How to test modern radars

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Using a spectrum analyzer for pulsed measurements has always required a careful understanding and knowledge of the parameters of the pulse signal, as well as the subsequent operation of the spectrum analyzer to make valid measurements. One of the primary uses of pulsed measurement techniques has been the accurate measurement of pulsed radar signals. Advances in the type of pulse and pulse train information can greatly improve the utility of the radar; however, these advances will increase the complexity of the measurements. Automatic pulse measurements have been introduced on modern spectrum analyzers to greatly simplify challenging new measurements.

This article looks at traditional pulse measurements using a typical spectrum analyzer with a traditional swept-tuned architecture, discusses some of the advances in radar waveforms, and reviews some of the important considerations for reducing the measurement uncertainty of these advanced pulse measurements on more modern spectrum analyzer architectures.

Basic Pulse Measurements

The main advantage of using a traditional spectrum analyzer is that it can be used to test frequency-dependent power components with a wide dynamic range. Simple measurements, such as checking the symmetry of the pulse spectrum, can validate the radar transmitter. An asymmetrical spectrum can waste power, generate unwanted spurious emissions, and degrade the overall performance of the radar.

When making measurements using the spectrum analyzer, particularly on signals with low duty cycles, one needs to be familiar with the parameters of the expected pulse and the important spectrum analyzer settings such as resolutions bandwidth (RBW), span, and sweep time in order to produce informative results.

Figure 1 shows the traditional swept-tuned architecture of the spectrum analyzer. A signal is filtered and downconverted to an IF frequency where various resolution bandwidth and video filters are applied to the signal while the local oscillator is swept across a frequency span. The resulting energy and frequency is plotted on the display.
Since a pulsed signal is not on at all times, the energy will not completely “fill” the spectrum on a single sweep. Figure 2 shows the spectral characteristics of a simple pulsed RF signal with a pulse width $\tau$ and the pulse repetition interval $T$. The amplitude of the spectral lines are determined by the envelope curve about the center frequency $f_0$.

When measuring the spectrum using a spectrum analyzer, it is possible to display the individual spectral lines or the envelope curve of the pulse spectrum depending on the instrument settings. The RBW should be set to a value significantly less than the pulse repetition frequency ($= 1/T$). The line spacing is equal to the pulse period (pulse repetition interval) and is independent of the setting for the sweep time on the analyzer. The height of the individual spectral lines is also independent of the RBW.

The largest spectral line displayed in the spectrum display is below the pulse amplitude of the actual pulse by the pulse desensitization factor"(PDF). The PDF is dependent upon the pulse width to the pulse period ratio:
PDF = $20 \times \log(\tau/T)$

Using the line spectrum, the peak power of the pulse signal can be calculated when placing a marker on the tallest spectral line (as shown in Figure 3):

$$\text{Peak power} = \text{marker reading} - \text{PDF} = \text{marker reading} - 20\times\log(\tau/T).$$

![Figure 3: Shows the line spectrum using 50 Hz RBW for 1000 Hz pulse interval](image)

When using the maximum peak detection method, if the RBW of the analyzer is increased such that it is greater than the reciprocal of the pulse period (but still smaller than the reciprocal of the pulse width), the spectrum analyzer will display the spectrum envelope. The amplitude of the envelope increases linearly with the RBW, thus doubling the RBW produces a 6dB increase in the amplitude.

By continuing to increase the RBW until the RBW is greater than the reciprocal of the pulse width, the spectrum analyzer can approximate the peak power of the pulse signal within the limitations of the resolution bandwidth of the traditional spectrum analyzer.

To demonstrate this limitation, Figure 4 shows the zero-span capture of three different pulse widths using a 10MHz RBW filter. While accurately representing the pulse widths for 500 and 200ns durations, when the pulse width of the signal is decreased to 100ns, the peak amplitude becomes reduced due to the filter bandwidth of the RBW filter. As the pulse width gets shorter, the limitations of the traditional spectrum analyzer impact the measurement uncertainty.
Increasing Complexities of Radar

Many modern types of radar have advanced beyond the simplistic traditional functions of range detection to improve range resolution, mitigate operational limitations, and improve function. The impact of these modern radar types increases the complexity and performance requirements of the traditional spectrum analyzer.

Pulse-Doppler radar provides radial speed information about the target in addition to range and direction. Using a typical coherent transmitter and receiver, the speed information can be derived from the pulse-to-pulse variations in the received signal. Pulse-to-pulse transmitter stability verification test has become much more demanding on the performance of the measurement equipment as phase information is not collected in a traditional spectrum analyzer.

Pulse compression radars are used to improve range resolution. Frequency modulation on pulse (FMOP) and phase modulation on pulse (PMOP) can substantially improve the ability to resolve multiple targets at greater distances. A 2GHz bandwidth FM chirp can resolve target variances less than 10cm apart. Some of the typical FMOP/PMOP techniques include: Linear frequency modulation (FM Chirp); non-linear frequency modulation; encoded pulse phase modulation (e.g. Barker codes); and polyphase modulation and time-frequency coded modulation. Not only do pulse compression radars tend to increase the need for analysis bandwidth with fast risetimes and reduced pulse widths, but to check for transmitter stability requires different types of waveform analysis not available on traditional spectrum analyzers. To collect the necessary phase information, a baseband I/Q conversion is required to perform the type of analysis needed to validate these types of radar transmitters.

An example of an advanced radar technique and associated measurement might be the use of a
staggered pulse repetition interval (PRI). A staggered PRI technique is used in most modern radars to overcome the limitations of a constant PRI. Constant PRI frequency radars are susceptible to self-jamming, blind speeds, false target recognition due to double echo returns, and can also be susceptible to jamming or spoofing.

Figure 5 shows the analysis of a multi-rate PRF transmitter. Not only is the PRI varied in this case, but the pulse widths are also varied on a pulse-to-pulse basis. This type of analysis on a traditional spectrum analyzer would not be possible as many of the measurements that were described earlier require a constant and stable PRI for timing and spectrum measurements.

![Figure 5: Measurements of Varying PRI Pulse Train Signal using the Rohde & Schwarz FSW Spectrum Analyzer and K6 Pulse Analysis Software](image)

> Modern spectrum analyzer architectures for testing advanced radars

Modern spectrum analyzer architectures for testing advanced radars

Performing analysis of modern radar signals requires a spectrum analyzer architecture that goes beyond the traditional swept-tuned spectrum analyzer. Modern spectrum analyzers now incorporate an FFT acquisition or vector signal analysis mode of operation. This class of spectrum analyzer is also called a signal analyzer, and real-time spectrum analyzers also use this similar acquisition architecture.

![Figure 6: Architecture of vector signal analyzer](image)
As shown in Figure 6, the vector signal analyzer has a similar front-end to a traditional swept spectrum analyzer with filtering and downconversion. However, once the signal is placed at an IF frequency, the entire spectrum of the downconverted signal is digitized by an A/D converter and recorded into memory. The time sampled data can then be converted through FFT and waveform processing where the spectrum, time, and phase information can be preserved for analysis.

With the vector signal analyzer, the bandwidth of the analysis is not limited by the maximum resolution bandwidth like the swept-analyzer, but the maximum IF bandwidth in the analyzer. The IF bandwidth is defined by the A/D converter, sampling rate, and associated IF filtering. Typical vector signal analyzers have 40 MHz, 80 MHz, and up to 160 MHz bandwidths for analysis enabling analysis of much faster risetime and pulse widths with a higher degree of certainty as shown in Figure 7.

Acquisitions are captured into memory and subsequent FFT and waveform analysis can be performed on the acquired signals.

![Figure 7: Wide IF bandwidths enable accurate peak-power measurements of narrow pulsewidths](image)

**Important considerations for pulse-pulse measurements**
Representing information on individual pulses and trending information requires advanced analysis in modern spectrum analyzers. Figure 8 shows an individual pulse analysis of a linear FM chirp. The displays show the pulse train for several pulses and tabulated analysis (green) for the individual pulses. The individual pulse analysis (blue) for the linear FM chirp is expressed in frequency, amplitude, and phase vs time displays using the pulse analysis.
Defining the pulse parameters
As shown in Figure 8, the vector signal analyzer provides a series of time domain views and measurement results that are not available on a swept tuned spectrum analyzer. To understand the importance of the measurement uncertainty associated with the results, it is important to define the parameters of the pulse.

The rise and fall times are typically measured between the 10-90% values exclusive of the overshoot and droop associated with the pulse. The pulse width is typically a measure of the 50% values of the rising and falling edge measured in linear units. The selection of the trigger point and phase
reference point for pulse-to-pulse measurements has a direct bearing on the measurement results.

When measuring the pulse-to-pulse performance of a radar transmitter, it is important to understand the variables that can impact the uncertainty of the measurement system for accurate Doppler measurements, which include:

- Signal-to-noise ratio
- Signal bandwidth and filtering
- Reference (or timebase) clock stability and trigger jitter
- Phase noise accumulation

The same variables can also contribute to the uncertainty in the signal generator when testing the receiver circuit and Doppler measurement accuracy.

Analyzing the variables

**Signal-to-Noise Ratio (SNR):**
As a general rule, the higher the level of SNR, the lower the uncertainty will be due to noise contribution. While this is not typically an issue when measuring a stable pulse, the uncertainty can increase if the pulse train is going through a power ramp mode of operation. One might also observe a power ramp making an over-the-air measurement if the measurement is located in a fixed position while the radar antenna rotates (ex. air traffic control radar). One also must be concerned about the measurement bandwidth of the instrument with respect to the bandwidth of signal of interest. Too much bandwidth can increase the noise power with respect to the signal.

**Signal Bandwidth and Filtering:**
The bandwidth of the IF acquisition system must be sufficient to accurately represent the risetime of the pulsed signal. As mentioned previously, too much IF bandwidth can increase the noise. However, if the bandwidth is artificially reduced to filter the pulse width of the signal, the pulse-to-pulse measurements could be artificially reduced by the measurement instrumentation. Applying filtering to prevent overshoot and preshoot of the rising and falling edges of the pulse can substantially improve measurement reproducibility as any ringing on the edges can impact the measurement points on a pulse-to-pulse basis. It is important that the selection of the pulse-to-pulse measurement point, or set of measurement points, is sufficiently far away in time from the edges of the pulse. Applying a Gaussian filter to smooth the pulse ringing can improve the measurement uncertainty of the pulse-to-pulse measurements. It should be noted that the filtering used to make stable pulse measurement will impact other measurements such as risetime and spectrum occupancy. Care should be taken to assure proper parameters are set for each measurement to assure reproducibility and accuracy of the results.

**Reference (Timebase) Clock Stability and Trigger Jitter:**
When measuring a radar signal, it is important to lock the timebase of the radar synthesizer to the measurement equipment. However, this is not always possible, especially when measuring signals over-the-air. Some radars, such as bistatic or multistatic radars, have receivers located a great distance from the transmitter and require synchronization via a reference clock (GPS). Between the reference clock short-term stability and the errors associated with trigger circuit synthesis, phase ambiguity can result in pulse-to-pulse errors.

**Phase Noise Accumulation:**
The impact of phase noise on the measurement uncertainty is directly proportional to the measurement time and the phase noise performance at different frequency offsets. Phase noise accumulation occurs in the interval between the reference measurement pulse and the pulse being
measured. The longer the period, the longer the accumulation of the close-in phase noise. Therefore, the performance of the phase noise at close-in offset frequencies can be one of the most important variables to pulse-to-pulse measurements.

Summary
Simple radar signals have been traditionally measured using swept-tuned spectrum analyzers. However, modern radar signals that now include phase and frequency modulation techniques or staggered PRI can no longer use a simple architecture to make meaningful results. Modern spectrum analyzer architectures, such as the vector signal analyzer, are now required to make measurements of advanced pulsed radar signals. It is important to select the vector signal analyzer with enough bandwidth and performance to make reproducible results. Vector signal analyzers, such as the Rohde & Schwarz FSW with Option K6, are now available with advanced signal analysis software to provide accurate scalar and vector measurement of pulse signals.

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About the Author
Darren McCarthy is the Aerospace and Defense Technical Marketing Manager for Rohde & Schwarz America. He has worked extensively in various Test and Measurement positions for the over 20+ years including R&D engineer, R&D project manager, Product Planning, Business and Market Development.

During his career, he has also represented the US as a Technical Advisor and Working Group Member for eight years on several IEC Technical Committees and Working Groups for international EMC standards, and currently represents R&S in several industry associations.

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