Radar Basics

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Figure 1: A Weather Radar Display

What is Radar?

Radar (RAdio Detection And Ranging) is actually a fairly simple process of bouncing radio waves off objects and looking at the reflections to determining presence, size, distance, position and speed.

Typically, radars illuminate their targets with an RF pulse and then listen for the return echo. Since the RF pulse propagates at the speed of light, the time it takes the echo to return is proportional to the distance from the target. This, of course, applies to a primary-radar, one that relies on reflected energy bouncing back off the target. Secondary-radars, that re-transmit the signal back from a transponder, have additional delays.

Transmitted RF signals are “bounced” off a target and a receiver measures the characteristics of the echo. Most often, low duty cycle pulses are used.

As the technology has evolved, the basic concept of radar has not changed. At the same time, the accuracy, resolution and number of radar applications has increased dramatically over time.

Radar Applications

Radar technology is used heavily in military applications. Ground-based radar is used for long-range threat-detection and air traffic control. Ship-based radar provide surface-to-surface and surface-to-air observation. Airborne radar is utilized for threat detection, surveillance, mapping, and altitude determination. Finally, missile radars are used for tracking and guidance.

There are many commercial aviation applications of radar such as air traffic control (ATC) long range surveillance, terminal air traffic monitoring, surface movement tracking, and weather surveillance. Additionally, short-range radar is increasingly being used in automotive applications for collision avoidance, driver assistance, and autonomous driving. Specialized radars can also be used to provide imaging through fog, through walls, and even underground.

Modern radars produce complicated pulses that can present significant measurement challenges. Improvements to range, resolution, and immunity to interference have motivated numerous coding schemes, frequency and phase modulated pulses, frequency chirped pulses, and narrow pulses with high overall bandwidth.

Frequency Bands

Radar frequency bands are classified into letter designations defined by the IEEE (see Table 1). The most commonly used bands used today for radar are the L-band through the KU-band or 1 – 18 GHz. Short-range automotive radar systems use the very high W-band frequencies in the 75+ GHz range.

Table 1 Common Radar Frequency Bands

Band	Use	Range
HF	Long-range, over the horizon (OTH)	3-30 MHz
VHF	Long-range, over the horizon (OTH)	30-300 MHz
UHF	Long-range, over the horizon (OTH)	300 MHz-3 GHz
L	Long range Air Traffic Control (ATC), surveillance	1-2 GHz
S	Medium Range, Airport Surveillance Radar (ASR), long range weather, marine radar	2-4 GHz
C	Weather, snow/ice mapping, precipitation detection	4-8 GHz
X	Missile guidance, marine radar, weather, ground surveillance, short-range airport tracking radar	8-12 GHz
Ku	High-resolution radar, satellite transponders	12-18 GHz
K	Cloud detection, police radar	18-27 GHz
Ka	Short range, airport surveillance, red-light traffic camera trigger	27-40 GHz
V	Very short range, space applications	40-75 GHz
W	Automotive/vehicle parking/warning radar systems, imaging	75-110GHz

Continuous Wave and Pulsed Radar

Radar systems can use continuous wave (CW) signals or, more commonly, low duty-cycle pulsed signals. CW radar applications can be simple unmodulated Doppler speed sensing systems such as those used by police and sports related radars, or may employ modulation in order to sense range as well as speed. Modulated CW applications have many specialized and military applications such as maritime / naval applications, missile homing, and radar altimeters. The detection range of CW radar systems is relatively short, due to the constraints of continuous RF power. There is no minimum range, however, which makes CW radar particularly useful for close-in applications.

Pulsed Radar

The radar measurements discussed in this document are all pulse measurements. Although there are several continuous transmission types of radar, primarily Doppler, the great majority of radars are pulsed. There are two general categories of pulsed radar, Moving Target Indicator (MTI) and Pulsed Doppler. MTI radar is a long-range, low pulse repetition frequency (PRF) radar used to detect and track small (~2m^2) moving targets at long distances (up to ~30km) by eliminating ground clutter (aka chaff). MTI is useful when velocity is not a big concern (i.e. “just tell me if something is moving”). Pulsed Doppler radar, in contrast, utilizes a high PRF to avoid “blind speeds” and has a shorter “unambiguous” range (~15km), high resolution, and provides detailed velocity data. It is used for airborne missile approach tracking, air traffic control, and medical applications (e.g. blood flow monitoring).

The RF pulse characteristics reveal a great deal about a radar's capability. Electronic Warfare (EW) and ELectronic INTelligence (ELINT) experts specialize in the study of these pulsed signals. Pulse characteristics provide valuable information about the type of radar producing a signal and what its source might be - sailboat, battleship, passenger plane, bomber, missile, etc.

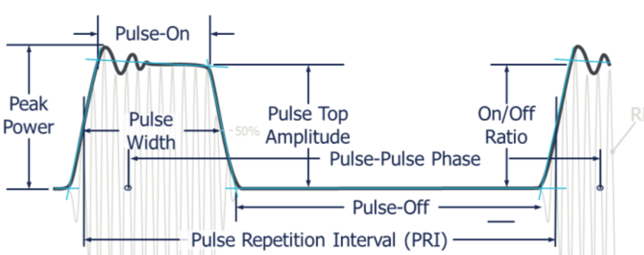

Figure 2. Common Pulse Characteristics

Pulsed radar typically utilizes very low duty cycle RF pulses (< 10%). The range and resolution is determined by the pulse repetition frequency (PRF), pulse width (PW), and transmit power. A wide PW generally provides better range, but poor resolution. Conversely, a narrow PW supports less range, but better resolution. This relationship constitutes one of the fundamental trade-offs in radar engineering. Pulse compression with a modulated carrier is often used to enhance resolution while maintaining a narrow PW allowing for higher power and longer range.

The Pulse Repetition Interval (PRI) is the time the pulse cycle takes before repeating. It is equal to the reciprocal of the PRF or Pulse Repetition Rate (PRR), the number of transmitted pulses per second. PRI is important because it determines the maximum unambiguous range or distance of the radar. In fact, pulse-off time may actually be a better indication of the radar system's maximum design range.

Traditional radar systems employ a Transmit/Receive (T/R) switch to allow the transmitter and receiver to share a single antenna. The transmitter and receiver take turns using the antenna. The transmitter sends out pulses and during the off-time, the receiver listens for the return echo. The pulse-off time is the period the receiver can listen for the reflected echo. The longer the off-time, the further away the target can be without the return delay putting the received pulse after the next transmitted pulse. This would incorrectly make the target appear to be reflected from a nearby object. To avoid this ambiguity, most radars simply use a pulse-off time that is long enough to make echo returns from very distant objects so weak in power, they are unlikely to be erroneously detected in the subsequent pulse's off-time.

Figure 3 illustrates the need for pulse compression to obtain good range and resolution. Wider PWs have higher average power, which increases range capability. However, wide PWs may cause echoes from closely spaced targets to overlap or run together in the receiver, appearing as a single target. Modulated pulses mitigate these issues, providing higher power and finer resolution to separate closely spaced targets.

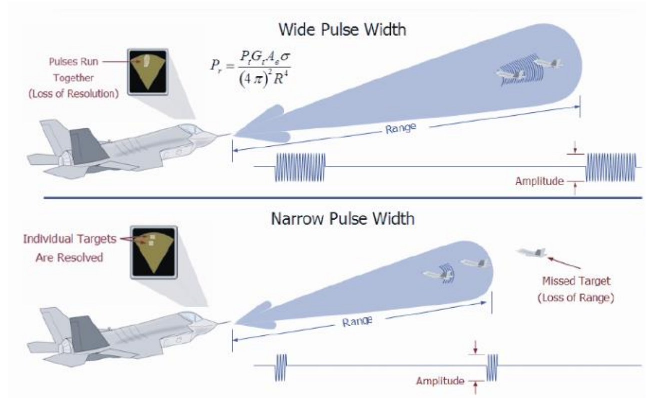

Figure 3. Pulse Width versus Resolution

Pulse Power

Another consideration for the maximum range of a radar is the transmitted power. Peak power is a measure of the maximum instantaneous power level in the pulse. Power droop, pulse top amplitude, and overshoot are also of interest. ELINT experts sometimes scrutinize these characteristics, as they provide additional information about a radar's characteristics.

Pulse top amplitude (Power) and Pulse Width (PW) are important for calculating the total energy in a given pulse (Power x Time). Knowing the duty cycle and the power of a given pulse, the average RF power transmitted can be calculated (Pulse Power x Duty Cycle).

Radar Equation

The Radar Equation, as it is commonly known, defines many of the engineering trade-offs encountered by radar designers.

$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R_t^2 R_r^2}$$

Equation 1. Radar Range Equation

The radar equation relates the expected receive power (P_r) to the transmitted pulse power (P_t); based on transmit antenna gain (G_t), area of the receive antenna (A_r), target cross section (aka reflectivity) σ, range from the transmitter antenna to the target (R_t), and range of the target to the receive antenna (R_r).

Unlike many communications systems, radar systems suffer from very large signal path losses. The round-trip distance is twice that of a typical communications link and there are losses associated with the radar cross-section and reflectivity of targets. As can be observed from the Radar Equation, the range term is raised to the fourth power in the denominator, underscoring the tremendous signal power losses radar signals experience. There are also several forms of the radar equation that take into account differing applications and antenna configurations.

Using the radar equation, the received signal level can be calculated to determine if sufficient power exists to detect a reflected radar pulse. Combining multiple pulses to accumulate greater signal power and average out the noise is also helpful for increasing the detection range.

Pulse Width

Pulse width is an important property of radar signals. The wider a pulse, the greater the energy contained in the pulse for a given amplitude. The greater the transmitted pulse power, the greater the reception range capability of the radar.

Greater pulse width also increases the average transmitted power. This makes the radar transmitter work harder. The difference in decibels (dB) between the pulse power and average power level is easily calculated using ten times the log of the pulse width divided by the pulse repetition interval.

Range is therefore limited by the pulse characteristics and propagation losses. The PRI and duty cycle set the maximum allowed time for a return echo, while the power or energy transmitted must overcome the background noise to be detected by the receiver.

Pulse width also affects a radar's minimum resolution. Echoes from long pulses can overlap in time, making it impossible to determine the nature of the target or targets. A long pulse return may be caused by a single large target, possibly an airliner, or multiple smaller targets closely spaced, possibly a tight formation of fighter aircraft. Without sufficient resolution, it is impossible to determine the number of objects that actually make up the echo return. Narrow pulse widths mitigate the overlapping of echoes and improve resolution at the expense of transmit power.

Pulse width thus affects two very important radar system capabilities - resolution and detection range. These two qualities are traded off against each other. Wider pulses equate to longer-range radars with less resolution, whereas narrow pulses equate to finer resolution but shorter range.

Narrow pulses also require greater bandwidth to correctly transmit and receive. This makes the pulse's spectral nature also of interest, which must be considered in the overall system design (see Figure 4).

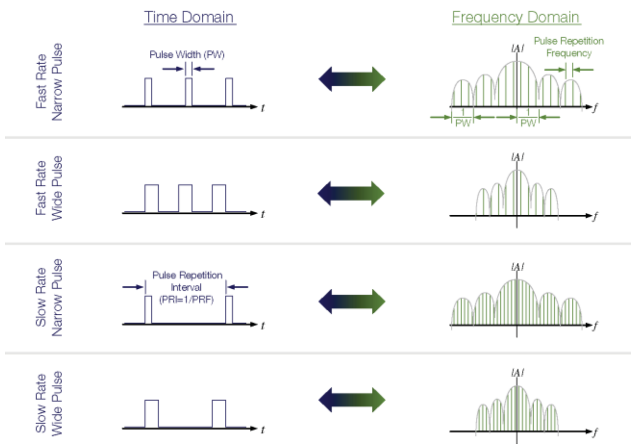

Figure 4. Pulse Time vs Frequency Characteristics

Pulse Modulation

While unmodulated pulsed radar are relatively simple to implement, they have drawbacks. As described previously, unmodulated pulses have relatively poor range resolution. To make the most efficient use of transmit power and optimize range resolution, most radars modulate pulses using a variety of techniques (see Figure 5).

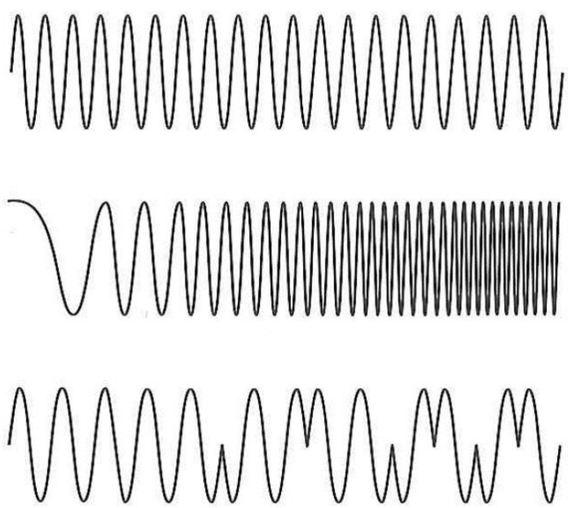

Figure 5. Common Pulse Modulations – constant CW (top), Linear FM (middle), Phase-Shift Keying (bottom)

Linear FM Chirps

The simplest pulse modulation scheme is the linear FM (LFM) chirp. It is also the most common types of pulse compression and is in wide use. Sweeping the carrier frequency throughout a pulse results in every part of a pulse being distinct and discernable. This enables pulse compression techniques to be utilized in the receiver, which is a very powerful radar technique for improving range resolution and making more efficient use of transmit power.

Phase Modulation

Phase modulation can also be used to differentiate segments of a pulse in a similar fashion as frequency hopping. Pulse phase modulation is often implemented as a version of Binary Phase-Shift Keying (BPSK). There are specific phase coding schemes, such as Barker Codes to ensure orthogonality of the coding while providing excellent range resolution.

Frequency Hopping

Another modulation technique utilizes several frequency hops within a pulse. If each frequency has a corresponding filter with the appropriate delay in the receiver, then all segments can be compressed together in the receiver. If the frequency hopping sequence remains the same for all pulses, then the receiver compression can even be implemented with a simple Surface Acoustic Wave (SAW) filter. One common form of frequency hopped coding is known as Costas Coding. This is a coding that intentionally reduces the side-lobes in the periodic auto-correlation function and has advantageous performance in the presence of Doppler effects. Additionally, the variable frequency pattern used by hopping pulses reduces susceptance to spoofing and jamming. This also reduces interference between transmitters in close proximity.

Digital Modulation

With the advancements of software defined radio and digital signal processing applied to radar, more complex pulse modulations are now used. For example, more effective anti-spoofing can be accomplished using M-ary PSK or QAM modulations. These modulations produce pulses that resemble noise as opposed to coherent frequencies, which makes them harder to detect. Other information can be encoded into these more complex digital modulations as well.

Pulse Compression

Basic pulsed radar using time-of-flight to measure target range has limitations. For a given pulse width, the range resolution is limited to the distance over which the pulse travels during the time of its duration. When multiple targets are at nearly equal distance from the radar, the return from the farthest target will overlap the return from the first target. In this situation, the two targets can no longer be resolved from each other with just simple pulses.

Using a short pulse width is one way to improve distance resolution. However, shorter pulses contain proportionately less energy, preventing reception at greater range due to propagation losses. Increasing the transmit power is impractical in many cases, such as for aircraft radar due to power constraints.

The answer to these challenges is the use of pulse compression. If a pulse can be effectively compressed in time, then the returns will no longer overlap. Pulse compression allows low amplitude returns to be "pulled" out of the noise floor. It is achieved by modulating the pulse in the transmitter so different parts of the pulse become more discernable. The actual time compression is accomplished by the radar receiver.

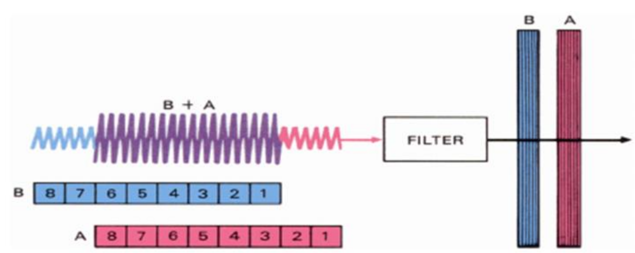

Figure 6. A matched filter in the receiver compresses the signal in time

The most common pulse compression technique linear frequency modulation, or LFM pulses. A LFM pulse is one where the pulse begins at one carrier frequency, then ramps linearly, up or down to an end frequency. LFM pulses are often called "chirps" or chirped pulses. Compression is achieved in the receiver by passing the signal through a matched filter (see Figure 6). This filter is designed to have a delay characteristic matched to the LFM frequency range, and delays portions of the modulated signal proportional to the carrier frequency. For example, the filter may delay the starting frequency of the LFM more than the ending frequency of the LFM, causing the leading edge of the pulse to be delayed more than the trailing edge. When the pulse passes through a receiver signal processor, the chirp will transform from a frequency chirp pulse to a narrow pulse containing all the frequencies overlapped. The width of the resulting pulse is dependent on the frequency resolution of the receiver processor. Bear in mind, there will be additional time-smearing and ringing due to non-linearity in the transmitted pulse.

When a pulse entering the receiver is a target return, there will likely be multiple close reflections due to the different surfaces of the target. If the compression signal processor has sufficient resolution, it can separate each of these reflections into discrete narrow pulses.

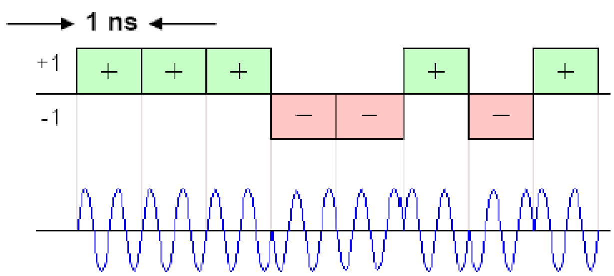

Figure 7. Barker coded binary phase shift keying (BPSK)

Another common pulse compression technique employs binary phase shift keying, or BPSK modulation, using a Barker coded sequence (see Figure 7). Barker codes are unique binary patterns that auto correlate against themselves at only one point in time. Barker Codes can vary in length from 2 - 13 bits, providing a corresponding compression ratio of 2 - 13. The compression is achieved in the receiver by sensing the auto-correlation of the Barker sequence within the detected pulse.

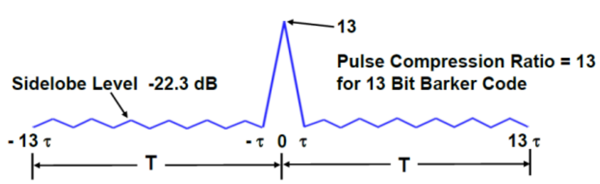

Figure 8. Barker coded spectrum showing side-lobe suppression

Lifecycle of Radar Measurement Tasks

The measurements needed for radar will vary depending on the job to be done and the type or radar to be characterized. From radar system design and component selection to the surveillance of deployed radars, accurate and fast measurements are required with reproducible results.

Challenges of Radar Design & Verification

When performing radar design verification, there is a need to assure the transmitted signal is correct, the receiver responds to and detects the correct signals, and that there are no spurious signals emitted from the transmitter. Unexpected outputs can range from unintended signals related to the desired pulse (such as harmonics, sub-harmonics, image mixing products, etc.), as well as spurious outputs unrelated to the desired pulse, such as radiation of internal local oscillators, coupling from digital clocks, spurious oscillations within RF circuitry, pulse errors, and so forth

In the modern world of "software defined" radar, modulated pulses, chirps, and other waveforms are usually not generated with traditional analog circuitry, but with Digital Signal Processors (DSP) and Direct Digital Synthesis (DDS) techniques. These digital techniques generate complicated signals directly at intermediate frequencies (IF) or RF frequencies. The signals only become analog when the synthesized digital data is passed through a digital-to-analog (D/A) converter.

Within the DSP, subtle software code and numeric errors such as poorly chosen filter constants, numeric rounding, or overflow errors can create very short-duration artifacts that may bear little or no relation to the desired output. A single DSP error can create momentarily incorrect RF output (i.e. a glitch). This can play havoc when filtered, amplified, and transmitted.

Spurious emissions can also interfere with other RF services in the deployment area and often provide a distinctive signature if they are specific to a particular transmitter design. Wideband radars can also “bleed” into surrounding spectrum causing unintended interference well outside the assigned spectrum.

Challenges of Production Testing

Production testing involves verification that each manufactured product meets its specifications. Test tasks include tuning and calibrating assemblies, along with the compensation and calibration of analog modules, linearizers, and amplifier components. Results must be accurate and repeatable to assure the final product will function as intended. As component and subsystem vendors make changes to their processes, continued verification of performance is required without varying the tests throughout the product lifecycle.

Automated testing reduces the chance for operator error, which is a drawback of manual test processes and manually operated test equipment. With automation, reproducibility of test results can be maintained regardless of production personnel changes and training requirements can be significantly reduced.

Signal Monitoring

Signal monitoring is a different challenge. For Signal Monitoring, there is less need to verify a specification, but more to identify signals that may be present in the surrounding area or show themselves only very rarely. These types of interfering signals can jam or reduce the effectiveness of a radar. When searching for pulsed or interfering signals, an RF analyzer must not “blink” when the signal appears. Discovering, triggering, and capturing infrequent signals or transient characteristics of signals are required before analysis can be performed.

Interference may be manifested not only as an infrequent problem, but may be an issue of multiple signals contending for the same spectrum, either intentionally or unintentionally. Discovering such overlapping signals can be very difficult using traditional test equipment.

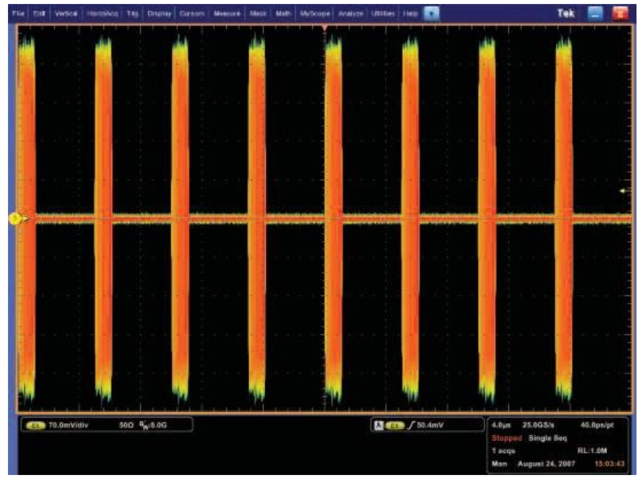

Figure 9. Oscilloscope trace of an RF pulse train

Basic RF Pulsed Radar Signals

A simple pulse can be a single frequency that is turned on for a short time and then off again. The signal travels from the transmit antenna, reflects off of a target and returns to the radar. The time it takes for the pulse to return represents the range, or distance to the target.

An oscilloscope can show the time domain voltage waveform of the transmitted pulse. This includes all individual cycles of the RF pulse as in Figure 9.

A RF detector can be used to create a trace of the envelope of the pulse, instead of the individual cycles. This makes triggering much easier. A Vector Signal Analyzer (VSA), or a spectrum analyzer in zero-span, can display amplitude versus time. This is the equivalent of using a RF detector. The lower trace in Figure 10 is a spectrum analyzer detected envelope of a single RF pulse seen in the voltage waveform of Figure 9.

A spectrum analyzer can also show the frequency spectrum of the pulse. The sin(x) / x (pronounced "sine x over x") classic pulse spectrum plot is seen in the upper trace. A VSA can use a Fast Fourier Transform (FFT), or other Discrete-Time Frequency Transformation (DTFT), to make such a spectrum plot of a single pulse. A swept spectrum analyzer must either be in a "maximum trace hold" mode, or it must sweep slowly enough that at least one pulse appears at each position across the screen to provide a complete spectrum view. Without additional frequency processing software, the oscilloscope provides only the voltage waveform.

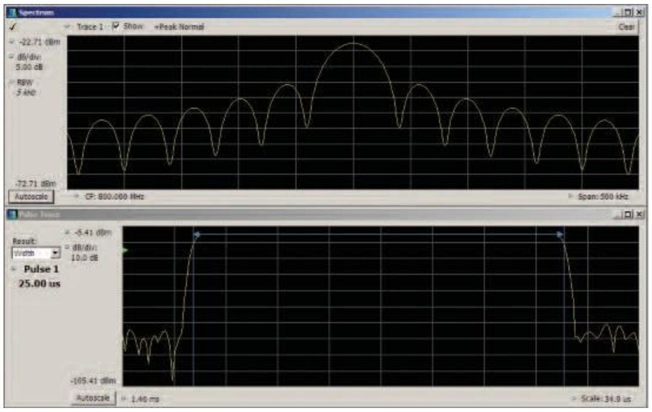

Figure 10. RF pulse spectrum (top) and pulse trace (bottom)

Transmitter Tests

Modern radars often generate pulses at an Intermediate Frequency (IF) where the processing is easier and then convert the IF frequency to the final CW frequency before amplifying it to the necessary high power. When testing an up-converter from the IF system, or testing the power amplifier, a radar pulse generator is needed in addition to the pulse analyzer.

There are several solutions available for generating radar pulses. Arbitrary Function Generators (AFGs), Arbitrary Waveform Generators (AWGs), and software to create the necessary pulses can generate baseband, IF, RF, or microwave signals using direct synthesis up to 10 GHz and higher. Test waveforms can be imported into the generators, synthesized, and replayed. Signal generation is often required in the selection and verification of analog transmitter components to test the margin of design and manufacturing processes.

Receiver Tests

Testing the receiver portion of a radar system, when the companion transmitter is not yet available, requires pulse generation equipment. However, verification of receiver performance under varying signal conditions may not be possible using the companion transmitter. This requires a generator with the capability to add impairments and distortions to generated pulses. Common impairments are in-channel and out-of-channel signals and noise to test desensitization or blocking. This will verify the limits of receiver functionality. A generator of waveforms with arbitrary variation of any part of a digitally created waveform fills this need.

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