APPLICATION NOTE

Surveying the Best Ways to Test Antennas and Antenna Arrays

Part 6

KEYSIGHT

The Radar Series

This application note is the sixth 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.

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 system.

Parts 2 and 3 of this 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. Part 4 examined the use of vector signal analysis (VSA) and wideband instruments—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 our ongoing discussion of practical test methods, we'll now take a closer look at the testing of antennas and antenna arrays. This topic spans a variety of test setups and test methods: far-field and near-field test ranges; multi-aperture and phased-array radar systems; and radar cross-section (RCS) measurements.

Across these requirements, narrowband or wideband measurement techniques may provide the desired results. Vector network analyzers can perform essential narrowband measurements of magnitude (gain), phase, and impedance, and they provide the sensitivity needed to obtain excellent results when dealing with extremely small signals in RCS testing. For wideband measurements, modular AXIe digitizers are the foundation of a flexible reference solution designed to address multi-channel antenna characterization.

Note: The appendix at the end of this application note presents the range equation and the system block diagram.

Understanding Antenna Measurements

Antenna performance is crucial to every radar system. Antenna gain is a key variable in the radar range equation (see appendix) and therefore directly affects range.

The gain value is defined as the maximum power relative to the power emanating from an isotropic antenna (i.e., a point source)[1] Gain is usually defined in logarithmic terms, namely dBi, which indicates dB relative to an isotropic antenna. It is expressed with the following equation:

$$G_{dBi} = 4\pi\eta A/\lambda^2$$

Where:

η = antenna efficiency

A = antenna area

λ = wavelength of the carrier signal in meters

In addition to gain, polarization is another important consideration for the transmitter and receiver antennas: the respective polarizations must match to ensure efficient signal transfer. Types of polarization include elliptical, linear (or vertical), and circular.

A radar antenna is designed to form a steerable beam. This beam is not perfect, and its width is defined to be the angle between the 3 dB points (Figure 1).

[1] This is why the gain is sometimes referred to as directivity. For more, please see pages 3-7 of *Part 1, A Framework for Understanding: Deriving the Radar Range Equation*, publication 5992-1386EN.

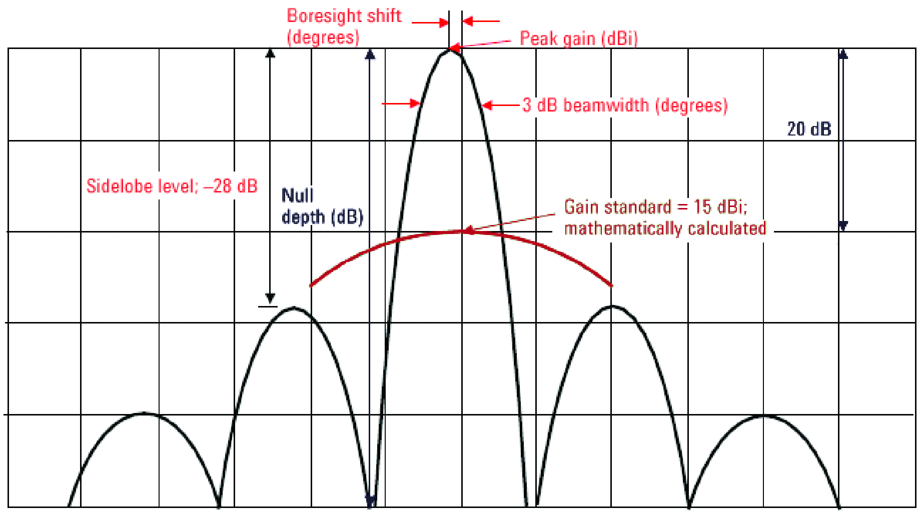

Figure 1. As shown by this plot of power density, a measurement of the antenna pattern makes it possible to determine several important characteristics.

The width is not necessarily the same in the horizontal and vertical directions. For example, a tracking antenna may have a "pencil" beam that is of equal width in the horizontal and vertical directions. In contrast, a search antenna may have a fan-shaped beam that is narrow in the horizontal and wide in the vertical. It is important to consider beam width and antenna gain together: as the beam is narrowed, the gain increases because the power is more focused.

Conventional radar systems rely on mechanical positioning systems to steer the beam. Many current-generation systems use electronically controlled antenna arrays, and this can greatly increase the speed and accuracy of beam steering. A so-called boresight measurement, which compares the intended and actual angles of the peak power, helps calibrate the direction of the beam. Greater accuracy in beam steering equates to greater accuracy in determining the direction of the target.

Sidelobes are an undesirable artifact of beam forming (refer back to Figure 1). Because these transmit energy in unwanted directions, they can produce false returns from objects close to the antenna—and this is why it is important to keep them as small as possible. Although sidelobes are generally small, they can be measured against theoretical limits for a specific type of antenna design.

Comparing Far-Field and Near-Field Testing

In addition to gain, polarization, beam width, boresight, and sidelobes, it is also common to measure frequency response (magnitude and phase) and impedance in a radar system. A vector network analyzer (VNA) is the ideal way to measure magnitude response, phase response, and impedance.

Two common approaches are often used to make these measurements on an antenna: far-field and near-field testing (Figure 2). Each method has advantages and disadvantages.

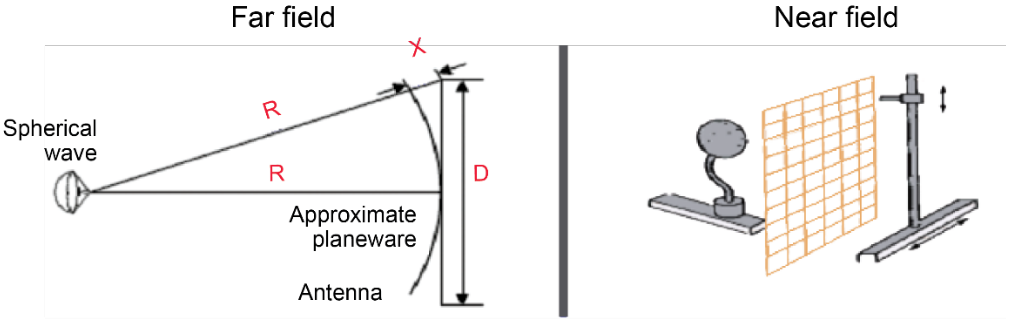

Figure 2. Far-field testing (left) is simpler and faster but has a large footprint. Near-field testing (right) needs less physical space but requires time-consuming measurements and complex calculations.

As the name implies, far-field antennas typically operate with a long distance between the transmit and receive antennas. The generally accepted far-field criteria is $R > 2D^2/\lambda$, which allows 22.5 degrees of phase variation across the aperture of the antenna-under-test (AUT). At this distance, the spherical radiated wavefront becomes almost planar across the aperture of the receive antenna, and this helps reduce receiving errors.

Near-field antennas usually operate at much shorter distances between the transmitting and receiving antennas. Very near the antenna plane, the field is reactive in nature and falls off more rapidly than the radiated near-field region. Measurements are made in the radiating near-field region at a distance defined as $\lambda/2\pi < R < 2D^2/\lambda$. As illustrated on the right side of Figure 2, this method acquires a series of measurement points spaced across a two- or three-dimensional grid. The resulting data set must be processed through transformation analysis to derive an equivalent far-field result.

Sketching large and small far-field test configurations

The footprint of a far-field test configuration may cover 30 to 3,000 feet (10 to 1,000 meters), and this is the primary drawback. Compared to the near-field method, two key advantages stand out: testing takes less time and requires fewer calculations.

During a far-field measurement, the radiated energy is measured in real-time as the AUT is rotated through a range of azimuth and elevation coordinates. The resulting data is a measure of amplitude, phase, or both, as a function of angular position. The rotation of the antenna is usually accomplished with a mechanical positioner that determines the exact position in the coordinate system but typically restricts movement to a single axis at a time.

Figure 3 shows an example far-field test configuration based on the Keysight PNA-X vector network analyzer. To help reduce signal loss and thereby enhance measurement sensitivity, the system uses three elements—two external mixers and an LO/IF distribution unit—that are placed near the antennas. In this example, the first down conversion is to an IF frequency of 7.438017 MHz [(9 x (100e6 / 121)], which is the second IF of the PNA-X.

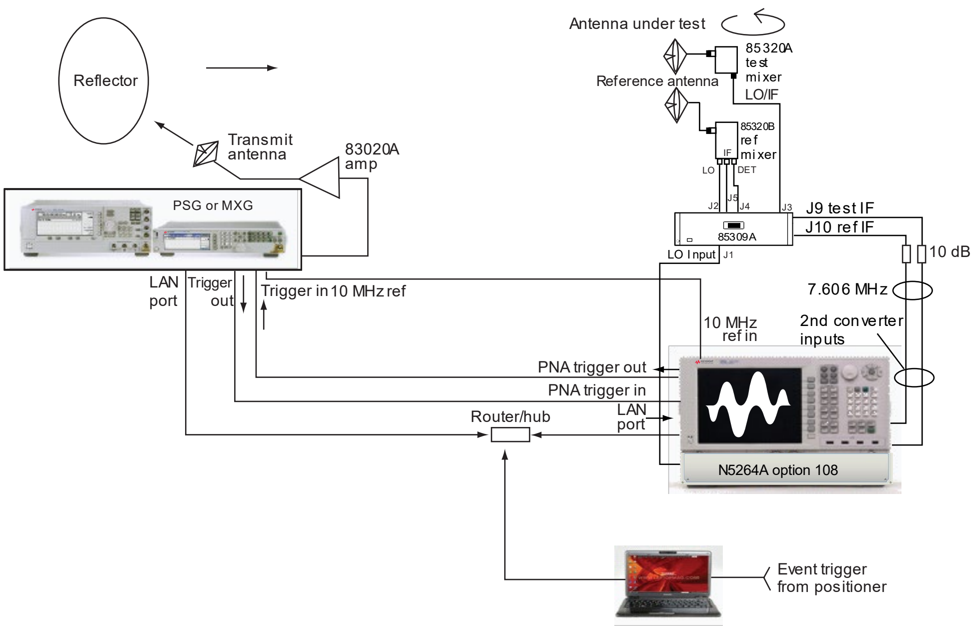

Figure 3. In this configuration, the use of external mixers placed close to the reference antenna and the AUT improves measurement sensitivity. Direct input of the IF signal into the VNA's second mixing stage also improves sensitivity.

Minimizing losses in the signal under test will help maximize receiver sensitivity. To help with this, the PNA-X provides a way to bypass the coupler and IF-converter stage (Option 020, IF Inputs for Antenna and Millimeter-Wave), improving sensitivity by as much as 20 dB.

For a larger far-field antenna range, controlling a remote microwave source across a significant distance can be problematic. The configuration shown in Figure 3 uses a PSG or MXG microwave signal generator, and the system utilizes TTL handshake triggers between the PNA-X and the signal generator. The long-distance physical connection can be made using low-cost fiber-optic transducers.

Figure 4 shows another example test configuration that can be used for smaller far-field ranges. This simpler configuration can be used when the range is small enough to ensure that any cable losses will not affect the measurement results. Optionally, optical extenders can be used for larger ranges; this will have a modest impact on output power but will not affect test throughput.

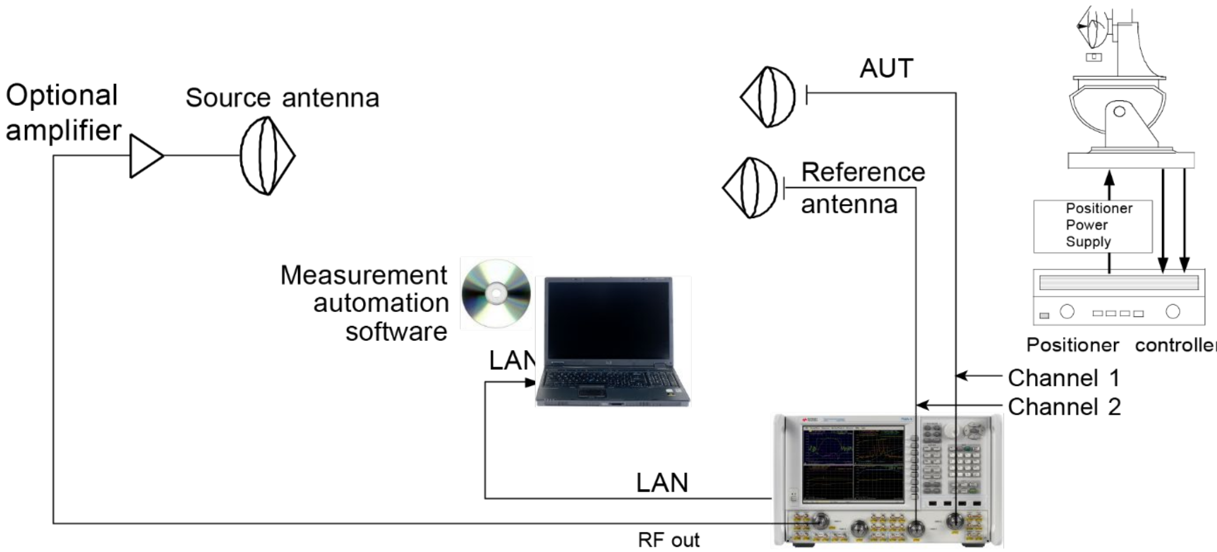

Figure 4. This simple test configuration, which includes a VNA, can be used for smaller far-field setups. The potential for cable losses limits the maximum size of this approach.

A small-range configuration has several advantages over a large-range configuration. Foremost, the VNA helps minimize cost, space, and complexity by providing the source and necessary receiver channels. Because the PNA-X can measure four independent inputs simultaneously, it provides a highly integrated and cost-effective solution. In addition, the high-performance spectrum analysis capability provides unparalleled insight by providing measurements of spurious signals simultaneously from all ports (Options 090, 093, and 094).

Once the test process has been established, analyzing the antenna pattern requires the completion of numerous gain and phase measurements relative to the known reference antenna while varying the angular position of the antenna. Although this is a laborious process when performed manually, readily available antenna-measurement software can control antenna position and synchronize the source and network analyzer during each measurement.

Outlining possible near-field test configurations

Near-field methods estimate the far-field response by taking a series of measurements and then applying a Fourier transform-based computational technique. In this process, the measurement system uses a computer-controlled arm to move a probe across the antenna aperture and through a series of points that are spaced every half-wavelength. Depending on the nature of the antenna, the test will use one of three scan patterns: planar, cylindrical, or spherical (Figure 5).

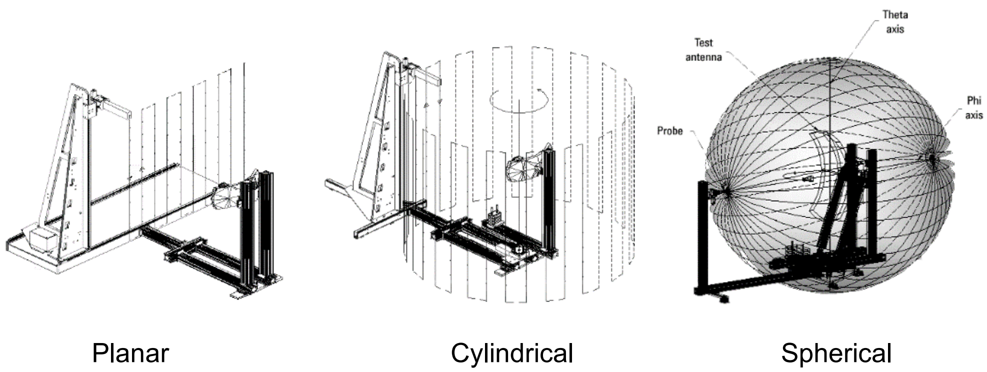

Figure 5. A near-field test uses different scan patterns, depending on the type and purpose of the antenna.

Near-field antenna ranges have several advantages over far-field ranges: require less space; protect antennas from weather; provide better security (e.g., for antenna and test frequencies); and cost significantly less for very large antennas. The main disadvantages are measurement complexity, test time, and the need to acquire, store, and process large amounts of data.

Figure 6 illustrates a basic near-field measurement configuration using a PNA-family network analyzer. This approach is similar to the small-range configuration: the network analyzer provides the source and the receiver channels; and third-party software controls the network analyzer, the positioner, and the collection of data. In this example, the external software also controls switching of the AUT polarization.

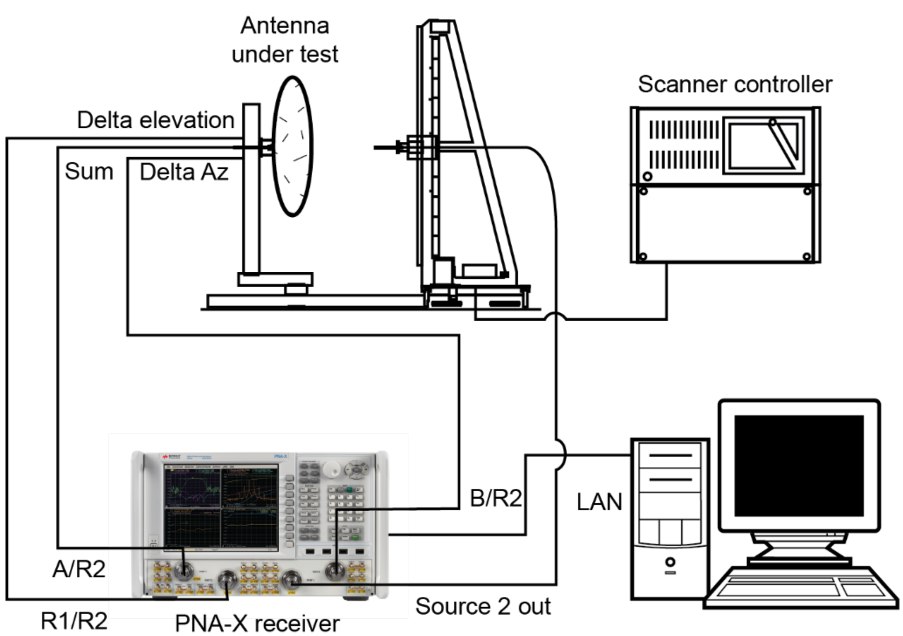

Figure 6. In this example test configuration, transformational analysis is used to extrapolate far-field results from near-field measurements.

To minimize test time, the source output frequency can be multiplexed during each data scan. One caveat: this can result in misalignment of the rectangular near-field grid between the forward and reverse data scan directions, and this will produce errors in the computed far-field pattern. Using the same scan direction will remove these errors, but it also doubles the test time.

Alternatively, the system can scan the frequencies in reverse order during the reverse scan. Performing a reverse sweep in conjunction with correct triggering between the forward and reverse passes ensures that each frequency set is spatially aligned on the rectangular near-field grid. This technique requires an RF source that supports a “reverse frequency list” operating mode. The PNA and PNA-X network analyzers include reverse-sweep and edge-triggering capabilities designed to support antenna measurements.

Viewing example measurements

Figure 7 shows two measurement results. The trace on the left shows a far-field antenna pattern for an X-band radar in the horizontal plane. Measurement results from the principal planes are often used to characterize antenna performance — gain, beam width, sidelobe level, etc. — and the results can come from far-field or near-field measurements.

The example on the right side of Figure 7 shows the cross-polarization in an antenna pattern. In essence, cross polarization is the difference in the result with opposite polarization. This case shows a difference of 30 dB, which is a good level of polarization purity. In general, a well-designed linear antenna will respond to only the polarization for which it was designed.

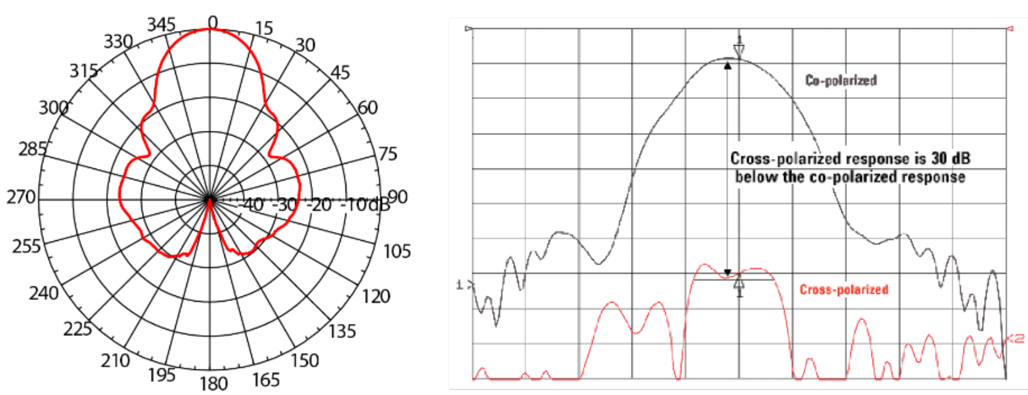

Figure 7. These examples show a horizontal-plane antenna pattern (left) and cross-polarization in an antenna pattern (right).

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Characterizing Multi-Aperture and Phased-Array Systems

A multi-aperture or phased-array antenna consists of numerous antennas or radiating elements that form a beam of specific shape or direction by manipulating the relative phase of each transmitted signal. Combining the elements of an array antenna with beamforming techniques enhances spatial selectivity and helps avoid interference.

The calibration and testing of these antennas can be quite challenging. As the number of elements increases, so does the time required to fully characterize the array. Thus, the ability to use multiple coherent measurement channels is an effective way to accelerate the testing of a phased array antenna that includes many elements.

The various components within an array contribute element-to-element magnitude (gain) and phase errors that can severely limit overall performance. Because phase is used to steer the beam, the errors due to any misalignment of the radiating elements must be calibrated out to ensure accurate and efficient operation.

Depending on the signal type, there are two ways to analyze the cross-channel response: one is a narrowband swept approach and the other is a wideband-stimulus/wideband-receiver approach. The narrowband method uses a swept or stepped tone and a narrowband receiver to measure one frequency at a time; after acquiring the full set of measurements it then performs cross-channel computations in the time domain. The wideband approach is much faster, making it possible to generate and measure all frequencies simultaneously and compute cross-channel spectra in the frequency domain.

The ideal measurement solution has the versatility to use either method, and a wideband digitizer with digital down conversion (DDC) provides the needed flexibility. As part of the digitizer, hardware-based DDC makes it possible to isolate the signal of interest (SOI) and then improve the signal-to-noise ratio (SNR) and dynamic range within the bandwidth of the SOI by reducing the amount of integrated noise in the time domain. In addition, the DDC reduces the amount of data to be acquired and transferred for a given measurement duration, and this means less work for any post-processing algorithms.

Figure 8 shows a generic block diagram for an eight-channel system capable of testing and calibrating array antennas. The signal path proceeds from left to right, originating with the antenna array under test. The system hardware attenuates and down converts incoming signals in pursuit of two goals: reducing the amplitude to match the full-scale input range of the digitizer and translating the signal frequency to an intermediate frequency (IF) that is within the bandwidth of the digitizer.

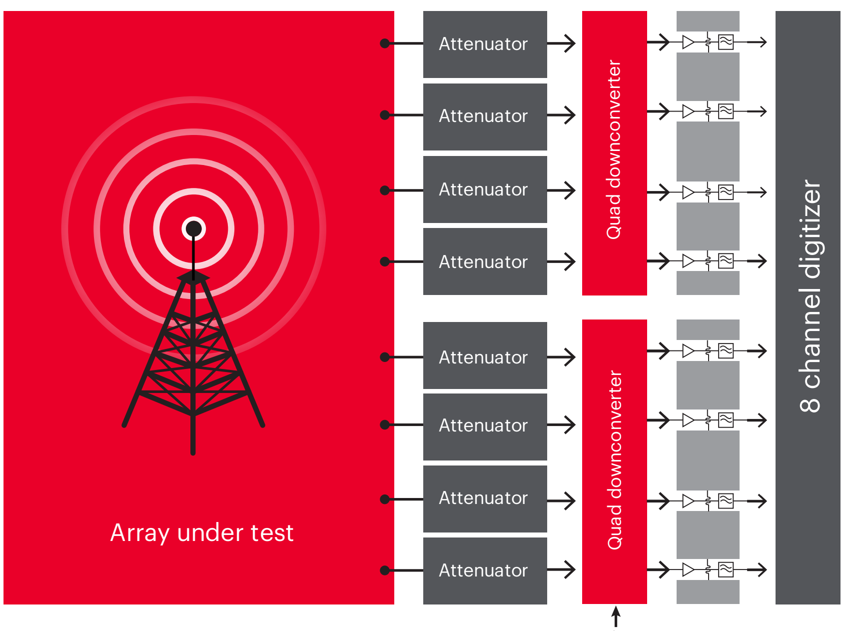

Figure 8. This generic configuration enables rapid, phase-coherent testing and calibration of multi-antenna arrays.

The Keysight multi-channel antenna calibration reference solution is a customizable starting point for these measurements (see sidebar). It enables engineers to use, enhance, or modify the system as needed to suit specific measurement needs: scalable channel count, options for down conversion of antenna receive channels, selectable analysis bandwidth, and a choice of RF/microwave sources and LOs. It can also be extended to wideband measurements as needs evolve.

The centerpiece of the reference solution is the M9703B AXIe 12-bit high-speed digitizer/wideband digital receiver with optional DDC. The M9703B provides eight synchronous acquisition channels with 12-bit resolution and the ability to capture signals from DC to 2 GHz at 1.6 GSa/s (or 3.2 GSa/s with interleaving) into 4 GB of memory. As technology evolves and arrays achieve greater densities, this type of scalable measurement platform can accommodate more digitizer channels and thereby provide a future-ready solution.

Multi-channel antenna calibration reference solution

This reference solution is a combination of hardware, software, and measurement expertise, providing the essential components of a narrowband antenna calibration test system. Phase-coherent sampling and parallel measurements across all input channels improves calibration and beamforming.

- Frequency range of DC to 40 GHz
- Narrowband analysis bandwidth of 300 MHz down to < 1 kHz (with DDC)
- 8x improvement in antenna calibration time with up to 40+ digitizer channels measured in parallel
- Narrowband, cross-channel magnitude and phase measurements with included software
- Optional 89600 VSA software enables more complete visualization via wideband signal analysis

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Measuring Radar Cross Section

The RCS of a target is a measure of its reflectivity in a given direction. There are three main contributors to RCS:

- Specular scattering: localized scattering dependent on the surface material and its texture
- Diffraction scattering: incident signal scattering at target edges and discontinuities
- Multiple bounce: reflections among target elements at offset angles

As shown by the radar equation (see Appendix), the RCS value s has a direct effect on the range of the radar. Although radar designers cannot control the cross-section of the target, they can utilize simulation tools capable of predicting the behavior of radar receivers in realistic environments.

Figure 9 shows a basic range setup for transmission and reception of co-polarized and cross-polarized signals. In this configuration, the network analyzer measures both polarizations simultaneously through independent measurement channels while also providing the source signal to the transmitting antenna.

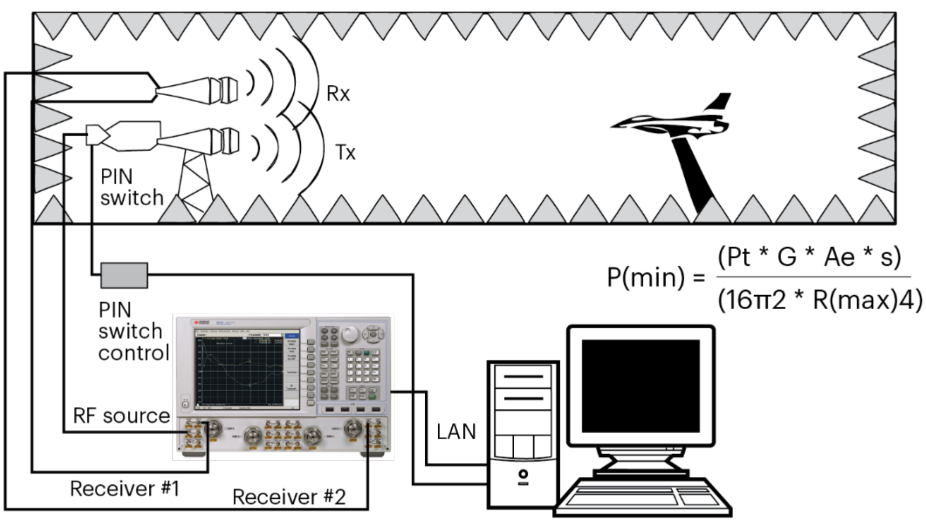
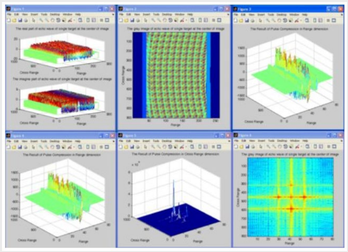


Figure 9. This example setup uses an anechoic chamber and a VNA to measure RCS.

Improvements in technology have enabled a greater understanding of how to minimize the reflected energy of an object. As a result, the actual returned signal levels are extremely small and can be acquired only with extremely sensitive measurement instrumentation. The received signal will be very small due to the $1/R^4$ attenuation of transmitted and reflected energy and the object reflection term, σ, which is optimized for the smallest possible return. The level of the returned signal is also affected by the need to use large distances (due to object size) and thereby ensure a planar wavefront.

1905EP SystemVue Radar Model Library



Explore tradeoffs in radar system architectures within an electronic system-level (ESL) design environment.

- Utilize dozens of highly parameterized simulation blocks and higher-level reference designs
- Create working system scenarios including radar processing blocks, environmental effects, and more, with support for the following technologies:
  - Pulsed-Doppler (PD) radar architectures
  - Ultra-wideband (UWB) radars and wideband receivers
  - Phased-array and digital-array radars (DAR)
  - Synthetic aperture radars (SAR) and beamforming for raster imaging and mapping
  - Stepped-frequency radars (SFR) for ground- and wall-penetrating designs
  - MIMO radars for increased range, resolution, and robustness
- Add targets, clutter, fading, noise, interferers and RF effects
- Model the probability of detection given an RCS value (σ)

As a result, instrumentation with very good sensitivity is essential. To achieve the best sensitivity, instruments such as the PNA-X network analyzer use mixer-based receivers that achieve better sensitivity than is possible with sampler-based converters.

Because the signals are minuscule, small reflections caused by elements in the range itself can contribute significant amounts of reflected energy. To solve this problem, advanced network analyzers such as the PNA and PNA-X provide a time-gating function that can remove the unwanted signals from the measurement. This is achieved by first computing an inverse fast Fourier transform (IFFT) on the measured frequency data, then mathematically removing the unwanted signals, and finally computing an FFT to restore the frequency-domain result. Figure 10 illustrates this concept, and more information is available in Keysight Application Note 1287-21, *Time-domain Analysis with a Network Analyzer,* publication 5989-5723EN.

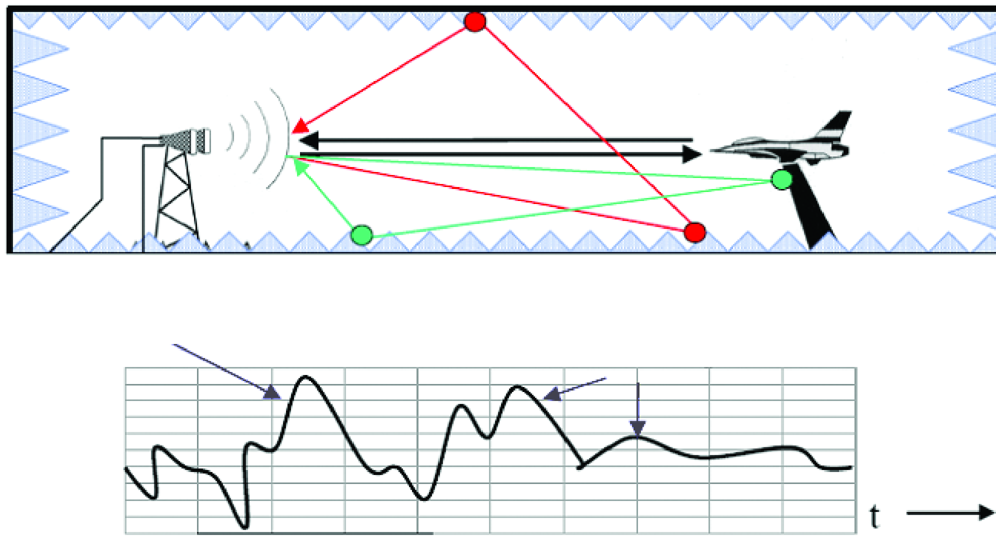


Figure 10. Because RCS signals are small, returns caused by the measurement chamber can interfere with measurement results. In advanced network analyzers, a gating function can be used to remove unwanted responses from the measurement.

One consequence of computing an IFFT on a finite-length sample block is the creation of repetitions of the fundamental signal in the time-domain result. These artifacts or “aliases” can be worked around through the process of testing to identify an alias-free measurement span. The width of the span will depend partly on the number of data points the network analyzer is able to measure and process. In a typical network analyzer, this value may be 1,601, which is enough to ensure alias-free measurements in many cases. However, because more may be needed, the PNA and PNA-X network analyzers can measure up to 20,001 points.

Conclusion

Antenna gain is a key variable in the radar range equation and therefore directly affects system performance. Other important characteristics include polarization, beam width, boresight, and sidelobes. A vector network analyzer is the ideal way to perform these measurements across a variety of measurement approaches: large or small far-field configurations; and planar, cylindrical, or spherical near-field configurations.

When working with multi-aperture or phased-array systems, factors such as array size and desired measurement time are key factors in choosing the best measurement solution. When only a few channels are needed, a VNA-based approach is sufficient; for double-digit channel counts, a multi-channel reference solution based on modular measurement hardware is more efficient.

Measuring RCS presents a different set of challenges, driven by minuscule signal levels that require highly sensitive, mixer-based measuring receivers to produce meaningful results. In addition, time gating may also be needed to enhance measurement results by excluding small reflections caused by elements within the test range.

The two remaining 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: *Active-Device Characterization in Pulsed Operation Using the PNA-X*, publication 5990-7781EN
- Application Note: *Time-domain Analysis with a Network Analyzer*, publication 5989-5723EN
- Brochure: *PNA-X Series Microwave Network Analyzers*, publication 5990-4592EN
- Data Sheet and Technical Specifications: *Keysight Spectrum Analyzer Option (090) for PNA/PNA-L/PNA-X*, publication N5224-90010
- Solution Brochure: *Multi-Channel Antenna Calibration, Reference Solution*, publication 5991-4537EN
- Configuration Guide: *Multi-Channel Antenna Calibration, Reference Solution*, publication 5991-4583EN
- Data Sheet: *Keysight M9703B AXIe High-Speed Digitizer/Wideband Digital Receiver*, publication 5992-1140EN
- Data Sheet: *Keysight W1905 Radar Modem Library*, publication 5990-6347EN

Appendix: The Radar Range Equation

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

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

Where:

- R_{max} = maximum distance in meters
- P_t = transmit power in dBW
- G = antenna gain in dB
- λ = wavelength of the radar signal in meters
- σ = RCS of target measured in dB_{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(4π)^4, which can also be written as 30 log(4π), and the 204 dBW/Hz is from Johnson noise at room temperature. The decibel term for RCS (σ) is expressed in dB_{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.

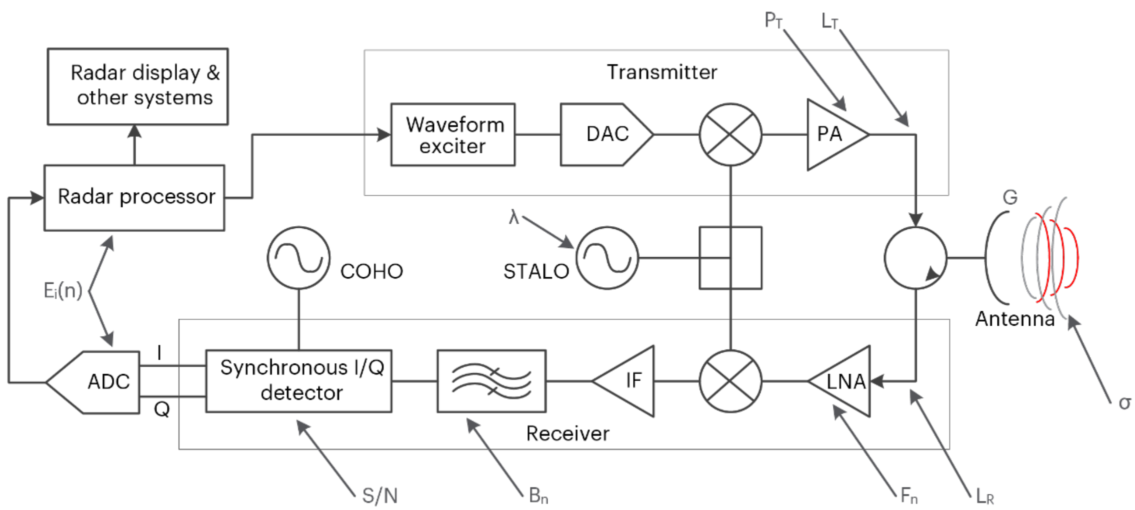


Figure A1. The variables in the radar range equation relate directly to key elements of this expanded block diagram.