

# **WMC: Baseband Corrections for Precision Millimeter-Wave Signal Measurements**

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K.U. Leuven**





# Millimeter-Wave Wireless: Alignment of three critical factors

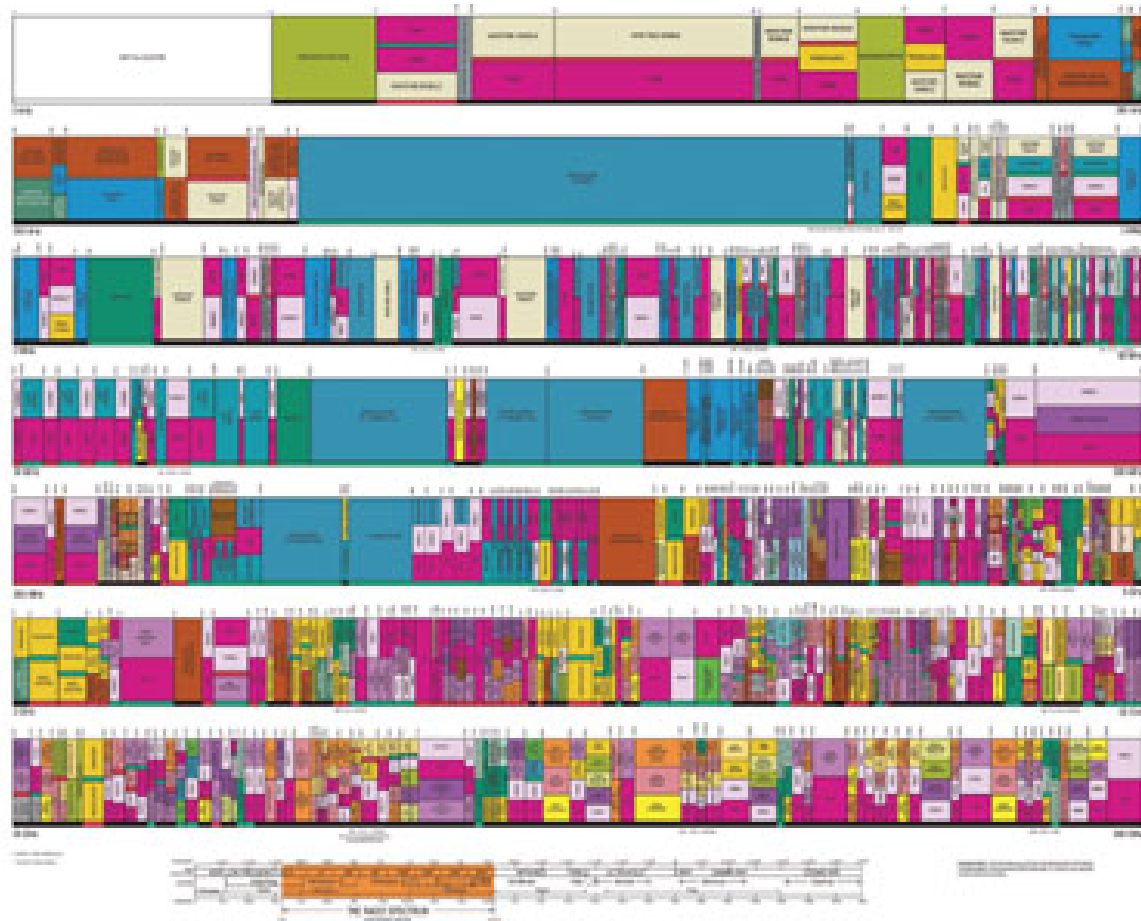
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- Regulatory
  - Millimeter-wave spectrum recently allocated by FCC in the U.S. for commercial use
- Technology
  - Silicon devices now have adequate speed for integrated antennas, transmitters and receivers
- International need
  - Mobile broadband networks are hot
  - “Spectrum crunch”: a top telecommunications industry priority



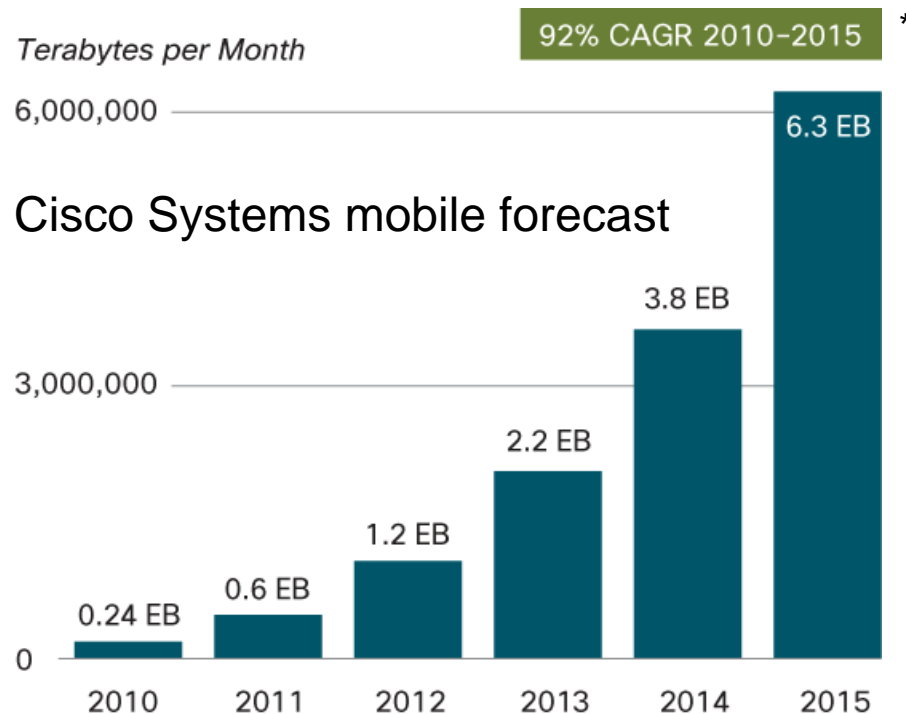


Kategorie	
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# What is the spectrum crunch?



Source: Cisco VNI Mobile, 2011

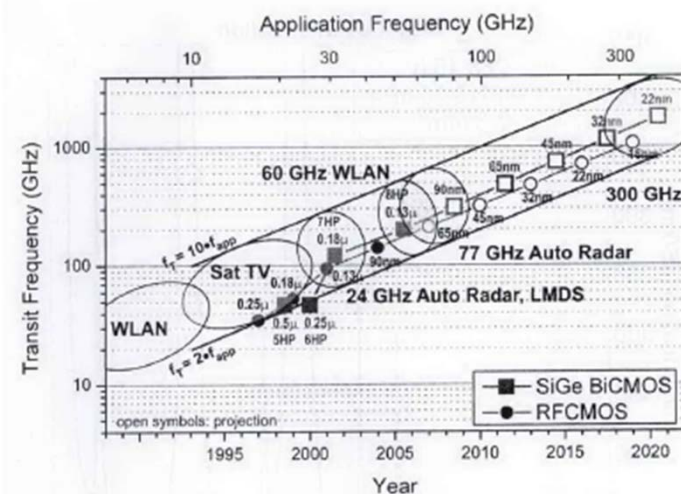
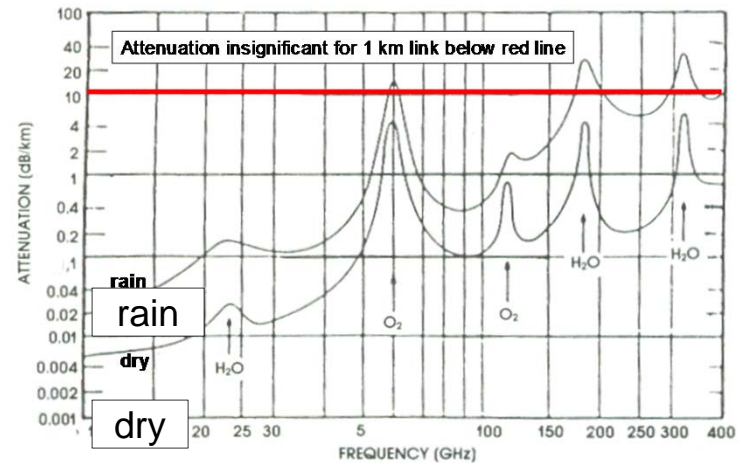
\* CAGR: Compound annual growth rate

- 3 % of wireless smart-phone customers use 40% of total available wireless bandwidth
  - 5000 % growth in demand for wireless internet data in the last three years
  - “The biggest threat to the future of mobile in America is the looming spectrum crisis.” (Julius Genachowski, Chair of the FCC)
- Cellular Telecommunications Industry Association keynote talks, October 2009



# Technical enablers

- Attenuation not significant for paths under 1 km
  - Well-suited for cellular and mesh-networked architectures
- Transistor speed
  - Microwave industry ready to exploit its cutting edge high-speed technology
- Short wavelengths enable active, agile, integrated antennas

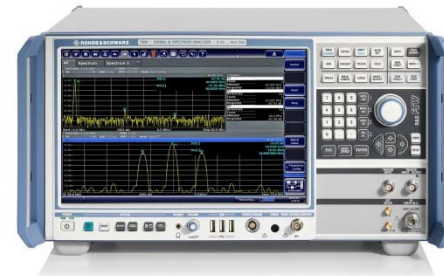
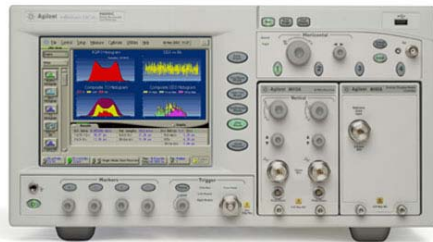




# Technical challenge: Hardware verification

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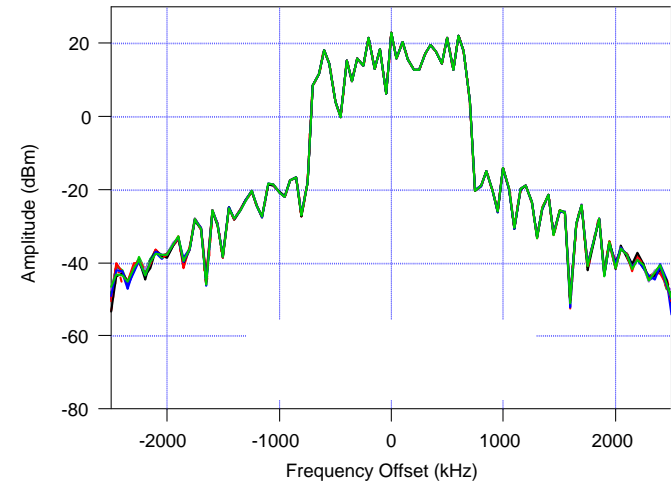
- Verifying sources and receivers of broadband digitally modulated signals at millimeter-wave frequencies
- Required measurement accuracy increases linearly with frequency
- Impedance, timing, nonlinearities: problematic at mm-wave



Lack of traceability for calibrations of commercial instruments inhibits knowledge of measurement accuracy



# Wireless measurements: hard at RF, harder at mm-wave

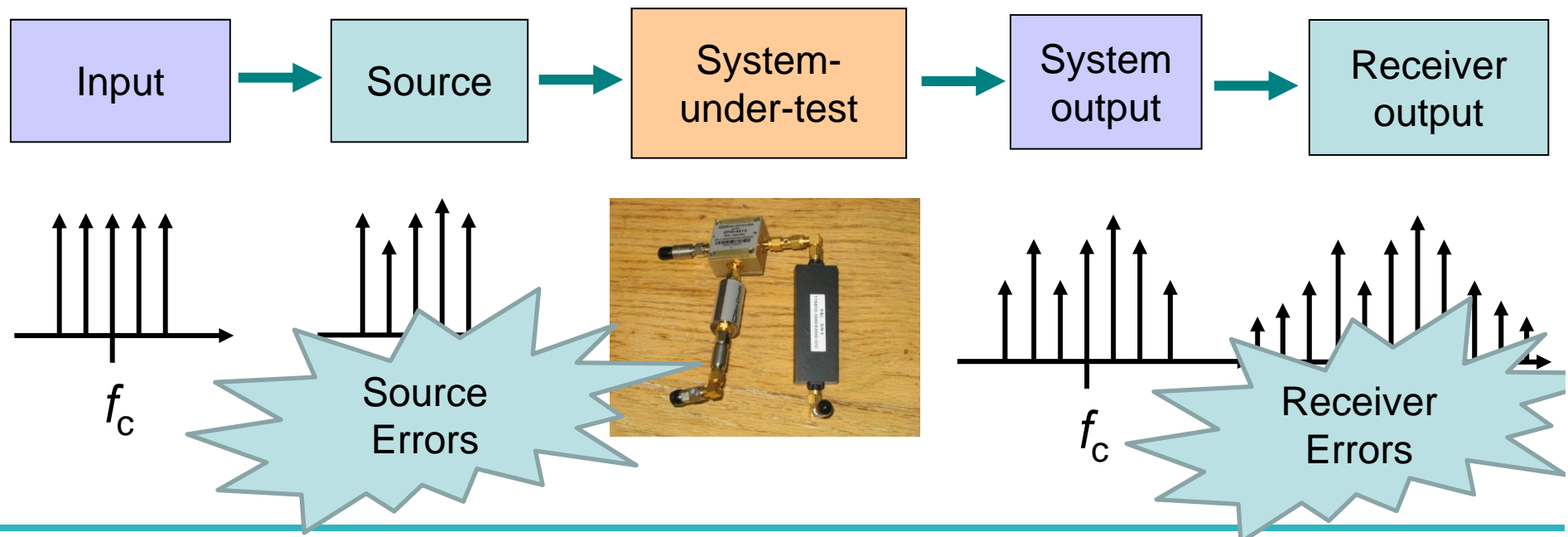


- Bandpass signals: Fast sampling for detail around carrier
- Multipath: Channel characterization, system equalization
- Effects of power amplifier: Nonlinear measurements
- Highly integrated systems: Free-field test



# Errors in Sources and Receivers

- Need for accurate test of system response
- Characterized source needed to characterize system-measurement receiver

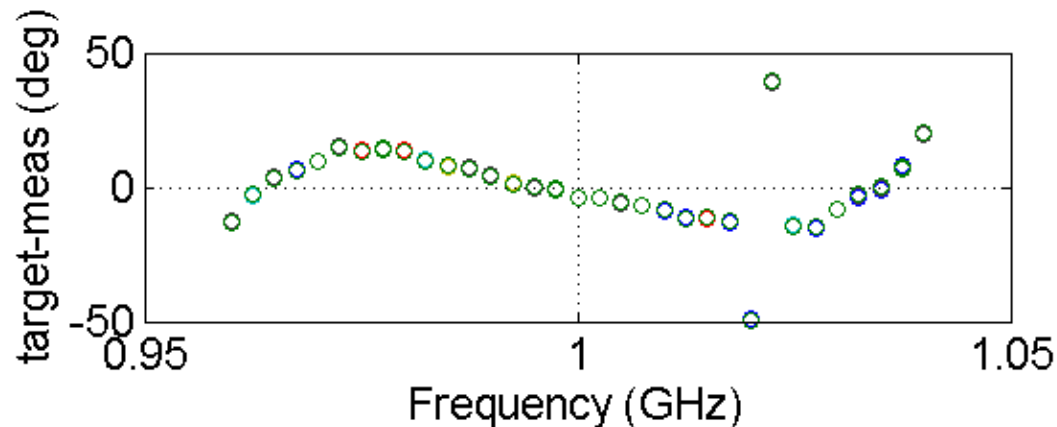






# Vector Response of Sources and Receivers

- Characterized source
- Issue: many types of modulated signals
  - Modulation format: peak-to-average power ratio (PAPR) and bandwidth
  - Sources optimized for various formats, bandwidths
  - How to generalize the calibration?

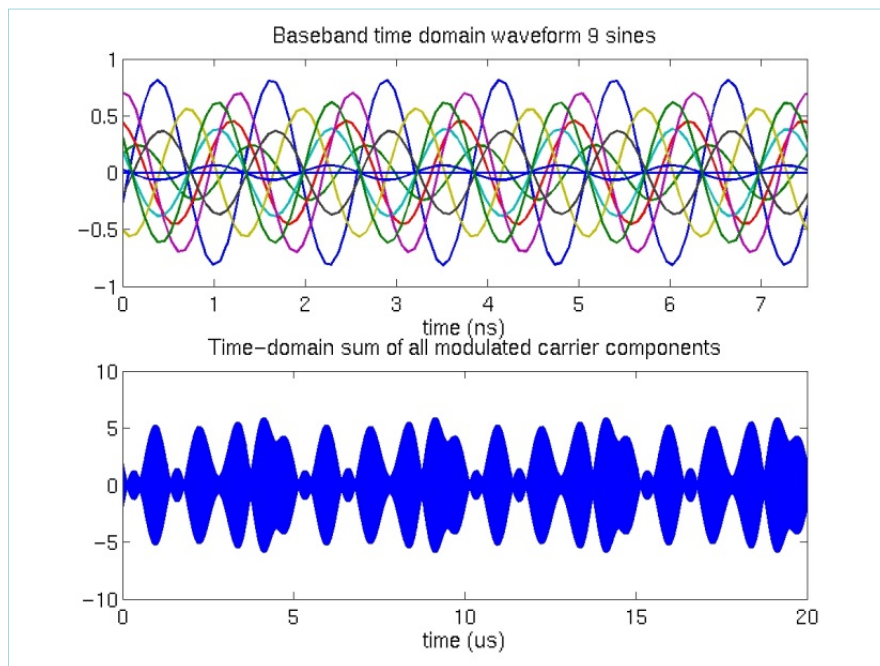


Phase response of vector source: BW = 80 MHz

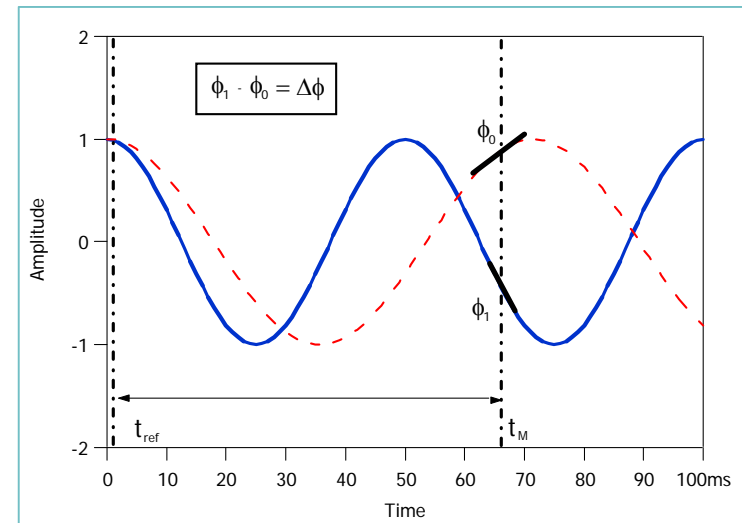


# Calibration signals: Multisines

Multisines replicate various PAPRs, bandwidth, frequency spacing and sampling of digitally modulated signals



**Top:** 9 frequency-offset sines  
**Bottom:** vector addition of sines



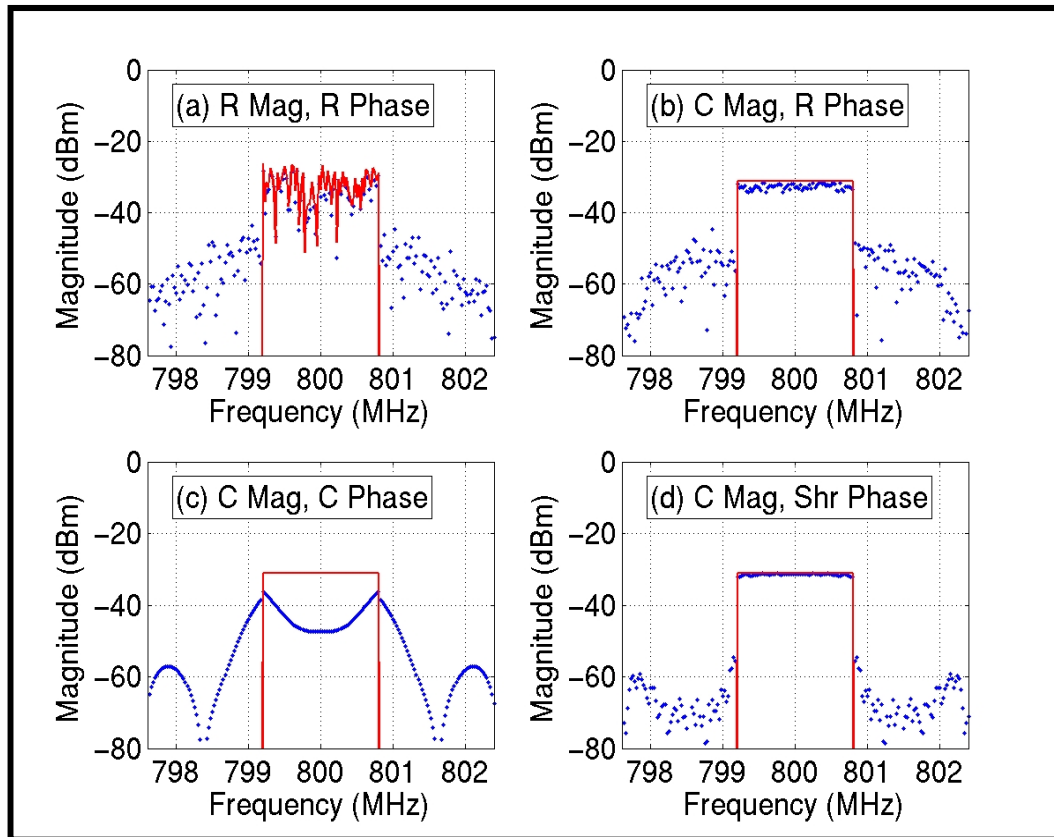
**Detrending:** Phase alignment based on finding reference time

**Low PAPR Schroeder phases:**

$$\phi_k = -k(k-1)\pi / F_k$$

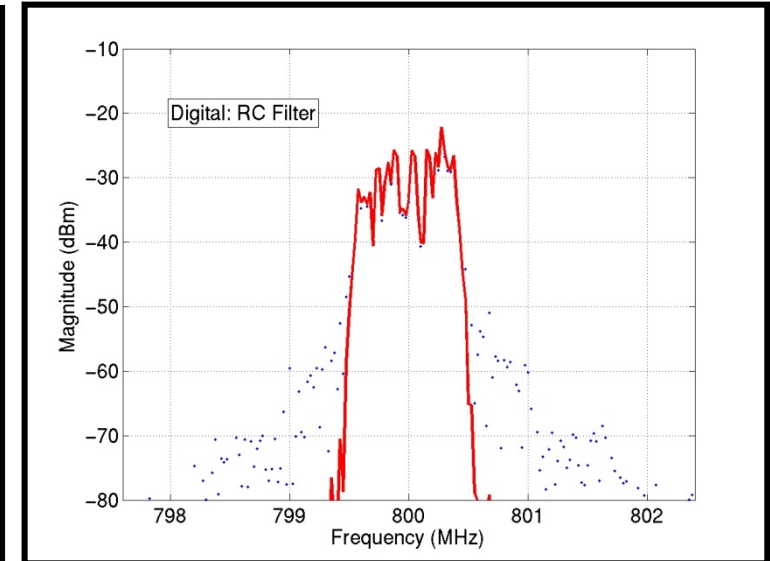


# Replicating waveform features



Four 65-tone multisines

— input  
— output



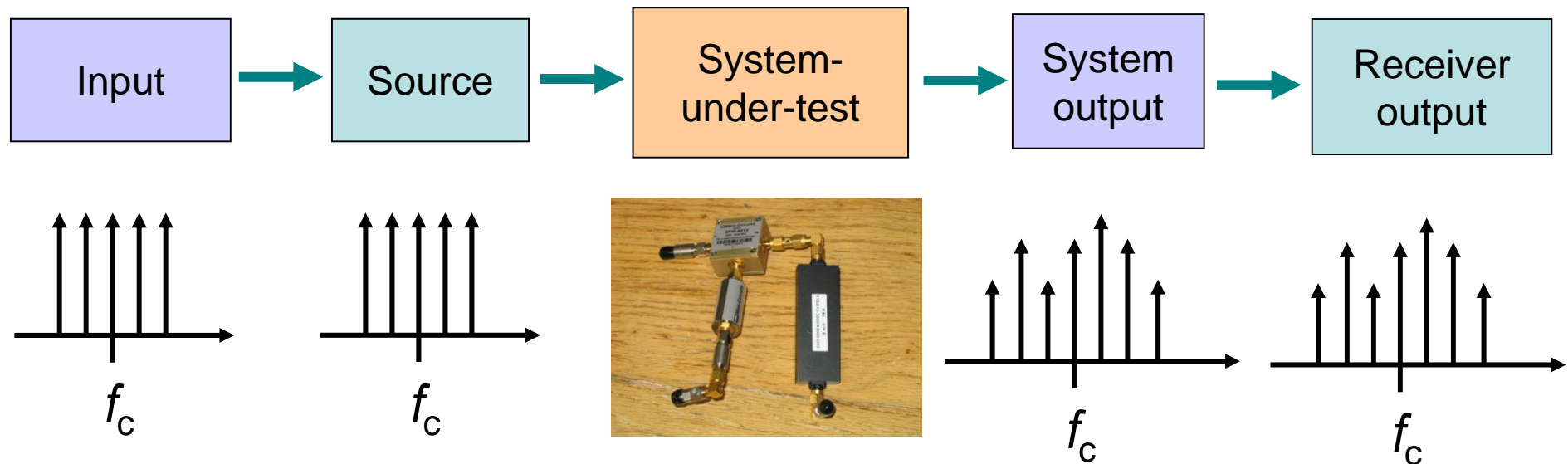
QPSK signal with  
raised cosine filtering

Relative phase sets  
signal's spectrum



# Calibrating source and receiver

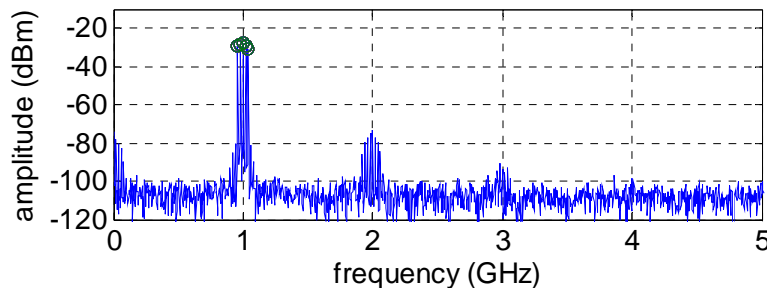
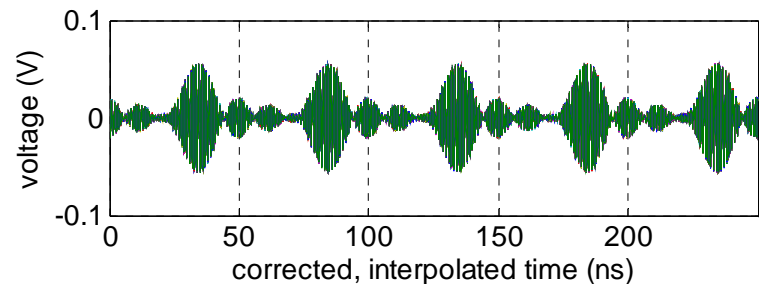
- Excite with multisines, measure imperfections
- Correct for imperfections before measuring system-under-test (with uncertainty)
- Reduce uncertainty with “best” measurement of source



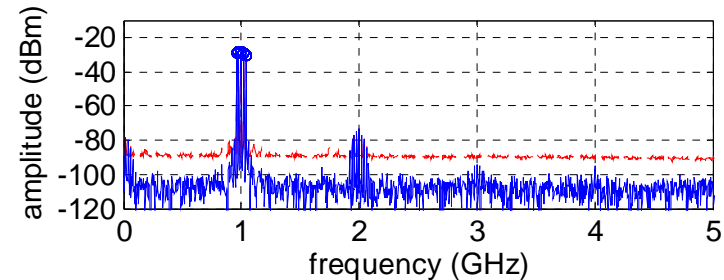
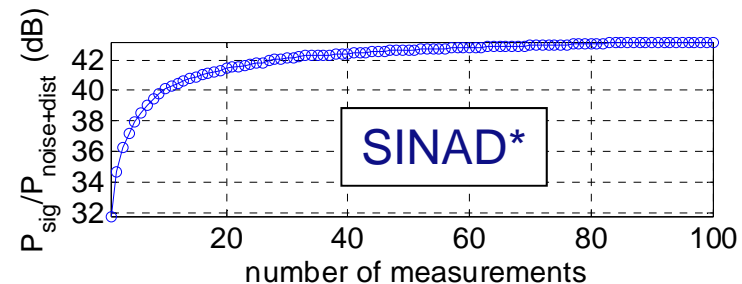


# Calibrated vector receiver: sampling oscilloscope

- Traceability: scope response
- Calibrated: time-base correction, mismatch correction
- Broadband: measure signal plus distortion
- Periodic signals: representative communication signals



Time-domain measurement: transform  
to frequency domain



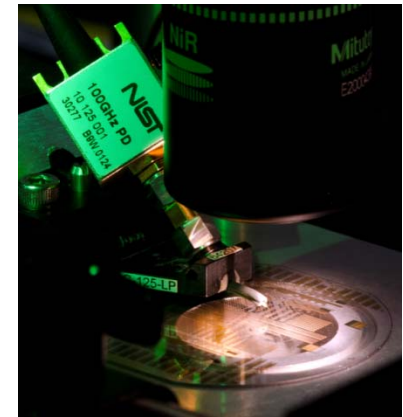
Time-domain averaging reduces  
noise floor

\* SINAD: Signal-to-interference-and-distortion ratio

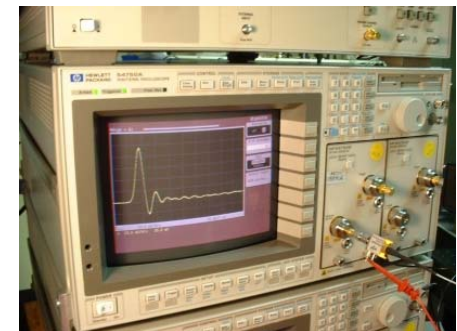


# Calibrating the oscilloscope

Calibrate a photodiode impulse source



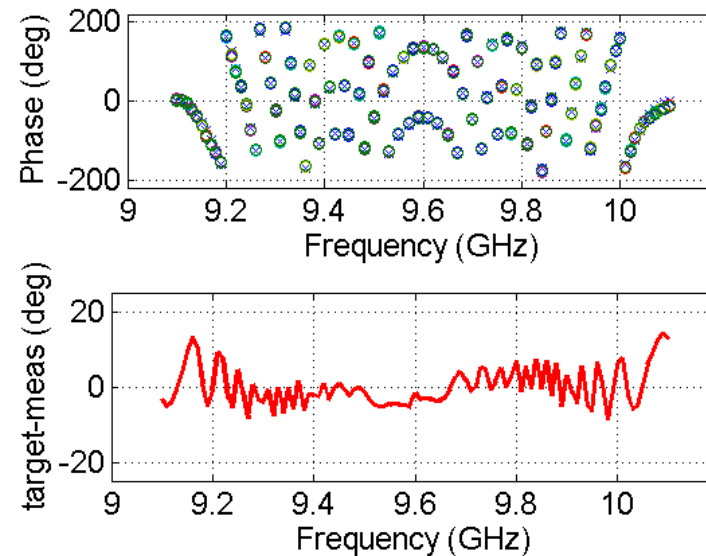
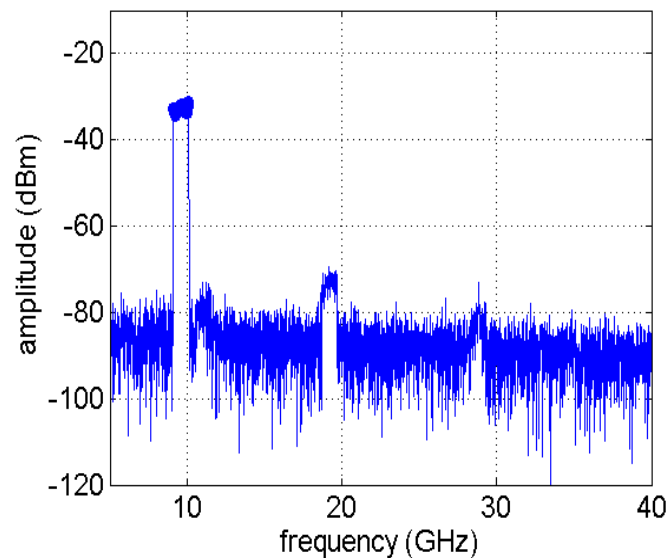
Use calibrated source to correct oscilloscope





# Vector sources are not ideal

Magnitude and phase distortion can affect error vector magnitude (EVM), bit error rate (BER), other metrics, especially for broadband signals

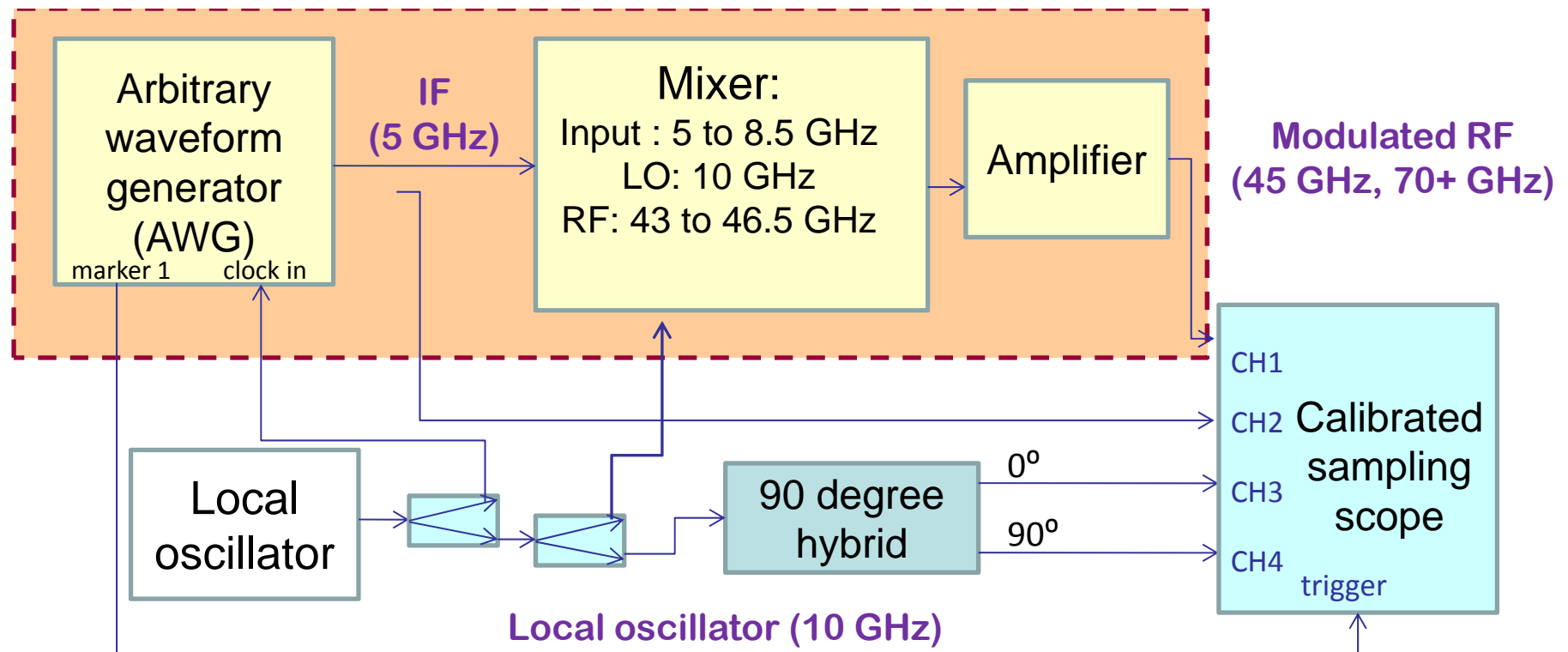


Scope: 10 GHz Schroeder multisine with 1 GHz modulation bandwidth:  
Phase error up to 15 degrees



# mm-wave sources are less so!

Verify source performance with calibrated sampling oscilloscope





# Lab-based mm-wave source

- Mixer LO
- AWG clock
- Scope time-base correction

Calibrated vector receiver  
(oscilloscope)

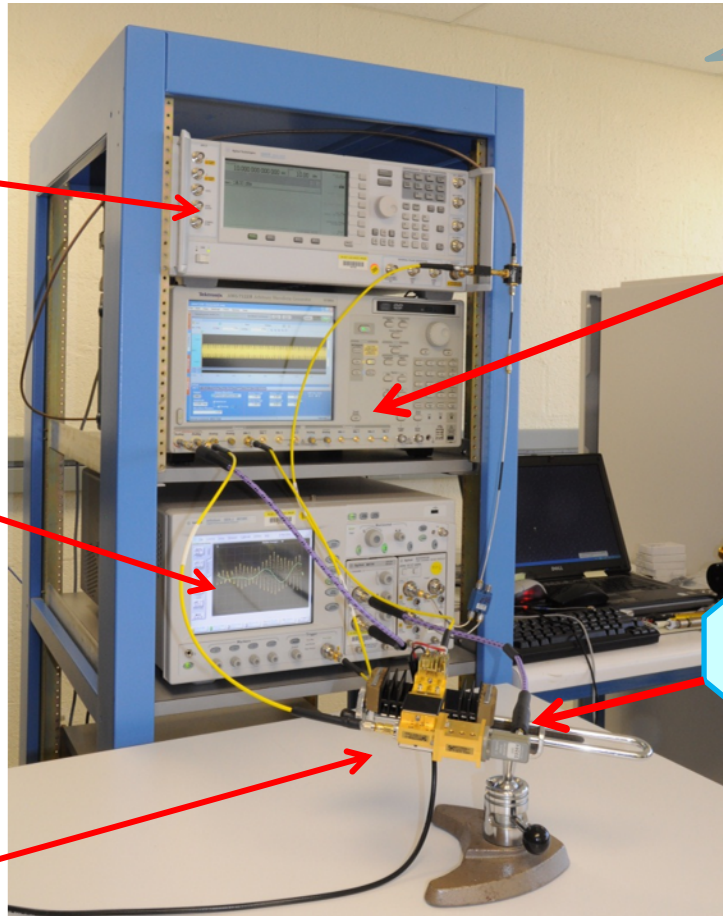
Nonideal frequency conversion

Frequency converter and amplifier

Baseband effects

Arbitrary waveform generator  
(IF = 5 GHz)

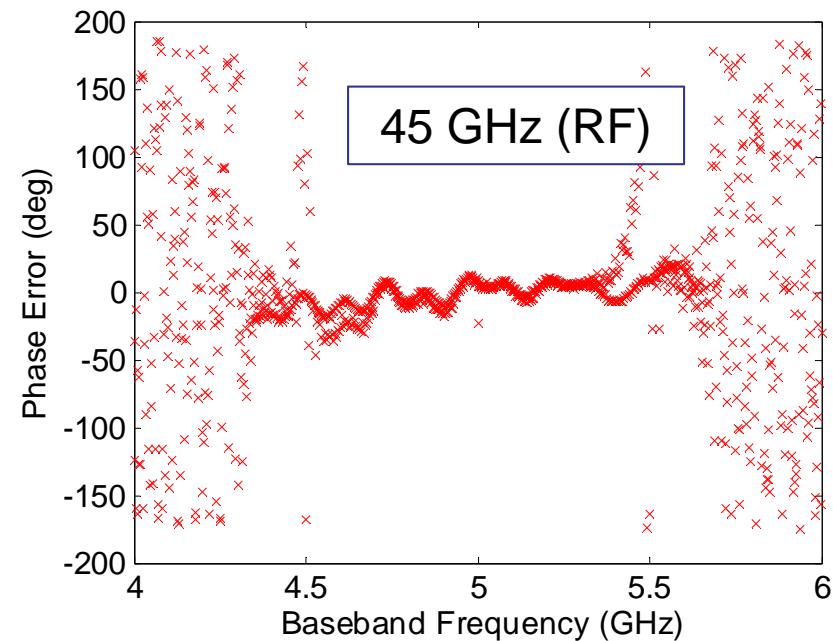
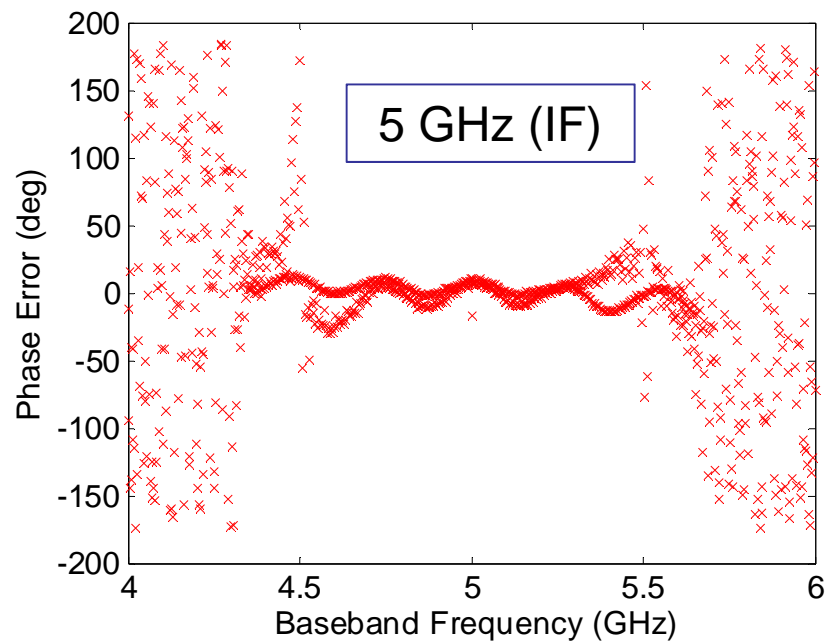
Modulated RF  
( $f_c = 45$  GHz)





# Imperfect source response

Calibrated scope measurement characterizes source



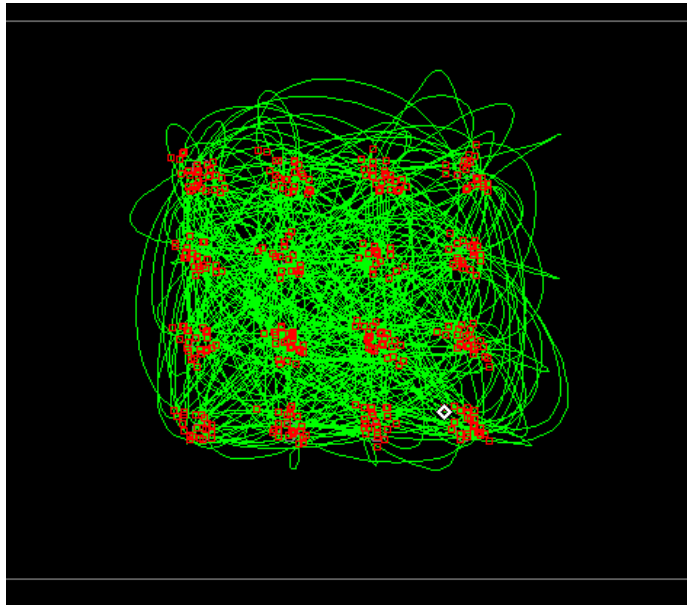
Majority of error introduced at baseband frequency



# Imperfect source response

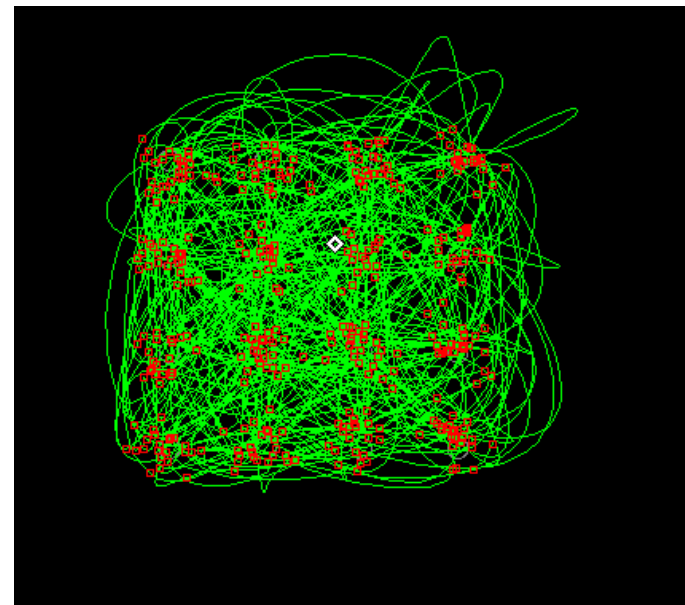
How do baseband errors affect a measurement?

Baseband effects



EVM = 9.5 %

Baseband effects + nonideal  
frequency conversion



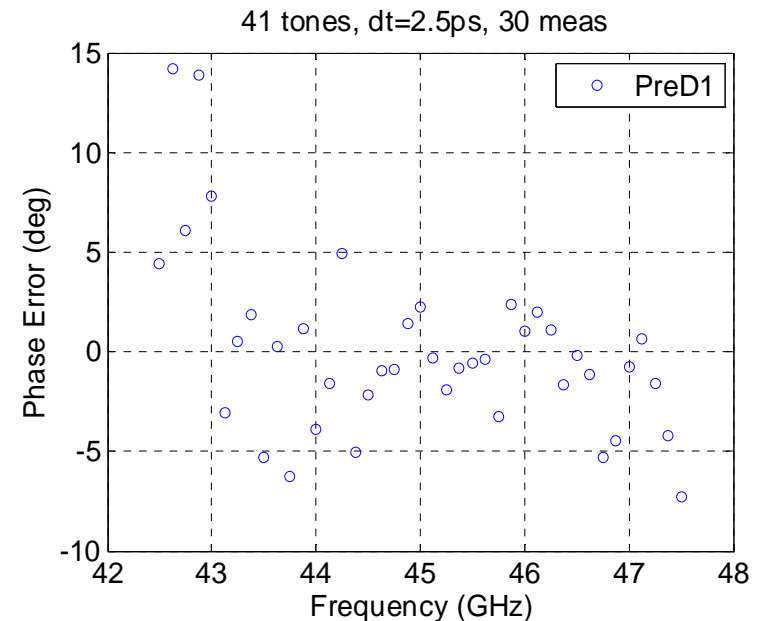
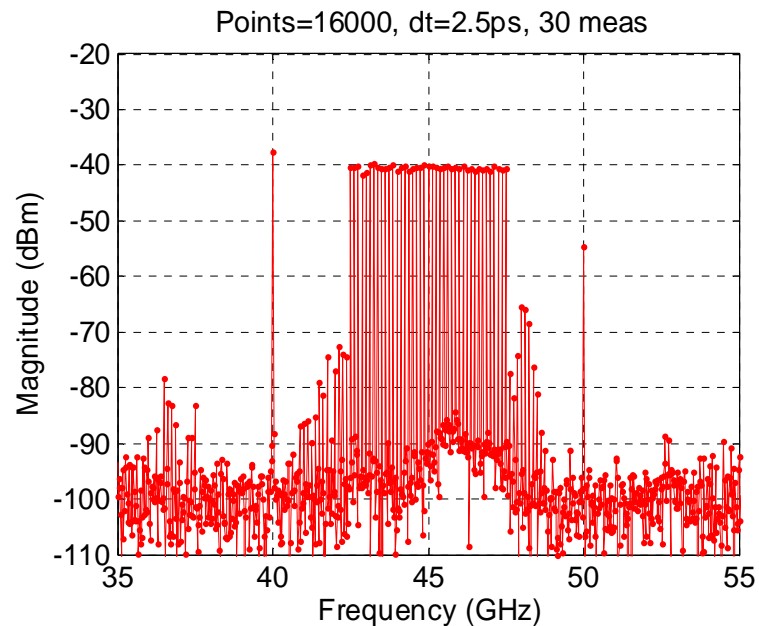
EVM = 11.9 %

16QAM signal with 1 GHz modulation bandwidth



# Correct source output

- Predistort AWG-based source input signals
- Iterative predistortion: linear and nonlinear response



In-band magnitude and phase errors are reduced with predistortion



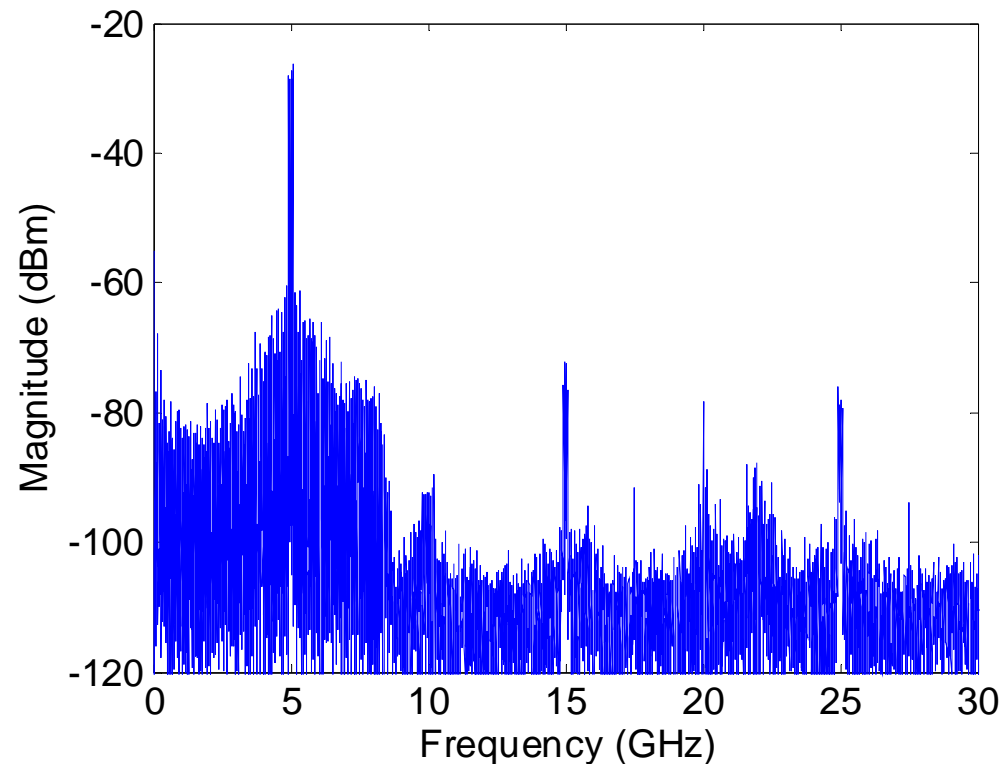
# Quantization noise and spurs

## Quantization noise

- Nonlinearity of ADC
- Limits effective number of bits of AWG

## Spurs

- Harmonics and mixing products caused by sampling
- Dithering improves AWG noise floor as much as 10 dB

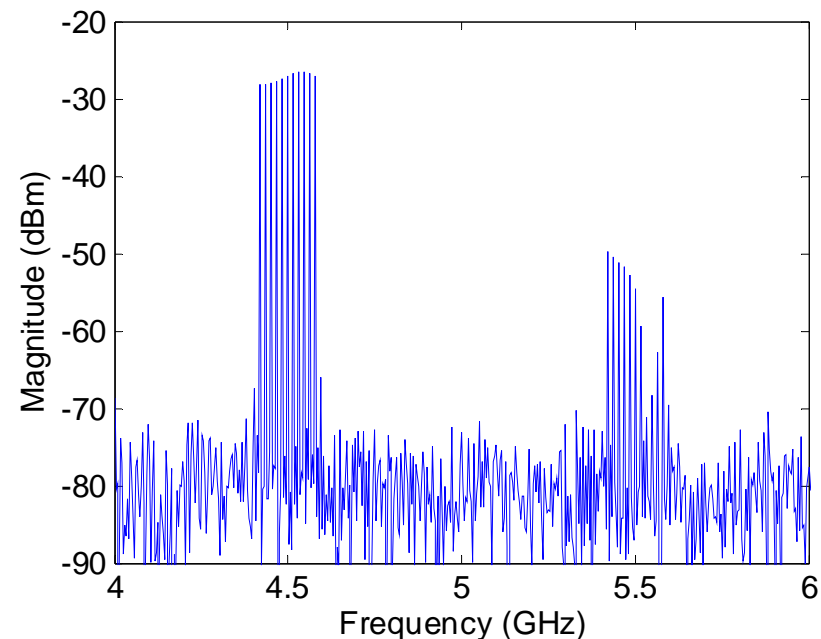
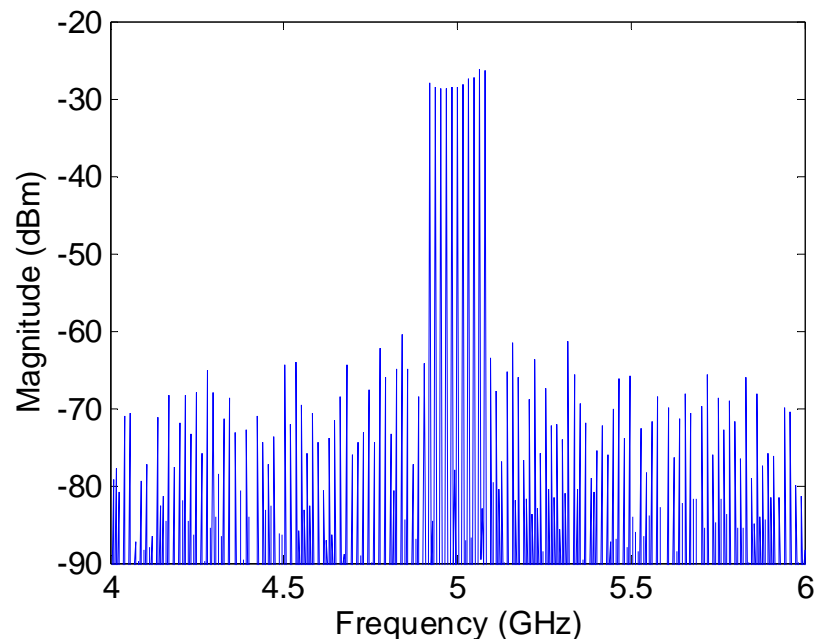


11-tone, Schroeder-phase multisine  
160 MHz modulation bandwidth



# Suppress in-band spurs

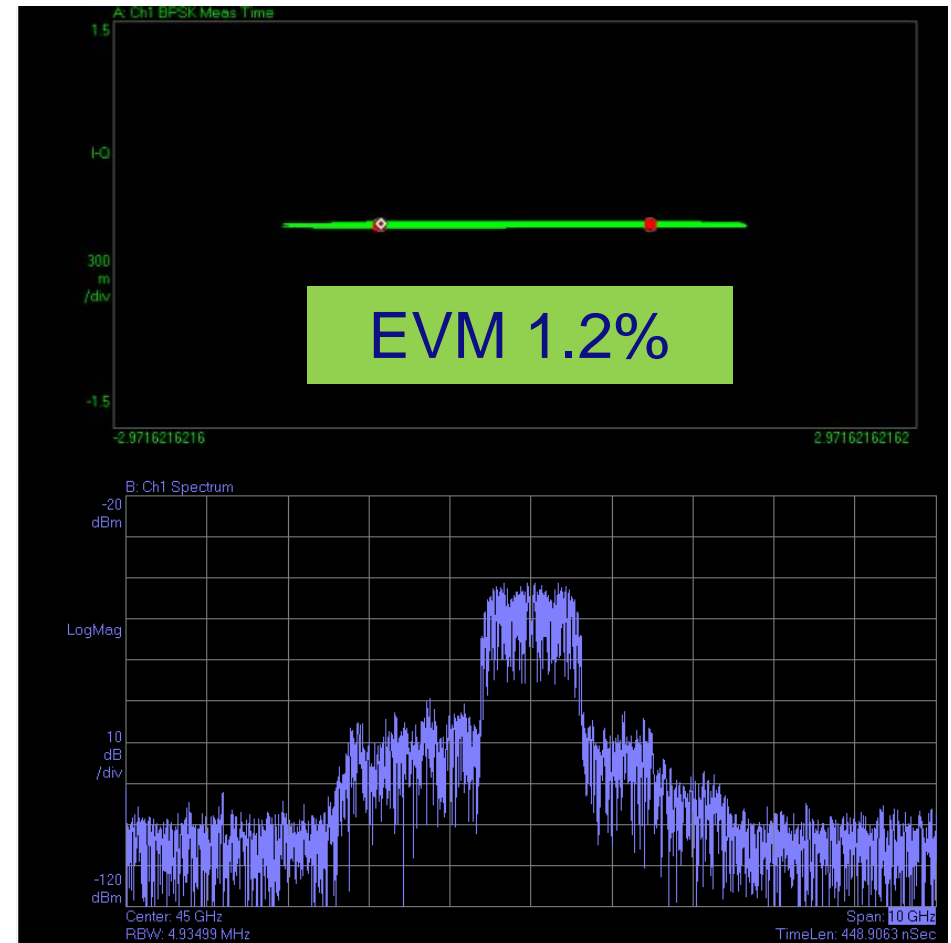
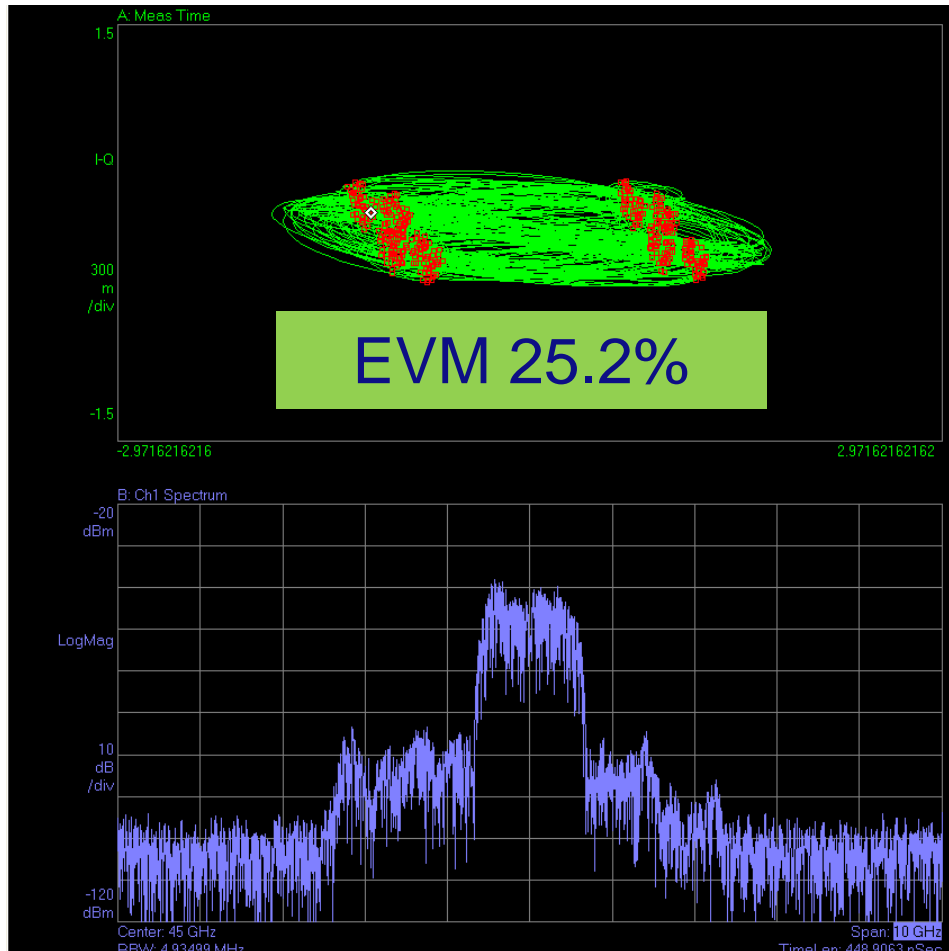
In-band spurs degrade generated baseband (IF) signal



Carrier offset moves spurs out of the passband of the signal, reduces in-band distortion and adjacent-channel power ratio



# Good baseband signals give good mm-wave measurements



1 GHz bandwidth BPSK signal at 45 GHz

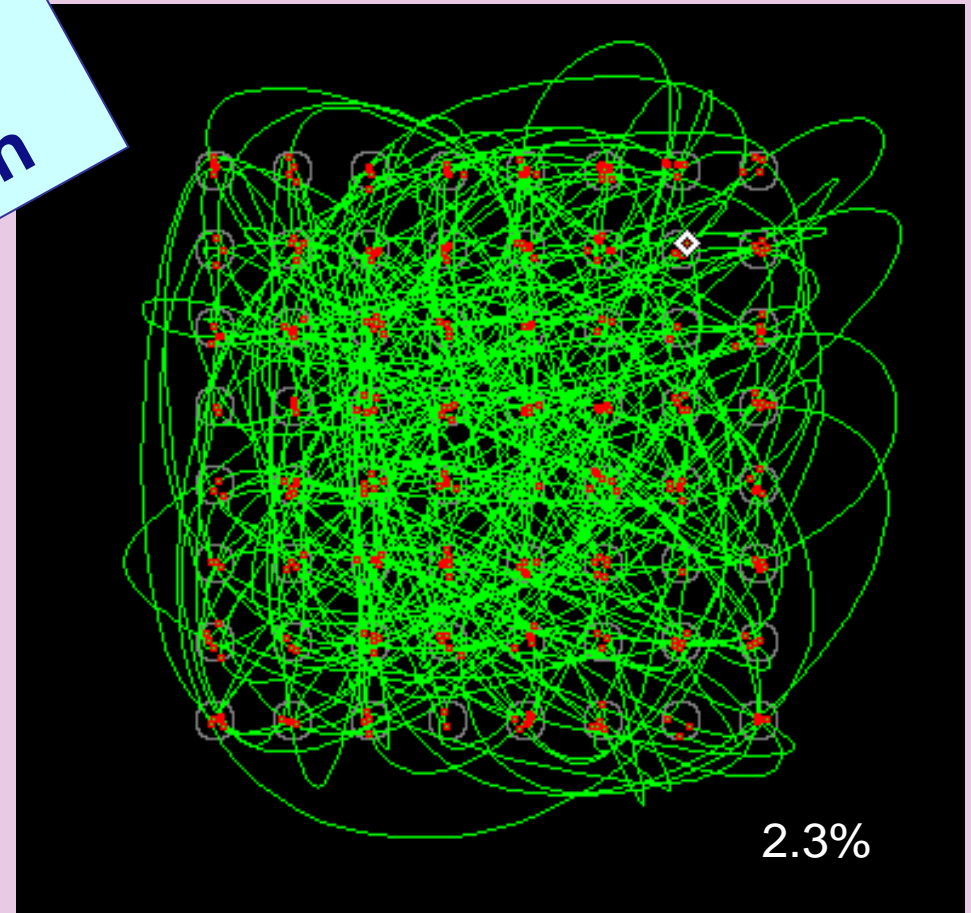


# Low-EVM 64 QAM waveform

**Allows mm-wave vector  
receiver calibration,  
system characterization**

45 GHz center frequency,  
1.2 GHz modulation bandwidth,  
512 symbols

EVM for 64 QAM



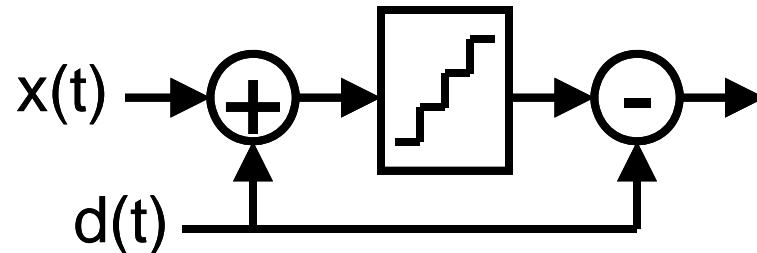


# Dithering to reduce ACPR

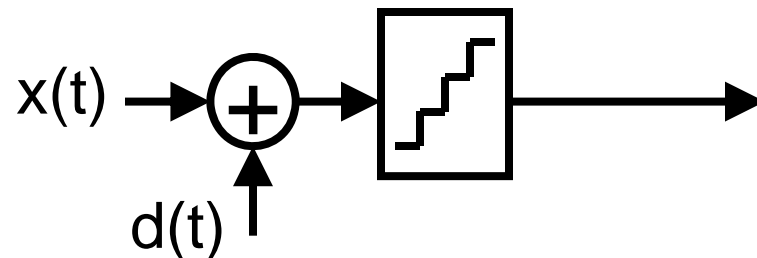
- Intentional addition of a special waveform to the input signal prior to the data conversion
  - Makes quantization noise less correlated to signal
  - Spreads quantization noise over frequency range
  - Reduces quantization noise

- Types:

- Subtractive



- Non-subtractive







# Non-subtractive dithering

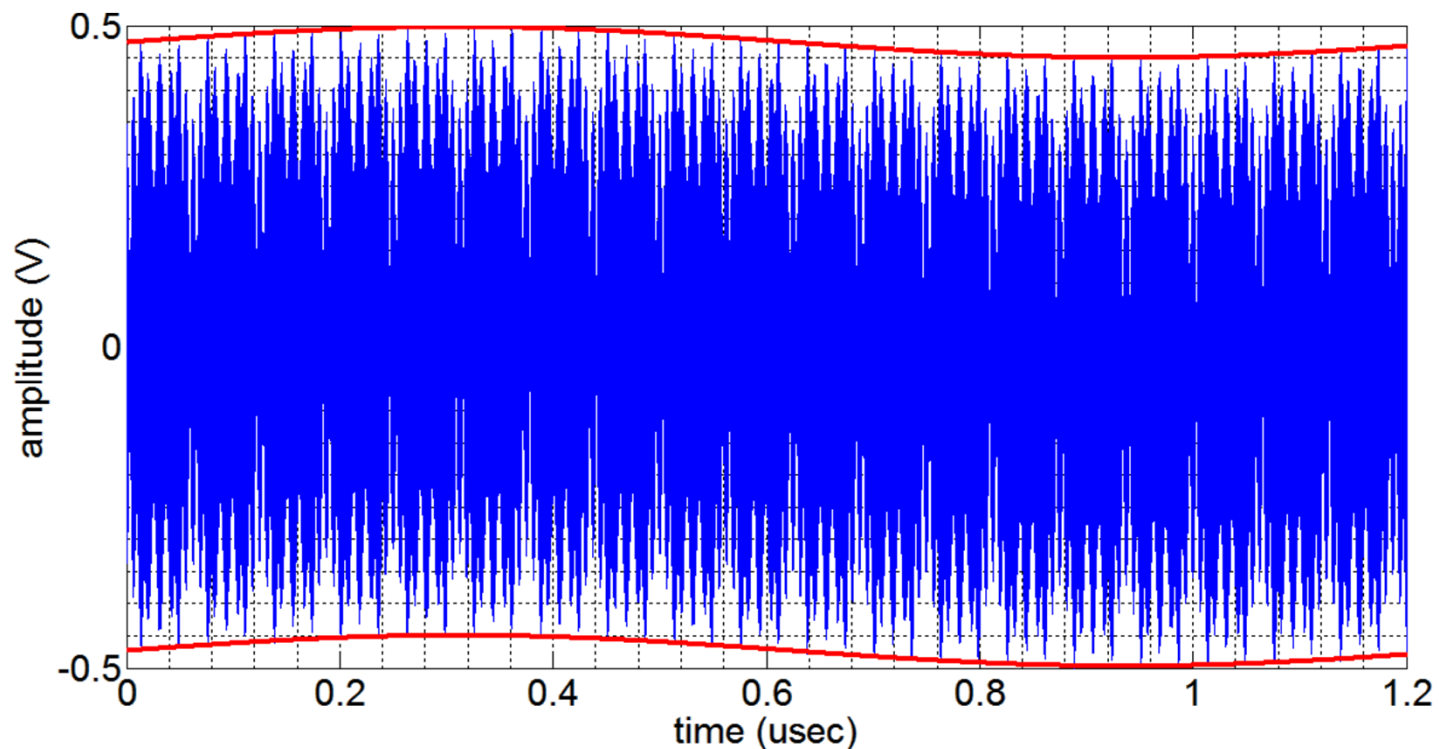
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- Dithering signals are chosen so that by filtering, they can be efficiently removed after conversion
- Ensemble dithering:
  - Record multiple periods of periodic waveform (multisine)
  - Add different dither to different ensemble member
  - Average over the whole ensemble to remove dither



# Time-Domain Ensemble-Averaged Dithering

- Use self-subtractive dither
- Repeat the waveform with time-varying additive dither







# Time-Domain Ensemble-Averaged Dithering

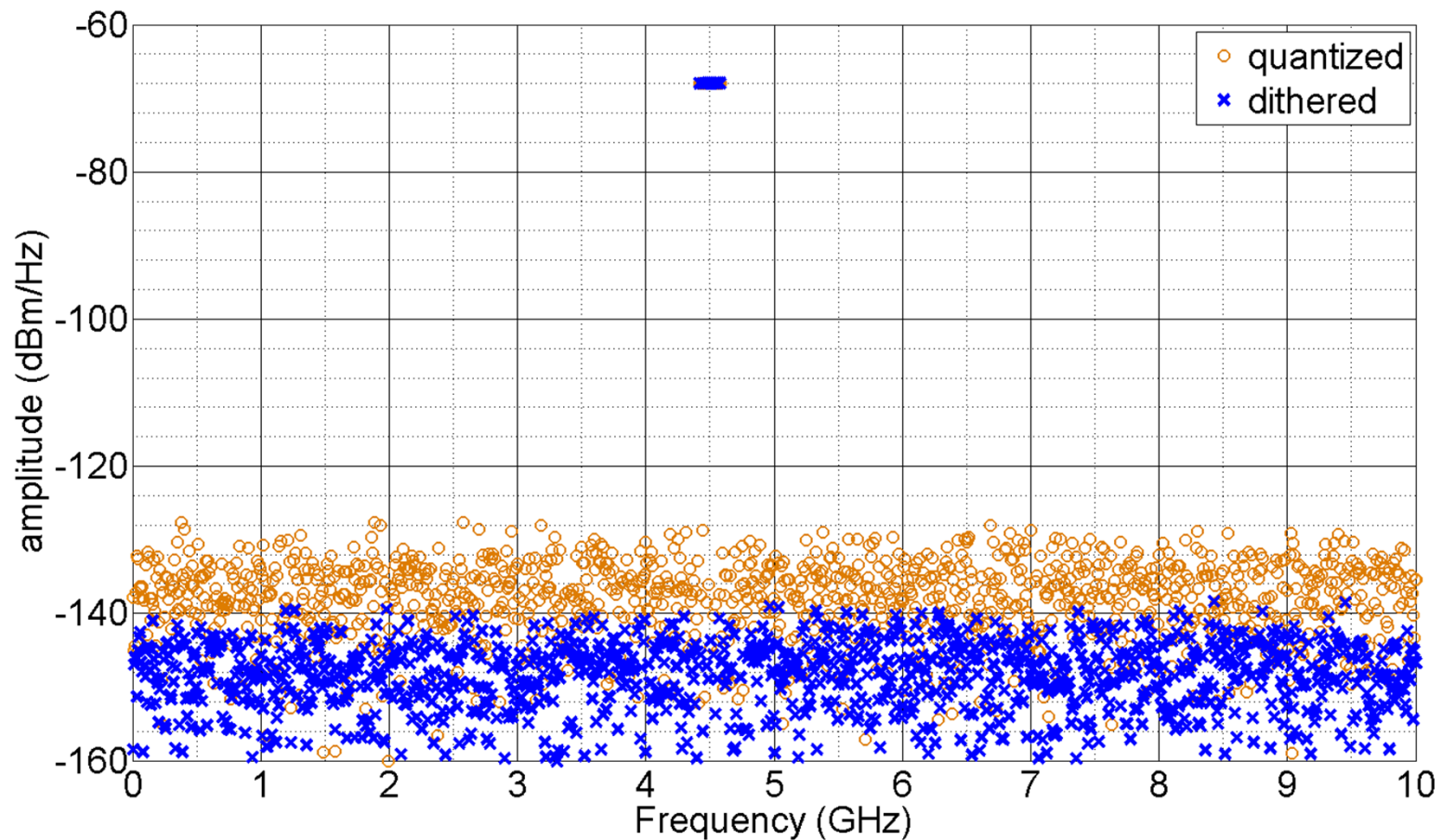
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- The averaged waveform effectively lacks the dithering component
- This is a suitable technique for test and characterization with a high-resolution requirement
- The quantization noise is reduced in post-processing



# Quantization noise reduced

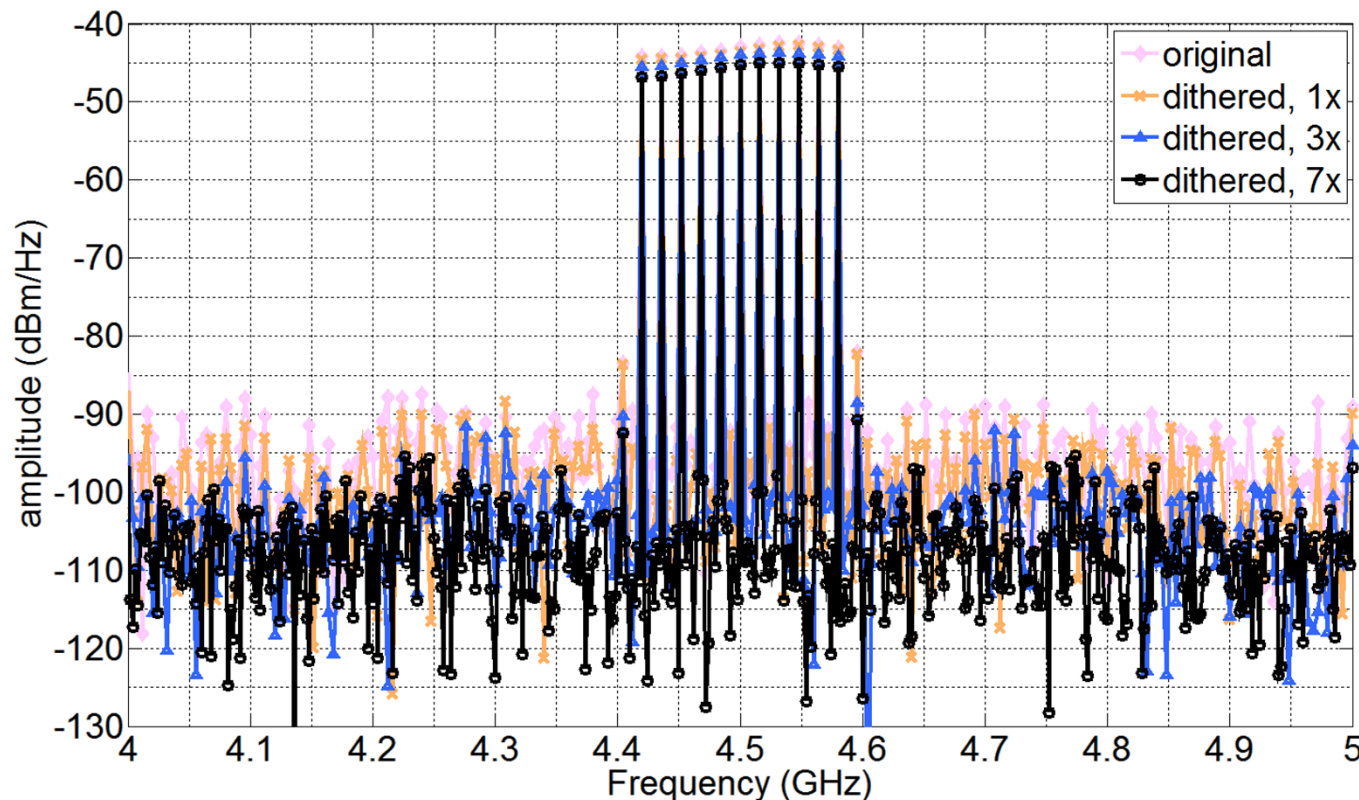
11-tone multisine,  $f_c = 4.5$  GHz, BW = 160 MHz





# Improved dither signal

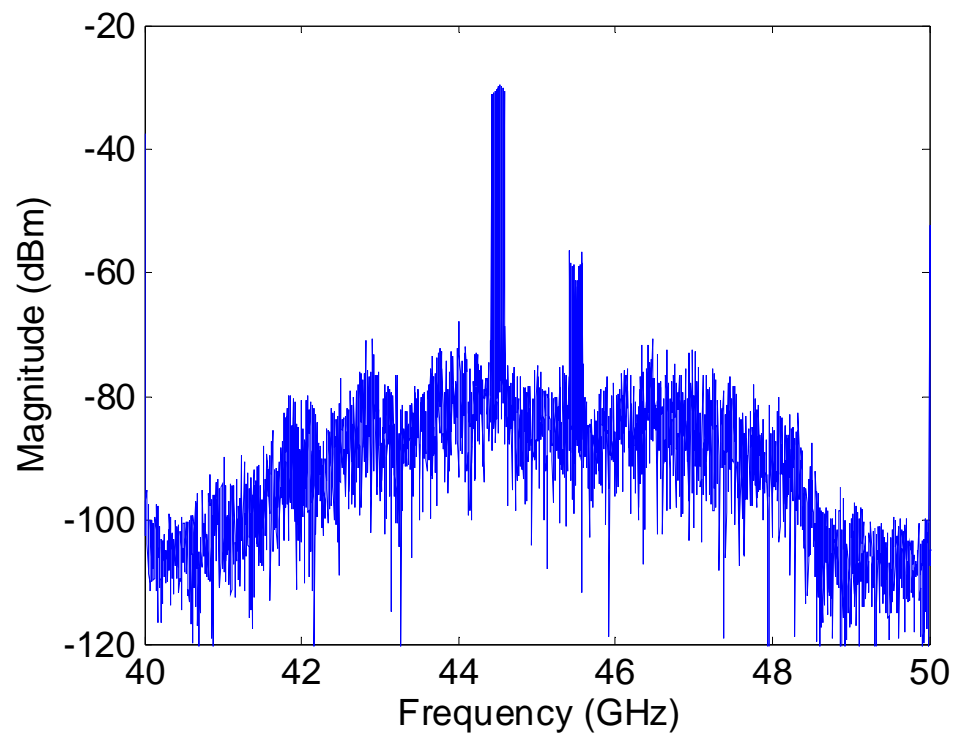
Use of larger dither signal to reduce non-idealities of signal generator in post processing





# mm-wave ACPR improved

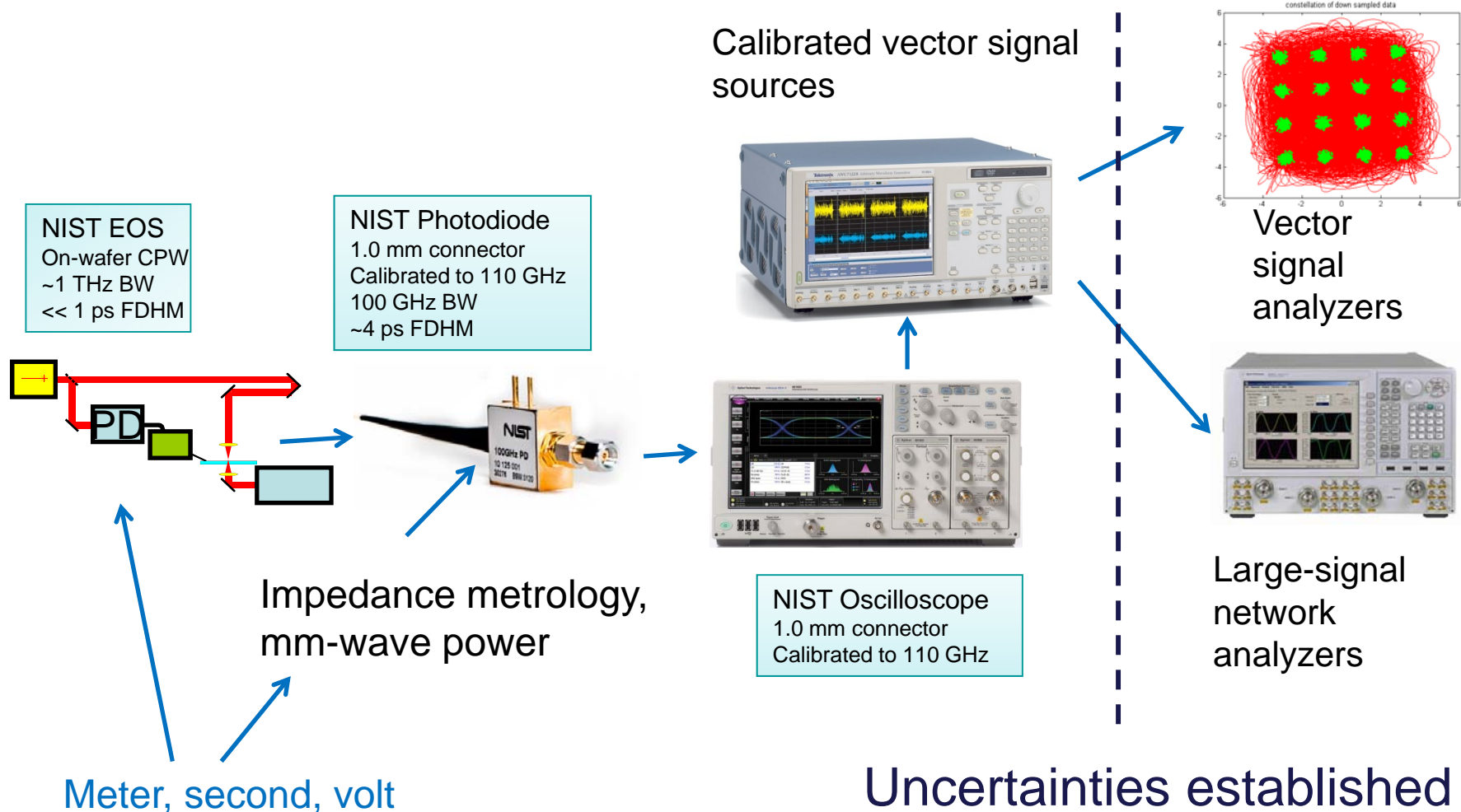
Baseband-frequency offset and dither improve mm-wave signal



Offset + Dithering  
(ACPR 52 dB)



# Looking forward

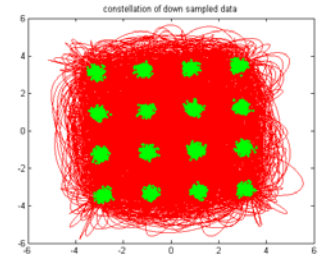




# Looking forward

## Measurements for millimeter-wave wireless

- Baseband and frequency conversion:
  - mixing products, spurs
  - quantization noise
- Calibrated sources and receivers
  - Distortion characterization
  - Known EVM
  - Traceability
- Baseband effects can muddy the waters at millimeter-wave frequencies!



Vector  
signal  
analyzers



Large-signal  
network  
analyzers