A Dual-Band High Power PNF Range with Interleaved T/R and Pulse Synchronization

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Abstract – Modern antenna range design is often a careful balance of several competing objectives. Some of these design parameters are defined by the antenna under test (AUT), i.e., millimeter wave (Ka-band) test frequencies, frequency-converting and non-converting AUTs, high-power radiation requirements, pulsed RF requirements, and interleaved transmit and receive (T/R) requirements. Other parameters are driven by the AUT’s application, like requirements for providing accurate pattern, gain, EIRP, and G/T predictions based on the measurement data. Yet other parameters are driven by cost and risk considerations, like the need for all-at-once acquisitions incorporating multi-frequency, multi-port, dual-pol, and multi-state measurements. Also included in the “cost and risk” category is the need to collect all these measurements in the least amount of time.

A planar near-field antenna range designed with all these parameters in mind has been realized and is currently operational. This 1 m x 1 m planar near-field range incorporates several novel electrical and mechanical features, and we illustrate these features in terms of their driving requirements and their limitations. Included in our discussion: modular T/R range “front ends,” reconfigurable probe networks, absorber cooling strategies, near-field probes for high-power measurements, interleaved single-port transmit and multi-port receive measurements, and distributed pulse mode range architectures.

Keywords – Range Design, Interleaved T/R, High Power, Millimeter Wave, Frequency Converting, G/T, EIRP, Active Antenna

I. INTRODUCTION

The modern antenna range has become far more complex in the past decade. The simple range of the past is often inadequate for today’s antenna subsystem designs featuring antennas that are no longer separable from the electronics behind them. More sophisticated tests are needed to characterize these compound assemblies of antennas, amplifiers, switches, and frequency converters. The “antenna range” has now become a much more intricate “subsystem test range,” providing capabilities far beyond simple pattern and gain measurements. Similarly, the Antenna Under Test (AUT) has now become the Unit Under Test (UUT) to acknowledge the wide range of functions and requirements that might be imagined for devices that integrate electromagnetics, mechanics, electronics, firmware, software and other technologies. We shall discuss a recently completed Subsystem Test Range that supports the measurement of particular test articles, but the solutions presented can be adapted in designing or upgrading ranges to test other integrated-antenna UUTs.

II. UNITS UNDER TEST / GENERAL REQUIREMENTS

Integrated antenna subsystems can take on any number of functions depending on the supported product, which may be a communicator, transponder, radar, or jammer. In our specific case (Figure 1) the UUTs are both “pulse-mode” devices that transmit a pulse for a short period and then switch to receive mode to listen for returning signals. The range equipment is responsible for generating synchronized digital Transmit/Receive and Pulse signals (Figure 2) to drive the UUT and range sources, as well as distributing these signals throughout the measurement system (Figure 3). The range is also responsible for re-routing various RF signals (Figure 4 and Figure 5) in synchrony with those digital signals to make all the measurements possible. For our purposes, we shall describe a few specific features of the UUTs to be tested in this range. While this range is designed to test two separate bands by replacing RF hardware, we will focus mainly on the features driven by two types of Ka-band UUTs.

Figure 1. Simplified block diagrams for two UUTs.
mode. In receive mode, the UUT has several discrete “ports” corresponding to different antenna patterns, and each port outputs a Ka-band signal. This unit is considered an “active” antenna as it may provide amplification in either or both directions, but it includes no frequency converting components. The electronics and antenna in this unit are completely integrated; the only access points are the aperture on one end, and the provided input and output ports on the other end. Table I lists the inputs and outputs for this Type 1 UUT.

<table>
<thead>
<tr>
<th>TABLE I. TYPE 1 UUT ATTRIBUTES.</th>
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<tr>
<td><strong>UUT Type 1</strong></td>
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<td><strong>Port Type</strong></td>
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<td>Input</td>
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<td>Input</td>
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<td>Aperture</td>
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B. Type 2 UUT

This device operates in pulsed transmit mode, accepting a Ka-band rectangular pulse which is amplified and transmitted. After the pulse is transmitted, the UUT switches to receive mode. In receive mode, the UUT has several discrete “ports” providing L-band signals from the UUT corresponding to different antenna patterns. These L-band signals have been down-converted within the UUT from the received Ka-band signals. This unit is an “active” antenna that provides amplification in both directions, as well as downconversion from Ka-band to L-band in the receive direction. The electronics and antenna in this unit are completely integrated; the only access points are the aperture on one end, and the provided input and output ports on the other end. Table II lists the inputs and outputs for this Type 2 UUT.

<table>
<thead>
<tr>
<th>TABLE II. TYPE 2 UUT ATTRIBUTES.</th>
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<tbody>
<tr>
<td><strong>UUT Type 2</strong></td>
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<td><strong>Port Type</strong></td>
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<td>Input</td>
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<td>Input</td>
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A. Type 1 UUT

This device operates in pulsed transmit mode, accepting a Ka-band rectangular pulse which is amplified and transmitted. After the pulse is transmitted, the UUT switches to receive
C. Complicating UUT and Test Factors

Three measurement requirements drove significant complexity into the range design. First, Type 1 and Type 2 units are to be tested in their “normal” operation mode, where they emit enough RF power to present a safety hazard to personnel and a fire hazard to typical absorber materials. The personnel hazard can be mitigated by enclosing the UUT and test range equipment in a shielded, interlock-controlled chamber (Figure 6), but the fire hazard must be mitigated in the range design – the range must be able to accommodate high RF power levels in continuous operation. Second, all tests are to be carried out using a Planar Near Field (PNF) geometry to conserve facility space and facilitate handling and mounting of the UUT. This forces the need to take phase-coherent measurements, as the near-field phase is necessary to generate far-field patterns. Third, test timeline requirements dictate that we acquire data for the Transmit and multiple Receive functions “simultaneously” (at least within the same scan) as this reduces the total UUT scan time by a factor of three or more [1]. The trade for the time savings is range complexity; the entire range needs to support Tx/Rx reversal and multi-port Receive measurements within the Pulse Repetition Interval (PRI) used to drive the UUT.

![Figure 6. Shielded test chamber.](image)

D. Test Requirements

In determining useful parameters for evaluating the performance of the integrated assemblies described here, it becomes evident that the familiar antenna range “gain” measurement is insufficient. Since the antenna aperture and the electronics are inseparable, the measured “gain” is a combination of antenna gain and electronics gain. It can be shown that the “antenna-only gain” may be helpful in determining useful performance parameters, but the “combined gain” is typically not helpful for system analysis [2]. Below is a brief discussion on the measured quantities of interest from this range.

1) Relative Patterns & Directivity: The traditional “antenna pattern” is still quite useful for evaluating integrated antenna subsystems, giving the engineer an assessment of spatial radiation intensity. Similarly, directivity gives a general idea of how “concentrated” the signal is at its peak. Unfortunately, these are only relative parameters – unless paired with other subsystem attributes like front-end noise figure or transmitted power, they don't provide enough information to determine the subsystem’s operational performance.

2) Effective Isotropic Radiated Power (EIRP): EIRP (typically expressed in units of dBW) is a measure of a UUT's Transmit effectiveness, and is often described as the amount of power that would need to be pumped into an isotropic radiator to produce an equivalent flux density to that radiated in the direction of interest by the UUT. Conversely, given peak EIRP and the radiation pattern, it is easy to calculate the flux density at any far-field point from the UUT. From flux density comes the signal available to any sort of receiving antenna at that point – a useful quantity in predicting communication system performance. EIRP is relatively easy to measure in a PNF range [3]. EIRP measurements are “calibrated” using the gain of the near field probe (which may be accurately measured by a qualified laboratory) and the response of a microwave power meter or signal analyzer (also calibrated).

3) Gain over Temperature (G/T): In the Receive direction, G/T (typically expressed in units of dB/K) provides a measure of the UUT’s sensitivity. In this case G is the “antenna-only gain” of the UUT, and T is the effective noise temperature of the UUT in a specific environment. This parameter provides an easy way to arrive at a signal-to-noise ratio (SNR) for the UUT, and thus assess overall system performance. It has been shown that G/T can be measured in a planar near-field range setting [2]. As in the far-field scenario, it is not possible to separate G and T from a PNF measurement but the ratio G/T is obtainable and is useful for link budget calculations. G/T measurements made using this method are “calibrated” using the known probe gain and the response of a calibrated signal analyzer.

4) Boresight Roll: The ability to roll the UUT about its boresight axis is quite useful for assessing measurement linearity [4]. In UUT-Transmit mode, analysis of boresight roll results allows confirmation that the entire range receive path, including range switches, amplifiers, and mixers, is free from compression – an important test when working with high-power transmitting antennas. This type of measurement is just as useful in UUT-Receive mode, allowing the range operator to confirm that internal components of the UUT (or the subsequent range receive path) have not been driven into compression. While not a required data output for the UUT itself, boresight roll testing improves accuracy and confidence in the Relative Pattern, Directivity, EIRP, and G/T measurements.
E. Physical Constraints

The mechanical design of a subsystem test range is influenced by the electrical and physical properties of the Units Under Test. Test article size, shape, and weight define physical mounting and movement constraints. UUT connection types (i.e., control, bias, power, data, thermal control) set constraints on mounting and positioning as well. For the PNF range geometry, the aperture size and desired far-field angle of coverage define the minimum size of the scan plane. Finally, radiation properties influence every aspect of the design. The highest test frequency sets accuracy bounds on the scan plane in all directions. The lowest test frequency sets a minimum useful z travel on the probe mount and the minimum absorber thickness. Antenna coverage angles define the extent of the absorber used in the range, and, high radiated power levels add the requirement for special absorber treatment, including heat-resistant materials and active thermal management. Some of the range requirements set by the UUTs described here are provided in Table III.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Constraint</th>
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<tbody>
<tr>
<td>Scanner X-, and Y-travel</td>
<td>( \geq 1 \times 1 \text{ m} )</td>
</tr>
<tr>
<td>Probe Z-travel</td>
<td>( \geq 5 \text{ cm} )</td>
</tr>
<tr>
<td>Mechanical Tolerances</td>
<td>Alignment, Position Error, Planarity, Probe Pointing suitable for ( \lambda = 7.5 \text{ mm} )</td>
</tr>
<tr>
<td>UUT Slide Travel</td>
<td>( \geq 1.5 \text{ m} )</td>
</tr>
<tr>
<td>UUT Positioner</td>
<td>Phi-axis Rotary for Boresight Roll Tests</td>
</tr>
<tr>
<td>Incident Power (cont.)</td>
<td>( &gt; 8 \text{ W/cm}^2 ) on scanner and probe</td>
</tr>
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</table>

III. Test Range Implementation

The general concept of a range offering the described functions has already been illustrated above and in Figure 3 through Figure 6. Here we shall discuss some of the implementation details needed to meet selected requirements.

A. Pulse-Mode T/R Operation

Test requirements for the two UUTs dictate that the range operates in pulse mode and switches between Tx and Rx modes in synchrony with the UUT. For this range, we decided not to use the common scheme of distributing individual TTL pulse trains along coaxial cables. Instead, distributing pulses in differential form reduces the likelihood of interference between signal lines. Also, since we have several pulsed signals to distribute, we decided to package them together in a multi-twisted-pair cable to simplify the wiring. This allows us to make sure lines are terminated properly and pulse edges are clean, even at the highest pulse rates. The pulse source, a Stanford Research DG645 Pulse Generator, feeds the Pulse Distribution Center (PDC). The PDC provides for conversion of the DG645’s pulse sequence to differential format, and also provides the drivers and terminations to fit purpose-built pulse distribution cables. To faithfully duplicate pulses for transmission to various points on the range, Timing Control Distributor (TCD) modules (shown in Figure 3) provide an active, well-terminated “split” that preserves the timing and edge quality of the pulses from the PDC. Finally, individual Digital Control Endpoint (DCE) modules (Figure 7) are used at each Pulse or T/R switch to provide clean control signals to those switches. Along with the Pulse and T/R signals, this system of modules and cables also carries separate digital signals to control various switches for the devices in the range, e.g. the probe polarization switch.

Figure 7. Digital Control Endpoint (DCE) module.

The RF components for pulsed T/R range operation include modules designed to produce RF pulses from the digital pulse signals. For the period where the UUT is in transmit mode, the RF pulse is produced by a PIN switch in the Transmit Control Module (TCM). When the UUT is in receive mode, the probe must transmit an RF pulse. A switch in the Probe Control Module (PCM) provides that pulse, again relying on the digital pulse signal. At the same time, these modules use the T/R signal to set the direction of signal flow. While the range mode of “T” or “R” is described by the UUT mode, in practice the probe is receiving while the UUT is transmitting and vice versa. Therefore, the digital T/R signal drives the UUT and associated modules directly but is inverted to “R/T” on the way to the Probe Control Module.

B. Two types of Ka-band UUTs

Because of the similarities between the two types of UUTs, a dual-conversion architecture (Figures 4 and 5) was selected for the range RF subsystem. The choice was made to duplicate the converting UUT’s mixer function in the receiver front end. In this way, the setup for a converting or non-converting UUT is almost identical. The RF cables are simply rearranged to provide the first mixer’s function either inside the UUT or in the Dual Downconverting Mixer (DDM) module nearby. The detail in Figure 8 shows how the connections are made, providing the same dual-conversion frequency scheme in both cases.
C. Incident RF Power on Scanner

In normal operation, the UUTs described here radiate RF power density levels that exceed the power handling capacity of standard absorber. To eliminate the fire hazard posed by these RF power levels, it was decided to use high-power “honeycomb” absorber in all areas where high field strength would be expected. Unlike the more common urethane foam absorber, the phenolic-coated plastic “honeycomb” substrate can withstand high temperatures and does not readily ignite even when overheated. On its own, this type of absorber can handle about 1.6 W/cm² but with active air cooling can continuously dissipate more than 12 W/cm² [5]. Because air cooling is a necessity, our design is based on maintaining continuous airflow through all absorber panels used in high-flux areas. This gave rise to the absorber/fan “modules” used on the scanner (Figure 9) which in turn led to the dual-carriage X-axis design that accommodates the absorber/fan “backwall” of the scanner system (Figure 10). The need for continuous airflow also led to a fan power, control, and monitoring subsystem. Finally, in an abundance of caution, we implemented a temperature alarm system based on infrared cameras to detect any “hot spots” on the absorber wall and shut down the system if the temperature anywhere on the absorber subsystem reaches a user-defined threshold (Figure 11).

D. Incident RF Power on Probe

The other location where the high incident power can cause trouble is at the probe itself. To get a known, well-behaved probe pattern (necessary to remove the probe’s effect from the near field measurement), reflections from and around the probe must be managed. Using an absorber collar would require active air cooling – too complex and bulky to fit around the relatively small Ka-band probe. The choice was made to simply direct incident energy away from the test zone using probe shaping [6]. Figure 12 shows a picture of the implemented probe design. The aperture is a simple circular waveguide, which has the advantage of being able to receive two orthogonal linear polarizations when paired with the orthomode transducer hidden behind the large conical “skirt.” The angle of the cone was chosen such that energy directed toward the probe would be scattered into the angled absorber panels at the edges of the scan plane.
Figure 12. Microwave Engineering & Manufacturing Corporation (MEMCO) Probe.

E. Band Changes

This range needs to be easily converted for operation to support UUTs with similar requirements in other bands. Since millimeter-wave testing is often waveguide-based, we chose to use Virginia Diodes VNAX modules (Figure 13) to provide frequency up- and down-conversion from Ku-band to any of the VDI-supported bands. This allows us to use similar Ku-band RF modules for control and switching. A diagram of the VDI-based RF subsystem is shown in Figure 14. The mechanical design of the alternate probes and electronic modules allows them to be easily substituted at the same mounting points as the Ka-band probes and electronic modules to facilitate quick conversion between bands. The most complicated swap is the probe subassembly, shown in Figure 15.

Figure 13. VDI millimeter-wave modules.

Figure 14. VDI-based RF diagram.

Figure 15. Probe swap process.

IV. Conclusion

Designing, constructing, and verifying this test facility involved many more details than can be covered in this short paper, but clearly test facilities intended for modern integrated antenna subsystems will require a much more detailed “fitting” to meet ever more complex requirements. The range designer must keep pace with a wider view of antenna technology which goes far beyond the electromagnetic aspects of the art. The hope is that future range designers can use some of the lessons learned here to improve upon antenna measurement system architecture and deliver well-optimized solutions for testing modern antenna subsystems.

REFERENCES
