Advances in Instrumentation and Positioners for Millimeter-Wave Antenna Measurements

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***Abstract* - Applications using millimeter-wave antennas have seen a strong growth in recent years. Examples are wireless HDTV, automotive radar, imaging and space communications. NSI has delivered dozens of antenna measurement systems operating at mm-wave frequencies. These are all based on standard mm-wave modules from vendors such as OML, Rohde & Schwarz and Virginia Diodes. This paper will present considerations for implementation of these systems, including providing the correct power levels, and interoperability with coaxial solutions. Many new mm-wave applications employ low to medium gain antennas that are more suited to spherical near-field and far-field measurement geometries. NSI has developed solutions to meet these needs.**

I. Introduction

Over the past twenty years, NSI has delivered dozens of antenna measurement systems used for mm-wave antenna measurements [1-4]. In recent years new applications that use low-gain antennas have led to an increased demand for spherical near-field and far-field measurement geometries.

In most cases such a geometry requires longer cables than can be supported with a basic network analyzer setup. When the scanner structure needs to accurately position relatively heavy mm-wave modules, the weight and complexity of the entire system quickly increases.

In this paper we look at the RF components used in these systems, some of the factors that affect their performance, two scanning geometries that limit motion of the antenna under test and efforts to reduce the system size and weight for future cost savings.

II. Components for Mm-Wave Measurements

NSI's involvement with mm-wave antenna measurements dates back to the Hewlett Packard (HP) 85301B system and its mm-wave extensions which were introduced in the early 1980s. These used source modules and harmonic mixers covering standard waveguide bands from 26.5 – 40 GHz up to 75 – 110 GHz, see Figure 1. The harmonic mixers shown here are still available today.

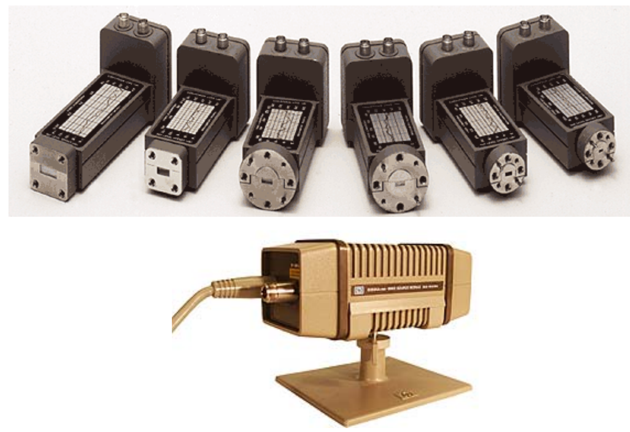

Figure 1. HP harmonic mixers (top) and source module

The HP source modules used passive multipliers that required a high input power level. The 11970-series harmonic mixers use high harmonics which limits performance. For example, in W-band the harmonic is 18.

In the mid 1990's, OML introduced VNA extension modules that packaged the multiplier, directional coupler and waveguide mixer in a single enclosure. These modules (see Figure 2) use active multipliers providing similar output power but at much lower input power levels (10 dBm vs. >20 dBm). The down-conversion is done at much lower harmonics, for example 8^{th} harmonic in W-band, improving the system sensitivity.

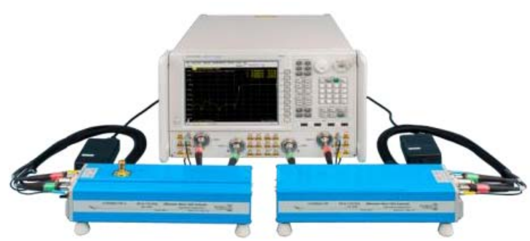

Figure 2. OML mm-wave modules

Currently a range of similar modules is available from a number of vendors, including OML, Virginia Diodes (VDI), Rohde & Schwarz (R&S) and others, and cover extended frequency ranges up to 1.1 THz.

III. RF Configurations for mm-Wave Antenna Measurements

Millimeter-wave modules include mixers and multipliers in the same way as distributed RF systems used in antenna measurement systems [5].

Two RF signals are required (RF and LO) which can be provided by a single VNA, or sometimes by a VNA with an external generator. A two-port Keysight (formerly Agilent) PNA provides the internal LO source output on the rear panel and this can be used as the LO source for the mm-wave modules, provided the IF frequency is the same as the PNA's internal IF. In this case the PNA needs to have options 080 (frequency offset mode) and 020 (rear-panel IF inputs).

For bench-top measurements using a 2-port VNA, a mm-wave test set provides the necessary interfaces to the mm-wave modules. The following Figure shows a Keysight PNA with N5261A mm-wave controller.

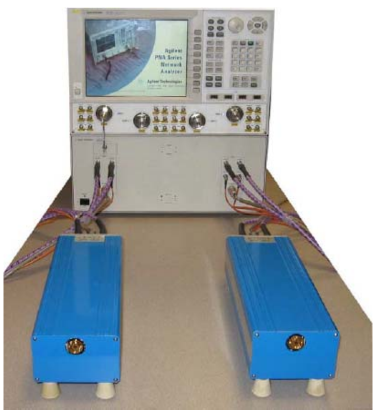

Figure 3. PNA with mm head controller and OML modules

A 4-port Keysight PNA or Rohde & Schwarz ZVA provides two independent source outputs on the front panel, with access to the internal front end to receive the IF signals from the mm-wave modules. A benefit of the 4-port VNA is that Ports 3 and 4 can be used simultaneously, simplifying the LO connections. This configuration requires a 4-port analyzer with frequency offset mode and configurable test set (receiver access jumpers). It can operate with a wide range of IF frequencies, typically 10 MHz to 300 MHz.

Figure 4. 4-Port PNA with VDI modules (picture courtesy of Keysight)

Figure 5 shows a schematic of the RF connections for such a setup.

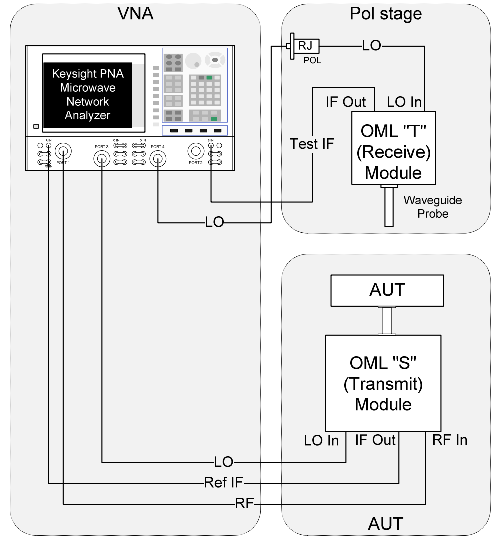

Figure 5. 4-port PNA with mm-wave modules

Both the 2-port and 4-port configurations shown above are well suited for desktop applications. In the case of antenna measurements, the NSI 100V-1x1 scanner has been used in this mode (see Figure 4).

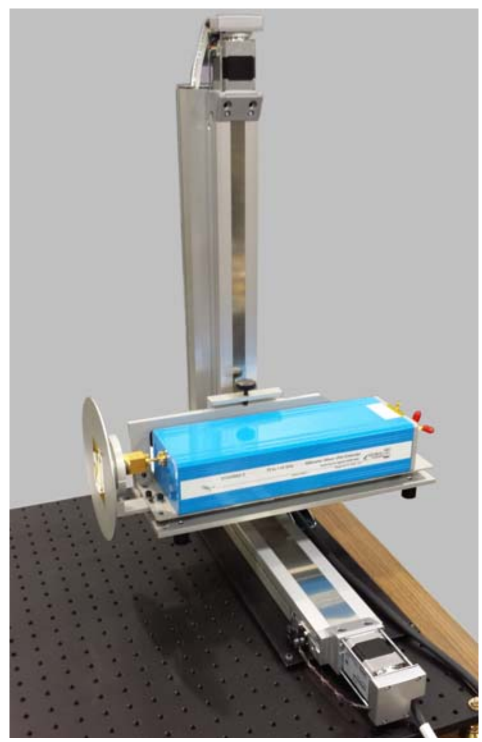

Figure 6. NSI-100V-1x1 scanner with OML mm-wave module

For larger systems requiring longer cables, the RF and LO power provided by the VNA will not be sufficient. External amplifiers can be added to the RF and LO cables, but the power level at the mm-wave modules needs to be carefully adjusted.

In a system that operates in both coaxial (up to 50 GHz) and waveguide frequency ranges (above 50 GHz) it is desirable to use the same components for both modes, to minimize reconfiguration when switching between coaxial operation and mm-wave mode.

For antenna measurement systems using the NSI Distributed Frequency Converter (DFC) this is accomplished by replacing the coaxial mixers with NSI-RF-5949 Mixer Interface Modules. Placed close to the mm-wave modules, these provide nearly constant LO power. For constant RF power, the NSI-RF-5820 Amplifier-Coupler or NSI-RF-5840 or -5850 Amp-Multiplier-Coupler modules provide a near-constant RF signal. Figure 7 shows such a setup configured for AUT Transmit mode. By moving the amplifier-coupler module to the probe and swapping the mm-wave modules the configuration can easily be switched to AUT Receive mode.

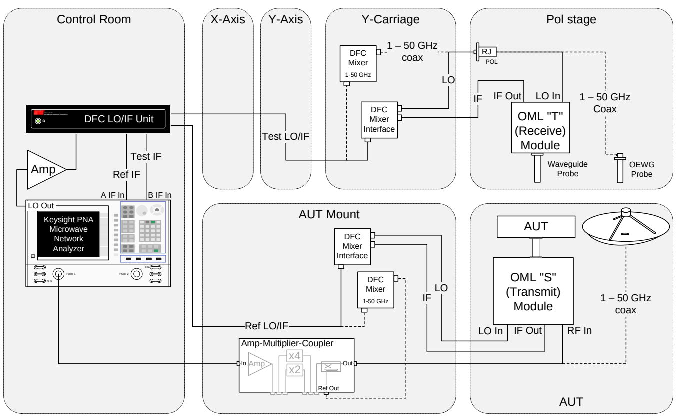

Figure 7. Keysight PNA with NSI DFC, 1 – 110 GHz

This configuration has been used on a variety of NSI systems, using OML, VDI and R&S mm-wave modules, using Keysight PNA and R&S ZVA network analyzers, as well as the NSI Panther receiver. The setup supports IF frequencies of up to 30 MHz, or up to 100 MHz if the NSI-RF-5945E LO/IF Unit with Extended IF is used. If required, an NSI-RF-5802E IF Downconverter can be used to convert the IF out of the modules to a suitable IF for the receiver or VNA. The latter uses a low-frequency, low-cost oscillator as its LO source.

IV. RF Performance Considerations

The RF performance of a mm-wave system can be affected by a number of issues. If not addressed, these can result in a system with degraded performance. The following aspects should be considered.

A. LO and RF power control at the module input.

On larger systems an amplifier must be used in the RF and LO cables to compensate for the power loss in long cables. The insertion loss of the cables increases with frequency. If the amplifier is operated in its linear region then the power slope at the module input will be the sum of the slopes of all the cables, both on the amplifier input and on its output. This makes it difficult to keep the power at the module within the operating band, which typcially is ±2 dB or less. In addition, operating the amplifier in its linear region means that there is no protection against an accidentally high source power setting. In that case the amplifier output could increase to its saturation point, which could be 5 to 10 dB higher and could easily damage the mm-wave module. A better approach is to operate the amplifier at or near near its saturation point. This eliminates the power slope caused by the amplifier input cables, and as a bonus protects the mm-wave module from an accidentally high source power setting. It also makes it easier to achieve the correct power at the modules for multiple waveguide bands that use different frequency ranges. A sloped attenuator can help flatten the power level across the frequency band. The attenuators used must be carefully determined for each system and mm-wave band.

B. Sensitivity to harmonics at the module input.

Some of the mm-wave modules, especially those in bands above 110 GHz, are highly sensitive to harmonics present on the RF or LO inputs. Whenever an amplifier is used to drive the modules, harmonics will be present and this can seriously affect the performance. This may be evident in large variations in the frequency response across the mm-wave band. To prevent amplifier harmonics from entering the mm-wave module, a low-pass filter can be used. To cover the filter needs for the most popular waveguide bands using modules from a variety of vendors, a limited set of only 4 different filters is sufficient. The filter cut-off frequencies are 12.5, 15, 16.75 and 18.75 GHz.

C. Amplifiers to improve dynamic range

Millimeter-wave measurements on low-gain antennas in far-field mode require a highly sensitive receiver for acceptable performance. Manufacturers of mm-wave modules often claim a dynamic range of 110 dB, but usually that is at 10 Hz IF bandwidth at which the measurement speed is very low. The power budget in Table I shows a calculation of the receiver signal-to-noise ratio (SNR) at different far-field distances.

TABLE I. Power Budget for Far-Field Test at 110 GHz

Tx module output power (typical)	+5.00	dBm	(OML Data)
Test Dynamic range (typical, at 10 Hz IFBW)	+110.00	dB	(OML Data)
Sensitivity (typical) at 10 Hz IFBW	-105.00	dBm	
Sensitivity (typical) at 1 kHz IFBW	-85.00	dBm	

Range Length	**0.5**	**1**	**2**	**4**	**m**
mm-wave module output power	+5.0	+5.0	+5.0	+5.0	dBm
Tx Antenna Gain (SGH)	+25.0	+25.0	+25.0	+25.0	dBi
Space Loss	-67.3	-73.3	-79.3	-85.3	dB
AUT Gain	+0.0	+0.0	+0.0	+0.0	dBi
Power level at mm-wave module	-37.3	-43.3	-49.3	-55.3	dBm
Receiver sensitivity (1 kHz IFBW)	-85.0	-85.0	-85.0	-85.0	dBm
Measurement SNR (1 kHz IFBW)	**48**	**42**	**36**	**30**	**dB**

As the range length increases, the SNR drops to unusable levels. The range length should be kept to the minimum as dictated by the far-field criterion. To improve the receiver sensitivity, a low-noise amplifier can be added. Amplifiers are available with in-line waveguide inputs and outputs; these can be inserted at the receive module input. With these, an SNR improvement of 25 dB should be possible. Amplifiers that cover full waveguide bands are available up to 110 GHz. An example is shown in Figure 8.

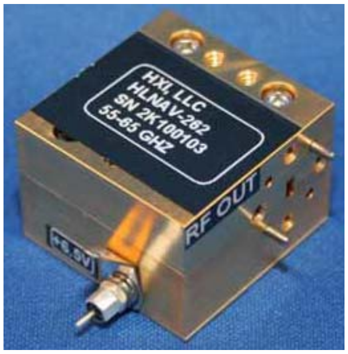

Figure 8. Example of Low-Noise Amplifier

V. SPHERICAL SCANNING GEOMETRIES

To address the need for measuring low-gain and omni-directional antennas in mm-wave mode, NSI has developed the NSI-700S-85 and NSI-700S-86 spherical near-field systems. The 700S-85 scanner is a swing-arm system with single-axis motion of the AUT, whereas the 700S-86 operates without AUT motion. The latter is especially useful for on-chip antenna testing using a probing station.

Figure 9. NSI-700S-85 Theta-over-Phi Swing Arm Spherical Near-Field Antenna Test System

First, the NSI-700S-85 spherical near-field/far-field system shown in Figure 9 has been designed to facilitate testing of low to medium gain antennas operating above 50 GHz. The antenna under test (WR10 SGH shown here) rotates as a function of ϕ around the vertical axis while the probe arm moves as a function of θ to acquire data over a spherical surface. This design allows testing of high frequency antennas with only a single axis of motion, reducing measurement errors related to alignment and gravitational sag. The implementation shown in Figure 9 uses OML modules, but also supports R&S and VDI units.

While originally designed to test antennas up to 110 GHz, the author of [6] has estimated that this system is capable of measuring antennas with the dimensions shown in Table II up to 500 GHz with a net far-field error level of -40 dB. This study concluded that the sensitivity to systematic θ error (swing arm droop) is low and can be successfully corrected for using mechanical alignment data. The effects of swing arm deflection were also found to be insignificant in the transformed far-field results. However, great care must be taken to minimize orthogonality errors between the θ and ϕ axes since the sensitivity to this type of error is high.

TABLE II. MAXIMUM DIMENSIONS OF AUT'S FOR THE NSI-700S-85 SPHERICAL NEAR-FIELD/FAR-FIELD TEST SYSTEM

Frequency	Max. AUT Diameter	
	SNF	Far-Field
150 GHz	100 mm	22 mm
300 GHz	50 mm	18 mm
500 GHz	30 mm	12 mm

Figure 10 shows the far-field directivity of a WR10 SGH as a function of frequency when measured from 75 to 110 GHz using the 700S-85 system. For comparison, the results obtained using a PNF system is shown, along with the theoretical directivity for this antenna. The peak deviation from the SNF results to the theoretical was less than 0.1 dB across the band.

Due to a small misalignment of the WR10 OEWG probe, an on-axis channel imbalance between the χ = 0° and χ = 90° orthogonal components was observed. To correct this, the channel-balance procedure described in [7] was used. Since the effects of probe position errors in spherical near-field measurements using OEWG probes is typically low [8, 9], this solution improved the channel balance between the two orthogonal components without adding any appreciable errors in the probe correction process.

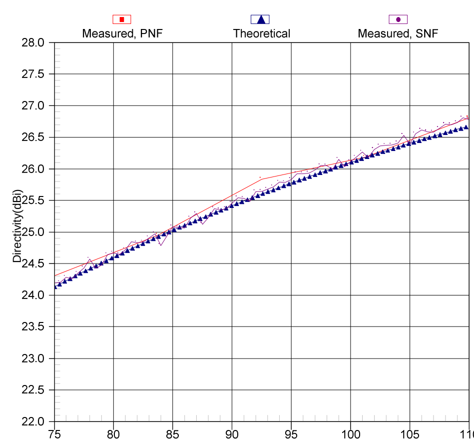

Figure 10. Directivity vs. Frequency of NSI-RF-SG10 Measured on NSI PNF and SNF Systems, compared to theoretical values

For some applications, it is desirable to have the AUT at rest during characterization. For this purpose, the NSI-700S-86 articulated spherical near-field antenna test system depicted in Figure 11 has been developed. This system permits spherical near-field and far-field measurements on antennas operating at mm-wave frequencies without the need for AUT movement during acquisition.

In Figure 11, the AUT is a chip antenna connected to an OML mm-wave module using a Cascade wafer probe and probe station. The radiating aperture of the antenna has been placed over the coordinate system origin (intersection of θ and ϕ axes) to reduce the volume of near-field data required to transform to the far field.

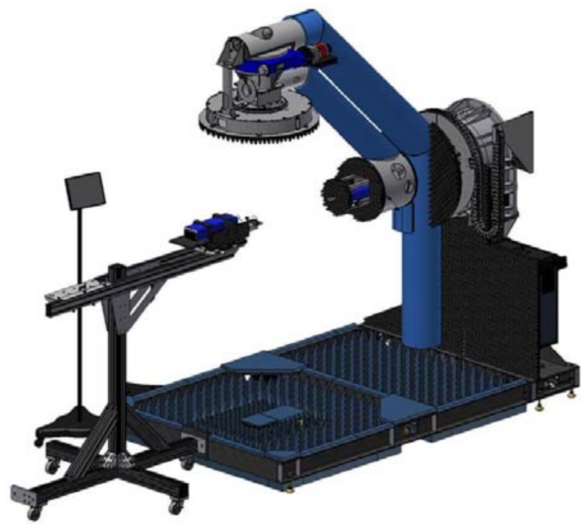

Figure 11. NSI-700S-86 Dual Swing Arm Spherical Near-Field Scanner for On-Chip mm-Wave Testing

The coordinate system for this scanner and relevant rotational axes are shown in Figure 12. A 150 mm positioner is used to rotate the probe and its mm-wave conversion module from $\chi = 0°$ to $90°$ to acquire dual-polarized data. A 300 mm rotation stage controls the θ-axis, which has mechanical limits at approximately $\pm 135°$ to prevent collision with the antenna under test and its mounting fixture. Lastly, a heavy-duty 500 mm positioner mounted to a support pedestal is used to control the scanner's horizontally-aligned ϕ-axis.

Since this scanner conforms to a conventional right handed polar spherical coordinate system, the θ and ϕ axes are perpendicular to one another at all rotational positions. To manage the various motor, control, power and RF cables during rotation, each axis is outfitted with a cable management track.

Accuracy data of the NSI-700S-86 scanner is presented in [10]; this also shows that measurement errors due to imperfect probe positioning on this scanner can be corrected with high accuracy.

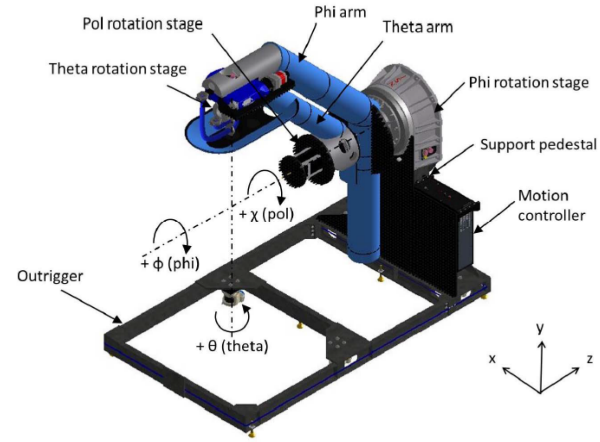

Figure 12. NSI-700S-86 showing Coordinate System and Rotation Axes

VI. MINIATURIZATION EFFORTS

As Figures 9 and 11 show, the mechanical structure required to position a fairly large and heavy mm-wave module with high accuracy is quite substantial. Miniaturized modules allow using a lighter mounting structure, which reduces the load on the polarization positioner, and in turn could reduce the weight and size of the swing arm and hence the entire scanner.

A number of vendors offer smaller mm-wave modules. Table III shows the lengths of both standard and miniaturized modules. Some of the smaller modules are also substantially lighter than their bigger brothers.

TABLE III. MM-WAVE MODULE LENGTH COMPARISON

Vendor	Type	Length (*)	Maximum frequency
OML	VNA2, T/R or S	370 mm (**)	500 GHz
	VNA2, T (Rx only)	162 mm (**)	500 GHz
	VNA3, S (Tx Only	228 mm (**)	110 GHz
VDI	Standard	327 mm (***)	1.1 THz
	Mini Tx/Rx	266 mm (***)	500 GHz
	Mini Rx (Rx only)	146 mm (***)	500 GHz
	Micro Rx (Rx only)	114 mm (***)	110 GHz
Anritsu	3743A	55 mm, 203 mm with heatsink	145 GHz

* excluding RF and control connectors
** includes 50 mm added space for DC connector
*** includes 50 mm waveguide section

Figure 11 shows 5 different mm-wave modules, each covering the WR-10 band.

Figure 13. From left: Anritsu, VDI Micro, VDI Mini, OML VNA2-T and OML VNA2-S modules

In addition to reduction in size of the mm-wave module, the polarization control can also be miniaturized. Instead of mounting the entire module on a support structure and rotating the assembly, if a waveguide rotary joint is used then it is possible to rotate only the waveguide.

Waveguide rotary joints covering the full band are available up to 110 GHz. Rotating the polarization can be done manually (as shown in Figure 14) or using a hollow-shaft positioner.

Figure 14. OML module with manually operated waveguide rotary joint.

Such a positioner can even accommodate the VDI Micro Rx module, for automated polarization rotation without waveguide rotary joint, see Figure 14.

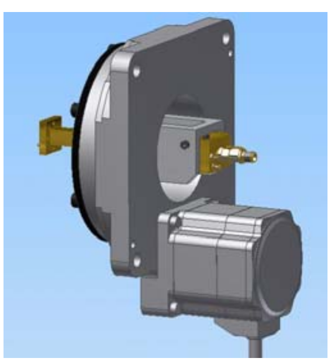

Figure 15. Concept drawing of VDI Micro Rx module mounted in rotator

Miniaturization efforts such as these are under way. However, a scanner built for small modules cannot accommodate full size modules and may not be able to operate above 110 GHz, and/or may be limited to operate in one mode (AUT transmit or AUT receive) only. Customers who wish to use existing mm-wave modules for antenna measurements should consider replacing the modules with miniaturized versions to allow using a smaller, faster and/or more accurate scanner.

VII. CONCLUSIONS

- NSI supports a wide range of instrumentation choices for mm-wave measurements, on small as well as very large antenna measurement systems
- On large systems with amplifiers in the RF and LO lines, careful adjustment of the RF and LO power is required.
- Operating amplifier at their saturation point helps level the power across the band and provides protection against accidental overload.
- Low-pass filters on the RF and LO inputs help improve the frequency response of the mm-wave modules.
- The NSI-700S-85 and -86 scanners provide spherical and far-field positioning solutions that reduce or eliminate AUT motion, which is especially useful for measuring chip antennas
- Using miniaturized mm-wave modules reduces the mechanical demands on the positioning system, which will lead to more accurate or lower cost scanner designs.

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