The Practical Physics Of

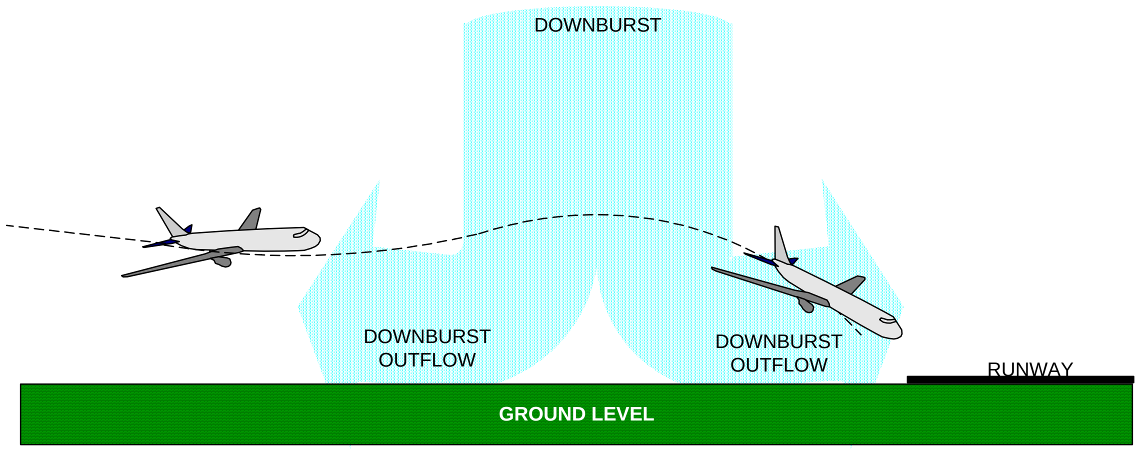
Airport Weather Radar

Expanded Edition

Low Level Wind Shear Management

Introduction

Low level wind shear presents an extreme hazard to aircraft during takeoff and landing. It has been determined to be responsible for a significant percentage of all commercial aviation fatalities. Low level wind shear is the result of downbursts which are often associated with thunderstorms.



When the downburst of air hits the ground, it spreads out sideways (outflow), much like the stream of water from a faucet hitting the bottom of the sink. As a result, low level wind shear occurs only at very low altitudes.

Small downbursts (less than 4 km in diameter) are called microbursts. Research has determined that microbursts are much more common, and occur much more frequently than had previously been thought.

When an aircraft first enters the outflow, it experiences a headwind. Near the center of the downburst, the headwind switches to a tailwind nearly instantaneously. The end result is that the aircraft suffers a sudden loss of air speed, which may cause a stall. At such a low altitude, recovery from a stall is virtually impossible.

Low level wind shear warning systems are designed to measure wind velocity and direction in areas where aircraft are near the ground, particularly the approach and departure flight paths near the ends of runways. The wind data is processed to detect divergent wind flow, i.e., whether or not there is a point which has wind flow away from it in all directions. If such a point is located, a wind shear alarm is sounded.

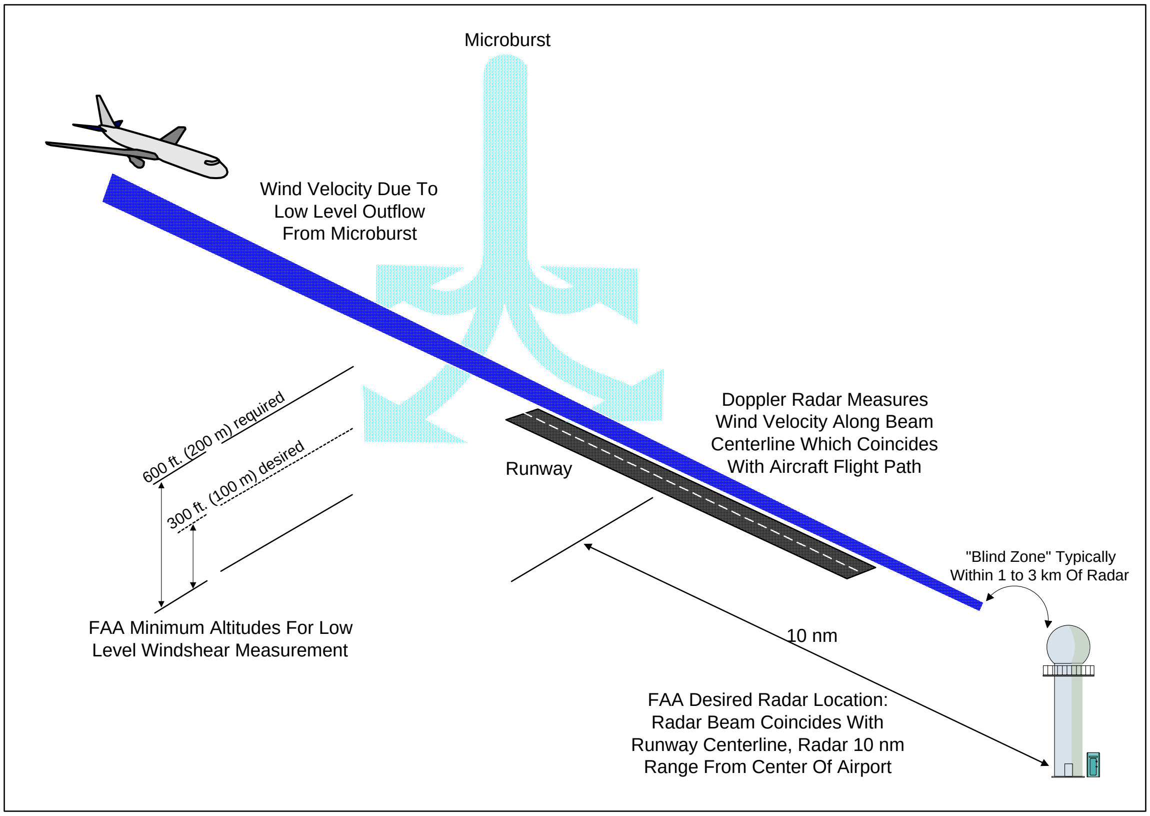
A high quality Doppler radar is an ideal device for detecting and measuring low level wind shear, because the radar can measure wind velocities accurately over a large area. Radar detection of low level wind shear is based on the ability of a Doppler radar to measure the horizontal velocity of particles in the atmosphere. Unfortunately, a single Doppler radar cannot measure wind direction, because the Doppler radar can only measure velocity along the centerline of the radar beam. This is called radial velocity.

However, it has been determined that if the Doppler radar beam approximately coincides with the aircraft's flight path, the radar can measure the wind velocity effects the aircraft will experience. Thus, if the radar is correctly located with respect to the runway, it will be able to accurately detect and measure the required low level wind shear velocities that would affect flight operations.

Radar Location

The U.S. Federal Aviation Agency (FAA) has devised a set of criteria for optimizing the location of a radar to detect low level wind shear near airports.

The nature of a wind shear event, and a summary of the FAA's desired radar location specifications are shown in the following diagram:



The location of the radar antenna with respect to the runway(s) to be protected is critical for measuring low level wind shear velocity along the aircraft flight path. The challenge for airport management is to find property for the weather radar antenna that is both available and technically satisfactory.

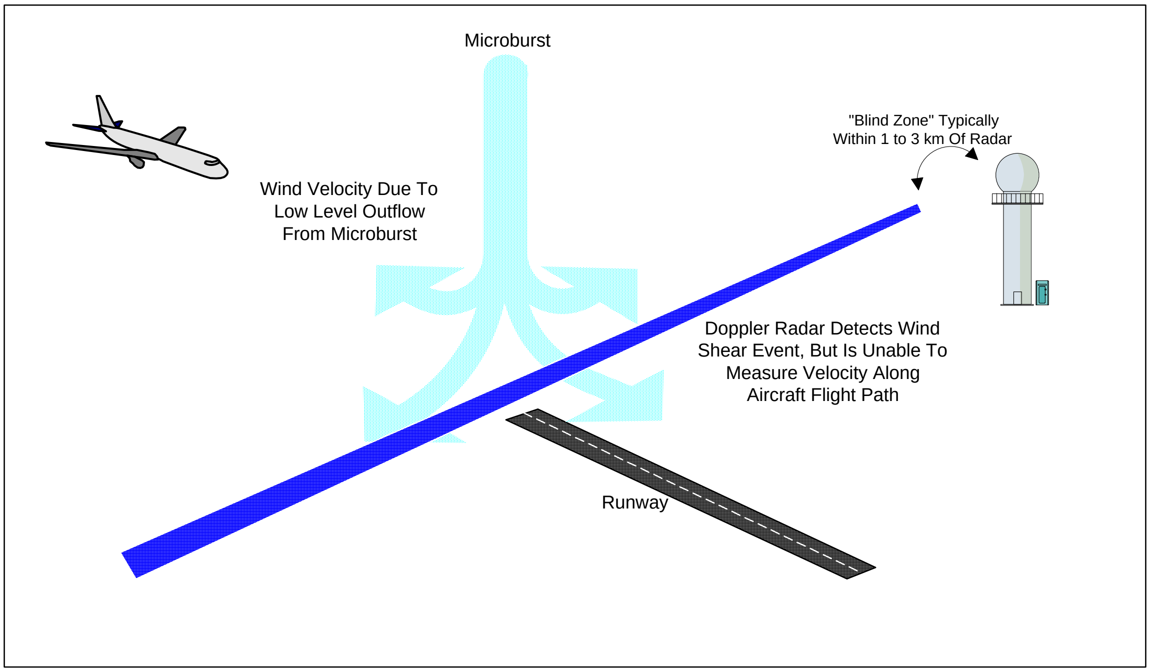
Unfortunately, in many cases, the most desirable location is not available. Then the radar must be built in a location that imposes technical limitations on the radar's performance. Maintaining safe airport flight operations depends on understanding those limitations.

Radar Beam Direction Relative To Runway

The basic physics of Doppler radar are such that the radar can accurately measure velocity only when the direction of motion is directly towards or away from the radar antenna. This is called radial velocity. The velocity of motion perpendicular to the radar beam will be measured as zero.

Accurate measurement of the wind velocity along the aircraft flight path requires that the radar beam coincide with the flight path. This is illustrated in the previous diagram. In the ideal case, the radar will be located so the radar beam "looks" straight along the runway centerline. In this location, the radar can accurately measure the wind velocity the aircraft will experience during approach or departure.

If the radar is located so the beam crosses the runway, as shown in the following diagram, the radar will still detect the presence of the microburst, but will be unable to accurately measure the velocity change the aircraft will experience.



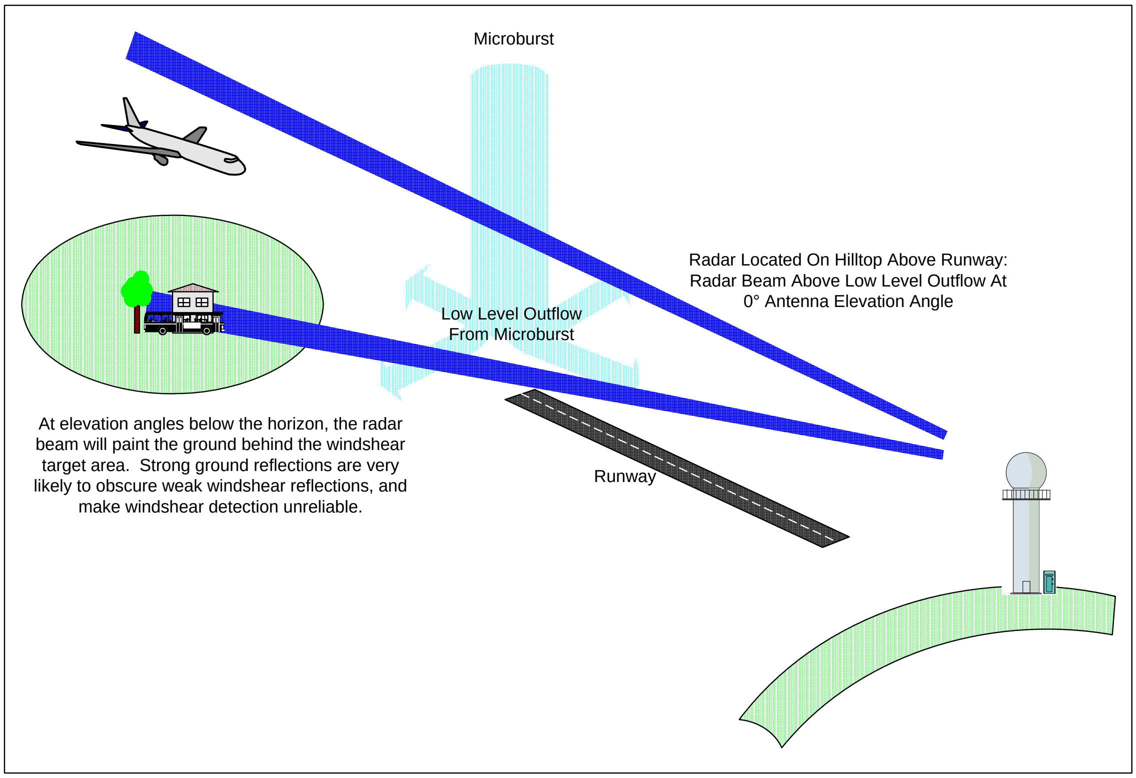
Research has shown that microburst outflow may be asymmetrical with velocity variations as much as 2:1 in different directions within the outflow area. Thus, when the radar beam is not aligned with the aircraft's flight path, the outflow velocities experienced by the aircraft can be expected to vary from one-half to twice the velocity the radar measures. Attempting to estimate the magnitude of the wind shear the aircraft will experience in this situation is likely to produce misleading results. The FAA *desires* that the angle between the radar beam centerline and the runway centerline be no more than 20°, and *requires* that it be no more than 30°.

However, even if the radar is in a location that does not permit accurate *measurement* of wind shear velocity, the radar's ability to do wind shear event *detection* is likely to improve the safety of flight operations.

Radar Beam Altitude

Another factor in the location of the radar is the altitude of the radar antenna with respect to the altitude of the runway. Low level wind shear happens at ground level. As a result, the outflow from a microburst spreads out in a relatively thin layer across the ground. Thus, the objective is to measure outflow velocity at the lowest possible altitude.

In the U.S. the FAA *desires* that wind shear detection radar provide reliable velocity data down to an altitude of no more than 300 ft. (100 m) above ground level (AGL), and *requires* that reliable velocity data be available down to no more than 600 ft. (200 m) AGL. The velocity values at the lowest altitude are the most important for proper wind shear detection and measurement.



If there is a hill in the vicinity of the airport, it is tempting to locate the radar on top of the hill. For many meteorological purposes, that is a good location. However, the hilltop location may place the radar beam above the most significant part of low level wind shear events. This is illustrated in the preceding drawing. Tilting the radar antenna down from the hilltop into the prime wind shear area is not likely to be useful. With the antenna "looking" down towards the ground, strong reflections from the ground are almost certain to overwhelm the weak reflections wind shear events often produce.

Distance From Airport To Radar

The final factor in the choice of a location for the radar is the distance from the areas requiring protection to the radar antenna. The most desirable location is to have the radar approximately 10 nm out from middle of the runway being protected.

The area of interest for the detection of low level wind shear typically includes the runway and a corridor 1 nm wide by 3 nm long off the end of each runway.

Having the radar too close to the runway may make it impossible to get good data. The "cone of silence" directly above the radar antenna is well known. Less well known is the "blind zone" that typically extends 1 to 3 km out from the radar antenna. This is the result of the finite switching time between transmit and receive within the radar. Close-in reflections simply come back too quickly to be received. Many radars can display reflectivity data at ranges of a few hundred meters. However, accurate Doppler velocity data, required for wind shear detection and measurement, typically requires a minimum of 1 to 3 km range.

A close-in location also means the antenna will have to scan to a higher elevation angle to detect high altitude precursors to a wind shear event. Scanning to the higher angle takes longer. This reduces the frequency of scanning at low angles for the most important part of flight path wind shear data.

Radar Location Summary

In the US, the Federal Aviation Agency (FAA) has done extensive research into selecting locations for its Terminal Doppler Weather Radar (TDWR) systems. The TDWR location criteria for US installations are summarized as follows:

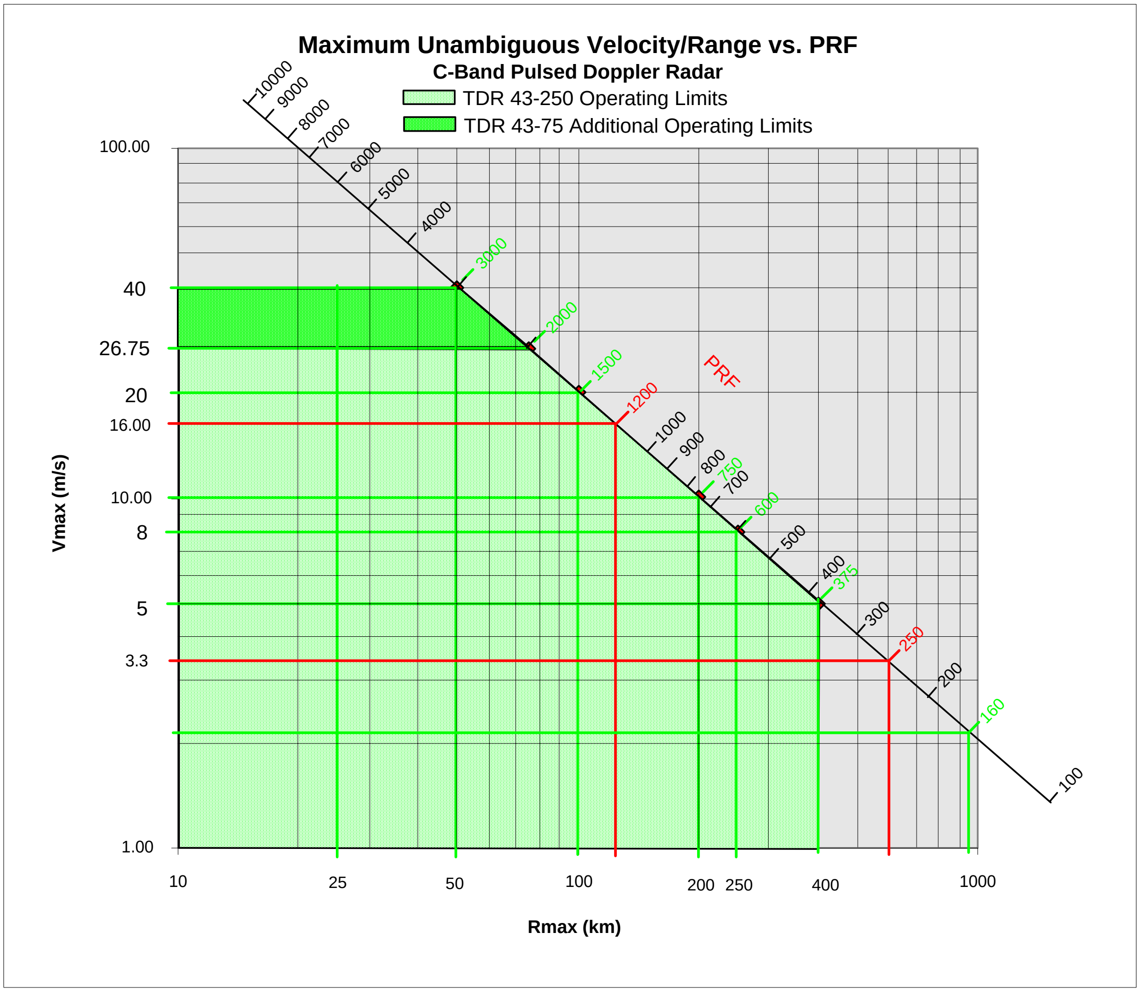
- The radar must have a clear unobstructed view of an area 1 nm wide, directly above the runway, and extending out for 3 nm from each end of the runway being protected.
- It is *desired* that the angle between the radar beam centerline and the runway centerline be no more than 20°. It is *required* that the angle between the radar beam centerline and the runway centerline be no more than 30°.
- It is *desired* that radar coverage extend down to an altitude of not more than 300 ft. above ground level. It is *required* that radar coverage extend down to an altitude of not more than 600 ft. above ground level.
- The radar should be located a distance of between 8 nm and 12 nm from the middle of the runway being protected.

A more detailed synopsis of the FAA's location requirements is attached.

Radar Characteristics

To reliably detect wind shear, a radar must have three characteristics; the ability to measure high velocities accurately, the ability to reject ground clutter and the sensitivity to detect very weak reflections.

Velocity Measurement

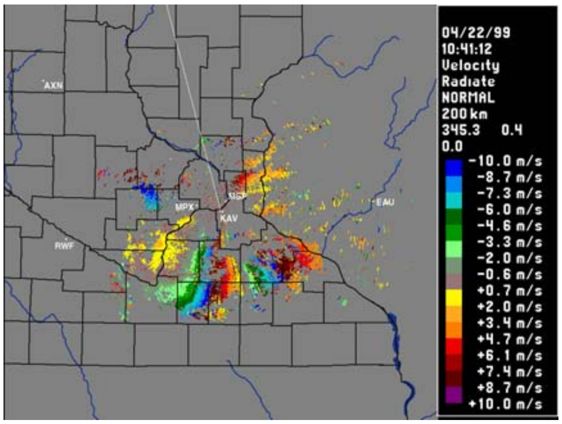


Measuring high velocities with a Doppler radar requires that the radar have a high PRF. Long ranges require a low PRF. This situation is often referred to as the "Doppler dilemma". It is the result of the basic physics of pulsed Doppler radar.

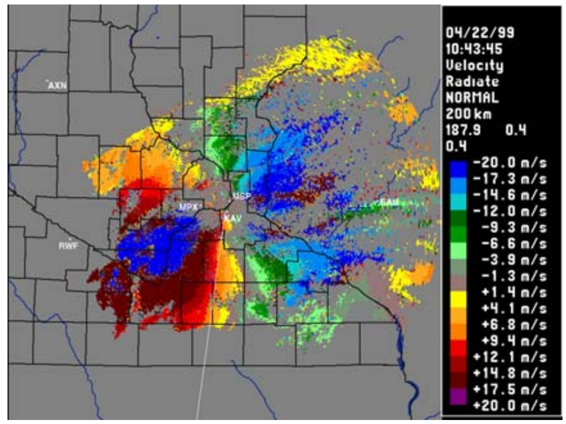
The preceding table indicates the relationship between PRF, velocity and range. Most conventional radars provide a choice between reflectivity mode with a PRF typically about 250, or velocity mode with a PRF typically about 1200. This is shown by the red lines in the chart above. This limits the maximum unambiguous velocity measurement to either 3.3 m/s (6.4 kts), or 16 m/s (31 kts) for this type of radar.

The exclusive TDR solid state DC modulator permits adjusting the PRF in a TDR radar from 160 to as high as 3000 (depending on model). This is shown in green. Thus, TDR radars can measure unambiguous velocities up to 26.75 m/s (51.9 kts) for xx84 models, and up to 40 m/s (77.6 kts) for xx70 models. The RDR-250GC can produce PRF's up to 2400 (32.1 m/s (62 kts)).

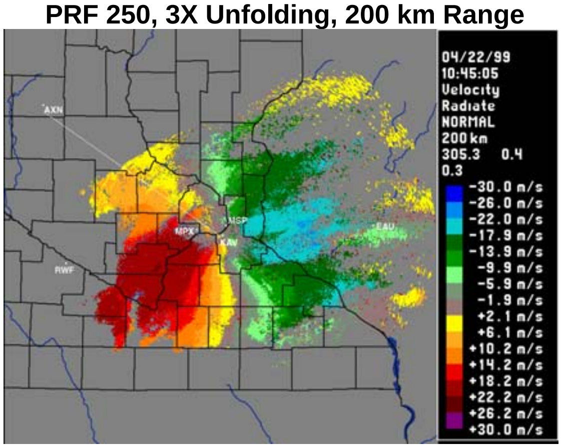
Velocity "folding" occurs when the actual wind velocity exceeds the maximum wind velocity the radar is capable of measuring.



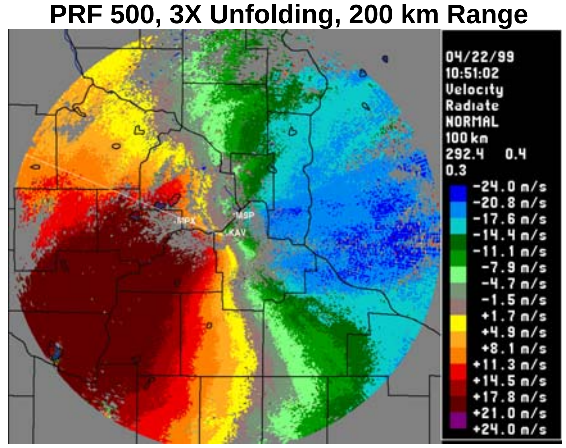
PRF 250, 3X Unfolding, 200 km Range



PRF 500, 3X Unfolding, 200 km Range



PRF 750, 3X Unfolding, 200 km Range



PRF 900, 2X Unfolding, 100 km Range

Wind towards the radar is shown in shades of blue and green. Wind away from the radar is shown in shades of yellow and red. Zero velocity is shown in gray. The rainbow effect, where dark red changes directly to blue, in the PRF 250 and PRF 500 images indicates velocity folding. When velocity folding occurs, it is extremely difficult, even for very experienced radar operators, to determine what is actually happening.
The images at PRF 750 and PRF 900 have no velocity folding. Comparing these images with the previous images clearly indicates the value of an adjustable PRF. ***Radtec weather radars have the ability to adjust PRF to provide an optimized view of actual weather conditions.***

Many radar systems include a "velocity unfolding" capability. Typically this uses a dual rate, pulse staggering technique to multiply the maximum velocity by a factor of 2 or 3. Radars that are fully coherent are typically stable enough to make the use of 2X unfolding reliable under most circumstances. Radars that are only "coherent on receive" may or may not have the stability to provide accurate velocity data with 2X unfolding.

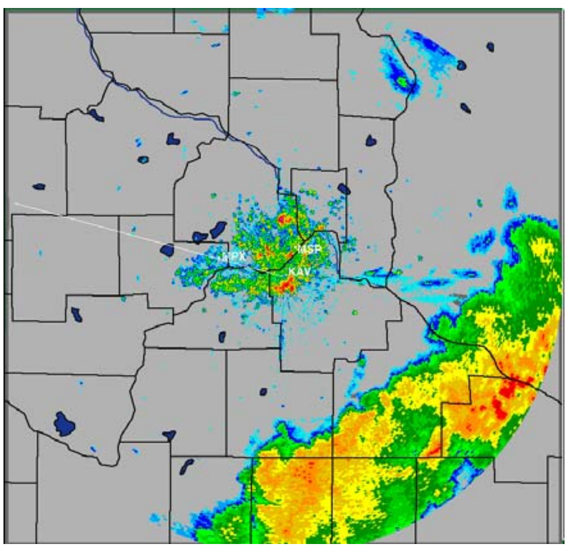
The use of 3X unfolding for aviation safety purposes is not recommended. With 3X unfolding, atmospheric turbulence reduces the reliability of the 3X unfolding technique. It may or may not provide accurate data. Unfortunately, the atmosphere usually tends to be the most turbulent when thunderstorms are present, and this is when the ability to measure high velocities, and detect low level wind shear, is often of most interest.

A few radars offer 4X unfolding, which is even more problematic than the use of 3X.

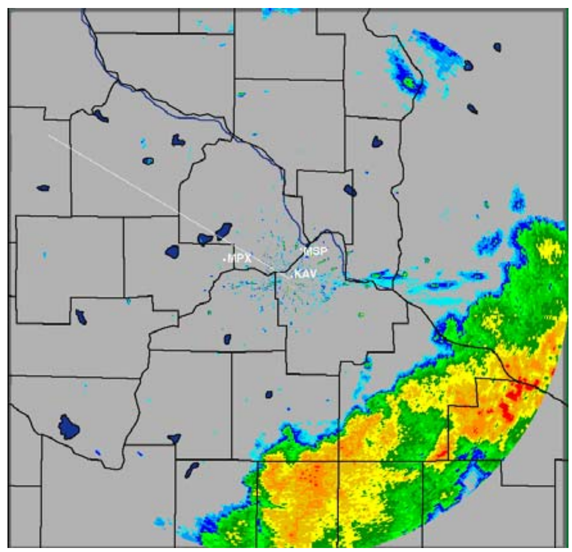
The preceding images were captured on a day when there was a steady wind out of the ENE at 40 to 50 mph with light rain. Because of the relatively uniform wind, the 3X unfolding is accurate.

Ground Clutter Rejection

Ground clutter is radar reflections from buildings, trees, vehicles, aircraft movement, etc. that are not related to weather. Ground clutter reflections tend to be much stronger than weather reflections, and consequently mask or obscure weather reflections.



Conventional Center Feed Antenna



Radtec Offset Feed Antenna
TDR 4370-C (-35 dB side lobes)

The reflections near the center of the image are ground clutter. It is virtually impossible to tell if there is any precipitation, much less wind shear, in an area with strong ground clutter. The practical reality is that, as the radar beam gets closer to the ground, the amount of interference from ground clutter increases.

Clutter is a particular problem in the vicinity of a major airport. Airports tend to have many surfaces that reflect radar signals as well as large numbers of vehicles moving in the area of interest.

The end result is that obtaining the best low level wind shear data at the required low altitudes is heavily dependent on a radar design that minimizes ground clutter. The FAA criteria requires that ground clutter obscure no more than 25% of the wind shear area of interest.

Most ground clutter is caused by radar signal energy that "leaks" out of the antenna at an angle away from the main radar beam. This leakage is referred as a side lobe. The objective is to design the antenna so as to reduce side lobes to the minimum possible value. Side lobes are typically measured in terms of decibels of suppression relative to the antenna's main beam. The best conventional center feed antennas have side lobe levels in the range of -25 to -28 dB.

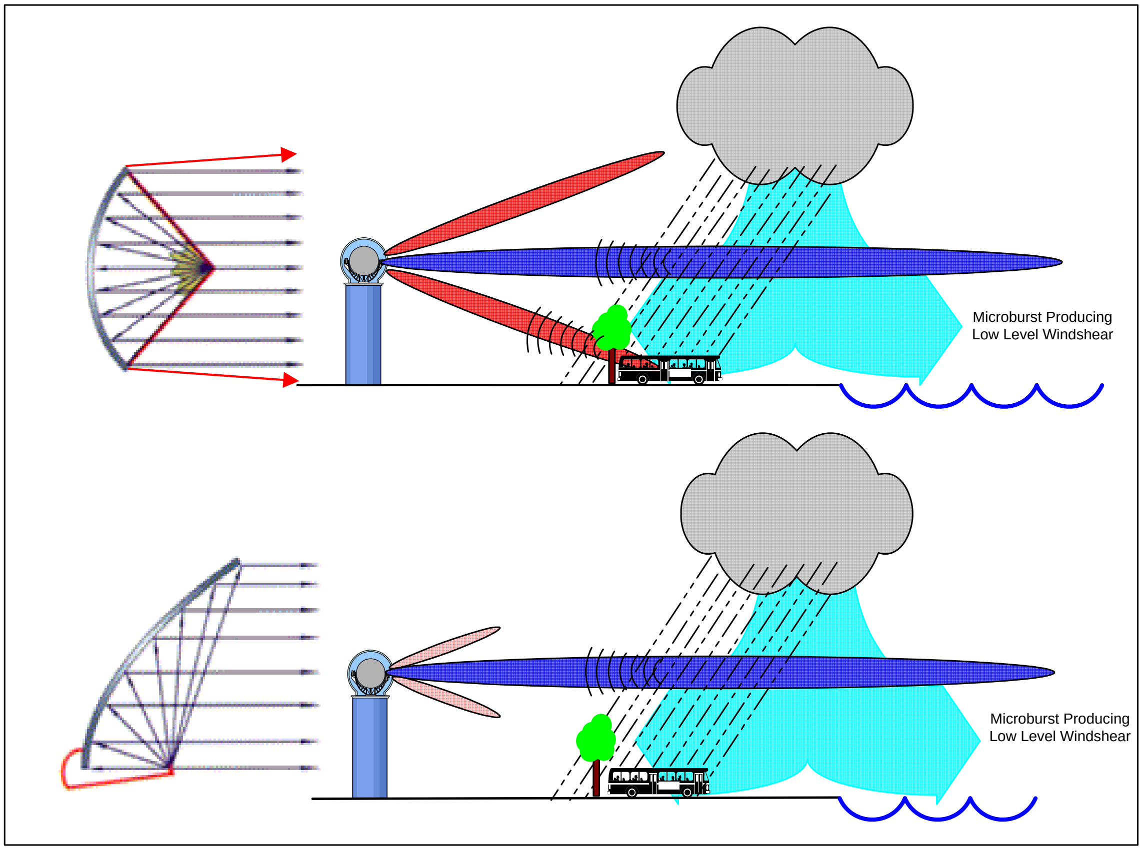
The exclusive Radtec offset feed antenna has side lobe suppression of -35 dB or better.

Several techniques have been developed for filtering out ground clutter that is not moving.

- Clutter mapping- A clutter map is a radar image made of the clutter on a clear day when there is no precipitation. Theoretically, the clutter map can be subtracted from a precipitation image, and leave only precipitation in the remaining image. In practice, clutter returns are often so much stronger than weather returns, that there is nothing left after subtracting the clutter map. The clutter map also assumes that clutter targets are always in exactly the same location.
- Velocity based clutter filter- With a Doppler radar, a filter can be set to remove all reflections that have zero or near zero velocity. This is a major step forward over clutter mapping. With velocity based filters, clutter targets can be removed dynamically from any location. To get the best performance from velocity based filters, the radar must be extremely stable in its operation. Typically, only fully coherent radars can take full advantage of velocity based filters.

The real problem is moving ground clutter. There is no known way to determine which moving targets are moving clutter, and which are moving weather. If the velocity based clutter filter is set to a high enough velocity to take out vehicles, trains, etc., it is virtually certain to also take out significant weather reflections.

The only known way to deal with moving clutter is to minimize the antenna side lobes, and simply avoid as much clutter as possible. The following diagram illustrates this:



The upper diagram indicates how antenna side lobes can cause ground clutter reflections which obscure wind shear reflections. The lower diagram shows reduced side lobes permitting the radar measure wind shear reflections with greatly reduced clutter.

Sensitivity

Often downbursts contain rain. If so, there are good precipitation targets to provide radar reflections. However, dry low level wind shear reflections may be extremely weak, sometimes only dust, leaves, and insects are stirred up by a dry wind shear event. The velocity must also be measured accurately in these situations.

Thus, for reliable detection of wind shear, the radar must be very sensitive, and be able to measure velocity very accurately. The U.S. FAA’s TDWR radar has been designed around a sensitivity of -10 dBZ, with a 6 dB signal to noise ratio, i.e., a net sensitivity of -16 dBZ when stated in the terms most radar manufacturers use to calibrate weather radars. The radar must be able to provide this sensitivity at the most distant point in the low level wind shear area of interest. TDR radars can easily provide this sensitivity.

Attachment A

Synopsis Of FAA Wind Shear Radar Location Requirements

The following parameters summarize the FAA's requirements:

- **Basic Coverage**
  - Out to a range of 48 nmi from radar
  - From ground level to 70,000 ft AGL
  - Not required in "Cone of Silence" directly above the radar

- **Operational Coverage**
  - **Principal Coverage Region (PCR)**
    - Out to a range of 6 nmi from center of the airport
    - From 600 ft AGL (airport), but preferably 300 ft. AGL up to 19,700 AGL
  - **Microburst Alert Warning Area (MAWA)**
    - 3 nmi off the ends of each runway
    - 1 nmi wide (centered on the runway)
    - From 600 ft AGL (airport), but preferably 300 ft. AGL up to 19,700 AGL
  - **Gust Front Coverage Region**
    - Out to a range of 31.8 nmi but preferably 40 nmi from center of airport
    - From 5,000 ft AGL (airport) up to 70,000 ft AGL

Specific Short-Range Siting Considerations

- **Blockage**
  - Undesirable in any direction
  - Particularly undesirable in prevailing weather approach direction
  - Most undesirable in direction of specific airport areas requiring protection

- **Clutter**
  - Undesirable over any area
  - Most undesirable over specific airport areas requiring protection
  - Unacceptable if it obscures more than 25% of microburst returns

- **Microbursts Outflows Occur at Low Altitudes**
  - Use of increased scan elevation angle to avoid clutter not available
  - Use natural terrain clutter fences between radar and airport if possible
  - Intervening terrain and structure locations must be carefully evaluated

General Site Area Identification

- **Preferred Radar-to-Airport Distance**
  - 10 nmi preferred
  - 8 nmi to 12.4 nmi acceptable
  - Distance less than 10 nmi requires higher scan elevation angle
  - Detection of microburst surface outflow more important than detection of high altitude microburst precursors

- **Required Radar-to-Airport Distance**
  - Must be more than 0.75 nmi from edge of MAWA (MAWA must be outside of radar's minimum detection zone)
  - Must be more than 3.9 nmi from edge of MAWA to reach 19,700 ft AGL over MAWA without exceeding 40° elevation angle.
  - May modify scan strategy to reach required altitude at close distance
  - May choose to limit coverage up to 19,700 ft AGL based on airport specific characteristics

- **Preferred/Required Aspect Angle**
  - Microbursts may have asymmetrical wind velocity differences of up to 2:1
  - Aspect angle is angle between runway centerline and line from the radar site to the runway centerline at the middle of the runway
  - Aspect angle of 0° is best
  - Aspect angle of less than 20° is preferred (Doppler radar reads 94% of true head/tail wind shear at 20°)
  - Aspect angle of less than 30° is required (Doppler radar reads 87% of true head/tail wind shear at 30°)

General Site Selection Process

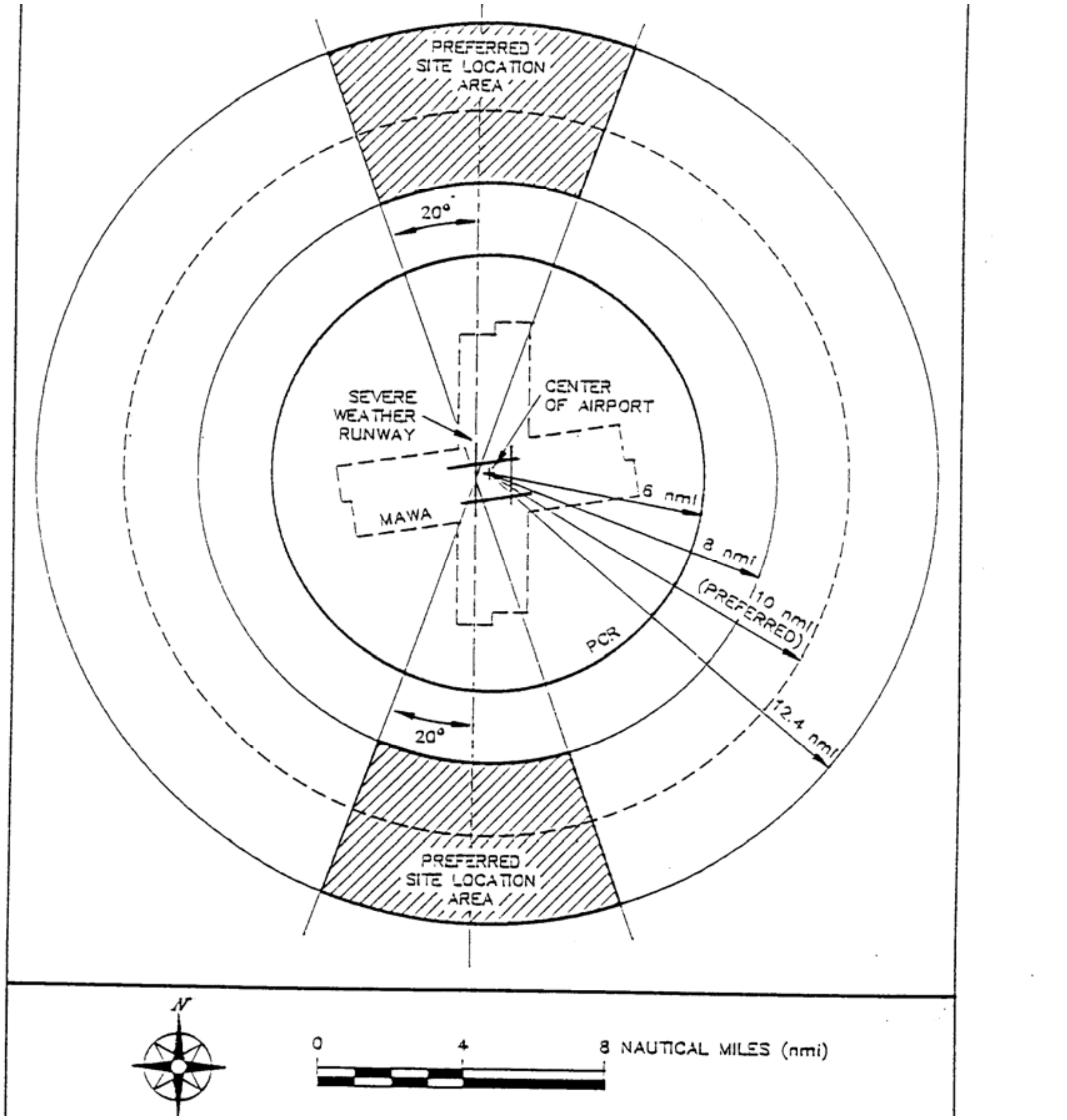
- **Achieve Optimum Radar Coverage of Important Areas**
  - Almost certain to require compromises
  - Emphasis on detection of low level wind shear outflow

- **Minimize Electromagnetic Interference (EMI)**
  - Identify potential sources that may interfere with radar
  - Identify areas/functions that may be susceptible to interference from radar

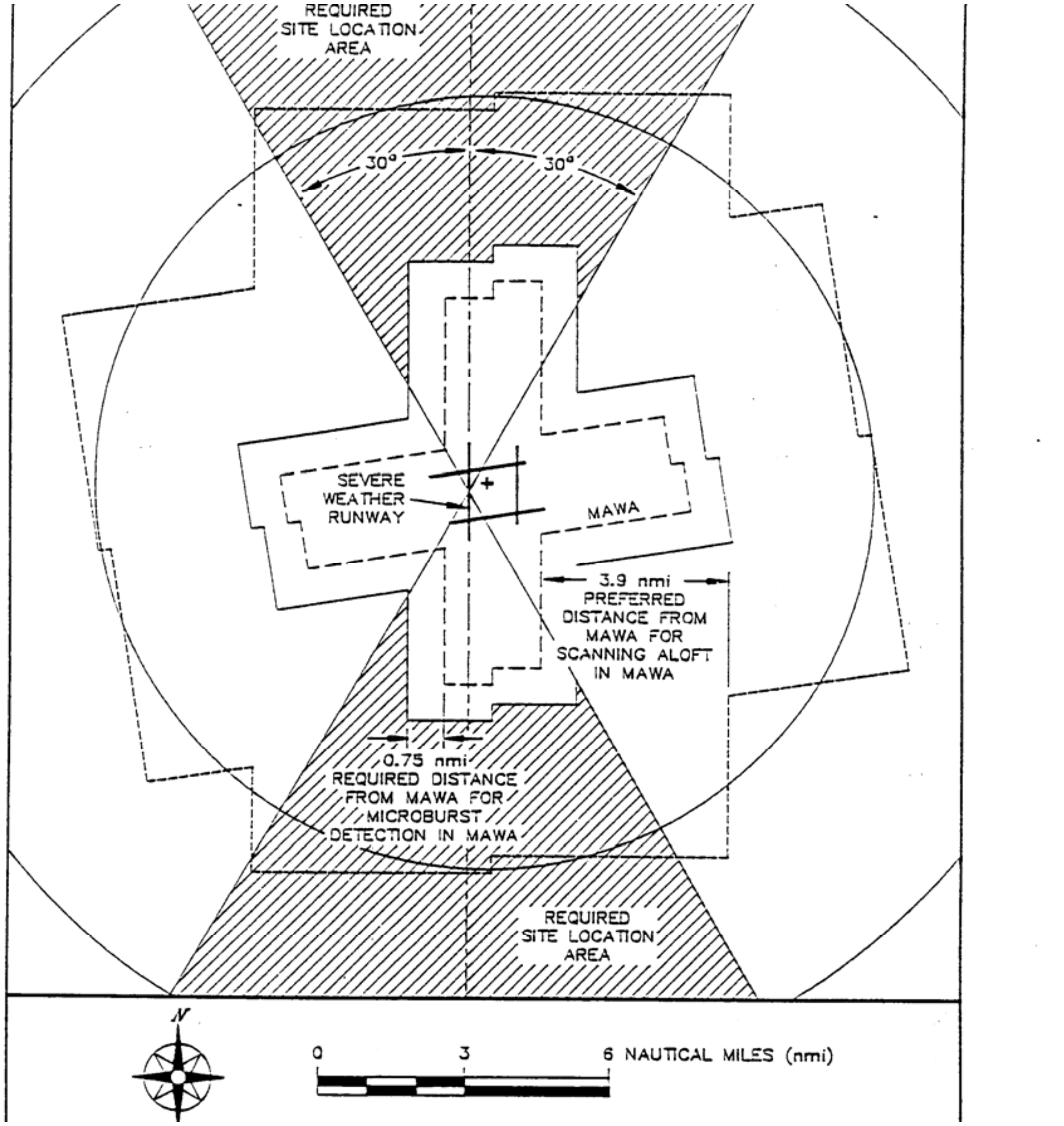
- **Site Must Be Accessible Year Round**
  - Sites subject to periodic isolation by flooding, snow etc. are not good choices

- **Utility Access**
  - Proximity to power, communication circuits, etc.
  - If natural gas is an approved emergency fuel for the UPS, site must also have access to gas service

- **Microwave Path (if microwave required)**
  - If available communication circuits from radar to airport force the use of a microwave link, the radar site location must also consider the microwave link signal path.



FAA Preferred Location For Wind Shear Detection Radar



FAA Required Location For Wind Shear Detection Radar