Multi-antenna Array Measurements Using Digitizers

Presented by: Alexander Dickson, Agilent Technologies
Multi-antenna Array Measurements

Agenda

• **Phased Array Applications Overview (10 min)**
  – Antenna architectures and enabling technology
  – Benefits of modern phased array antennas
  – Test challenges of phased arrays

• **Testing Multi-Element Array Antennas (15 min)**
  – Phase and gain measurements
  – Using complex signals
  – Sensitivity to match BW
  – Accelerate your measurements
Multi-antenna Array Measurements

Agenda (cont.)

• **Configuring a Test System (10 min)**
  – Phase coherence
  – Digitizer features
  – Conversion loss / NF, power levels
  – Occupied dynamic range
  – System-level calibration

• **Realized Solution (10 min)**
  – M9703A digitizer
  – DDC and segmented memory
  – Measurement example
# Antenna Architectures

<table>
<thead>
<tr>
<th>Parabolic Dish Antenna</th>
<th>Mechanically Steered Array</th>
<th>Passive Electronically Scanned Array</th>
<th>Active Electronically Scanned Array</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="#">RADAR Dish Antenna</a></td>
<td><a href="#">Marconi Martello S-723</a></td>
<td>[AEGIS AN/SPY1D(V)](# *)</td>
<td><a href="#">APAR</a></td>
</tr>
</tbody>
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<tr>
<th>1940 - Cavity Magnetron</th>
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* APAR: AEGIS Passive Array Radar

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*Note: The images and text provided are placeholders and should be replaced with actual content.*
Modern Active Electronically Scanned Phased Array (AESA)

Key Benefits

• Fixed position antenna
• Ability to form multiple agile beams
• Fast scan rates with hard to predict, irregular scan patterns
• Independent transmit/receive modules per element
• Reduced power loss from integration of RF source on each T/R
• Graceful degradation – single source failure will not cripple system

Historical Phased Array Test Challenges

Aligning Radiating Elements for Optimum Performance

- Phase and amplitude errors lead to an increase in side lobe levels (SLL)
- Large side lobes indicate a waste of beam forming power and cause interference
- Average side lobe level due to phase and amplitude errors (normalized to isotropic level and using $\lambda/2$ element spacing) [1]:

\[
\overline{SLL_O} = \pi (\overline{\phi^2} + \overline{\delta^2})
\]

- Where $\phi$ is the phase error variance (radians) and $\delta$ is the fractional amplitude error variance

New, or growing Challenges

• Array Element Counts Increasing 
  (*need speed without loss of accuracy*)

• Digital Moving Closer to the Antenna 
  (*may not have access to stimulus in analog form*)

• Broadband Modulated Signals (not just pulsed) 
  (need to generate and capture full-bandwidth signals)

• Multi-Function 
  (need flexible measurement system, other types of signal analysis such as modulation accuracy)
  – Search, SAR, etc.
  – Communications
Multi-antenna Array Measurements

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• Testing Multi-Element Array Antennas (15 min)
  – Phase and gain measurements
  – Using complex signals
  – Sensitivity to match BW
  – Accelerate your measurements
Measuring Relative Phase and Gain

Two Approaches

• **Narrow Band Approach**
  – Swept or stepped tone
  – Narrowband receiver
  – Measure one freq at a time
  – Cross-channel computations in time domain
  – Lower variance by integrating longer (narrower RBW)

• **Broadband Approach**
  – Broadband stimulus
  – Wideband receiver
  – Measure all frequencies simultaneously
  – Compute cross-channel spectrum
  – Lower variance by averaging

Network Analyzers are limited to narrowband measurements

Digitizers and VSA’s with DDC’s have adjustable bandwidths
Digital Down-conversion (DDC)

What is a digital down-converter?

*It’s a flexible processing block that allows an ADC to run at full rate while the output sample rate and bandwidth are optimized to match the current signal.*

- Digital signal processing
- Produces complex I&Q samples from real ADC samples
- Frequency translation (tune)
- Filter and decimation (zoom)
What a DDC Does For You:

• Isolate the signal of interest
• Improve the analog performance and dynamic range (SNR, ENOB), by reducing the amount of integrated noise
• Extend the amount of capture memory (in seconds), or reduce the amount of data that need to be transferred for a given duration.
• Reduce the workload on post-processing algorithms \(\rightarrow\) less data to analyze
DDC - Tune Result
For a proper analytic signal, the **negative frequencies** need to be removed by the decimation filters.
DDC - Real vs. Complex

Real-Only signals are conjugate symmetric about DC
Minimum sample rate: 2*f1

Complex signals can be asymmetrical about DC
Minimum sample rate: B

Bandwidth that determines sample rate

- Real signals are only signals are conjugate symmetric about DC
- Complex signals can be asymmetrical about DC

2 Step Process
Tune (shift)
Zoom (filter and decimate)
With reduced bandwidth there is less noise power (and spurious) to interference with amplitude and phase measurements.
DDC – Noise Reduction in Time Domain

Phase measured from reference channel to other channels

Decimation Ratio = 2
Decimation Ratio = 4
Decimation Ratio = 8
Narrow-Band
Computing Cross-Channel Time

Let \( r(t) \) be the reference channel and \( x(t) \) be the signal on one of the receive channels. The test signal is positioned away from spurs and does not have to be at the center of the IF.

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 \( r(t) \).

In Matrix Form the complex number the can be converted to amplitude and phase is:

\[
G_1 = \frac{X R'}{R R'}
\]

In Summation Form the computation is:

\[
G_1 = \frac{\sum_{n=0}^{N-1} x(nT) \times r(nT) \times r(nT)^*}{\sum_{n=0}^{N-1} r(nT) \times r(nT)^*}
\]

This calculation is unbiased as the expected value of the noise and off-frequency spurious is zero.

Use \( N=1 \) when the DDC bandwidth provides sufficient isolation from system spurs and integrated noise power.

Use \( N > 1 \), i.e. 10 or 100 samples, to reduce the phase variance due to noise and spurious.

\[
Mag = \sqrt{Im(G1)^2 + Re(G1)^2}
\]

\[
Phase = \tan^{-1}\left(\frac{Im(G1)}{Re(G1)}\right)
\]

\( G_1 \) = Complex ch-ch ratio (I&Q) Use this to compute relative mag and phase using:
Frequency Domain Approach (wideband)

\[ S_y = HS_x + S_N \]

- \( H(f) \) is DUT transfer function
- \( x(t) \) is a broadband signal with energy at all frequencies of interest (noise, chirp, etc.)
- \( S_x \) is the vector input spectrum of \( x(t) \) computed as the FFT(\( x(t) \))
- \( S_y \) is the vector output spectrum
- \( S_N \) is noise

\[ S_x(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \]
Frequency Domain Approach (wideband)

\[ S_X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \]

\[ H(f) = \frac{S_Y}{S_X} \]

\[ S_Y = HS_X + S_N \]

\[ H_{est} = \frac{G_{YX}}{G_{XX}} \]

\[ G_{YX} = S_Y S_X^* \]

\[ G_{XX} = S_X S_X^* \]

* conjugate operation
Comparing Wide- and Narrow-Band Response Methods

• Narrowband is familiar (traditional network analysis, classic RADAR signal)
• Tones used in narrowband have a 0dB peak/avg, with all of the source power at one frequency. May have better dynamic range.
• Narrow RBW’s may have long settling times which slow measurements or degrade accuracy
• Wideband signals can be almost anything provided there’s energy at the frequencies of interest. May even be DUT generated. Can use chirps for 0dB pk/avg. Lower spectral power density than a tone.
• Wideband signals that mimic DUT signals may be more DUT friendly, or provide a more realistic answer in the presence of nonlinearities. Pulse shaping, if present, doesn’t need to be gated.
• For narrow RBW’s wideband measurements may be faster as all frequencies are captured in parallel. However, there are many variables such as data transfer time and number of averages that also need to be considered
Multi-antenna Array Measurements

Agenda (cont.)

• **Configuring a Test System (10 min)**
  – Phase coherence
  – Digitizer features
  – Conversion loss / NF, power levels
  – Occupied dynamic range
  – System-level calibration

• **Realized Solution (10 min)**
  – M9703A digitizer
  – DDC and segmented memory
  – Measurement example
Configuring a Test System

DUT

Attenuator ➔ Quad Downconverter ➔ Digitizer

Attenuator ➔ Quad Downconverter

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Attenuator ➔ Quad Downconverter

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Attenuator ➔ Quad Downconverter

LO
Requirements for a Digitizer

Feature List:

• Multi-channel (n inputs), where n >= antennas in a group
• Sufficient 3dB analog BW
• Digital down converter (DDC)
• Phase coherent inputs (< 1 degree phase diff)
• Scalable platform
Requirements for RF Signal Chain

Signal Path Analysis

- Cable losses along signal path (vary depending on frequency)
- Cascaded Noise Figure (Friis)

\[ F_{\text{sys}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}} \]

- Understand the SNR and absolute power level at digitizer input
Measuring Digitizer Ch-Ch Phase Coherence

Two Methods Used:

• Sine-fit
  – Mathematic sine fit to single tone samples
  – Based on IEEE basic test methods for digitizers
  – Relatively slow as compared to DDC

• DDC (software)
  – Uses complex samples
  – Complex conjugate ratio method cancels common mode phase modulation
Measuring Digitizer Ch-Ch Phase Coherence

<table>
<thead>
<tr>
<th>Input Power (dBm)</th>
<th>Sinefit Method Skew Variance (sec^2)</th>
<th>DDC Method Skew Variance (sec^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ch1Ch3</td>
<td>Ch2Ch7</td>
</tr>
<tr>
<td>6.5</td>
<td>4.81E-26</td>
<td>2.02E-24</td>
</tr>
<tr>
<td>-3.5</td>
<td>1.17E-27</td>
<td>9.54E-26</td>
</tr>
<tr>
<td>-13.5</td>
<td>4.15E-27</td>
<td>1.26E-25</td>
</tr>
<tr>
<td>-23.5</td>
<td>1.61E-26</td>
<td>1.09E-25</td>
</tr>
<tr>
<td>-33.5</td>
<td>3.41E-26</td>
<td>1.16E-25</td>
</tr>
<tr>
<td>-43.5</td>
<td>1.79E-25</td>
<td>1.05E-24</td>
</tr>
<tr>
<td>-53.5</td>
<td>1.30E-23</td>
<td>6.16E-24</td>
</tr>
</tbody>
</table>

![Graph showing cross-channel skew variance vs input signal power](image-url)
System Level Calibration

Considerations:

• How accurate is good enough?

• At what is your IF center frequency and IF BW?

• Using the DDC?

• Using one or more digitizers?

• What software environment are you using?

• Do you have data on complex frequency response for all signal path blocks out to the calibration reference plane?
System Level Calibration (cont.)

IF Magnitude and Phase Calibration with Channel Matching

Convolution of response for source, signal path and digitizer is represented in digitized waveform FFT (divide out source and signal path):

* \( W_1 = \text{Source} \times \text{SP}_1 \times \text{Digitizer Response}_1 \)

* Note: Need to account for splitter impact on ch-ch phase. Possibly using differential 2-step cal.
System Level Calibration (cont.)

Magnitude

Phase

![Graphs showing magnitude and phase](image)

![Customer report](image)
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Agilent M9703A High-Speed Digitizer

Reduce the test time of your DUT with the new M9703A! Higher number of synchronous acquisition channels, wider signal capture with the best accuracy and flexibility, and optimized throughput

Key Features
- 12 bit Resolution
- 8 channels @ 1.6 GS/s
- Interleaving option to get 4 ch @ 3.2 GS/s
- DC to 2 GHz analog 3dB bandwidth
- Optional real-time digital downconversion (DDC) on 8 phase-coherent channels
- Up to 256 MS/ch memory and segmented acquisition
- > 650 MB/s data transfer
- Agilent 89600 Software support

M9703A OS support
- Windows
- XP (32-bit)
- Vista (32/64-bit)
- 7 (32/64-bit)
- Linux

Drivers – MD1 software
- IVI-C, IVI-COM
- LabVIEW
- MATLAB (through IVI-COM)

OTS application software
- MD1 soft front panel
- AcqirisMAQS U1092A-S01/S02/S03
- 89600 VSA software
M9703A - DDC Features and Benefits

- Reduce the bandwidth to match the signal
  - Reduce noise (including quantization noise) and interference,
  - Allows lower sample rate without aliasing
- Reduce sample rate to the appropriate values for the signal being analyzed.
  - More efficient use of memory allows longer duration captures
  - Or, allows less data to transfer for the same duration
- Baseband (0 Hz, real-only) or use LO (complex) to “tune”

x8

<table>
<thead>
<tr>
<th>Sample Rate</th>
<th>Analysis Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6 GS/s</td>
<td>1 GHz</td>
</tr>
<tr>
<td>400 Ms/s</td>
<td>300 MHz</td>
</tr>
<tr>
<td>200 Ms/s</td>
<td>160 MHz</td>
</tr>
<tr>
<td>100 Ms/s</td>
<td>80 MHz</td>
</tr>
<tr>
<td>50 Ms/s</td>
<td>40 MHz</td>
</tr>
<tr>
<td>50/2^N Ms/s</td>
<td>40/2^N MHz</td>
</tr>
</tbody>
</table>
M9703A’s Segment Memory Mode

Optimum Memory Utilization

- Accelerate test time with fewer samples
- Reduced acquisition cycle time
- Longer duration acquisitions

Segmented memory optimizes capture time by dividing the digitizer’s available acquisition memory into smaller segments.
Demo Setup

AWG Configured to Generate 100MHz Wide LFM Chirp

Digitizer Configured as a Multi-channel Tuned Receiver

Signals here have bandwidth…

And because they have BW, we can compute FRF at multiple frequencies.
The Hardware
Broadband Stimulus Signals
Chirped Pulse (e.g. Radar)

- Pulse Width: 4usec
- BW” 100 MHz
- Uniform Window
- Trigger Delay
- 250 avgs/sec
MATLAB Demo: M9703A Cross Channel Phase

Customer Requirement:
- Multi-antenna array measurements
- Element to element phase alignment for narrowband and wideband signals
- Obtain down-converted IQ data for further analysis

Hardware/Software:
- N6171A MATLAB software
- Agilent M9703A High Speed Digitizer
- Agilent M8190A Arbitrary Waveform Generator

Demonstration:
- Configure M9703A and acquire baseband IQ signals
- Calculate and visualize:
  - Signal phase of each of the first four channels of M9703A
  - Narrowband Signal: Cross Channel phase correlation
  - Wideband Signal: Frequency Response Function (FRF) magnitude and phase of channels 2x1, 3x1, and 4x1
Measurement Throughput

<table>
<thead>
<tr>
<th>Segment</th>
<th>Intervals</th>
<th>Rearm Time</th>
<th>DUT Time</th>
<th>Acquisition Cycle</th>
<th>Time/Interval</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 us</td>
<td>100</td>
<td>160 us (1.56 MSa/s)</td>
<td>80 us</td>
<td>660 us</td>
<td>6.6 us</td>
<td>152k int/sec/ch or 1.2M meas/sec</td>
</tr>
<tr>
<td>500 us</td>
<td>100</td>
<td>80 us (3.125 MSa/s)</td>
<td>80 us</td>
<td>580 us</td>
<td>5.8 us</td>
<td>172k int/sec/ch or 1.4M meas/sec</td>
</tr>
<tr>
<td>500 us</td>
<td>10</td>
<td>40 usec (6.25 MSa/s)</td>
<td>80 us</td>
<td>580 us</td>
<td>58 us</td>
<td>17.2k int/sec/ch or 138k meas/sec</td>
</tr>
</tbody>
</table>

Acquire: 100 intervals (tones) or 10 intervals (broadband)
Variance and Power are closely related. For small angles we can use the relationship $x \approx \sin(x)$ and we also recognize that not all of the noise power goes to changing angle, it also changes amplitude. For a single channel we can show that the angle variance is

$$\text{Single Channel Angle Variance} = \left(\frac{180}{\pi}\right)^2 \times \frac{-\text{SNR}}{10}$$

Noise is complex: $N_R + jN_I$

Noise Power: $N_R^2 + N_I^2$

For a nominal angle of zero degrees, only the imaginary element of the noise contributes to the angular variance hence the angular variance in radians is half the normalized noise variance

Noise on each channel is uncorrelated so we can simply add the variances to get:

$$\text{Cross Channel Angle Variance} = \left(\frac{180}{\pi}\right)^2 \times \left(\frac{-\text{SNR}_\text{STIM}}{10} \right) + \left(\frac{-\text{SNR}_\text{RESPONSE}}{10} \right)$$
EXAMPLE (using only the digitizer noise)

\[
\text{DUT}
\]

-10dBm \quad \text{Ch1 (stim)} \quad -50dBm \quad \text{chN (resp)}

M9703
Noise Figure \sim 30\text{dB} (1\text{V range})

\[
\text{SNR} = \text{SigLevel} - (\text{Noise Density} + 10\log_{10}(\text{ENBW})) \quad \text{where ENBW} \sim 1/T
\]

\[
\text{Cross Channel Angle Variance} = \left(\frac{180}{\pi}\right)^2 \times \left(10^{\frac{-\text{SNR\_STIM}}{10}} \frac{1}{2} + 10^{\frac{-\text{SNR\_RESPONSE}}{10}} \frac{1}{2}\right)
\]

Assume T= 100 usec

\[
\text{SNR\_STIM} = -10 - (-174 + 30 + 10\log_{10}(1.0/100\text{usec})) = 94 \text{ dB}
\]

\[
\text{SNR\_RESP} = -50 - (-174 + 30 + 10\log_{10}(1.0/100\text{usec})) = 54 \text{ dB}
\]

Angle Variance = 6.5 mDeg\(^2\) or equivalently a standard deviation of 0.08 degrees
Summary and Conclusion

Using an Agilent M9703A digitizer with DDC in a solution for multi-antenna array measurements provides the following benefits:

1) Multi-channel coherent measurement solution (< 1 deg)
2) Fast, adjustable BW measurements producing complex samples with just enough sample rate (reduced variance)
3) Integrated 89600 VSA control (w/ hardware DDC acceleration) to leverage wealth of existing, industry standardized measurements

For more information:

www.agilent.com/find/axie-antennatest