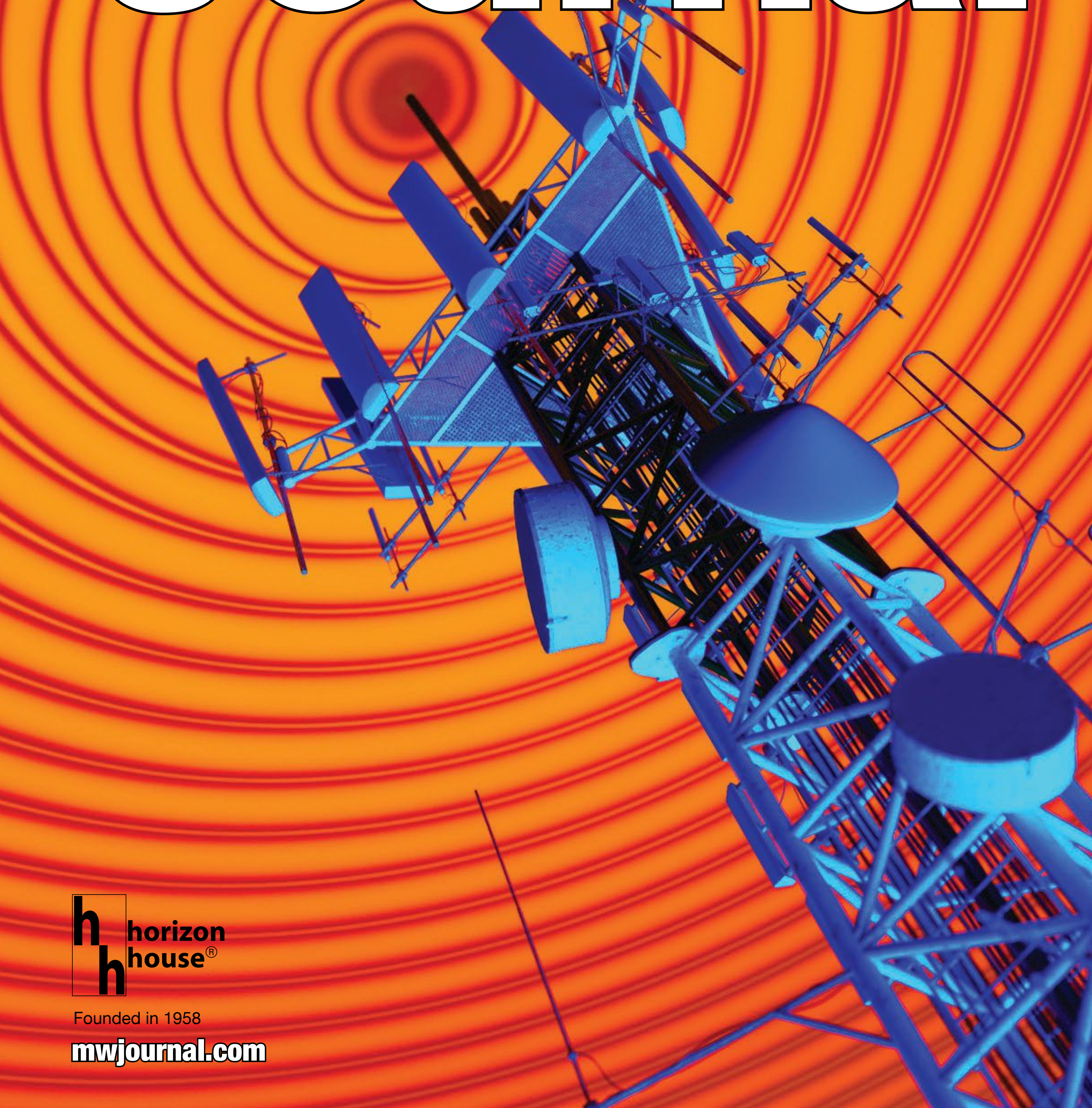
Vol. 68 • No. 1

January 2025

Microwave Journal



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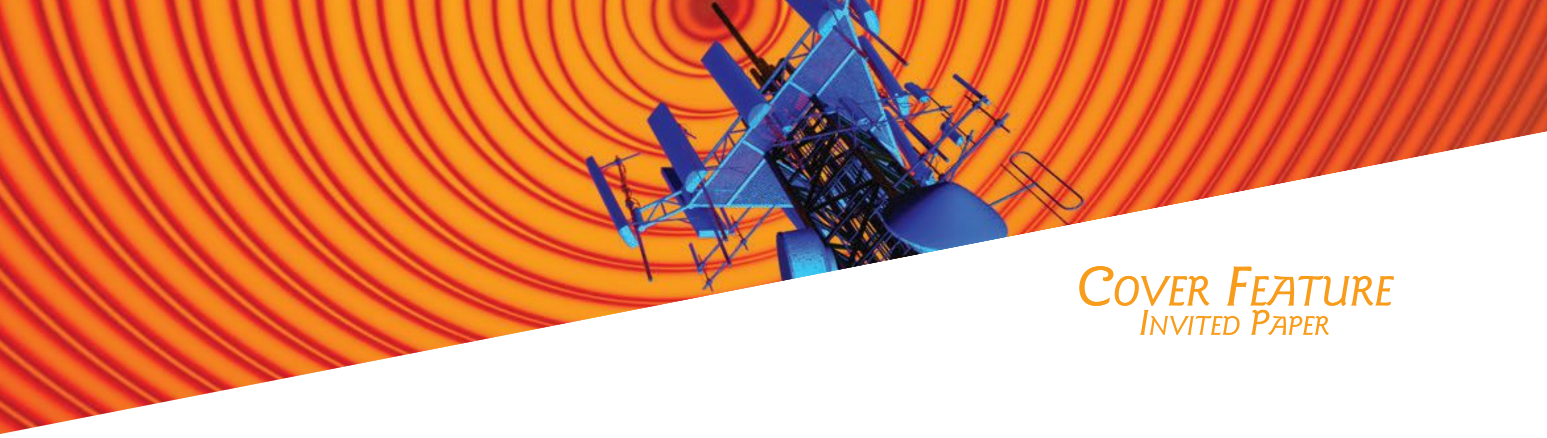

Evaluating Antenna Testing Options

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Over the past several years, rapid changes have taken place in the field of antenna testing. With more antenna types and new applications emerging at higher frequencies, there is increased urgency to refine established test strategies and develop new ones. For those who are new to antenna testing or are just getting reacquainted after several years away from the practice, it can be instructive to brush up on the fundamentals of antenna testing and study recent trends.

THE BASICS

The basic methods of antenna testing have not changed substantially, but the options for how and where to test antennas have shifted. The options enable various levels of cost, convenience, accuracy and sophistication. In particular, compact antenna test ranges (CATRs) are more widely available and operate at higher frequencies, up to 330 GHz or beyond.

For antenna measurements above 100 GHz, many CATR designs can be customized for specific waveguide bands by selecting different vector network analyzer (VNA) frequency extender modules and suitable feed antennas. For example, Eravant offers an open CATR with reflector options of 300 × 300 mm or 600 x 600 mm, as shown in ***Figure 1***. These CATRs are available with VNA frequency extenders and feed antennas operating up to 330 GHz.

MilliBox has developed a series of CATR designs using modular anechoic enclosures. The MBX32CTR CATR from MilliBox provides measurement solutions for frequencies up to 330 GHz, as well. An example of their test range is shown in ***Figure 2***.

Rohde & Schwarz provides a selection of mmWave CATR designs that feature shielded anechoic environments. ***Figure 3*** shows a Rohde & Schwarz CATR with a shielded enclosure surrounding an anechoic chamber. Other commercially available antenna ranges include many traditional far-field ranges, as well as a variety of near-field (NF) scanning systems. ***Figure 4*** shows a planar NF system from ASYSOL. The ASYSOL systems, along with others, typically operate at frequencies from microwave to mmWave bands.

For those requiring only occa-

Fig. 1 **Eravant CATR.**

Fig. 2 **MilliBox MBX32CTR CATR.**

Fig. 3 **Rohde & Schwarz ATS1800C CATR.**

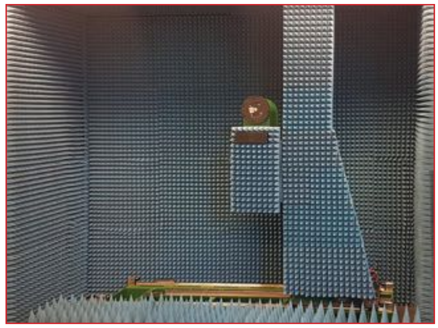

Fig. 4 **ASYSOL planar near-field system.**

Fig. 5 **Quadsat drone for airborne antenna measurement services.**

sional antenna tests, one of the most common strategies is to use someone else's antenna range. At first glance, this can seem like an inconvenient and expensive option until the time and cost of acquiring and maintaining a suitable antenna range is appreciated. Gaining experience using a variety of antenna ranges is one of the best ways to become familiar with current practices and equipment. Many companies offer economical antenna testing services, with some bringing their test equipment to the antenna rather than the other way around. For example, Quadsat provides airborne antenna measurement services for high gain outdoor antennas with drones. A Quadsat drone that provides these services is shown in ***Figure 5***.

At the high end of the cost and complexity spectrum, complete antenna test ranges are available with fully engineered anechoic chambers, positioning systems, computer platforms, software and test equipment. A wide variety of configuration options can tailor antenna ranges to meet specific needs. Configuring a complete antenna range requires a team with advanced knowledge to perform tasks related to design, planning, construction, calibration, operation and maintenance.

Less complicated and lower-cost solutions are also available. Antenna range components like anechoic chambers, positioning systems, test equipment and software can be developed in-house or purchased individually. A list of companies in

TABLE 1

ANTENNA TESTING COMPANIES AND CAPABILITIES

	Products & Services					
Company	Antenna Test Ranges	Anechoic Chambers	Scanning System Components	Control & Analysis Software	Antenna Test Instrumentation	Measurement Services
Antenna Systems Solutions	■	■	■	■	■	■
AP Americas		■				
Chamber Services Inc.		■				
Comtest Engineering		■				
Delta Sigma Company	■	■	■			
Eravant	■				■	■
ETS-Lindgren Inc.	■	■	■		■	
JEM Engineering					■	■
Keysight	■				■	
Microwave Vision Group	■	■	■	■		■
MilliBox	■	■	■			
Next Phase Measurements	■	■	■	■		
NSI-MI Technologies	■		■	■		
Rohde & Schwarz	■		■	■	■	
TDK RF Solutions		■	■			■

this space, along with the products and services offered by these companies, is shown in ***Table 1***. Companies that supply these components can provide expert advice based on specific testing needs and they may refer customers to existing facilities to serve as points of reference. In general, the antenna testing community is open and cooperative on all levels, making it one of the most rewarding career paths available. Its participants span a diverse range of skills and interests.

At any level of knowledge and resources, there is no substitute for experimentation to learn about antenna measurements. There are many sources of useful information for understanding established practices as well as the underlying electromagnetic and signal-processing theories. Some companies, such as NSI-MI, offer online short courses that cover introductory and advanced topics related to antenna measurements, NF theory and compact range design.[1] Additionally, professional organizations such as the Antenna Measurement Techniques Association offer introductory boot camps for those who are new to the field.[2]

IEEE practice standards are some of the best sources of information on the topic. IEEE Std 149-2021, "Recommended Practice for Antenna Measurements," underwent a significant overhaul in 2021. Recognizing that no measurement is truly complete without a statement of uncertainty, the standard provides a comprehensive treatment of antenna measurement uncertainty.[3] As an illustrative example, the recommended uncertainty analysis is applied to a hypothetical compact antenna test range.

IEEE Std 149-2021 covers a wide range of theoretical and practical topics. However, it no longer includes NF antenna measurements, which are now covered by IEEE Std 1720-2012, "Recommended Practice for Near-Field Antenna Measurements."[4,5] Updates to this standard are underway, with the next release expected in 2025.

Physical standards are also being developed to enable different measurement groups to evaluate and compare test results. One such

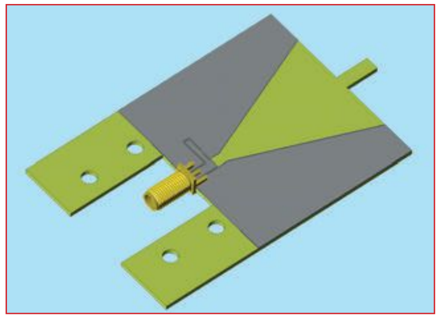

Fig. 6 **A wideband antenna measurement standard to compare test results.**

standard is an antenna that was first established as a benchmark for computational electromagnetics.[6] With an operating bandwidth of approximately 4 to 12 GHz, the antenna shown in ***Figure 6*** was developed for UWB applications. It is easily fabricated using an FR-4 substrate with a single metal layer and the design can serve as a common measurement standard. The design is being shared among a diverse collection of antenna test facilities to compare test measurement results across different antenna ranges.[7]

ANTENNA MEASUREMENT METHODS

One of the most straightforward ways to measure the gain of an antenna is to compare its response to a known standard. In this gain transfer method, a total of three antennas are required: One serves as the transmit antenna, another as a reference antenna and the third as the antenna under test (AUT). Two measurements are needed, with the first establishing a calibration response through the reference antenna. The other measurement has the AUT inserted in place of the reference antenna.

A number of complications can arise when using the gain transfer method. If the antennas are not far enough apart, multiple reflections between the antennas can introduce significant error terms. If the "quiet zone" established by the transmit antenna is not sufficiently quiet, meaning it is not adequately low in amplitude and phase variations, additional errors are introduced. Sources of error can also include multipath interference caused by nearby surfaces or cables, electrical loading of antennas by support structures, interference signals (equipment leakage), antenna mismatch errors, the limited accuracy of test equipment or antenna alignment errors. Ultimately, gain uncertainty for the AUT cannot be better than that of the gain standard used.

Another common gain measurement technique is direct or absolute measurement. This approach requires two identical antennas or three antennas that are not identical but have certain restrictions on their polarization. The test system is calibrated by recording the receiver's response when it is connected to the signal source directly or through a calibrated shorting cable. The two-antenna method measures transmission loss with two identical antennas separated by a known distance. The Friis transmission equation yields the combined gain of the antenna pair. The gain of either antenna is the square root of the antenna gain product.

The three-antenna method measures the gain product for three different antenna pairs. The gain of each antenna is computed from a system of three equations with three unknowns. Both the two- and three-antenna methods assume that the antennas are separated by far-field distances, which are often regarded as greater than $2D^2/\lambda$ where D is the effective aperture width and λ is the wavelength. However, at this distance, the interaction between directional antenna pairs may be enough to raise gain uncertainty to an unacceptable level. Distances of at least $32D^2/\lambda$ are often recommended to limit proximity effects adequately.

At mmWave frequencies, far-field separation can be problematic if there is insufficient signal power to overcome transmission losses. The problem may be aggravated if gain patterns must be measured over a significant dynamic range. Greater signal strength may also be necessary if antenna polarization must be measured as well.

A variety of enhanced measurement methods have been developed to extrapolate far-field antenna gain from measurements obtained at NF distances.[8,9] Extrapolated gain is a well-known strategy for accurately calibrating standard gain antennas, with uncertainties of ±0.1 dB achievable with sufficient effort. Both the amplitude and phase of antenna pair responses are required to perform gain extrapolation, necessitating the use of a vector signal analyzer.

During gain extrapolation tests, signal transmission between antenna pairs is measured over a range of separation distances. The result is a set of S_{21} data with increasing attenuation over distance. Rather than a smooth amplitude curve that follows a 1/d trend, the data usually contains additional features caused by multiple reflections between the antennas and various other proximity effects. When third-order reflections between the antennas are dominant, the amplitude data contains periodic variations with a spatial period of $\lambda/2$.

Extrapolated gain data can be analyzed to produce a best-fit mathematical expression for the coupled signal versus distance, normalized to 1/d. The form of the expression is a power series with each summation term a constant multiplied by $1/d^n$, where d is distance and n indicate the n^{th} term. The first-order term in the series, for which n = 0, represents the far-field gain product of the antenna pair when d is extrapolated to infinity.

To mathematically derive the first-order term in the power series, traditional gain extrapolation techniques require large sets of S_{21} measurements. These measurements are obtained at intervals of about one-tenth of a wavelength over distances spanning 200 to 300 wavelengths. This amount of data is typically necessary to produce accurate high-order terms in the signal versus distance power series.

A recently demonstrated gain extrapolation method offers a new approach that dramatically reduces the number of S_{21} samples needed while compressing the span of measurement distances.[10] The technique involves accurately locating the positions of successive minima and maxima in signal amplitude, with one S_{21} sample taken at each location. The paired measurements are repeated about a dozen times at regularly spaced intervals over a span of about 40 wavelengths. Demonstrated results are comparable to those achieved using traditional methods that require thousands of S_{21} measurements. One caveat is that multipath effects must be negligible, making the new method best suited for directional antennas and well-controlled test environments.

NF SCANNING

NF antenna ranges are widely regarded as providing the best measurements in terms of accuracy and versatility. However, they typically have higher hardware costs and greater measurement times compared to other range types. NF theory states that when electromagnetic fields are measured with sufficient accuracy and resolution over a closed surface surrounding a transmitting antenna, it is possible to compute the fields at any arbitrary point outside of the antenna's reactive zone.[11] The computations are complex and require significant computing resources and specialized software to perform functions such as field transformations, spatial filtering and probe correction.

Depending on the surfaces they scan, NF systems are categorized as either spherical (SNF), cylindrical

(CNF) or planar (PNF). PNF systems are widely used for directional radiators such as horn, lens and reflector antennas, as well as antenna arrays. CNF scanners are often realized within a PNF system by adding a positioner that rotates the AUT.

PNF and CNF systems cannot probe an entire closed surface unless multiple scans are performed with different antenna orientations. When significant fields exist outside of the scanned area, their omission from far-field gain calculations contributes to computational errors. SNF data can be easier to process mathematically, and probe corrections are generally more straightforward. As a result, many SNF ranges provide better performance for similar levels of cost and effort when compared to other NF systems.

At mmWave frequencies, many antennas are small enough to be scanned using a commercially available six-axis robot. Such robots can manipulate field probes over a range of surface profiles, including planar, cylindrical and spherical. They can also perform extrapolated gain measurements and other tests using the same antenna and probe configurations as those used for NF scans.

At frequencies above 100 GHz, significant challenges face designers and operators of NF systems. In general, NF techniques require probe positioning uncertainties of λ/50 or less. At 100 GHz, this corresponds to 60 microns. This level of mechanical precision stretches the capabilities of many robotic systems as well as the dimensional probes and laser trackers required for calibration. As a result, NF measurements at frequencies above 300 GHz will remain only marginally practical until robotic systems with greater accuracy and speed are developed. However, ongoing efforts are addressing these challenges.

At the National Institute of Standards and Technology (NIST), researchers are pushing NIST-developed NF scanning techniques to frequencies as high as 500 GHz. The Configurable Robotic MilliMeter-wave Antenna facility (CROMMA) is one of the most advanced positioning systems currently in use for precision NF measurements.[12] The facility has successfully profiled antennas operating at 183 GHz and can perform NF measurements as high as 500 GHz. NF measurements being performed at this facility are shown in ***Figure 7***.

CROMMA uses a six-axis COTS robot to manipulate field probes with repeatability and accuracy of approximately 25 microns. The range of motion for field probes is roughly 4 m vertically and 5 m horizontally. To calibrate the system, the probe carrier is moved throughout the robot's reach while laser trackers scan targets located on the carrier. When a field probe is mounted onto the carrier, a separate calibration fixture uses high-resolution cameras to find the center of the probe aperture and determine its position and orientation relative to reference points on the carrier assembly.[13]

Some commercially available NF systems are reported to be usable at frequencies reaching 110 GHz or higher. Unfortunately, the suppliers of NF ranges are hesitant to indicate expected accuracies at such frequencies because measurement results depend significantly on how their systems are used in specific situations. As more NF test results are reported for sub-THz wavelengths, the capabilities of these antenna test systems should become more apparent.

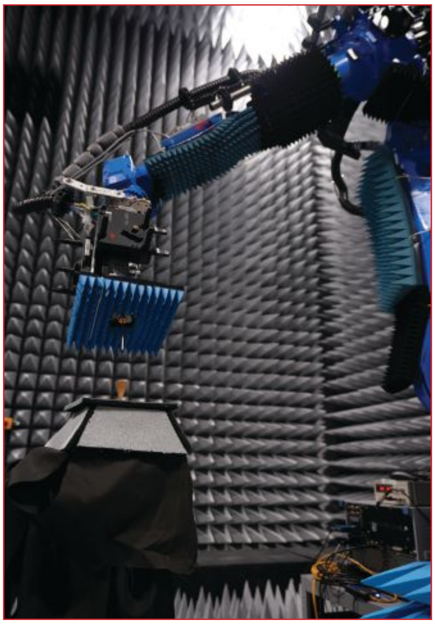

Fig. 7 CROMMA performs NF measurements. (*Photo used with permission.* Rebecca Jacobson, National Institute of Standards and Technology.)

CONCLUSION

Commercial and defense applications are moving higher in frequency to provide better performance to the end user. This means that test techniques and equipment must lead the charge to support a wide range of new, higher frequency components and systems. This article has presented an overview of some of the techniques, products, services and companies that will make the vision of higher frequency systems a reality. ■

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