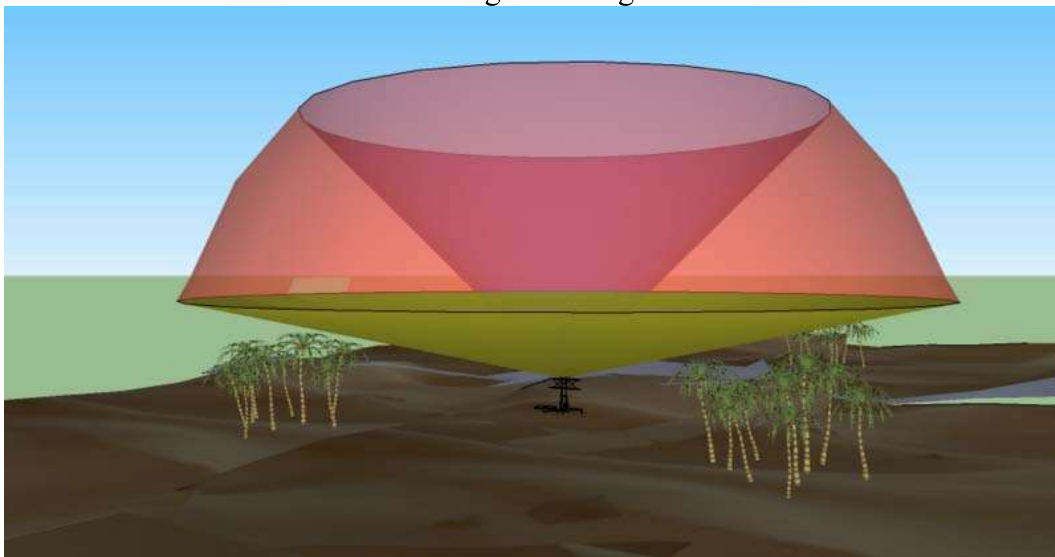
r : distance k_e : 4/3 (Standard refraction coefficient)

a_e : Earth radius θ_e : Elevation angle

h_a : Height of radar above ground



Echos height above ground



Scanned volume by using multiple elevation angles

Assuming the Earth is round, with knowledge of the variation of the index of refraction through air and the distance to the target, one can calculate the height above ground of the target. The image to the left shows the calculation of the height depending on the elevation angle of the antenna and other considerations.

Each Weather radar network use a series of typical angles that will be set according to the needs. After each scanning rotation, the antenna elevation is changed for the next sounding. This scenario will be repeated on many angles to scan all the volume of air around the radar within the maximum range. Usually, this scanning strategy is completed within 5 to 10 minutes to have data within 15 km (9 mi) above ground and 250 km (155 mi) distance of the radar. For instance in Canada, the 5 cm (2 in) weather radars use angles ranging from 0.3 to 25 degrees. The image to the right shows an hypothetical volume scanned when multiple angles are used.

Due to the Earth curvature and change of index of refraction with height, the radar cannot "see" below the height above ground of the minimal angle (shown in green) or closer to the radar than the maximal one (show as a red cone in the center).

Calibrating intensity of return

Because the targets are not unique in each volume, the radar equation has to be developed beyond the basic one:

$$P_r = \left[P_t \frac{G^2 \lambda^2 \sigma^0}{(4\pi)^3 R^4} \right] \propto \frac{\sigma^0}{R^4}$$

where P_r is received power, P_t is transmitted power, G_t is the gain of the transmitting antenna, λ is radar wavelength, σ is the radar cross section of the target and R is the distance from transmitter to target.

In this case, we have to add the cross sections of all the targets:

$$\sigma^0 = \bar{\sigma}^0 = V \sum \sigma_j^0 = V \eta$$

$$\left\{ \begin{array}{l} V = \text{scanned volume} \\ = \text{pulse length} \times \text{beam width} \\ = \left[\frac{c\tau}{2} \right] \left[\frac{\pi R^2 \theta^2}{4} \right] \end{array} \right.$$

where c is the light speed, τ is temporal duration of a pulse and θ is the beam width in radians.

In combining the two equations :

$$P_r = \left[P_t \frac{G^2 \lambda^2}{(4\pi)^3 R^4} \right] \left[\frac{c\tau}{2} \right] \left[\frac{\pi R^2 \theta^2}{4} \right] \eta = \left[P_t \tau G^2 \lambda^2 \theta^2 \right] \left[\frac{c}{512(\pi^2)} \right] \frac{\eta}{R^2}$$

Which leads to:

$$P_r \propto \frac{\eta}{R^2}$$

Notice that the return now varies inversely to R^2 instead of R^4 . In order to compare the data coming from different distances from the radar, one has to normalize them with this ratio.

Data types

Reflectivity (in decibel or dBZ)

Return echoes from targets, reflectivity, are analyzed for their intensities to establish the precipitation rate in the scanned volume. The wavelengths used (1 to 10 cm) ensure that this return is proportional to the rate because they are within the validity of Rayleigh scattering which states that the targets must be much smaller than the wavelength of the scanning wave (by a factor of 10).

Reflectivity perceived by the radar (Z_e) varies by the 6th power of the rain droplets' diameter (D), the square of the dielectric constant (K) of the targets and the drop size distribution (e.g. $N[D]$ of *Marshall-Palmer*) of the drops. This gives a truncated Gamma function, of the form:

$$Z_e = \int_0^{D_{max}} |K|^2 N_0 e^{-\Lambda D} D^6 dD$$

Precipitation rate (R), on the other hand, is equal to the number of particles, their volume and their fall speed ($v[D]$) as:

$$R = \int_0^{D_{max}} N_0 e^{-\Lambda D} (\pi D^3 / 6) v(D) dD$$

So Z_e and R have similar functions that can be resolved giving a relation between the two of the form:

$$Z = aR^b$$

Where a and b depend on the type of precipitations (snow, rain, convective or stratiform) which have different Λ , K , N_0 and v .

- As the antenna scans the atmosphere, on every angle of azimuth it obtains a certain number of return from each targets encountered. Reflectivity is then averaged for that target to have a better data set.
- Since variation in diameter and dielectric constant of the targets can lead to large variability in power return to the radar, reflectivity is expressed in dBZ (10 times the logarithm of the ratio of the echo to a standard 1 mm diameter drop filling the same scanned volume).

How to read reflectivity on a radar display

Radar returns are usually described by colour or level. The colours in a radar image normally range from blue or green for weak returns, to red or magenta for very strong returns. The numbers in a verbal report increase with the severity of the returns. For example, the U.S. National Doppler Radar sites use the following scale for different levels of reflectivity:

- magenta: 65 dBZ (extremely heavy precipitation, possible hail)
- red: 52 dBZ
- yellow: 36 dBZ
- green: 20 dBZ (light precipitation)

Strong returns (red or magenta) may indicate not only heavy rain but also thunderstorms, hail, strong winds, or tornadoes, but they need to be interpreted carefully, for reasons described later.

Aviation conventions

When describing weather radar returns, pilots, dispatchers, and air traffic controllers will typically refer to three return levels:

- **level 1** corresponds to a green radar return, indicating usually light precipitation and little to no turbulence, leading to a possibility of reduced visibility.
- **level 2** corresponds to a yellow radar return, indicating moderate precipitation, leading to the possibility of very low visibility, moderate turbulence and an uncomfortable ride for aircraft passengers.
- **level 3** corresponds to a red radar return, indicating heavy precipitation, leading to the possibility of thunderstorms and severe turbulence and serious structural damage to the aircraft.

Aircraft will try to avoid level 2 returns when possible, and will always avoid level 3 unless they are specially-designed research aircraft.

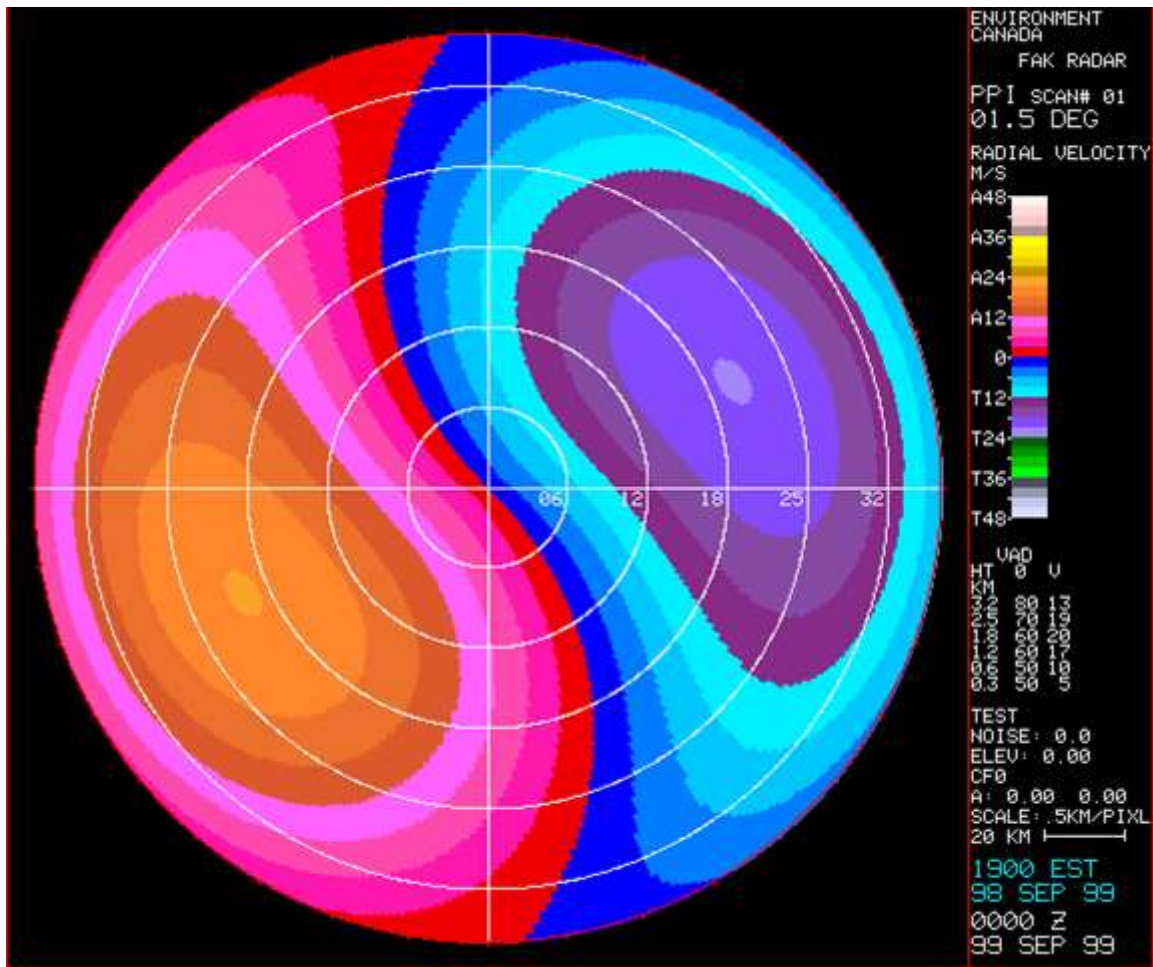
Precipitation types

Some displays provided by commercial weather sites, like The Weather Channel or *Intellcast*, show precipitation types during the winter month : rain, snow, mixed precipitations (sleet and freezing rain). This is not an analysis of the radar data itself but a post-treatment done with other data sources, the primary being surface reports (METAR).

Over the area covered by radar echoes, a program assigns a precipitation type according to the surface temperature and dew point reported at the underlying weather stations. Precipitation types reported by human operated stations and certain automatic ones (AWOS) will have higher weight. Then the program does interpolations to produce an image with defined zones. These will include interpolation errors due to the calculation. Mesoscale variations of the precipitation zones will be lost, too. More sophisticated program will use the numerical weather prediction output from models, such as NAM and WRF, for the precipitation types and apply it as a first guess to the radar echoes. Then use the surface data for final output.

Until dual-polarization (section Polarization below) data are widely available, any precipitation types on radar images are only indirect information and must be taken with care.

Velocity



Idealized example of Doppler output. Approaching velocities are in blue and receding velocities are in red. Notice the sinusoidal variation of speed when going around the display at a particular range.

Pulse pair

Any rain drops or snow flakes in motion affect the frequency of the returned radar beam according to the Doppler effect. With velocities of less than 70 m/s (150 miles/h) for weather echos and radar wavelength of 10 cm (4 in), it amounts to only $10^{-5}\%$. This difference is too small to be noted by electronic instruments. However, as the targets move slightly between each pulse, the returned wave has a noticeable phase difference or *phase shift* from pulse to pulse.

Doppler weather radars are using this phase difference (pulse pair difference) to calculate the precipitation's motion. The intensity of the successively returning pulse from the same scanned volume where targets have slightly moved is :

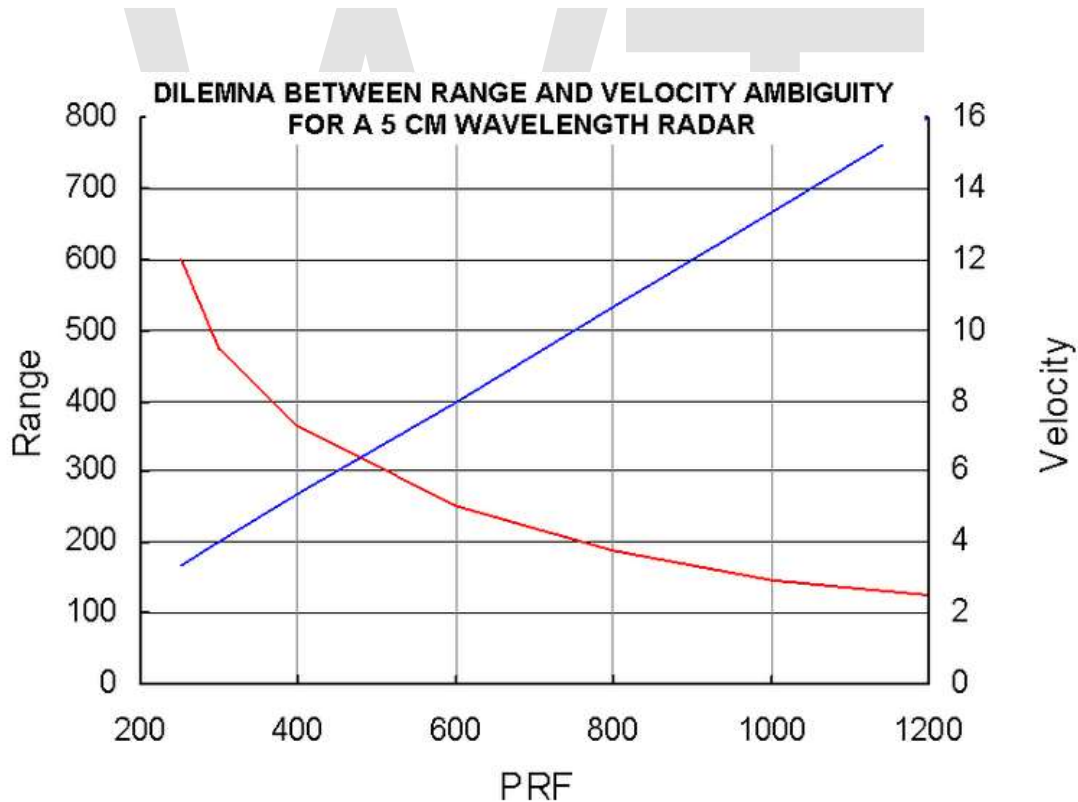
$$I = I_0 \sin\left(\frac{4\pi(x_0 + v\Delta t)}{\lambda}\right) = I_0 \sin(\Theta_0 + \Delta\Theta) \begin{cases} x = \text{distance radar to target} \\ \lambda = \text{radar wavelength} \\ \Delta t = \text{time between two pulses} \end{cases}$$

So
$$\Delta\Theta = \left(\frac{4\pi v \Delta t}{\lambda}\right)$$

$$v = \text{target speed} = \frac{\lambda \Delta\Theta}{4\pi \Delta t}$$

This speed is called the radial Doppler velocity because it gives only the radial variation of distance versus time between the radar and the target. The real speed and direction of motion has to be extracted by the process described below.

Doppler dilemma



Maximum range from reflectivity (red) and unambiguous Doppler velocity range (blue) with pulse repetition frequency.

The phase between pulse pairs can vary from $-\pi$ and $+\pi$, so the unambiguous Doppler velocity range is

$$V_{\max} = \pm \frac{\lambda}{4\Delta t}$$

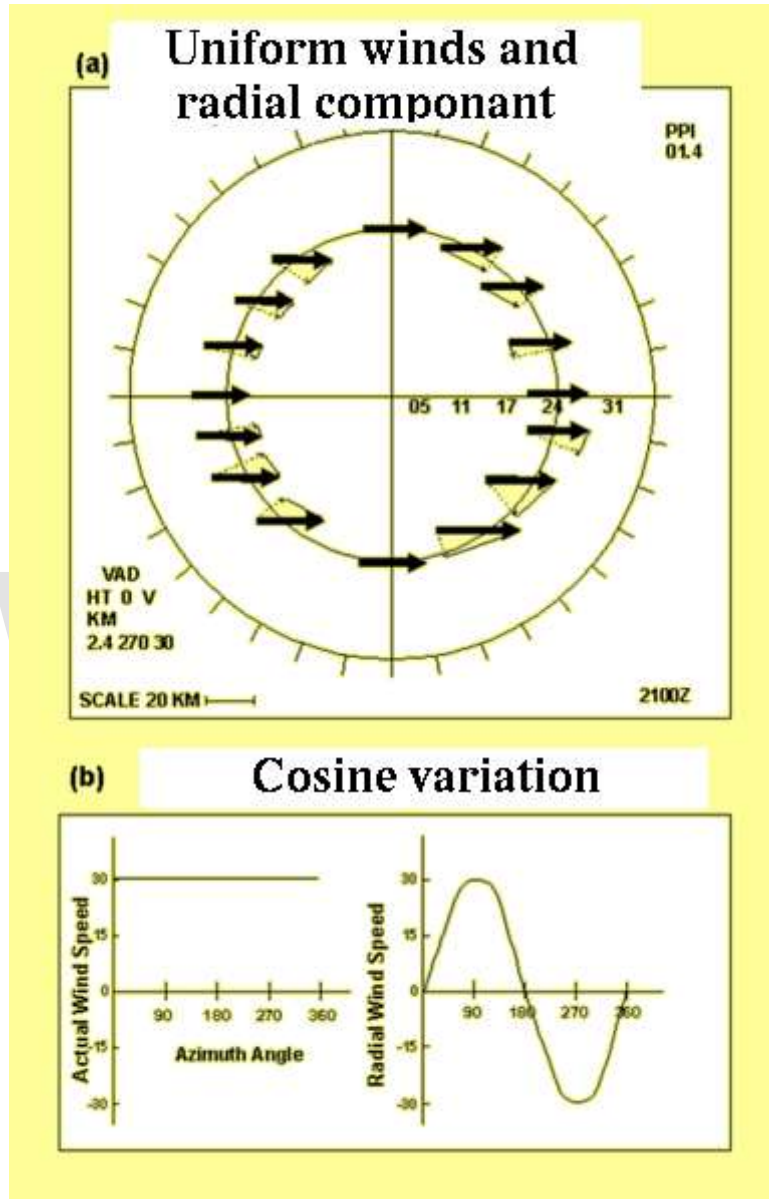
This is called the Nyquist velocity. This is inversely dependent on the time between successive pulses: the smaller the interval, the larger is the unambiguous velocity range. However, we know that the maximum range from reflectivity is directly proportional to Δt :

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

The choice becomes increasing the range from reflectivity at the expense of velocity range, or increasing the latter at the expense of range from reflectivity. In general, the useful range compromise is 100 to 150 km (93 mi) for reflectivity. This means for a wavelength of 5 cm (2 in), like on the image, an unambiguous velocity range of 12.5 to 18.75 m/s is produced (for 150 km and 100 km, respectively) . For a 10 cm (4 in) radar like the NEXRAD the unambiguous velocity range would be doubled.

Some techniques using two alternating pulse repetition frequencies (PRF) permit to extend the Doppler range. The velocities noted with the first pulse rate could be equal or different with the second. For instance, if the maximum velocity with a certain rate is 10 m/s and the one with the other rate is 15 m/s. The data coming from both will be the same up to 10 m/s and differ afterward. It is then possible to find a mathematical relation between the two returns and calculate the real velocity beyond the limitation of the two PRF.

Doppler interpretation



Radial component of real winds when scanning on 360 degrees.

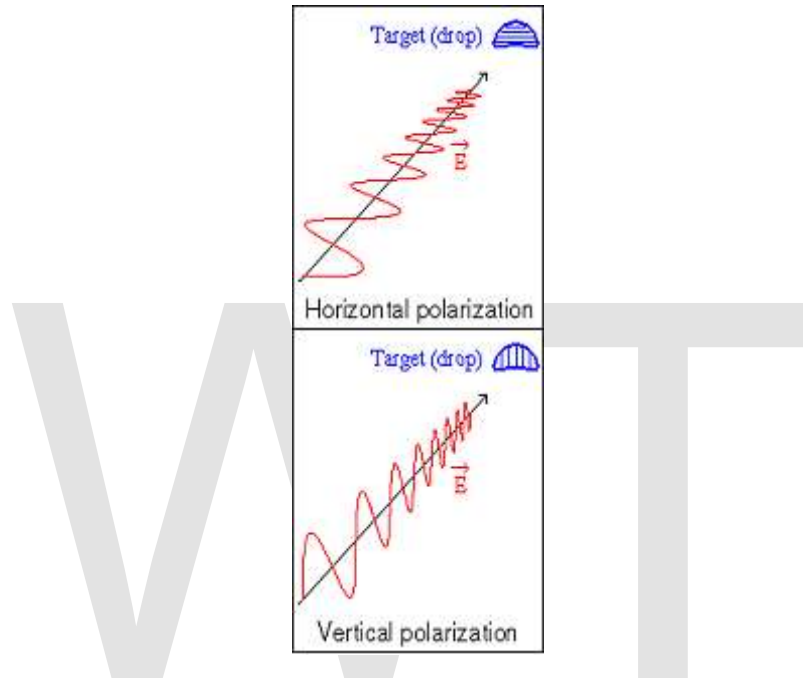
If one thinks of an autumn rain uniformly filling the radar area coverage and moving from west to east, one notes that a radar beam pointing west will "see" the raindrops moving toward itself, while a beam pointing east will "see" the drops moving away. On the other hand, looking north or south, since there is no motion toward the radar in those directions, the radial velocity is null.

As the beam is scanning 360 degrees around the radar, data will come from all those angles and be the radial projection of the actual wind on the individual angle. The intensity pattern formed by this scan can be represented by a cosine curve, as seen on the

right. One can then calculate the direction and the strength of the motion of particles as long as there is enough coverage on the radar screen.

However, the rain drops are falling. As the radar only sees the radial component and has a certain elevation from ground, the radial velocities are contaminated by some fraction of the falling speed. This component is negligible in small elevation angles, but must be taken into account for higher scanning angles.

Polarization



Targeting with dual-polarization will reveal the form of the droplet

Most liquid hydrometeors have a larger horizontal axis due to the drag coefficient of air while falling (water droplets). This causes the water molecule dipole to be oriented in that direction so radar beams are generally polarized horizontally to receive the maximal return.

If we decide to send simultaneously two pulses with orthogonal polarization: vertical and horizontal, Z_V and Z_H respectively, we receive two sets of data proportional to the two axis of the droplets that are independent:

- Differential Reflectivity (Z_{dr}) – The differential reflectivity is the ratio of the reflected vertical and horizontal power returns as Z_V/Z_H . Among other things, it is a good indicator of drop shape and drop shape is a good estimate of average drop size.
- Correlation Coefficient (ρ_{hv})– A statistical correlation between the reflected horizontal and vertical power returns. High values, near one,

indicate homogeneous precipitation types, while lower values indicate regions of mixed precipitation types, such as rain and snow, or hail.

- Linear Depolarization Ratio (*LDR*) – This is a ratio of a vertical power return from a horizontal pulse or a horizontal power return from a vertical pulse. It can also indicate regions where there is a mixture of precipitation types.
- Specific Differential Phase (θ_{dp}) – The specific differential phase is a comparison of the returned phase difference between the horizontal and vertical pulses. This change in phase is caused by the difference in the number of wave cycles (or wavelengths) along the propagation path for horizontal and vertically polarized waves. It should not be confused with the Doppler frequency shift, which is caused by the motion of the cloud and precipitation particles. Unlike the differential reflectivity, correlation coefficient and linear depolarization ratio, which are all dependent on reflected power, the specific differential phase is a "propagation effect." It is a very good estimator of rain rate and is not affected by attenuation.

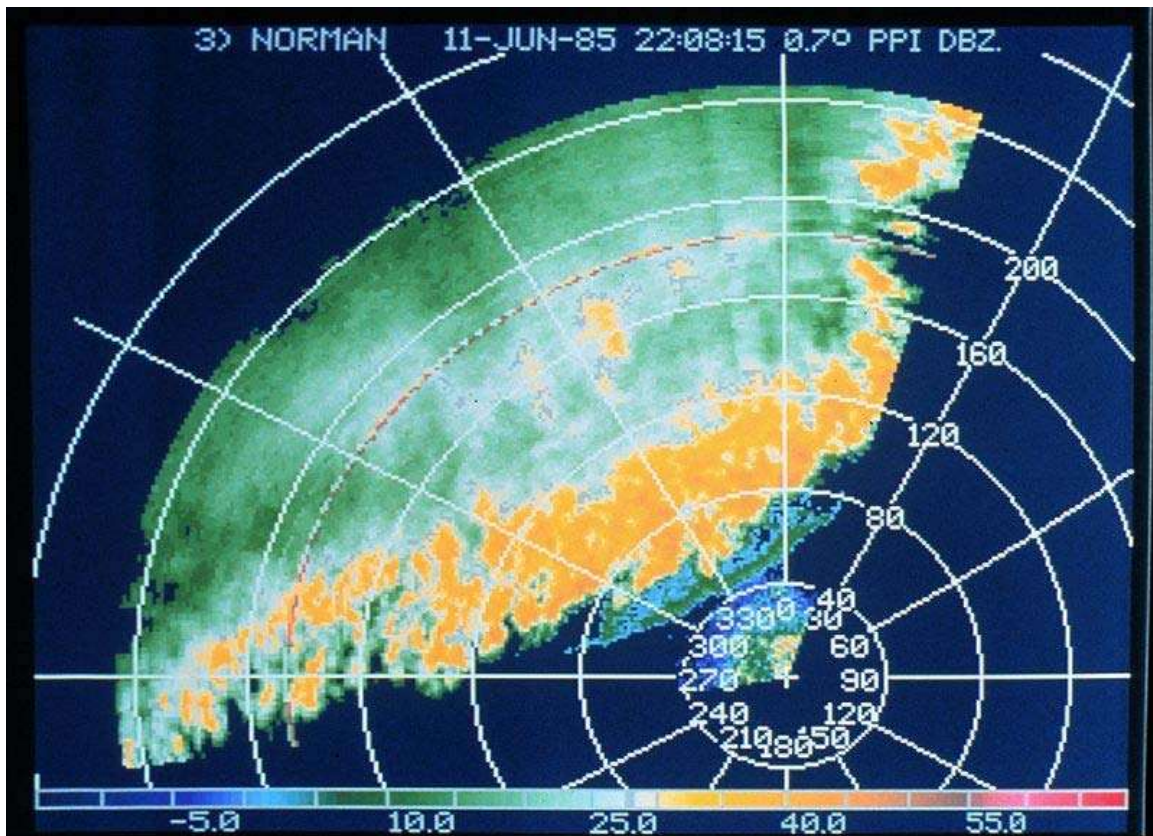
With this new knowledge added to the reflectivity, velocity, and spectrum width produced by Doppler weather radars, researchers have been working on developing algorithms to differentiate precipitation types, non-meteorological targets, and to produce better rainfall accumulation estimates. In the U.S., NCAR and NSSL have been world leaders in this field.

NOAA has set up a test bed for dual-polametric radar at NSSL and plans to equip all its 10 cm (4 in) wavelength NEXRAD radars with dual-polarization by the end of the decade. McGill University J. S. Marshall Radar Observatory in Montreal, Canada has converted their instrument (1999) and the data are used operationally by Environment Canada in Montreal. Another Environmental Canada radar in King City (North of Toronto) was dual-polarized in 2005, this one works on a 5 cm (2 in) wavelength which gives new challenges, specifically greater attenuation. Environmental Canada is working on converting all of its radars to dual-polarization. Finally, Météo-France is working on the subject and hopes to set up their first polarized radars in 2008.

Main types of radar outputs

All data from radar scans are displayed according to the need of the users. Different outputs have been developed through time to reach this. Here is a list of common and specialized outputs available.

Plan position indicator



Thunderstorm line viewed in reflectivity (dBZ) on a PPI

Since data are obtained one angle at a time, the first way of displaying them has been the Plan Position Indicator (PPI) which is only the layout of radar return on a two dimensional image. One has to remember that the data coming from different distances to the radar are at different heights above ground.

This is very important as a high rain rate seen near the radar is relatively close to what reach the ground but what is seen from 160 km (99 mi) (100 miles) away is about 1.5 km (1 mi) above ground and could be far different from the amount reaching the surface. It is thus difficult to compare weather echoes at different distance from the radar.

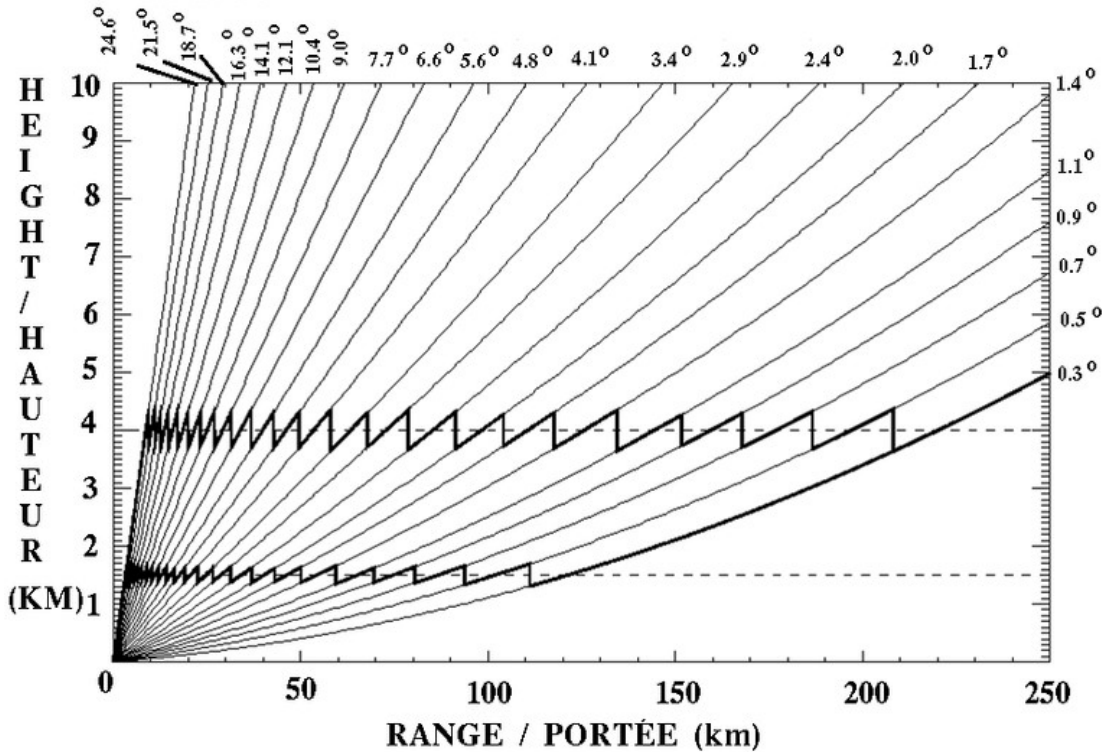
PPIs are afflicted with ground echoes near the radar as a supplemental problem. These can be misinterpreted as real echoes. So other products and further treatments of data have been developed to supplement its shortcomings.

USAGE: Reflectivity, Doppler and polarimetric data can use PPI.

N.B.: In the case of Doppler data, two points of view are possible: relative to the surface or the storm. When looking at the general motion of the rain to extract wind at different

altitudes, it is better to use data relative to the radar. But when looking for rotation or wind shear under a thunderstorm, it is better to use the storm relative images that subtract the general motion of precipitation leaving the user to view the air motion as if he would be sitting on the cloud.

Constant Altitude Plan Position Indicator



Typical angles scanned in Canada. The zigzag represent data angles used to make CAPPIs at 1.5 & 4 km (2 mi) of altitude

To avoid some of the problems on PPIs, the CAPPI or Constant Altitude Plan Position Indicator has been developed by researchers in Canada. It is basically a horizontal cross-section through radar data. This way, one can compare precipitation on an equal footing at difference distance from the radar and avoid ground echoes. Although data are taken at a certain height above ground, a relation can be inferred between ground stations reports and the radar data.

CAPPIs call for a large number of angles from near the horizontal to near the vertical of the radar to have a cut that is as close as possible at all distance to the height needed. But even then, after a certain distance, there isn't any angle available and the CAPPI becomes the PPI of the lowest angle. The zigzag line on the angles diagram above shows the data used to produce a 1.5 and 4 km (2 mi) height CAPPIs. Notice that the section after 120 km (75 mi) is using the same data.

Usage

Since the CAPPI uses the closest angle to the desired height at each point from the radar, the data can originate from slightly different altitudes, as seen on the image, in different points of the radar coverage. It is therefore crucial to have a large enough number of sounding angles to minimize this height change. Furthermore, the type of data must be changing relatively gradually with height to produce an image that is not noisy.

Reflectivity data being relatively smooth with height, CAPPIs are mostly used for displaying them. Velocity data, on the other hand, can change rapidly in direction with height and CAPPIs of them are not common. It seems that only McGill University is producing regularly Doppler CAPPIs with the 24 angles available on their radar. However, some researchers have published papers using velocity CAPPIs to study tropical cyclones and development of NEXRAD products. Finally, polarimetric data are recent and often noisy. There doesn't seem to have regular use of CAPPI for them although the *SIGMET* company offers software capable to produce those type of images.

Real time examples

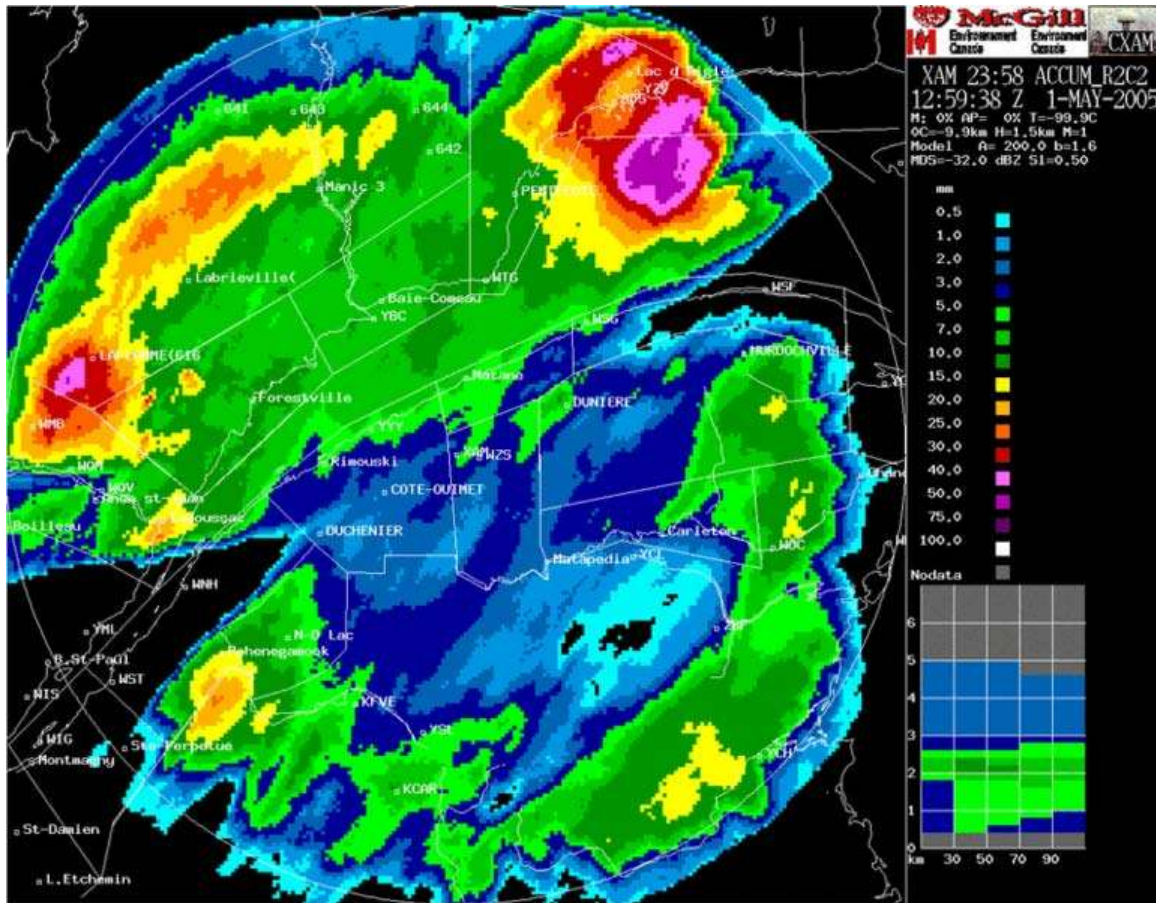
- McGill University
- Environment Canada

Vertical composite

Another solution to the PPI problems is to produce images of the maximum reflectivity in a layer above ground. This solution is usually taken when the number of angles available is small or variable. The American National Weather Service is using such Composite as their scanning scheme can vary from 4 to 14 angles, according to their need, which would make very coarse CAPPIs. The Composite makes sure that no strong echo is missed in the layer and a treatment using Doppler velocities eliminates the ground echoes. Comparing base and composite products, one can locate virga and updraft zones.

Real time example: NWS Burlington radar, one can compare the BASE and COMPOSITE products

Accumulations



24 hours rain accumulation on the Val d'Irène radar in Eastern Canada. Notice the zones without data in the East and Southwest caused by radar beam blocking from mountains.

One of the main use of radar is to be able to assess the amount of precipitations fallen over large basins for hydrological purpose. For instance, river flood control, sewer management and dam construction are all areas where planners want accumulation data. It ideally completes surface stations data which they can use for calibration.

To produce radar accumulations, we have to estimate the rain rate over a point by the average value over that point between one PPI, or CAPPI, and the next; then multiply by the time between those images. If one wants for a longer period of time, one has to add up all the accumulations from images during that time.

Echotops

Aviation is a heavy user of radar data. One map particularly important in this field is the Echotops for flight planning and avoidance of dangerous weather. Most country weather radars are scanning enough angles to have a 3D set of data over the area of coverage. It is relatively easy to estimate the maximum altitude at which precipitation is found within

the volume. However, those are not the tops of clouds as they extend to higher altitudes than the precipitation.

Vertical cross sections

To know the vertical structure of clouds, in particular thunderstorms or the level of the melting layer, a vertical cross sections product of the radar data is available to meteorologist. This is done by displaying only the data along a line, from coordinates A to B, taken from the different angles scanned.

Range Height Indicator

When a weather radar is scanning in only one direction vertically, it obtains high resolution data along a vertical cut of the atmosphere. The output of this sounding is called a *Range Height Indicator* (RHI) which is excellent for viewing the detailed vertical structure of a storm. This is different from the vertical cross section mentioned above by the fact that the radar is making a vertical cut along specific directions and does not scan over the entire 360 degrees around the site. This kind of sounding and product is only available on research radars.

Radar networks



Berrimah Radar in Darwin, Northern Territory Australia

To help meteorologists to spot dangerous weather, mathematical algorithms have been introduced in the weather radar treatment programs. These are particularly important in the analyzing the Doppler velocity data as they are more complex. The polarization data will even need more algorithms.

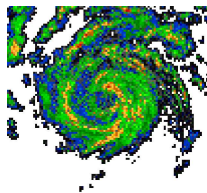
Main algorithms for reflectivity:

- Vertically Integrated Liquid (VIL) is an estimate of the total mass of precipitation in the clouds.
- *VIL Density* is VIL divided by the height of the cloud top. It is a clue to the possibility of large hail in thunderstorms.
- *Potential wind gust*, which can estimate the winds under a cloud (a downdraft) using the VIL and the height of the echotops (radar estimated top of the cloud) for a given storm cell.
- Hail algorithms that estimates the presence and its potential size.

Main algorithms for Doppler velocities:

- Mesocyclone detection: it is triggered by a velocity change over a small circular area. The algorithm is searching for a "*doublet*" of inbound/outbound velocities with the zero line of velocities, between the two, along a radial line from the radar. Usually the mesocyclone detection must be found on two or more stacked progressive tilts of the beam to be significative of rotation into a thunderstorm cloud.
- TVS or Tornado Vortex Signature algorithm is essentially a mesocyclone with a large velocity threshold found through many scanning angles. This algorithm is used in NEXRAD to indicate the possibility of a tornado formation.
- Wind shear in low levels. This algorithm detects variation of wind velocities from point to point in the data and looking for a *doublet* of inbound/outbound velocities with the zero line perpendicular to the radar beam. The wind shear is associated with downdraft, (downburst and microburst), gust fronts and turbulence under thunderstorms.
- VAD Wind Profile (VWP) is a display that estimates the direction and speed of the horizontal wind at various upper levels of the atmosphere, using the technique explained in the Doppler section.

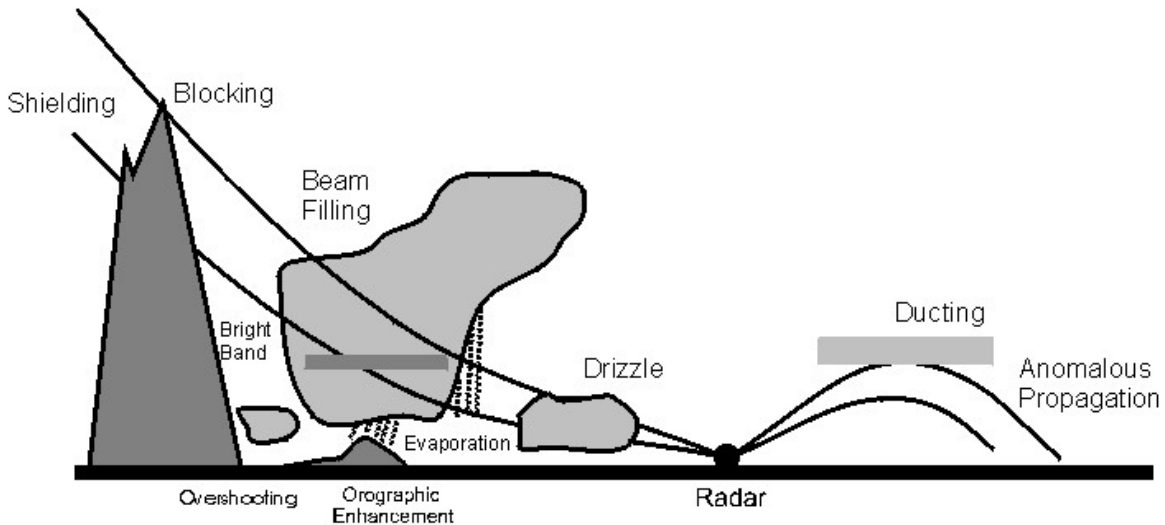
Animations



PPI reflectivity loop(in dBZ) showing the evolution of a hurricane

The animation of radar products can show the evolution of reflectivity and velocity patterns. The user can extract information on the dynamics of the meteorological phenomena, including the ability to extrapolate the motion and observe development or dissipation. This can also reveal non-meteorological artifacts (false echoes) that will be discussed later.

Limitations and artifacts



Radar data interpretation depends on many hypotheses about the atmosphere and the weather targets. They are:

- International Standard Atmosphere.
- Targets small enough that they obey the Rayleigh scattering so the return is proportional to the precipitation rate.
- The volume scanned by the beam is full of *meteorological* targets (rain, snow, etc..), all of the same variety and in a uniform concentration.
- No attenuation
- No amplification
- Return from side lobes of the beam are negligible.
- The beam is close to a Gaussian function curve with power decreasing to half at half the width.
- The outgoing and returning waves are both polarized similarly.
- There is no return from multiple reflections.

One has to keep in mind that these hypotheses are not necessarily met in many circumstances. One has to be able to recognize the truth from the false echoes.

Anomalous propagation (non-standard atmosphere)

The first assumption is that the radar beam is moving through air that cools down at a certain rate with height. The position of the echoes depend heavily on this hypothesis. However, the real atmosphere can vary greatly from the norm.

Super refraction

It is very common to have temperature inversions forming near the ground, for instance air cooling at night while remaining warm aloft. As the index of refraction of air decreases faster than normal the radar beam bends toward the ground instead of continuing upward. Eventually, it will hit the ground and be reflected back toward the radar. The processing program will then wrongly place the return echoes at the height and distance it would have been in normal conditions.

This type of false return is relatively easy to spot on a time loop if it is due to night cooling or marine inversion as one sees very strong echoes developing over an area, spreading in size laterally but not moving and varying greatly in intensity. However, inversion of temperature exists ahead of warm fronts and the abnormal propagation echoes are then mixed with real rain.

The extreme of this problem is when the inversion is very strong and shallow, the radar beam reflects many times toward the ground as it has to follow a waveguide path. This will create multiple bands of strong echoes on the radar images.

This situation can be found with inversions of temperature aloft or rapid decrease of moisture with height. In the former case, it could be difficult to notice.

Under refraction

On the other hand, if the air is unstable and cools faster than the standard atmosphere with height, the beam ends up higher than expected. This places the precipitation at a much higher altitude than it actually is. This situation is very difficult to spot.

Non-Rayleigh targets

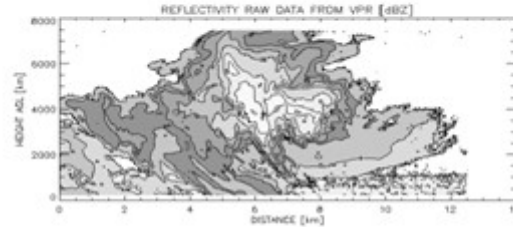
If we want to reliably estimate the precipitation rate, the targets have to be 10 times smaller than the radar wave according to Rayleigh scattering. This is because the water molecule has to be excited by the radar wave to give a return. This is relatively true for rain or snow as 5 or 10 cm (4 in) radars are used.

However, for very large hydrometeors, since the wavelength is on the order of stone, the return levels off according to Mie theory. A return of more than 55 dBZ is likely to come from hail but won't vary proportionally to the size. On the other hand, very small targets, like cloud droplets, are too small to be excited and don't give a recordable return on common weather radars.

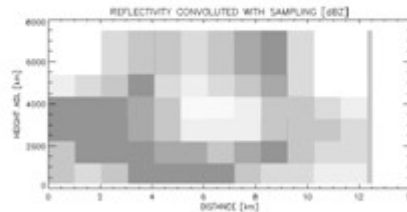
Resolution and partially filled scanned volume

PARTIAL BEAMFILLING ON REFLECTIVITY GRADIENT

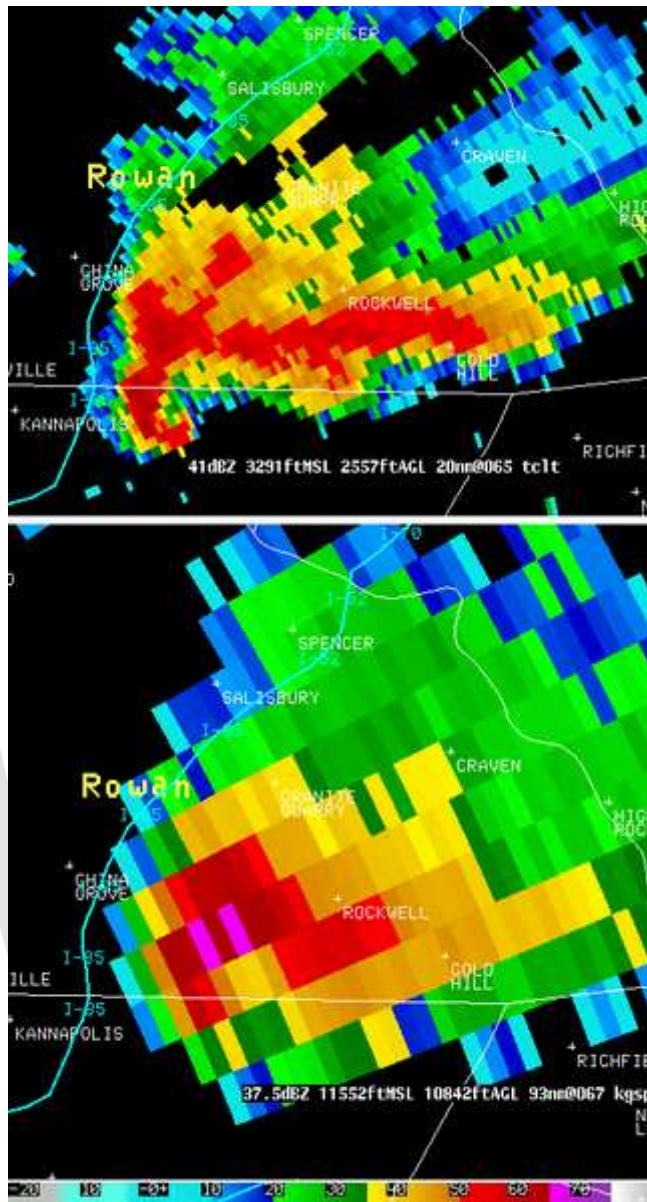
Thunderstorm cross-section from a wind profiler



Simulation of the same data but with a scanning radar at 60 km distance



Profiler high resolution view of a thunderstorm (top) and by a weather radar (bottom).



A supercell thunderstorm seen from two radars almost colocated. The top image is from a TDWR and the bottom one from a NEXRAD.

As demonstrated at the start, radar beams have a physical dimension and data are sampled every degree, not continuously, along each angle of elevation. This results in an averaging of the values of the returns for reflectivity, velocities and polarization data on the resolution volume scanned.

In the figure to the left, at the top is a view of a thunderstorm taken by a wind profiler as it was passing overhead. This is like a vertical cross section through the cloud with 150 m vertical and 30 m horizontal resolution. We can see that the reflectivity has large variations in a short distance. Now compare this with a simulated view of what a regular weather radar would see at 60 km (37 mi) (40 miles) at the bottom. Everything has been

smoothed out. Not only the coarser resolution of the radar blur the image but the sounding incorporate area that are echo free, thus extending the thunderstorm beyond its real boundaries.

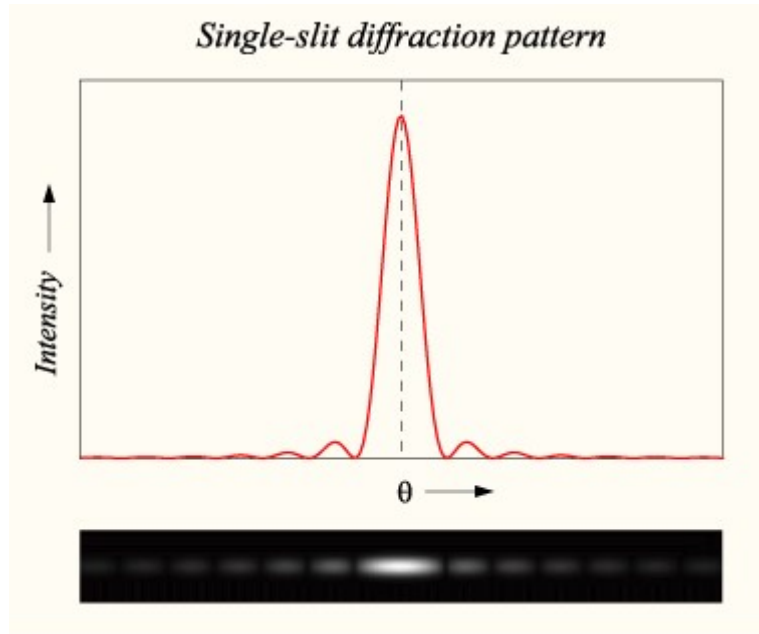
This shows how the output of weather radar is only an approximation of the reality. The image to the right compare real data from two radars almost colocated. The TWDR has about half the beamwidth of the other and one can see twice more details than with the NEXRAD.

Naturally, resolution can be improved by newer equipment but some things cannot. As mentioned previously, the volume scanned increases with distance so the possibility that the beam is only partially filled increases too. This leads to underestimation of the precipitation rate at larger distances and fools the user into thinking that rain is lighter as it moves away.

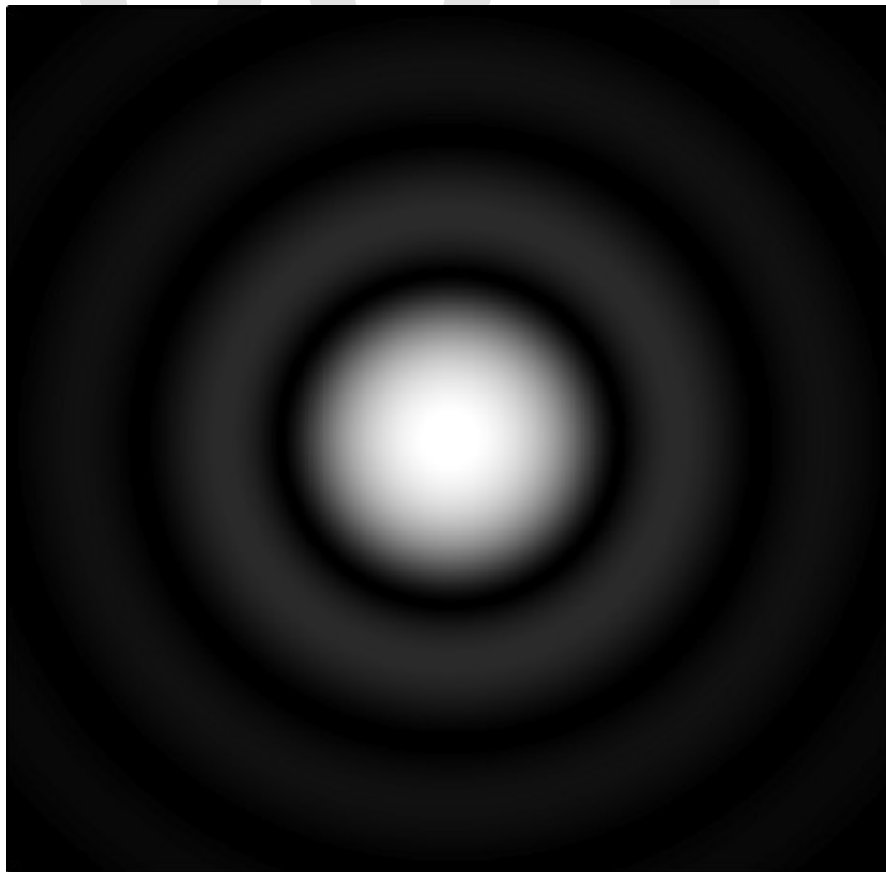
Beam geometry

The radar beam has a distribution of energy similar to the diffraction pattern of a light passing through a slit. This is because the wave is transmitted to the parabolic antenna through a slit in the wave-guide at the focal point. Most of the energy is at the center of the beam and decreases along a curve close to a Gaussian function on each side as mentioned before. However, there are secondary peaks of emission that will sample the targets at off-angles from the center. All is done to minimize the power sent by those lobes but they are never zero.

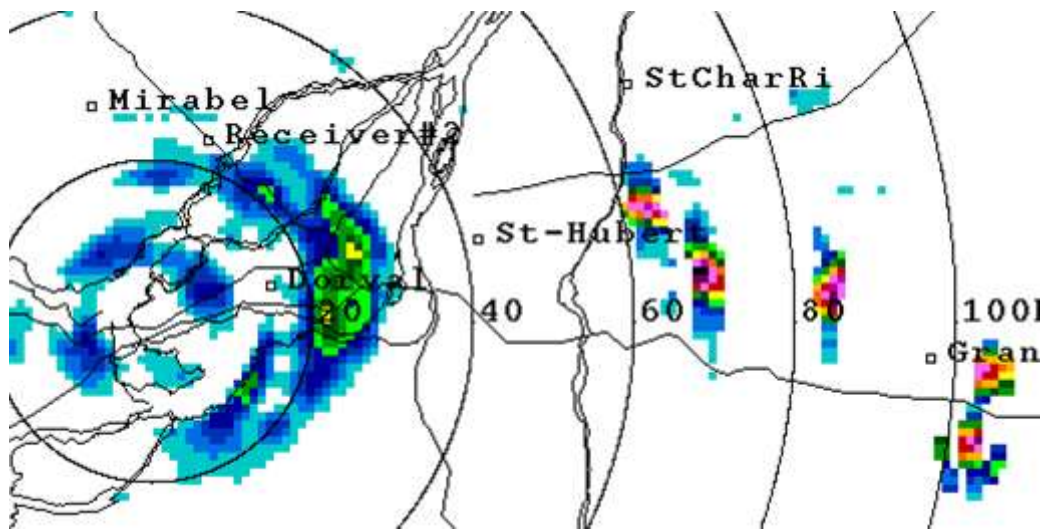
When a secondary lobe hits a very reflective target, like a mountain or a strong thunderstorm, some of the energy is sent back to the radar. This energy is relatively weak but arrives at the same time the central peak is illuminating a different azimuth. The echo is thus misplaced by the processing program. This has the effect of actually broadening the real weather echo making a smearing of weaker values on each side of it. This causes the user to overestimate the extent of the real echoes.



Idealized energy distribution of a radar beam (Central lobe at 0 and secondary lobes on each side)



Diffraction by a circular slit simulating the energy viewed by weather targets



The strong echoes are returns of the central peak of the radar from a series of small hills (yellow and reds pixels). The weaker echoes on each sides of them are from secondary lobes (blue and green)

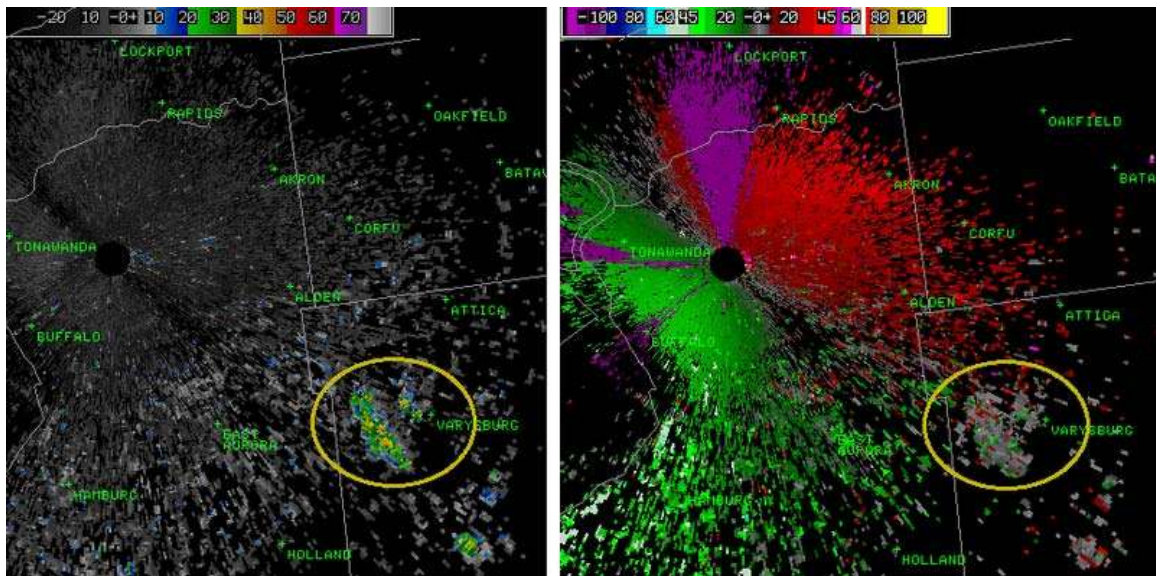
Non weather targets

There is more than rain and snow in the sky. Other objects can be misinterpreted as rain or snow by weather radars. Insects and arthropods are swept along by the prevailing winds, while birds follow their own course. As such, fine line patterns within weather radar imagery, associated with converging winds, are dominated by insect returns. Bird migration, which tends to occur overnight within the lowest 7,000 feet (2,100 m) of the Earth's atmosphere, contaminates wind profiles gathered by weather radar, particularly the WSR-88D, by increasing the environmental wind returns by 15 knots (28 km/h) to 30 knots (56 km/h) Other objects within radar imagery include::

- Thin metal strips (chaff) dropped by military aircraft to fool enemies.
- Solid obstacles such as mountains, buildings, and aircraft.
- Ground and sea clutter.
- Reflections from buildings if the radar is close enough to a city (called urban spikes).

Each of them has their own characteristics that make it possible to distinguish them to the trained eye but they may fool a layman. It is possible to eliminate some of them with post-treatment of data using reflectivity, Doppler, and polarization data.

Wind farms

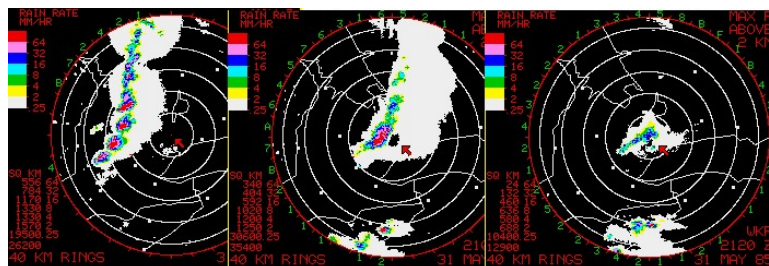


Reflectivity (left) and radial velocities (right) southeast of a NEXRAD weather radar. Echoes in circles are from a wind farm.

The rotating blades of windmills on modern wind farms can return the radar beam to the radar if they are in its path. Since the blades are moving, the echoes will have a velocity and can be mistaken for real precipitation. The closer the wind farm is to the radar, the more important is this artifact as the combined signal from many towers is stronger. If the conditions are right, the radar can even see a doublet of toward and away velocities that can generate false positives for the tornado vortex signature algorithm on weather radar, as happened in 2009 in Dodge City, Kansas.

Finally, the windmills are blocking a part of the radar beam and thus attenuating the return from precipitations in the lee of them, leading to underestimation.

Attenuation



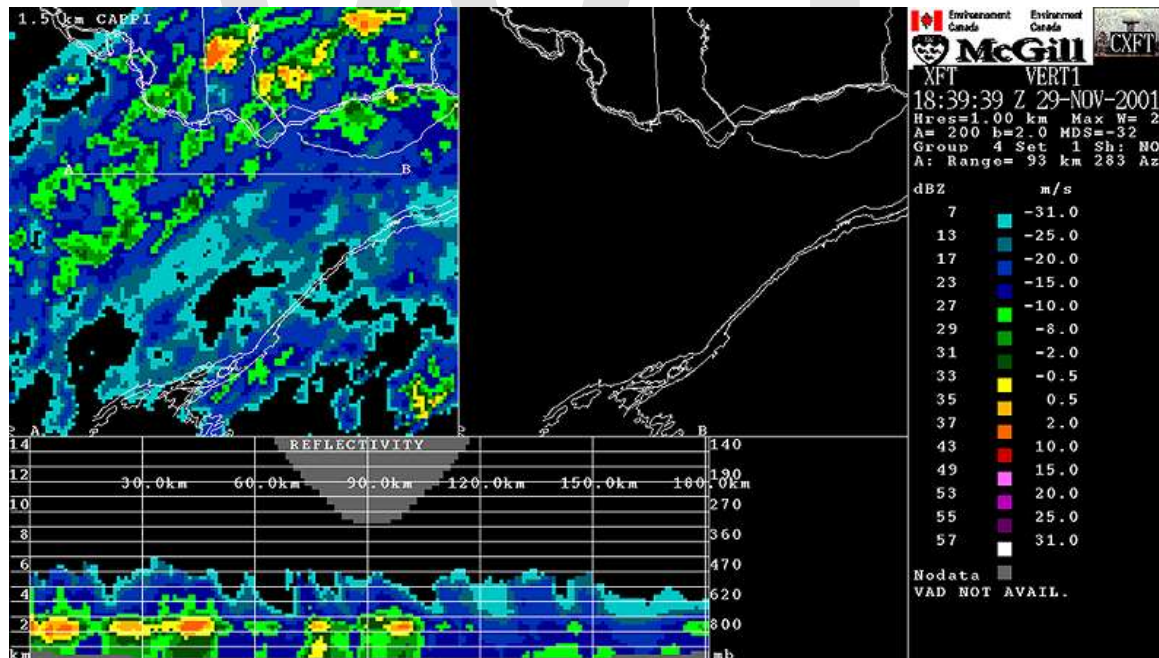
Example of strong attenuation when a line of thunderstorms move over (from left to right images) a 5 cm (2 in) wavelength weather radar (red arrow). Source: Environment Canada

Micro-waves used in weather radars can be absorbed by rain, depending on the wavelength used. For the 10 centimeter radars, this attenuation is negligible. That is the reason why countries with high water content storms are using 10 centimeter wavelength like in the United States with NEXRAD. The cost of a larger antenna, klystron and other related equipments is offset by this benefit.

For a 5 centimeter radar, absorption becomes important in very heavy rain and this attenuation leads to underestimation of echoes in and beyond a strong thunderstorms line. Canada and other northern countries use this less costly kind of radars as their precipitations are usually less intense. However, users have to remember this effect when interpreting data. The images above show how a strong line of echoes seems to vanish as it moves over the radar. To compensate for this behaviour, radar sites are often chosen to somewhat overlap in coverage to give different points of view of the same storms.

Shorter wavelengths are even more attenuated and are only useful on short range radar. Many television stations in the United States have 3-centimeter radars to cover their audience area. Knowing their limitations and using them with the local NEXRAD can supplement the data available to a meteorologist.

Bright band



1.5 km altitude CAPPI at the top with strong contamination from the brightband (yellows). The vertical cut at the bottom show that this strong return is only above ground.

As we have seen previously, the reflectivity depends on the diameter of the target and its capacity to reflect. Snow flakes are large but weakly reflective while rain drops are small but highly reflective.

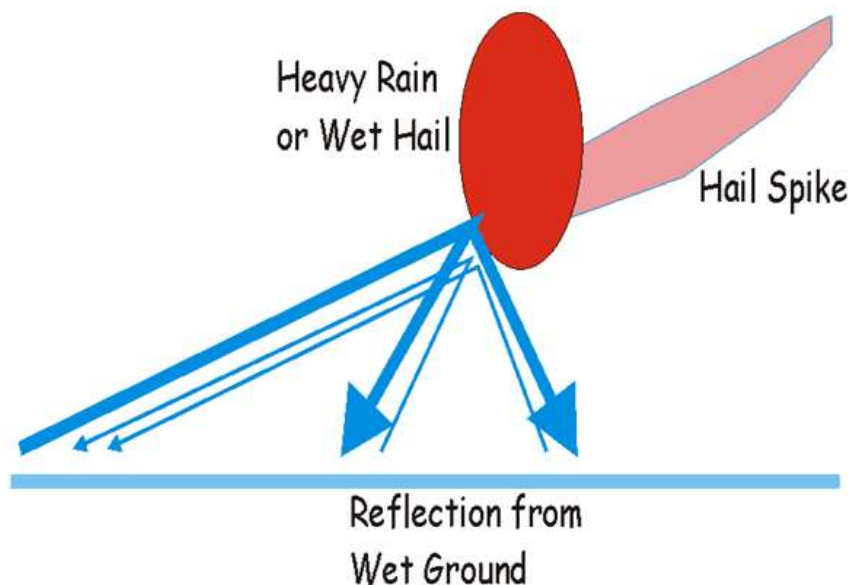
When snow falls through a layer above freezing temperature, it melts and eventually becomes rain. Using the reflectivity equation, one can demonstrate that the returns from the snow before melting and the rain after, are not too different as the change in dielectric constant compensate for the change in size. However, during the melting process, the radar wave "sees" something akin to very large droplets as snow flakes become coated with water.

This gives enhanced returns that can be mistaken for stronger precipitations. On a PPI, this will show up as an intense ring of precipitations at the altitude where the beam crosses the melting level while on a series of CAPPs, only the ones near that level will have stronger echoes. A good way to confirm a bright band is to make a vertical cross section through the data like in the picture above.

An opposite problem is that drizzle (precipitation with small water droplet diameter) tends not to show up on radar because radar returns are proportional to the sixth power of droplet diameter.

Multiple reflections

Three Body Scattering

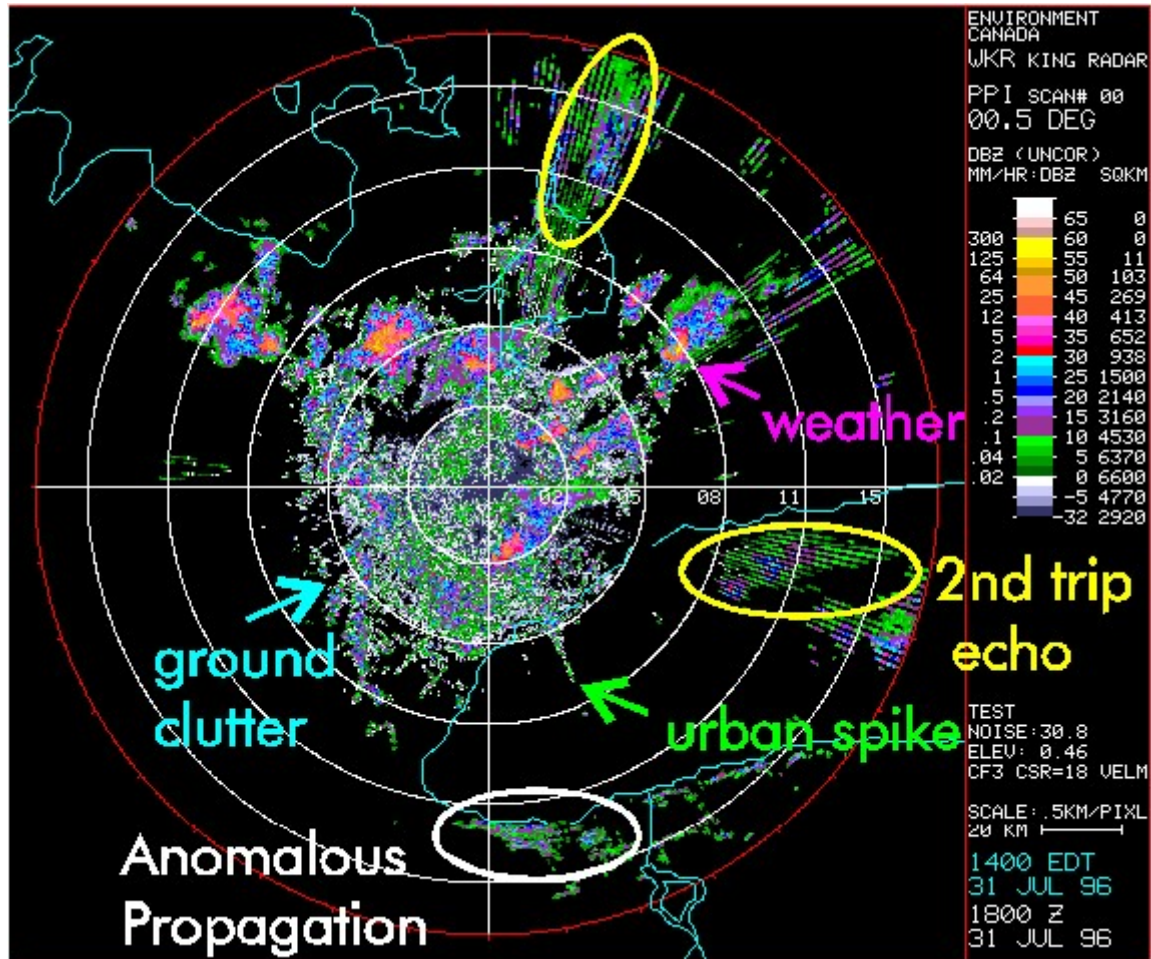


It is assumed that the beam hits the weather targets and returns directly to the radar. In fact, there is energy reemitted in all directions. Most of it is weak, and multiple reflections diminish it even further so what can eventually return to the radar from such an event is negligible. In some cases though, this cannot be.

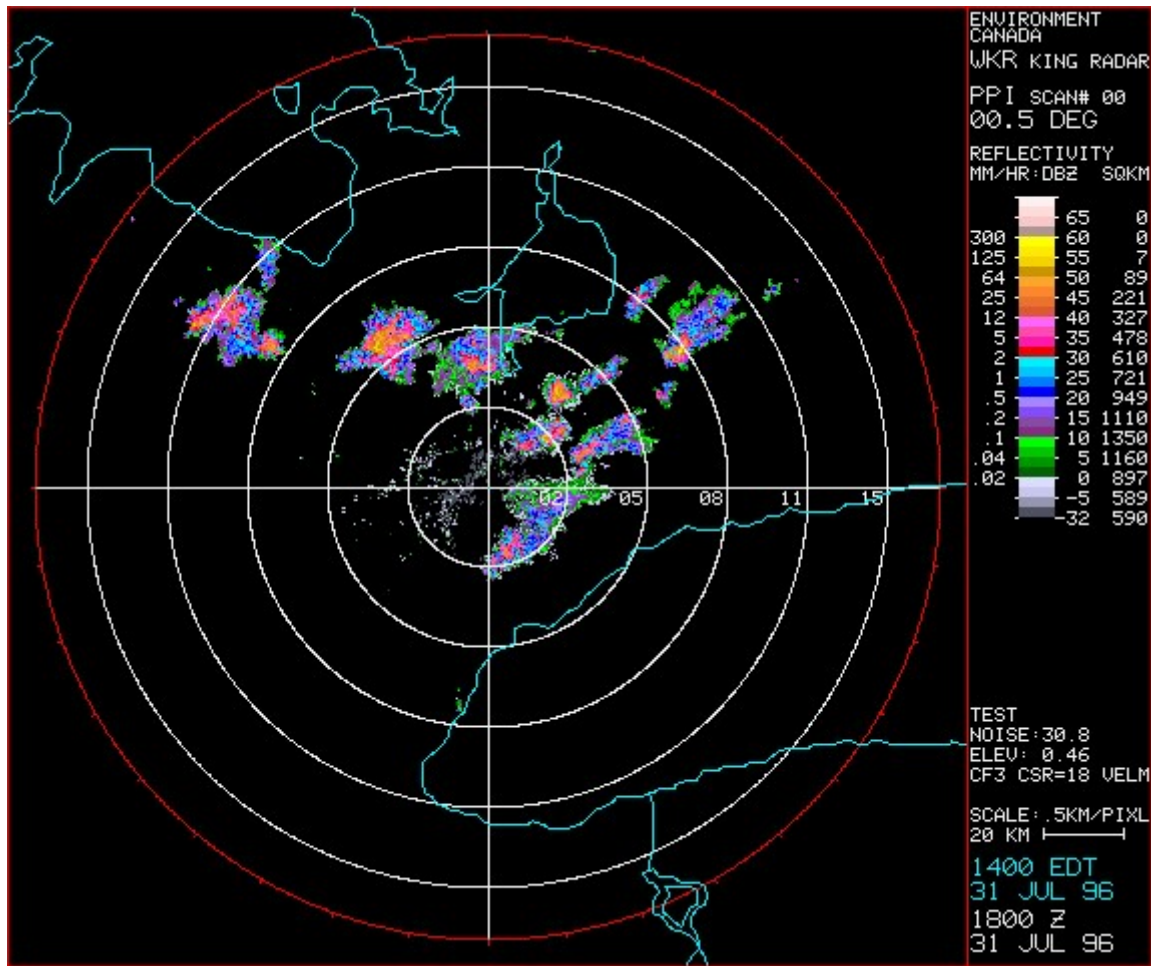
For instance, when the beam hits hail, the energy spread toward the wet ground will be reflected back to the hail and then to the radar. The resulting echo is weak but noticeable. Due to the extra path length it has to go through, it arrives later at the antenna and is placed further than its source. This gives a kind of triangle of false weaker reflections placed radially behind the hail.

Solutions for now and the future

Filtering



Radar image of reflectivity with many non-weather echoes.



The same image but cleaned using the Doppler velocities.

These two images show what can be achieved already to clean up radar data. The output on the left is made with the raw returns and it is difficult to spot the real weather. Since rain and snow clouds are usually moving, one can use the Doppler velocities to eliminate a good part of the clutter (ground echoes, reflections from buildings seen as urban spikes, anomalous propagation, etc..). The image on the right has been filtered using this property in a somewhat complex technique.

However, not all non-meteorological targets remain still; one can think of birds for instance. Others, like the bright band, depend on the structure of the precipitations. Polarization offers a direct typing of the echoes which could be used to filter more false data or produce separate images for specialized purposes. This recent development in this field is bound to improve the quality of radar products.

Mesonet



Phased Array Weather Radar in Norman, Oklahoma

Another question is the resolution. As mentioned previously, radar data are an average of the scanned volume by the beam. Resolution can be improved by larger antenna or denser networks. A program by the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) aims to supplement regular NEXRAD using many low cost X band (3 cm) weather radar mounted on cellular telephone towers. These radars will subdivide the large area of the NEXRAD into smaller domains to look at altitudes below its lowest angle. These will give details not currently available.

Using 3-cm wavelength radars, the antenna of each radar is small (about 1 meter diameter) but the resolution is similar at short distance to that of NEXRAD. The

attenuation is significant due to the wavelength used but each point in the coverage area is seen by many radars, each viewing from a different direction and compensating for data lost from others.

Electronic sounding

Timeliness is also a point needing improvement. With 5 to 10 minutes time between complete scans of weather radar, a lot of things can be missed in the development of a thunderstorm. A Phased-array radar is being tested at the National Severe Storms Lab in Norman, Oklahoma, to speed up the gathering of data.

Specialized applications



Weather radar on the wing of Pilatus PC-12

Avionics weather radar

Aircraft application of radar systems include weather radar, collision avoidance, target tracking, ground proximity, and other systems. For commercial Weather Radar Systems, ARINC 708 is the primary weather radar system using an airborne pulse-Doppler radar.

Antennas

Unlike ground weather radar, which is set at a fixed angle, airborne weather radar is being utilized from the nose or wing of an aircraft. Not only will the aircraft be moving up, down, left, and right, but it will be rolling as well. To compensate for this, the antenna is linked and calibrated to the vertical gyro located on the aircraft. By doing this, the pilot is able to set a pitch or angle to the antenna that will enable the stabilizer to keep the antenna pointed in the right direction under moderate maneuvers. The small servo motors will not be able to keep up with too abrupt maneuvers, but it will try. In doing this the pilot is able to adjust the radar so that it will point towards the weather system of interest. If the airplane is at a low altitude, the pilot would want to set the radar at a high angle above the horizon line so that ground clutter is not all that is being displayed on the plan position indicator (PPI). Similarly, if the airplane is at a very high altitude the pilot would want to set the radar at a low or negative angle. The goal here is to point the radar towards the clouds wherever they may be in respect to the aircraft, and if the pilot changes the direction of the airplane the stabilizer will adjust itself accordingly so that the pilot doesn't have to fly with one hand and adjust the radar with the other. The stabilizer is meant to help display the information that the pilot requests, while the airplane is in motion.

Receivers/Transmitters

There are two major systems when talking about the receiver/transmitter: the first is high-powered systems, and the second is low-powered systems; both of which operate in the X-band frequency range (8,000 to 12,500) MHz. High-powered systems operate at power levels between 10,000 and 60,000 watts. These systems consist of magnetrons and vacuum tubes that are fairly expensive (approximately \$1,700) and allow for considerable amounts of noise due to irregularities with the system. Thus, these systems are highly dangerous for arcing and are not safe to be used around ground personnel. However, the alternative would be the low-powered systems. These systems operate between 100 to 200 watts, and require a combination of high gain receivers, signal microprocessors, and transistors to operate as effectively as the high-powered systems. The complex microprocessors help to eliminate noise, providing a more accurate and detailed depiction of the sky. Also, since there are fewer irregularities throughout the system, the low-powered radars can be used to detect turbulence via the Doppler Effect. Furthermore, since the low-powered systems operate at considerable less wattage, they are safe from arcing and can be used at virtually all times.

Thunderstorm Tracking

Digital radar systems now have capabilities far beyond that of their predecessors. Digital systems now offer thunderstorm tracking surveillance. This provides users with the ability to acquire detailed information of each storm cloud being tracked. Thunderstorms are first identified by matching precipitation raw data received from the radar pulse to some sort of template preprogrammed into the system. In order for a thunderstorm to be identified, it has to meet strict definitions of intensity and shape that set it apart from any

non-convective cloud. Usually, it must show signs of organization in the horizontal and continuity in the vertical : a core or a more intense center to be identified and tracked by digital radar tracking systems. Once the thunderstorm cell is identified, speed, distance covered, direction, and Estimated Time of Arrival (ETA) are all tracked and recorded to be utilized later.

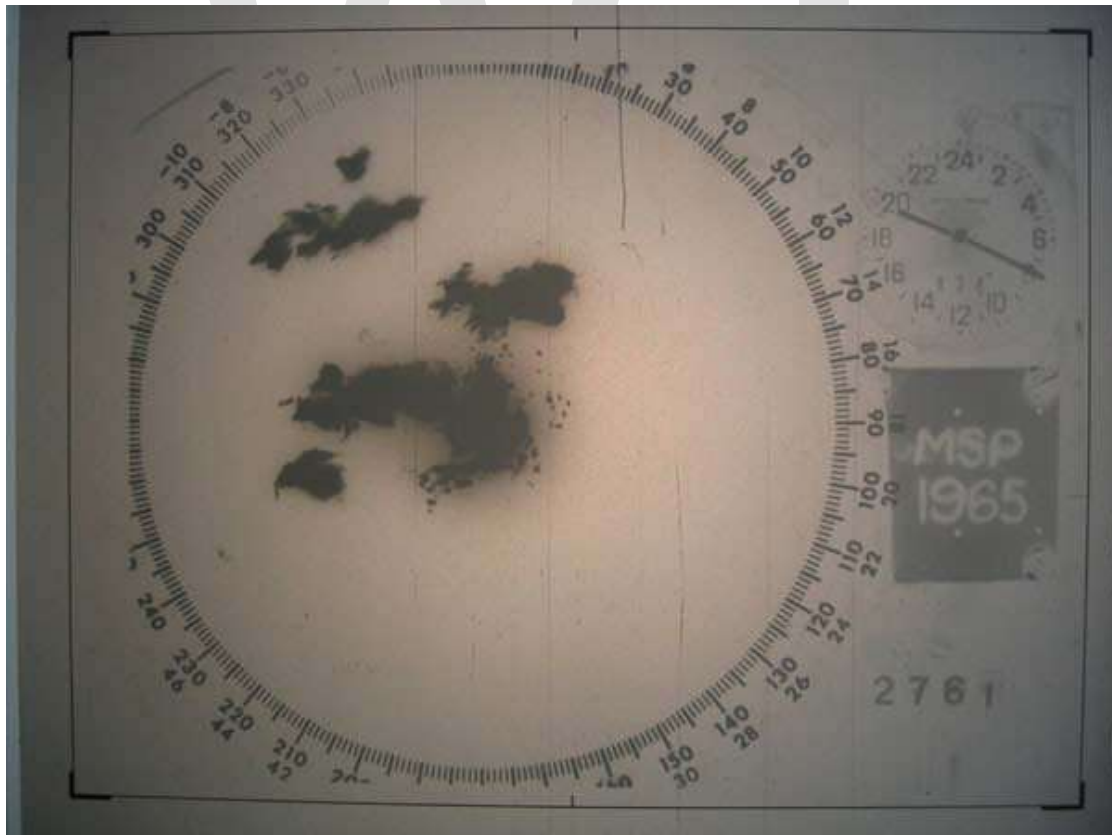
WWT

Chapter-2

Convective Storm Detection

Convective storm detection is the observation of deep, moist convection (DMC); this term includes the minority of storms which do not produce lightning and thunder. Convective storms produce tornadoes as well as large hail, strong winds, and flash flooding. The detection of convective storms relies on direct eyewitness observations, for example from storm spotters; and on remote sensing, mostly weather radar. Some in situ measurements are used for direct detection as well, notably, wind speed reports from surface observation stations. It is part of the *integrated warning system*, consisting of prediction, detection, and dissemination of information on severe weather to the public.

History



1960s radar technology (WSR-57) displaying supercells over the Twin Cities during the 1965 Twin Cities tornado outbreak.

Rigorous attempts to warn of tornadoes began in the United States in the mid-20th century. Before the 1950s, the only method of detecting a tornado was by someone seeing it on the ground. Often, news of a tornado would reach a local weather office after the storm.

But, with the advent of weather radar, areas near a local office could get advance warning of severe weather. The first public tornado warnings were issued in 1950 and the first tornado watches and convective outlooks in 1952. In 1953 it was confirmed that hook echoes are associated with tornadoes. By recognizing these radar signatures, meteorologists could detect thunderstorms likely producing tornadoes from dozens of miles away.

Storm spotting

In the mid 1970s, the US National Weather Service (NWS) increased its efforts to train storm spotters to identify and report key features of storms which indicate severe hail, damaging winds, and tornadoes, as well as damage itself and flash flooding. The program was called Skywarn, and the spotters were local sheriff's deputies, state troopers, firefighters, ambulance drivers, amateur radio operators, civil defense (now emergency management) spotters, storm chasers, and ordinary citizens. When severe weather is anticipated, local weather service offices request that these spotters look out for severe weather, and report any tornadoes immediately, so that the office can issue a timely warning.

Usually spotters are trained by the NWS on behalf of their respective organizations, and report to them. The organizations activate public warning systems such as sirens and the Emergency Alert System, and forward the reports to the NWS, which does directly disseminate information and warnings through its NOAA Weather Radio All Hazards network. There are more than 230,000 trained Skywarn weather spotters across the United States.

In Canada, a similar network of volunteer weather watchers, called Canwarn, helps spot severe weather, with more than 1,000 volunteers. In Europe, several nations are organizing spotter networks under the auspices of Skywarn Europe and the Tornado and Storm Research Organisation (TORRO) has maintained a network of spotters in the United Kingdom since the 1970s.

Storm spotters are needed because radar systems such as NEXRAD, and satellite images, do not detect tornadoes or hail, only indications that the storm has the potential. Radar and satellite data interpretation will usually give a warning before there is any visual evidence of such events, but ground truth from an observer can either verify the threat or determine it is not imminent. The spotter's ability to see what these remote sensing devices cannot is especially important as distance from a radar site increases, because the radar beam becomes progressively higher in altitude further away from the radar, due to curvature of Earth and the spread of the beam with distance. Therefore, when far from a radar, only precipitations and velocities high in the storm are observed. The important

areas might not then be sampled or the resolution of the data might be poor. Also, some meteorological situations leading to tornadogenesis are not readily detectable by radar and on occasion tornado development may occur more quickly than radar can complete a scan and send the batch of data.

Visual evidence



A rotating wall cloud with rear flank downdraft clear slot evident to its left rear.

Storm spotters are trained to discern whether a storm seen from a distance is a supercell. They typically look to its rear, the main region of updraft and inflow. Under the updraft is a rain-free base, and the next step of tornadogenesis is the formation of a rotating wall cloud. The vast majority of intense tornadoes occur with a wall cloud on the backside of a supercell.

Evidence of a supercell comes from the storm's shape and structure, and cloud tower features such as a hard and vigorous updraft tower, a persistent and/or large overshooting top, a hard anvil (especially when backsheared against strong upper level winds), and a corkscrew look or striations. Under the storm and closer to where most tornadoes are found, evidence of a supercell and likelihood of a tornado includes inflow bands (particularly when curved) such as a "beaver tail", and other clues such as strength of inflow, warmth and moistness of inflow air, how outflow- or inflow-dominant a storm appears, and how far is the front flank precipitation core from the wall cloud.

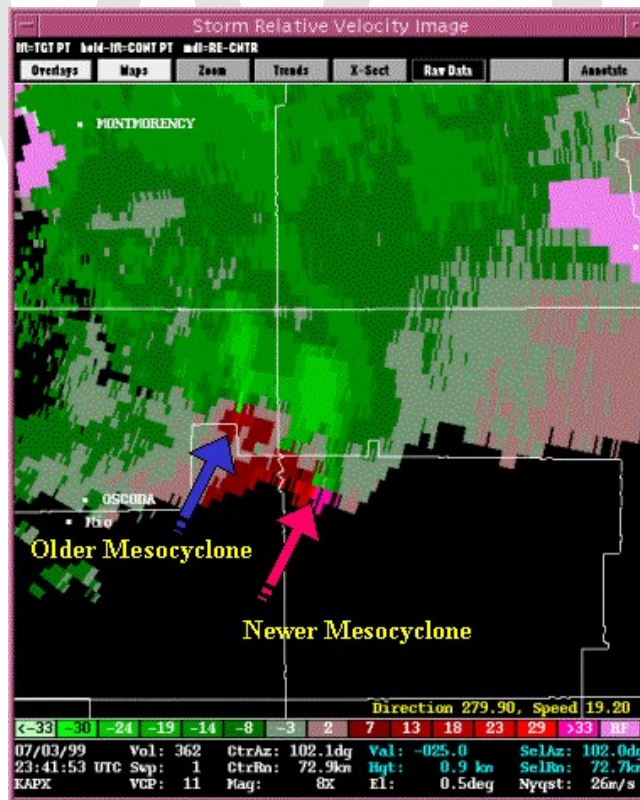
Tornadogenesis is most likely at the interface of the updraft and front flank downdraft, and requires a balance between the outflow and inflow.

Only wall clouds that rotate spawn tornadoes, and usually precede the tornado by five to thirty minutes. Rotating wall clouds are the visual manifestation of a mesocyclone. Barring a low-level boundary, tornadogenesis is highly unlikely unless a rear flank downdraft occurs, which is usually visibly evidenced by evaporation of cloud adjacent to a corner of a wall cloud. A tornado often occurs as this happens or shortly after; first, a funnel cloud dips and in nearly all cases by the time it reaches halfway down, a surface swirl has already developed, signifying a tornado is on the ground before condensation connects the surface circulation to the storm. Tornadoes may also occur without wall clouds, under flanking lines, and on the leading edge. Spotters monitor all areas of a storm and their surroundings.

Radar

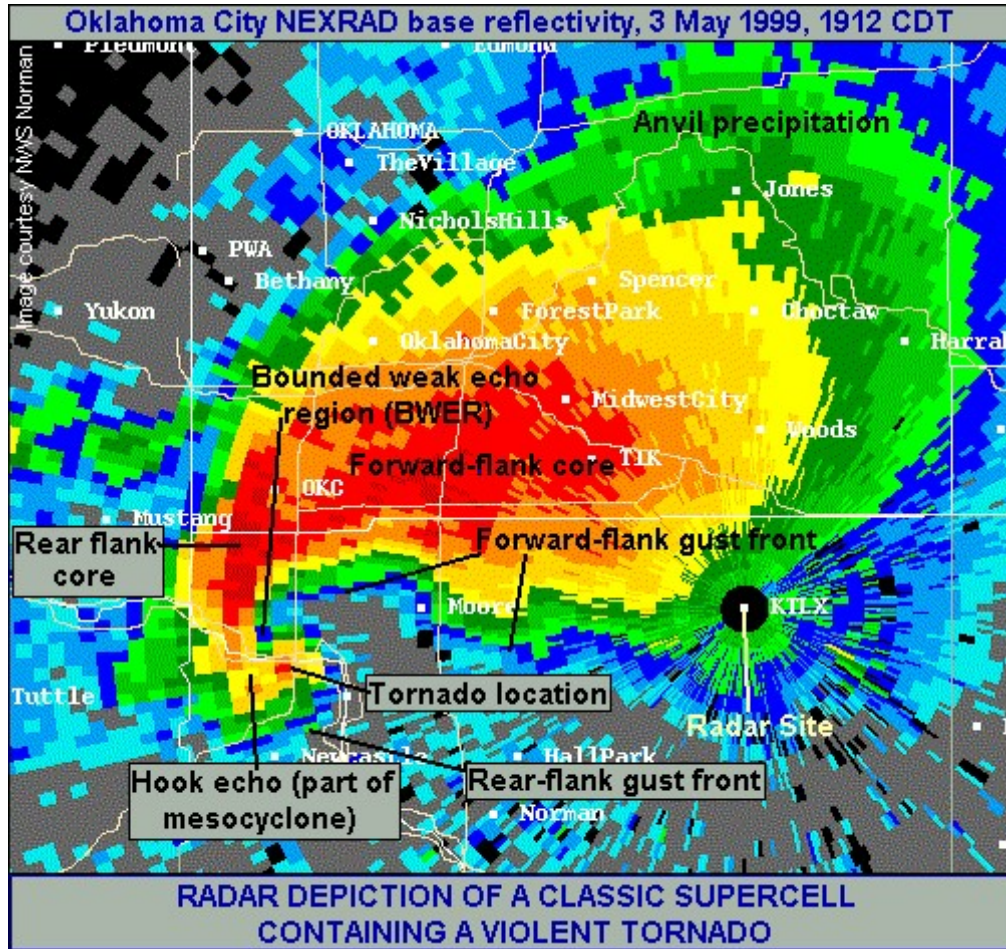
Today, most developed countries have a network of weather radars, which remains the main method of detecting signatures likely associated with tornadoes and other severe phenomena as hail and downbursts. Radar is always available, in places and times where spotters are not, and can also see features that spotters cannot, in the darkness of night and processes hidden within the cloud as well as invisible processes outside the cloud.

Tornadoes

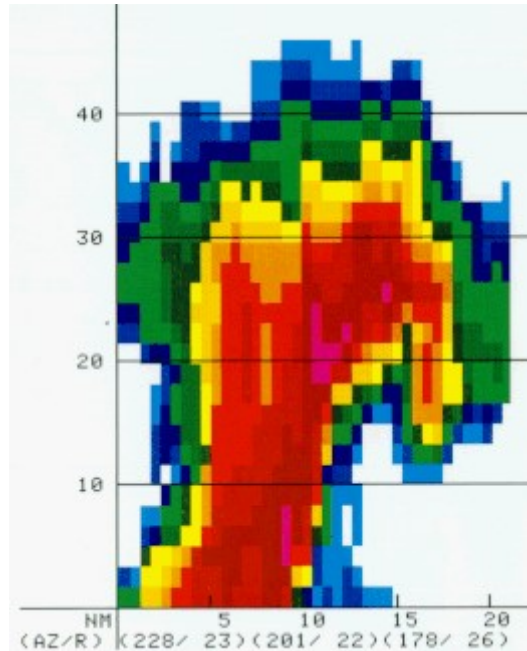


Doppler NEXRAD radar image of two mesocyclones with one supercell passing over Northern Michigan on July 3rd, 1999 at 23:41 UTC. Rotations is seen as small couplets

of red (away) and green (toward) radial velocities. The thick circles represents 3D vortices which have been classified as mesocyclones near the ground by a detection algorithm. The left mesocyclone is associated with a tornado while to the right a larger area of rotation has developed.



A classic hook echo. The tornado associated with this echo was part of the 1999 Oklahoma tornado outbreak. It reached F5 strength on the Fujita scale.



Vertical cross-section through a supercell exhibiting a BWER.

In short-term prediction and detection of tornadoes, meteorologists integrate radar data with reports from the field and knowledge of the meteorological environment. Radar analysis is augmented by automated detection systems called algorithms. Meteorologists first look at the atmospheric environment as well as changes thereof, and once storms develop, storm motion and interaction with the environment.

An early step in a storm organizing into a tornado producer is the formation of a weak echo region (WER) with a tilted updraft. This is an area within the thunderstorm where precipitation should be occurring but is "pulled" aloft by a very strong updraft. The weak echo region is characterized by weak reflectivity with a sharp gradient to strong reflectivity above it and partially surrounding the sides. The region of the precipitation lofted above the WER is the echo overhang consisting of precipitation particles diverging from the storm's summit that descend as they are carried downwind. Within this area, a bounded weak echo region (BWER) may then form above and enclosing the WER. A BWER is found near the top of the updraft and nearly or completely surrounded by strong reflectivity, and is indicative of a supercell capable of cyclic tornadogenesis. A mesocyclone may descend or a tornado may form in the lower level of the storm simultaneously as the mesocyclone forms.

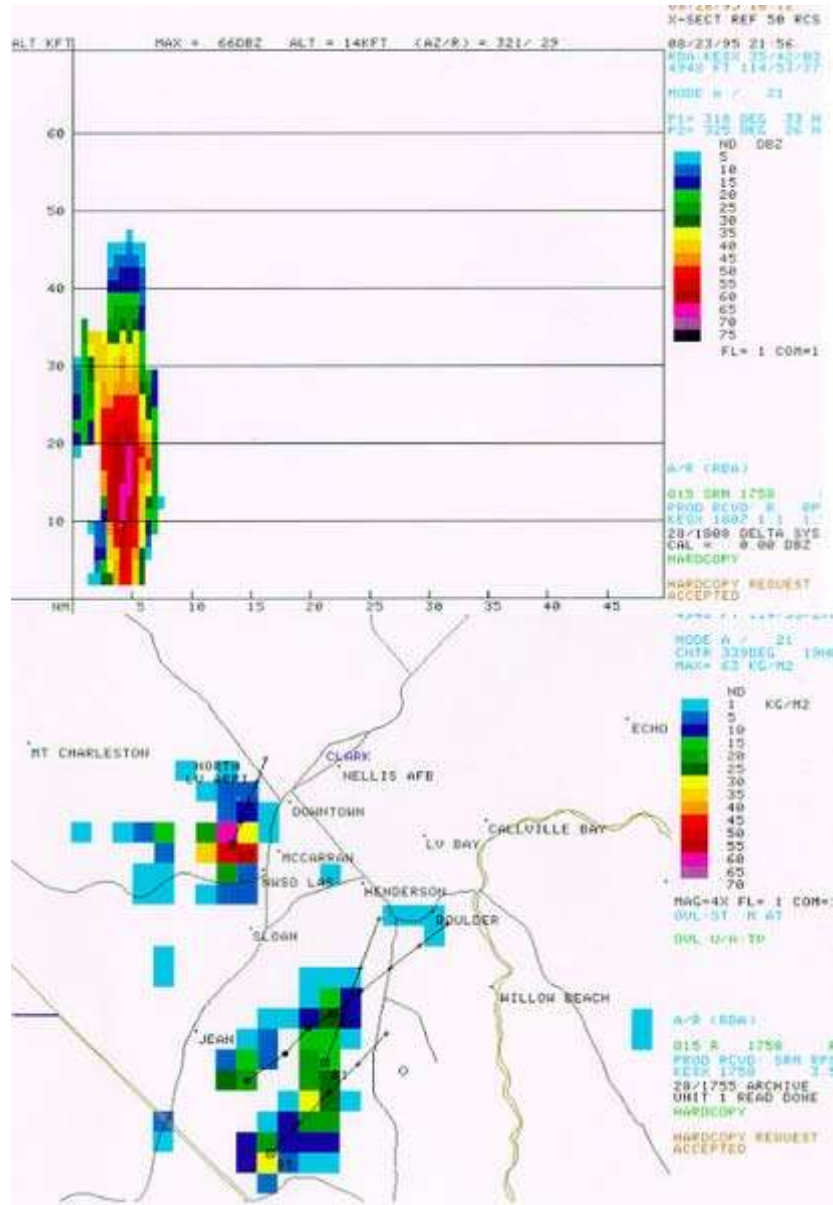
In reflectivity (precipitation intensity) data, a tight echo gradient (particularly on the inflow area) and a fan shape generally indicate a supercell. A V-notch or "flying eagle echo" tend to be most pronounced with intense classic supercells, the type of supercell that produces most of the strongest, largest, and longest lived tornadoes. This is not to be confused with an inflow notch; which is a lower level indentation in the precipitation where there is little to no reflectivity, indicative of strong, organized inflow and a severe storm that is most likely a supercell. The rear inflow notch (or weak echo channel) occurs

to the east or north of a mesocyclone and hook echo. Forward inflow notches also occur, particularly on high-precipitation supercells (HP) and quasi-linear convective systems (QLCS).

In the United States and a few other countries, Doppler capable weather radar stations are used. These devices are capable of measuring the radial velocity, including radial direction (towards or away from the radar) of the winds in a storm, and so can spot evidence of rotation in storms from more than a hundred miles (160 km) away. A supercell is characterized by a mesocyclone, which is usually first observed in velocity data as a tight, cyclonic structure in the middle levels of the thunderstorm. If it meets certain requirements of strength, duration, and vorticity, it may trip the mesocyclone detection algorithm (MDA). Tornado signatures are indicated by a cyclonic inbound-outbound velocity couplet, where strong winds flowing in one direction and strong winds flowing in the opposite direction are occurring in very close proximity. The algorithm for this is the tornadic vortex signature (TVS). TVS often also forms first in the middle levels of the thunderstorm and may descend and tighten into a tornado. The TVS is smaller and found at lower level than the MDA, and usually is the tornado cyclone not the actual tornadic circulation. The TVS is, however, indicative of a likely tornado or an incipient tornado. The couplet and TVS typically precede tornado formation by 10–30 minutes but may occur at nearly the same time or precede the tornado by 45 minutes or more. The hook echo feature is formed as the RFD occludes precipitation around the mesocyclone and is also indicative of a probable tornado (tornadogenesis usually ensues shortly after the RFD reaches the surface).

After the implementation of the WSR-88D network in the U.S., the probability of detection of tornadoes increased substantially, the average lead time rose from four minutes to thirteen minutes, and a 2005 NOAA report estimates that as a result of improved warnings that there are 45 percent fewer fatalities and 40 percent fewer injuries annually.

Hail, downburst and downpour



Vertical cross-section of a thunderstorm at the top and VIL value of 63 kg/m² with that cell at the bottom (red one), giving potential for hail, downpour, and/or downdraft

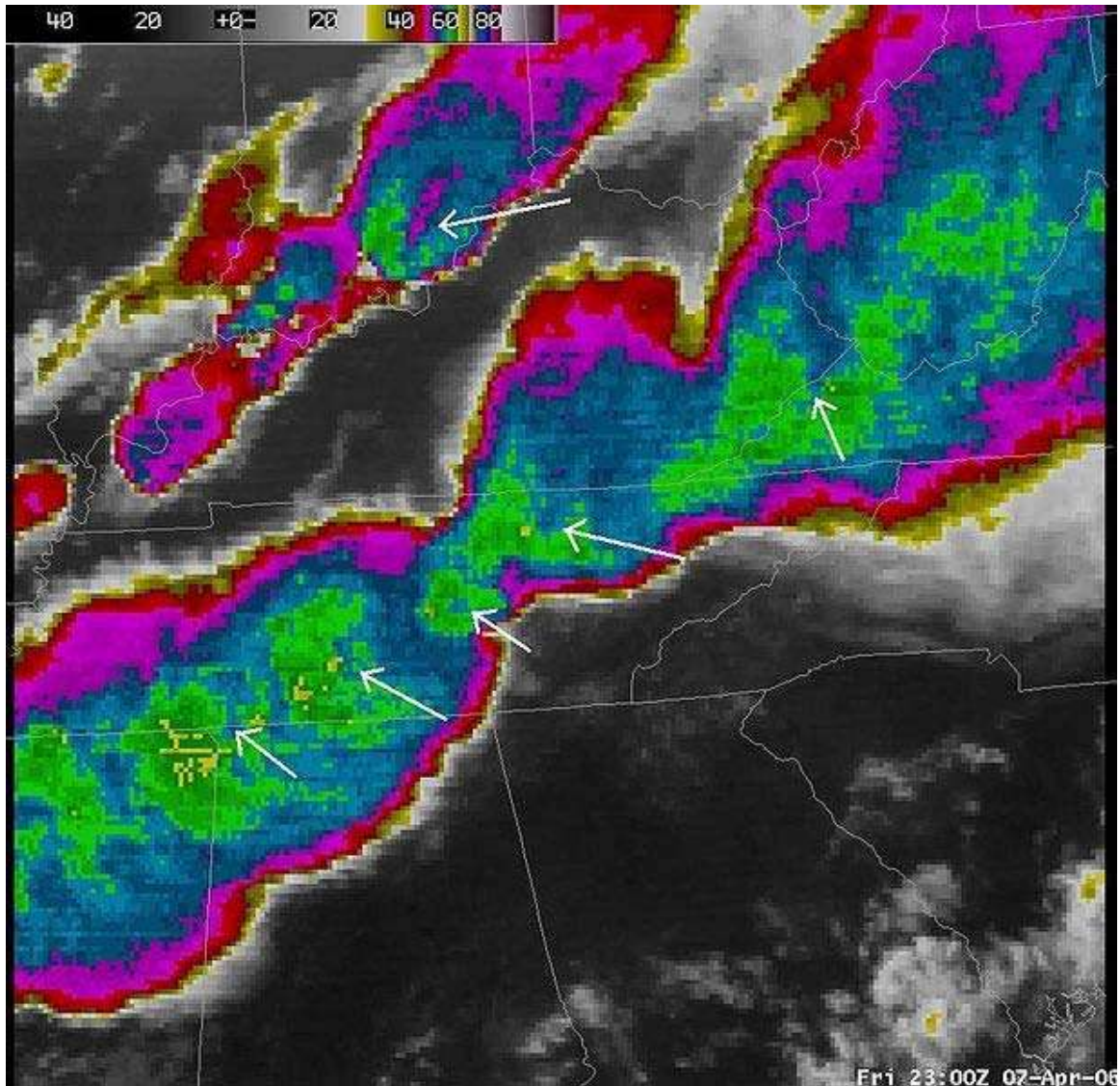
Hail forms in a very intense updraft in a supercell or a multicellular thunderstorm. As for tornadoes, BWER detection and a tilted updraft are indicative of that updraft but does not lead to predict hail. The presence of a hail spike in the reflectivity pattern is an important clue. It is an area of weak reflectivity extending away from the radar immediately behind a thunderstorm with hail. It is caused by radiation from the radar bouncing from hailstone to hailstone or the ground before being reflected back to the radar. The time delay between the backscattered radiation from the storm and the one with multiple paths causes the reflectivity from the hail to appear to come from a farther range than the actual storm. However, this artefact is visible mostly for extremely large hail.

What is needed is a knowledge of the water content in the thunderstorm, the freezing level and the height of the summit of the precipitation. One way of calculating the water content is to transform the reflectivities in rain rate at all levels in the clouds and to sum it up. This is done by an algorithm called *Vertically integrated liquid*, or VIL. This value represent the total amount of liquid water in the cloud that is available. If the cloud would rain out completely, it would be the amount of rain falling on the ground and one can estimate with VIL the potential for flash flood.

However, the reflectivities are greatly enhanced by hail and VIL is greatly overestimating the rain potential in presence of hail. On the other hand, National Weather Service meteorologists have found that the VIL density, that is to say VIL divided by the maximum height of the 18 dBZ in the cloud, is a good indicator of the presence of hail when it reach 3.5. This is a crude yes/no index and other algorithms have been developed involving VIL and the freezing level height. More recently, dual polarization of weather radar have shown promising direct detection of hail.

VIL can be used to estimate the potential for downburst, too. A convective downdraft is linked to three forces in the vertical, namely perturbation pressure gradient force, buoyancy force and precipitation loading. The pressure gradient force was neglected as it has significant effect only on the updraft in supercells. With this assumption and other simplifications (e.g. requiring the environment of the air parcel to be static on the time scale of the downdraft). The resulting momentum equation is integrated over height to yield the kinetic energy of the parcel on descending to the surface and is found to be the negative CAPE of a dry air parcel injected into the storm, plus de motion of the convective cell. S. R. Stewart, from NWS, has published in 1991 an equation relating VIL and the echo tops that give the potential for surface gust using this concept. This is a predictive result that gives a certain lead time. With the Doppler velocity data, the meteorologist can see the downdraft and gust fronts happening, but since this a small scale feature, detection algorithms have been developed to point convergence and divergence areas under a thunderstorm on the radar display.

Satellite imagery



Infrared weather satellite image at 23Z 7 April 2006 associated with a significant tornado outbreak in the eastern United States with arrows pointing to the enhanced-v signatures.

Most populated areas of the earth are now well covered by weather satellites, which aid in the nowcasting of severe convective and tornadic storms. These images are available in the visible and infrared domains. The infrared (IR: 10-13 μm) images permit estimation of the top height of the clouds, according to the air mass soundings of the day, and the visible (VIS: 0.5-1.1 μm) ones will show the shape of the storms by its brightness and shadow produced. Meteorologists can extract information about the development stage of a thunderstorms by recognizing specific signatures in both domains. Visible imagery permits the most detailed imagery whereas infrared imagery has the advantage of availability at night. Sensors on satellites can also detect emissions from water vapor (WV: 6-7 μm), but mostly in the middle to upper levels of the troposphere, so

thunderstorms are only seen after being well developed. It is, however, useful in convective storm prediction, as it illustrates the placement and movement of air masses and of moisture, as well as shortwaves and areas of vorticity and lift.

Severe storms have a very strong updraft. The rising air parcels in that column accelerate and will overshoot the equilibrium level before being pulled back by negative buoyancy. This means the cloud tops will reach high levels than the surrounding cloud in the updraft region. This overshooting top will be noticeable by a colder temperature region in the thunderstorm on infrared images. Another signature associated with this situation is the Enhanced-V feature where the cold cloud tops forming at the overshooting top fan out in a V shape as cloud matter is blown downwind at that level. Both features can be seen on visible satellite imagery, during daytime, by the shadows they cast on surrounding clouds.

In multi-cellular storms and squall lines, the mid-level jet stream is often intersecting the line and its dry air introduced into the cloud is negatively unstable. This results in a drying of the cloudy air in the region where the jet plunges groundward. On the back edge of the line, this shows as clear notches where one can find stronger downdrafts at the surface. These kind of lines will have a very characteristic undulating pattern caused by the interference of the gust fronts coming from different parts of the line.

Finally, in any type of thunderstorms, the cold pool of air associated with the downdraft will stabilize the air and form a cloud free area which will end along the gust front. This front, moving into a warm and unstable air mass, will lift it and cumulus clouds appear on satellite pictures. This line is likely the point of further convection and storms. One can notice it at the leading edge of a squall line, in the southeastern quadrant of a supercell (northern hemisphere), or different regions around other thunderstorms. They may also be visible as an outflow boundary hours or days after convection and can pinpoint areas of favored thunderstorm development, possible direction of movement, and even likelihood for tornadoes.

Lightning detection

Usually in conjunction with data sources such as weather radar and satellites, lightning detection systems are sometimes utilized to pinpoint where thunderstorms are occurring (and to identify lightning hazard). Currently, most lightning data provided in real-time is from terrestrial sources, specifically, networks of ground-based sensors, although airborne sensors are also in operation. Most of these only provide latitude & longitude, time, and polarity of cloud-to-ground strikes within a limited range. Increasing in sophistication and availability, and affording data for a very wide area, are satellite-based lightning detectors which initially included optical sensors indicating flash rates and horizontal location but now radio frequency receivers that can identify intra-cloud flashes with the addition of altitude, as well.

Lightning data is useful in suggesting intensity and organization of convective cells as well trends in thunderstorm activity (particularly growth, and to a lesser degree, decay). It

is also useful in the early stages of thunderstorm development. This was especially true when visible and infrared satellite data was delayed, but continues to be useful in detecting thunderstorms in stages of development before there is a substantial radar signature or for areas where radar data is lacking.

Personal lightning detection systems are also available, which may provide strike time, azimuth, and distance. In addition, lightning prediction systems are available and used mostly by parks and other outdoor recreational facilities, or meteorologists contracted to provide weather information for them.

WWT

Chapter-3

Wind Profiler and Three Body Scatter Spike

Wind profiler



A radar wind profiler.



The TRITON transportable SODAR system used to measure wind profiles from Second Wind.

A **wind profiler** is a type of weather observing equipment that uses radar or sound waves (SODAR) to detect the wind speed and direction at various elevations above the ground. Readings are made at each kilometer above sea level, up to the extent of the troposphere (i.e., between 8 and 17 km above mean sea level). Above this level there is inadequate water vapor present to produce a radar "bounce." The data synthesized from wind direction and speed is very useful to meteorological forecasting and timely reporting for flight planning. A twelve hour history of data is available through NOAA websites.

Radar wind profiler

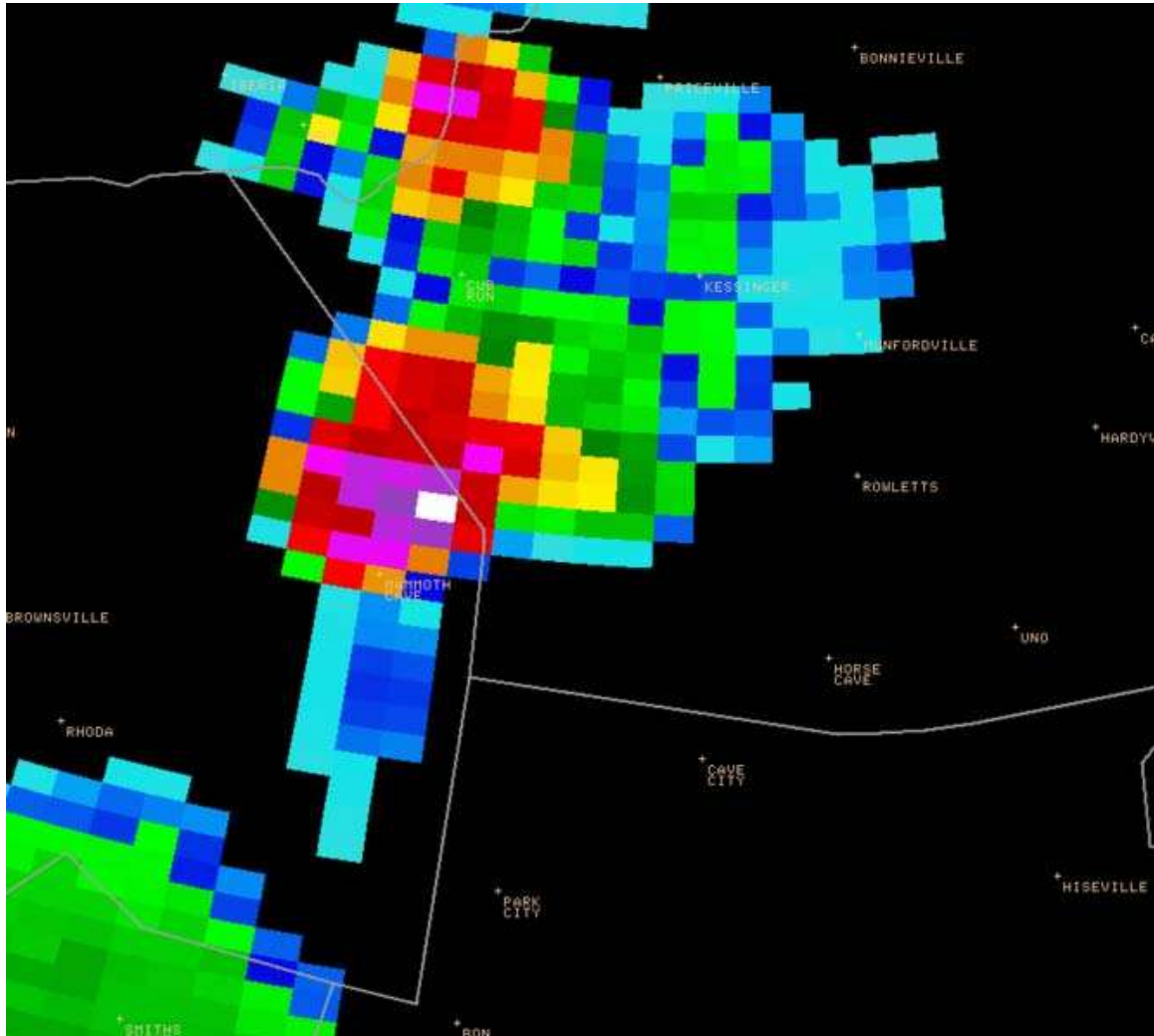
Pulse-Doppler radar wind profilers operate using principles similar to those used by Doppler sodars, except that electromagnetic (EM) signals are used rather than acoustic signals to remotely sense winds aloft. In a typical implementation, the radar can sample along each of five beams: one is aimed vertically to measure vertical velocity, and four are tilted off vertical and oriented orthogonal to one another to measure the horizontal components of the air's motion. A UHF profiler includes subsystems to control the radar's transmitter, receiver, signal processing, and Radio Acoustic Sounding System (RASS), if provided, as well as data telemetry and remote control.

The radar transmits an electromagnetic pulse along each of the antenna's pointing directions. The duration of the transmission determines the length of the pulse emitted by the antenna, which in turn corresponds to the volume of air illuminated (in electrical terms) by the radar beam. Small amounts of the transmitted energy are scattered back (referred to as backscattering) toward and received by the radar. Delays of fixed intervals are built into the data processing system so that the radar receives scattered energy from discrete altitudes, referred to as range gates. The Doppler frequency shift of the backscattered energy is determined, and then used to calculate the velocity of the air toward or away from the radar along each beam as a function of altitude. The source of the backscattered energy (radar "targets") is small-scale turbulent fluctuations that induce irregularities in the radio refractive index of the atmosphere. The radar is most sensitive to scattering by turbulent eddies whose spatial scale is $\frac{1}{2}$ the wavelength of the radar, or approximately 16 centimeters (cm) for a UHF profiler.

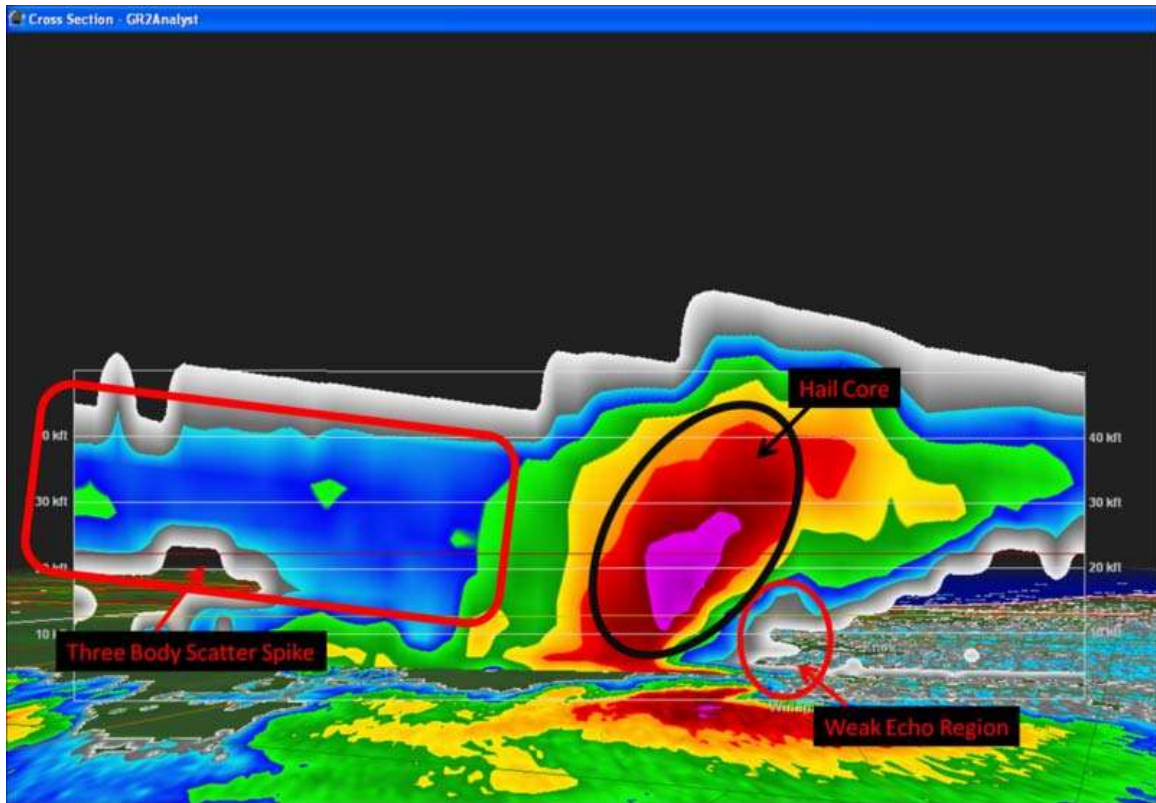
A profiler's (and sodar's) ability to measure winds is based on the assumption that the turbulent eddies that induce scattering are carried along by the mean wind. The energy scattered by these eddies and received by the profiler is orders of magnitude smaller than the energy transmitted. However, if sufficient samples can be obtained, then the amplitude of the energy scattered by these eddies can be clearly identified above the background noise level, then the mean wind speed and direction within the volume being sampled can be determined. The radial components measured by the tilted beams are the vector sum of the horizontal motion of the air toward or away from the radar and any vertical motion present in the beam. Using appropriate trigonometry, the three-dimensional meteorological velocity components (u,v,w) and wind speed and wind direction are calculated from the radial velocities with corrections for vertical motions.

A boundary-layer radar wind profiler can be configured to compute averaged wind profiles for periods ranging from a few minutes to an hour. Boundary-layer radar wind profilers are often configured to sample in more than one mode. For example, in a "low mode," the pulse of energy transmitted by the profiler may be 60 m in length. The pulse length determines the depth of the column of air being sampled and thus the vertical resolution of the data. In a "high mode," the pulse length is increased, usually to 100 m or greater. The longer pulse length means that more energy is being transmitted for each sample, which improves the signal-to-noise ratio (SNR) of the data. Using a longer pulse length increases the depth of the sample volume and thus decreases the vertical resolution in the data. The greater energy output of the high mode increases the maximum altitude to which the radar wind profiler can sample, but at the expense of coarser vertical resolution and an increase in the altitude at which the first winds are measured. When radar wind profilers are operated in multiple modes, the data are often combined into a single overlapping data set to simplify postprocessing and data validation procedures.

Three body scatter spike



Example of a three body spike : the weak triangular echoes behind the red and white thunderstorm core.

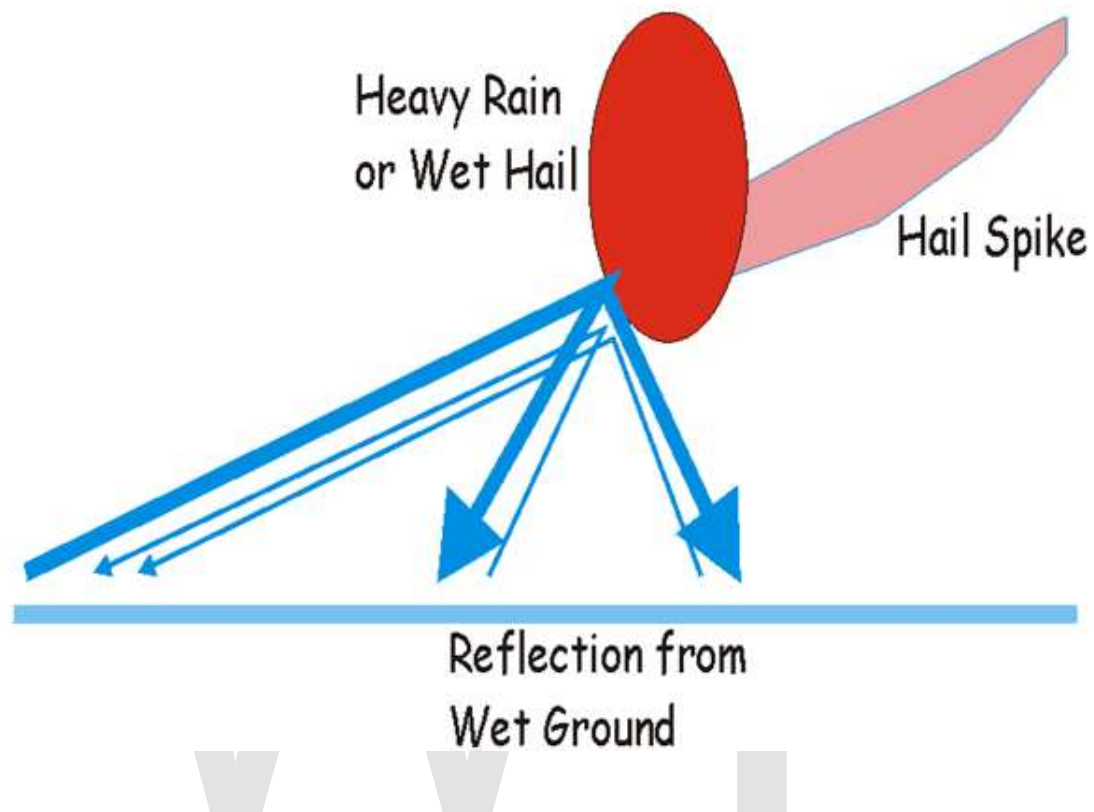


A cross-Section of a Three body spike from an Anti-Cyclonic Thunderstorm.

A **three body scatter spike** or TBSS is an artifact on a weather radar display indicative of large hail. They are identified by a spike of weak reflectivity echos that extend out from a thunderstorm, and away from the radar site.

Cause

Three Body Scattering



Also known as hail spikes, these are the result of energy from the radar hitting hail and being deflected to the ground, where they deflect back to the hail and then to the radar. Because of the energy hitting the ground at least once and the hail multiple times, it has a weaker return echo than the energy that went from the radar to the hail and back to the radar. The spike occurs where the energy took more time to go from the hail to the ground and back as opposed to the energy that went direct from the hail to the radar. This results in the radar picking up the energy at a later time which puts the echo further away from the radar than the actual location of the hail on the same radial path.

Since hail cores are most intense at higher elevations, hail spikes only appear at the levels aloft that accompany the most intense hail. Because of this, hail spikes are usually not seen at lower elevations. Another restriction to detection is that the signal of the radar beam has to do multiple reflections, each time weakening it. So hail spikes are usually noticeable only in extremely large hailstone cases.

Use in forecasting

Because of their observed accuracy in indicating large hail aloft, TBSS's are used operationally by the National Weather Service to identify thunderstorms that could likely produce large, severe hail. This would warrant the issuance of a severe thunderstorm warning or mention of large hail in a tornado warning.

WWT

Chapter-4

Plan Position Indicator and Bounded Weak Echo Region

Plan position indicator

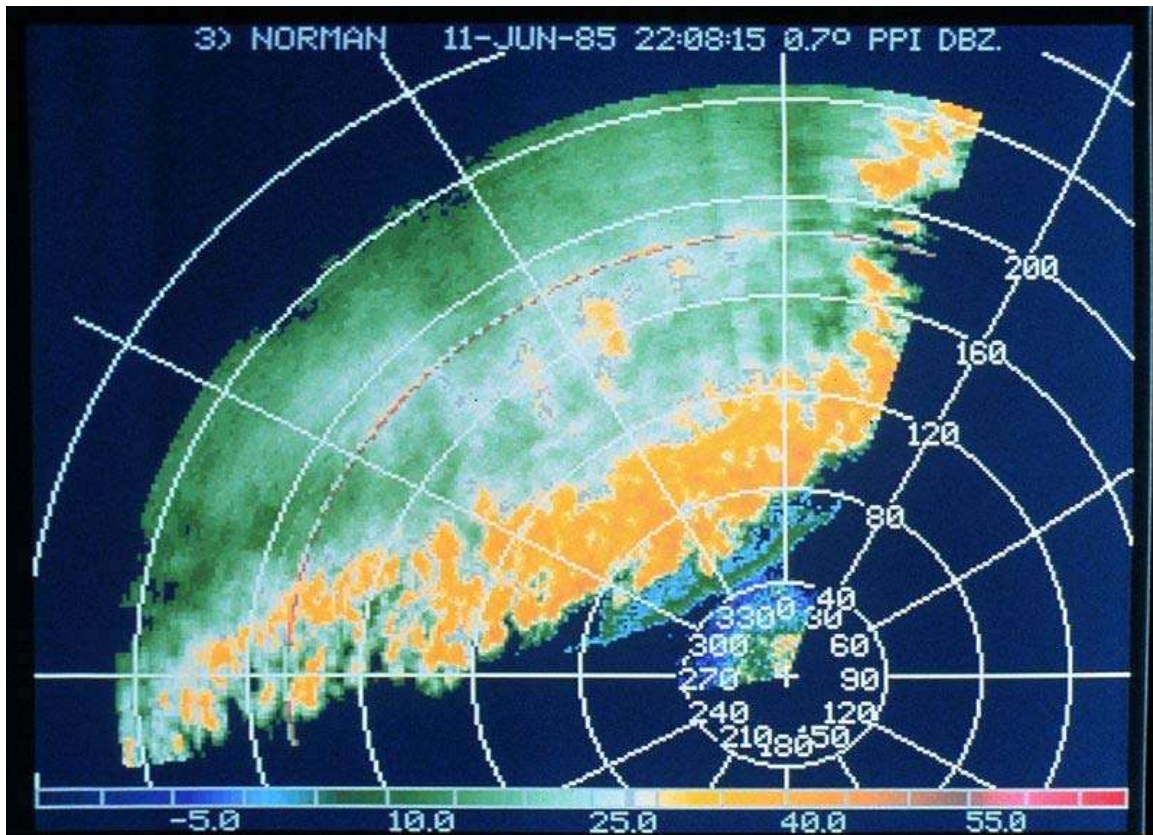


Image of a thunderstorm line (in dBZ) seen on a 0.7 degree elevation PPI (NOAA)

The **plan position indicator (PPI)**, is the most common type of radar display. The radar antenna is usually represented in the center of the display, so the distance from it and

height above ground can be drawn as concentric circles. As the radar antenna rotates, a radial trace on the PPI sweeps in unison with it about the center point.

Description

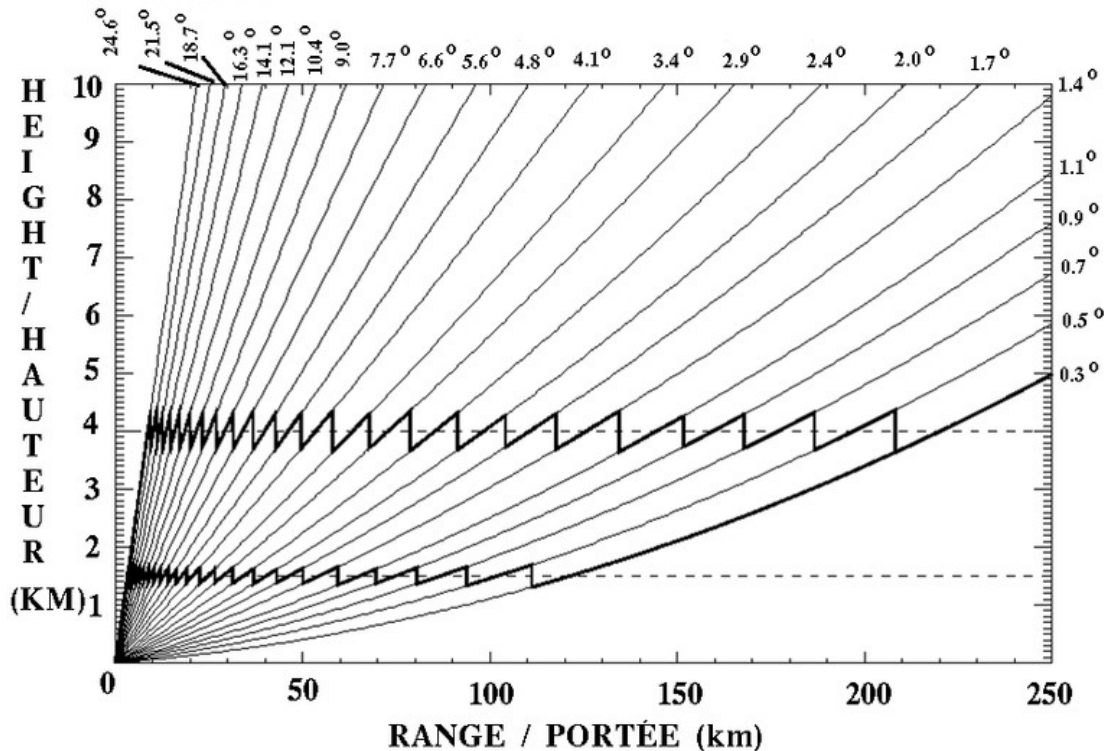


Diagram showing the evolution of the height above ground, in kilometers, with the distance to the radar for the 24 PPI angles used on the Canadian weather radars (curved lines)

The radar antenna sends pulses while rotating 360 degrees around the radar site at a fixed elevation angle. It can then change angle or repeat at the same angle according to the need. Return echoes from targets are received by the antenna and processed by the receiver and the most direct display of those data is the PPI.

It is to be noted that the height of the echoes increases with the distance to the radar, as represented in the image to the right. This change is not a straight line but a curve as the surface of the Earth is curved and *sinks* below the radar horizon. For fixed-site installations, north is usually represented at the top of the image. For moving installations, such as ship and aircraft radars, the top represents the front part of the ship or aircraft, *i.e.*, its heading (direction of travel) and this is usually represented by a lubber line. The signal represented is the reflectivity at only one elevation of the antenna, so it is possible to have many PPIs at one time, one for each antenna elevation.

History



A photograph of an H2S PPI display taken during an attack on Cologne - the annotations were added later for post-attack analysis

The PPI display was first used prior to the start of the Second World War in a Jagdschloss experimental radar system outside Berlin. The first production PPI was devised at the Telecommunications Research Establishment, UK and was first introduced in the H2S radar blind-bombing system of World War II.

Originally, data was displayed in real time on a cathode ray tube, and thus the only way to store the information received was by taking a photograph of the screen. With the development of more sophisticated radar systems, it became possible to digitize data and store it in memory, allowing access at a later date.

Philo Taylor Farnsworth, the American inventor of all-electronic television in September 1927, has contributed to this in an important way. Farnsworth refined a version of his picture tube (cathode ray tube, or CRT) and called it an "Iatron;" generically known as a storage tube. It could store an image for milliseconds to minutes and even hours. One version that kept an image alive about a second before fading proved to be a useful for

radar. This slow-to-fade display tube was used by air traffic controllers from the very beginning of radar usage.

Uses

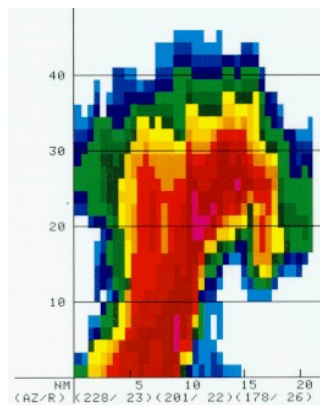


Simplified Plan Position Indicator radar display

The PPI is used in many domains involving radars, including air traffic control, meteorology, on board ships and aircraft etc. In meteorology, a competing display system is the CAPPI (Constant Altitude Plan Position Indicator) when a multi-angles scan is available.

Using computers to process data, modern sonar and lidar installations can mimic radar PPI displays too.

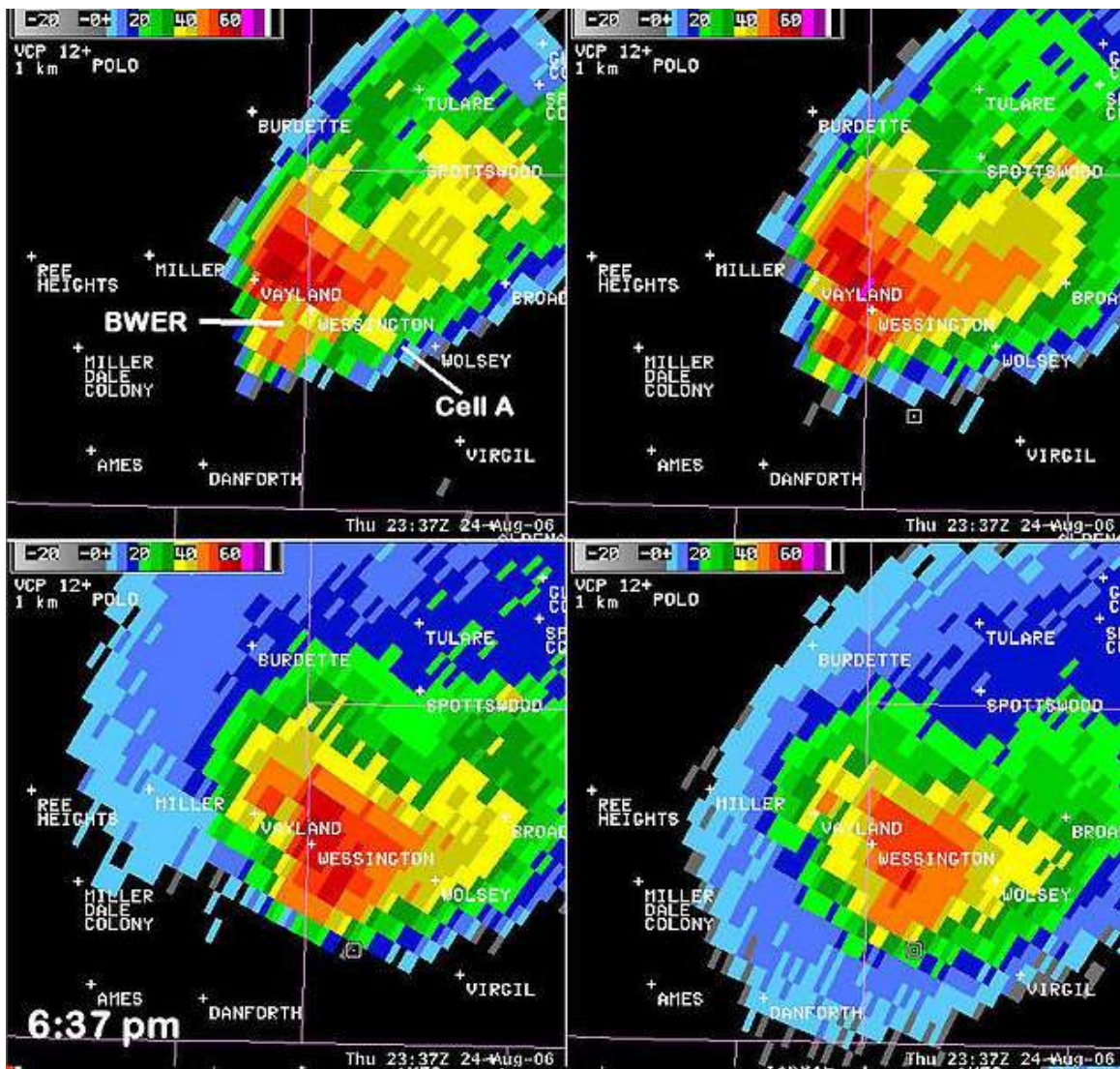
Bounded weak echo region



Vertical cross-section through a supercell showing the BWER.

The **bounded weak echo region**, also known as a **BWER** or a vault, is a radar signature within a thunderstorm characterized by a local minimum in radar reflectivity at low levels which extends upward into, and is surrounded by, higher reflectivities aloft. This feature is associated with a strong updraft and is almost always found in the inflow region of a thunderstorm. It cannot be seen visually. The BWER has been noted on radar imagery of severe thunderstorms since 1973 and has a lightning detection system equivalent known as a *lightning hole*.

Description and attributes



BWER associated with a tornadic supercell in 2006, as seen from different elevation angles. The lower angles (upper left) shows a weaker area of reflectivity but not at higher levels.

The BWER is a nearly vertical channel of weak radar echo, surrounded on the sides and top by significantly stronger echoes. The BWER, sometimes called a vault, is related to the strong updraft in a severe convective storm that carries newly formed atmospheric particulates, called hydrometeors, to high levels before they can grow to radar-detectable sizes. BWERs are typically found at midlevels of convective storms, 3 kilometres (1.9 mi) to 10 kilometres (6.2 mi) above the ground, and are a few kilometers in horizontal diameter. Identifying the location of the updraft region is important because it is linked to locations where severe weather normally occurs. The presence of a BWER has been part of a method to diagnose thunderstorm strength as part of the Lemon technique since 1977. The updraft strength within the BWER supports the growth of large hailstones just above the vault, which can be displaced slightly into the direction of motion of the parent supercell storm.

Detection

The bounded weak echo region (BWER) is a region of low radar reflectivity bounded above by an area of higher radar reflectivity which shows evidence of a strong updraft within mesocyclones. Radar analysts have recognized this phenomenon since at least 1973, using different elevation scans. Methods of objectively corroborating that a BWER is associated with a mesocyclone is done by using a weather radar with Doppler effect to obtain the precipitations velocities. This has been available operationally in United States since 1997 with the NEXRAD network. When using the lightning detection system, lightning holes (uncovered in 2004) correspond to where a BWER would be seen on radar.

A cross-section of the three-dimensional reflectivity of a thunderstorm shows the vault better. Algorithms were developed by the J.S. Marshall Radar Observatory of McGill University in Canada to locate the overhang region in a thunderstorm by the late 1980s. Its radar uses 24 angles, giving it good vertical resolution. In United States, fewer scanning angles are made within the WSR-88D radar which makes it more difficult to detect the overhang. Once the overhang is located, it is possible to make a cross-section to view if it is related with a BWER. However, since 1997 algorithms have been developed by the National Weather Service to determine regions of reflectivity gradient in three dimensions and the presence of BWER in convection.

The development of a pronounced BWER can lead to tropical cyclone-like radar signatures over land when located with a low angle plan position indicator (PPI). When using the lightning detection system, lightning holes (uncovered in 2004) correspond to where a BWER would be seen on radar.

Chapter-5

Terminal Doppler Weather Radar and OU-PRIME

Terminal Doppler Weather Radar



Airports with a TDWR in the US. Another in San Juan, Puerto Rico, is not on this map.

Terminal Doppler Weather Radar (TDWR) is a doppler weather radar system used primarily for the detection of hazardous wind shear conditions on and near major airports in the United States. As of 2009, there are 45 such radars across United States, and a number have been sold to other countries, such as China (Hong Kong). Funded by the United States Federal Aviation Administration, TDWR was developed in the early 1990s at Lincoln Laboratory, part of the Massachusetts Institute of Technology, to assist air

traffic controllers by providing real-time wind shear detection and high-resolution precipitation data.

The primary advantage of TDWR over previous radars is that it has a finer range resolution—meaning it can see smaller areas of the atmosphere. The reason for the resolution is that the TDWR has a narrower beam than traditional radar systems, and that it uses a set of algorithms to reduce ground clutter.

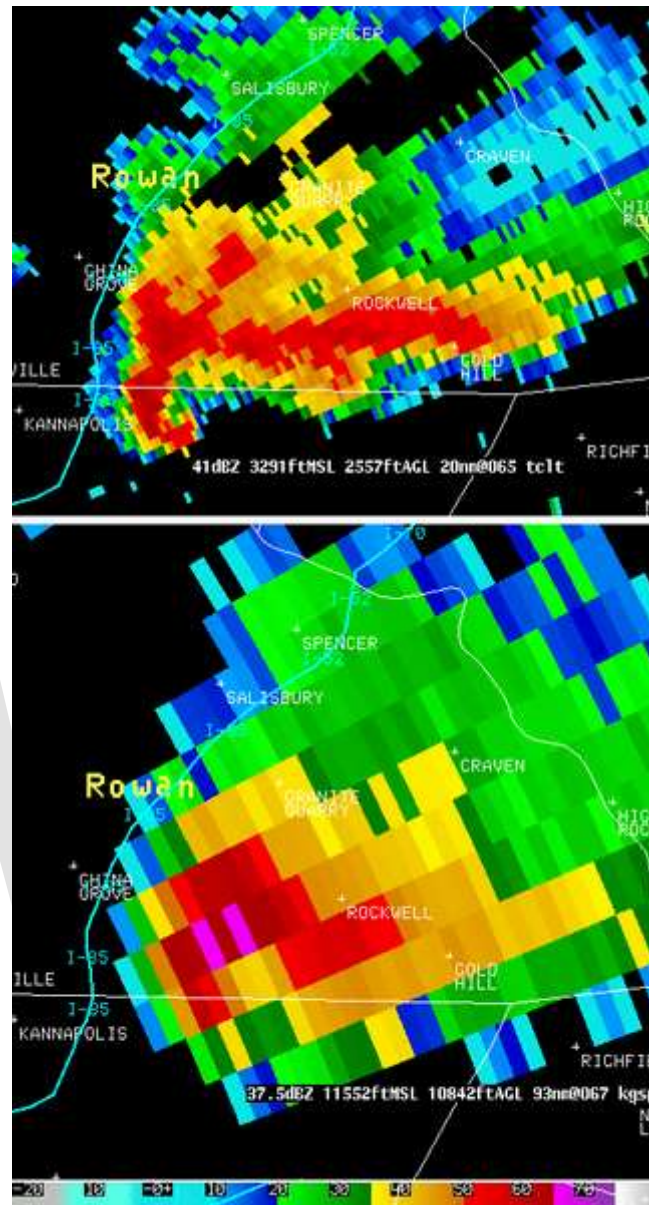
Characteristics

The TDWR uses a 5 cm wavelength carrier wave with an angular resolution beam of 0.55 degrees. In reflectivity, the resolution in distance is 150 meters within 135 kilometers of the radar and 300 meters from 135 km to 460 km to the radar. The reason for this difference is that the width resolution being angular, at larger range the width of the beam becomes quite large and to obtain a better averaging of data in a resolution volume, one has to increase the number of range pulse bins. This cut off is arbitrarily set for the software at 135 km.

In radial velocities, data are available up to 90 km from the radar with the full angular resolution of 0.5 degrees and range resolution of 150 meters. Because of the Pulse Repetition Frequency used, there is aliasing and the maximum non-ambiguous velocity is 20 to 30 knots.

TDWR can perform near-surface scans at a 0.1-0.3 degree angle of inclination from the Earth's surface every minute. It can also perform composite scans in which the radar observes at several different angles of inclination in order to obtain a fuller picture of the atmospheric conditions; each such composite scan requires 6 minutes.

Comparison with NEXRAD



Located in near identical locations, a TDWR return (top) and NEXRAD return (bottom) showing the improved resolution in reflectivity, but also showing the attenuation in the TDWR due to absorption from heavy precipitation as a black gap.

Advantages

A NEXRAD weather radar currently used by the National Weather Service is a 10 cm wavelength radar capable of a complete scan every 4.5 to 10 minutes, depending on the number of angles scanned. Its resolution is 1.25 degrees in width and 250 meters in range. The non-ambiguous radial velocity is 62 knots up to 230 km from the radar.

The range resolution of the TDWR is nearly twice the one of the NEXRAD. This will give much better details on small features in precipitation patterns, particularly in thunderstorms, in reflectivity and radial velocity. However, this finer resolution is only available up to 135 km from the radar; beyond that, the resolution is close to that of the NEXRAD.

Shortcomings

The shorter 5 cm wavelength, which is closer to the size of a raindrop than the 10 cm wavelength, is partially absorbed by precipitation. This is a serious drawback to using TDWR, as the signal can be strongly attenuated in heavy precipitation. This attenuation means that the radar cannot "see" very far through heavy rain and could miss severe weather such as strong thunderstorms which may contain the signature of a tornado, when there is heavy rain falling between the radar and that storm. When heavy rain is falling on the radome, the range of the TDWR is further limited. Finally, hail in a thunderstorm scanned by a TDWR can entirely block the signal as its size is larger than the wavelength. So a total attenuation behind a storm should raise the possibility of hail in the observer's mind.

A second problem is the smaller non-ambiguous radial velocity or Nyquist velocity. In the case of the TDWR, this means the velocity of precipitations moving at a speed beyond 30 knots away or toward the radar will be analyzed incorrectly because of aliasing. Algorithms to correct for this do not always yield the proper results. NEXRAD has a threshold that is twice as high (62 knots) and thus less processing and interpretation are needed. Because of this, the resolution of radar reflectivity for small scale features such as mesocyclones might be better in TDWR, but the velocity resolution may be worse.

Thus, it is best to use the TDWR in conjunction with a traditional NEXRAD nearby to ensure that nothing is missed.

Data processing improvements

The National Severe Storms Laboratory (NSSL) has a program of development and improvement of radar products extracted from data obtained from TDWR and NEXRAD radars. The *Severe Weather Warning Applications and Technology Transfer* (SWAT) group is sponsored by the National Weather Service and the FAA. It is working in 2009 on better filtering of non-weather echoes, better dealiasing algorithms of velocities, techniques to extract horizontal the wind field from one or multiple radars. NSSL has been providing TDWR data to NWS office since the late 1990's.

OU-PRIME



Lifting of radome base for OU-PRIME



Installation of 8.5-meter dish for OU-PRIME



Completion of radome for OU-PRIME



Commissioning of OU-PRIME on April 4, 2009



OU-PRIME after completion, September 2009

OU-PRIME (Polarimetric Radar for Innovations in Meteorology and Engineering) is an advanced Doppler weather radar. It was completed in January 2009 after a ten-month construction period and commissioned on April 4, 2009. It is operated by the Atmospheric Radar Research Center (ARRC) at the University of Oklahoma (**OU**). The radar was built to provide OU students and faculty a platform for research and education in the field of radar meteorology. This C-band polarimetric radar has the highest resolution of any C-band, polarimetric, research, weather radar in the United States and possibly the world.

System characteristics

OU-PRIME, aka OU', is located on the Research Campus of the University of Oklahoma within walking distance of the National Weather Center building. Through a unique design, OU-PRIME can provide real-time time-series data providing opportunities for rapid developments in radar signal processing algorithms. Because of its C-band wavelength and 1 MW transmit power, OU-PRIME is extremely sensitive to clouds with approximately 10 dB more sensitivity over the NEXRAD system (S-band).

Characteristics :

- Radiating Center Height is 80 feet (24.4 m)
- Operating frequency is 5510 MHz (C-band)
 - Wavelength: 5.44 cm
 - Pulse Length: 0.4, 0.8, 1.0, 2.0 usec
 - Pulse Repetition Frequency: 300-2000 Hz, 1-Hz step
- 1 MW Peak Power (magnetron with solid-state modulator)
- 8.5-meter Andrew's precision C-band dish
 - High angular resolution: 0.5 degree @ -3 dB points
 - Gain: 50 dBi
 - Sidelobe Level: Better than -26 dB one-way
 - Cross-Pol: Better than -30 dB
- Rotation rate: 6-25 deg/sec under typical scanning (30 deg/sec Max)
- Minimum Detectable Signal: -112 dBm
 - Radar Sensitivity: -18 dBZ at 50 km
 - Noise Figure: 3 dB
- Simultaneous dual-polarization
- Flexible computing platform for real-time algorithm development
- Real-time I/Q data recording/processing
 - A/D converter resolution: 16 bit
 - Receiver bandwidth: 6 MHz
 - Gate spacing: 25-500 m
 - Number of range gates: up to 2200
 - Clutter suppression: 60 dB (automatic detection/suppression using CLEAN-AP)

Chapter-6

NEXRAD and ARMOR Doppler Weather Radar

NEXRAD

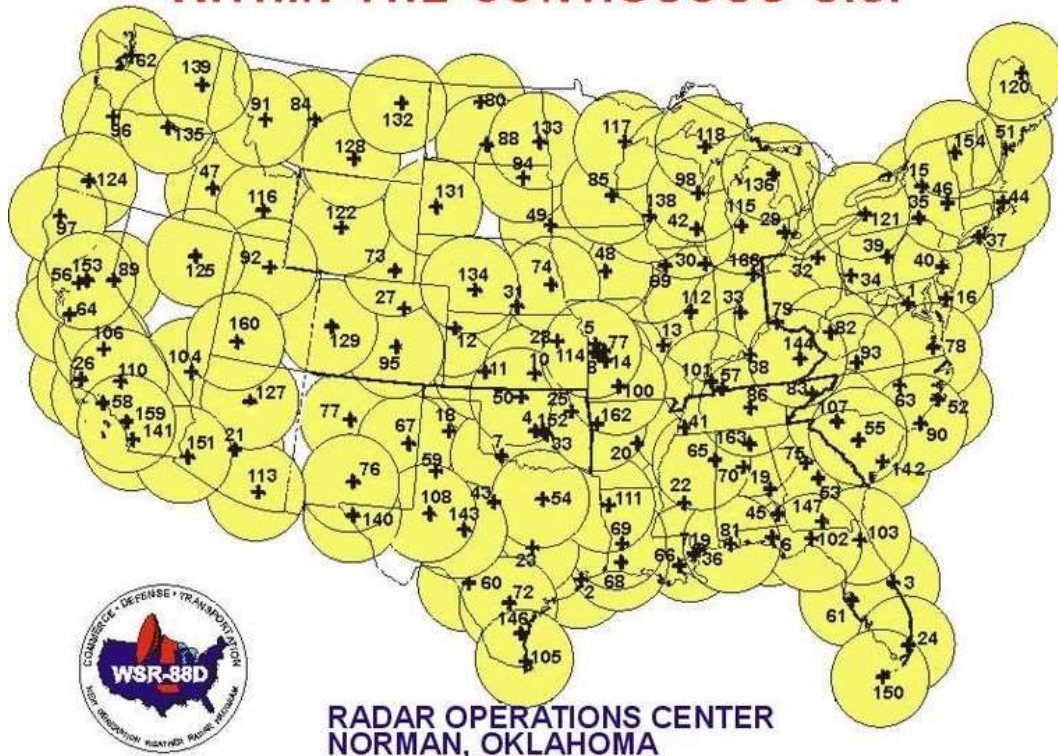


NEXRAD Radar at the WSR-88D Radar Operations Center

NEXRAD or **Nexrad (Next-Generation Radar)** is a network of 159 high-resolution Doppler weather radars operated by the National Weather Service, an agency of the National Oceanic and Atmospheric Administration (NOAA) within the United States Department of Commerce. Its technical name is **WSR-88D**, which stands for **W**eather **S**urveillanc**e** **R**adar, **1988**, **D**oppler. NEXRAD detects precipitation and atmospheric movement or wind. It returns data which when processed can be displayed in a mosaic map which shows patterns of precipitation and its movement. The radar system operates in two basic modes, selectable by the operator – a slow-scanning **clear-air mode** for analyzing air movements when there is little or no activity in the area, and a **precipitation mode**, with a faster scan for tracking active weather. NEXRAD has an increased emphasis on automation, including the use of algorithms and automated volume scans.

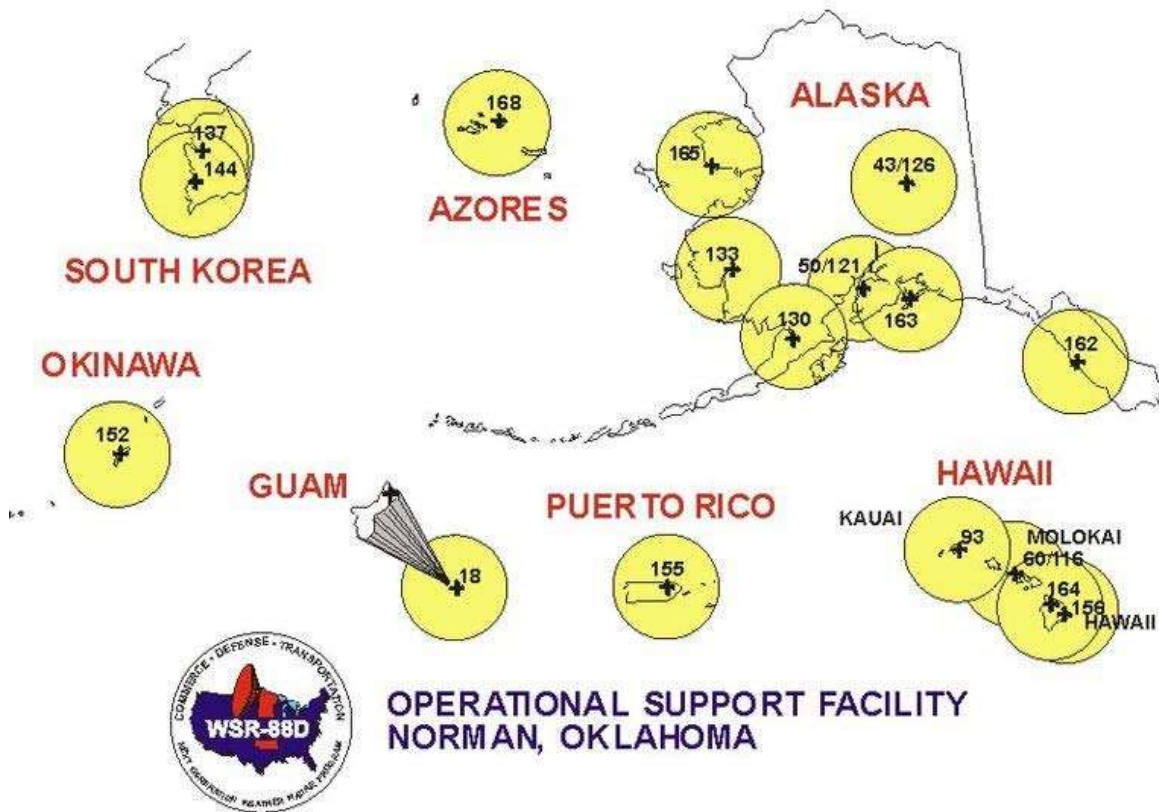
Deployment

COMPLETED WSR-88D INSTALLATIONS WITHIN THE CONTIGUOUS U.S.



Continental US sites

COMPLETED WSR-88D INSTALLATIONS



Alaska, Hawaii, territories, and military base sites

In the 1970s, the US Department of Commerce, Department of Defense, and the Transportation Department found the need to replace the existing national radar network, consisting of non-Doppler **WSR-74** and **WSR-57** radars developed in 1974 and 1957, respectively, to better serve their operational needs. The Joint Doppler Operational Project (JDOP) was formed in 1976 at the National Severe Storms Laboratory to study the usefulness of using Doppler radar to identify severe and tornadic thunderstorms. Tests over the next three years, conducted by the National Weather Service and the US Air Force Weather Service, found that Doppler radar provided much improved early detection of severe thunderstorms. A working group that included the JDOP published a paper providing the concepts for the development and operation of a national weather radar network. In 1979, the NEXRAD JSOP was formed to move forward with the development and deployment of the proposed NEXRAD radar network. The JSOP group needed to select a contractor to develop and produce the radars that would be used for the national network. Radar systems developed by Raytheon and Unisys were tested during the 1980s. Unisys was selected as the contractor, and was awarded a full-scale production contract in January 1990.

Installation of a prototype was completed in the Fall of 1990 in Norman, Oklahoma. The first installation of a WSR-88D for operational use in everyday forecasts was in Sterling, Virginia on June 12, 1992. The last system was installed in North Webster, Indiana on August 30, 1997. The site locations were strategically chosen to provide the most overlapping coverage between radars in case one failed during a severe weather event. Where possible, they were co-located with NWS Weather Forecast Offices to permit quicker access to maintenance technicians.

The NEXRAD radars incorporated a number of improvements over the radar systems previously in use. The new system provided Doppler velocity, improving tornado prediction ability. It provided improved resolution and sensitivity, allowing operators to see features such as cold fronts, thunderstorm gust fronts, and mesoscale features of thunderstorms that had never been visible on radar. The NEXRAD radars also provided volumetric scans of the atmosphere allowing operators to interrogate the vertical structure of storms and provide detailed wind profiles above the radar site. The radars also had a much increased range allowing detection of weather features at much greater distances from the radar site.

Scan strategies

Unlike its predecessors, the WSR-88D antenna is not directly controllable by the user. Instead, the radar system continually refreshes its three-dimensional database via one of several predetermined scan patterns. Since the system samples the atmosphere in three dimensions, there are many variables that can be changed, depending on the desired output. There are currently nine Volume Coverage Patterns (VCP) available to NWS meteorologists. Each VCP is a predefined set of instructions given to the antenna that control the rotation speed, transmit/receive mode, and elevation angles. The radar operator chooses from the VCPs based on the type of weather occurring:

- Clear Air or Light Precipitation: VCP 31 and 32
- Shallow Precipitation: VCP 21
- Convection: VCP 11, 12, 121, 211, 212, and 221

VCP	Scan Time (min)	Elevation scans	Elevation angles (°)	Usage	Special attributes
11	5	14	0.5, 1.5, 2.4, 3.4, 4.3, 5.3, 6.2, 7.5, 8.7, 10, 12, 14, 16.7, 19.5	Convection, especially when close to the radar	Has the best overall volume coverage.
211				Convection, especially when close to the radar	Improves range-obscured velocity data over VCP 11
12	4.5	14	0.5, 0.9, 1.3, 1.8, 2.4, 3.1, 4.0, 5.1, 6.4,	Convection, especially activity at longer ranges	Focuses on lower elevations to better sample the lower

212		8.0, 10.0, 12.5, 15.6, 19.5	Widespread severe convective events	Improves range-obscured velocity data over VCP 12
121	6		Large number of rotating storms, tropical systems, or when better velocity data is needed.	Scans lower cuts multiple times with varying pulse repetitions to greatly enhance velocity data.
21	9	0.5, 1.5, 2.4, 3.4, 4.3, 6.0, 9.9, 14.6, 19.5	Shallow precipitation	Rarely used for convection due to sparse elevation data and long completion time.
221	5		Widespread precipitation with embedded convection. (i.e., tropical systems)	Improves range-obscured velocity data over VCP 121
31			Detecting subtle boundaries or wintry precipitation	Long-pulse
32	10	0.5, 1.5, 2.5, 3.5, 4.5	Slow rotation speed allows for increased sensitivity. Default clear-air mode, reduces wear on antenna.	Short-pulse

Enhancements

Super resolution

Deployed from March to August 2008, the Super Resolution upgrade is the capability of the radar to produce much higher resolution data. Under legacy resolution, the WSR-88D provides reflectivity data at 1 km by 1 degree to 460 km range, and velocity data at 0.25 km by 1 degree to a range of 230 km. Super Resolution provides reflectivity data with a sample size of 0.25 km by 0.5 degree, and increase the range of Doppler velocity data to 300 km. Initially the increased resolution is only available in the lower scan elevations. Super resolution makes a compromise of slightly decreased noise reduction for a large gain in resolution.

The improvement in azimuthal resolution increases the range at which tornadic mesoscale rotations can be detected. This allows for faster lead time on warnings and

extends the useful range of the radar. The increased resolution (in both azimuth and range) increases the detail of such rotations, giving a more accurate representation of the storm. Super Resolution also provides additional detail to aid in other severe storm analysis. Super Resolution extends the range of velocity data and provides it faster than before, also allowing for faster lead time on potential tornado detection and subsequent warnings.

Future enhancements

Dual polarization

The next major upgrade is polarimetric radar, which adds vertical polarization to the current horizontal radar waves, in order to more accurately discern what is reflecting the signal. This so-called dual polarization allows the radar to distinguish between rain, hail and snow, something the horizontally polarized radars cannot accurately do. Early trials have shown that rain, ice pellets, snow, hail, birds, insects, and ground clutter all have different signatures with dual-polarization, which could mark a significant improvement in forecasting winter storms and severe thunderstorms. The deployment of the dual polarization capability (Build 12) to NEXRAD sites will begin in 2010 and last until 2012. The Vance AFB radar is the first operational WSR-88D to be modified to Dual Polarization. The modified radar went operational on 3 March 2011.

Phased array

Beyond dual-polarization, the advent of phased array radar will probably be the next major improvement in severe weather detection. Its ability to rapidly scan large areas would give an enormous advantage to radar meteorologists. Any large-scale installation by the NWS is unlikely to occur before 2010. Such a system would more likely be installed separate from the existing WSR-88D network, perhaps only in areas like the Great Plains where tornadoes are more common.

Applications

Usage

NEXRAD data are used in multiple ways. It is used by National Weather Service meteorologists and is freely available to users outside of the NWS, including researchers, media, and private citizens. The primary goal of NEXRAD data is to aid NWS meteorologists in operational forecasting. The data allows them to accurately track precipitation and anticipate its development and track. More importantly, it allows the meteorologists to track and anticipate severe weather and tornadoes. Combined with ground reports, tornado and severe thunderstorm warnings can be issued to alert the public about dangerous storms. NEXRAD data also provides information about rainfall and aids in hydrology forecasting. Data is provided to the public in several different forms. The most basic form is graphics published to the NWS website. Data is also available in two similar, but different, raw formats. Available directly from the NWS is

Level III data. Level III data consists of reduced resolution, low-bandwidth, base products as well as many derived, post-processed products. Level II data consists of only the base products, but at their original resolution. Because of the higher bandwidth costs, Level II data is not available directly from the NWS. The NWS distributes this data freely to several top-tier universities who in turn distribute the data to private organizations.

ARMOR Doppler Weather Radar



ARMOR radar

ARMOR (Advanced Radar for Meteorological and Operational Research) Doppler weather radar is one of the most advanced radar systems in the world. It is located at the Huntsville International Airport in Huntsville, Alabama. The radar is a collaborative effort between WHNT-TV and the University of Alabama at Huntsville.

Historic

This radar was originally a National Weather Service (NWS) local warning radar (WSR-74C) installed in 1977. It was refurbished and upgraded to Pulse-Doppler capabilities in 1991. When the NEXRAD network replaced previous NWS radars, it was donated to the

UAH Department of Atmospheric Science in 2002 and upgraded to dual-polarimetry using the SIGMET Antenna Mounted Receiver in the Fall 2004.

Then Baron Radar division of Baron Services, Inc., Huntsville, AL, In , upgraded the transmitter in 2005 to a 350 kW solid state transmitter. In the Fall of 2006, a high performance *Seavey* dual-polarization antenna and Orbit pedestal were purchased for ARMOR by the same company and made fully functional by the end of October.

ARMOR is the first dual polarimetric radar used in broadcast television news, and one of the first systems of its type open for educational use to a public university, The University of Alabama in Huntsville (UAH). Baron has, to date, installed all broadcast dual-polarization radars in the world.

Description

ARMOR is a C-Band (5625 MHz) radar with a 1 degree resolution in azimuth. The pulse length can vary from 0.4 to 2.5 microseconds and its peak power is 350 kW. It transmits and receives Vertical and Horizontal polarized signals.

Usages

The following is information about the radar and its advanced systems:

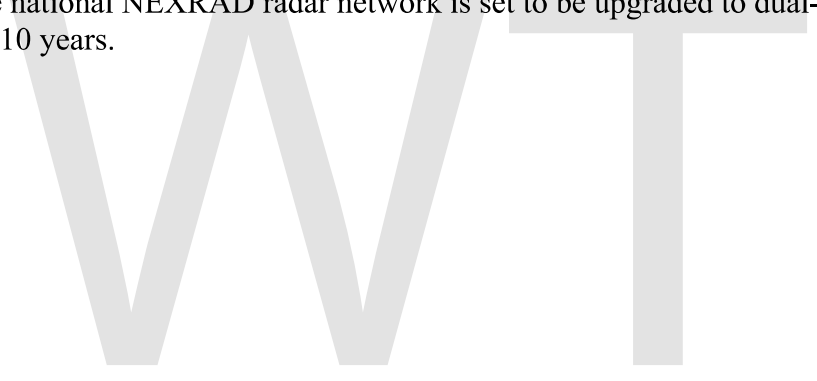
- One of a kind technology transfer via real-time use of ARMOR in the broadcast meteorology domain.
- Real-time operational feed to NWS for nowcasting and training at NWS WFO Huntsville
- Supports basic thunderstorm, cloud physics, cloud electrification and precipitation research within the UAH/NASA Severe Thunderstorm Observations and Research Meteorological NETWORK (STORM-NET)
- Source for Satellite precipitation mission ground truth and physical validation via precipitation microphysics retrieval and kinematic measurements (dual-Doppler)
- Vastly improved Quantitative Precipitation Estimation (QPE) for surface hydrological and water cycle studies
- Operational meteorological decision support tool development and data assimilation (e.g. NASA-SPoRT)
- Detailed cloud kinematic, microphysical, electrification, and lightning studies using the NASA Northern Alabama Lightning Mapping Array (NASA-MSFC/NSSTC Thunderstorm and Lightning Group), ARMOR polarimetric variables and real-time dual-Doppler capability.

- Potential hydrological data input for assimilation into local distributed runoff models, regional flood plain studies/planning
- Near surface wind retrievals for assimilation into pollutant dispersion models
- Boundary layer studies including identification of biological flyers

Users

In a unique partnership, this research radar is used by Meteorologists at WHNT-TV for forecasting and on air severe weather coverage. ARMOR was the first dual polarimetric capable radar installed by a television station. The data received from the radar is continuously archived at the National Space Science and Technology Center at UAH for full volumetric and surveillance scans.

ARMOR also deploys a live feed to the Huntsville National Weather Service Office making it one of the first NWS offices to gain first hand experience with dual-pole radar. Currently the national NEXRAD radar network is set to be upgraded to dual-pole within the next 5 to 10 years.



Chapter-7

WSR-74



WSR-74C radar from Central Illinois WFO

WSR-74 RADARs were **Weather Surveillance Radars** designed in 1974 for the National Weather Service. They were added to the existing network of the WSR-57 model to improve forecasts and severe weather warnings. Some have been sold to other countries like Australia, Greece, and Pakistan.

Radar properties

There are two types in the WSR-74 series, which are almost identical except for operating frequency. The WSR-74C (used for local warnings) operates in the C band, and the WSR-74S (used in the national network) operates in the S band (like the WSR-57 and the current WSR-88D). S band frequencies are better suited because they are not attenuated significantly in heavy rain while the C Band is strongly attenuated.

The WSR-74C uses a wavelength of 5.4 cm. It also has a dish diameter of 8 feet, and a maximum range of 579 km (313 nm) as it was used only for reflectivities.

History



WSR-74C Radar in Darwin, Northern Territory Australia

The WSR-57 network was very spread out, with 66 radars to cover the entire country. There was little to no overlap in case one of these vacuum-tube radars went down for maintenance. The WSR-74 was introduced as a "gap filler", as well as an updated radar that, among other things, was transistor-based.

WSR-74C radars were generally local-use radars that didn't operate unless severe weather was expected, while WSR-74S radars were generally used to replace WSR-57 radars in the national weather surveillance network. When a network radar went down, a nearby

local radar might have to supply updates like a network radar. Corpus Christi became the first operational site for the WSR-74C on February 1, 1976.

128 of the WSR-57 and WSR-74 model radars were spread across the country as the National Weather Service's radar network until the 1990s. They were gradually replaced by the WSR-88D model (Weather Surveillance Radar - 1988, Doppler), constituting the NEXRAD network. The WSR-74 had served the NWS for two decades.

Thirteen WSR-74Cs still have not been decommissioned and, of those, eight remain in active use today. No WSR-74Ss are in the NWS inventory today, having been replaced by the WSR-88D. Some of these radars are in commercial use.

Radar sites in the US

WSR-74 sites include the following two categories:

WSR-74C Site	Commissioned	Decommissioned
Abilene, TX (ABI)	August 27, 1977	April 30, 1997
Akron, OH (CAK)	June 1, 1977	November 15, 1995
Albany, NY (ALB)	July 27, 1977	November 2, 1995
Alpena, MI (APN)	June 8, 1977	December 9, 1996
Atlanta, GA (ATL)		
On a building between Hartsfield and downtown to this day.	October 20, 1976	February 1, 1996
Augusta, GA (AGS)	July 1, 1976	July 30, 1996
Austin, TX (AUS)	April 9, 1976	October 13, 1995
Baton Rouge, LA (BTR)	October 20, 1978	May 14, 1996
Beckley, WV	November 1,	January 12, 1996

(BKW)	1977	
Billings, MT (BIL)]	April 18, 1978	May 30, 1996
Bismarck, ND (BIS)	October 5, 1978	February 28, 1996
Burlington, VT (BTV)	Late 1977	January 29, 1998
Charlotte, NC (CLT)	February 28, 1978	September 17, 1996
Chattanooga, TN (CHA)		June 10, 1998
Cheyenne, WY (CYS)	September 15, 1976	April 24, 1996
	August 4, 1976	
Cleveland, OH (CLE)	Replaced a WSR-3.	November 15, 1995
	November 9, 1977	
Columbia, MO (COU)	Replaced a WSR-3.	June 19, 1996
	January 26, 1976	
Columbia, SC (CAE)		October 25, 1995
	JReplaced a WSR-1.	
Columbus, GA (CSG)	April 2, 1979	April 3, 1996
	June 9, 1977	
Columbus, OH (CMH)	Replaced a WSR-3.	December 1, 1995
	February 18, 1977	
Concordia, KS (CNK)	Replaced a WSR-3.	November 9, 1995
Corpus Christi, TX (CRP)	February 1, 1976	March 10, 1997

Duluth, MN (DLH)	1977	March 25, 1997
Erie, PA (ERI)	August 30, 1977	January 15, 2000?
Fort Smith, AR (FSM)	November 25, 1975 Replaced a WSR-3. March 12, 1976	July 7, 1998
Fort Wayne, IN (FWA)	Replaced a WSR-3. June 6, 1978	July 8, 1998
Goodland, KS (GLD)	Replaced a WSR-3. June 28, 1977	October 25, 1995
Harrisburg, PA (HAR)	June 28, 1977	January 12, 1996
Hartford, CT (BDL)	April 1977	November 2, 1995
Houghton Lake, MI (HTL)		December 9, 1996
Huntsville, AL (HSV)	1977.	December 15, 1999?
(Doppler capability after July 1991)	Replaced a WSR-3.	Now the ARMOR radar.
Indianapolis, IN (IND)	September 28, 1977	February 28, 1996
Las Vegas, NV (LAS)		September 1, 1995
Los Angeles, CA (LAX)		
On top of the Federal Building in Westwood to this day.		May 15, 1995

Louisville, KY (SDF)		July 19, 1994
Lubbock, TX (LBB)		April 3, 1996
Macon, GA (MCN)	April 18, 1977	April 3, 1996
Madison, WI (MSN)	1972	May 7, 1996
At Madison Airport.		
Marquette, MI (MQT)		July 16, 1996
Meridian, MS (MEI)	November 2, 1976	December 26, 1996
Mobile, AL (MOB)		October 12, 1995
Moline, IL (MLI)	August 30, 1977	January 19, 1996
Montgomery, AL (MGM)	1977	June 4, 1996
(Doppler capability after 1982)		
Muskegon, MI (MKG)	March 25, 1976	August 13, 1996
Norfolk, NE (OFK)	May 14, 1976	March 25, 1997
North Platte, NE (LBF)		November 27, 1996
Omaha, NE (OVN)	1977	July 10, 1996
Paducah, KY (PAH)		
At the Paducah Airport.	1984	February 23, 1996
Phoenix, AZ (PHX)		August 15, 1994
Portland, OR (PDX)		January 30, 1996

Raleigh, NC (RDU)	May 19, 1977	December 22, 1995
Rapid City, SD (RAP)		November 4, 1996
Rochester, MN (RST)	April 1976	January 9, 1997
San Angelo, TX (SJT)	October 1977	April 22, 1997
Savannah, GA (SAV)	November 15, 1982	February 11, 1997
Shreveport, LA (SHV)		June 5, 1996
Sioux Falls, SD (FSD)	1976	October 4, 1996
South Bend, IN (SBN)	October 22, 1982	July 8, 1998
Springfield, IL (SPI)	October 16, 1980	July 30, 1996
Topeka, KS (TOP)	1976	November 2, 1995
Tucson, AZ (TUS)	January 1983	March 14, 1996
Tulsa, OK (TUL)	March 12, 1976	April 5, 1995
Tupelo, MS (TUP)	April 1, 1983	December 6, 1995
Waco, TX (ACT)	November 8, 1976	September 13, 1995
Waterloo, IA (ALO)	November 19, 1976	January 17, 1997
Wichita Falls, TX (SPS)	February 5, 1977	December 26, 1996
Williston, ND (ISN)	February 21, 1978	Not decommissioned
Worcester, MA (ORH)	July 2, 1976	April 5, 1995

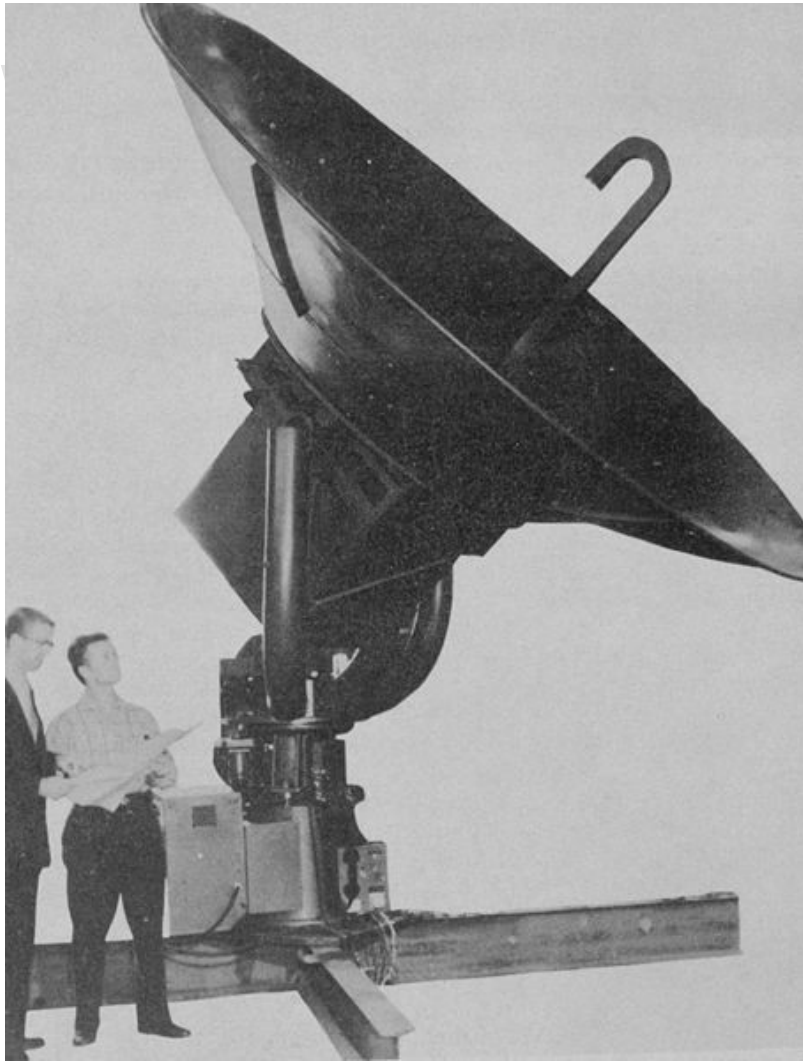
WSR-74S Site	Commissioned	Decommissioned
Alliance, NE (AIA)	June 10, 1977	January 17, 1997
Binghamton, NY	March 8, 1978	September 26,

(BGM)		1995
Charleston, WV (CRW)	May 16, 1977	January 12, 1996
WSR-74S providing local coverage		
Chatham, MA (CHH)	May 6, 1983	April 5, 1995
	March 9, 1984	
Detroit, MI (DTW)	Replaced a WSR-57. February 1, 1978	November 9, 1995
Fargo, ND (FAR)	Was a WSR- 74C from Oct. 9, 1976 to Nov. 27, 1977	November 27, 1996
Jackson, KY (JKL) WSR-74S providing local coverage	April 1, 1981	July 1, 1997
	1980.	
Key West, FL (EYW)	Replaced a WSR-57.	October 20, 1998
Longview, TX (GGG)	March 1, 1978	March 14, 1996
Marseilles, IL (MMO)	November 1, 1974.	
(Doppler capability)	Replaced a WSR-57 at Chicago.	January 19, 1996
Memphis, TN (MEG)	January 1986.	
At East Memphis/Agricenter site	Replaced a WSR-57.	June 21, 1995
Monett, MO (UMN)	March 16, 1971	February 1, 1996
	Replaced a	

	WSR-57	
Patuxent River, MD (NHK)	Early 1980s.	
At Patuxent River NAS	Replaced a WSR-57 at Washington, DC.	November 17, 1995
	March 5, 1985	
Portland, ME (PWM)	Replaced a WSR-57.	September 13, 1995
San Juan, Puerto Rico (SJU)		February 26, 1999
WSR-74S providing local coverage		
Volens, VA (VQN)	April 12, 1977	December 1, 1995
West Palm Beach, FL (PBI)		October 13, 1995
WSR-74S providing local coverage		

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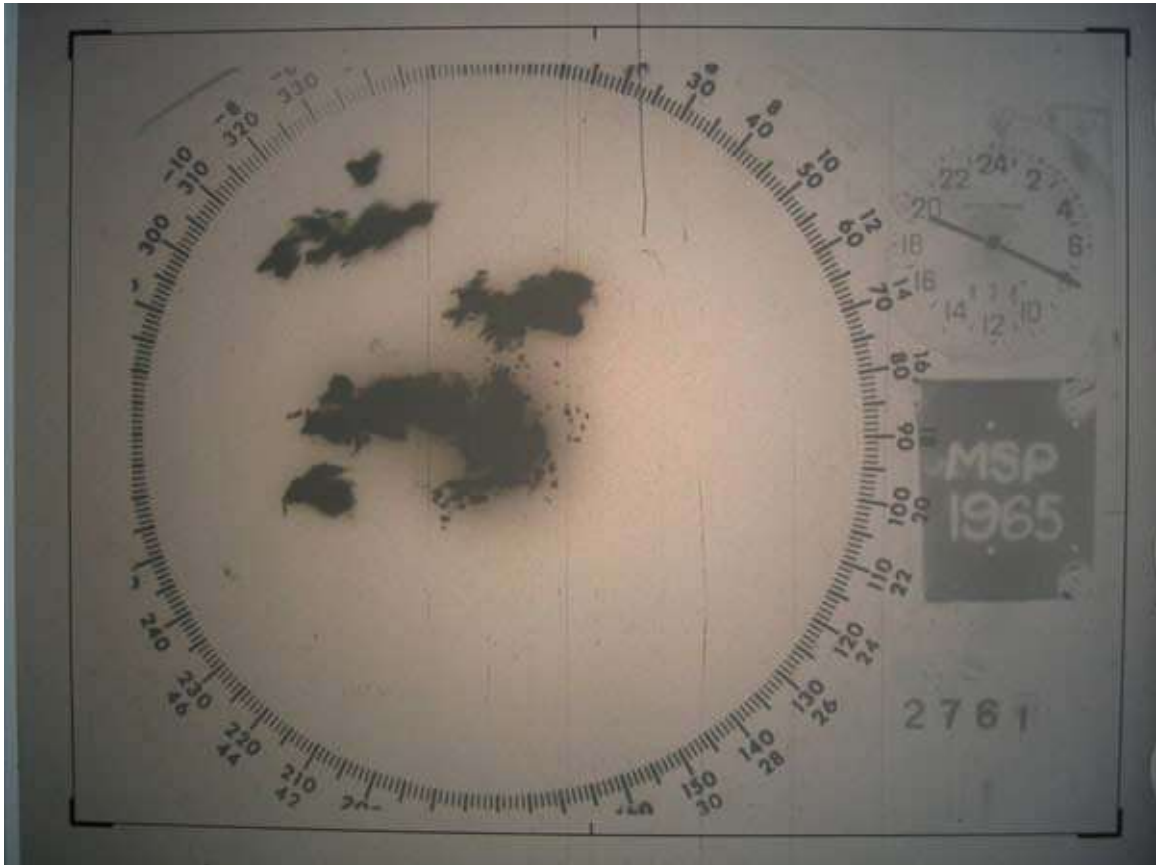
WSR-57



WSR-57 radar antenna from NOAA

WSR-57 radars were the USA's main weather surveillance radar for over 35 years. The National Weather Service operated a network of this model radar across the country, watching for severe weather.

History



Radar image of tornado-producing supercells over Minneapolis, 1965

The WSR-57 (Weather Surveillance Radar - 1957) was the first 'modern' weather radar. Initially commissioned at the Miami Hurricane Forecast Center, the WSR-57 was installed in other parts of the CONUS (continental United States). The WSR-57 was the first generation of radars designed expressly for a national warning network.

The WSR-57 was designed in 1957 using World War II technology. It gave only coarse reflectivity data and no velocity data, which made it extremely difficult to predict tornadoes. Weather systems were traced across the radar screen using grease pencils. Forecasters had to manually turn a crank to adjust the radar's scan elevation, and needed considerable skill to judge the intensity of storms based on green blotches on the radar scope.

The military designation for the WSR-57 is AN/FPS-41.

NOAA has interesting pictures of the Charleston, SC WSR-57 radar image of Hurricane Hugo in 1989. At the National Hurricane Center (NHC), Hurricane Andrew in 1992 blew the WSR-57 dish off their roof. The NHC report on Hurricane Andrew shows its last radar image, as well as images from nearby WSR-88D radars.

As the network of WSR-57 radars aged, some were replaced with WSR-74S models of similar performance but with better reliability. WSR-57 operators sometimes had to scramble for spare parts no longer manufactured in this country. One hundred twenty-eight of the WSR-57 and WSR-74 model radars were spread across the country as the National Weather Service's radar network until the 1990s. They were gradually replaced by the WSR-88D model (Weather Surveillance Radar - 1988, Doppler), constituting the NEXRAD network.

The last WSR-57 radar in the United States was decommissioned on December 2, 1996.


Radar sites

The 66 former sites of the WSR-57 include the following:

Site (Site ID)	Commissioned (Date / Chronological Rank)	Decommissioned
Miami, FL (MIA) Moved to Coral Gables in 1967.	June 26, 1959 1st	August 24, 1992 Destroyed during Hurricane Andrew.
Kansas City, MO (MCI) The dome still resides downtown.	1959 2nd	November 9, 1995
Charleston, SC (CHS)	1959 About 16th	December 2, 1996
Key West, FL (EYW?)	Early 1960 Among first 31	Early 1980s Replaced by a WSR-74S.
Wichita, KS (ICT)	June 22, 1960 Among first 31	November 9, 1995
Cincinnati, OH (CVG)	1960 (testing in June)	June 21, 1996

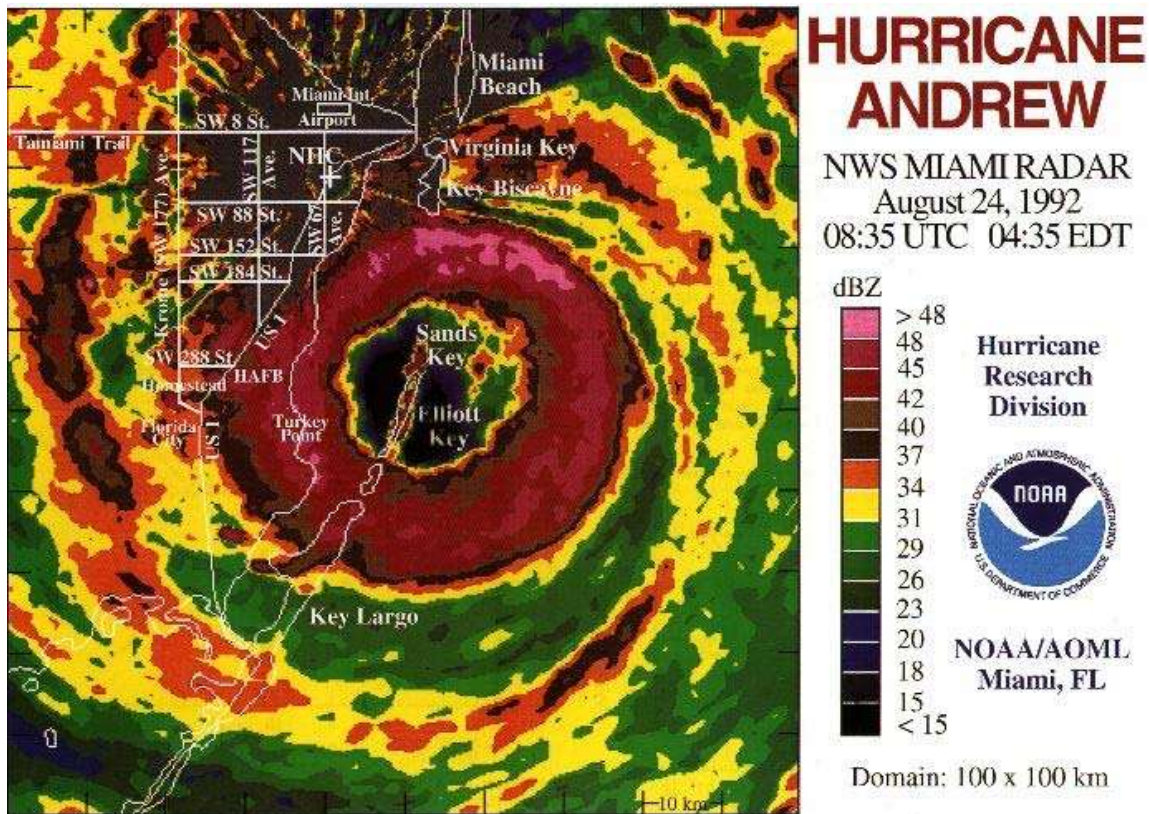
(Covington, KY) at the Greater Cincinnati Airport.	About 16th	
St. Louis, MO (STL)	July 1960 Among first 31	June 19, 1996
Wilmington, NC (ILM)	Before September 1960 Among first 31	November 16, 1995
Tampa Bay Area, FL (TBW)	1960 Among first 31	November 9, 1995
Galveston, TX (GLS)	1960 Among first 31	May 22, 1995
Brownsville, TX (BRO)	March 1961 About 16th	February 28, 1996
Fort Worth, TX (FTW) moved to Stephenville, TX (SEP) in October 1973.	April 5, 1961 Among first 31	August 1, 1995
Detroit, MI (DET)	September 12, 1961 Among first 31	Replaced with a WSR-74S.
Amarillo, TX (AMA)	1961 Among first 31	September 15, 1994
Norman, OK - NSSL Research radar; not part of the national network.	1962? Probably not counted among first 31	1980s
Catalina Island, CA (STC?) a.k.a. Santa Catalina - atop Blackjack Mountain.	Early 1963? Among first 31	1960's

Little Rock, AR (LIT was the WSR-57 designator. LZK is the WSR-88D and WFO Designation.)	1959 Among first 31	Moved to North Little Rock Airport with NWSFO in 1975. Final decommissioning was June 8, 1995
Sacramento, CA (SAC)	Early 1960s Among first 31	August 24, 1995
Washington, D.C. (IAD) At Washington Dulles International Airport, Dulles, VA.	Early 1960s Among first 31	Early 1980s Replaced by a WSR-74S at Patuxent River, MD.
Apalachicola, FL (AQQ)	Early 1960s Among first 31	January 19, 1996
Daytona Beach, FL (DAB)	Early 1960s Among first 31	December 1, 1995
Des Moines, IA (DSM)	Early 1960s Among first 31	May 7, 1996
Chicago, IL (?)	Early 1960s Among first 31	Early 1980s Replaced by a WSR-74S at Marseilles, IL
Evansville, IN (EVV)	Early 1960s Among first 31	July 12, 1996
Lake Charles, LA (LCH)	Early 1960s Among first 31	October 12, 1995
New Orleans, LA (MSY) At Slidell, LA	Early 1960s Among first 31	August 22, 1995
Minneapolis, MN (MSP) At the airport	Early 1960s Among first 31	April 3, 1996
Missoula, MT (MSO)	Early 1960s	December 12, 1995

At Point Six Mountain	Among first 31	
Atlantic City, NJ (ACY)	Early 1960s Among first 31	September 13, 1995
New York City, NY (NYC) At 30 Rockefeller Plaza. 	Early 1960s Among first 31	September 26, 1995
Oklahoma City, OK (OKC)	Early 1960s Among first 31	July 25, 1994
Portland, ME (?) At Brunswick Naval Air Station	November 1969	Replaced by a WSR-74S.
Jackson, MS (JAN) At Jackson International Airport at Thompson Field.	1969	June 21, 1995
Limon, CO (LIC)	1960s	December 22, 1995
Garden City, KS (GCK)	1960s	September 1, 1994
Grand Island, NE (GRI)	1960s	January 19, 1996
Buffalo, NY (BUF)	1960s	February 14, 1996
A note on the chronological ranks - The first 31 were built through the early 1960s, at existing Weather Bureau offices. 14 were along the Gulf and Atlantic coasts. 11 were in the Midwest. 3 were inland of the East Coast, and California and Montana had one each on mountaintops. The late 1960s saw 14 more built east of the Rockies.		
Nashville, TN (OHX) At Old Hickory Lake	November 1970	January 19, 1996
Memphis, TN (MEG?)	February 1971	December 1985

At the Millington Naval Air Station.		Replaced by a WSR-74S.
Medford, OR (MFR)	June 1971	August 30, 1996
Centreville, AL (CKL) Next to Brent, AL		June 27, 1995
Pensacola, FL (PNS/NPA)		January 19, 1996
Athens, GA (AHN)		September 13, 1996
Waycross, GA (AYS)		January 19, 1996
Cape Hatteras, NC (HAT)		December 6, 1995
Pittsburgh, PA (PBZ)		May 10, 1995
Huron, SD (HON)		November 4, 1996
Bristol, TN (TRI)		January 19, 1996
Midland/Odessa, TX (MAF)		June 4, 1996
Neenah, WI (EEW)	1972?	November 2, 1995
Hondo, TX (HDO)	July 1971 Last (66th)	March 14, 1996

Radar properties



Last image of the Miami's WSR-57 blown off by Hurricane Andrew.

- The radar uses a wavelength of 10.3 cm. This corresponds to an operating frequency of 2890 MHz. This frequency is in the S band, which is also used by today's weather radar network.
- WSR-57 radars had the following interesting statistics:
 - Dish diameter: 12 feet (3.7 m)
 - Power output: 410,000 watts
 - Maximum range: 915 km (494 nm)