SOLUTION BRIEF

Fast Calibration and Characterization Test Solution for Phased Array Antennas

Dramatically Improves the Speed of Calibration, Verification, and Parametric Tests.

KEYSIGHT

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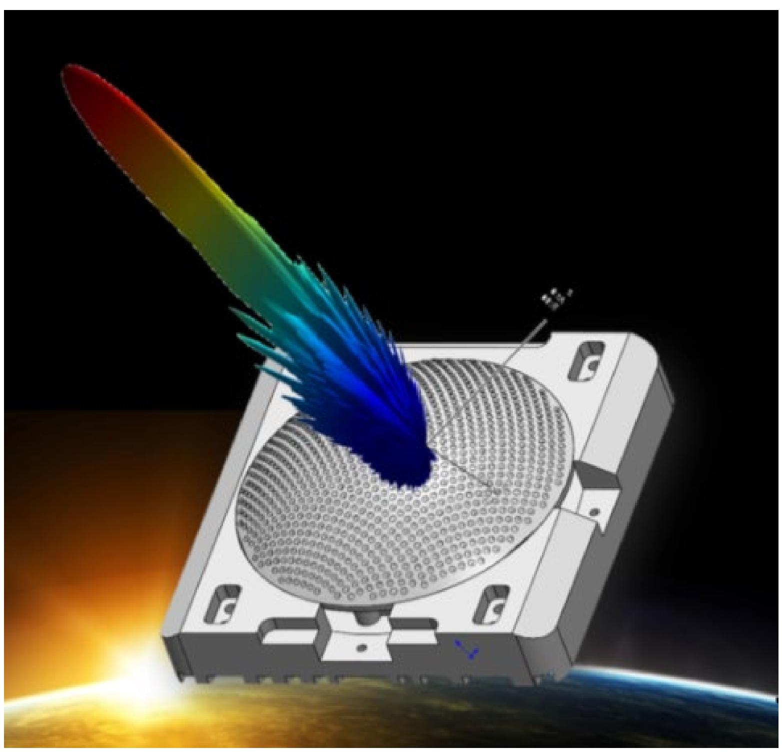
Evolution of Satellite Communications

Satellite communication systems play a vital role in modern communication applications and the growth within the satellite communication market continues to expand rapidly with advances in technology. Increasingly, complex information and data throughput support advancements in radar, surveillance, and navigation systems play an important role in mission-critical military applications. In addition, access to low Earth orbit (LEO) satellites will make it more cost-effective to support commercial applications like 5G, on satellite networks.

Modern satellite networks operate at higher frequencies and use active phased array antenna systems which are key to realizing the ubiquitous connectivity and sensing requirements of next-generation satellite communication applications. Phased array antennas, or active electronically scanned arrays (AESAs), are now highly integrated, which is driving the need for fast over-the-air testing. In fact, AESAs can support thousands of radiating elements to electronically steer beams quickly and independently and point them to precise locations. Phased array antennas utilize electronic means to rotate or steer the beam, thus improving speed and reliability over mechanical pointing methods. In addition, more complex software-defined phased array antenna systems provide mission flexibility to the communication link by enabling a change of function in real time. For example, you can switch rapidly from a defense radar to 5G antenna communications.

However, the phased array design and development process is complex as well as time and resource-consuming, as many barriers still exist when transitioning from single-element antennas to phased array solutions. A compact antenna range coupled with commercial test equipment and measurement software provides an economical and fast solution for calibrating and testing the performance of these antennas.



A Modern Approach to Active Array Testing

Keysight's phased array control and calibration test solution delivers a convenient and flexible measurement system that accommodates a wide variety of phased array antenna performance verification tests. These tests include fast gain and phase calibration, effective isotropic radiated power (EIRP), antenna radiation pattern, antenna gain-to-noise-temperature (G/T), modulation distortion (error vector magnitude (EVM) and adjacent channel power ratio), and radio frequency to direct digital measurements. The solution offers a comprehensive and user-friendly software interface that integrates and synchronizes digital control of Keysight's high-performance test instruments (PNA-X vector network analyzer and VXG vector signal generator), the antenna under test (AUT) beamforming integrated circuits, and Keysight's compact antenna test range (CATR) positioner and temperature control unit.

Overall Solution Diagram

Shown below are the main components of Keysight's turnkey phased array test solution. This solution uses a modern approach for high-speed phased array calibration and beamforming measurements.

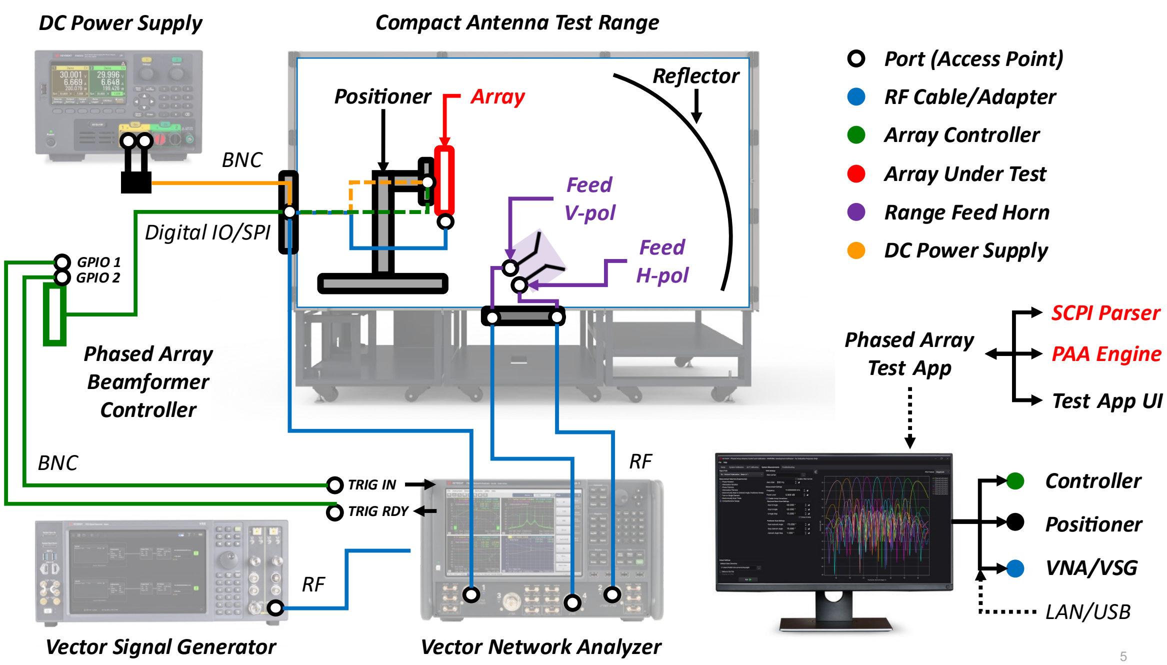


Figure 1. Keysight's Phased Array Antenna Control and Calibration test solution including a diagram of the compact antenna range (CATR) shielded anechoic chamber, phased array beamformer controller, and supporting test equipment for phased array measurements.

Compact Antenna Test Range Solutions

Keysight's Compact Antenna Test Range (CATR) solutions are designed to integrate with the device development workflow from the early chipset and device prototyping through design verification, conformance, and carrier acceptance testing. The CATR is a shielded anechoic chamber with a rolled-edge reflector and a roll-over azimuth positioner. The chamber provides an indirect far-field (IFF) measurement environment for characterizing antenna system performance from microwave through millimeter wave frequencies. There are several advantages to using a CATR versus measuring in the direct far-field (DFF). By using a reflector, the fixed CATR method allows measurements of both the individual elements and the full array with near plane-wave illumination in a much shorter distance than would be possible with a DFF measurement, which requires a distance greater than $L=2D^2/\lambda$ in order to have less than 22.5° of phase taper across an antenna aperture with diameter D, where λ is the wavelength. A CATR also has much less path loss than an equivalent DFF solution since the spherical wavefront from the feed only spreads radially until it reaches the reflector. From this point on, the beam is collimated, and the power no longer decreases appreciably with distance. Therefore, the CATR chamber provides lower signal path loss than DFF in a small compact, and portable anechoic chamber.

Figure 2. Keysight's F9650A CATR shielded anechoic chamber with frequency coverage from 6 to 110 GHz (left image) and the interior view of the rolled-edge reflector (right image). Find the complete list of Keysight's over-the-air test chambers at Over-The-Air Test | Keysight. Keysight also supports larger chambers and quiet zone sizes of 60, 80 and 150 cm options, and larger. Please contact Keysight representative for more information.

Temperature Control Unit for Space Applications

The temperature control unit (TCU) enables testing under a range of thermal conditions from -40°C to +100°C. This is accomplished by injecting hot or cold clean dry air into the antenna under test (AUT) temperature enclosure which encapsulates the AUT. The enclosure is made from polymethacrylimide (PMI) based structural foam material offering very low transmission loss for waves propagating through the shell of the enclosure.

Antenna Measurement Toolset Software

The S7601A Antenna Measurement Toolset is a comprehensive software solution to test and verify different types of antennas for cellular, automotive, radar and satellite communications. For phased arrays and passive antenna pattern measurements, Keysight's F7601000A Antenna Measurement Toolset Application provides the following options.

The F7601001A Antenna Pattern Measurement option performs spherical antenna pattern measurements and calculates metrics like directivity, efficiency, gain, beamwidth and sidelobe levels. Vector antenna pattern data captured using one of Keysight's vector network analyzers can be used to calculate circular and elliptical polarization information from the orthogonal measurements obtained using the CATR's dual-linearly-polarized feed horn. The graphical user interface allows manipulation of the pattern in 3D and extraction of user-defined cuts through the 3D surface, as well as evaluation of the various metrics associated with the antenna measurement.

Option F7601002A Phased Array Antenna Control and Calibration allows for complete control of a user's phased array and beam-forming chipset(s) through our standard SCPI command set. Keysight supports antenna-under-test (AUT) drivers developed for industry-standard chipsets, as well as user-provided custom drivers for other chipsets. Keysight's proprietary phased array calibration algorithm provides rapid calibration of each array element for R&D and production applications. When coupled with the Antenna Pattern Measurement option, the system can measure the phased array's beamforming pattern to quickly compare radiated performance before and after calibration.

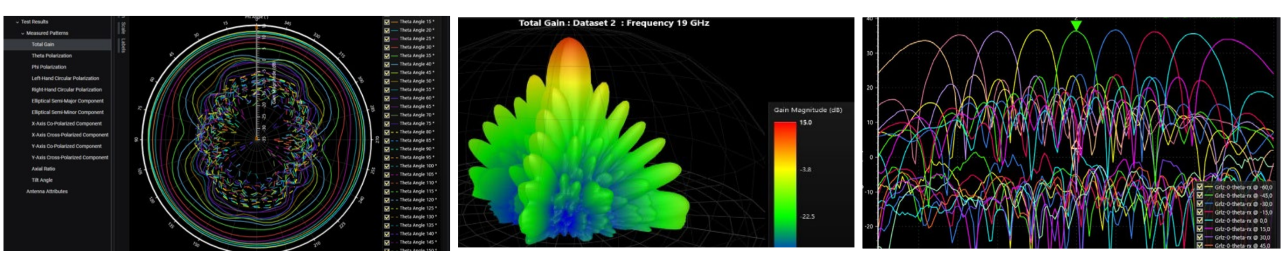


Figure 3. Keysight's Antenna Measurement Toolset software offers many graphical features, shown here are polar phi cut, three-dimensional array, and multi-beam scan patterns.

Phased Array Beamformer Topology Selection

Based on the design characteristics specified for the emission states (transmit only, receive only, half-duplex), the number of simultaneous beams (single or dual beam), and array element polarization (horizontal (H) or vertical (V), right hand circular polarized (RHCP), left hand circular polarized (LHCP)), a diagram of the beamformer circuit design and connections between the beamformer channels, and the array element feeds are displayed on the user interface (UI). This beamformer selection process limits the number of unique RF paths that can be controlled for calibration and measurements.

Over-the-Air (OTA) Test System Connections

Provides VISA addresses and test connections to each of the core components of the OTA test system including the phased array antenna under test (AUT) controller, vector network analyzer (Instrument), and chamber positioner (Positioner). The chamber positioner must be roll-over-azimuth (Roll/Az).

Phased Array Setup and Display

Specify the design characteristics for a rectangular phased array under test, or other array geometries with custom map file, including the number of radiating elements per row and column, element spacing, and range and resolution of the beamformer attenuation and phase control. A two-dimensional grid of the phased array elements is automatically generated and can display the read and write status of the beamformer circuit control registers, with success and failure (green and red) and the temperature in degrees Celsius.

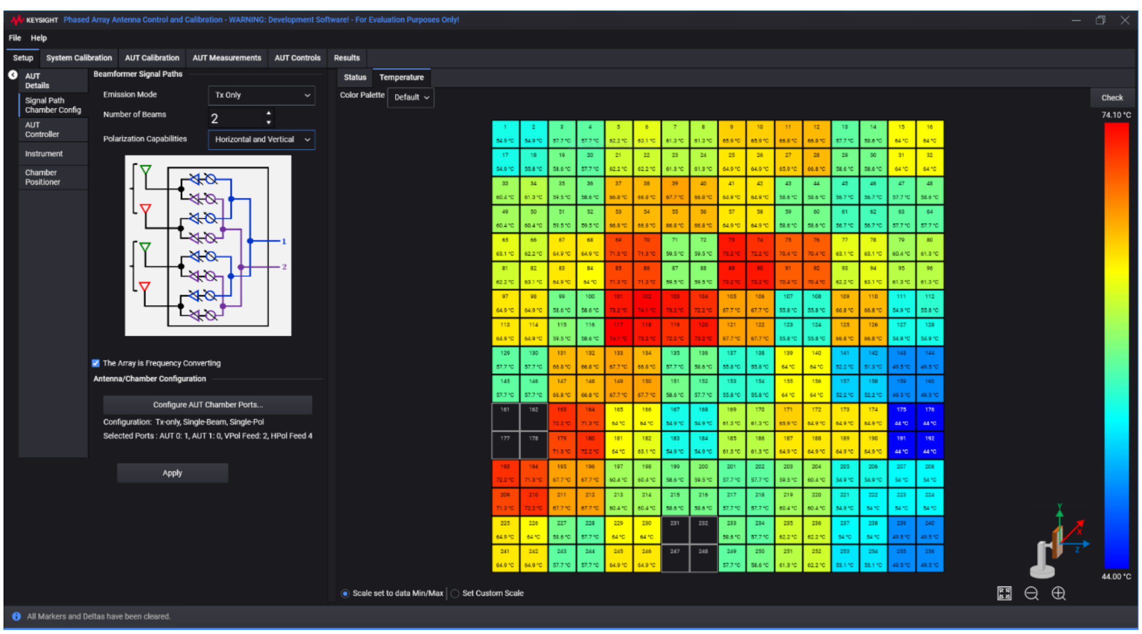
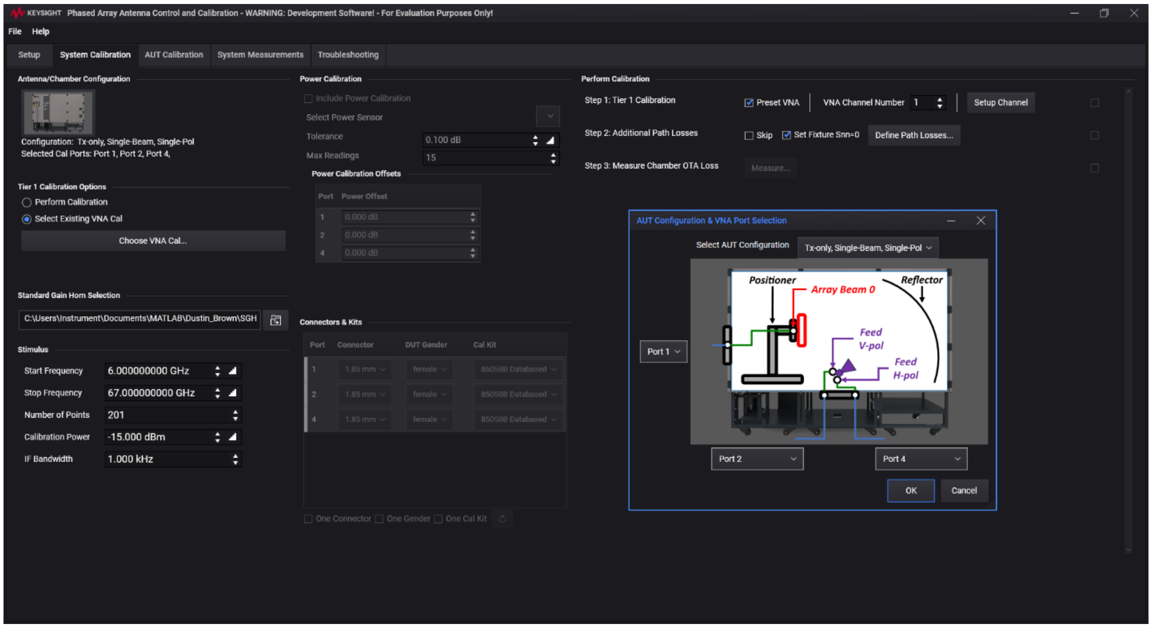


Figure 4. Phased array antenna setup display showing element temperature in degrees Celsius. The elements displayed in black are malfunctioning.

System Calibration

Full system calibration is also supported within the Phased Array Antenna Control and Calibration software interface enabling a fast and unified location for all calibration requirements of the system.



Chamber Configuration

Using the dialog box that shows a sample diagram of the compact antenna test range, select a test configuration for the phased array that generates a set of recommended connections between the network analyzer ports and the phased array and dual-linear feed antenna ports. Alternatively, designate a custom set of port connections.

Chamber Cable Calibration (Tier 1)

Perform a first-stage calibration of the network analyzer to eliminate the frequency response of cables connecting the network analyzer ports to the AUT and feed antenna. Select stimulus settings for the network analyzer calibration (frequency span, number of points, port power, intermediate frequency bandwidth (IFBW)) and include port power calibration, if desired. Calibration kit options are also displayed in the user interface for selection.

Reference Antenna Gain Calibration (Tier 2)

Perform a second-stage calibration of the network analyzer to measure the gain of a reference antenna, such as a standard gain horn (SGH). Provide an S2P file or CSV file for the reference antenna. An automated measurement of the SGH is performed on both ports of the dual-linear feed horn antenna, and a new calibration file is generated and applied, which ensures that the applicable transmission S-parameters are correlated with the realized gain of the antenna or phased array under test.

Phased Array Beamformer Calibration

Keysight’s proprietary phased array calibration algorithm provides rapid calibration of each array element, reducing test time from hours to just minutes. Antenna array calibration is a critical aspect of phased array systems since accurate pointing of a beam demands precise control of phase and amplitude. For a phased array system to operate optimally, it must undergo a calibration process to compensate for relative RF variances between channels due to manufacturing differences in RF components, the printed circuit board, and the beamforming network. Additionally, electronic components vary with operating conditions, such as frequency and temperature, and will require stored calibration files as the operating condition changes.

With a well-calibrated system, all the antenna elements add constructively allowing for maximum antenna gain. This enables signal conditioning, such as tapering and null steering. However, the calibration of a phased array antenna can be a complex and time-consuming process. Keysight has developed a solution to quickly calibrate and characterize an active phased array antenna using a vector network analyzer and a compact antenna test range (CATR). Pairing the CATR with Keysight’s PNA-X vector network analyzer and VXG vector signal generator enables a suite of calibration routines and beam pattern measurements that sweep across azimuth and elevation. Keysight’s phased array antenna calibration software characterizes the amplitude and phase of each array element with high levels of accuracy and reduces calibration time from hours to only minutes.

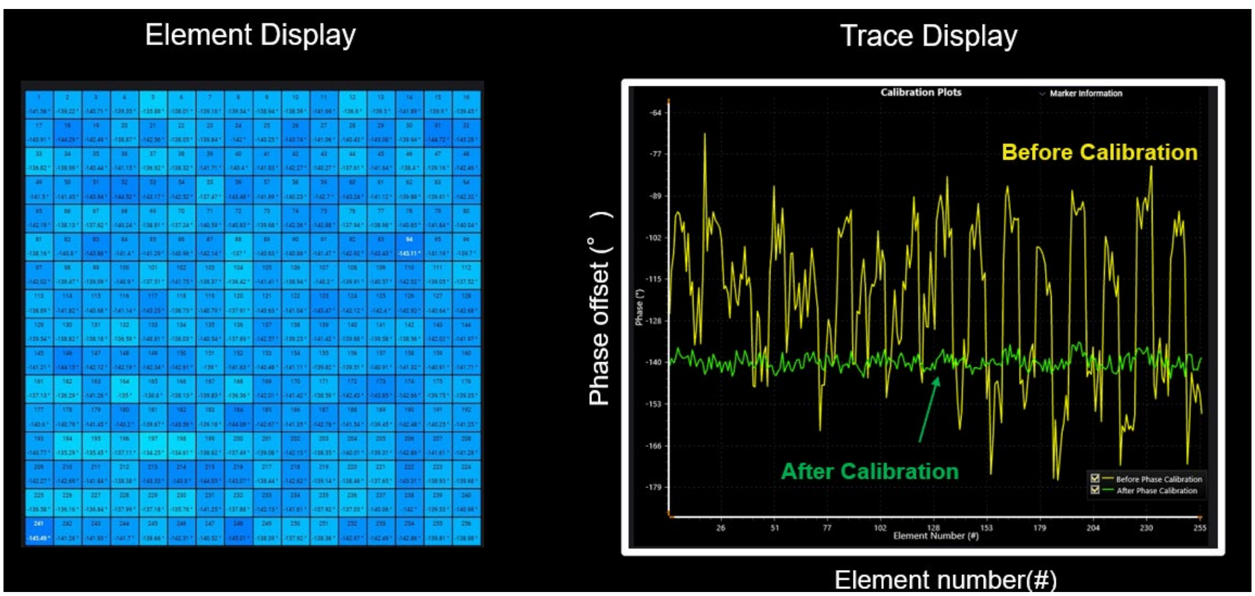


Figure 3. Phased array phase rotation measures a single element as the phase is rotated. This image shows all elements before and after calibration to a certain phase target. The calibration of a 1024 element array is performed in less than 1 minute, where a planar near-field measurement could take hours.

Calibrate Your Array in Minutes, Not Hours

Calibrate the phase and/or attenuation of the beamformer channels (for a unique signal path specified by combination of the emission, beam number, and element feed polarization) connected to each phased array element as follows: 1) select network analyzer settings (frequency, port power, IFBW) which ensure a sufficient dynamic range for measurements of individual active elements; then 2) select a single element to use as a reference and the attenuation and phase to be applied sequentially to each element in the calibration process; and 3) perform a calibration. Sequential measurements of each element are performed, and attenuation/phase offsets are calculated to normalize measured transmission S-parameter results of all other elements to those of the reference element. These offsets are stored in memory and (optionally) applied to the beamformer circuits. These offsets can also be saved into a CSV file and loaded again at a later time.

Phased Array Leakage Correction

While inclusion of leakage correction is optional, it is highly recommended and frequently necessary to ensure that gain and phase of the individual element channels are measured accurately during the array beamformer calibration process. Leakage correction includes a series of Keysight-patented techniques for eliminating the effects of leakage (radiated power from elements other than the single element under test). Leakage correction enables fast and effective beamformer calibration in a compact antenna test range environment, where radiated power from the entire array is captured by the reflector and received by the feed horn antenna (for transmitting AUT).

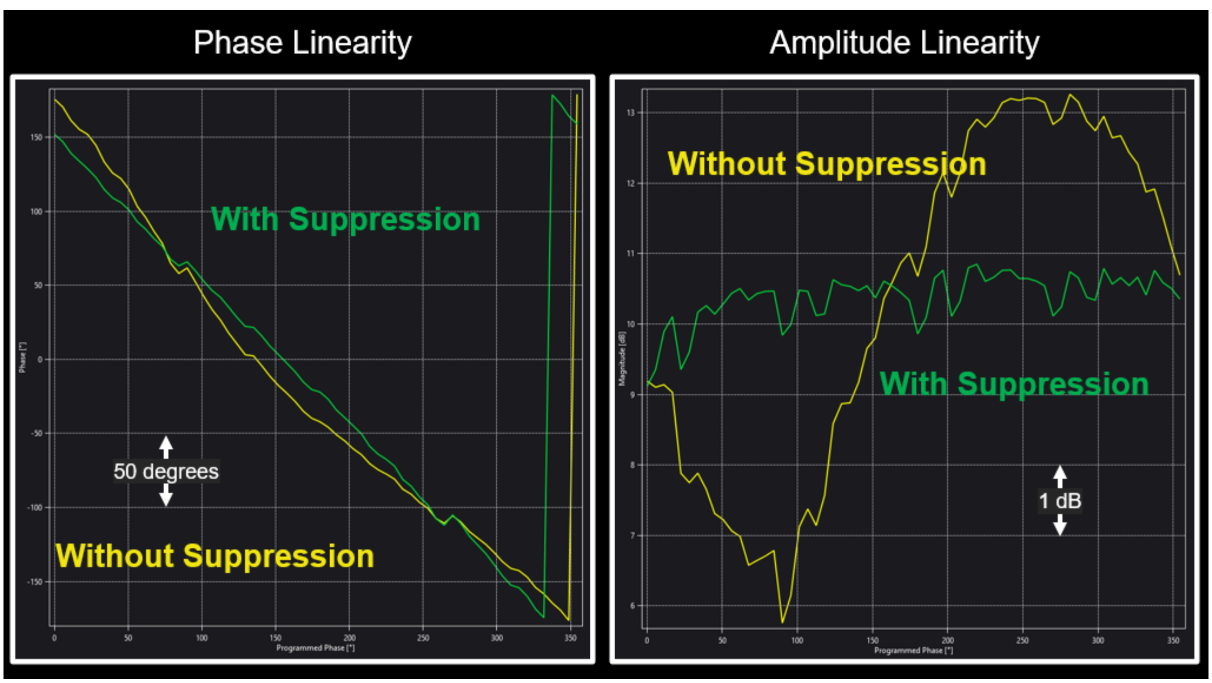


Figure 4. Phased array phase rotation measurement (linearity and amplitude linearity plots) showing the effect of leakage suppression. Leakage suppression enables measurement of the true element responses to achieve unmatched array calibration accuracy.

Phased array calibration can have a substantial impact on beam scan power and sidelobe uniformity. Shown below is the effect of accurate array calibration on beam scan measurements. The boresight main lobe array gain improved by 1.32 dB, and the phase offset was improved by 2.00 degrees. Additionally, the null depth and symmetry of the sidelobe levels are visibly improved, as well as the nulls across the array plane.

Figure 5. Phased array beam scan boresight main lobe gain showing 25.58 dB gain 2.00 degrees phase offset before calibration (yellow trace Marker 1) and 24.26 dB gain and 0.00 degrees phase offset after calibration (green trace Marker 2).

Calibration Verification Measurements

Perform a series of measurements to examine the quality of the beamformer calibration, including phase gradients, element phase rotations, and boresight gain measurements of the fully active phased array before and after the calculated calibration offsets are applied to the beamformers.

Antenna Under Test (AUT) Measurements

Attenuation and Phase Rotation Measurements

A transmission S-parameter measurement is taken for all possible attenuation and/or phase states of a selected beamformer channel (active element and selected signal path consisting of emission state, beam number, and element feed polarization). For a beamformer with a 6-bit phase shift register, this will generate a trace with 64 points, each representing a unique phase state.

Attenuation and Phase Gradient Measurements

A transmission S-parameter measurement is taken for each element in the phased array, where each one is programmed to the same attenuation and/or phase setting (for the selected signal path consisting of emission state, beam number, and element feed polarization). For a phased array with 256 elements, this will generate a trace with 256 points, one for each element at the selected attenuation or phase state specified in dB or degrees, respectively.

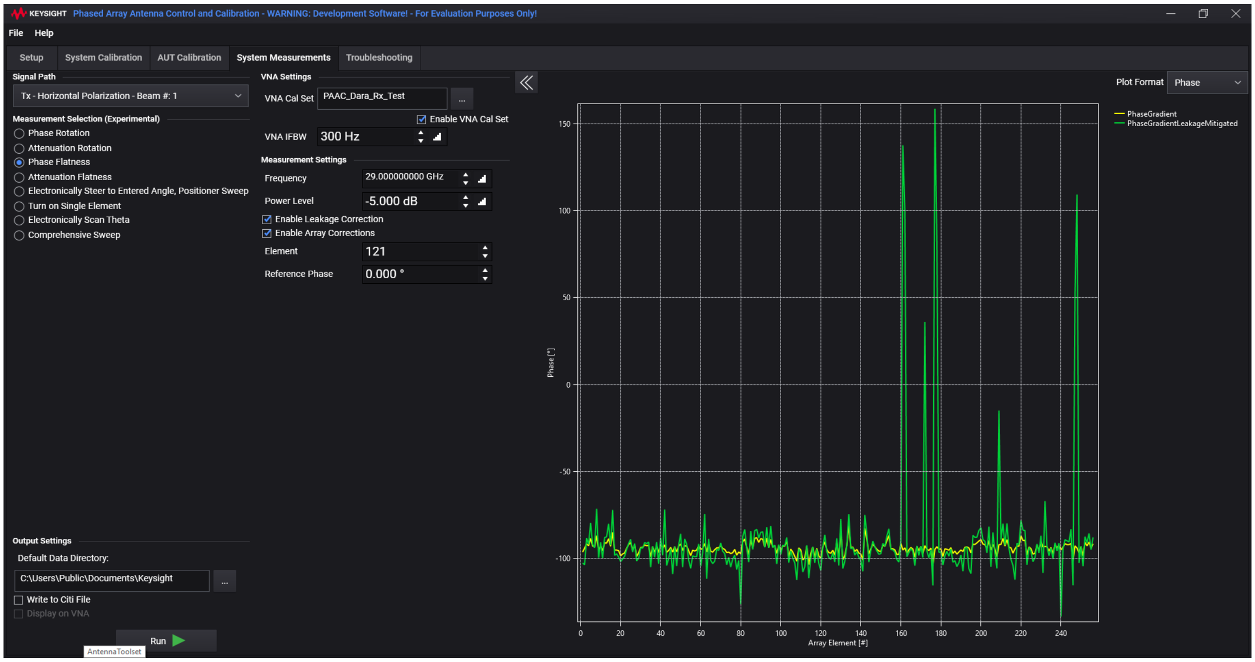


Figure 6. Phase flatness measured with and without leakage suppression.

Automated Beam Scan Measurements (Electronically Scan Theta)

A transmission S-parameter measurement is taken for each beam steering angle (specified as one of multiple theta angles) within a user-defined plane (specified as a single phi angle) for the selected signal path. For this measurement, the AUT positioner remains stationary. This measurement is typically performed at boresight only to verify the peak gain of the array, for example.

Automated Beam Pattern Measurements (Comprehensive Sweep)

A transmission S-parameter measurement is taken for each beam steering angle (specified as one of multiple theta angles) within a user-defined plane (specified as a single phi angle) and for each AUT positioner angle (specified as one of multiple AUT positioner azimuth angles). The measurement is performed for the user-selected signal path (e.g. Transmit, Beam 1, Vertical polarization) and beamformer calibration state with attenuation and/or phase corrections activated or deactivated. The measurement results in a 2D cut of the beam patterns for each of the specified beam steering angles, which can be plotted in the UI or on the network analyzer as CITI file. Beam width and beam scan loss over the specified scan range may be determined via the available trace marker options.

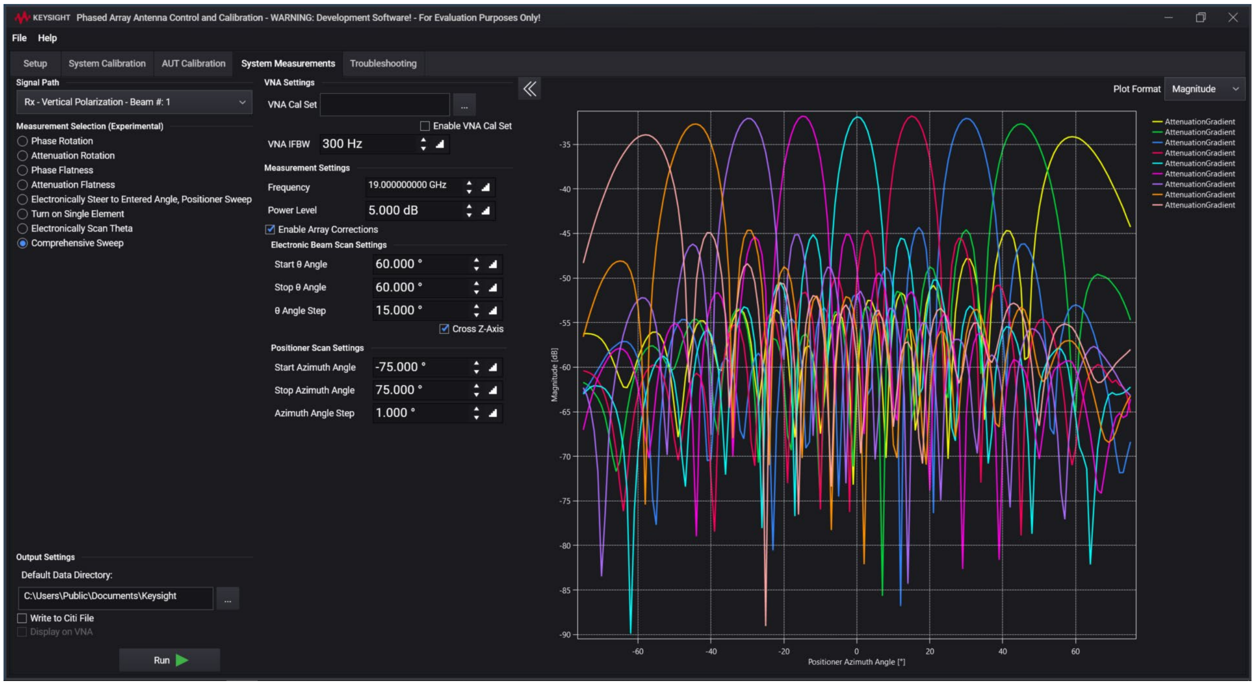


Figure 7. Mechanical scan of the positioner moved from -75^{o} to +75^{o}, and for each step of the positioner the beam was electronically steered to 9 different directions, all in one quick measurement.

Comprehensive Sweep and Beam Steer Commands

Get multiple beam pattern traces for different steering angles, element feeds, and calibration. For example, you can sweep the AUT positioner along the azimuth from ϕ_{start} to ϕ_{stop} in user-defined ϕ_{step} increments while programming the phased array and capturing data for user-defined sets of beam steering angles, element feeds (polarization), and calibration states.

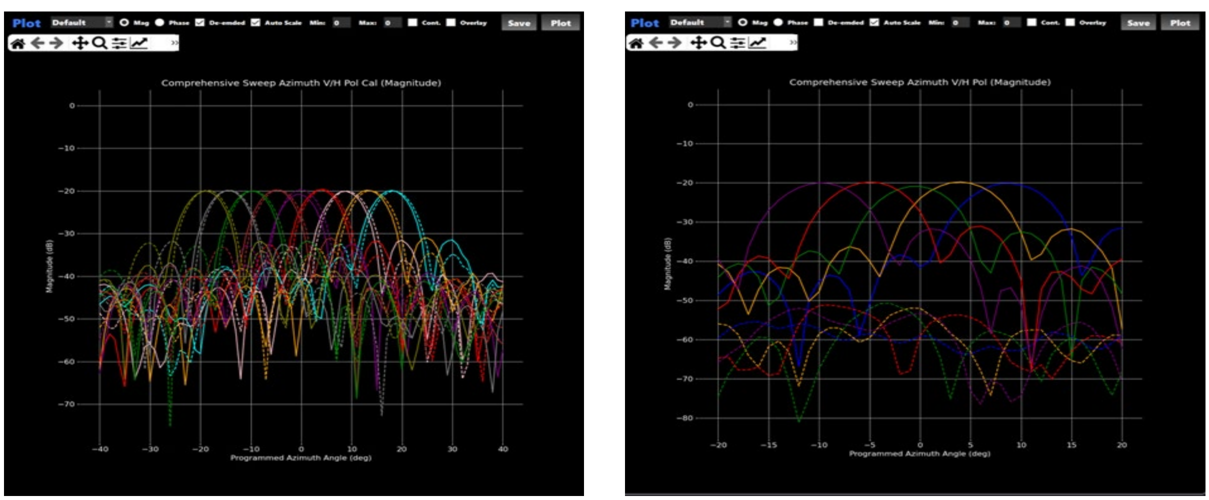


Figure 8. Comprehensive beam sweep azimuth showing the calibrated versus uncalibrated array (left image) and comprehensive beam sweep azimuth showing the co-polarization versus cross-polarization of the array (right image).

AUT Troubleshooting Features

- **Array Element List Definitions:** Users will be able to select two or more array element numbers and assign and save them to a customized list (e.g. array list #1 = elements 3, 13, 34, 54, 107, and 156). Beamformer attenuation/phase control settings may then be applied to every element within this user-defined list.
- **Independent Element Attenuation/Phase Control:** Individual array element channels (specified by element number and selected signal path) can be independently controlled to set the desired attenuation/phase states.
- **Toggle Options for Application of the Base and/or Calibration State Files:** Users will be able to activate or deactivate attenuation/phase offsets from base state and beamformer calibration files.
- **Beam Steering Function:** Steer the beam to a single direction (theta, phi)
- **Polarization Control:** Set to V, H, RHCP, or LHCP mode (if dual-linear)
    - 12 dB Unselected Output
        - 15 dB (Both Input and Selected Output)
        - 12 dB Unselected Output
- **Switching speed:** < 1 ns (10%-90% RF)
- **DC coupled:** < −45 dBc @ 10 MHz and 5 dBm < −65 dBc @ 2 GHz and 5 dBm

Network Analyzer Application Measurements

Keysight’s antenna test solutions can be configured with a variety of RF and radio communication test equipment, including Keysight’s popular line of vector network analyzers, such as our PNA-X series. Keysight's PNA-X includes two internal signal sources, a signal combiner, S-parameter and noise receivers, pulse modulators and generators, and a flexible set of switches and RF access points. These hardware features provide a powerful core for a broad range of linear and nonlinear measurements, all with a single set of connections to your device under test.

A wide variety of metrics can be obtained in a single test configuration, including effective isotropic radiated power (EIRP), radiation patterns versus beam scan angle, beam scan range and loss, cross-polarization isolation, gain compression, modulation distortion (EVM), adjacent channel power (ACPR), and gain-over-noise-temperature (G/T).

Analyze Wideband Modulated Satellite Signals

Keysight's VXG vector signal generator offers high output power with ultra-low phase noise for your most demanding wireless, automotive, and aerospace and defense applications. With the addition of a vector signal generator that can provide the desired modulated stimulus, the network analyzer can be setup to measure the EVM and ACPR of the signal resulting from transmission and reception by the AUT. Nonlinear measurements of the array, such as swept gain compression and error vector magnitude (EVM), in the classic “bathtub curve” of EVM vs. power, are made by driving the device into compression using a wideband modulated signal through a booster amplifier. Using the modulation distortion measurement class and PathWave Vector Signal Analysis software, the channel and signal distortion characteristics can be viewed in both the frequency and time domains.

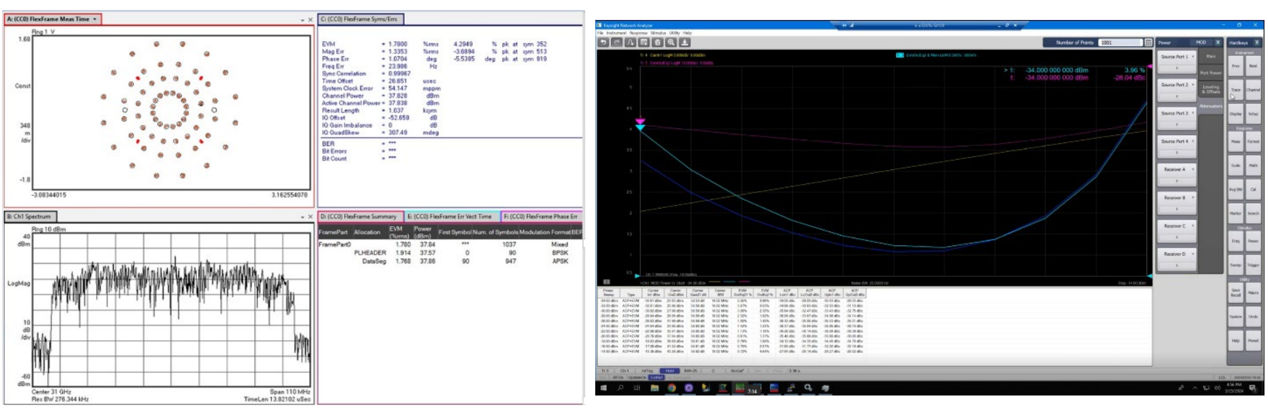


Figure 9. Demodulation and analysis of a digital video broadcast signal (DVB-S2X) with PathWave Vector Signal Analysis software (left) and Modulation Distortion (EVM) vs. Output Power “Bathtub Curb” (right).

Return Loss and Cross-Polarization Ratio (XPR)

Additional S-parameter traces can be setup on the network analyzer to measure the return loss (S11) and cross-polarization ratio (e.g. S21/S41 for a Transmit AUT with a dual-linear feed) of the phased array under test.

Effective Isotropic Radiated Power (EIRP)

Additional traces can be set up on the network analyzer to measure the power for receivers, which is correlated with EIRP following the power and standard gain horn calibration procedures from the system calibration tab within the Phased Array Calibration and Control software application. EIRP is typically referenced to a compression point of the AUT, such as P1dB. Prerequisite compression measurements can also be performed with the power sweep options available for the network analyzer.

Gain-Over-Temperature (G/T)

Gain-to-noise temperature (G/T) and signal-to-noise ratio (SNR) are common figures of merit, which replace noise figure measurements for active antennas. The PNA-X combines the antenna's gain measurement and the phased array antenna system's noise power to directly measure G/T. The G/T of a receiving phased array can be measured directly on the network analyzer, using the noise figure measurement class and equation editor (to combine results of the phased array gain and noise temperature measurements). The phased array port must be connected to port 2 of a PNA-X to utilize the low-noise receiver for this measurement.

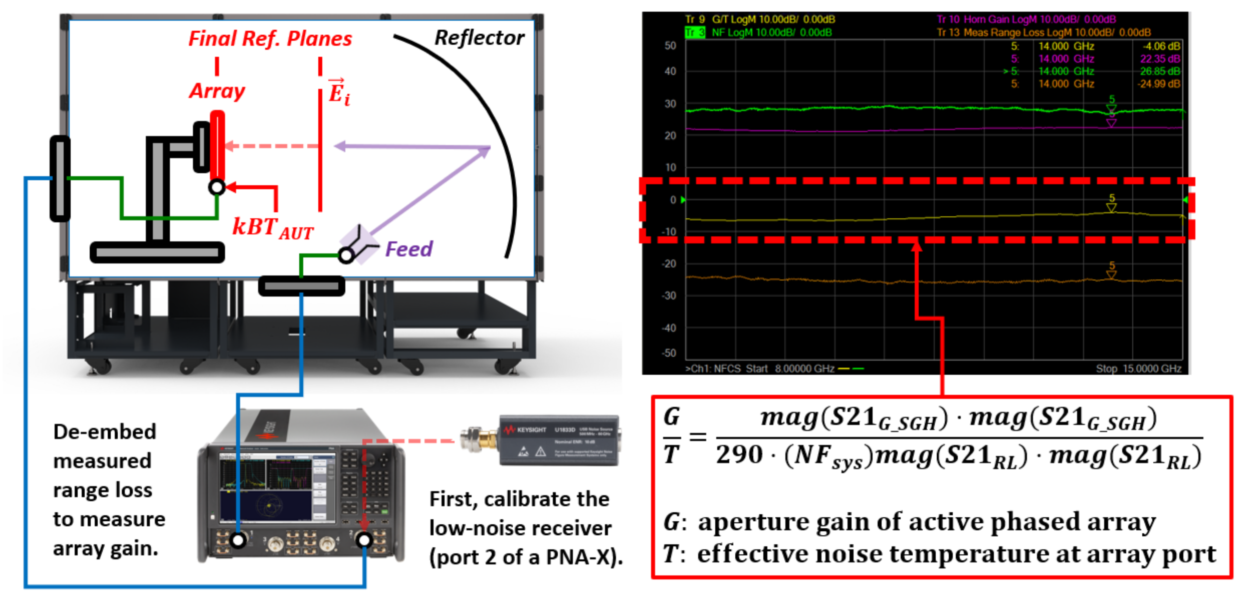


Figure 10. Diagram showing how to make noise figure measurements for receiver arrays using the PNA-X vector network analyzer.

Test Solution Configuration in Brief

Table 1. Below is a brief overview of the hardware and software options discussed in this document. Please contact Keysight for a detailed configuration specific to your device under test. Find additional information on this solution at www.keysight.com/find/ota-test. Installation of the chamber and consulting services for system bring-up, integration, software setup, workflow training, and initial phased array OTA measurement support are also available and quoted with each system.

Model	Description	Recommended Options
N5244B	PNA-X Microwave Network Analyzer, 10 MHz to 43.5 GHz	• N5244B-422, 4-port, configurable test set • N5244B-029, add noise receiver to 43.5 GHz
F9650A	Compact Antenna Test Range (CATR), 6 GHz to 110 GHz, 40 cm Quiet Zone	• Contact Keysight for configuration. • Other CATR solutions available, including 60 cm, 80 cm, 1.5 m QZ, and greater QZ options
M9484C	VXG Vector Signal Generator, 9 kHz to 54 GHz	• Other frequency options available.
F7601000A F7601001A F7601002A F9629001A	Antenna Measurement Toolset Antenna Pattern Measurement Phased Array Antenna Control and Calibration Chamber Control Software	• Required option for software application. • Required for 2D/3D pattern measurements. • Required for array control and calibration. • Required for CATR and positioner control.

Installation of the chamber and consulting services for system bring-up, integration, software setup, workflow training, and initial phased array OTA measurement support are also quoted with each system.

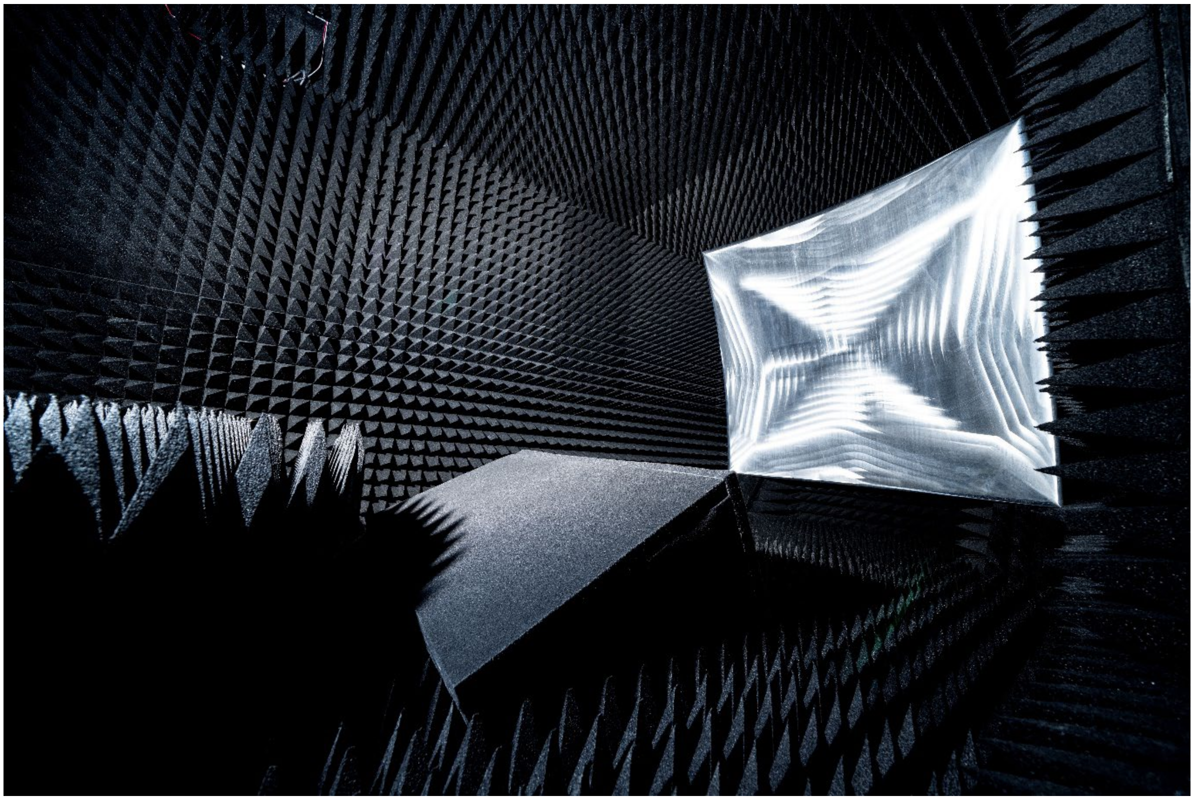


Figure 11. Inside view of CATR showing reflector and absorber material.

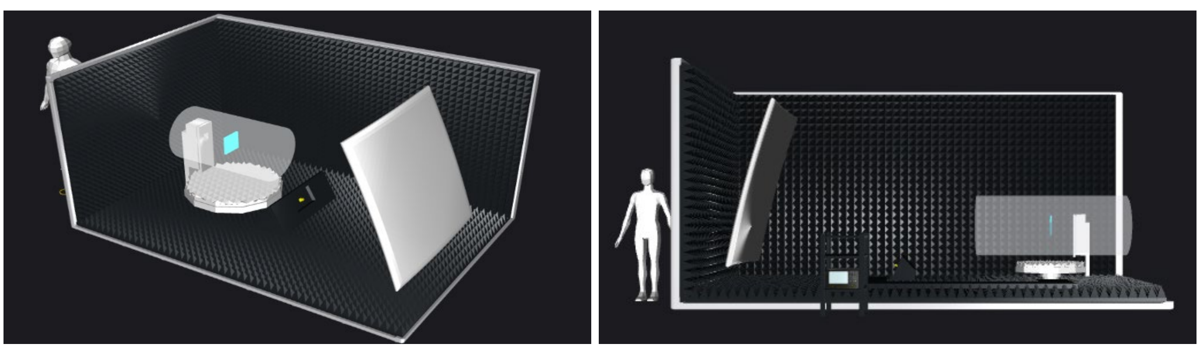


Figure 12. Drawings of 60 cm (left) and 80 cm (right) CATR Quiet Zone solutions.