Measuring Radar Signals with Vector Signal Analyzers and Wideband Instruments

Part 4
As derived in Part 1 of this series, the radar range equation captures the essential variables that define the maximum distance at which a given radar system can detect objects of interest. Because those variables relate directly to the major sections of the system block diagram, they provide a powerful framework for the essential process of understanding, characterizing and verifying the actual performance of any radar system.

Parts 2 and 3 of the series defined the pulsed radar signal, described ways to measure the power in those signals, and presented readily available ways to measure the essential characteristics of pulsed signals: frequency, timing, power and spectrum.

In our ongoing discussion of practical test methods, the next step is to examine the use of vector signal analyzers (VSAs) and wideband instruments—signal analyzers and oscilloscopes—to measure the frequency and phase in today’s increasingly complex radar signals. Compared to traditional approaches that combine multiple instruments, these integrated tools provide enhanced ease of use that makes it easier to produce accurate, repeatable measurement results.

The radar series
This application note is the fourth in a series that delves into radar systems and the associated measurement challenges and solutions. Across the series, our goal is to provide a mix of timeless fundamentals and emerging ideas.

In each note, many of the sidebars highlight solutions—hardware and software—that include future-ready capabilities that can track along with the continuing evolution of radar systems.

Whether you read one, some or all of the notes in the series, we hope you find material—timeless or timely—that is useful in your day-to-day work, be on it new designs or system upgrades.
VSA: Understanding the Inner Workings

Unlike a spectrum analyzer, a vector signal analyzer captures the magnitude and phase information within a measured signal. As a result, a vector signal analyzer can perform advanced analysis including demodulation of highly complex signals. It can also display measurements and results in the time, frequency and modulation domains. A short diversion to explain the inner workings of these analyzers will make this clearer and also provide hints that will ensure useful results when measuring pulsed radar signals.

As additional background, a VSA was originally a unique, dedicated instrument (sidebar). Today, these capabilities are implemented as powerful standalone applications such as Keysight’s industry-leading 89600 VSA software. 89600 VSA can run inside a variety of Keysight signal analyzers, oscilloscopes and logic analyzers, adding deep analysis capabilities to a variety of measurement engines. The PC-compatible software also supports several Keysight modular instruments (e.g., digitizers and VSAs).

Reviewing the key concepts

The inner workings of any signal analyzer that uses the fast Fourier transform (FFT) to produce a frequency spectrum may seem foreign or mysterious, at least initially. Fortunately, the fundamentals are a combination of familiar concepts from communications theory (e.g., Fourier) and sampling theory (e.g., Nyquist and Shannon).

In simple terms, a vector signal analyzer calculates a frequency spectrum by sampling the incoming signal, storing a finite-sized block of the sampled time-domain data (i.e., the time record), and performing an FFT on the data block. If the selected combination of center frequency and span moves the start frequency away from zero (or above the analyzer’s minimum frequency), then the analyzer uses mixing to translate the incoming signal down to an intermediate frequency (IF) section where the band-limited signal is sampled by an analog-to-digital converter (ADC). The results are stored as a time record that is used calculate results such as an FFT spectrum.

Starting with a high-speed, high-resolution ADC, the maximum measurement (or analysis) bandwidth is a function of the ADC’s maximum sampling rate. Referring to Nyquist theory, typical sampling factors range from 2.0 to 2.56 depending in part on the quality of the analog anti-aliasing filters used in the analyzer’s front end. Thus, a sampling frequency of 2.048 GHz, a Nyquist factor of 2.048, and a steep anti-aliasing filter yields a maximum bandwidth of 1.0 GHz.

Resolution in the frequency domain is proportional to the size of the time record. For example, using a 2,048-point time record and applying the relevant Nyquist factor typically provides 800 to 1,000 lines of resolution in the frequency spectrum. In most implementations, the size of the time record is a power of two and other common points/lines pairs range from 64/30 to 16,384/8,000.

Taking a look back

This technology has a long history, dating back to the 1970s and the first FFT-based signal analyzers. Within the limits of ‘70s-era ADC and DSP technology, the top-end frequency was 20 or 25 kHz and the main applications were sound, vibration, mechanical analysis and closed-loop control systems.

In the 1980s, Hewlett-Packard was a leading innovator in what it called dynamic signal analyzers. All models provided time-domain measurements (in baseband mode) and spectrum analysis with 80 dB dynamic range and high-resolution zoom analysis anywhere within the instrument’s frequency range.

As ADC, DSP, CPU and memory technology progressed, analyzers moved to higher frequencies. In the early 1990s, the first vector signals analyzers, the HP 89400 series, had a maximum frequency of 10 MHz and offered built-in modulation analysis.

Today, these technologies are embedded in many of Keysight’s signal analyzers and vector signal analyzers. Current advances in ADC and DSP technologies have enabled analysis bandwidths of 1 GHz with high dynamic range in RF, microwave and millimeter-wave applications.

www.keysight.com/find/X-Series
www.keysight.com/find/vseries
www.keysight.com/find/VSA
Going a bit deeper

Inherent in the process is an assumption that the time-domain signal used in the FFT calculation repeats indefinitely. This is a valid assumption when working with transient or impulsive signals—including pulse-modulated signals—that can be arranged to occur entirely with the time record. It’s also valid with continuous wave (CW) signals that align with the time record in such a way that complete cycles are contained within the data block (Figure 1).

![Figure 1. The “repeating” assumption is valid when the time record contains an integer number of complete cycles of a CW signal.](image)

The situation changes when working with CW, swept, burst, chirped or modulated signals that are not perfectly aligned with or fully captured in the time record. Improper alignment causes discontinuities at the beginning and end of the data block, violating the “repeating signal” assumption (Figure 2).

![Figure 2. A misaligned signal violates the “repeating” assumption and causes discontinuities that will affect the FFT results.](image)

When this occurs, the calculated spectrum follows Fourier theory and includes innumerable frequency components of declining amplitude centered on the true spectrum. This phenomenon, called leakage, produces a spectrum shape similar to that shown in Figure 3.

![Figure 3. Time-domain discontinuities produce leakage in the frequency domain, resulting in a distorted spectrum result.](image)
The general solution to this problem is to weight each block of sampled data with a "window function" that forces both ends of the time record to zero. Figure 4 illustrates the process.

Even though the windowing function changes the shape of the time-domain waveform, the shape is designed to have minimal effect on the spectral result. Because the resulting waveform is more compatible with the "repeating" assumption, there are fewer leakage effects and the result is an accurate frequency-domain representation of the spectrum, as shown in Figure 5.
Because different signals or applications require different treatment, most vector signal analyzers include a variety of window functions, and the key difference is a tradeoff between dynamic range and amplitude accuracy. Window functions typically have descriptive names—uniform, flat top—or carry the name of the person who created them—Hamming, Blackman. Each has specific advantages and common uses, and Table 1 includes the window functions available in the 89600 VSA software, summarizing the common uses and normalized equivalent noise bandwidth (ENBW) for each type. Because most pulsed radar signals tend to be self-windowing, the uniform window is often the best choice because it has no effect on the time-domain waveform and avoids any resulting tradeoffs.

Table 1. Selecting the best window depends on the application and the desired results.

<table>
<thead>
<tr>
<th>Window type</th>
<th>Common uses</th>
<th>ENBW Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform or rectangular</td>
<td>Transient and self-windowing data</td>
<td>1.0</td>
</tr>
<tr>
<td>Hanning</td>
<td>General purpose</td>
<td>1.5</td>
</tr>
<tr>
<td>Gaussian top</td>
<td>High dynamic range</td>
<td>2.2153497</td>
</tr>
<tr>
<td>Flat top</td>
<td>High amplitude accuracy</td>
<td>3.8193596</td>
</tr>
<tr>
<td>Blackman-Harris</td>
<td>Relatively high dynamic range</td>
<td>2.0043529</td>
</tr>
<tr>
<td>Kaiser-Bessel</td>
<td>Relatively high dynamic range</td>
<td>2.0012660</td>
</tr>
</tbody>
</table>

When performing spectrum analysis with a vector signal analyzer, four factors determine the equivalent resolution bandwidth (RBW) in the resulting frequency spectrum: the user-selected frequency span, the user-selected number of spectral lines, the choice of window, and the window's normalized ENBW. For a 1 GHz span with 4,000-line resolution, the basic RBW is 250 kHz. However, if the Hanning window is selected, it has an ENBW multiplier of 1.5 (see Table 1) and the logical equivalent of RBW is 375 kHz (1.5 x 250 kHz). Fortunately, the analyzer performs all of these calculations automatically and displays the relevant values on the measurement trace.

Note that there is an inverse relationship between RBW and measurement time. In a swept analyzer, narrower RBW settings require longer sweeps and thereby increase the likelihood of missing transient information. In a vector signal analyzer, a narrower RBW requires a longer time record—and this will result in the acquisition of more time-domain information that may include multiple pulses in the FFT calculation.
Measuring power and pulse characteristics

Similar to a spectrum analyzer, spectrum results from a vector signal analyzer can be used to determine average power and peak power. The most direct way to ensure accurate results is to set the analyzer to measure the line spectrum with an RBW that is less than 0.3 times the pulse repetition frequency (PRF). This ensures that the analyzer will resolve each spectral component.

In this scenario, the average power and peak power can be determined with the same method as the line-spectrum mode in a spectrum analyzer. However, this is not normally done because a vector signal analyzer makes it possible to make such measurements directly in separate time-domain displays.

Typical vector signal analyzers also include band power (similar to channel power) and occupied bandwidth (OBW) functions. Additional measurements such as complementary cumulative distribution function (CCDF), spectrogram, and time-gated spectrum are also available.

To ensure accurate results, the analyzer must calculate the frequency spectra from a representative time-domain sample of the waveform. If the time record contains only a fraction of the signal relative to its period, then the displayed level of the spectrum may reflect neither the correct spectral characteristics nor the true power level of the signal. This can be resolved by either increasing the FFT measurement time to include several pulse periods or setting the RBW to satisfy the line-spectrum criterion (e.g., 0.3 x PRF).

1. For a detailed explanation, please refer to The Radar Series, Part 3, Measuring the Characteristics of Pulsed Radar Signals, publication 5992-1521EN.
Working in the time domain

When characterizing radar signals with a vector signal analyzer, the available time-domain displays are a logical and intuitive way to measure average power, peak power, pulse power, duty cycle, pulse width, pulse period, and pulse shape. To enable cross-domain insights, the 89600 VSA software can display time- and frequency-domain views of the signal simultaneously.

Figure 6 shows six measurements of a radar chirp using a PXA X-Series signal analyzer and the 89600 VSA software. Time-domain displays and markers enable measurements of power and pulse parameters as well as pulse droop, pulse-to-pulse phase continuity, and frequency versus time (or group delay).

Using time-gated analysis

In a vector signal analyzer, time-gated analysis computes the FFT using only the samples collected during a specific time interval. Similar to an oscilloscope, a vector signal analyzer can perform single-shot time-gated measurements. With the 89600 VSA software, the process is as easy as dragging and dropping the gate onto the time-domain display of the waveform.

Time-gated analysis makes it possible to examine the spectral characteristics of an individual pulse, a portion of a pulse, or a transient. As an example, Figure 7 shows the time-gated spectrum of a simple RF pulsed radar signal. There are two reasons for the leakage in the displayed spectrum: the “repeating signal” assumption and the small discontinuities at the beginning and end of the time record (i.e., the uniform window does not affect the early and late samples).

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89600 VSA software

Two 89600 VSA software is a comprehensive set of tools for demodulation and vector signal analysis. These tools enable you to explore virtually every facet of a signal and optimize your most advanced designs.

- Quantify spectral performance with high-resolution, FFT-based measurements
- Analyze time-domain signal quality using pulse timing features, CCDF, and more
- Characterize complex modulation schemes with constellation, EVM, decoded bits, and more
- Use the multi-measurement capability to quickly characterize numerous signals or devices simultaneously

You can choose the best front-end hardware for your application: the software supports more than 45 Keysight measurement platforms including signal analyzers, oscilloscopes, logic analyzers, and modular products (AXIe and PXIe).

Find us at www.keysight.com
Viewing dynamic behavior

A display called the spectrogram simplifies the visual recognition of major signal characteristics by plotting frequency and amplitude versus time. Each one-pixel line of the spectrogram is an overhead view of a single spectrum measurement with amplitude values encoded in color. Depending on the vertical time scale, a spectrogram can contain hundreds or even thousands of spectrum measurements. Figure 8 shows an example measurement of a frequency-agile signal captured using a wideband oscilloscope and displayed as a spectrogram using the 89600 VSA software.

Figure 8. By plotting frequency (x-axis) versus time (y-axis) versus amplitude (see color scale at left), a spectrogram is a visually efficient way to characterize the frequency-domain behavior of one or more signals versus time.
Making gap-free measurements

Another useful feature of a vector signal analyzer is the ability to perform gap-free measurements. All data within the time record is being captured and processed, and there are no gaps between time records. This can be done via time capture and post-processing or, with a suitably equipped analyzer, in real time on live signals up to a maximum bandwidth that depends in part on the processing power (e.g., CPU and DSP) within the instrument. The maximum capture length is typically many time records—thousands or millions—depending on the available acquisition memory within the signal analyzer.

Measuring and analyzing captured data

The 89600 VSA software has a record/playback capability that enables gap-free measurements on acquired data. A signal recorded (i.e., captured) into memory can be played back and analyzed at the same center frequency and span as the acquisition or, because all data is available, at different center frequencies and spans within the original captured span without capturing new data.

Figure 9 shows two separate spectrograms from a gap-free capture of a chirped radar signal. The spectrograms show, with different levels of detail, the linearly changing frequency of the chirp and pulse widths of the signal.

![Spectrograms](image)

In this example, a capability called overlap processing was used to change the playback rate and thereby reveal more detail about the spectral content. In the VSA software, the amount of overlap relative to successive time records is selectable between 0 and 99.99 percent. In effect, the analysis "scrolls through" the capture buffer during post-processing, enabling you to understand the behavior of the signal independent of the windowing effects on any individual time record. One key benefit is elimination of issues with amplitude accuracy that arise from windowing when a pulse, burst or transient is near either edge of an individual time record.
Measuring and analyzing live signals

Performing gap-free analysis on live signals requires a real-time spectrum analyzer (RTSA) or the addition of RTSA capability to a signal analyzer. The phrase “real-time analysis” and its attendant capabilities can mean different things to different people. Fortunately, the core concept can be defined as follows: in a spectrum or signal analyzer with a digital IF section, real-time operation is a state in which all signal samples are processed, gap-free, for some sort of measurement result or triggering operation. In most cases the measurement results are scalar—power or magnitude—and correspond to a traditional power spectrum measurement.¹

RTSA capability is available as an option to the UXA, PXA and MXA X-Series signal analyzers. Table 2 summarizes the maximum available analysis bandwidths and real-time bandwidths for those analyzers. The real-time-capable X-Series analyzers are compatible with the 89600 VSA software, creating a solution that combines RTSA capabilities with deeper analysis of pulsed, chirped and modulated signals.

Table 2. The latest X-Series signal analyzers with multi-touch offer a range of choices in analysis bandwidth and real-time bandwidth.

<table>
<thead>
<tr>
<th>Model</th>
<th>Maximum analysis bandwidth</th>
<th>Maximum real-time bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>UXA (N9040B)</td>
<td>25 MHz standard; 40 MHz, 25 MHz, 510 MHz, 1 MHz optional</td>
<td>255 or 510 MHz</td>
</tr>
<tr>
<td>PXA (N9030B)</td>
<td>25 MHz standard; 40, 85, 125, 255 and 510 MHz optional</td>
<td>85, 160, 255 or 510 MHz</td>
</tr>
<tr>
<td>MXA (N9020B)</td>
<td>25 MHz standard; 40, 85, 125, 160 MHz optional</td>
<td>85, 125 or 160 MHz</td>
</tr>
</tbody>
</table>

¹ As a reminder, the record/playback method in the previous section provides gap-free vector analysis in the time, frequency and modulation domains.
Measuring power statistics: CCDF

The complementary cumulative distribution function is used to measure the statistical power characteristics of a signal. It calculates the peak-to-average power ratio and plots the power on a graph that shows power in decibels above average power on the horizontal axis and percentage of time on the vertical axis.¹ The CCDF result makes it possible to determine the percentage of time the signal is at a specific power level above the average power. This measurement is especially useful for determining the power characteristics of shaped pulses or for revealing the peak-to-average (i.e., duty cycle) of radar signals with varying PRF.

Figure 10 shows an example CCDF measurement for a simple pulse and a raised-cosine shaped pulse. The peak-to-average ratio of the simple pulse is equivalent to its duty cycle. In contrast, the shaped pulse shows a more gradual transition in power levels. Note that both the time percentage (y-axis) and power exceeding average power (x-axis) are on logarithmic scales.

Figure 10. This CCDF plot describes the power statistics of two types of pulses, a rectangular pulse (red) and a raised-cosine pulse (purple), by plotting the percentage of time (y-axis) the signal spends above the average power in dB (x-axis). The grey trace is a CCDF reference curve of band-limited Gaussian noise.

¹. Peak-to-average is equal to duty cycle for basic pulses.
Characterizing modulation on a pulse

Because a vector signal analyzer operates on both magnitude and phase, it can measure modulation on a pulse. As an example, this is useful when measuring phase error on a chirped radar signal. Because phase error is directly proportional to the frequency change, the result is an analysis of the chirp's frequency modulation.

The ability to view phase as a function of time is useful when analyzing pulse-coded modulation. Typically, the coding is applied to the pulse by modulating the phase. Figure 11 shows an example of this measurement: notice the 180-degree phase shift in the phase-versus-time display at the upper right.

Performing wideband signal analysis

Until recently, there were very few commercial, off-the-shelf (COTS) solutions for wideband measurements at high frequencies. The typical approach has been to insert a block downconverter into the signal path in front of a digitizer, which could be a signal analyzer, oscilloscope or modular instrument (e.g., PXIe-based VSA). Today, the growing availability of microwave-capable oscilloscopes and signal analyzers with wider analysis bandwidths has opened the door to accurate, repeatable measurements of wideband radar systems in a single instrument.

Enhancing the typical approach

Placing a downconverter in the signal path has two important problems. For one, the linearity of the converter—phase and amplitude—must be properly calibrated to ensure meaningful measurements. The other: the calibration of a block downconverter is often difficult and has limited versatility.

When using this approach, the 89600 VSA software includes a calibration wizard, which is a powerful utility that determines the overall frequency response (amplitude and phase) of the downconverter and digitizer in combination. The wizard uses a Keysight signal generator to provide a stimulus signal, and this can be used to calibrate the wideband IF of the Keysight PXI signal analyzer. It can also be used to provide system-level calibration of a system that uses a PXA as the downconverter and an oscilloscope as the measurement engine.

When facing stringent requirements for dynamic range, focusing solely on the resolution of the digitizer is insufficient. In the case of demodulation measurements, complete system performance—phase linearity, amplitude linearity, noise floor—is more often the limiting factor in measurement performance.
Exploring Keysight’s range of COTS solutions

One way to view the range of readily available solutions is to plot carrier frequency versus spectral bandwidth. Figure 12 includes a variety of instruments from Keysight—signal analyzers and oscilloscopes—as well as downconverters from Virginia Diodes, Inc. (VDI), a Keysight solution partner.

Another factor is the number of simultaneous measurement channels needed to accelerate measurement time. This can be an important consideration when characterizing phased-array radar systems that contain dozens or hundreds of transmit/receive modules. Figure 13 maps analysis bandwidth versus number of channels for a variety of Keysight oscilloscopes and signal analyzers.

The one-channel PXA signal analyzer can measure signals with carrier frequencies up to 50 GHz and offers up to 510 MHz of analysis bandwidth. Similarly, the single-channel UXA can handle carrier frequencies up to 50 GHz and offers a maximum analysis bandwidth of 1 GHz. Note that it is possible to link multiple PXAs or UXAs to create a multi-channel solution.
An S-Series oscilloscope provides two channels with 8 GHz bandwidth or four channels with 4 GHz bandwidth. The V-Series oscilloscope offers two channels with 33 GHz bandwidth or four channels with 16.6 GHz bandwidth. The Z-Series oscilloscope offers two channels with 63 GHz bandwidth or four channels with 32 GHz bandwidth.

An oscilloscope can handle signals with spectral widths nearly up to its bandwidth. One requirement: the carrier plus modulation must be sampled with enough bandwidth to capture both. For example, a signal with a 6 GHz carrier and a 2 GHz wide modulation would fit within the 8 GHz bandwidth of an S-Series oscilloscope and could therefore be evaluated.

Utilizing a wideband signal analyzer

As noted at the beginning of this section, typical wideband measurements have often used a spectrum analyzer as a downconverter and an oscilloscope as a wideband digitizer. Unfortunately, this approach lacks the usability and dynamic range of a signal analyzer that includes a fully integrated wideband digitizer. With the UXA, Keysight has broken the gigahertz barrier, offering the industry’s first signal analyzer with integrated 1 GHz analysis bandwidth (Option N9040B-H1G).

The UXA offers a big step forward in usability by providing factory calibration and operational alignments across the full 1 GHz bandwidth. Integration into the signal analyzer delivers several other benefits: 1 GHz coverage across the full frequency range (3 Hz to 50 GHz); seamless switching between swept, vector and real-time measurements; and easy operation through the streamlined multi-touch user interface (UI). This combination of capabilities enables informative measurements of pulsed signals in less time (Figure 14).

A wideband analyzer also offers benefits in measuring narrower pulsed signals. For example, when measuring pulse rise-times or viewing parameters such as overshoot or droop, the wider analyzer bandwidth offers a faster sample rate, providing more resolution for these measurements.

It’s also important to see multiple emitters in any radar or EW signal environment. These emitters likely will also have some intra-pulse modulation and can occur over a wide bandwidth. The UXA can capture multiple emitters across 1 GHz of bandwidth and calculate statistics over a long time period. In addition, the optional N9067C pulse application automatically detects and analyzes pulses, providing comprehensive results that enable full characterization of captured pulses.

Figure 14. The UXA's wide integrated bandwidth simplifies the measurement of linear FM-modulated pulses.
Using an oscilloscope

For RF designs that need bandwidths greater than 510 MHz or 1 GHz, a digitizing oscilloscope is an important tool that can assume the role of “wideband RF receiver.” In these applications, the Keysight Infiniium S-Series, V-Series and Z-Series oscilloscopes can be used to make a variety of FFT and wideband RF measurements, and the input channels are magnitude-flat, phase-linear and phase-coherent. Analysis capabilities include built-in math programming, and these functions can also incorporate custom, MATLAB-based programs or algorithms.

The high sample rate and deep memory available in Keysight oscilloscopes makes it possible to capture a radar pulse and extract its envelope information and the embedded coding. Many of the capabilities built into today’s scopes also support detailed troubleshooting and analysis. For example, the scope can directly digitize a signal at RF or IF and then process the signal with internal math functions to plot a histogram or calculate parameters such as absolute value (Figure 15).

Oscilloscopes such as the Keysight Infiniium V-Series and Z-Series also have a special digitizing mode called segmented memory that enables you to capture long stretches of time-domain signals at very high sample rates. This is accomplished by creating “virtual” segments within the memory that are filled only when a pulse is present. The result is very high-speed digitizing that conserves memory in between pulses with a low duty cycle, and the intervals between pulses are time-stamped with the same accuracy as that of the high-speed samplers.

The multi-channel, phase-coherent nature of an oscilloscope can also be utilized to study multi-channel emitters. For example, with the 89600 VSA software running on an Infiniium oscilloscope, you can directly access and analyze four phase-coherent channels. In addition, you can chain together multiple oscilloscopes to achieve as many phase-coherent channels as necessary.

In radar systems that have more than 300 MHz of instantaneous bandwidth above 63 GHz, the Keysight N5280A and N5281A downconverters provide four channels of phase-coherent frequency conversion. With frequency width of up to 1.5 GHz (N5280A) and frequency range of up to 50 GHz (N5281A), these devices can downconvert ultra-wideband radar signals into the direct digitizing range of Infiniium series oscilloscopes. When system characterization requires time-correlated measurements between the analog and digital domains, a configuration that includes a Keysight mixed-signal oscilloscope (MSO series) provides an easy, efficient solution.
Conclusion

In the design of radar and EW systems, increasingly complex pulse compression techniques are being deployed to maximize resolution and range, or to reduce the likelihood of detection. To help you identify and measure performance, test solutions must deliver high resolution, excellent dynamic range and wide analysis bandwidth. Keysight's range of COTS solutions includes vector signal analysis software, wideband signal analyzers and multi-channel wideband oscilloscopes. Compared to traditional approaches, these tools provide enhanced ease of use that simplifies the process of producing accurate, repeatable measurement results.

Subsequent application notes in this series will continue to focus on measurements that are relevant to the major sections of the block diagram: transmitter, receiver, duplexer and antenna. As appropriate, we will continue to associate the parameters of the range equation with each block or component.

Related Information

- Application Note: Radar Measurements, publication 5989-7575EN
- Application Note: Infiniium Oscilloscopes Used for Wideband RF Measurements, publication 5992-1242EN
- Application Note: Making Wideband Measurements Using the PXA Signal Analyzer as a Downconverter with Infiniium Oscilloscopes and 89600 VSA Software, publication 5990-9108EN
- Application Note: New Pulse Analysis Techniques for Radar and EW, publication 5992-0782EN
- Application Note: Infiniium Oscilloscopes Used for Wideband RF Measurements, publication 5992-1242EN
- Application Brief: Simplifying the Analysis of Wideband Pulsed Signals, publication 5992-1502EN
- Product Overview: Wideband Vector Signal Analysis Systems, publication 5989-9054EN
- Brochure: X-Series Signal Analyzers, publication 5992-1316EN
- Brochure: 89600 VSA Software, publication 5990-6553EN
- Data Sheet: UXA X-Series Signal Analyzer, Multi-touch, N9040B, publication 5992-0090EN
- Data Sheet: Infiniium S-Series High-Definition Oscilloscopes, publication 5991-3904EN
- Data Sheet: Infiniium V-Series Oscilloscopes, publication 5992-0425EN
- Data Sheet: Infiniium Z-Series Oscilloscopes, publication 5991-3868EN
Appendix: The Radar Range Equation

Part 1 of this series presented a derivation of the radar range equation. As a refresher, here is the simplified version of the equation expressed in log form (dB):

\[
40 \log(R_{\text{max}}) = P_t + 2G + 20 \log \lambda + \sigma + E_i(n) + 204 \text{dBW/Hz} - 10 \log(B_n) - F_n - (S/N) - L_t - L_r - 33 \text{ dB}
\]

Where:
- \( R_{\text{max}} \) = maximum distance in meters
- \( P_t \) = transmit power in dBW
- \( G \) = antenna gain in dB
- \( \lambda \) = wavelength of the radar signal in meters
- \( \sigma \) = RCS of target measured in dB\(\text{sm}\) or dB relative to a square meter
- \( F_n \) = noise figure (noise factor converted to dB)
- \( S/N \) = minimum signal-to-noise ratio required by receiver processing functions to detect the signal in dB

The 33 dB term comes from 10 \( \log(4\pi) \), which can also be written as 30 \( \log(4\pi) \), and the 204 dBW/Hz is from Johnson noise at room temperature. The decibel term for RCS \( (\sigma) \) is expressed in dB\(\text{sm}\) or decibels relative to a one-meter section of a sphere (e.g., one with cross section of a square meter), which is the standard target for RCS measurements. For multiple-antenna radars, the maximum range grows in proportion to the number of elements, assuming equal performance from each one.

Figure A1 shows an expanded view of the transmitter and receiver sections of a typical block diagram. It shows a hybrid analog/digital design that enables many of the latest techniques. The callouts indicate the location of key variables within the simplified radar equation.

![Figure A1. The variables in the radar range equation relate directly to key elements of this expanded block diagram.](image-url)

1. A Framework for Understanding: Deriving the Radar Range Equation, Keysight publication 5992-1386EN

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For more information on Keysight Technologies’ products, applications or services, please contact your local Keysight office. The complete list is available at: [www.keysight.com/find/contactus](http://www.keysight.com/find/contactus)