Digitizer-Based Phase Coherent Measurements for Multi-Antenna Phased Array Applications

Alexander Dickson, Agilent Technologies

Multi-Antenna Array Measurements

Agenda

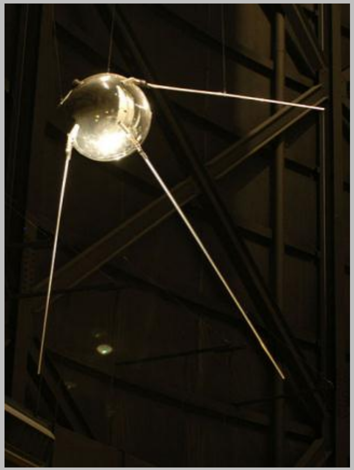
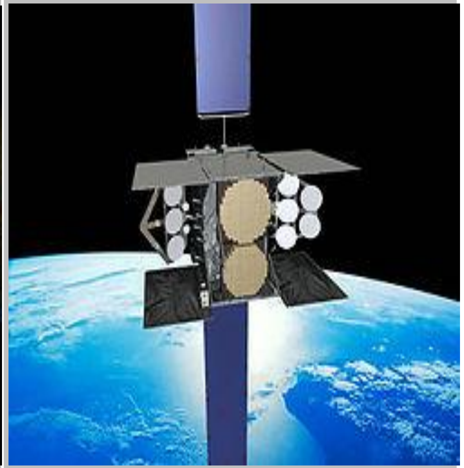
- **Phased Array Applications Overview**
  - Benefits of modern phased array antennas
  - Test challenges of phased arrays
- **Testing Multi-Element Array Antennas**
  - Phase and gain measurements
  - Using complex signals
  - Sensitivity to match BW
  - Accelerate your measurements

Multi-Antenna Array Measurements

Agenda (cont.)

- **Configuring a Test System**
  - Phase coherence
  - Digitizer features
  - Conversion loss / NF, power levels
  - Occupied dynamic range
  - System-level calibration
- **Realized Solution**
  - M9703A digitizer
  - DDC, 89600 VSA HW extension and segmented memory
  - General block diagram
  - Measurement example

Satellite

Sputnik 1	DCSC	MILSTAR	Boeing 702
http://en.wikipedia.org/wiki/Sputnik_1 		http://en.wikipedia.org/wiki/Milstar 	 http://en.wikipedia.org/wiki/Boeing_702

http://en.wikipedia.org/wiki/Defense_Satellite_Communications_System

Modern Active Electronically Scanned Phased Array (AESA)


Multiple Spot Beams created from a single AESA antenna

Key Benefits

- Fixed position antenna
- Ability to form multiple agile beams
- Communicate with multiple spatially distributed ground stations
- 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

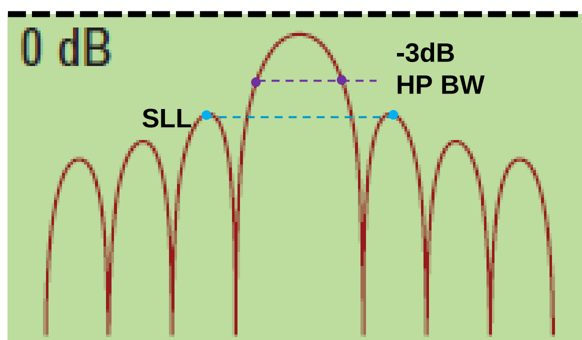
Historical Phased Array Test Challenges

Aligning Radiating Elements for Optimum Performance

- Phase and amplitude errors lead to an increase in sidelobe levels (SLL)
- Large sidelobes indicate a waste of beamforming power and cause interference
- Average sidelobe level due to phase and amplitude errors (normalized to isotropic level and using λ/2 element spacing) [1]:

$$\overline{SLL_O} = \pi\left(\overline{\emptyset^2} + \overline{\delta^2}\right)$$

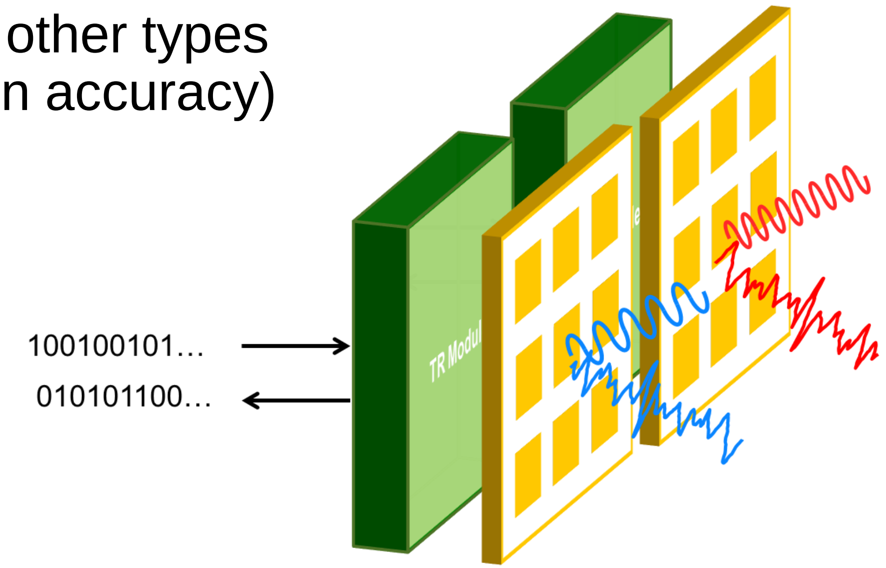
- Where ∅ is the phase error variance (radians) and δ is the fractional amplitude error variance



[1]: J. Ruze, "Pattern degradation of space fed phased arrays," MIT Lincoln Laboratory, Project Rept. SBR-1, Dec. 1979.

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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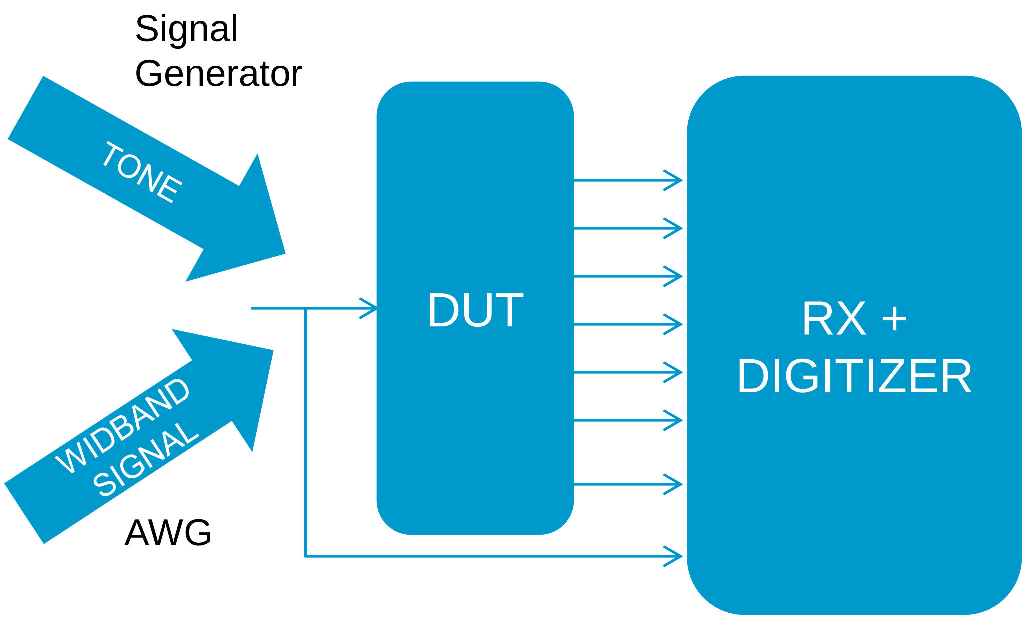
- **Phased Array Applications Overview**
  - Antenna architectures and enabling technology
  - Benefits of modern phased array antennas
  - Test challenges of phased arrays
- **Testing Multi-Element Array Antennas**
  - Phase and gain measurements
  - Using complex signals
  - Sensitivity to match BW
  - 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

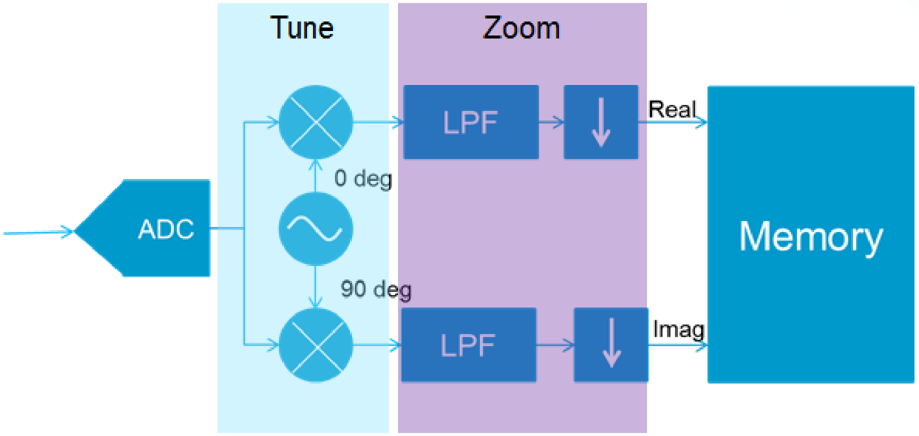
Digitizers and VSA's with DDC's have adjustable bandwidths

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.

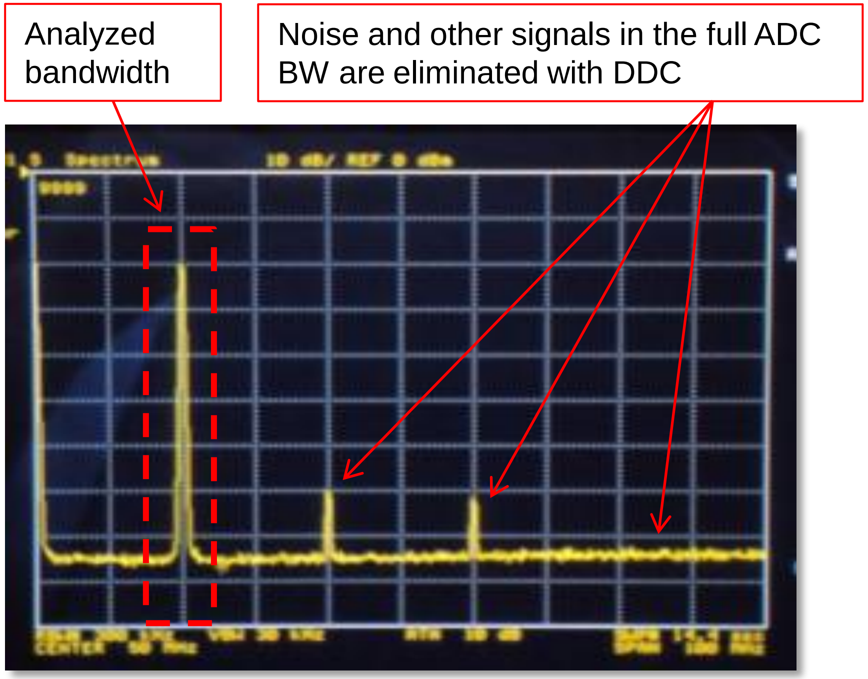
- Digital signal processing
- Produces complex I&Q samples from real ADC samples
- Frequency translation (tune)
- Filter and decimation (zoom)



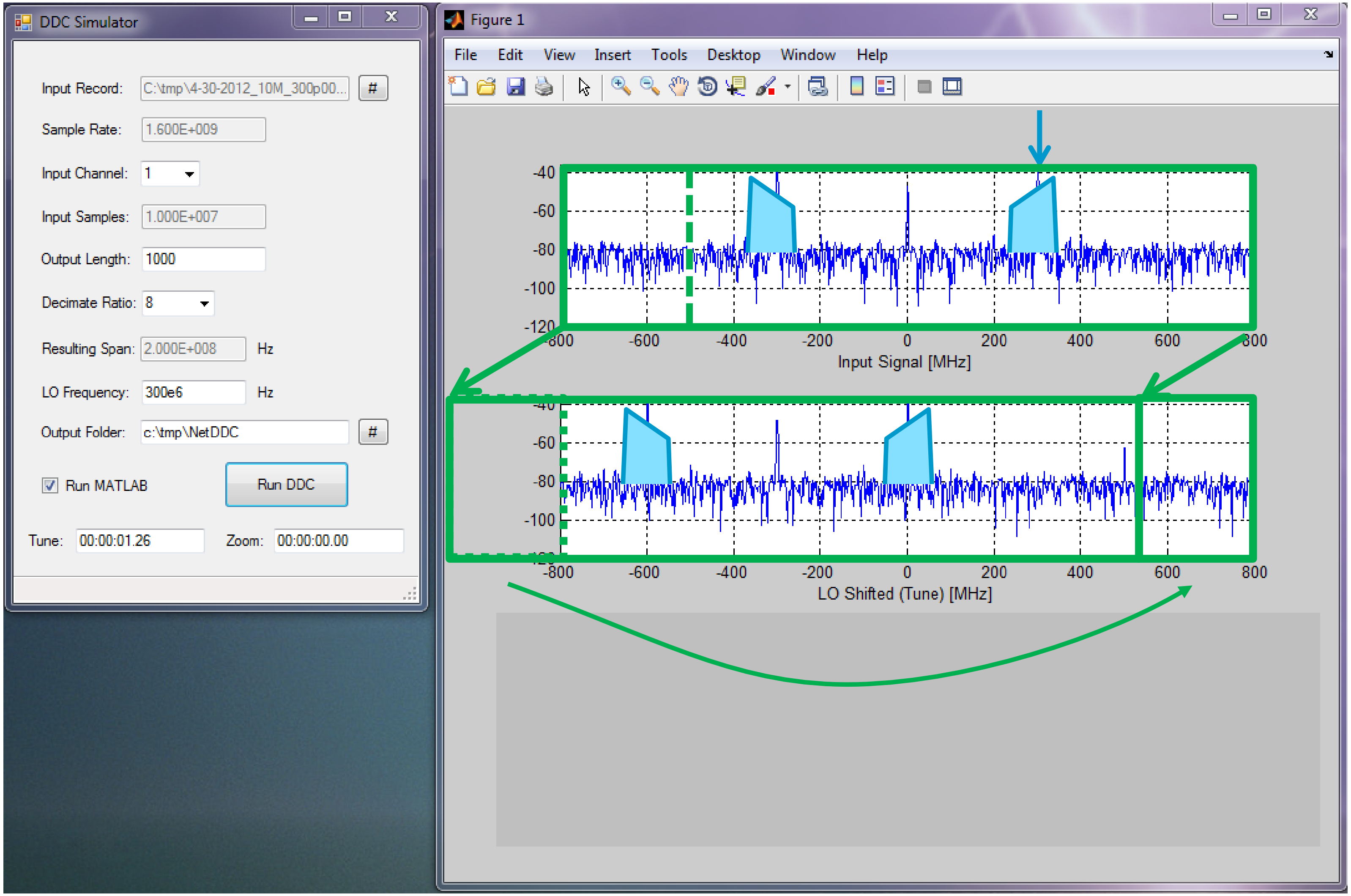
DDC Benefits

What a DDC Does For You:

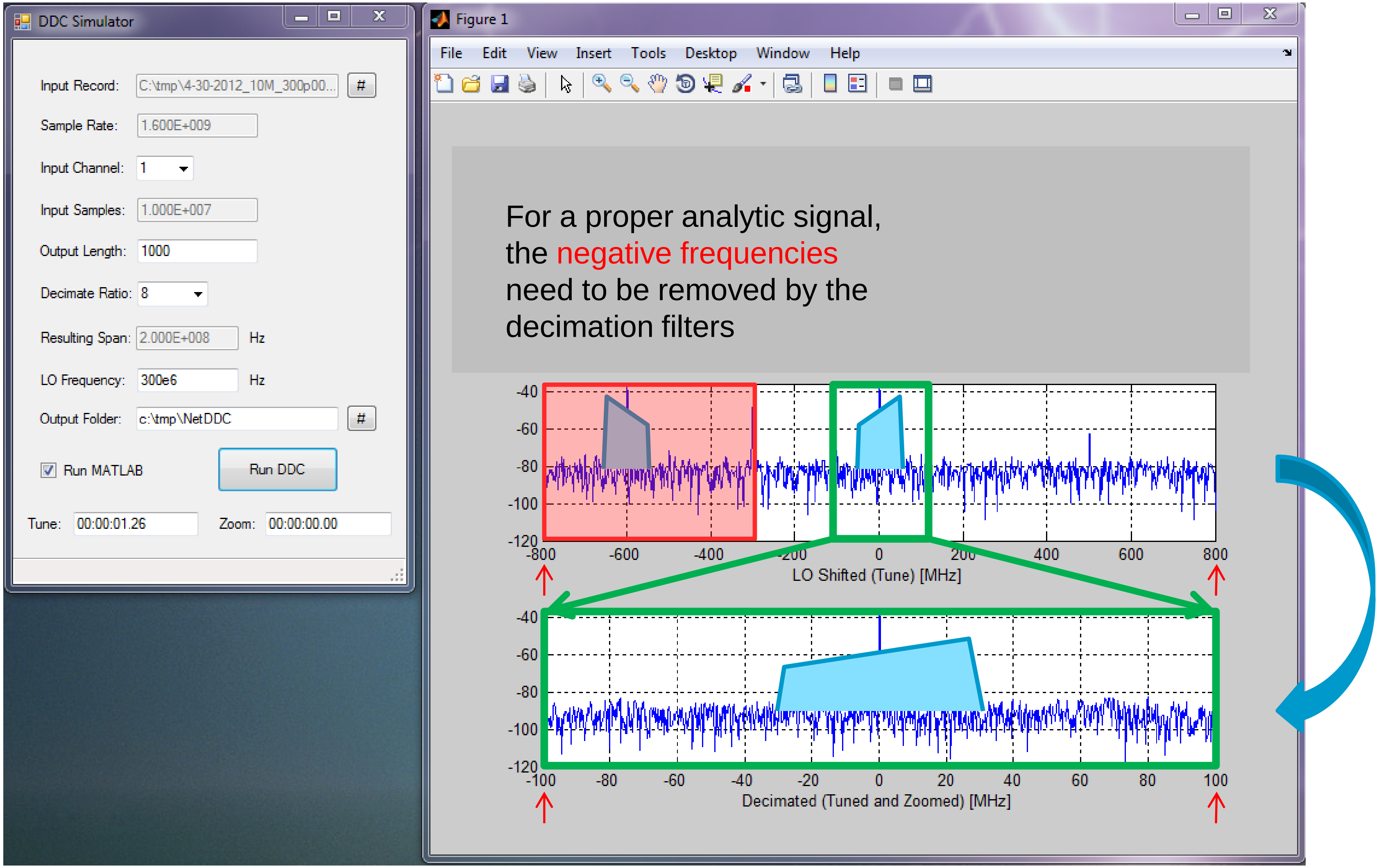
- Isolate the signal of interest
- Improve the analog performance and dynamic range (SNR, ENOB), by reducing the amount of integrated noise
- Extend the amount of capture memory (in seconds), or reduce the amount of data that need to be transferred for a given duration.
- Reduce the workload on post-processing algorithms → less data to analyze



DDC - Tune Result

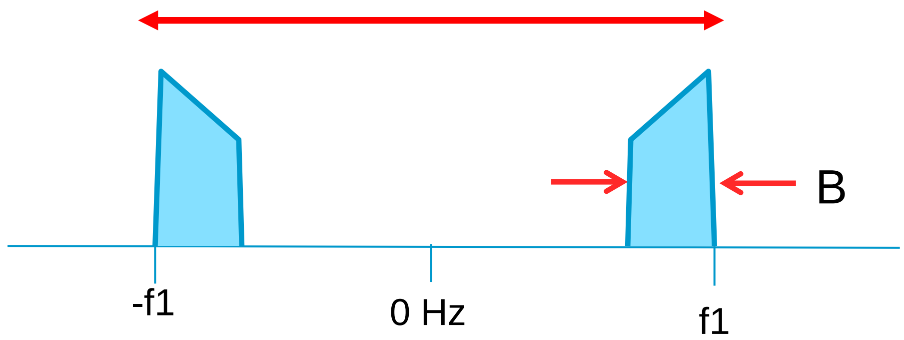


DDC - Zoom Result



DDC - Real vs. Complex

Bandwidth that determines sample rate

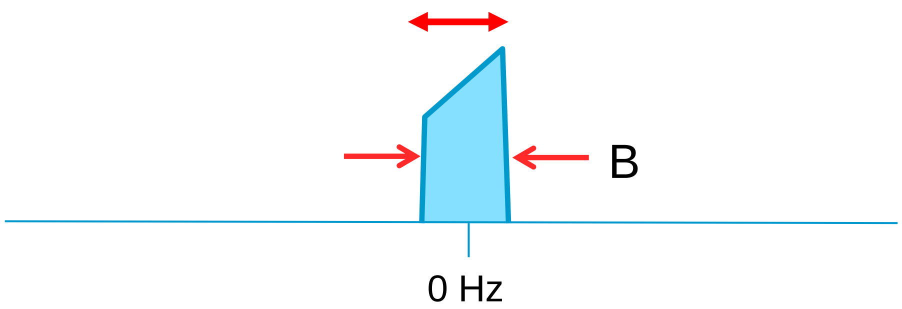


Real-only signals are conjugate symmetric about DC

Minimum sample rate: **2*f1**

2 Step Process
Tune (shift)
Zoom (filter and decimate)

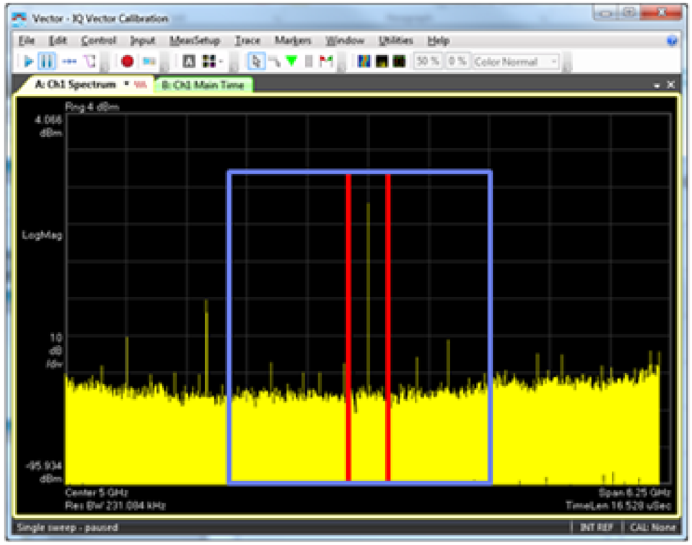
Bandwidth that determines sample rate

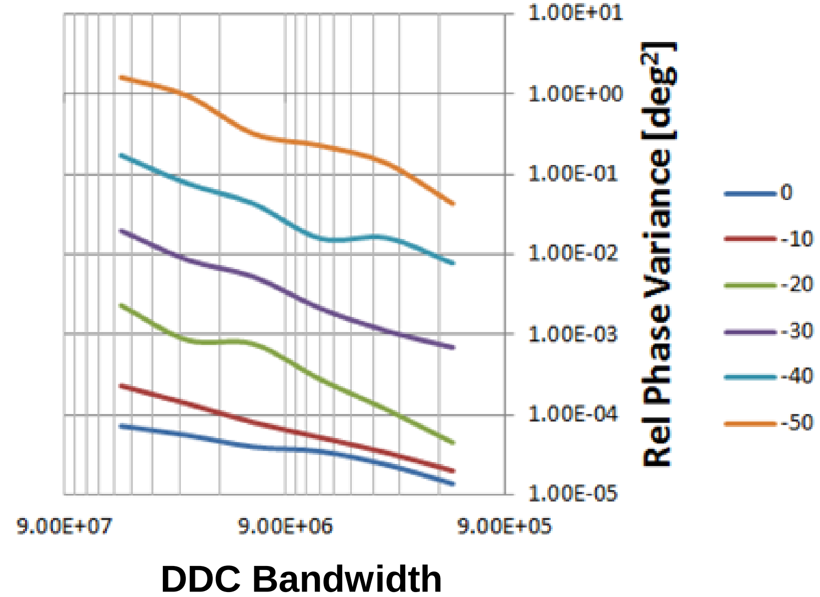


Complex signals can be asymmetrical about DC

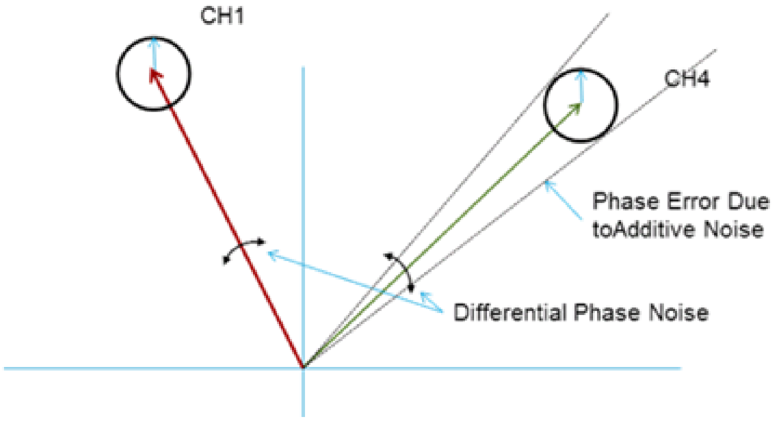
Minimum sample rate: **B**

DDC – Process Gain for Measurements

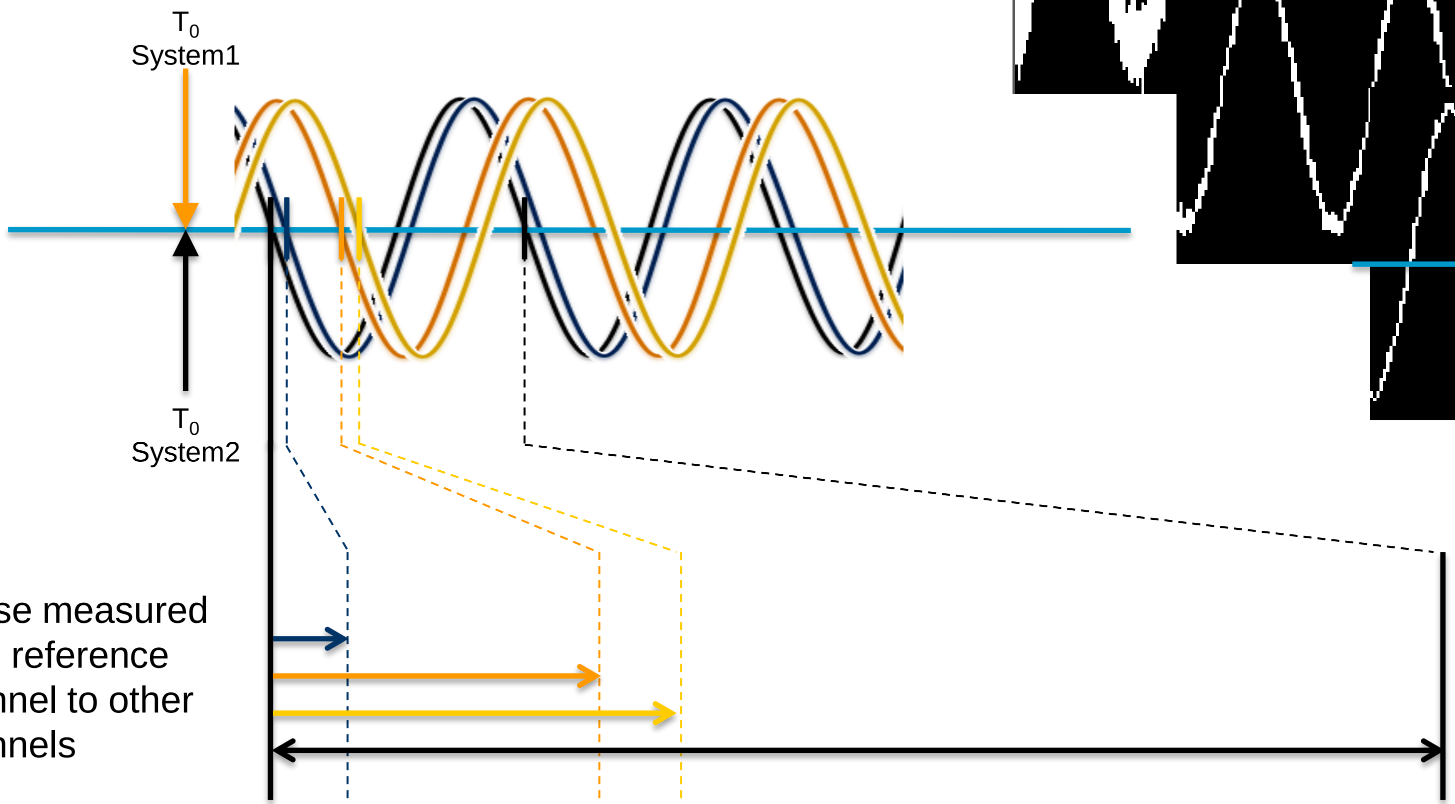


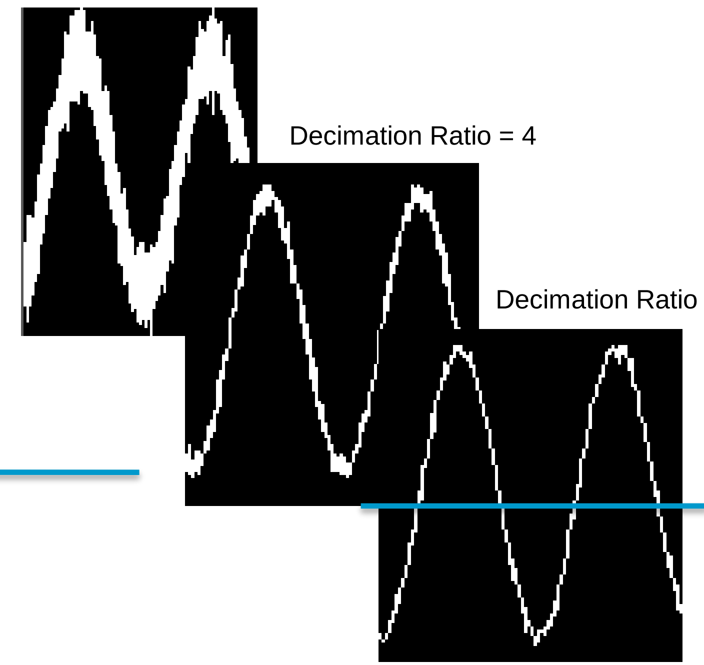


With reduced bandwidth there is less noise power (and spurious) to interference with amplitude and phase measurements



DDC – Noise Reduction in Time Domain





Phase measured from reference channel to other channels

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:

$$\boldsymbol{G1} = \frac{XR'}{RR'}$$

where R' is the conjugate transpose of R

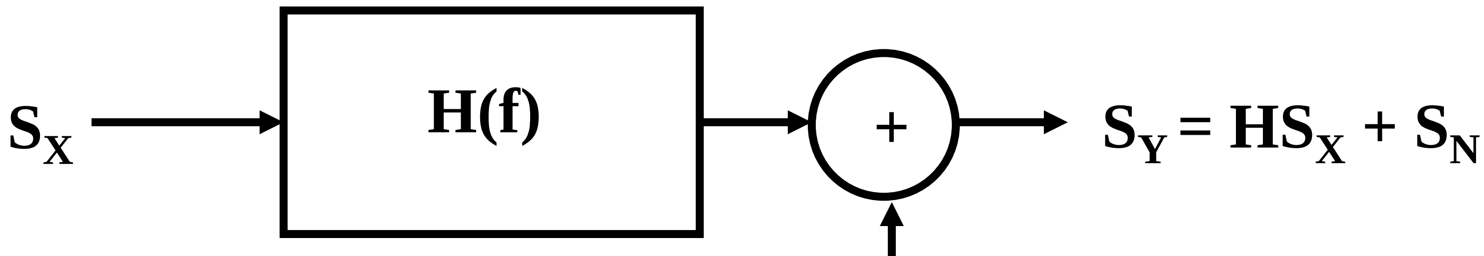
In Summation Form the computation is:

$$\boldsymbol{G1} = \frac{\sum_{n=0}^{N-1} \boldsymbol{x(nT)} * \boldsymbol{r(nT)}^*}{\sum_{n=0}^{N-1} \boldsymbol{r(nT)} * \boldsymbol{r(nT)}^*}$$

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.

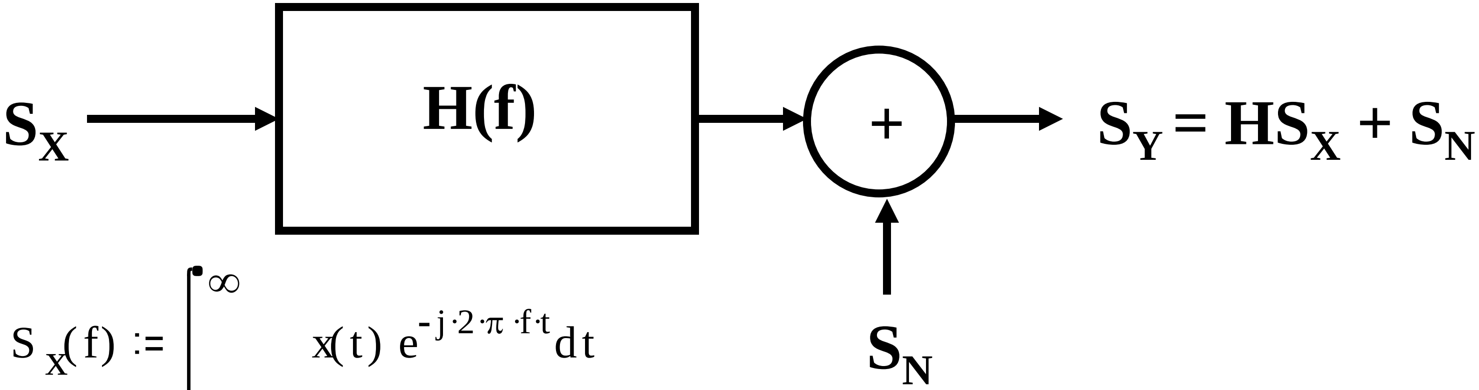
Frequency Domain Approach (wideband)



$$S_X(f) := \int_{-\infty}^{\infty} x(t)\, e^{-j \cdot 2 \cdot \pi \cdot f \cdot t}\, dt$$

- x(t) is a broadband signal with energy at all frequencies of interest (noise, chirp, etc)
- Sx is the vector input spectrum of x(t) computed as the FFT(x(t))
- Sy is the vector output spectrum
- Sn is noise

Frequency Domain Approach (wideband)



$$S_X(f) := \int_{-\infty}^{\infty} x(t)\, e^{-j\cdot 2\cdot \pi \cdot f\cdot t}\, dt$$

$$H_{est} = \overline{S_Y / S_X}$$

$$H_{est} = \overline{G_{YX}} / \overline{G_{XX}}$$

$$G_{YX} = S_Y S_X{}^*$$

$$G_{XX} = S_X S_X{}^*$$

$\overline{}$ Average operation

* conjugate operation

Comparing Wide- and Narrow-Band Response Methods

- Narrowband is familiar (traditional network analysis, classic radar signal)
- Tones used in narrowband have a 0 dB 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 0 dB 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

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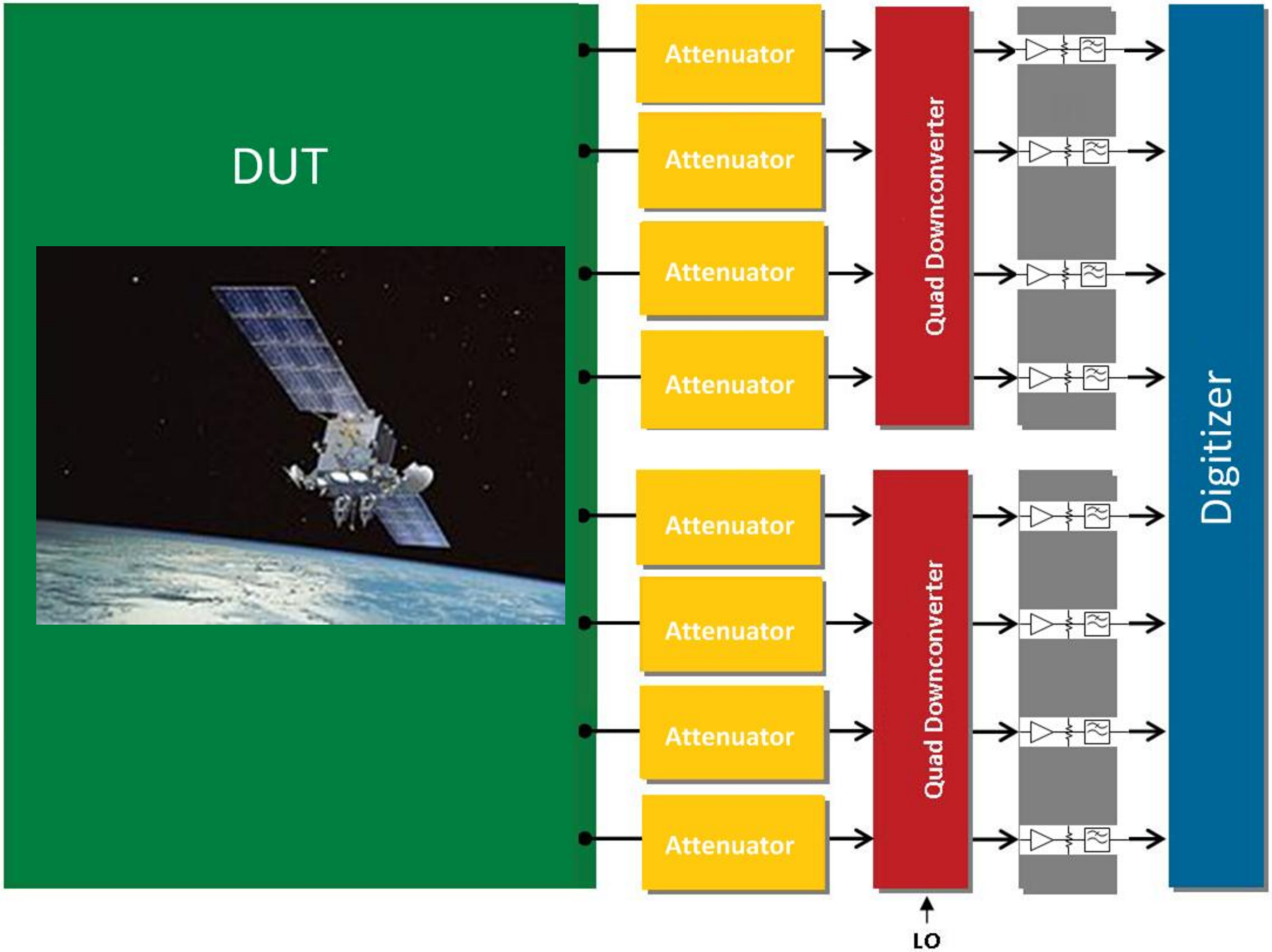
- **Configuring a Test System**
  Phase coherence
  – Digitizer features
  – Conversion loss / NF, power levels
  – Occupied dynamic range
  – System-level calibration
- **Realized Solution**
  – M9703A digitizer
  – DDC, 89600 VSA HW extension and segmented memory
  – General block diagram
  – Measurement example

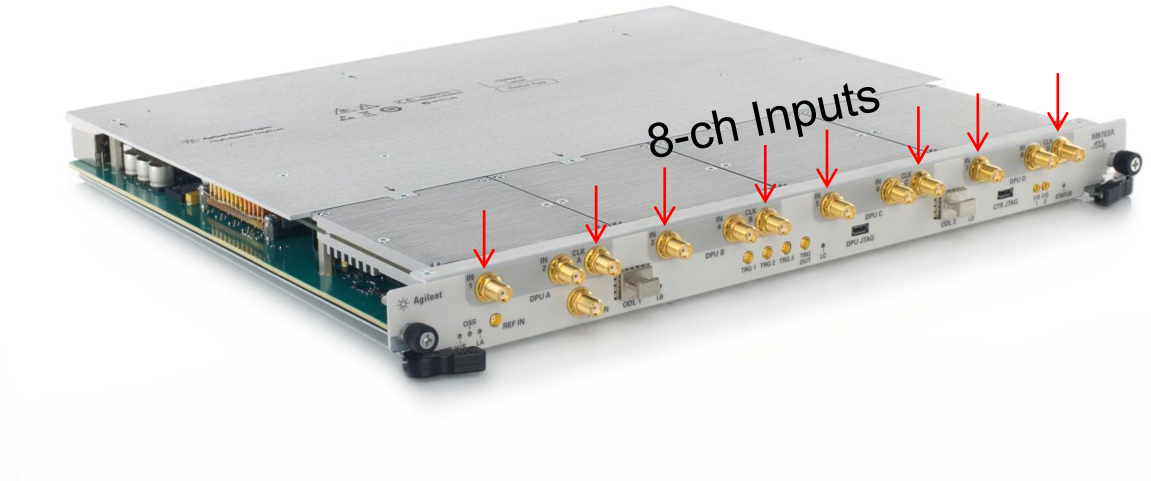
Configuring a Test System



Requirements for a Digitizer

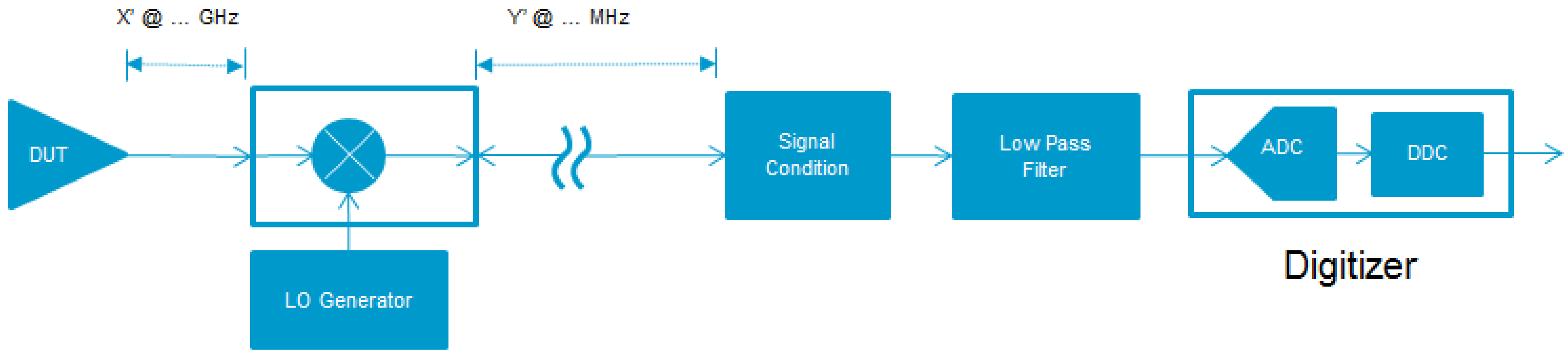
Feature List:

- 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)

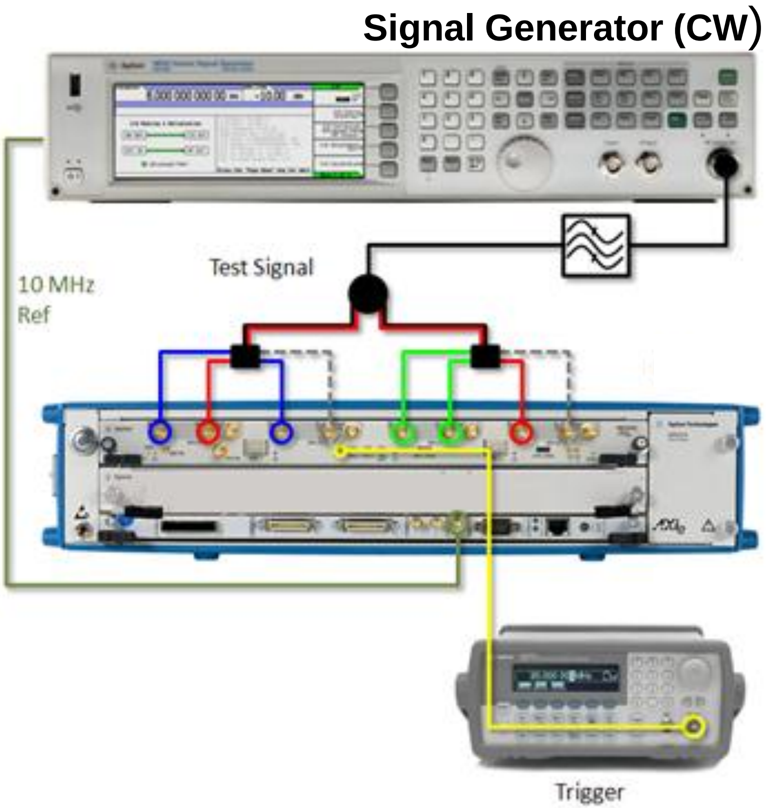
$$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

- Understand the SNR and absolute power level at digitizer input

Measuring Digitizer Ch-Ch Phase Coherence

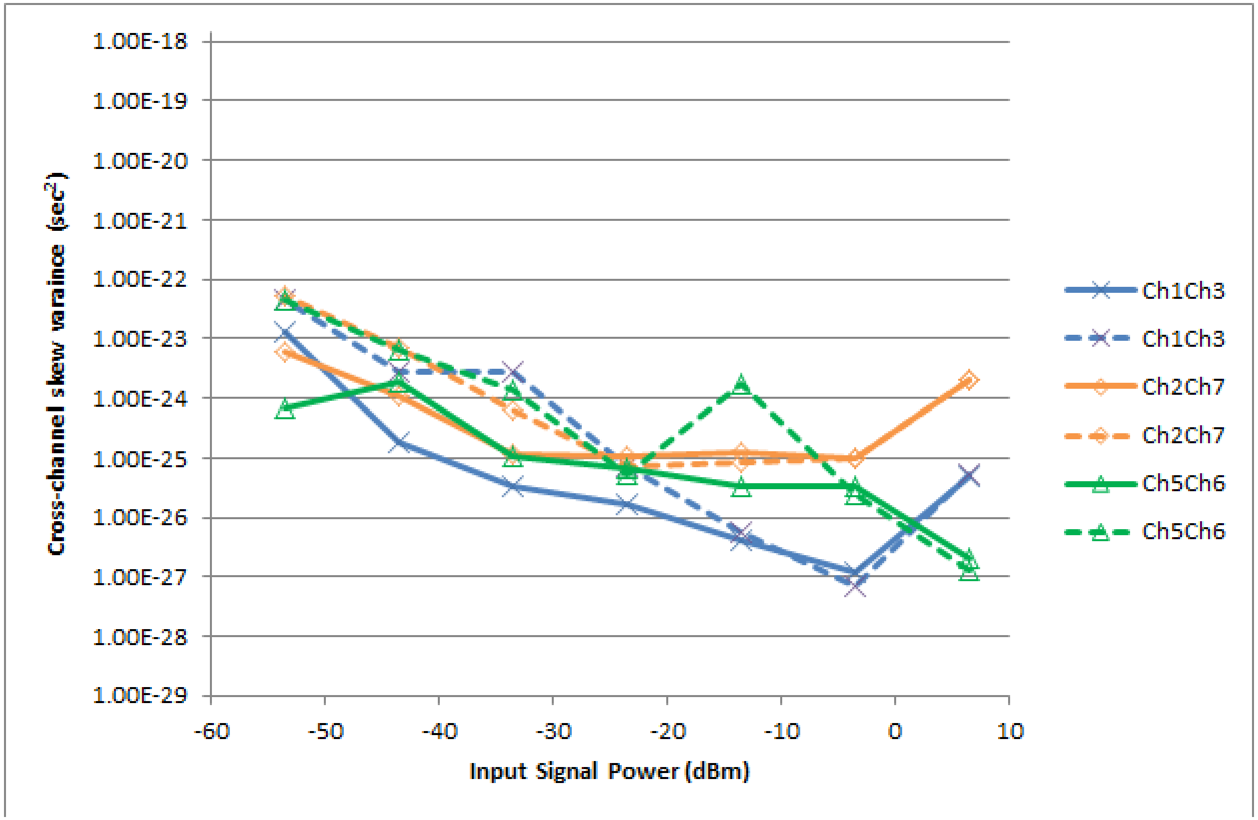
Two methods used:

- 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

Input Power (dBm)	Sinefit Method Skew Variance (sec^2)			DDC Method Skew Variance (sec^2)		
	Ch1Ch3	Ch2Ch7	Ch5Ch6	Ch1Ch3	Ch2Ch7	Ch5Ch6
6.5	4.81E-26	2.02E-24	2.10E-27	5.49E-26	1.97E-24	1.30E-27
-3.5	1.17E-27	9.54E-26	3.25E-26	7.07E-28	9.90E-26	2.53E-26
-13.5	4.15E-27	1.26E-25	3.31E-26	5.81E-27	8.64E-26	1.75E-24
-23.5	1.61E-26	1.09E-25	6.65E-26	7.21E-26	7.23E-26	5.51E-26
-33.5	3.41E-26	1.16E-25	[illegible]	[illegible]	[illegible]	[illegible]
-43.5	1.79E-25	1.05E-24	[illegible]	[illegible]	[illegible]	[illegible]
-53.5	1.30E-23	6.16E-24	[illegible]	[illegible]	[illegible]	[illegible]



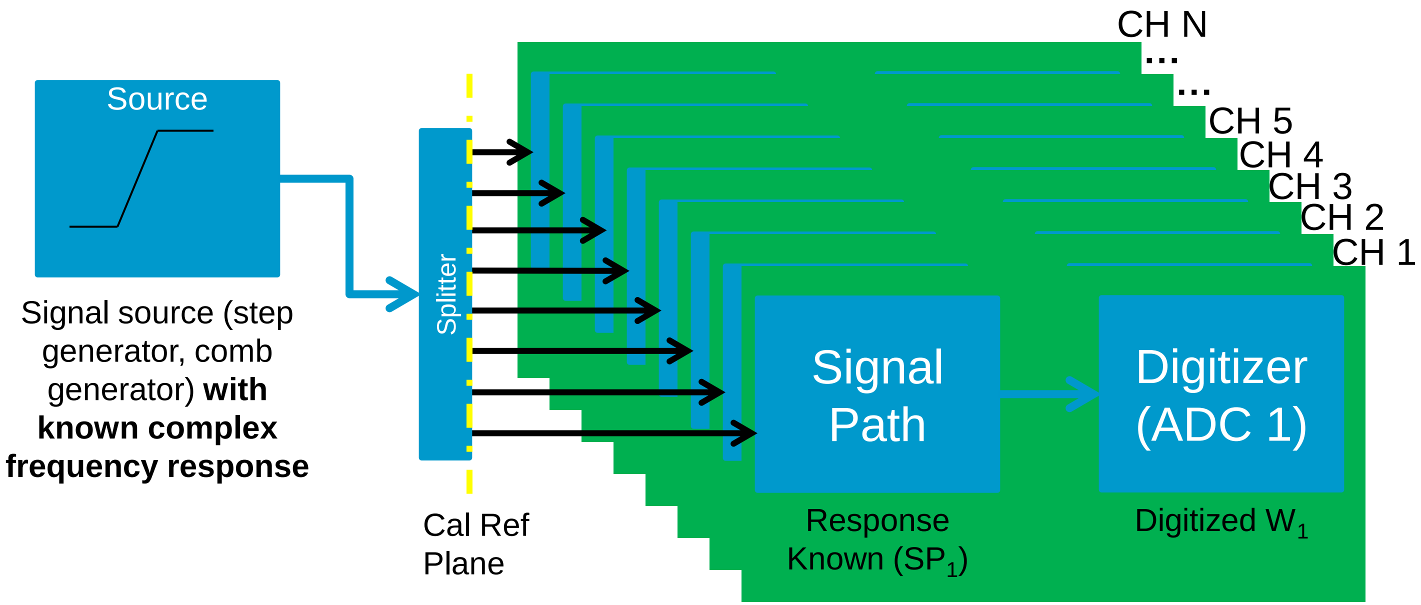
System Level Calibration

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 = Source * SP_1 * Digitizer $Response_1$

* Note: Need to account for splitter impact on ch-ch phase. Possibly using differential 2-step cal.

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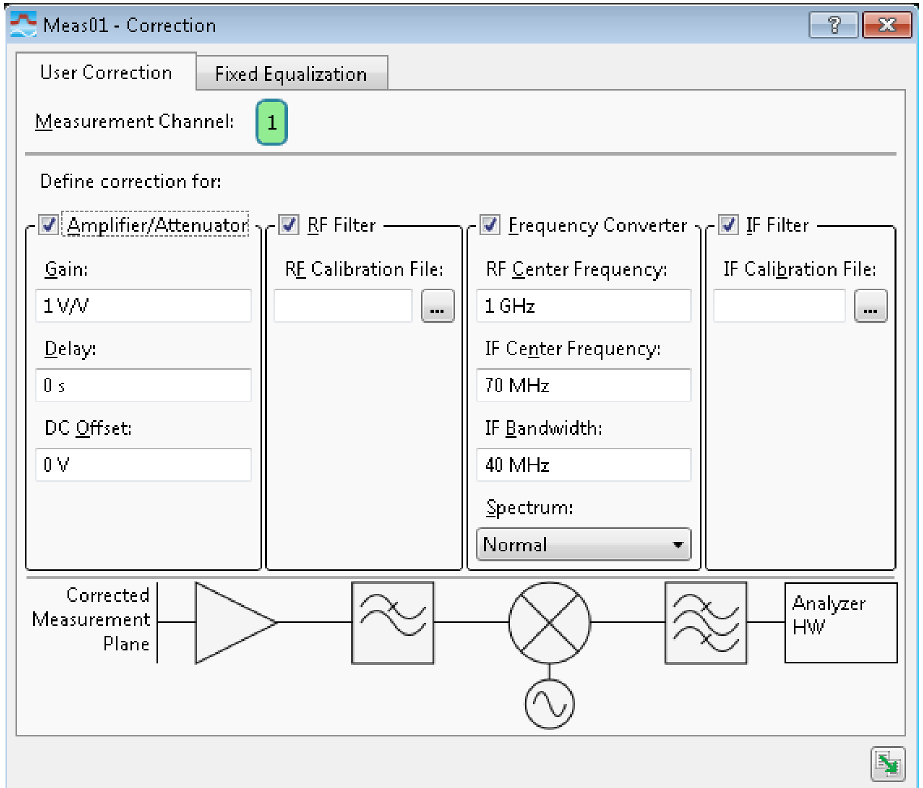
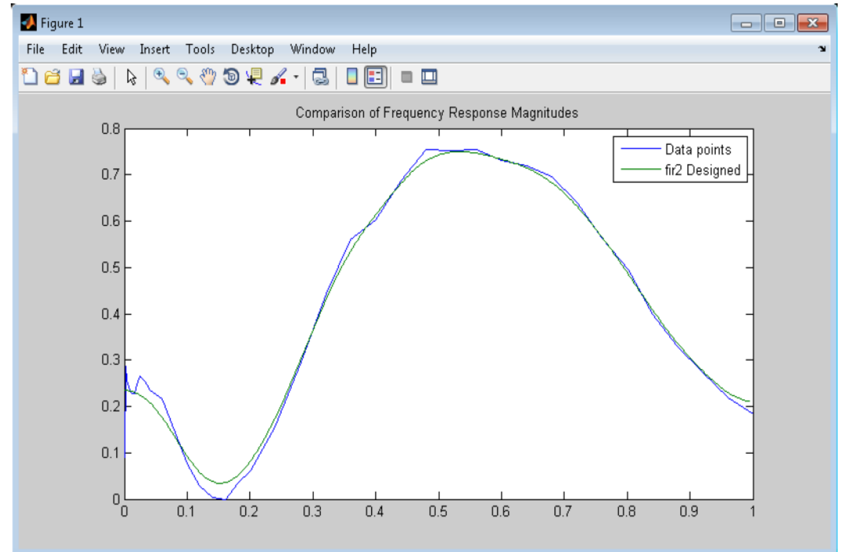
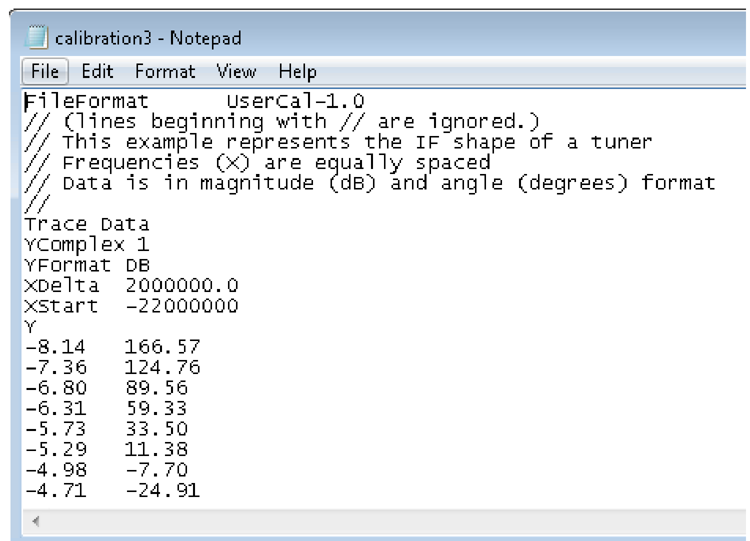
System Level Calibration (cont.)





Filter design DC (0) to 250 MHz (1) for channel 7 of the digitizer used.




```
FileFormat       UserCal-1.0
// (lines beginning with // are ignored.)
// This example represents the IF shape of a tuner
// Frequencies (X) are equally spaced
// Data is in magnitude (dB) and angle (degrees) format
//
Trace Data
YComplex 1
YFormat DB
XDelta  2000000.0
XStart  -22000000
Y
-8.14   166.57
-7.36   124.76
-6.80   89.56
-6.31   59.33
-5.73   33.50
-5.29   11.38
-4.98   -7.70
-4.71   -24.91
```

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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

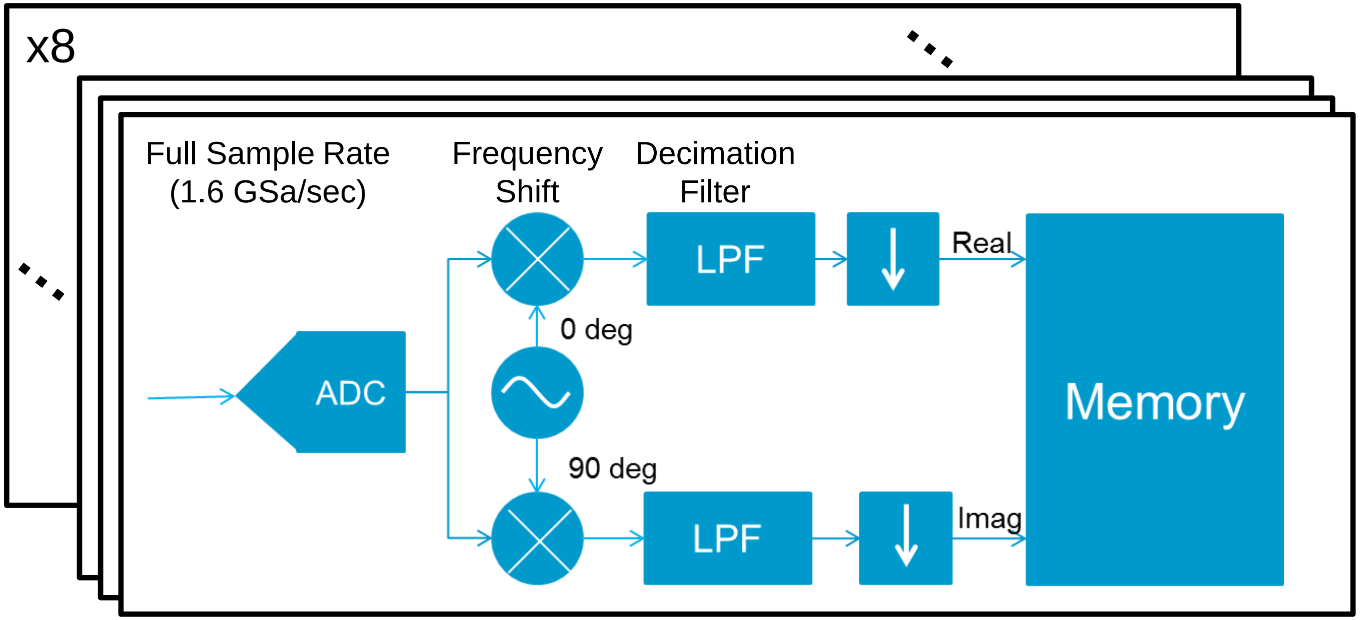
- MD1 soft front panel
- AcqirisMAQS U1092A-S01/S02/S03
- 89600 VSA software

M9703A – Key Performance Characteristics

ENOB	48 MHz	8.7 *(typical)*
	100 MHz	8.8 *(typical)*
	410 MHz	8.2 *(8.8, typical)*
SFDR	48 MHz	58 dBc *(typical)*
	100 MHz	60 dBc *(typical)*
	410 MHz	52 dBc *(60 dBc, typical)*
Time Skew* *proportional to phase offset	Max ch-ch skew	± 50 ps *(nominal)*
	Ch-ch skew variance	± 100 fs *(nominal)*

M9703A - DDC Features and Benefits

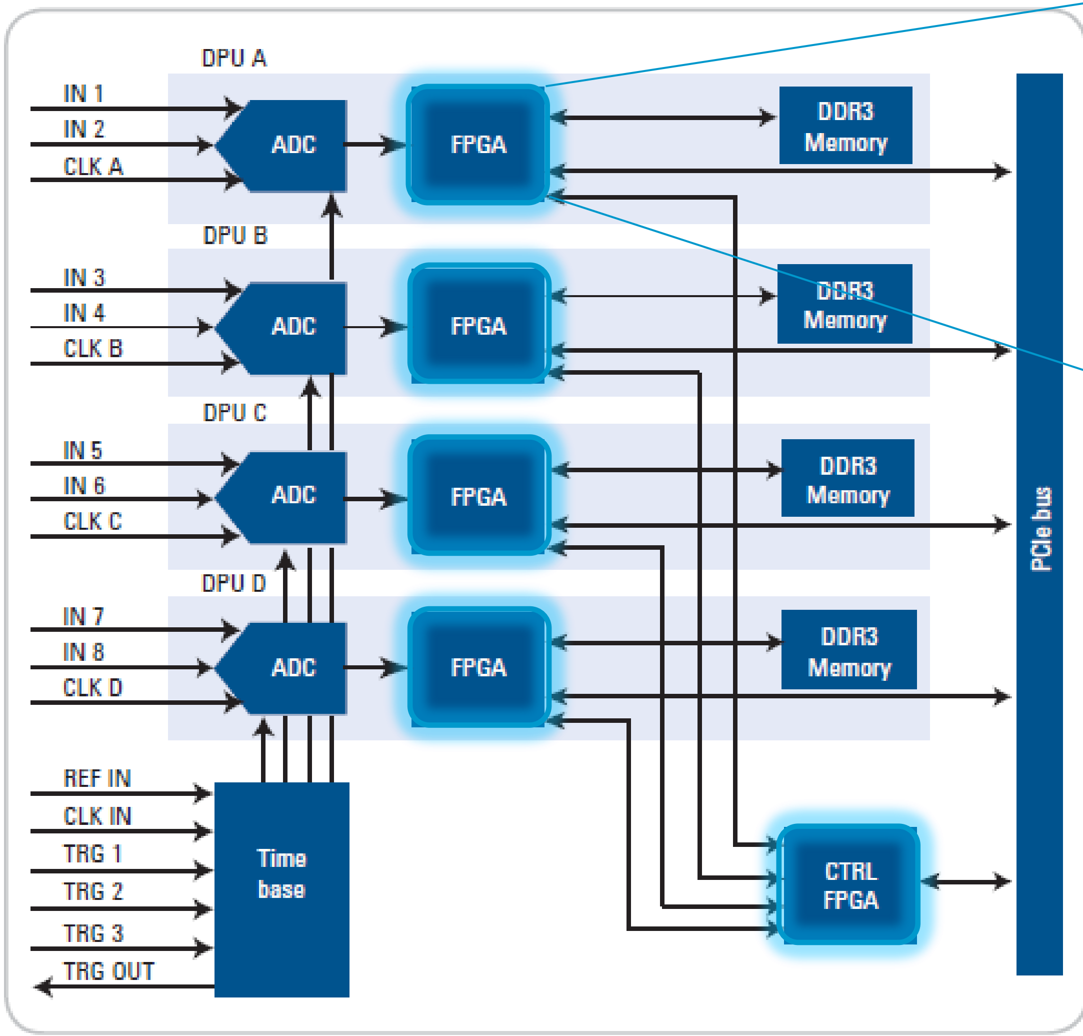
- **Reduce the bandwidth to match the signal**
  - Reduce noise (including quantization noise) and interference,
  - Allows lower sample rate without aliasing
- **Reduce sample rate to the appropriate values for the signal being analyzed.**
  - More efficient use of memory allows longer duration captures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

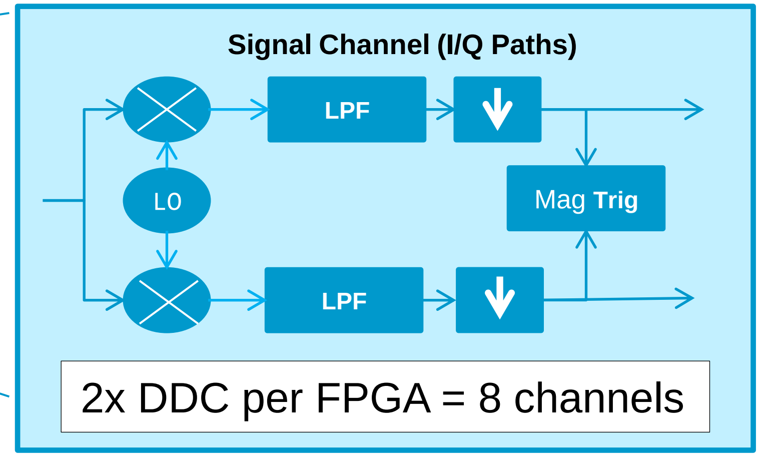


Sample Rate	Analysis Bandwidth
1.6 GS/s	1 GHz
400 Ms/s	300 MHz
200 Ms/s	160 MHz
100 Ms/s	80 MHz
50 Ms/s	40 MHz
$50/2^N$ Ms/s	$40/2^N$ MHz

M9703A –DDC Block Diagram

Built-in FPGAs- 4 processing per module





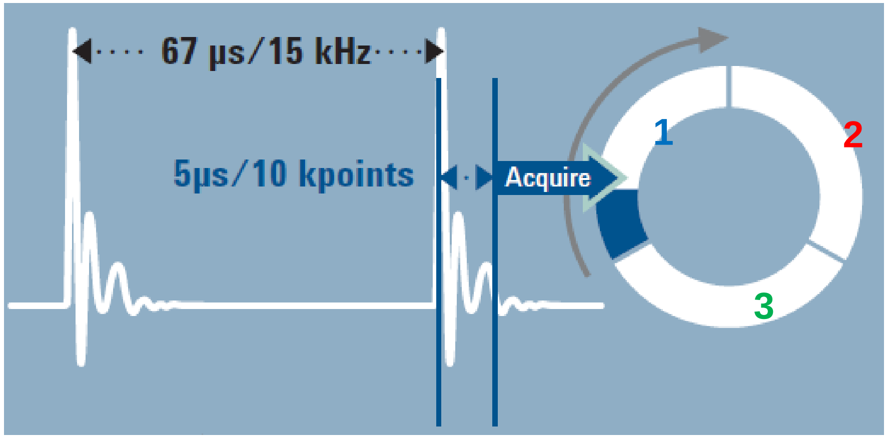
- Agility to tune/zoom, trigger, and analyze only the signal of interest.
- **Independent IF tuning** (0.01Hz) over the full digitizer bandwidth
- **Transfer only the data that you want → reduce the workload on post-processing algorithms**

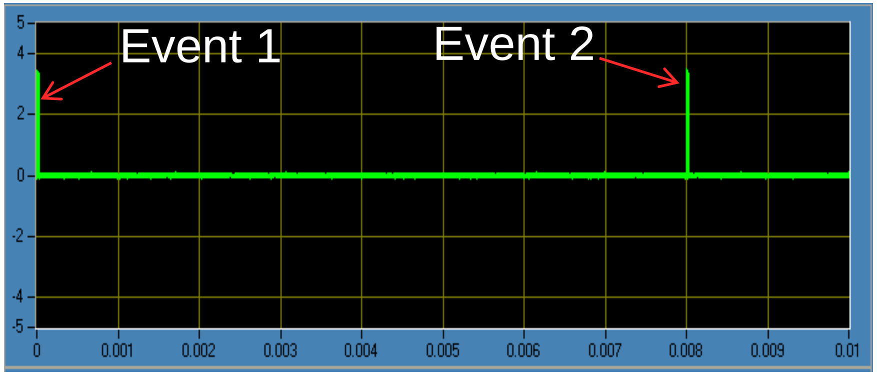
M9703A's Segment Memory Mode

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.





M9703A Hardware Extension for 89600 VSA

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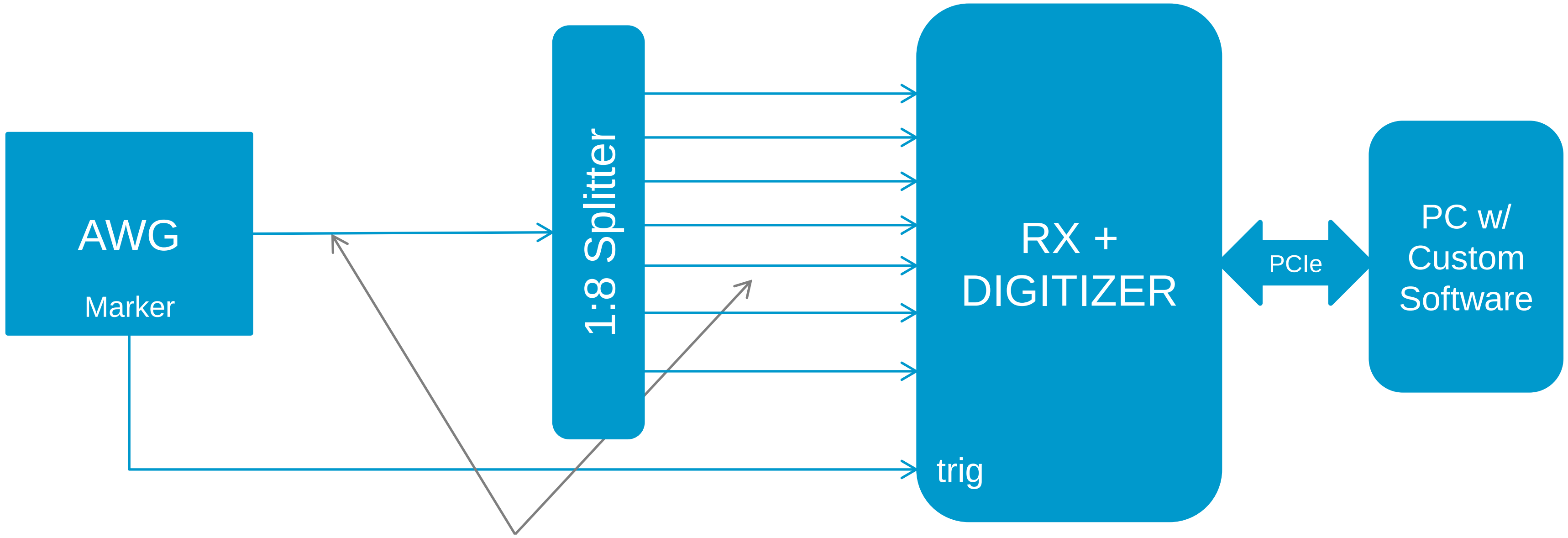
M9703A Hardware
Extension of 89600 VSA
Software

- Seamless control of M9703A from 89600 VSA software
- Recognizes DDC supported spans and uses DDC as appropriate
- Supports IF Magnitude trigger
- Multi-channel support (up to 8 measurements)
  – with new 89600 ver. 16.0

Narrowband Demo Setup

AWG Configured to Phase Modulated Signal (mimic LO output)

Digitizer Configured as a Multi-channel Narrow-band Tuned Receiver



Signals here are Phase Modulated, Constant Frequency

Because they are phase modulated, they have bandwidth.

Narrow vs. Wide

Narrowband stepped sine approach

f_1 | f_2 | f_3 … f_N

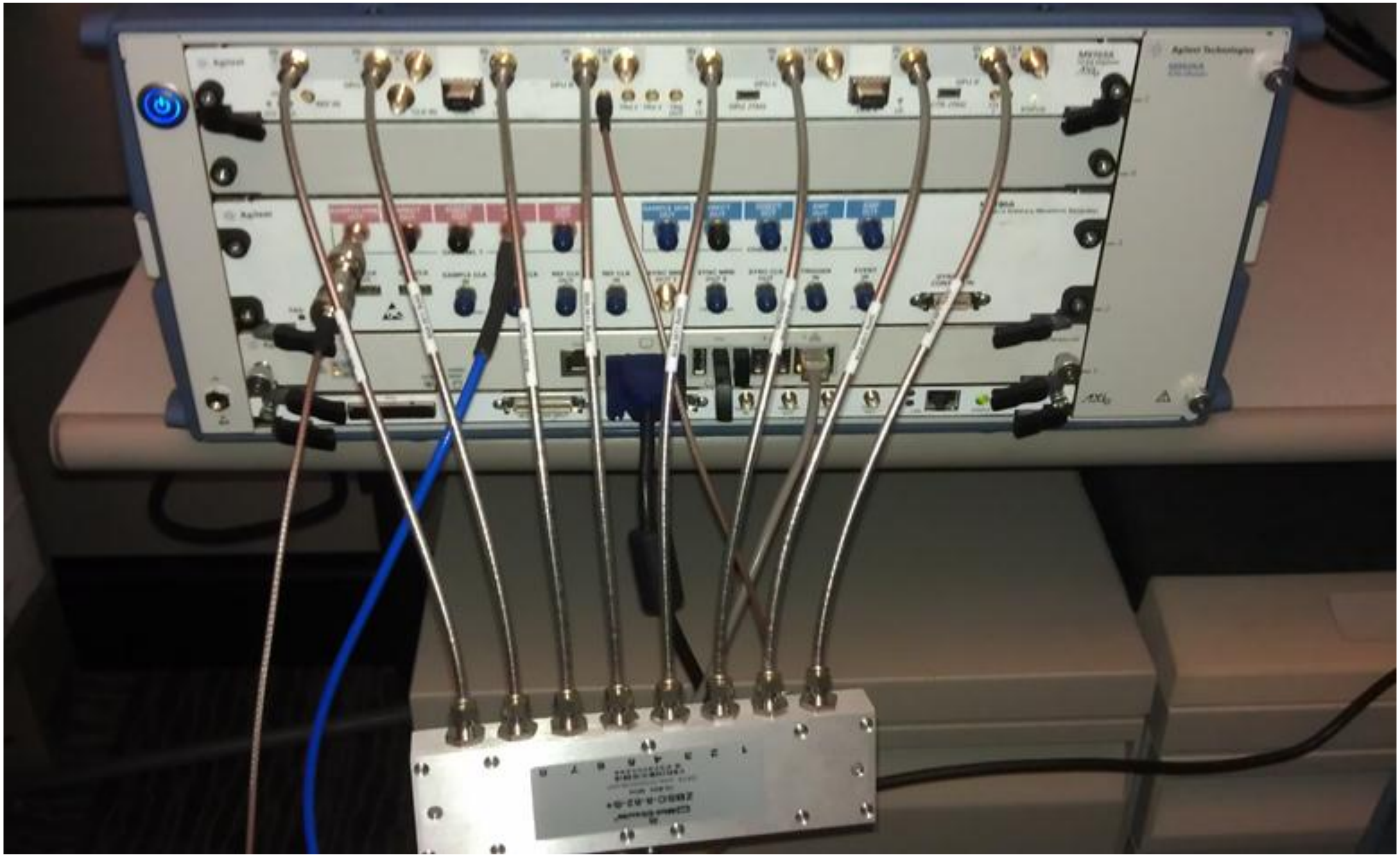
- Timing synchronization and control of frequency steps
- Easy cross-channel computation
- May be harder to determine the phase response of a single channel (element)
- One, up to N frequencies captured per measurement

Broadband approach

f_{all}

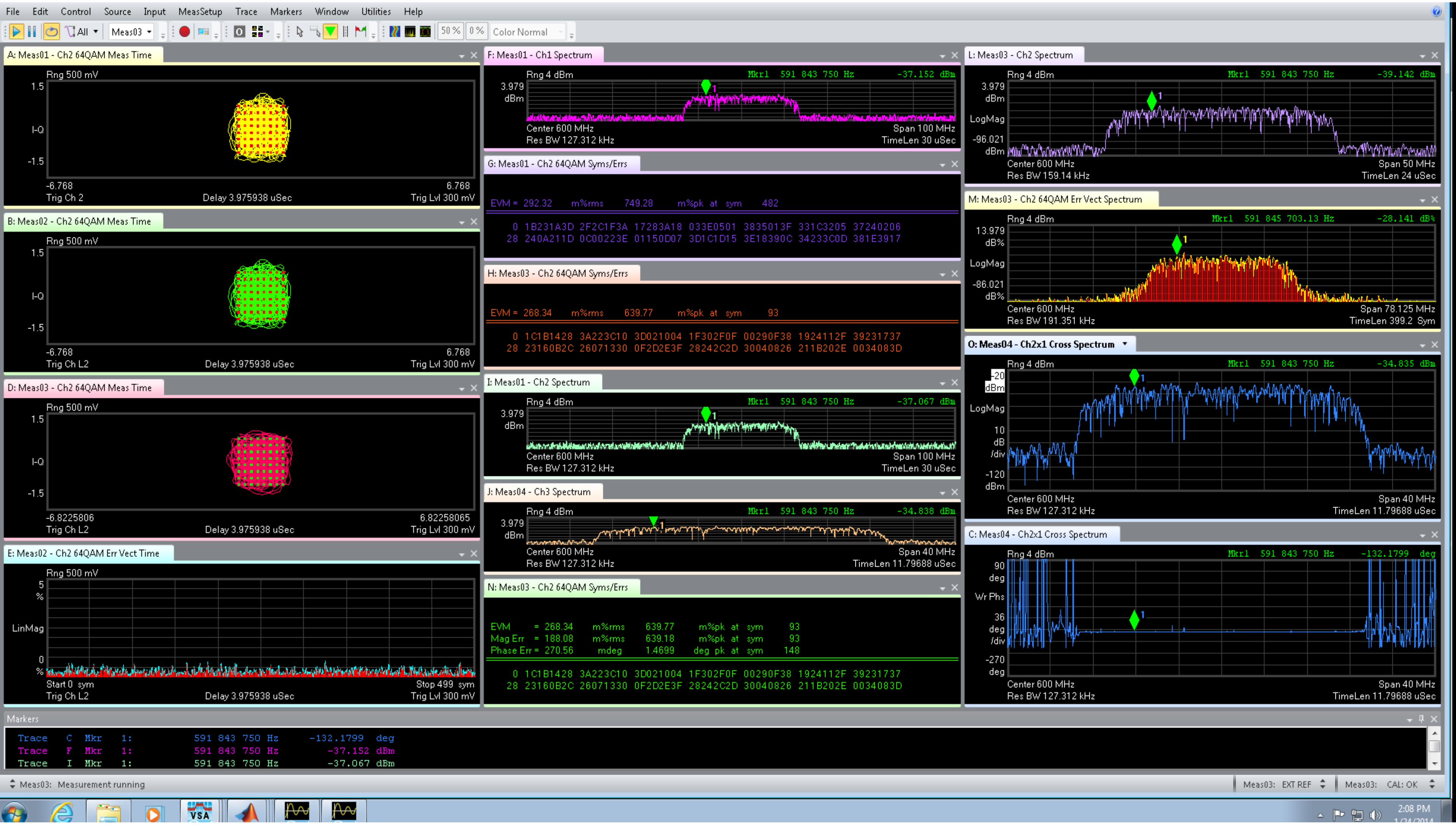
- Less to synchronize
- Easy cross-channel computation
- Easier to determine single channel (element) phase response
- All frequencies captured in a single measurement, but multiple measurement required for averaging

The Hardware

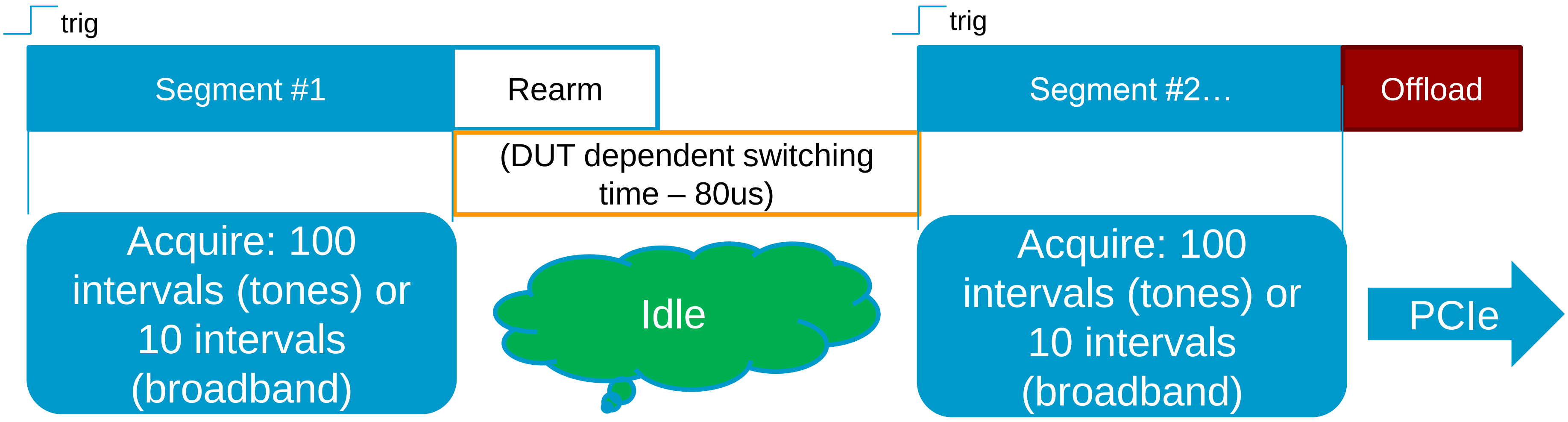


Broadband Stimulus Signals

64 QAM (e.g. SATCOM)



Measurement Throughput



Segment	Intervals	Rearm Time	DUT Time	Acquisition Cycle	Time/Interval	Speed
500 µs	100	160 µs (1.56 MSa/s)	80 µs	660 µs	6.6 µs	152 k int/sec/ch or 1.2 M meas/sec
500 µs	100	80 µs (3.125 MSa/s)	80 µs	580 µs	5.8 µs	172k int/sec/ch or 1.4 M meas/sec
500 µs	**10**	40 µsec (6.25 MSa/s)	80 µs	580 µs	58 µs	17.2 k int/sec/ch or 138 k meas/sec

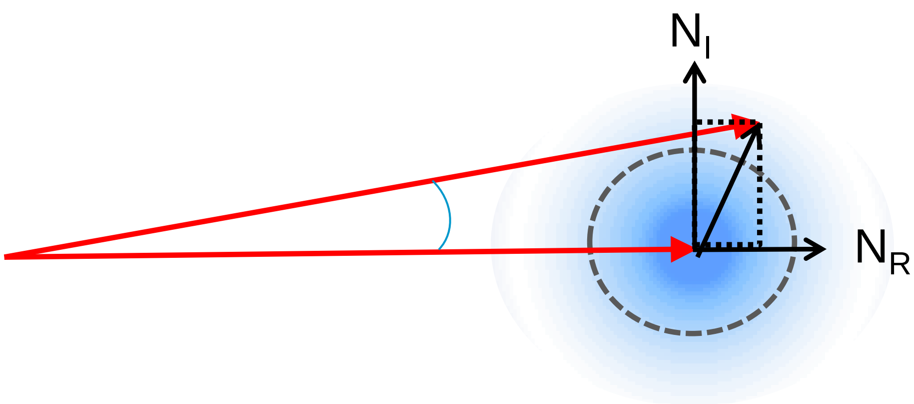
Estimating Cross Channel Phase Variance

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

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

Noise is complex: $N_R + jN_I$

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

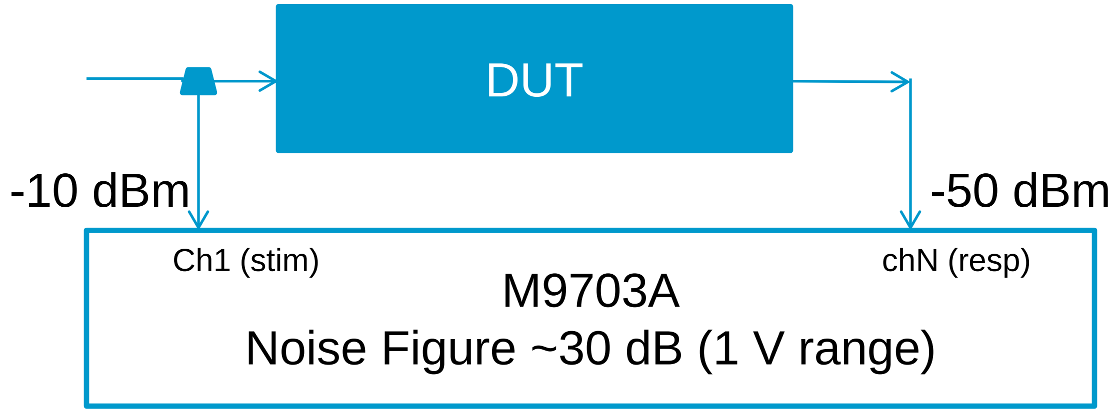


For a nominal angle of zero degrees, only the imaginary element of the noise contributes to the angular variance hence the angular variance in radians is half the normalized noise variance

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

$$Cross\ Channel\ Angle\ Variance = \left(\frac{180}{\pi}\right)^2 * \left(\frac{10^{\frac{-SNR\_STIM}{10}}}{2} + \frac{10^{\frac{-SNR\_RESPONSE}{10}}}{2}\right)$$

Example (using only the digitizer noise)



SNR = SigLevel – (Noise Density + 10 log10 (ENBW)) where ENBW ~= 1/T

$$Cross\ Channel\ Angle\ Variance = \left(\frac{180}{\pi}\right)^2 * \left(\frac{10^{\frac{-SNR\_STIM}{10}}}{2} + \frac{10^{\frac{-SNR\_RESPONSE}{10}}}{2}\right)$$

Assume T= 100 usec

SNR_STIM = -10 – (-174 + 30 + 10log10(1.0/100usec)) = 94 dB
SNR_RESP = -50 – (-174 + 30 + 10log10(1.0/100usec)) = 54 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

www.agilent.com/find/m9703A

Backup Slides

Antenna Architectures

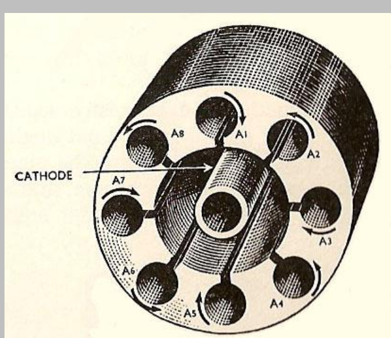
Parabolic Dish Antenna	Mechanically Steered Array	Passive Electronically Scanned Array	Active Electronically Scanned Array

Radar Dish Antenna

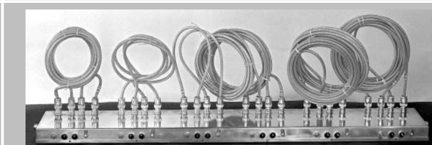
Marconi Martello S-723

AEGIS AN/SPY1D(V)

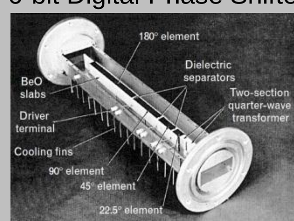
APAR



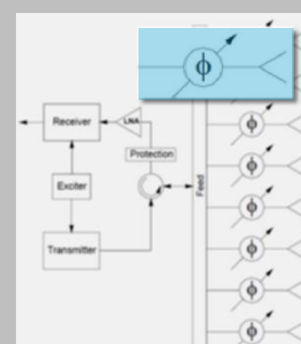
1940 - Cavity Magnetron



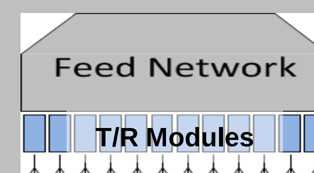
6-bit Digital Phase Shifter

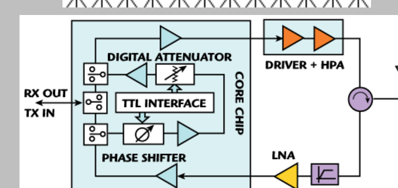


4-bit Digital Phase Shifter



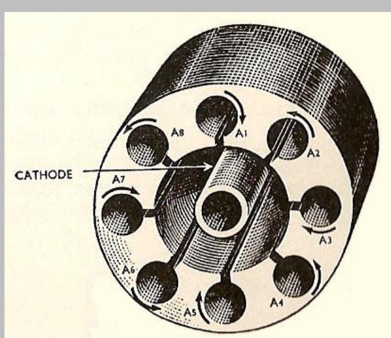
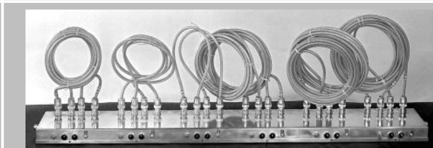
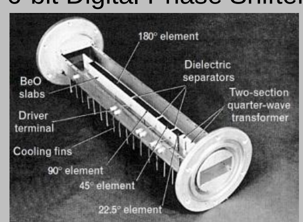
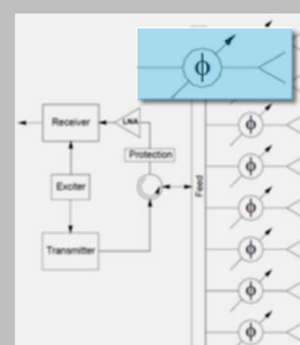
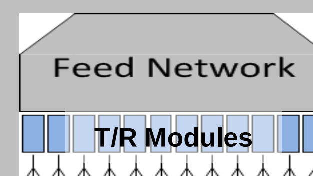
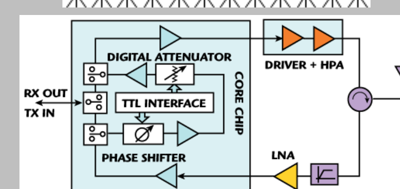
Integrated Phase Shifters





T/R Module

Antenna Architectures *Continued…*

Parabolic Dish Antenna	Mechanically Steered Array	Passive Electronically Scanned Array	Active Electronically Scanned Array
 Radar Dish Antenna	 Marconi Martello S-723	 AEGIS AN/SPY1D(V)	 APAR
 1940 - Cavity Magnetron	 6-bit Digital Phase Shifter  4-bit Digital Phase Shifter	 Integrated Phase Shifters	  T/R Module

Modern Active Electronically Scanned Phased Array (AESA)

AESA Installed on First US Air Force F15C – http://www.aviationnews.eu/

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

Modern Active Electronically Scanned Phased Array (AESA)

Artist impression of an Advanced Extremely High Frequency spacecraft

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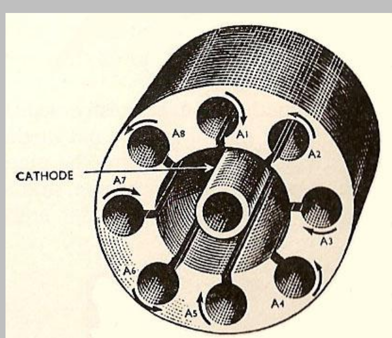
Antenna Architectures *Continued…*

Parabolic Dish Antenna

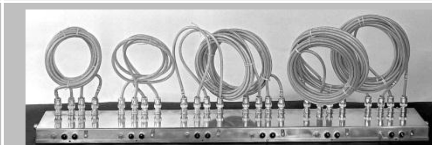
Erdfunkle Raisting



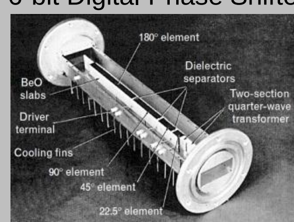
1940 - Cavity Magnetron

Mechanically Steered Array

Project SCORE



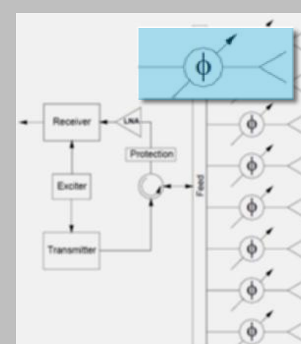
6-bit Digital Phase Shifter



4-bit Digital Phase Shifter

Passive Electronically Scanned Array

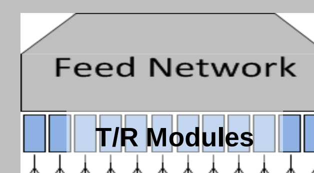
MILSTAR

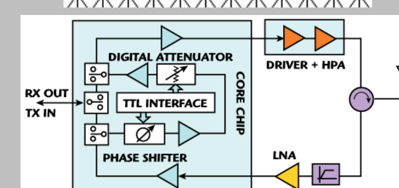


Integrated Phase Shifters

Active Electronically Scanned Array

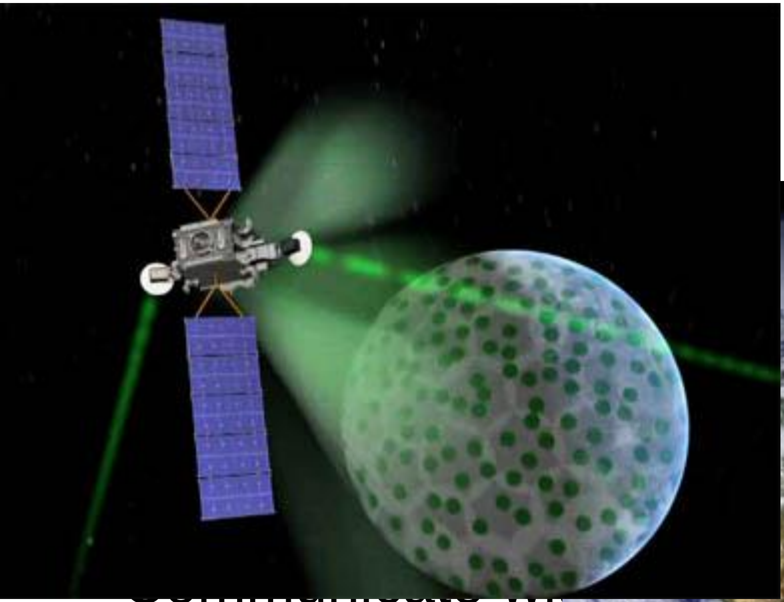
Boeing 702HP

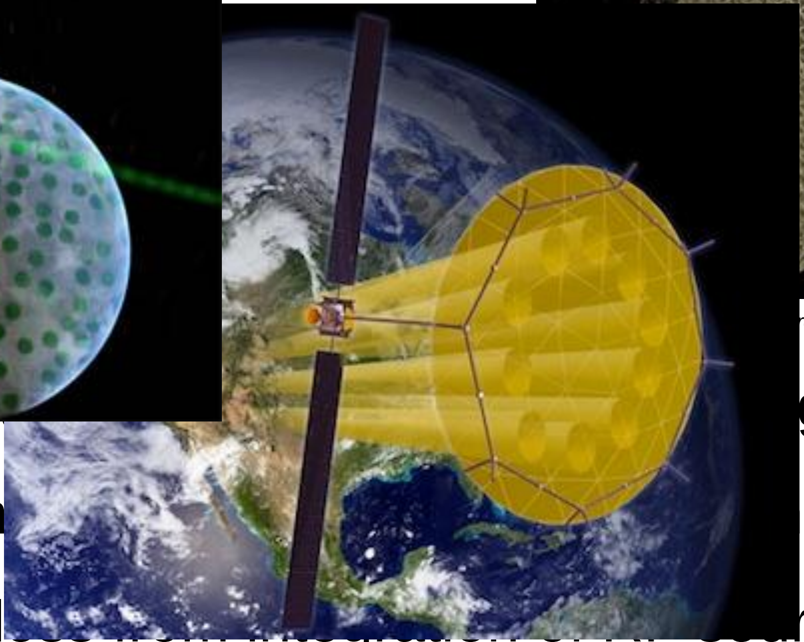


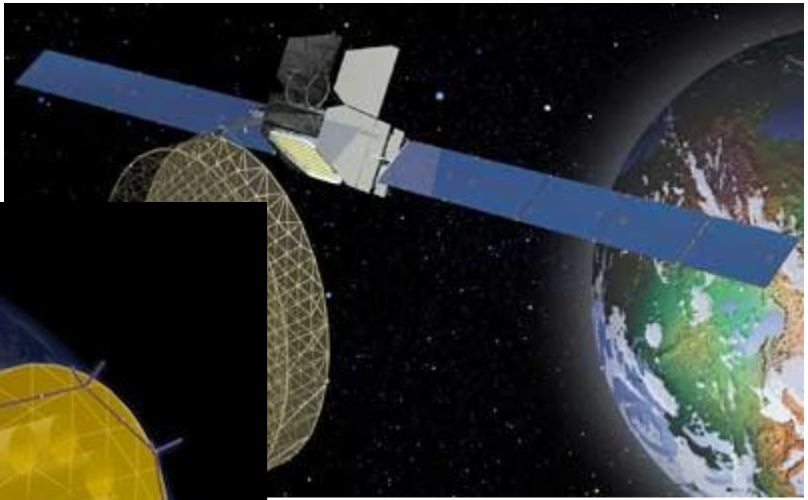


T/R Module

Modern Active Electronically Scanned Phased Array (AESA)







…reated from a single AESA antenna

- … ground stations.
- Independent tran… …ent
- Reduced power l… …rce on each T/R
- Graceful degradation – single source failure will not cripple system

Broadband Stimulus Signals

Chirped Pulse (e.g. Radar)

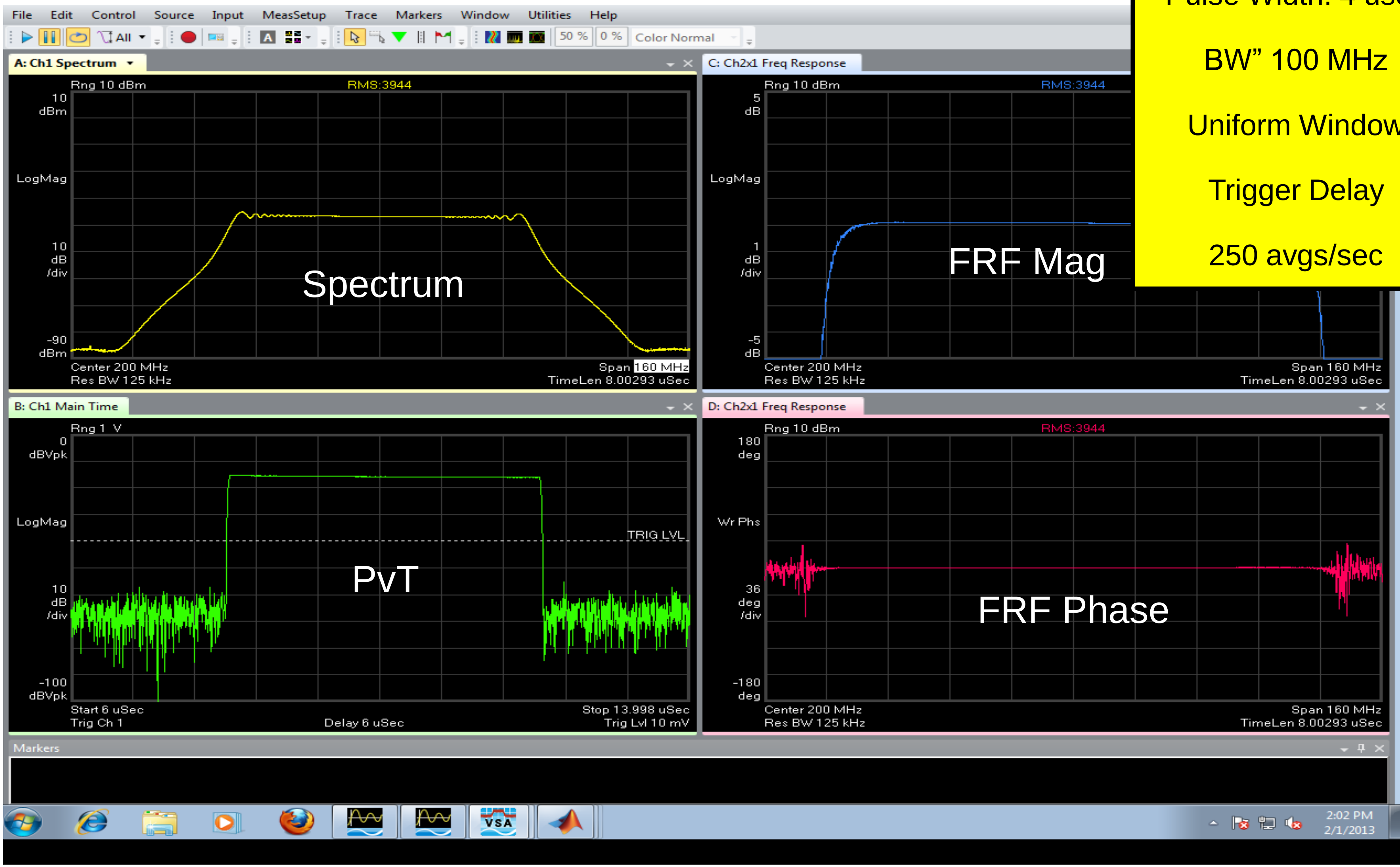
Pulse Width: 4 usec

BW” 100 MHz

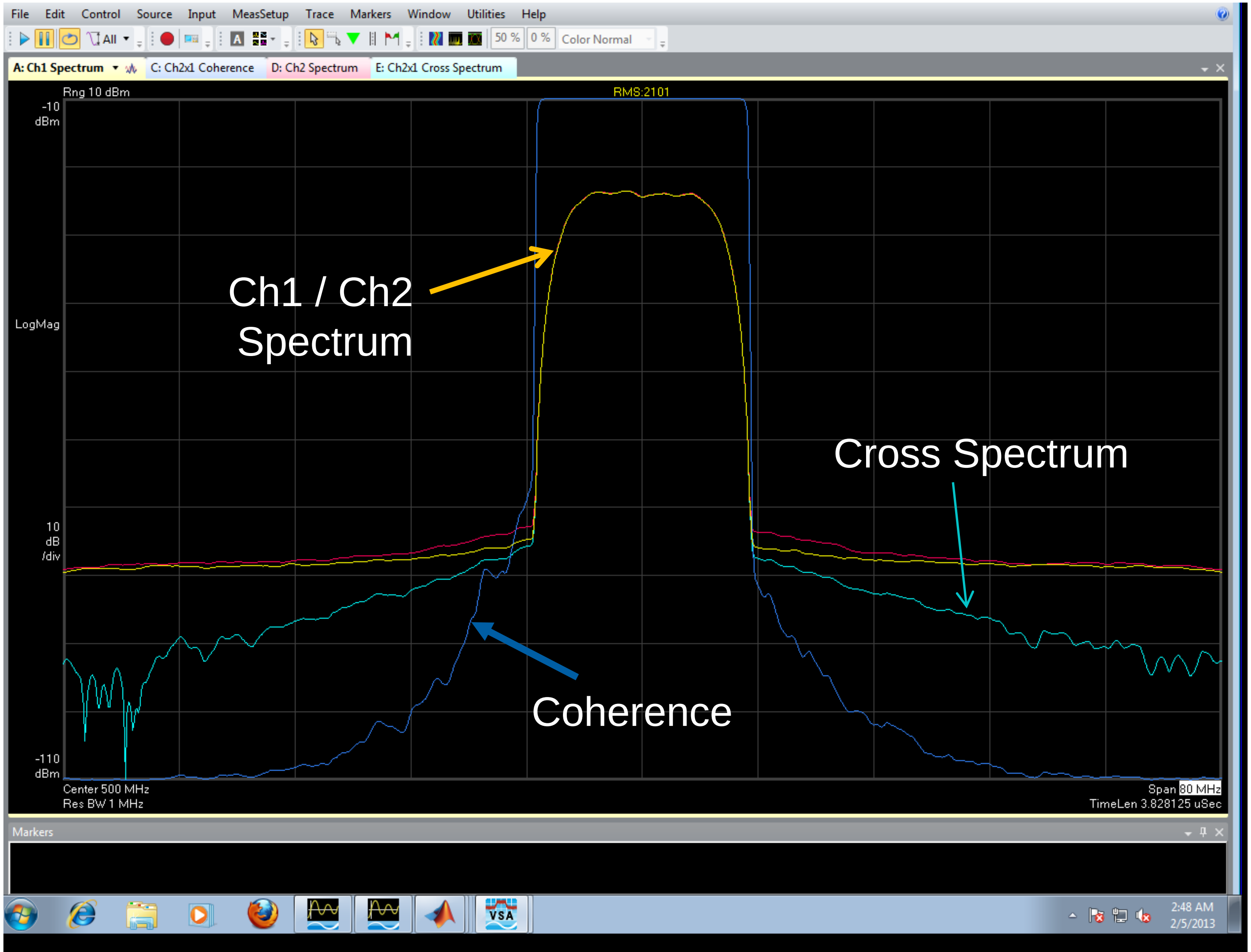
Uniform Window

Trigger Delay

250 avgs/sec

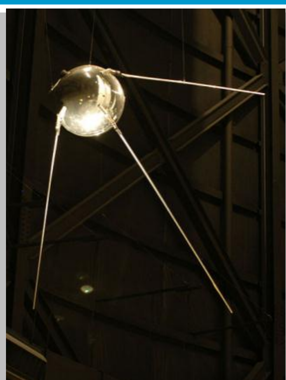


Cross Spectrum and Coherence

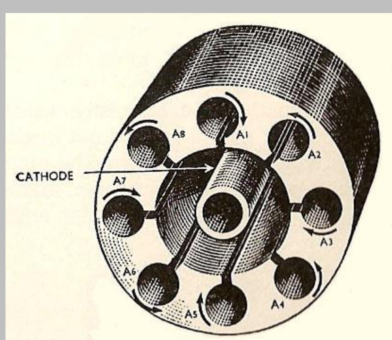


Antenna Architectures *Continued…*

Parabolic Dish Antenna



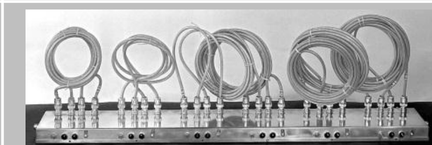
Sputnik 1



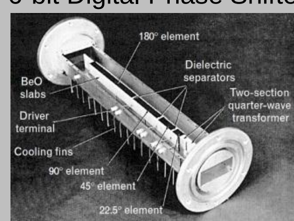
1940 - Cavity Magnetron

Mechanically Steered Array

Project SCORE



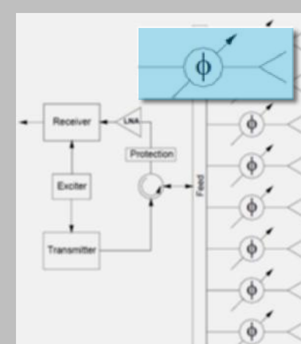
6-bit Digital Phase Shifter



4-bit Digital Phase Shifter

Passive Electronically Scanned Array

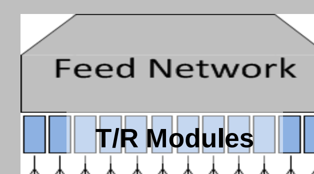
MILSTAR

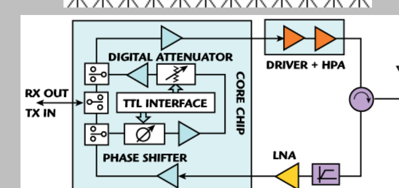


Integrated Phase Shifters

Active Electronically Scanned Array

Boeing 702HP





T/R Module