

## **Radar Performance**

The actual performance of a weather system is a combination of many factors. Peak power, receiver sensitivity, pulse rate, pulse width and antenna size to name a few. The following pages describe the effect those factors have on radar performance.

As a practical matter, the primary factors limiting performance are typically the transmitter's maximum duty cycle, and the receiver's noise figure. Both are the result of the real world of physics applied to the transmitter and receiver. Other factors, such as antenna size, are factors which can be solved by simply spending more money. The physics of duty cycle and noise figure are not so easy.

The transmitter duty cycle limits both the maximum pulse rate and the maximum pulse width. The duty cycle is dependent on the transmitter design and type (magnetron, Klystron or solid state), the modulator and high voltage power supply and the physics associated with each of these technologies.

Wider pulses improve the radar's ability to detect weak precipitation at long ranges. Pulse width is limited by the transmitter's maximum duty cycle. Typically, many radars limit the maximum pulse width to approximately 2 microseconds. This limits the sensitivity at longer ranges.

Higher pulse rates are required to measure higher velocities. This is also limited by the transmitter's maximum duty cycle. Typically, many radars limit the maximum pulse rate to approximately 1200 pulses per second. This limits the maximum velocity measurement capability.

### **Pulse Width And Sensitivity**

The radar system's pulse width, minimum detectable signal (MDS), receiver bandwidth and range resolution are all related.

Changing the radar transmitter's pulse width changes the radar's sensitivity and range resolution. Unfortunately, those changes oppose each other. *Wider pulses effectively increase the radar's sensitivity* to weak atmospheric events, and increase the radar's ability to penetrate heavy precipitation. Narrower pulses improve the radar's range resolution.

*The end result is that, in a given weather environment, there is one unique pulse width that will produce the best data.*

Many radars typically provide fixed pulse widths of about 0.8  $\mu$ sec for velocity mode and about 2.0  $\mu$ sec for reflectivity mode. These fixed values are compromises which produce useful results under many conditions, but restrict the radar's ability to provide the best data under a wide range of conditions.

The following series of images clearly indicates the improvement in sensitivity that increased pulse width provides. All data for these images was processed using 12 bit A/D conversion, 256 levels (8 bits) of reflectivity for processing, and 16 levels (4 bits) of reflectivity for display.

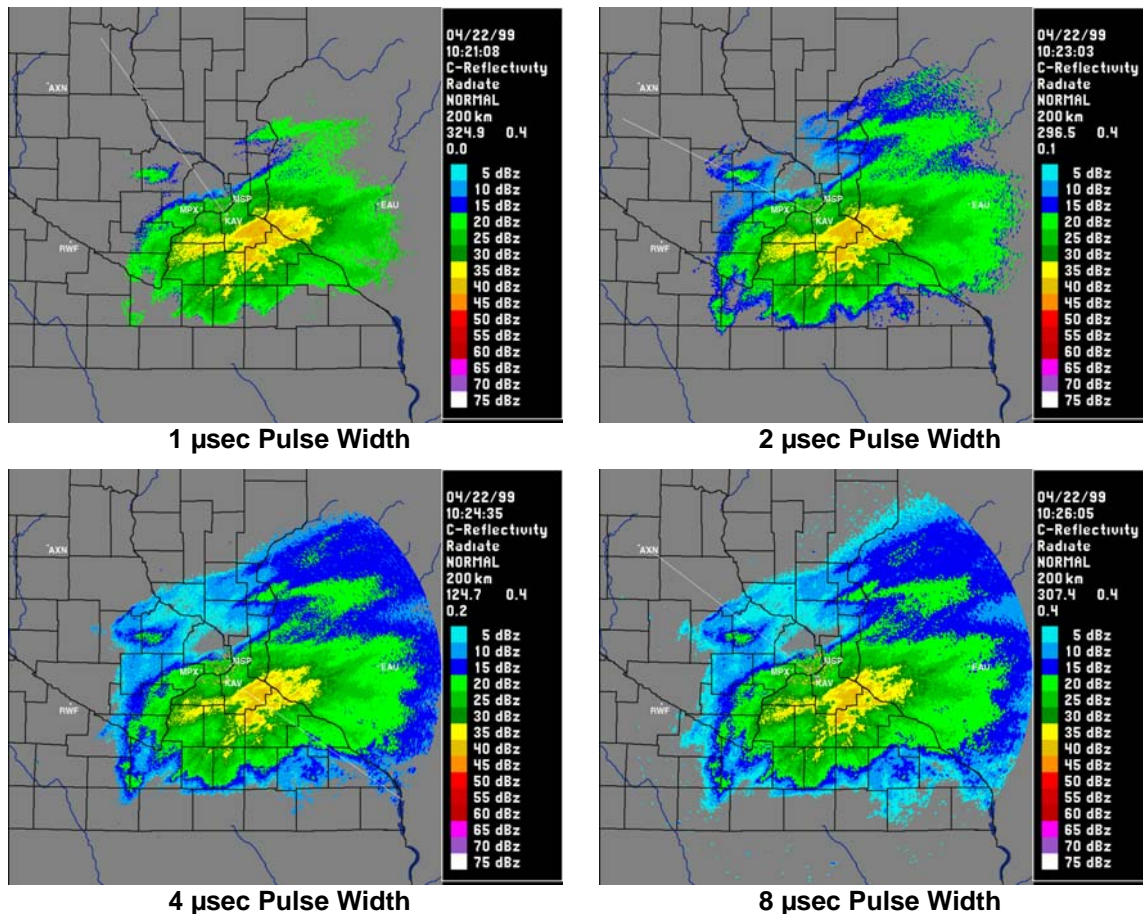


Figure 1 - Same Storm Images Showing Improved Detection Of Weak Precipitation With Wider Pulses

Using wider pulses improves the radar's ability to detect weak precipitation in two ways. First, by increasing the receiver's sensitivity and second by increasing the amount of signal power reflected by the precipitation.

### Receiver Sensitivity

The term "Minimum Detectable Signal" (MDS) is worth a comment. The formal definition is based on a statistical analysis of the probability of accurate detection of a very weak signal (Ref: Skolnik, *Radar Handbook - 2 ed.*, pg. 213-214, and *IEEE Std. 686-1982*). As an alternative that is much more clearly defined, many makers of weather radar systems have adopted a definition of MDS as being a signal to noise ratio of 0 dB for the noise level and bandwidth of the receiver. In other words, the minimum detectable signal is equal to the receiver's noise power level.

For C-band, that equation is:

$$N_{Po} = -114\text{dB/mHz} + 10\log\text{BW(mHz)} + \text{Noise Figure(dB)}$$

The best available receiver technology currently limits the receiver's noise figure to around 3dB (less is better). Applying this to the bandwidths and NF for a weather radar produces the following MDS values:

I/F B/W (mHz)		10 log B/W	NF (dB)	MDS (dB)
0.15	-114	-8.24	3	-119
0.5	-114	-3.01	3	-114
1	-114	0.00	3	-111
2	-114	3.01	3	-108

Table 1- MDS vs. Bandwidth At Specified Receiver Noise Figure (3 dB)

Radar theory and industry convention is to match receiver bandwidth to transmitter pulse width according to the  $T = 1/\tau$  relationship. The following table illustrates how the pulse width and receiver bandwidth affect the MDS:

Pulse Width (µsec)	I/F Bandwidth	MDS
>5.0	150 kHz	-119
1.9 - 5.0	500 kHz	-114
0.6 - 1.9	1 MHz	-111
<0.6	2 MHz	-108

Table 2 - Bandwidth And MDS For Radar Pulse Width Ranges

The radar control software must automatically select the appropriate receiver filter whenever the user selects a new pulse width.

### Precipitation Reflections

The Probert-Jones equation is the basic equation which defines the operation of all weather radar systems. It relates the radar's operating parameters to the amount of power reflected by the target precipitation.

That reflected power is received by the radar. All other things being equal, doubling the pulse width doubles the power reflected by precipitation. Thus, increasing the pulse width provides additional power to penetrate heavy precipitation.

The Probert-Jones equation:

$$P_r = \frac{P_t G^2 \theta^2 H \pi^3 K^2 L Z}{1024 (\ln 2) \lambda^2 R^2}$$

$P_r$	Reflected signal power received at the radar antenna
$P_t$	Transmitted power- fixed by transmitter design
$G$	Antenna gain- fixed by antenna design
$\theta$	Antenna beamwidth- fixed by antenna design
$H$	Pulse width- most radars limit this to a choice of 2 values
$K^2$	Physical constant - typically 0.93 for rain or 0.197 for ice
$L$	Loss factor- determined by radar installation and atmospheric factors
$Z$	Target reflectivity- determined by the type and intensity of precipitation
$\lambda$	Transmitter wavelength- fixed by transmitter design
$R$	Range- distance from radar antenna to target

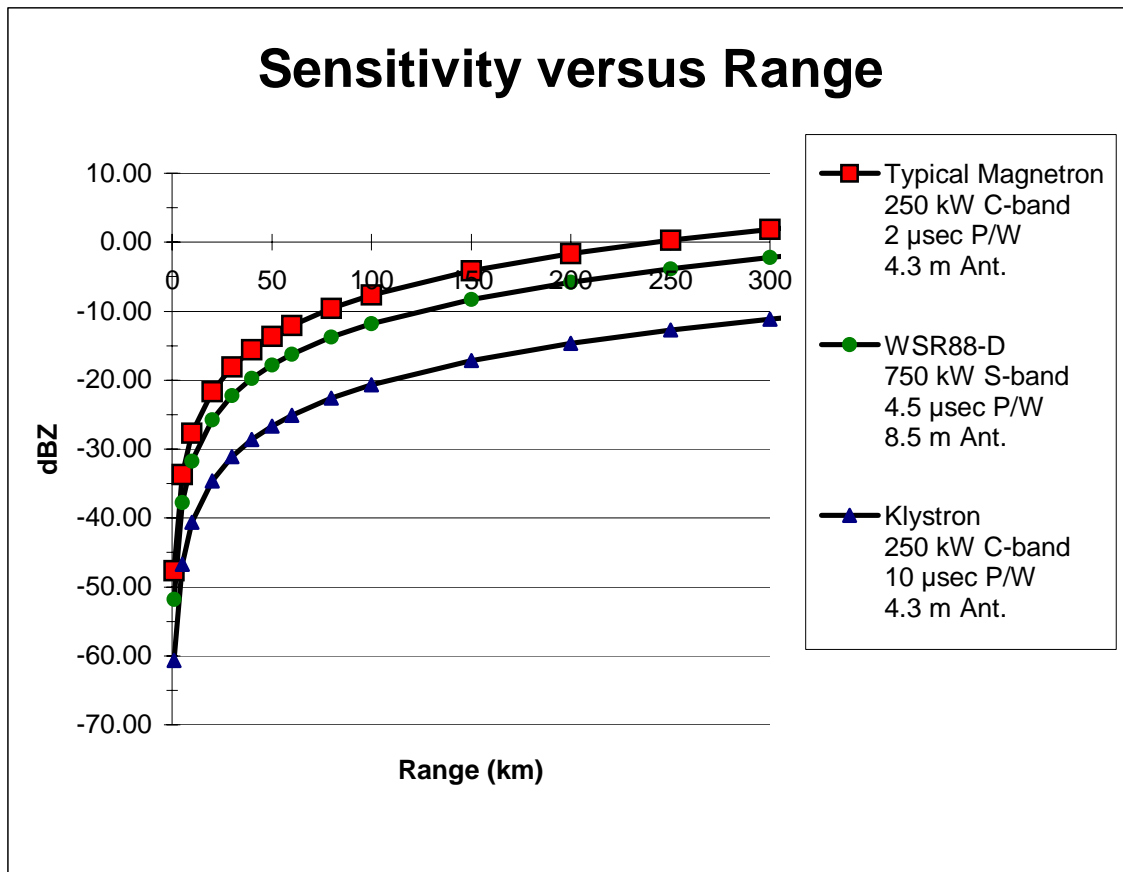
With all other things equal, doubling the pulse width (H) doubles the reflected power. The effect this has on the detection of weak precipitation is clearly shown in the previous series of images. This is subject to the Probert-Jones assumption that the precipitation area must be large enough to fill the entire pulse volume.

The maximum pulse width that is available is limited by the transmitter's duty cycle. Many radars have a duty cycle rating that limits the maximum pulse width to about 2.0 microseconds at the pulse rates that are required for long range (400 km) weather detection. Longer pulses, if they are available, can provide better detection of weak precipitation.

### Sensitivity Data

The following graph compares the dBZ sensitivity versus range between a typical magnetron radar at 2  $\mu$ sec pulse width, a WSR88-D (NEXRAD) radar at 4.5  $\mu$ sec pulse width, and a Klystron radar at 10  $\mu$ sec pulse width.

Please note that on this graph, lower is better (more sensitive).



Graph 1 – Sensitivity At Range Curves For Typically Weather Radar Systems

This graph indicates the compares sensitivity at range for typical weather radar systems.

The table on the following page indicates the parameters used to calculate these sensitivity curves.

	Typical Magnetron 250 kW C-band 2 μsec P/W 4.3 m Ant.	WSR88-D 750 kW S-band 4.5 μsec P/W 8.5 m Ant.	Klystron 250 kW C-band 10 μsec P/W 4.3 m Ant.	
Transmitter Power:	250000	750000	250000	Watts
Transmit Frequency:	5.60	2.75	5.60	GHz
Antenna Gain:	44.0	45.0	44.0	dB
Beam Width:	0.95	0.95	0.95	Degrees
Minimum Discernible Signal:	-113	-113	-119	dB
Losses:	1.0	1.0	1.0	dB
Pulse Width:	2.0	4.5	10.0	μsec
X Constant:	24.615	24.615	24.615	(Probert-Jones 17.756 or 24.615)

Range:	dBz min	dBz min	dBz min
200km:	-1.64	-5.76	-14.63
100km:	-7.67	-11.78	-20.65
50km:	-13.69	-17.80	-26.68
1km:	-47.67	-51.78	-60.65

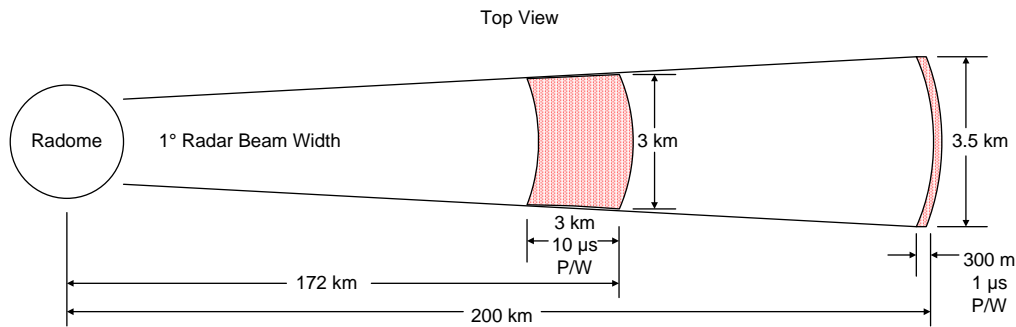
Table 3 - Radar Characteristics Used To Calculate Typical Sensitivity Curves On Previous Page

### Pulse Width And Range Resolution

Range resolution is defined as the smallest visible distance between two separate storm cells along the radar beam's centerline, i.e., in the radial direction. Storm cells that are closer than that minimum distance will be displayed on the radar as a single cell. Note that azimuth resolution is the distance between storm cells in the azimuth direction. Azimuth resolution is determined by the antenna's beam width.

The maximum range resolution is one-half the pulse length. This value can be calculated from simple geometric relationships. An example is shown in the following diagram:

## Radar Resolution vs. Beam Width, Range and Pulse Length



## Pulse Width, Range Resolution and Azimuth Resolution

This diagram shows the pulse volume for a 10  $\mu$ sec pulse, and for a 1  $\mu$ sec pulse. In the radial direction, the 10  $\mu$ sec pulse has a length of 3 km, and the 1  $\mu$ sec has a pulse length of 300 m. Thus the maximum radial resolution is 1.5 km for a 10  $\mu$ sec pulse, and 150 m for a 1  $\mu$ sec pulse. This is the maximum resolution set by the basic physics of radar. Other practical factors may reduce the actual resolution. For example, if the radar's signal processor does not have the capacity to process range bins rapidly enough, resolution will be lost, even though the radar may use very narrow pulses.

For many operational meteorological purposes, such as providing public warnings of approaching severe weather, heavy rains that could produce flash floods, etc., atmospheric events 3 km and larger are of primary interest.

Therefore, pulse widths up to 10  $\mu$ sec can meet the Probert-Jones equation assumption of precipitation filling the entire pulse volume and provide accurate data for events 3 km and larger in size. Pulse widths of 10  $\mu$ sec provide 1.5 km range resolution.

For large severe storms, such as in the tropics, pulse widths up to 20  $\mu$ sec can provide superior storm penetration and still provide 3 km range resolution.

The following images provide a visual comparison of data captured at 2  $\mu$ sec and 16  $\mu$ sec pulse width.

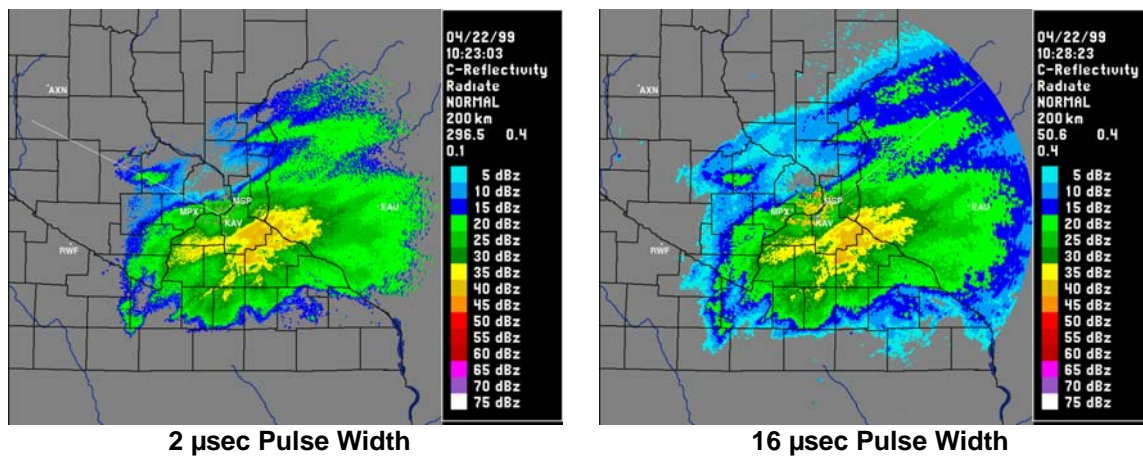


Figure 2 – Same Storm Images Showing Minimal Loss Of Visible Resolution At Very Wide Pulse Widths

For many operational meteorological purposes, the loss of resolution caused by going to the greater pulse width is not significant, because of the relatively large size of the meteorological targets. In fact, it is likely that the decreased resolution is more than offset by the increased visibility of weak precipitation at the greater pulse width.

The following table indicates the pulse length and corresponding range resolution for various pulse widths.

P/W (µsec)	Pulse Length (m)	Range Resolution(m)	Comments
0.5	150	75	
0.8	240	120	Typical magnetron radar pulse width in velocity mode
1	300	150	
2	600	300	Typical magnetron radar pulse width in reflectivity mode
4.5	1349	675	WSR-88D (NEXRAD) pulse width
10	2998	1499	Provides maximum sensitivity/penetration consistent with 3 km storm cell size

Table 4 - Pulse Width, Length And Resolution

For meteorological research purposes, it is often desirable to have the highest resolution possible. Thus, a narrow beam and a narrow pulse width is usually specified for research purposes.

The ideal situation would be to have a radar that can provide both wide and narrow pulses that could be selected as the situation required. In addition, the ability to adjust pulse rates over a wide range permits obtaining the best available Doppler velocity data at a given range.

### **Pulse Rate And Velocity Measurement**

In a pulsed Doppler radar system, the maximum unambiguous range, maximum unambiguous velocity and Pulse Repetition Frequency (PRF) are interrelated. This is sometimes referred to as the “Doppler Dilemma”. It is due to the basic laws of physics of pulsed radar (the Nyquist theorem applied to the Doppler principle), and applies to all pulsed Doppler radar systems.

*Higher PRF’s are required to measure higher velocities, and lower PRF’s are required for longer ranges.*

*The end result is that for a given range, there is one unique PRF that will permit measurement of the maximum unambiguous velocity.*

Most Doppler radar systems typically provide a choice of fixed PRF’s; one for velocity mode (typically about 1200) and one for reflectivity mode (typically about 250).

The ability to adjust the PRF over a wide range permits selecting the optimum PRF such that the maximum unambiguous velocity can be measured for the range in use. This is illustrated in the following images.

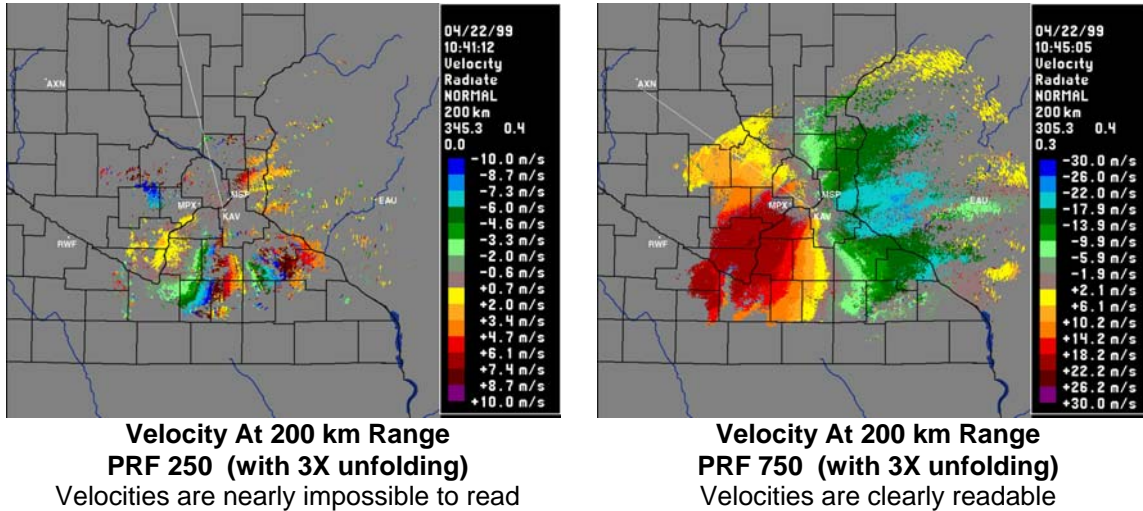


Figure 3 – Same Storm Images Showing Higher PRF's Ability To Measure Higher Velocities Correctly and Intelligibly

The following graph illustrates relationship between PRF, maximum unambiguous velocity and maximum unambiguous range for a C-band radar. Note that the values on this chart are valid only for C-band.

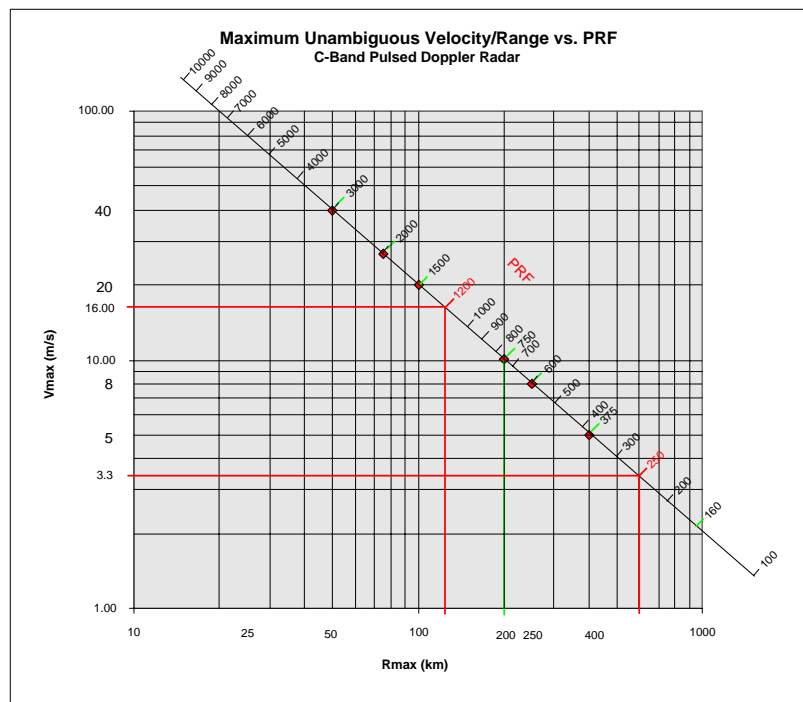


Chart 2 - Maximum Unambiguous Range/Velocity vs. Pulse Rate

The red lines show the typical operating values for many weather radars: a PRF of 1200 for velocity mode, and a PRF of 250 for reflectivity mode.

The relationship between velocity and PRF expressed by the following formula:

$$V_{\max} = \frac{PRF \lambda}{4}$$

Where:  
 $V_{\max}$  = maximum unambiguous velocity  
 $PRF$  = pulse repetition frequency (pulses per second)  
 $\lambda$  = transmitted wavelength (0.0535 m for C-band, 5600 MHz)

The relationship between range and PRF is expressed by the following formula:

$$R_{\max} = \frac{c}{2(PR F)}$$

Where:  
 $R_{\max}$  = Maximum unambiguous range  
 $c$  = Speed of light (approx. 300,000 km/sec)  
 $PRF$  = Pulse repetition frequency (pulses per second)

While these equations are relatively simple, there is some fairly complex physics behind them. Going through that physics is beyond the scope of this presentation. However, **the end result is that, at any given range, there is one unique PRF that will provide the maximum velocity measurement capability.**

Again, the radar transmitter's duty cycle limits the performance. The maximum PRF, and thus the maximum velocity, is limited by the duty cycle in velocity mode.

## Bibliography

Rinehart, R.E., 1997: *Radar For Meteorologists 3rd Edition*. Rinehart Publications, P.O. Box 6124, Fargo, North Dakota, 58206-6124, USA (email: radarwx@aol.com)

Doviak, Richard J., and Dusan S. Zrnic, 1993: *Doppler Radar and Weather Observations, 2nd Edition*. Academic Press, Inc., Orlando, FL (www.academicpress.com)

Skolnik, Merrill, 1990: *Radar Handbook 2nd Edition*, Chapter 23- Meteorological Radar, McGraw-Hill, New York, NY. (www.mcgrawhill.com)