Radar Basics – Part 2: Pulse Doppler Radar

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Doppler processing became possible with digital computers; today, nearly all radar systems incorporate Doppler processing.

Measuring round trip return timing is fundamental to radar, but it can be difficult to distinguish returns from the target of interest and other objects or background located at similar distances. The use of Doppler processing allows another characteristic of the return to be used – relative velocity. Doppler processing became possible with digital computers and today, nearly all radar systems incorporate Doppler processing.

By measuring the Doppler rate, the radar is able to measure the relative velocity of all objects returning echoes to the radar system – whether planes, vehicles, or ground features. Doppler filtering can be used to discriminate between objects moving at different relative velocities. An example is airborne radar trying to track a moving vehicle on the ground. Since the ground returns will be at the same range as the vehicle, the difference in velocity will be the means of discrimination.

Doppler effect

The relationship between wavelength and frequency is:

$\lambda = v / f$

where:
f = wave frequency (Hz or cycles per second)
λ = wavelength (meters)
v = speed of light (approximately 3 x 108 meters/second)

What happens in a radar system is that the pulse frequency is modified by the process of being reflected by a moving object. Consider the transmission of a sinusoidal wave. The distance from the crest of each wave to the next is the wavelength, which is inversely proportional to the frequency.

Each successive wave is reflected from the target object of interest. When this object is moving towards the radar system, the next wave crest reflected has a shorter round trip distance to travel, from the radar to the target and back to the radar. This is because the target has moved closer in the interval of time between the previous and current wave crest.

As long as this motion continues, the distance between the arriving wave crests is shorter than the distance between the transmitted wave crests. Since frequency is inversely proportional to wavelength, the frequency of the sinusoidal wave appears to have increased. If the target object is moving away from the radar system, then the opposite happens. Each successive wave crest has a longer round trip distance to travel, so the time between arrival of receive wave crests is lengthened, resulting in a longer (larger) wavelength, and a lower frequency.

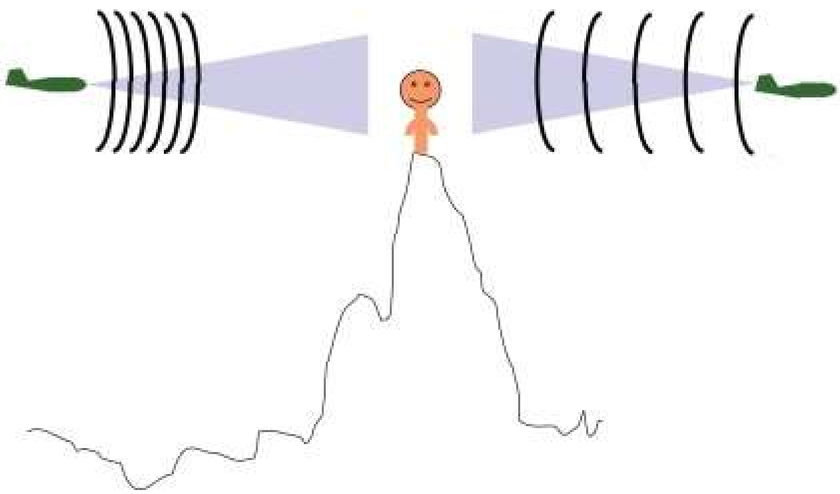

Figure 1. Doppler frequency shifting

This effect only applies to the motion relative to the radar and the target object. If the object is moving at right angles to the radar there will be no Doppler frequency shift. An example of this would be airborne radar directed at the ground immediately below the aircraft. Assuming level terrain and the aircraft is at a constant altitude, the Doppler shift would be zero, as there is no change in the distance between the plane and ground.

If the radar is ground-based, then all Doppler frequency shifts will be due to the target object motion. If the radar is a vehicle or airborne-based, then the Doppler frequency shifts will be due to the relative motion between the radar and target object.

This can be of great advantage in a radar system. By binning the receive echoes both over range and Doppler frequency offset, target speed as well as range can be determined. Also, this allows easy discrimination between moving objects, such as an aircraft or vehicle, and the back ground clutter, which is generally stationary.

For example, imagine there is a radar operating in the X band at 10 GHz (λ = 0.03m or 3cm). The radar is airborne, traveling at 500 mph, is tracking a target ahead moving at 800 mph in the same direction. In this case, the speed differential is –300 mph, or –134 m/s.

Another target is traveling head on toward the airborne radar at 400 mph. This gives a speed differential of 900 mph, or 402 m/s. The Doppler frequency shift can be calculated as follows:

$$f_{Doppler} = 2\, v_{relative} / \lambda$$

First target Doppler shift = 2 (–134m/s) / (0.03m) = –8.93 kHz

Second target Doppler shift = 2 (402m/s) / (0.03m) = 26.8 kHz

The receive signal will be offset from 10 GHz by the Doppler frequency. Notice that the Doppler shift is negative when the object is moving away (opening range) from the radar, and is positive when the object is moving towards the radar (closing range).

Pulsed frequency spectrum

For this to be of any use, the Doppler shift must be measured. First, the spectral representation of the pulse must be considered.

The frequency response of an infinite train of pulses is composed of discrete spectral lines in the envelope of the pulse frequency spectrum. The spectrum repeats at intervals of the PRF.

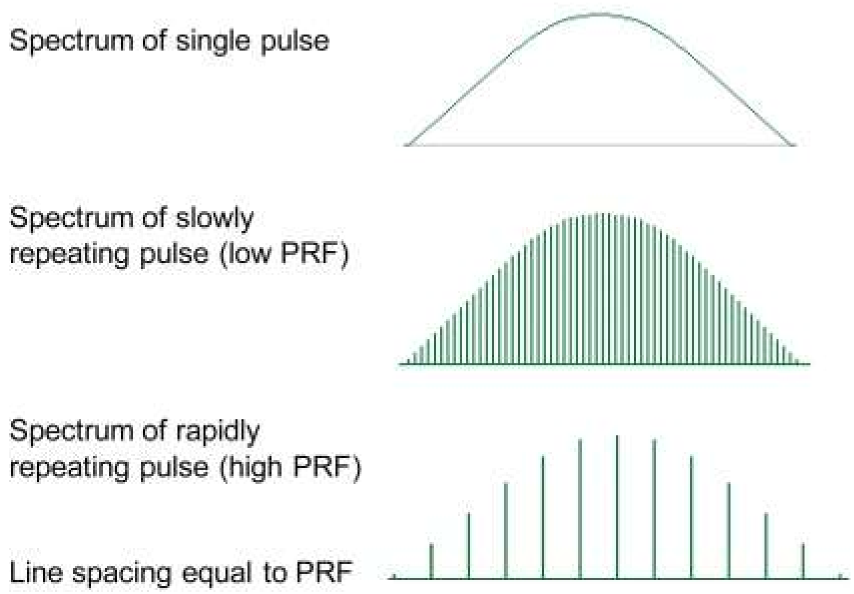

Figure 2. Pulse frequency spectrum

What is important is that this will impose restrictions on the detectable Doppler frequency shifts. In order to unambiguously identify the Doppler frequency shift, it must be less than the PRF frequency. Doppler frequency shifts greater than this will alias to a lower Doppler frequency. This ambiguity is similar to radar range returns beyond the range of the PRF interval time, as they alias into lower range bins.

$$f_{Doppler} = 2\, v_{relative} / \lambda$$

Doppler frequency detection is performed by using a bank of narrow digital filters, with overlapping frequency bandwidth (so there are no nulls or frequencies that could go undetected). This is done separately for each range bin. Therefore, at each allowable range, Doppler filtering is applied. Just as the radar looks for peaks from the matched filter detector at every range bin, within every range it will test across the Doppler frequency band to determine the Doppler frequency offset in the receive pulse.

Doppler ambiguities

Doppler ambiguities can occur if the Doppler range is larger than the PRF. For example, in military airborne radar, the fastest closing rates will be with targets approaching, as both speeds of the radar-bearing aircraft and the target aircraft are summed. This should assume the maximum speed of both aircraft.

The highest opening rates might be when a target is flying away from the radar-bearing aircraft. Here, the radar-bearing aircraft is assumed to be traveling at minimum speed, as well as the target aircraft flying at maximum speed. It is also assumed that the target aircraft is flying a large angle θ from the radar-bearing aircraft flight path, which further reduces the radar-bearing aircraft speed in the direction of the target.

The maximum positive Doppler frequency (fastest closing rate) at 10 GHz / 3 cm is:

Radar –bearing aircraft maximum speed: 1200 mph = 536 m/s
Target aircraft maximum speed: 1200 mph = 536 m/s
Maximum positive Doppler = 2 (1072m/s) / (0.03m) = 71.5 kHz

The maximum negative Doppler frequency (fastest opening rate) at 10 GHz / 3 cm is:

Radar-bearing aircraft minimum speed: 300 mph = 134 m/s
Effective radar-bearing aircraft minimum speed with θ = 60 degree angle from target track (sin (60) = 0.5): 150 mph = 67 m/s
Target aircraft maximum speed: 1200 mph = 536 m/s
Maximum negative Doppler = 2 (67–536 m/s) / (0.03m) = 31.3 kHz

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This results in a total Doppler range of 71.5 + 31.3 = 102.8 kHz. Unless the PRF exceeds 102.8 kHz, there will be aliasing of the detected Doppler rates, and the associated ambiguities.

If the PRF is assumed at 80 kHz, then Doppler aliasing will occur as shown in Figure 3.

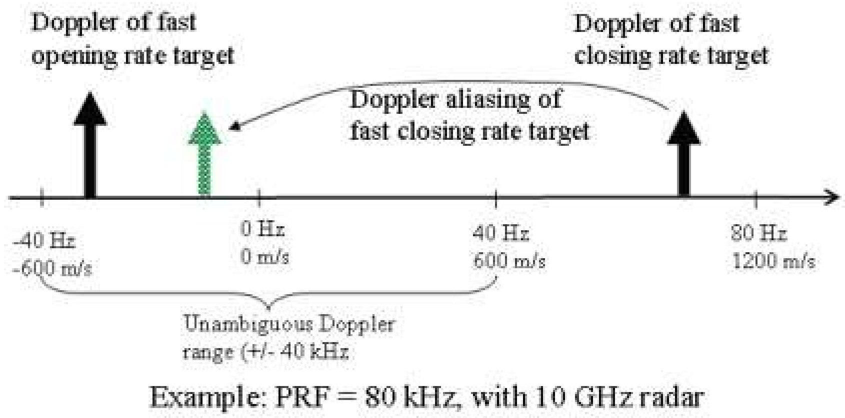

Figure 3. Doppler aliasing example

Radar clutter

There are two categories of radar clutter. There is mainlobe clutter and sidelobe clutter. Mainlobe clutter occurs when there are undesirable returns in the mainlobe or within the radar beamwidth. This usually occurs when the mainlobe intersects the ground. This can occur because the radar is aimed downward (negative elevation), there is higher ground such as mountains in the radar path, or even if the radar beam is aimed level and as the beam spreads with distance hits intersects the ground. Because the area of ground in the radar beam is often large, the ground return can be much larger than target returns.

Sidelobe clutter is unwanted returns that are coming from a direction outside the mainlobe. Sidelobe clutter is usually attenuated by 50 dB or more, due to the antenna directional selectivity or directional radiation pattern. A very common source of sidelobe clutter is ground return. When radar is pointed toward the horizon, there is a very large area of ground area covered by the sidelobes in the negative elevation region. The large reflective area covered by the sidelobe can cause significant sidelobe returns despite the antenna attenuation.

Different types of terrain will have a different “reflectivity”, which is a measure of how much radar energy is reflected back. This also depends on the angle of the radar energy relative to the ground surface. Some surfaces, like smooth water, reflect most of the radar energy away from the radar transmitter, particularly at shallow angles. A desert would reflect more of the energy back to the radar, while wooded terrain would reflect even more. Man made surfaces, such as in urban areas; tend to reflect the most energy back to the radar system.

Often targets are moving, and Doppler processing is an effective method to distinguish the target from the background clutter of the ground. However, the Doppler frequency of the ground will can be non-zero if the radar is in motion. Different points on the ground will have different Doppler returns, depending on how far ahead or behind the radar-bearing aircraft that a particular patch of ground is located. Doppler sidelobe clutter can be present over a wide range of Doppler frequencies.

Mainlobe clutter is more likely to be concentrated at a specific frequency, since the mainlobe is far more concentrated (typically 3 to 6 degrees of beam width), so the patch of ground illuminated is likely to be far smaller and all the returns at or near the same relative velocity.

A simple example (as shown in Figure 4) can help illustrate how the radar can combine range and Doppler returns to obtain a more complete picture of the target environment.

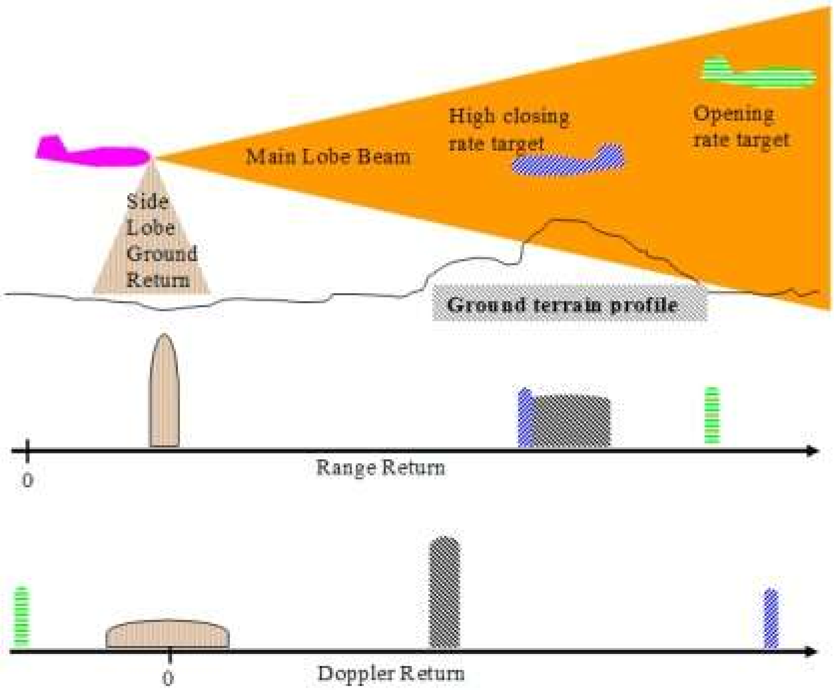

Figure 4. Interpreting Doppler radar returns

Figure 4 illustrates unambiguous range and Doppler returns. This assumes the PRF is low enough to receive all the returns in a single PRF interval and the PRF is high enough to include all Doppler return frequencies.

The ground return comes though the antenna sidelobe, known as sidelobe clutter. The reason ground return is often high is due to the amount of reflective area at close range, which results in a strong return despite the sidelobe attenuation of the antenna. The ground return will be at short range, essentially the altitude of the aircraft. In the mainlobe, the range return of the mountains and closing target are close together, due to similar ranges. It is easy to see how if just using the range return, it is easy for a target return to be lost in high terrain returns, known as mainlobe clutter.

The Doppler return gives a different view. The ground return is centered around 0 Hz. The ground slightly ahead of the radar-bearing plane is at slightly positive relative velocity, and the ground behind the plane is at slightly negative relative velocity. As the horizontal distance from the radar-bearing plane increases, the ground return weakens due to increased range.

The Doppler return from mountain terrain is now very distinct from the nearby closing aircraft target. The mountain terrain is moving at a relative velocity equal to the radar-bearing plane's velocity. The closing aircraft relative velocity is the sum of both aircrafts velocity, which is much higher, producing a Doppler return with a high velocity. The other target aircraft, which is slowly opening the range with radar-bearing aircraft, is represented as a negative Doppler frequency return.

PRF tradeoffs

Different PRF frequencies have different advantages and disadvantages. The following discussion summarizes the trade-offs.

Low PRF operation is generally used for maximum range detection. It usually requires a high power transmit power, in order to receive returns of sufficient power for detection at a long range. To get the highest power, long transmit pulses are sent, and correspondingly long matched filter processing (or pulse compression) is used. This mode is useful for precise range determination. Strong sidelobe returns can often be determined by their relatively close ranges (ground area near radar system) and filtered out.

Disadvantages are that Doppler processing is relatively ineffective due to so many overlapping Doppler frequency ranges. This limits the ability to detect moving objects in the presence of heavy background clutter, such as moving objects on the ground.

High PRF operation spreads out the frequency spectrum of the receive pulse, allowing a full Doppler spectrum without aliasing or ambiguous Doppler measurements. A high PRF can be used to determine Doppler frequency and therefore relative velocity for all targets. It can also be used when a moving object of interest is obscured by a stationary mass, such as the ground or a mountain, in the radar return. The unambiguous Doppler measurements will make a moving target stand out from a stationary background. This is called mainlobe clutter rejection or filtering. Another benefit is that since more pulses are transmitted in a given interval of time, higher average transmit power levels can be achieved. This can help improve the detection range of a radar system in high PRF mode.

Medium PRF operation is a compromise. Both range and Doppler measurements are ambiguous, but each will not be aliased or folded as severely as the more extreme low or high PRF modes. This can provide a good overall capability for detecting both range and moving targets. However, the folding of the ambiguous regions can also bring a lot of clutter into both range and Doppler measurements. Small shifts in PRFs can be used to resolve ambiguities, as has been discussed, but if there is too much clutter, the signals may be undetectable or obscured in both range and Doppler.

FM ranging

One solution is to use the high PRF mode to identify moving targets, especially fast moving targets, and then switch to a low PRF operation to determine range. Another alternative is to use a technique called FM ranging. In this mode, the transmit duty cycle becomes 100% and the radar transmits and receives continuously.

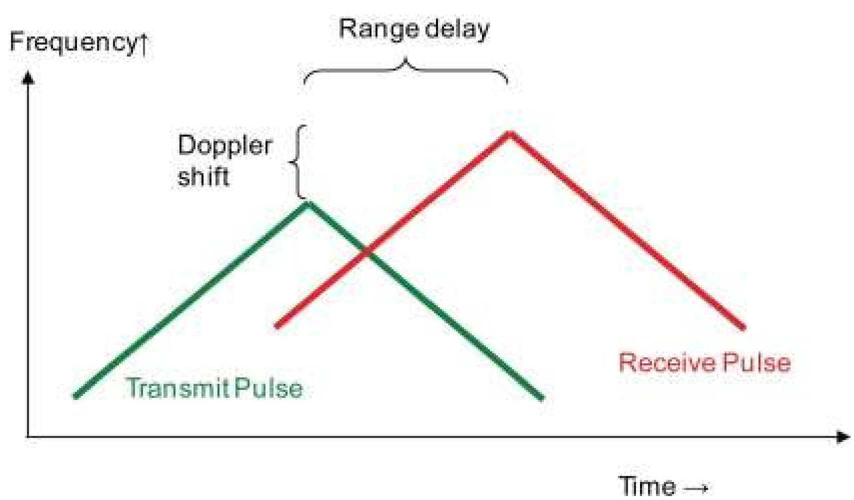

Figure 5. FM ranging

The transmission is a continuously increasing frequency signal, and then at the maximum frequency, abruptly begins to continuously decrease in frequency until it reaches the minimum frequency. This cycle then repeats. The frequency over time looks like a “saw tooth wave”. The receiver can operate while during transmit operation, as the receiver is detecting time delayed versions of the transmit signal, which is at a different frequency than current transmit operation. Therefore, the receiver is not desensitized by the transmitter’s high power at the received signal frequency.

Through Doppler detection of what frequency is received, and knowing the transmitter frequency ramp timing, can be used to determine round-trip delay time, and therefore range. And the receive frequency “saw tooth” will be offset by the Doppler frequency. On a rapidly closing target, the receive frequencies will be all offset by a positive $f_{Doppler}$, which can be measured by the receiver once the peak receive frequency is detected.

In summary, Doppler processing enables radar systems to discriminate in target velocity, as well as range and angle of the target. This is critical to distinguish moving targets from the background clutter. Doppler processing depends on frequency domain processing, which can be efficiently computed using an algorithm known as the Fast Fourier Transform, or FFT. In **Part 3 < http://www.eetimes.com/design/programmable-logic/4216880/Radar-Basics---Part-3--Beamforming-and-radar-digital-processing>** of the series on radar, an examination of how beamforming, pulse compression and Doppler processing can be implemented in radar systems will be examined.

Also see **Part 1 < http://www.eetimes.com/design/programmable-logic/4216104/Radar-basics---Part-1>** of this five-part mini-series on “Radar Basics”.

About the author

As senior DSP technical marketing manager, Michael Parker is responsible for Altera’s DSP-related IP, and is also involved in optimizing FPGA architecture planning for DSP applications.

Mr. Parker joined Altera in January 2007, and has over 20 years of DSP wireless engineering design experience with Alvarion, Soma Networks, TCSI, Stanford Telecom and several startup companies.

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