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 the 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.1

Parts 2 and 3 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. Part 4 examined the use of vector signal analysis (VSA) and wideband instruments—via signal analyzers and oscilloscopes—to measure frequency, phase, and more, in today’s increasingly complex radar signals. Part 5 provided a closer look at the testing, analysis and optimization of the components and subassemblies used in today’s radar systems. In Part 6 the focus was on the best ways to test antennas and antenna arrays, surveying the narrowband and wideband measurements that can be made with vector network analyzers and multi-channel digitizer-based systems.

Continuing our discussion of practical test methods, we’ll now explore three ways to assess and improve radar system performance: noise figure, time sidelobe level and phase noise. Noise figure has a direct effect on receiver performance; time sidelobe level affects spatial resolution, dynamic range, and more; and phase noise causes sidebands that reduce signal-to-noise ratio. This note presents a variety of ways to measure and characterize each of these parameters.

The radar series
This application note is the seventh 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.

1. The appendix at the end of this application note presents the range equation and the system block diagram.
Using Noise Figure to Optimize Receiver Performance

As captured in the derivation of the radar range equation, the threshold of the radar receiver depends on four factors: noise figure (NF); Boltzmann’s constant multiplied by temperature (kT); the noise bandwidth of the system (Bn); and the signal-to-noise ratio (SNR, or S/N in the derivation).\(^1\) The kT term is the familiar –204 dBW/Hz, essentially a constant with little opportunity for improvement. The radar design itself determines the system bandwidth, and the SNR cannot be improved once the signal reaches the receiver. This puts the focus on NF as a key factor in the optimization of the receiver.

NF is a figure of merit for all RF systems and, as such, is used as a key performance parameter. A low noise figure provides improved SNR in an analog receiver, and it reduces the bit error ratio in a digital receiver. As a parameter in a communication link budget, lower NF in a receiver enables use of smaller antennas or lower transmitter power for the same system performance.

Examining another essential equation

Delving into the details of NF, it is useful to consider Friis’s formula for noise factor. To clarify terms, noise factor (F) is a unitless value that is the ratio of the S/N at the input over the S/N at the output of each component or stage. Noise figure is 10 log (F) and is expressed in decibels.

Friis’s formula calculates total noise factor as a sum of the individual noise factors of successive components in a system:

\[
F_{\text{Total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}
\]

Here, \(F_n\) is the noise factor of each successive element. One aspect is striking: the first component in the chain typically has the greatest effect on \(F_{\text{Total}}\) (and therefore NF) because all of the other contributors are reduced by the gain of the preceding elements.

In a radar system, that first component is typically an amplifier. From this, one might be inclined to believe that improvements in NF—and therefore system performance—can be achieved at little cost. For example, today’s low-noise amplifiers can deliver very low noise figures, and when carefully designed into the receiver architecture, the system noise figure penalty would be minimal. Consequently, reducing receiver noise by 3 dB would seem more economical than increasing transmitter power by the same amount (almost always a high-cost endeavor).

Reality is not quite that simple. The receiver must also provide adequate gain, phase stability, amplitude stability, dynamic range and reliability as well as fast recovery from overload and jamming. In addition, it must also include protection against overload or saturation and burnout from nearby transmitters. As a result, many radar systems do not utilize low-noise RF amplifiers in the receiver frontend. Instead, these use a mixer as the first stage of the receiver.

\(^1\) A simplified version of the equation is in the Appendix at the end of this note, and the full derivation is presented in A Framework for Understanding: Deriving the Radar Range Equation, publication 5992-1386EN.
Measuring noise figure

Even with the preceding reality check, NF is a critical metric that needs to be optimized within the full set of constraints. Today, two methods are commonly used to measure noise figure: the Y-factor or “hot/cold source” method and the direct noise or “cold source” method. The remainder of this section presents both techniques and the instruments used to make the associated NF measurements.

Applying the Y-factor method

This tried-and-true technique is not the simplest, but it is the oldest and most prevalent. The essential element is a noise source that is placed at the input of the device under test (DUT). When the noise source is turned on (“hot source”) it generates excess noise compared to a passive termination at room temperature. Although the noise source is not actually hot in a physical sense, its excess noise can be described by an equivalent temperature that would produce the same amount of noise as a hypothetical termination at that same temperature. When the noise source is turned off (“cold source”) it emulates the electrical characteristics that would be present with the room-temperature passive termination.

Noise power measurements are made at each of the two termination states, “hot” and “cold” (i.e., noise source on and off). The ratio of these two powers is called the Y factor.

The other important element in the NF calculation is the excess noise ratio (ENR). This value is part of the calibration data provided with the noise source. In practice, the noise source is an external measurement accessory that can be used with a dedicated noise-figure analyzer or with a spectrum analyzer, signal analyzer or network analyzer configured with an NF measurement application. ENR is defined as follows:

\[ \text{ENR} = \frac{T_h - T_c}{T_0} \]

Where:

- \( T_h \) = noise temperature of the source in “hot” or “on” mode
- \( T_c \) = noise temperature of the source in “cold” or “off” mode
- \( T_0 \) = the reference temperature of 290 K
Applying the Y-factor method (continued)

The Y-factor value and the ENR are used to calculate the overall noise factor for the system:

\[ F_{sys} = \frac{ENR}{Y-1} \]

Note that this equation yields the noise factor for the entire system—including the measurement instruments. When the gain of the DUT is high, the noise factor for the system may be used to approximate the noise factor of the DUT. If this is not the case, then a calibration must be performed to remove the noise-factor effects of the instrumentation. This requires that the measurement system first measure its own noise factor and gain and then calculate out its own contribution using Friis's equation.\(^1\)

The Y-factor method is the technique used in many dedicated noise-figure analyzers and in spectrum or signal analyzers that offer a built-in noise figure measurement application. Examples include the Keysight NFA Series noise figure analyzers (see sidebar) as well as the UXA, PXA and MXA X-Series signal analyzers when configured with the N9069C noise figure measurement application with multi-touch user interface. The NFA and the measurement apps simplify NF characterization by automating the measurement process and the associated calculations, and by supporting the SNS Series noise sources.

In practice, the Y-factor process has two major steps: a calibration, which is made with the noise source but without the DUT; and the measurement, which is performed with the DUT connected between the noise source and the analyzer input (Figure 1).

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1. For a detailed description, please see the Keysight Application Note Noise Figure Measurement Accuracy – The Y-Factor Method, publication 5952-3706E.
Using the cold-source method

With the cold-source or direct-noise measurement technique, only one noise-power measurement is made at the output of the DUT, and the input is terminated with a source impedance that is at room temperature. This method also requires an independent measurement of DUT gain.

Consequently, this technique is well suited to the capabilities of a vector network analyzer (VNA) because it can make very accurate error-corrected measurements of gain. However, the VNA must be capable of making measurements with noise-based and continuous-wave (CW) signals. As an example, the Keysight PNA-X microwave network can be configured to make NF measurements.

Using a VNA has several advantages. One is the ability to make other important measurements through the same set of connections to the DUT. For example, the PNA-X can measure NF, gain, intermodulation distortion (IMD), S-parameters, and X-parameters. In addition, the PNA-X can apply error-correction techniques that compensate for imperfect system-source match using an electronic calibration (ECal) module as an impedance tuner. With these advanced features and very good input sensitivity, the PNA-X is Keysight’s highest performing NF solution.

Selecting the best NF measurement solution

The best solution depends on factors such as the measurement objectives, the relative NF and gain of the DUT, and the available equipment budget.

In general, a signal analyzer-based solution has the lowest incremental cost and provides the versatility to perform measurements such as transient spectrum, IMD and spurious. However, a signal analyzer will generally have greater measurement uncertainty than a dedicated NF analyzer because most have an inherently higher noise figure. If the DUT has high gain, however, the noise figure of the measuring analyzer will have minimal effect on measurement uncertainty and a signal analyzer-based solution may be the best choice.

A dedicated noise figure analyzer such as the Keysight NFA Series is designed to provide low inherent noise figure and low measurement uncertainty. The NFA may be the best alternative when a high level of measurement accuracy is required but the extra performance and cost of an NF-capable VNA are not.

As noted earlier, implementing the cold-source solution with the PNA-X offers the highest level of performance available from Keysight. The graph in Figure 2 compares example accuracies from the Y-factor method (with a traditional NF solution) and that of the cold-source method (using the PNA-X with source correction and vector calibrations). Results are shown with and without a switch in the Y-factor solution (red and yellow traces, respectively).

Figure 2. An NF solution based on the PNA-X vector network analyzer provides the best measurement uncertainty due to its high sensitivity and ability to use vector error corrections to subtract impedance mismatch and other errors.
Using Time Sidelobe Level to Predict System Performance

In a pulsed radar system, the use of modulation to achieve pulse compression provides enhanced spatial resolution as well as extended range for a given level of output power. As an example, a system that uses linear frequency-modulated (LFM) chirp pulses experiences changes in spatial resolution due to variations in pulse width, chirp bandwidth and chirp linearity.

Unfortunately, traditional RF pulse measurements are poor predictors of performance in systems that use pulse compression. One alternative is a technique called the time sidelobe level (SLL) measurement. This method distills a large number of potential signal impairments down to a simple metric that can be used to determine if the performance of the radar under test—spatial resolution, dynamic range, and more—will fit the intended application.

Understanding time sidelobes

Time sidelobes are the result of return-pulse energy that resides outside the pulse bandwidth. In the time domain, this is indicated by a spreading in time (i.e., range) of the return pulse.

When pulse-compression techniques are used, any anomaly within the transmit or receive chain can contribute to the time SLL. If the transmitter produces a less-than-ideal pulse, time sidelobes will appear when the return signal is passed through the correlation filter and compressed. If any RF or IF mismatches occur in the receive path, or if the correlation filter is not properly optimized, then the time sidelobe level will increase.

Current-generation systems typically implement correlation filters using DSP rather than analog technology. As a result, the waveform of the compressed pulse is mathematically deterministic and repeatable—and this means it can be easily optimized through simulation.
Applying the time sidelobe method

The detector in a radar receiver correlates the transmitted signal with echoes and noise received over time. When the received signal matches the transmitted signal, a correlation peak occurs and target detection is marked at that time.

An ideal correlation peak would be infinitely narrow, have a value of one, and be surrounded by noise-like sidelobe levels. At the other extreme, the correlation between a pure signal and pure noise is zero.

System impairments ranging from perfectly generated compressed pulses to internal reflections from filters can cause correlation sidelobe levels that are well above the noise floor (Figure 3). It is difficult to judge the effect of such impairments on a compressed pulse; however, the SLL technique provides quantitative measurements of transmitted pulse shapes and received signals.

An accurate measurement of SLL requires a filter that is perfectly correlated to the desired pulse shape. The first step is to build an ideal waveform that represents the desired compressed pulse: the essential parameters are bandwidth, pulse wide, and chirp or modulation characteristics. This type of modeling can performed using software such as SystemVue or Signal Studio from Keysight or MATLAB from The MathWorks. The ideal, mathematically generated representation of the compressed pulse (i.e., repeatable with no impairments added) can be stored in memory and recalled later to correlate measured waveforms and enable calculations of SLL.

When modeled in software, the FM chirp pulse waveform for the SLL measurement and calculation should be designed to imitate the operational waveform of the radar system. For systems that feature multiple operating modes, corresponding pulse waveforms should be created and multiple SLL measurements performed.

When measuring pulse waveforms that will be correlated for SLL calculations, instrument calibration and waveform correction are also important factors. The reason: the wideband nature of most compressed pulses gives rise to potential inaccuracies in both phase and amplitude versus frequency within the measurement instrument. Two things will help prevent these inaccuracies from affecting SLL measurements: a measuring receiver with built-in equalization; and signal-generation software or hardware that has pre-distortion or real-time correction capabilities.
Weighting the output signal

Amplitude weighting of the output signal is generally used to reduce the time sidelobes to acceptable levels. Unfortunately, signal weighting can cause a decrease in SNR.

A variety of well-understood windowing functions can be used to provide the necessary weighting. Table 1 shows the suppression levels and SNR changes associated with five commonly used windows. Figure 4 provides a graphical representation of the Hamming window function in the time domain (left) and its corresponding frequency response (right).

Table 1. Five of the most popular windowing functions have well-understood effects on the output signal.

<table>
<thead>
<tr>
<th>Weighting function</th>
<th>Peak sidelobe level (dB)</th>
<th>SNR loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>–13.2</td>
<td>0</td>
</tr>
<tr>
<td>Hamming</td>
<td>–42.8</td>
<td>1.34</td>
</tr>
<tr>
<td>Hann</td>
<td>–32.0</td>
<td>1.40</td>
</tr>
<tr>
<td>Blackman</td>
<td>–58.0</td>
<td>2.37</td>
</tr>
<tr>
<td>Blackman-Harris (three-term)</td>
<td>–67.0</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Figure 4. Viewing the Hamming window function in the time domain (left) and frequency domain (right) illustrates the relationship between weighting and filtering.
Making time sidelobe measurements

The measurement process starts with detailed knowledge of the ideal compressed pulse, as described above. The next requirement is a suitable wideband instrument—signal analyzer, oscilloscope, or logic analyzer—equipped with VSA software. Examples include Keysight UXA, PXA and MXA signal analyzers; Keysight Infiniium V-Series and Z-Series oscilloscopes; and Keysight 16900 logic analyzers. These are all compatible with the 89600 VSA software, which is capable of implementing the mathematics needed to perform and display the time sidelobe measurement.

The instrument is used to acquire and digitize the measured waveform. The VSA software can be configured to use the time cross-correlation identity, an approach that is much less cumbersome than performing a time-domain cross correlation between data files. Using the identity makes it possible to take the measured frequency data and multiply it by the ideal pulse created in software. Before making the measurement, the ideal pulse must be imported into the VSA software and transformed into its file format; the imported file and the measured data must also have the same sample rate.

Once these operations are complete, the measurement can be performed. Within the VSA software, the measured frequency data (with real and imaginary values) is multiplied by the ideal pulse. The product is processed with the inverse fast Fourier transform (IFFT) to compute the time cross-correlation needed for the SLL measurement.

Applying the results

SLL offers an effective go/no-go assessment of a radar system’s field performance because the time from the main correlation lobe to the minimum-discernable sidelobe is directly related to the minimum spatial resolution. SLL also provides assurance that no other internally generated sidelobe will affect the overall performance of the radar.

The correlation function is also directly tied to the probability of target detection. From this, a sufficiently low SLL value ensures that the radar hardware under test will have sufficient dynamic range (i.e., sensitivity) to detect weak target-return signals.

At the component level, time sidelobe testing can help identify problems in analog microwave devices. Rather than sifting through a vast number of measurements, time sidelobe levels can be evaluated for impairments at any point within the system—and this makes it possible to determine if the radar pulses can deliver the required level of performance. In addition, the ability to assess pulse quality virtually anywhere between the transmitter and the receiver detector makes SLL a valuable diagnostic tool. For example, one quick SLL measurement can pinpoint either the transmitter or receiver as the source of a problem. Subsequent measurements can quickly isolate signal impairments that may cause radar performance to fall short of system requirements.
Characterizing Phase Noise and Improving SNR

Phase noise, amplitude modulation (AM) noise and spurious signals ("spurs") have significant implications for the performance of a radar system. For example, phase noise and AM noise in the receiver will decrease the SNR. Noise on the transmit signal may mask low-level Doppler target signals in the presence of clutter. Spurs created by unwanted discrete AM or phase modulation (PM) oscillations can produce false targets.

In high-performance systems, phase noise is especially troublesome. This type of noise is the result of random fluctuations in phase caused by instabilities in the time domain. In the time domain, this effect is called jitter. In the frequency domain, this instability manifests itself as sidebands that spread power to adjacent frequencies. If the phase variations are random or random-like, then the sidebands will slope downward from the signal (Figure 4). Phase variations in the signal due to specific non-random oscillations will appear as discrete spectral components or spurs.

![Figure 5. Phase noise causes sidebands that spread power into adjacent frequencies, reducing the system's SNR.](image)

In a radar system, good phase noise performance is crucial in stable local oscillators (STALOs) and coherent oscillators (COHOs) because the signals they produce are at the heart of the system. Any phase impairments on these signals will be multiplied as they are upconverted to the higher frequencies, and this will cause a reduction in SNR.

The presence of phase noise and AM noise on the transmit signal can have an especially negative effect on moving target indicator (MTI) radars. These work on the principle that the return from a moving target will be shifted in frequency by Doppler effects. Typically, the target returns are small when compared to clutter caused by stationary objects (e.g., the ground, mountainsides, etc.). Because clutter and target returns are at different frequencies, the clutter is filtered out. Unfortunately, a typical clutter-canceling filter cannot remove any noise on the clutter.

1. AM noise also spreads power to adjacent frequencies, but this effect tends to be dominant at wide frequency offsets; phase noise dominates at closer-in frequency offsets.
Measuring phase noise

A variety of solutions are available for the measurement and characterization of phase noise. As is often the case, the best choice will depend on performance requirements and cost constraints.

Instruments capable of measuring phase noise include signal analyzers, signal-source analyzers and purpose-built phase noise test systems. The lowest-cost solution is often a signal analyzer equipped with a phase noise measurement application that integrates the required functionality into the analyzer interface. A signal-source analyzer (SSA) such as the Keysight E5052B SSA provides high performance and greater efficiency when measuring oscillators and phase-locked loops (PLLs). While a dedicated phase noise test system is often the most complex and costly alternative, it offers the best performance and the greatest flexibility. The dedicated system may be the only way to measure pulsed and residual phase noise. Residual and pulsed phased noise measurements are especially important in Doppler radar systems.

Making a direct spectrum measurement of phase noise

Phase noise measurements made with a signal analyzer require direct analysis of the spectrum and an examination of the levels of the phase-noise sidebands. The range of phase noise offsets and levels that can be measured depend on the available resolution bandwidth (RBW) settings and the phase noise of the analyzer itself.

A direct measurement of phase noise can be performed manually with any signal analyzer through its marker functions; however, the process can become tedious and time-consuming.\(^1\) As a convenience, most signal analyzers include an automated noise-marker function. The phase noise marker result is the combination of phase noise and AM noise; phase noise is often the dominant contributor.

The simpler approach is a built-in measurement application that automates the process and displays the results in the standard format (e.g., log magnitude normalized to dBc/Hz versus log frequency). Figure 6 shows an example phase noise measurement made with a Keysight PXA X-Series signal analyzer and a phase noise measurement application (N9068A/B) that works with CW signals. The PXA is able to measure offsets as close as 100 Hz, and its specified phase noise performance is \(-134 \text{ dBc/Hz} \) (10 kHz offset, 1 GHz, DDS LO).

![Figure 6. With its phase noise measurement application, the PXA X-Series signal analyzer displays measurement results as a function of offset frequency from the carrier signal.](image)

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1. For more information, see Keysight Application Note 1303, *Spectrum Analyzer Measurements and Noise*, publication 5966-4008E.
Measuring phase noise using a phase detector

To achieve the best sensitivity and accuracy, most dedicated phase noise and signal-source analyzers are based on a phase detector (Figure 7). Most phase detectors are balanced mixers that require RF and reference signals. When those signals are in quadrature and are applied to the balanced mixer, the IF output provides a measure of the instantaneous phase difference between the two signals.

\[
\Delta V_{\text{out}} = K \phi \Delta \phi_{\text{in}} \quad \text{for small differences in phase}
\]

Figure 7. With a phase detector, the measurement compares the test signal to a phase-locked reference signal and variations in phase to produce an output voltage that is processed to determine the phase noise result.

In most implementations, the quadrature phase relationship is maintained using a narrowband PLL. The instantaneous phase difference is represented by voltage changes around zero volts. Using the double-balanced mixer in quadrature suppresses amplitude noise while measuring phase noise. The noise voltage (i.e., the IF output) is then amplified and spectrally processed to determine noise and spurious signals as a function of offset frequency.\(^1\)

Measurement sensitivity is limited by the phase noise of the reference oscillator or any microwave downconverter used in the test setup. Recent-generation phase noise analyzers use advanced cross-correlation techniques to improve measurement performance beyond that of the reference oscillator and downconverter. This is especially useful when measuring voltage-controlled oscillators (VCOs), which tend to have very low far-from-carrier phase noise characteristics.

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1. Phase noise measurement systems also typically include a separate AM detector to measure amplitude noise and spurious signals as function of offset frequency. The AM-detector implementation may be diode- or mixer-based.
Measuring phase noise using an SSA

The Keysight E5052B SSA is designed for rapid, efficient execution of cross-correlation techniques, which can reduce the effects of noise generated by analyzer’s internal reference sources. To further ensure a very high level of performance at a reasonable price, the analyzer includes its own reference oscillators.

Figure 8 shows example phase noise measurements made with and without cross correlation in the SSA. While the 10-times cross correlation result exhibits a 5 dB improvement, the tradeoff is a test time that is 10 times longer than that of the measurement made without correlation.

In addition to phase noise, the DSP-based SSA also provides many other functions that are useful in the testing of radar oscillators. Because it samples the incoming signal, the SSA includes the ability to analyze amplitude, frequency and phase as a function of time. It can also perform transient analysis by detecting frequency changes or anomalies, and these can be used to trigger and capture transient events such as the "phase hits" shown in Figure 9.

Figure 9. The Keysight SSA includes time-domain analysis and advanced functions such as frequency-boundary triggering that enhance analysis of transient events.
Measuring phase noise with a dedicated test system

Compared to the preceding approaches, a system such as the Keysight E5505A phase noise measurement solution offers greater flexibility and performance. Its capabilities are especially useful in radar development because it can perform pulsed absolute and residual (or additive) phase noise measurements. It is also able to measure over a wide range of offsets, from 0.1 Hz to 100 MHz.

An E5505A system has five main elements: phase noise test set with detector and PLL; low-noise downconverter; external reference oscillator; digitizer-based signal analyzer, swept spectrum analyzer, or both; and PC-based software.

With its modular architecture, different hardware components can be used to satisfy a variety of measurement requirements. Optional capabilities include absolute or residual measurements, CW or pulsed phase noise and spurious measurements, and AM noise measurements. The E5505A is also effective in automated-test environments for two reasons: it is fully programmable and it can share components such as the reference source and signal analyzer for other tests.

Conclusion

Noise figure, time SLL and phase noise are crucial characteristics that can have a profound effect on the performance of every radar system. These measurements can be performed efficiently and accurately using purpose-built solutions or general-purpose analyzers equipped with specialized measurement applications. Ultimately, the ability to measure, analyze and understand these parameters in a radar system enables improvements in spatial resolution, dynamic range, SNR, and more.

The final application note in this series will wrap up our 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: Noise Figure Measurement Accuracy – The Y-Factor Method, publication 5952-3706E
- Application Note: Spectrum Analyzer Measurements and Noise, publication 5966-4008E
- Application Note: High-Accuracy Noise Figure Measurements Using the PNA-X Series Network Analyzer, publication 5990-5800EN
- Application Note: Optimizing On-Wafer Noise Figure Measurements to 67 GHz, publication 5991-2524EN
- Data Sheet: NFA X-Series Noise Figure Analyzer, Multi-touch, publication 5992-1270EN
- Brochure: X-Series Signal Analyzers, publication 5992-1316EN
- Technical Overview: Noise Figure X-Series Measurement App, Multi-touch (N9069C), publication 5992-0851EN
- Technical Overview: N4000A, N4001A, N4002A SNS Series Noise Sources, publication 5988-0081EN
- Brochure: PNA-X Series Microwave Network Analyzers, publication 5990-4592EN (note: see pages 12-15 for information about Options 028 and 029, noise figure)
- Application Note: Pulsed Carrier Phase Noise Measurements, publication 5968-2081E
- Technical Overview: Phase Noise X-Series Measurement App, Multi-touch (N9068C), publication 5992-0896EN
- Data Sheet: E5052B Signal Source Analyzer, publication 5989-6388EN
- Data Sheet: E5500 Series Phase Noise Measurement Solutions, publication 5989-0851EN

Previous Application Notes in this Series

- Part 1, A Framework for Understanding: Deriving the Radar Range Equation, publication 5992-1386EN
- Part 2, Defining the Pulsed Radar Signal and the Essential Measurements of Signal Power, publication 5992-1484EN
- Part 3, Measuring the Characteristics of Pulsed Radar Signals, publication 5992-1521EN
- Part 4, Measuring Radar Signals with Vector Signal Analyzers and Wideband Instruments, publication 5992-1580EN
- Part 5, Characterizing Radar Components and Subassemblies, publication 5992-1712EN
- Part 6, Surveying the Best Ways to Test Antennas and Antenna Arrays, publication 5992-1886EN
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):

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

Where:
- \( R_{\text{max}} \) = maximum distance in meters
- \( P_t \) = transmit power in dBW
- \( G \) = antenna gain in dB
- \( l \) = wavelength of the radar signal in meters
- \( s \) = RCS of target measured in \( \text{dB}_{\text{sm}} \) 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 (s) is expressed in \( \text{dB}_{\text{sm}} \) 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.
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