Creating Multi-Emitter Scenarios for Radar and Electronic Warfare (EW) Testing

Part 8
The Radar Series, Part 8

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 frequency, timing, power and spectrum of pulsed signals. Part 4 examined the use of vector signal analysis (VSA) with wideband 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 radar components and subassemblies. 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. Part 7 continued our discussion of practical test methods, focusing on three ways to assess and improve radar system performance: noise figure, time sidelobe level and phase noise.

To conclude the series, we turn to multi-emitter testing of radar and electronic warfare (EW) systems. Realistic testing of these systems depends on the generation of signals that accurately simulate multi-emitter environments consisting of thousands of emitters and millions of pulses per second, all arriving from multiple directions. Traditionally, this has required the use of large, complex systems not readily available to R&D engineers. New technology built into commercial, off-the-shelf (COTS) “agile signal generators” provides an integrated, lower-cost solution that fits on an engineer’s test bench. This technology also enables developers to generate increasingly complex simulations that get closer to reality and, ultimately, provide deeper confidence in EW system performance.

The radar series

This application note is the eighth and final installment 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.
Outlining the Most Common Direction-Finding Methods

An EW receiver parameterizes every incoming RF pulse from all inbound threats. The result is a set of pulse descriptor words (PDWs) that contain essential information such as time of arrival, frequency, angle of arrival (AoA), pulse width, and modulation on pulse (MOP).

EW receivers use direction-finding (DF) methods to sort radar threats into different categories. AoA and frequency are primary parameters because they change more slowly than other attributes. The rate of change is on the order of hundreds of milliseconds to several seconds depending on the velocities and ranges of the platforms carrying the threat radars and EW receivers. Once the threats are sorted and tracked, they are presented to the pilot on a display according to type and relative bearing.

Three DF techniques are most common: amplitude comparison, time difference of arrival (TDOA), and interferometry (i.e., phase difference). We’ll take a brief look at each; however, interferometry is noteworthy because it lends itself to effective simulation of AoA scenarios in a lab setting.

Amplitude comparison

This is the most common DF method, often used in radar-warning receivers designed many years ago. The amplitude-comparison monopulse technique relies on the signal ratio $P_2/P_1$ from two displaced antenna patterns originating from one phase center and overlapping in the far field.

As shown in Figure 1, the antenna boresights are oriented 90 degrees apart to ensure there will be a measurable power difference in each channel when the same pulse is incident on both patterns. The power difference gives a meaningful result in the arctangent of $P_2/P_1$, which yields the AoA relative to the boresight of antenna 1.

This method provides DF accuracy of 10 to 15 degrees because the measured cross-channel power levels will vary due to aircraft motion and amplitude attenuation by the aircraft (i.e., “shadowing”). This level of inaccuracy is deemed acceptable because resolution is generally more important than accuracy when using AoA. Resolution is the ability to distinguish co-located threats such as different radars within a single surface-to-air missile (SAM) site.

![Figure 1](image1.png)
Time difference of arrival (TDOA)

TDOA derives AoA based on the difference between the arrival times of one waveform at two antennas. Knowing the signal travels at the speed of light ($c$) and the two antennas are separated by a fixed distance ($d$), we can take the arcsine of the ratio ($\text{TDOA} \times c)/d$ to determine the angle of arrival (Figure 2).

One note: While the result is not directly related to wavelength, it does require precise knowledge of the delays that occur within each receiver channel, and these vary with frequency.

Figure 2. The arcsine of the ratio ($\text{TDOA} \times c)/d$ provides the AoA value. The value $S$ is the difference in path length for the same pulse incident on antennas 1 and 2.
Interferometry

As with TDOA, interferometry uses the arcsine of a ratio. In this case, the EW receiver is measuring the phase difference between antenna apertures, \( \phi \) (\( \phi \)). The EW receiver also measures the wavelength, lambda (\( \lambda \)), using an instantaneous frequency measurement (IFM) receiver that determines the frequency of a pulse within a few megahertz. The distance between antenna apertures (\( d \)) is known with a specific uncertainty. Thus, the resulting equation for AoA is \( \arcsin \left( \frac{\phi \lambda}{-2\pi d} \right) \).

In general, a longer baseline (i.e., the distance between apertures) is used because this provides better accuracy and less sensitivity to uncertainty. At long distances, however, the phase difference will wrap around, leaving some ambiguity in the measurement. This is why most modern systems use more than one baseline and will use a shorter baseline to resolve the ambiguities.

Figure 3. The arcsine of the ratio \( \frac{\phi \lambda}{-2\pi d} \) provides the AoA value. As in TDOA, \( S \) is the difference in path length for the same pulse incident on antennas 1 and 2.
Accurately Simulating Multi-Emitter Environments

Whichever DF method is used, the EW system must operate in a spectral environment containing tens to hundreds of radar threats that produce millions of radar pulses per second. Figure 4 shows a general overview of a spectral environment crowded with radar emitters.

Simulating this environment is a major challenge, especially in the design phase. In EW design, the density and frequency range of the environment make it impractical to simulate multiple emitters using a single conventional signal source (e.g., one based on fractional-N synthesis), or even a small number of such sources, because they cannot change settings quickly enough. Creating density requires the ability to simulate many emitters with a single source. When required to produce even greater signal density, or to simulate AoA, the solution is to utilize and synchronize multiple sources, each of which is capable of simulating many emitters.

The ability to simulate multiple emitters at multiple frequencies depends on a few key attributes: pulse repetition frequency (PRF) and duty cycle; the number of emitters; and the ability of the source to rapidly and coherently switch frequency, amplitude and modulation settings. When simulating multiple emitters, pulse collisions are a limiting factor in the use of a single signal generator. The percentage of pulse collisions increases with the number of emitters and the use of higher PRFs.
A source’s agility is the main factor in its ability to simulate multiple emitters. For example, the settling time for changes in frequency or amplitude—whichever is greater—determines the transition time between playing one PDW and the next. Total pulse density for a single source is limited by the sum of that transition time and the width (in time) of the transmitted pulses (Figure 5). This “lockout period” should be as short as possible, and therefore the source settling times should also be as brief as possible.

![Diagram](image)

Figure 5. During the lockout period, the source is not available to simulate a different threat: if it is switching, it can’t play a pulse; if it is playing a pulse, it can’t switch.

To simulate high pulse density and allow for the possibility of some overlapping pulses, it may be necessary to combine multiple sources. As more sources are added to the test configuration, pulse density should scale easily and seamlessly until ultimately reaching the desired tradeoff between realism and cost. Making this work requires precise synchronization between all the connected sources.
Comparing the Available Architectures

Simulation of EW environments is a special and demanding case of traditional RF and microwave signal generation. To enable simulation of AoA, the process requires the ability to synchronize multiple signal sources and produce complex pulse environments through tight control of timing, amplitude and phase. In addition, threats often use modulation-on-pulse (MOP) such as linear frequency modulation (LFM) chirps and phase coding, and certain types of MOP are increasingly wideband (e.g., LFM and nonlinear FM or NLFM). Because real-world scenarios can last from minutes to hours, the signal generator should be able to directly understand and play PDWs streamed in real time via LAN or low-voltage differential signaling (LVDS), or played back from internal or external storage media.

Assessing analog synthesis

Unfortunately, these requirements are often at odds with typical signal-generator architectures and topologies. For indirect analog synthesis, a phase-locked loop (PLL) architecture can provide low phase noise, accurate amplitude and high dynamic range (e.g., low spurious and intermodulation distortion) when locked to a stable frequency reference. Unfortunately, the PLL approach lacks the agility needed for EW simulation because various elements in the signal-generation chain use filtering mechanisms that create delays.

Direct analog synthesis uses several frequency references (perhaps derived from a single crystal reference) that are combined through math operations—multiplication, division, addition or subtraction—to create the desired output frequency. Although the arithmetic operations and their configuration can be switched rapidly to enable frequency agility, this approach is more complicated and costly than indirect synthesis and generally cannot provide phase-coherent or phase-continuous output signals.

Getting closer to reality

Both approaches to analog synthesis have limitations in the creation of complex multi-emitter environments. A digital alternative called direct digital synthesis (DDS) uses high-speed DACs to provide virtually instantaneous changes in frequency and amplitude.

Despite the theoretical advantages, typical DDS-based solutions have fallen short in terms of bandwidth or signal quality, especially spurious-free dynamic range (SFDR), because DACs with higher sample rates have generally produced lower-quality signals.

Implementing DDS with a higher-quality DAC provides significant advantages in EW applications, whether the need is for an agile LO or realistic simulations of the signal environment:

- High agility in frequency, amplitude and phase
- Creation of MOP in the DDS
- Phase repeatability to simulate multiple emitters with different phases using one signal generator
- Multi-instrument coherence by sharing the DAC clock
- Excellent SFDR
In addition, linking an FPGA to the DDS provides the ability to directly play streamed PDWs and frequency-modulated continuous-wave (FMCW) waveforms for scenarios lasting an infinite length of time. The core of this DDS architecture is a unique high-speed DAC that can produce wideband MOP and FMCW signals with excellent purity (Figure 6).

By incorporating these capabilities, the Keysight UXG agile signal generator brings extensive and realistic testing to the earlier stages of EW system design and test. As a result, multi-emitter testing with AoA can be done using benchtop instruments that scale in channel and port count. This enables engineers to optimize and verify system performance while avoiding the expense, potential delays, and poor repeatability of anechoic or flight testing.

This performance is delivered with tremendous agility through solid-state switches that provide fast switching over a wide power range without distorting pulsed signals. In-band switching speed is 50 to 100 ns, and switching across bands is 180 ns. In addition, frequency changes are phase-coherent, meeting a crucial need for realistic EW simulation (Figure 7).

Off the shelf, the UXG is a powerful building block when used as either a dependable LO or a scalable threat simulator. By blurring the lines between analog and vector technologies, the UXG enables you to accelerate the integration of new intelligence into up-to-date signal scenarios.

- Update frequency, amplitude, and phase in as little as 180 ns
- Generate wide chirps that are 10 to 25 percent of carrier frequency
- Create pulses as narrow as 10 ns with 3 ns rise/fall times and 90 dB on/off ratio
- Increase the reliability of your test system: the UXG is a slide-in replacement for legacy fast-switching sources
- Add complexity and custom IQ modulation on a pulse by pulse basis with the UXG Vector Adapter.
The UXG also includes a solid-state attenuator that provides 80 to 90 dB of agile amplitude range, which is essential when simulating AoA and antenna scanning. Combining that amplitude range with an SFDR of approximately 70 dBc, the UXG provides significantly better performance than either a traditional microwave vector signal generator (VSG) or an arbitrary waveform generator (AWG). In comparison, VSGs and AWGs are typically limited to 50 dB of amplitude range, depending on the resolution and spur performance of the instrument’s DAC.

<table>
<thead>
<tr>
<th></th>
<th>I/Q waveform</th>
<th>PDW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size per unit</td>
<td>4 bytes per sample</td>
<td>8 bytes per PDW</td>
</tr>
<tr>
<td>Rate</td>
<td>12 GSa/s</td>
<td>100,000 PDW/s</td>
</tr>
<tr>
<td>Total memory</td>
<td>(4 * 12x10^9 * 5) = 240 GB</td>
<td>(8 * 10^6 * 5) = 4 MB</td>
</tr>
</tbody>
</table>

### Adding More Realism to Threat Scenarios

While it’s essential to create emitters with the desired fidelity and density, it’s also important to match the geometry and kinematics of real-world EW scenarios. This is important in part because some of the latest standoff jamming systems use active electronically scanned array (AESA) technology capable of precise beam forming to minimize the loss of jamming power due to beam spreading towards a threat.

### Creating simulations with discrete components

In the past, simulations were typically created using a separate component for each emulator function: signal generation, modulation, pulsing, attenuation, amplification and phase shifting. The same PDW could be sent to each functional component to create outputs on a pulse-to-pulse basis.

With this approach, time synchronization poses significant challenges in system configuration and operation. For example, a wide variety of settling times and latencies must be fully characterized to minimize lockout periods and thereby fully optimize pulse density.

These systems can be scaled to create multiple coordinated channels. However, they require a tremendous amount of equipment, resulting in a large physical footprint and a high price tag. The more cost-effective alternative is an integrated signal generator based on DDS technology.

### Representing signals: PDWs versus I/Q

AWGs and VSGs commonly use in-phase/quadrature (I/Q) representation because it is an efficient way to produce virtually any type of signal or modulation. In contrast, PDWs are optimized for pulsed signals and limited types of modulation (e.g., chirps, LFM). The key difference is in the amount of memory each method needs when producing long simulations of complex signal environments.

Consider a simple radar scenario that generates five seconds of a pulsed RF signal over a 5 GHz bandwidth with a density of 10,000 pulses per second. As shown in Table 1, the PDW approach requires 60,000 times less memory to produce this scenario. Of course, clever use of sequencing or DDS will make the I/Q method more memory-efficient. By the same token, sequencing also makes the PDW approach more efficient. In general, trading off the flexibility of I/Q for the efficiency of PDW enables you to create longer threat scenarios in less memory.
Using a highly integrated signal generator

As implemented in the UXG, agile signal generation has four important advantages. First, it can digitally control the extreme fine-tuning of frequency and phase within a single clock cycle. Second, it provides fast frequency hopping with the phase continuity and phase repeatability needed to simulate pulse-Doppler radars at different frequencies while maintaining their original phase relationships. Third, it ensures numerical precision and repeatability through creation of modulation in the frequency domain. Fourth, it enables simple multi-instrument synchronization by sharing a common DAC reference in a master/slave configuration.

Two additional advantages are relevant to EW engineers. A DDS that uses a digital modulator for amplitude, frequency and phase modulation can create signals in the numerically controlled oscillator. Also, LFM chirps and Barker codes can be directly synthesized using the numerically controlled oscillator.

Simplifying signal creation

Creating realistic multi-emitter EW scenarios is a complex challenge that involves correctly interleaving multiple pulse trains as well as identifying, counting, and prioritizing pulse collisions. For increased realism, it’s necessary to add antenna radiation, scan patterns, and PRI patterns to the pulse train. Managing all these parameters manually can be a daunting task.

Keysight’s Multi-Emitter Scenario Generation (MESG) software is a flexible suite of signal-creation tools that will reduce the time you spend on signal simulation. It provides Keysight-validated, performance-optimized multi-emitter signals for UXG agile signal generators. The software simplifies threat interleaving and enables you to more quickly and easily create scenarios for EW system test applications such as threat de-interleaving, sorting, and identification; subsystem interface management and threat correlation; and electronic countermeasures. Once signals are created in Signal Studio, they can be downloaded directly to the UXG as a PDW list.

Conclusion

Realistic testing of radar and EW systems depends on the generation of signals that accurately simulate multi-emitter environments consisting of thousands of emitters and millions of pulses per second, all arriving from multiple directions. New technology built into the UXG—a COTS agile signal generator—provides an integrated solution that fits on your test bench. This technology also enables you to generate increasingly complex simulations that get closer to reality and, ultimately, provide deeper confidence in EW system performance.

This is the final application note in this series. Across the series, our goal has been to provide a mix of timeless fundamentals and emerging ideas. Whether you choose to 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. For your reference, a list of the seven previous notes follows the Related Information, below.
Related Information

- Application Note: Radar Measurements, publication 5989-7575EN
- Application Note: Electronic Warfare Signal Generation: Technologies and Methods, publication 5992-0094EN
- Brochure: UXG Agile Signal Generator, N5193A, publication 5992-0091EN
- Data Sheet: UXG Agile Signal Generator, 10 MHz to 20 or 40 GHz, publication 5992-0092EN
- Technical Overview: Signal Studio for Multi-Emitter Signal Generation, N7660B, publication 5992-00405EN

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
- Part 7, Assessing and Improving Radar System Performance, publication 5992-2155EN
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):

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

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 \( \text{dBsm} \) 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 \( 10 \log(4\pi)^3 \), 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 \( \text{dBsm} \) 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.

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

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