Keysight Technologies
Increase Test Throughput with the Multi-Channel Antenna Calibration, Reference Solution

Application Note
Introduction

For multi-channel antennas (e.g. phased arrays), a significant amount of production test time is spent on calibration. Large arrays can consist of hundreds or thousands of elements and it is necessary to characterize the phase and gain alignment between these elements to ensure precise beam-forming. In addition, the test time to align these elements can increase dramatically as the number of elements increases. Hence, the ability to accelerate testing by using multiple coherent measurement channels is a significant benefit. Advancements in antenna and radar technologies also require a scalable and flexible platform that can accommodate future requirements.

This application note describes an innovative solution for accelerating the calibration of multi-channel antennas using a reference solution based on high-speed, multi-channel digitizers with real-time digital down conversion (DDC). The reference solution utilizes narrowband analysis to measure the element-to-element phase and magnitude errors of the antenna elements. This enables the test engineer to quickly and accurately identify misalignment of radiating elements and calibrate them out to ensure efficient operation of the array.
Key Measurement Challenges

The element-to-element phase and amplitude (gain) errors of the various components in the array are significant limitations to its overall performance. For example, phase and gain mismatches of antenna elements lead to increased sidelobe levels as shown in figure 1.

In a transmit antenna configuration for RADAR, the sidelobes transmit energy into free space (i.e. not in the intended direction as the antenna) and it can be reflected back and cause interference with the signal that is returning off of the target. In addition to increased interference with the signal of interest, large sidelobes indicate a waste of beamforming power and create a large radiated signature making the antenna more easily detected by jamming systems. In receive mode, large sidelobes will pick up more interference and reduce the signal-to-noise (SNR) ratio in the receiver.
Gain and phase errors directly contribute to sidelobe errors. The average sidelobe level due to these errors (normalized to isotropic level and using λ/2 element spacing) can be determined by the following formula:

\[
SLL_0 = \pi (\varphi^2 + \delta^2)
\]

where \( \varphi \) is the phase error variance (radians) and \( \delta \) is the fractional amplitude error variance.

Therefore, these phase and amplitude errors introduced by the misalignment of the radiating elements must be calibrated out so that the antenna operates efficiently and effectively. Calibrating out these errors however, presents the antenna test engineer with a number of challenges:

- Given that the beam-forming capability of a modern phase array antenna must be precise, it is critical to achieve phase-coherent sampling across all measurement channels. It is also important to select a measurement system that provides relative magnitude and phase measurements with a low-enough variance across measurement channels to achieve desired sidelobe levels.
- Array element counts are increasing, therefore calibration times are increasing. An increase in measurement speed is needed without sacrificing accuracy to minimize impact on test times. Therefore, measurements require high resolution sampling of IF signals and sources with fast frequency switching.
- The need to test and calibrate multiple antenna types requires a measurement system with wideband capability or flexibility to add more measurement channels in the future.
- In some cases, it is necessary to disaggregate the measurement. For example, mixers may need to be as close as possible to the antenna, with digitizers in a rack with controller.

**Measurement Requirements**

Today, a multi-port, network analyzer is typically used to make relative gain and phase measurements on the antenna. The measurements are generally made serially across all of the antenna ports, or channels, using a switch matrix. This can result in significant test times, especially for large arrays consisting of hundreds or thousands of elements.

To decrease measurement times during the antenna calibration process, measurements can be made in parallel using multi-channel, phase-coherent, digitizers. A multi-channel test signal configuration (in receive mode) is shown in figure 2. For receive mode, the antenna is excited by the microwave source and received signals are measured at the RF ports of the antenna. To measure the received signal, this system uses various signal conditioning elements and downconverters in addition to the digitizers.

The signal path flows from left to right, originating with the AUT (antenna under test) and then through several stages of signal conditioning and down conversion depending on the application. There are several things to consider:

- Translating the RF/μW signal from the antenna elements down to an intermediate frequency (IF) that is within the bandwidth range of the digitizer using downconverters
- Matching the signal level from the AUT to the input of the down converters
- Amplifying or attenuating the down converter output signal to a level that falls close to the full-scale range of the digitizer (maximizes the dynamic range of the digitizer)
- Adding a low-pass filter if image protection is required

While the diagram above illustrates the system configuration for receiver calibration, the same equipment can generally be used for transmitter calibration as well. In this case, additional digitizer channels would be required to measure the reference and probe receive signals while the antenna is transmitting.
Methods for measuring relative phase and gain

Depending on the test signals being used for array calibration, there are two basic methods which can be used to measure and analyze the cross-channel response for relative phase and gain measurements on a multi-channel antenna:

- The first method is a narrowband approach that uses a swept or stepped tone with a receiver to measure one frequency at a time and perform cross-channel computations in the time domain. This method is therefore limited to narrowband measurements but utilizes simpler computations for relative phase and gain.
- The second method uses a broadband stimulus and a wideband receiver to measure all frequencies simultaneously and compute the cross-channel spectrum.

The focus of this application note will be on the narrowband method for calculating cross-channel amplitude and phase.

Digital Down-Conversion

One of the key elements of a multi-channel antenna test system is a DDC. As depicted here in figure 3, a DDC is a two-stage digital signal processing block that processes the data taken directly from the ADC at full sample rate. The resulting output sample rate and bandwidth are optimized to match the signal being used to test the antenna.

Figure 3. DDC block diagram.
The signal processing blocks of the digitizer with DDC perform the following operations as shown in figure 4:

- **ADC**: The Analog-to-Digital Converter (ADC) digitizes the real signal at a minimum sampling rate defined by the Nyquist criteria to be $2x$ the highest frequency component of the test signal being received by the antenna. Often, the digitizer over-samples the signal such that the input signal occupies only a small portion of the actual digitizer analog bandwidth.

- **Tune**: This step is the tune stage (frequency translation). In this stage, a digital LO which matches the center frequency of the real signal is mixed with the signal along two split paths with a forced 90 degree phase separation (cos and sin) producing I&Q components. This step takes the complex signal which is symmetrical around DC and translates it the spectrum to DC (blue arrow in figure 4).

- **Zoom**: The next stage of processing from the DDC is the zoom or decimate stage. With the signal already frequency translated to DC, the task now is to reduce the sample rate to a value appropriate for the input signal's bandwidth and filter out the unwanted redundant frequencies (green arrows in figure 4). This process of filtering reduces the bandwidth and therefore decreases the amount of integrated noise in the signal.

- **Memory**: after frequency translation and decimation, the data is stored as complex I&Q samples to the digitizer's memory until it is off-loaded from the digitizer for processing.

![Figure 4. DDC operational steps.](image-url)
Utilizing a DDC for multi-channel antenna calibration has many benefits:

- By reducing noise in the time domain, the DDC effectively improves the sensitivity for phase and amplitude measurements.
- Since only the decimated data samples are stored in memory, the DDC increases the amount of measurement intervals that can be stored in memory or reduces the amount of data that needs to be transferred to a computer for post-processing.
- Reducing the amount of data for each measurement interval can also reduce the workload on post-processing algorithms since there is less data to analyze.

In summary, converting real samples from the ADC to in-phase (I) and quadrature (Q) samples, which can then be digitally filtered to achieve optimal sensitivity on the measurements, is the most efficient and accurate method for measuring relative phase and amplitude over a reduced set of required samples. There is a trade-off between narrowing DDC bandwidth even further (to lower the variance) and encroaching on the signal spectrum we’re trying to measure. Hence, a combination of the DDC and integration is a practical approach.

**Narrowband analysis and computing cross-channel results**

The I&Q sampling methods described above help provide a simple way of calculating complex cross-channel ratios for measuring relative phase and amplitude. The following methodology can be used to perform phase and magnitude calculations in the presence of spurious and noisy signals assuming a narrowband signal. In this example, r(t) is the reference channel and x(t) is the signal on one of the receive channels, both functions of time.

Typically, a number of sample points would be taken for each measurement interval allowing for a dwell time for each interval. The result is two complex matrices for each measurement interval (each measurement interval could be samples taken at a given test signal frequency or a particular antenna gain/phase state):

Let $X = [x_0 \ x_1 \ x_2 \ \ldots \ x_{n-1}]$ be N complex samples of $x(t)$
Let $R = [r_0 \ r_1 \ r_2 \ \ldots \ r_{n-1}]$ be N complex samples of $r(t)$

Using the complex representation of the reference and measurement channels (X and R), we can compute a cross-channel ratio ($G_1$):

$$G_1 = \frac{X}{R}$$

This is normalized to a real-only denominator by multiplying by the conjugate of $R$ as shown (in Matrix form):

$$G_1 = \frac{XR^*}{RR^*}$$

In summation form, this can be expressed as:

$$G_1 = \frac{\sum_{n=0}^{N-1} x(nT) \ast r(nT)^*}{\sum_{n=0}^{N-1} x(nT) \ast r(nT)^*}$$

By integrating over a number of samples as shown above, we can reduce the phase variance due to noise and spurs. The end result of this process is a single I&Q point for each measurement interval. We can then calculate the relative magnitude and phase from the reference channel as follows:

$$\text{Mag} = \sqrt{G_1^2 + G_1^2}$$

$$\text{Phase} = \tan^{-1} \frac{G_1}{G_1^*}$$
Configuring a Solution

Now that we have seen how a digitizer-based system can be used make cross-channel, amplitude and phase measurements on a multi-channel antenna, we can define a practical example of a test system.

Digitizer requirements

As shown above, a wideband digitizer is the heart of the multi-channel measurement system. Using a multi-channel digitizer to test multiple antenna elements/channels in parallel can accelerate test speeds. In a phased array antenna with hundreds or thousands of elements, where it is necessary to characterize each element in a relative way to the others, the ability to accelerate the test by using multiple input channels is a significant benefit. Other requirements of such a digitizer are summarized below:

- The digitizer must have sufficient 3dB analog bandwidth necessary for characterizing signals across the different possible functions in the phased array. The narrowband approach requires less bandwidth, but a wideband approach will require much more. A digitizer with wideband capability can provide the flexibility to meet future needs.
- Since the antenna beam is steered by changes in phase, it is essential to use a digitizer with phase coherent inputs. This typically requires a phase coherence <1 degree but ultimately depends on antenna phase shifter resolution
- Using a digitizer with DDC capability can provide significant advantages. If the DDC is real-time (implemented in an FPGA for example), it can also speed-up the overall test process and maximize utilization of digitizer memory
- A digitizer built using a scalable platform (for example a modular format) increases flexibility for future test cases.

Reference Solution

Keysight has developed a multi-channel antenna calibration Reference Solution based on the concepts discussed above. This Reference Solution is a combination of hardware, software, and measurement expertise providing the essential components of a narrowband antenna calibration test system. The M9703A was selected for the system and is uniquely suited to this application due to the real-time DDS capability and wide bandwidth. It also has excellent channel-to-channel phase-coherence across multiple modules. While the Reference Solution is targeted at narrowband measurements, the M9703A can be used with wider bandwidth signals (up to 300 MHz with DDC and 600 MHz without DDC).

A block diagram of the Reference Solution is shown in figure 5. In this example, the signal routing is illustrated for 8 of the available 16 channels. The signal from the antenna is first downconverted using a Keysight M9362A-D01 quad downconverter. Each downconverter module contains four, phase-coherent mixers with a signal range up to 40 GHz depending on option. The Keysight M9352A Quad amplifier/attenuator modules provide signal conditioning prior to the M9703A digitizers. Also shown in this example is the Keysight N5193A UXG agile signal generator supplying the antenna test signal while the Keysight N5183B MXG microwave signal generator is being used as the local oscillator for the down converters (using a power divider). The Keysight M9037A PXIe embedded controller is being used to control both the AXIe and PXIe chassis.
Reference Solution software

The Keysight multi-channel antenna calibration Reference Solution includes software which was specifically designed for this application. It is made up of two parts: 1) evaluation GUI and 2) .NET Class Library. Source code is provided so that the antenna test engineer can use as is or enhance to fit a specific application.

Evaluation GUI

The Reference Solution GUI provides a tool for demo and evaluation of this digitizer-based solution. It provides the following functions:

- Digitizer and test setup/control (Figure 6)
- Visualizing cross-channel results, phase and magnitude (Figure 7)
- Measurement interval isolation (setup of windowing and integration) (Figure 8)
- Software preferences, status, utility, and file functions
Figure 6. Test setup and control.

Figure 7. Absolute and relative phase plots.

Figure 8. Absolute and relative phase plots after integration and windowing.
.NET Class Library

The Reference Solution is supplied with a class library which automates collection of measurements on or more M9703A digitizers in a multi-module synchronous set. It uses digital downconversion (I&Q samples) and optionally segmented (multi-record) memory. It also provides methods to extract single channel and cross-channel phase and gain measurements. This allows the antenna test engineer to focus on processing and analyzing the measurement results, rather than focusing on how to extract the relevant data out of the digitizer(s). The library is compiled as a 64-bit class library in .NET Framework 4.5 (Visual Studio 2012) in Windows 7 or 8 (64-bit). Source code for this class library is also provided allowing the test engineer to modify as required.

Measurement example

An example multi-channel antenna measurement scenario is shown in figure 9. Calibrating a multi-channel antenna typically involves making measurements at multiple frequency points and multiple antenna states (including phase and gain settings). In this example, we have two measurement loops, frequency and antenna state. Given the fast switching time of the UXG signal generator, we loop through all frequencies before changing to the next antenna state. Also shown in this diagram are the M9703A digitizer measurement intervals consisting of 16 samples for each frequency. The digitizer is re-armed after step through all of the frequency steps (at the same time as the DUT switches state).

![Figure 9. Example multi-channel antenna measurement scenario](image-url)
For this example, we make the following assumptions:

- 1 MHz bandwidth (using DDC) with M9703A decimated sample rate of 1.56 MSa/s for I,Q
- M9703A Measurement time = 640 ns sample period * 16 (integration for comparable sensitivity) = 10 µs
- DUT state switching and digitizer re-arm time = 2.5 µs
- N5193A UXG frequency time = 120 ns (using list mode)
- Test conditions: 1000 DUT states, 30 frequencies, 39 measurement channels (plus reference channel)

To estimate the time it takes to make these measurements, we use the following:

\[
\text{Total Measurement Time} = (Dwell + \text{Freq sw Time} + \text{Freq Pts} + \text{Rearm(SST)} + \text{DUT STs})
\]

\[
\text{Total Measurement Time} = (10 \mu s + 120 \text{ ns}) \times 30 + 2.5 \mu s \times 1000
\]

Total Measurement Time = 0.31 sec

In this case, we produce 18.75M total I&Q samples with a combined 8 Bytes per I&Q pair for a total of 150 MB. These I&Q samples are then transferred to the computer for integration and computation of phase/magnitude data. Transferring this data to the M9037A embedded controller takes approximately 0.375 seconds assuming a typical transfer rate for the M9703A of 400 MB/s.

**Conclusion**

While testing fast is often associated with lower resolution measurements, using the M9703A digitizer as the measurement core of an antenna array test solution enables increased test throughput with optimized sensitivity and resolution. The phase coherent, multi-channel M9703A digitizer enables increased production capacity by performing multiple measurements in parallel.

Furthermore, with the use of DDC digital signal processing algorithms, engineers can trade-off analysis bandwidth for signal to noise ratio to customize the solution for each test without swapping out the digitizer hardware.

The Keysight Multi-Channel Antenna Calibration Reference Solution, based on the M9703A digitizer, offers a modular and flexible solution. It can easily be scaled to accommodate additional antennas in the array under test. The Reference Solution provides software specially designed to make cross-channel amplitude and phase measurements and the software can be modified to meet application specific requirements.
### Ordering information

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M9703A</td>
<td>AXIe 12-bit digitizer</td>
</tr>
<tr>
<td>M9703A-SR2</td>
<td>Maximum sampling rate, 1.6 GS/s</td>
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<tr>
<td>M9703A-DDC</td>
<td>Real-time digital downconversion</td>
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<td>M9703A-F10</td>
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<td>M9703A-M16</td>
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<td>M9352A</td>
<td>PXI amplifier/attenuator</td>
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<tr>
<td>M9362A-D01</td>
<td>PXIe quad downconverter</td>
</tr>
<tr>
<td>M9362AD01-F26</td>
<td>10 MHz – 26.5 GHz frequency range</td>
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<tr>
<td>M9362AD01-F40</td>
<td>10 MHz – 40 GHz frequency range</td>
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<tr>
<td>M9018A</td>
<td>18-slot PXIe chassis</td>
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<tr>
<td>M9037A</td>
<td>PXIe high-performance embedded controller</td>
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<td>M9037A-WE7</td>
<td>Windows embedded standard 7 (64-bit)</td>
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<tr>
<td>M9037A-M08</td>
<td>Adds 8 GB memory</td>
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<tr>
<td>M9037A-M16</td>
<td>Adds 16 GB memory</td>
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<td>M9502A</td>
<td>2-slot AXIe chassis</td>
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<tr>
<td>M9505A</td>
<td>5-slot AXIe chassis</td>
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<tr>
<td>M9514A</td>
<td>14-slot AXIe chassis</td>
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<tr>
<td>M9514A-521</td>
<td>Adds AXIe system module</td>
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<tr>
<td>N5183B</td>
<td>MXG microwave analog signal generator</td>
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<td>N5183B-1E1</td>
<td>Step attenuator, 115 dB</td>
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<tr>
<td>N5183B-1EA</td>
<td>High output power</td>
</tr>
<tr>
<td>N5183B-520</td>
<td>Frequency range, 9 kHz to 20 GHz</td>
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<tr>
<td>N5183B-532</td>
<td>Frequency range, 9 kHz to 31.8 GHz</td>
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<td>N5183B-540</td>
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<td>N5193A-EP1</td>
<td>Enhanced phase noise</td>
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<td>N5193A-FR1</td>
<td>1 Hz frequency resolution</td>
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<tr>
<td>N5193A-PM1</td>
<td>Pulse modulation</td>
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<tr>
<td>N5193A-SS1</td>
<td>1 μs switching speed</td>
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<tr>
<td>N5193A-SS2</td>
<td>250 ns switching speed</td>
</tr>
<tr>
<td>N5193A-UNT</td>
<td>AM, FM, phase modulation, and narrowband chirp</td>
</tr>
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</table>
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