# Uncertainty and Modulated Signals

## *Focus on Traceable Measurements*

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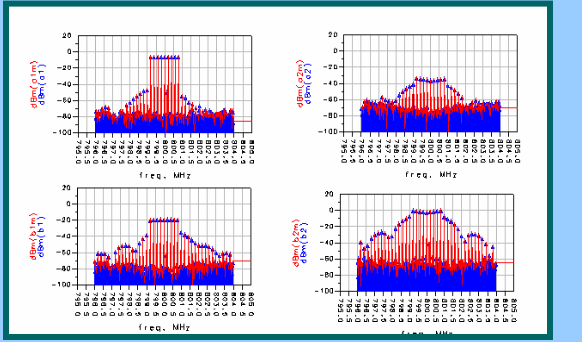
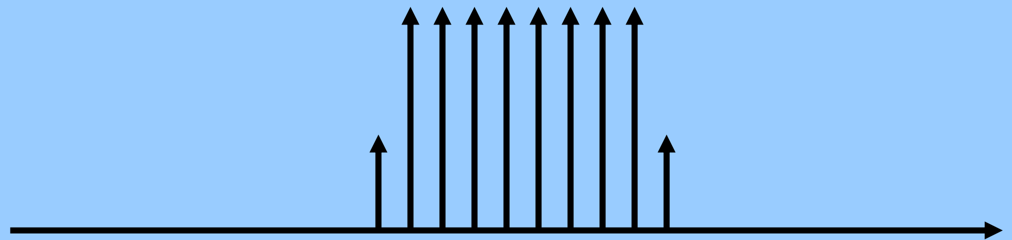
# Outline



- Introduction: Traceable Measurements
- Measuring modulated signals: *Scalar*
  - traceable instruments
  - example: NPL peak power meter calibration
- Measuring modulated signals: *Vector*
  - traceable instruments
  - calibration signals
  - example I: NIST oscilloscope calibration
  - example II: uncertainty in determining phase
- Conclusion

# Measuring Modulated Signals

**Modulated signal:** A signal containing multiple frequency components



*frequency*

***Key:*** **Instruments with traceability to fundamental physical units**

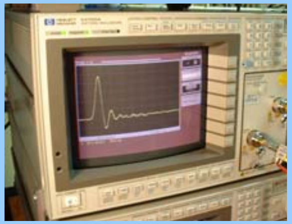
- **National Metrology Institutes certify traceability**
- **Uncertainty statement provides limits on expected range of measured values**

# Fundamental Measurement Traceability

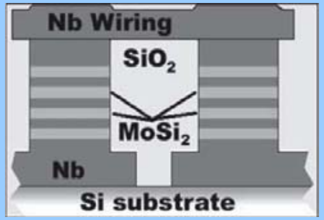
Calibrations tending toward *fundamental traceability* to SI units or calculable physical phenomena

Vector Network Analyzers:
Dimension of an air-dielectric transmission line

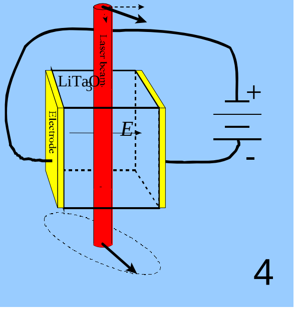
Power Meters, Noise sources:
Temperature



AC Voltage:
Josephson junction arrays



Electro-optic sampling systems:
Calculable electrooptic effect in materials



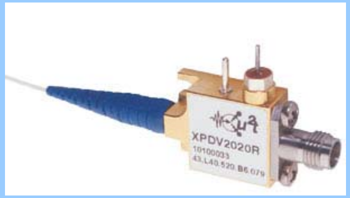
# Derived Measurement Traceability

Calibrations that use a series of *transfer standards*:

Oscilloscope calibrations

Digital sampling oscilloscope

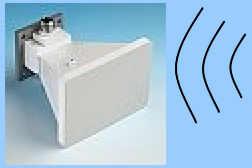
Transfer standard: Photodiode



Source calibrations

Vector signal generator, pulsed source, comb generator

Transfer standard: Oscilloscope



Receiver calibrations

LSNA, peak-power meters, VSA, antennas

Transfer standard: Calibrated source

# Derived Measurement Traceability

Commonly used for modulated signal traceability

Issues:

**+**

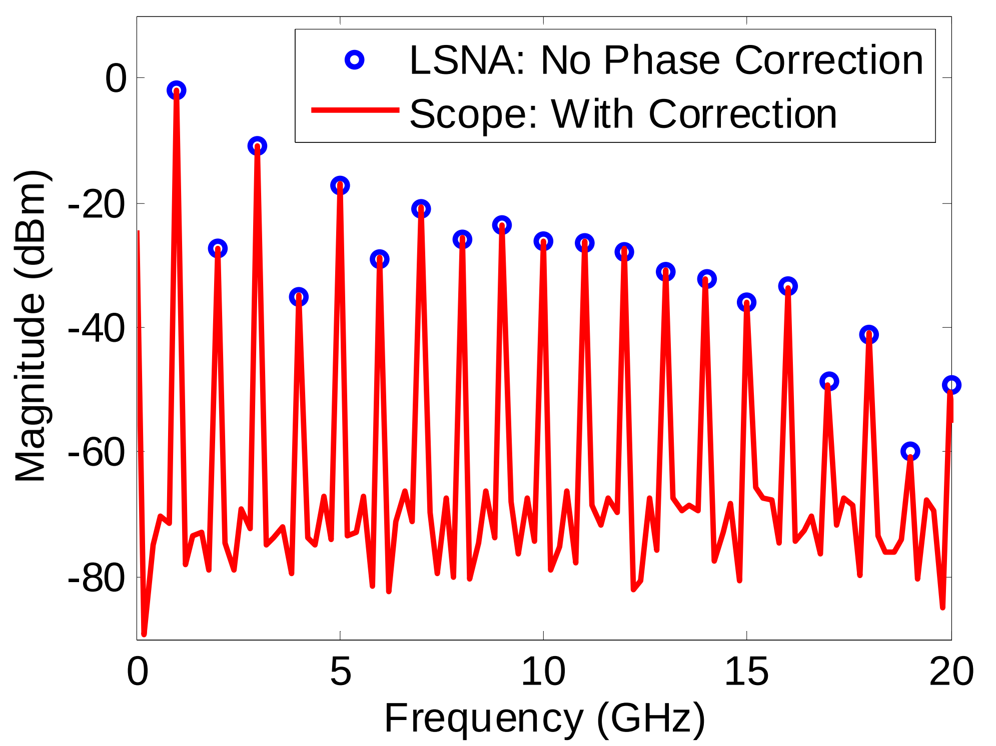
- Can provide traceability to many types of instruments
- Same methods can be applied across instruments: Almost a black-box approach

**-**

- Higher uncertainties
- Sometimes difficult to combine uncertainties
- Instrument-specific issues:
  - timebase distortion (oscilloscope)
  - IF calibration (LSNA)

# Measuring Modulated Signals

## *Scalar:* Accurate power in all measured frequency components



Measurement of square wave:
fundamental and harmonics

# Instruments for Scalar Modulated-Signal Measurements

## Spectrum Analyzer

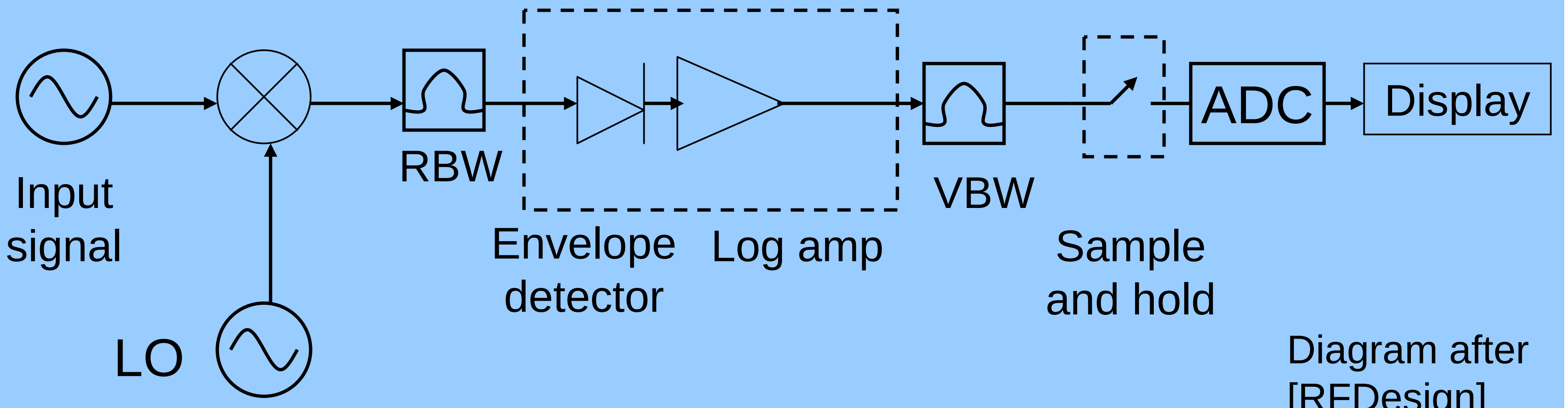


Diagram after [RFDesign]

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- Good dynamic range
- Readily available, inexpensive

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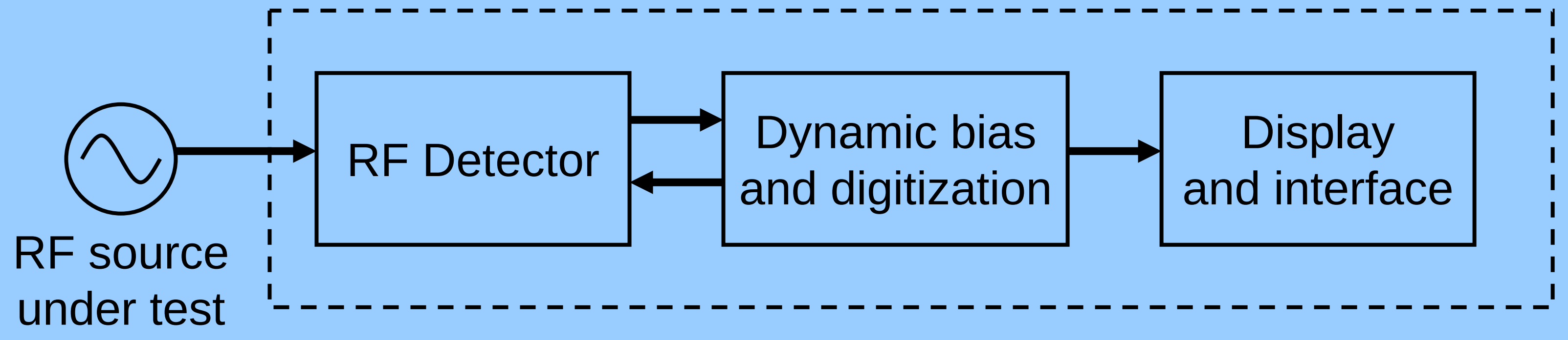
- Higher uncertainties due to system drift and repeatability
- Diode detector: temperature sensitive

# Instruments for Scalar Modulated-Signal Measurements

## Peak Power Meter



Block diagram of peak power meter, after [NPL1]

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- Relatively inexpensive and straightforward to use

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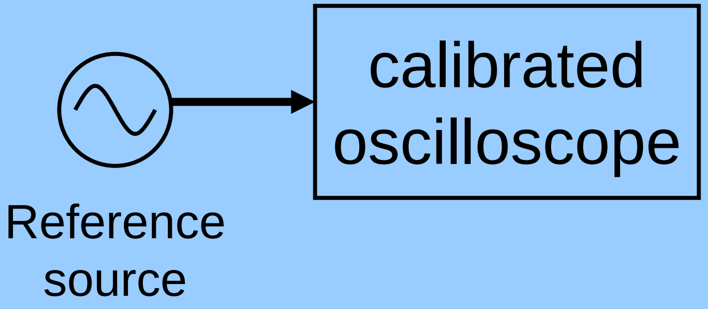
- Traceability derived from complex scope cal
- Diode detector: temperature sensitive

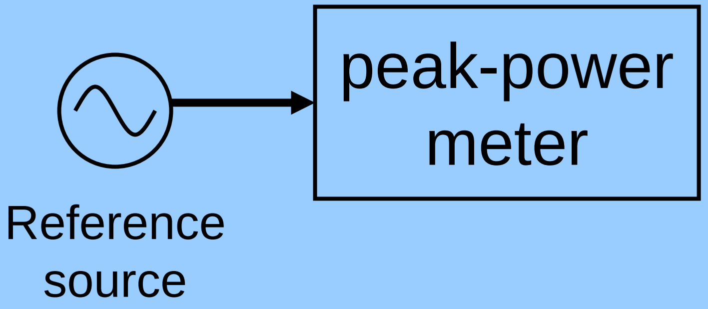
# Calibration of Instruments for Scalar Modulated-Signal Measurements

## Example: NPL peak power meter calibration [NPL1]

Step 1:
Characterize the
reference source



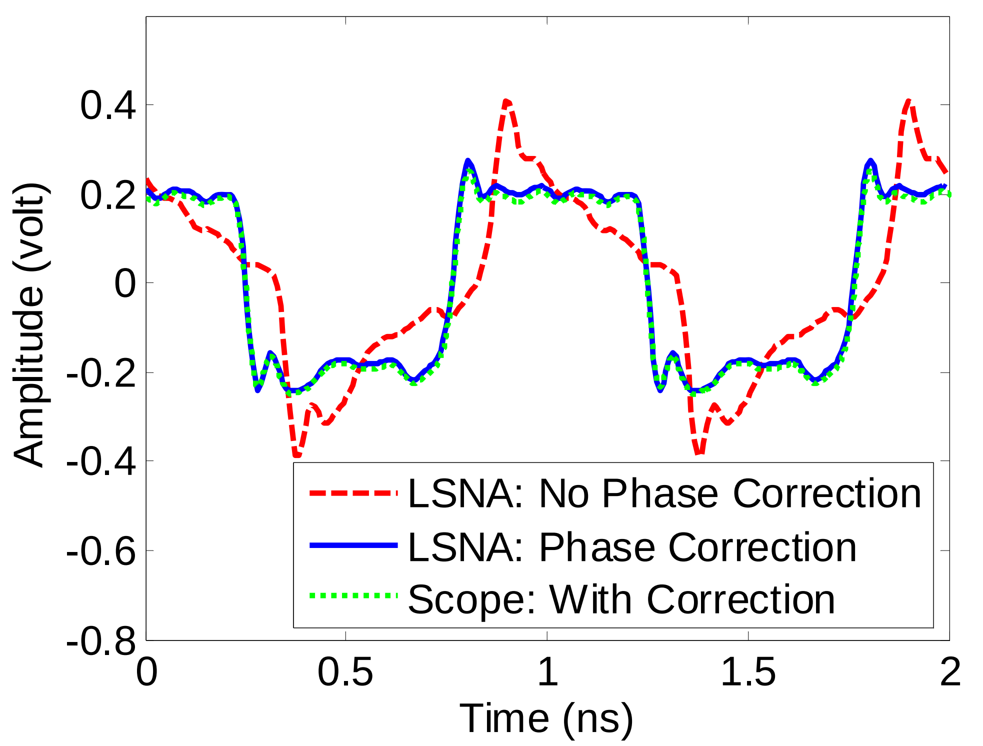
Step 2: Use reference
source as transfer
standard to calibrate
peak-power meter



Separating response of signal generator from peak-power meter provides traceability

# Measuring Modulated Signals

## *Vector:* Accurate *relative phase* of all measured components



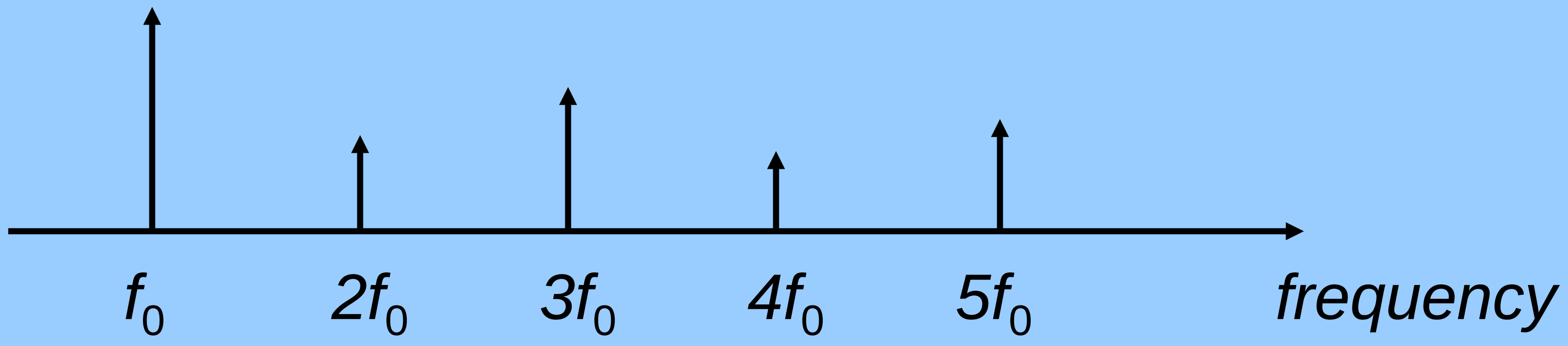
Enables time-domain representation

Graph from [RF Book]

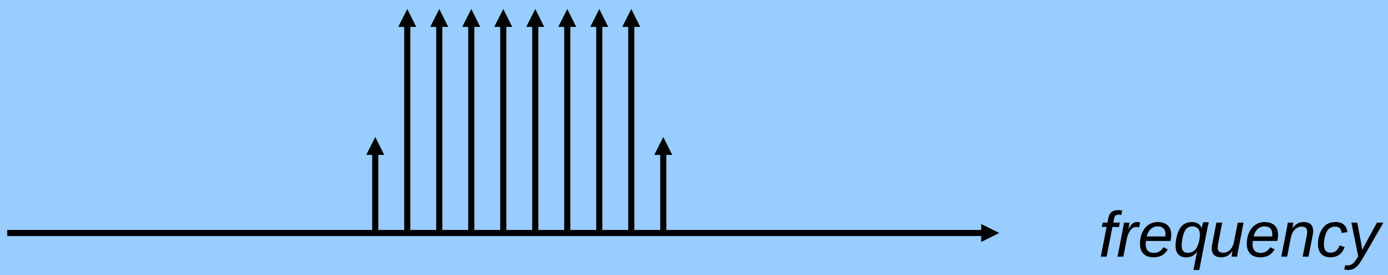
# **Vector** Measurement of Modulated Signals

*Key:* Accurate magnitude and relative phase of

Broadband signal: fundamental and harmonics

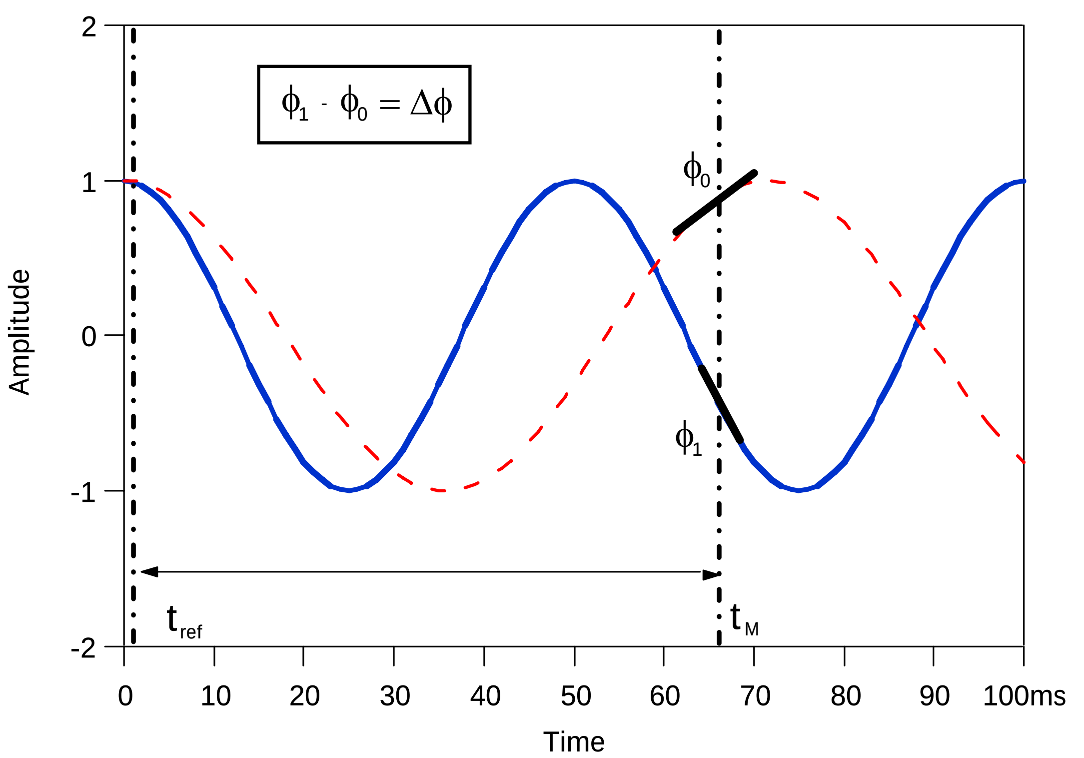


Bandpass signal: frequencies around the carrier



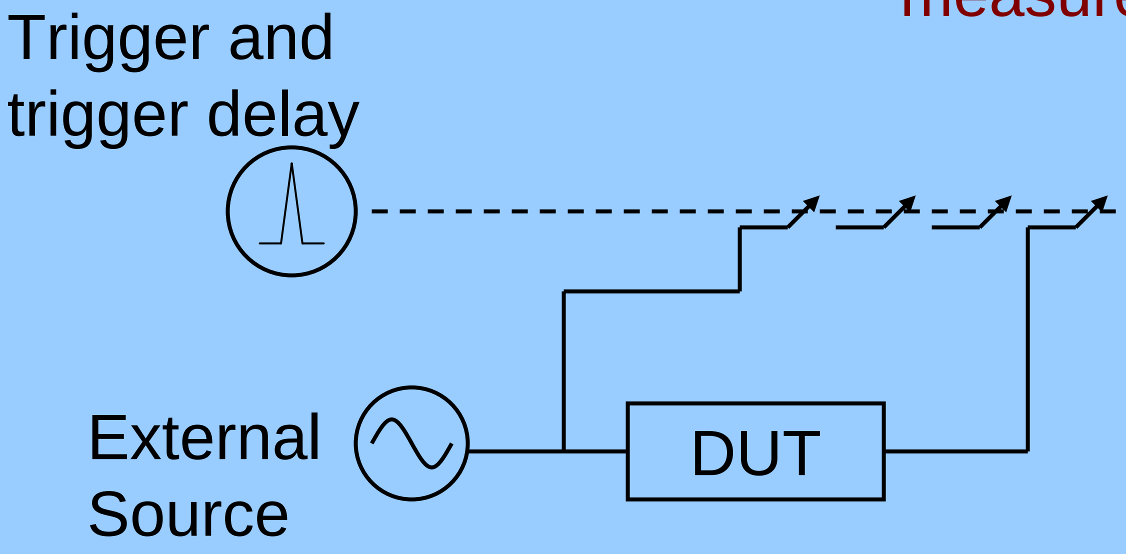
# Relative Phase

Measured phases may appear random unless sampled simultaneously



# Instruments for Vector Modulated-Signal Measurements

**Digital Sampling Oscilloscope:** Good for waveform measurements



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- Broadband acquisition: relative phase maintained
- Aperiodic signals OK

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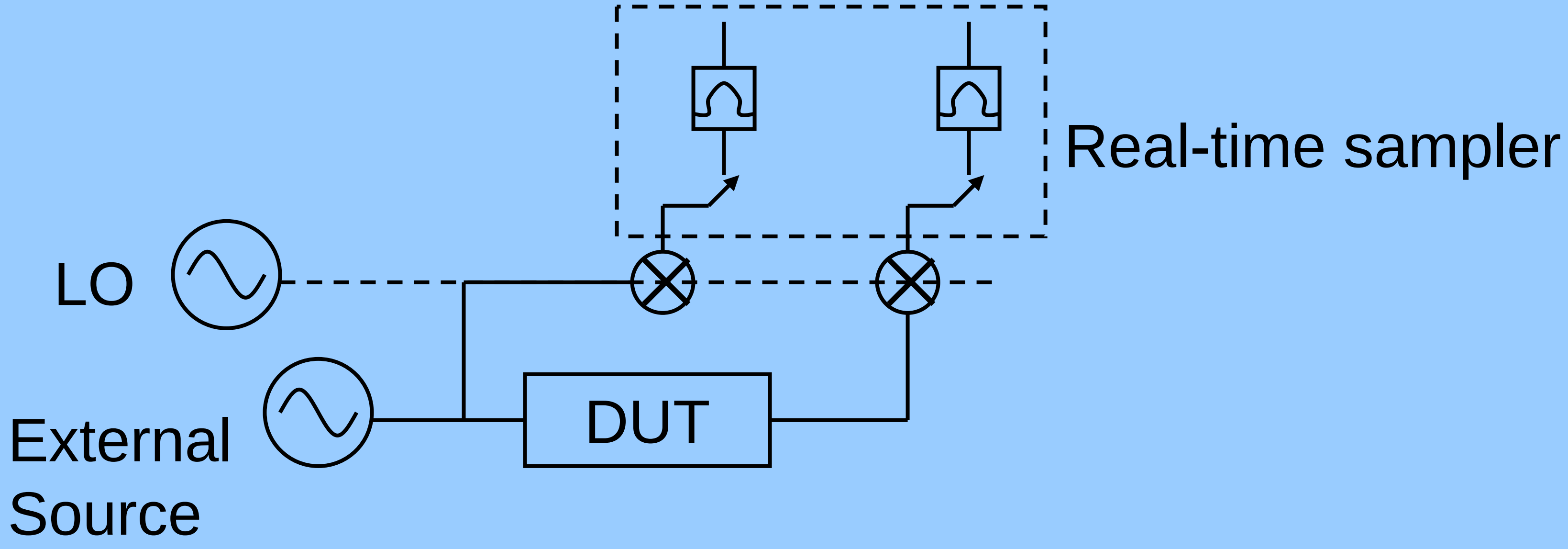
- Broadband acquisition: low dynamic range
- Calibration difficult
- Single (or two) channel

# Instruments for Vector Modulated-Signal Measurements

**Vector Signal Analyzer:** Good for modulated measurements



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- RT sampling maintains relative phase

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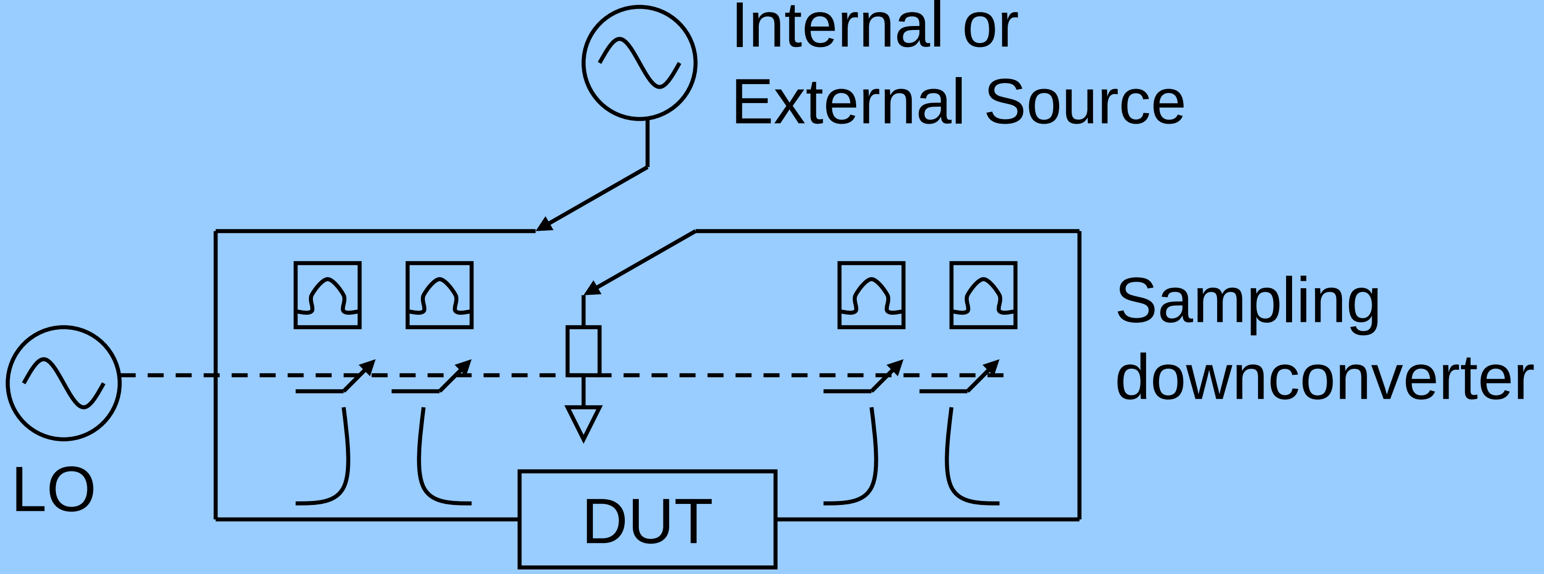
- No harmonics
- Calibration difficult

# Instruments for **Vector** Modulated-Signal Measurements

**Large Signal Network Analyzer:** Good for multisine measurements



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- Test set calibration
- Two-port measurement
- RT sampling

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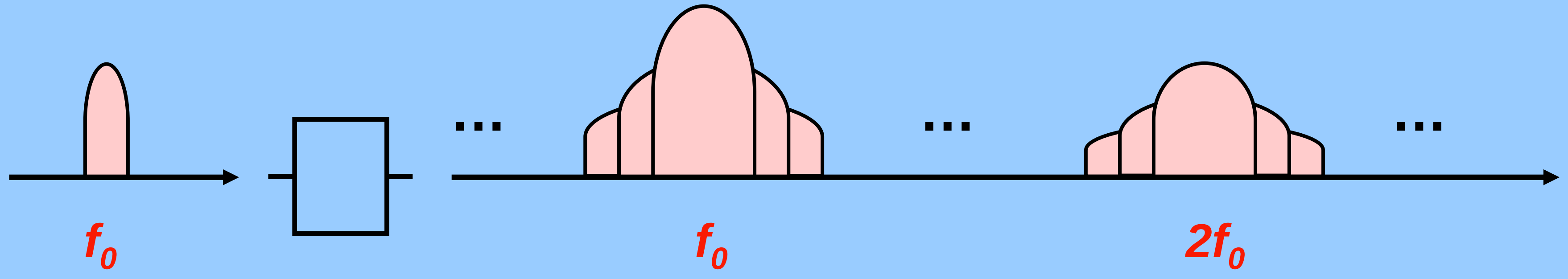
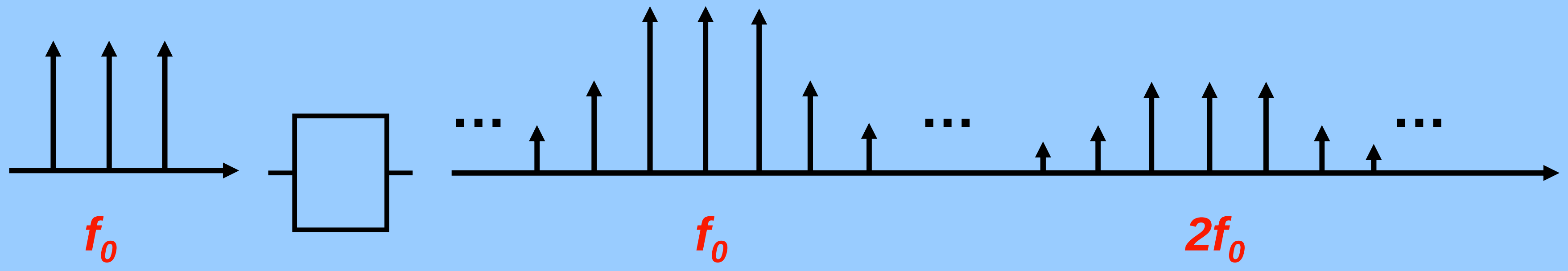
- Narrow IF bandwidth
- Expensive

# Modulated versus Multisine Signals



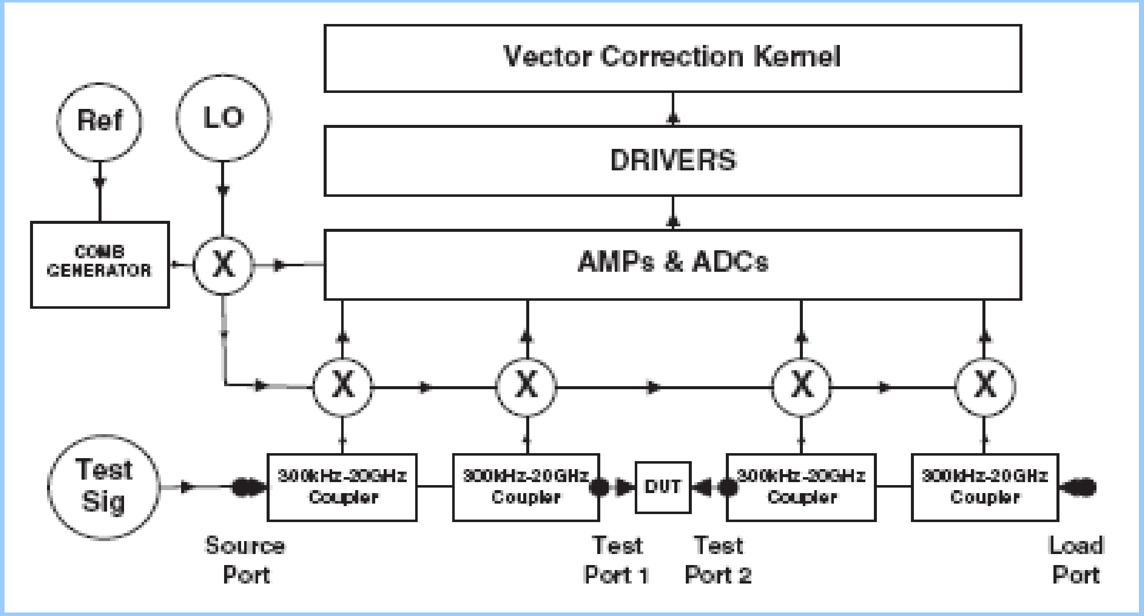
*approximated by multisines*



[Myslinski]

# Instruments for Vector Modulated-Signal Measurements

**Phase Quattro:** Good for multisine measurements



From [Blockley1]

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- Traceable to VNA
- High dynamic range
- Wide full bandwidth
  (0.3 MHz - 20 GHz)

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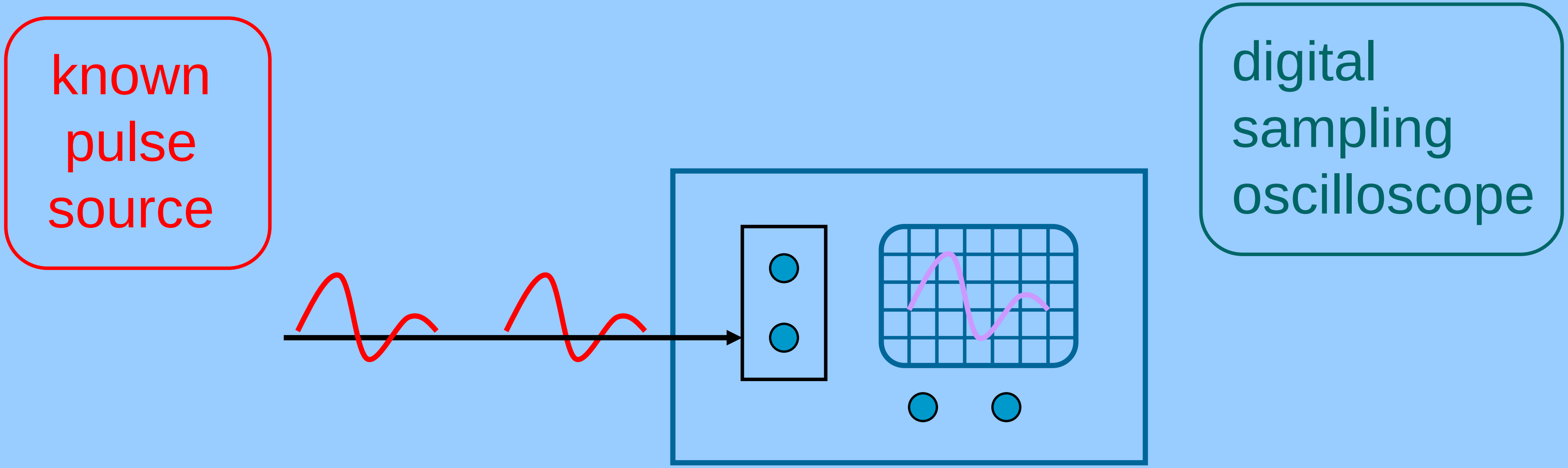
- 4-channel VNA required

# Calibration Signals

Well-established "known pulse" scope calibration [pulse]:

Differences between "known" and "measured" = calibration coefficients



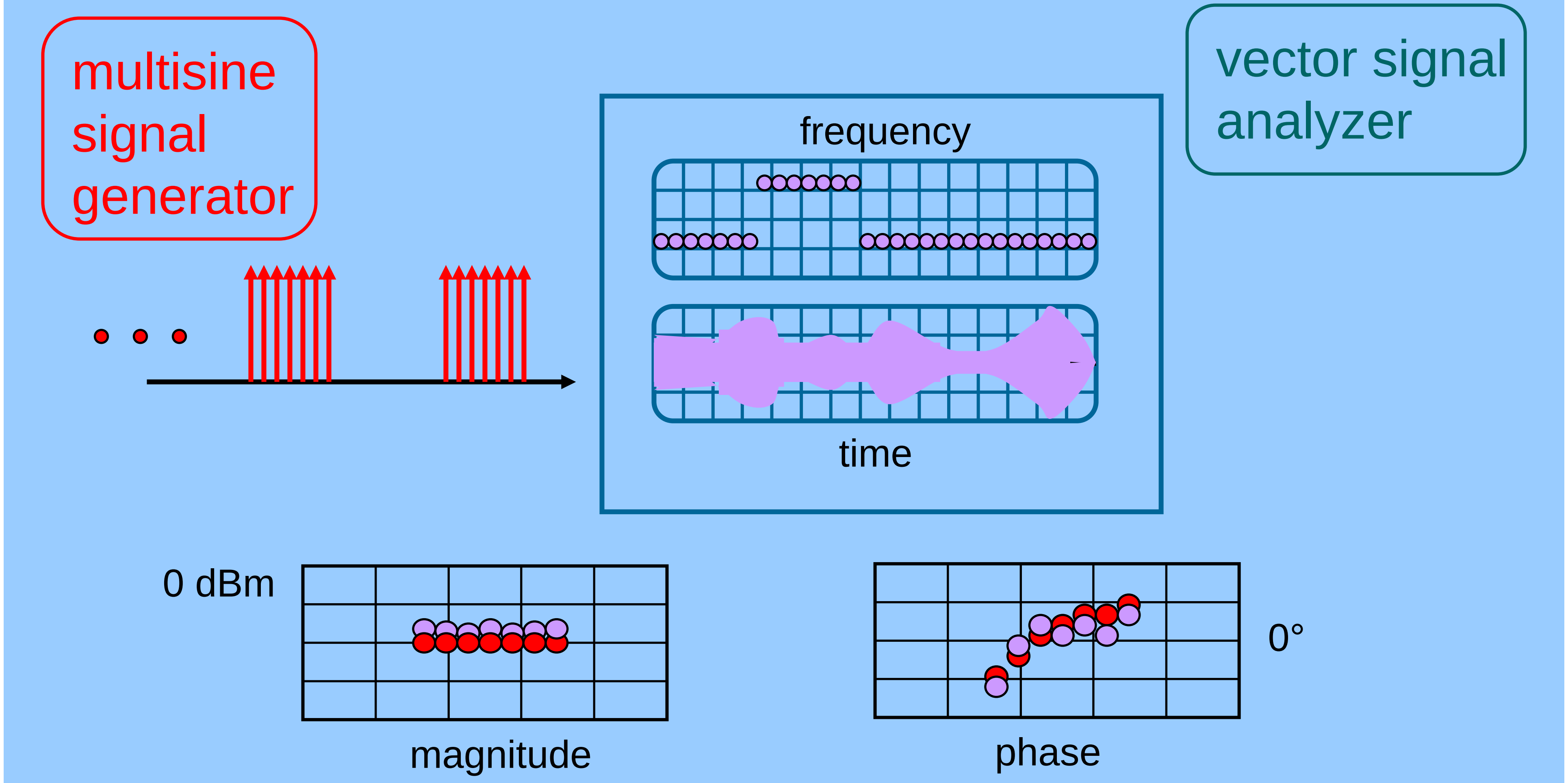
known pulse source

digital sampling oscilloscope

- Many NMIs have pulse calibration services
- Pulses have energy over broad bandwidth: For wireless, we want a signal whose bandwidth better matches instrumentation

# Calibration Signals

## “Known Spectrum” Multisine Calibration

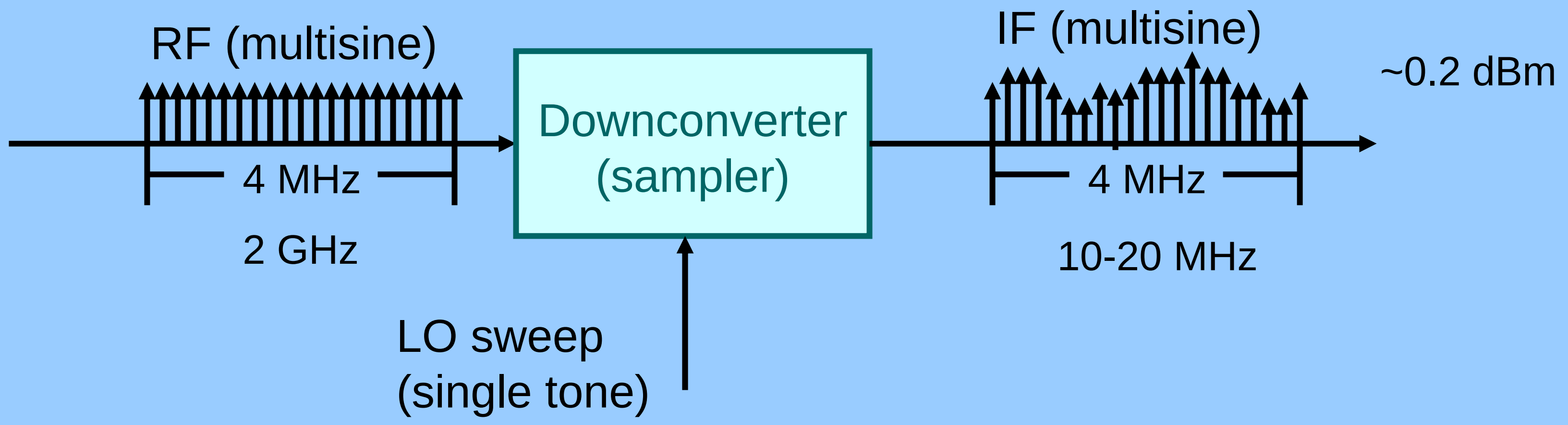

multisine signal generator

vector signal analyzer

Used by manufacturers to calibrate vector receivers

# Multisine Calibration Example

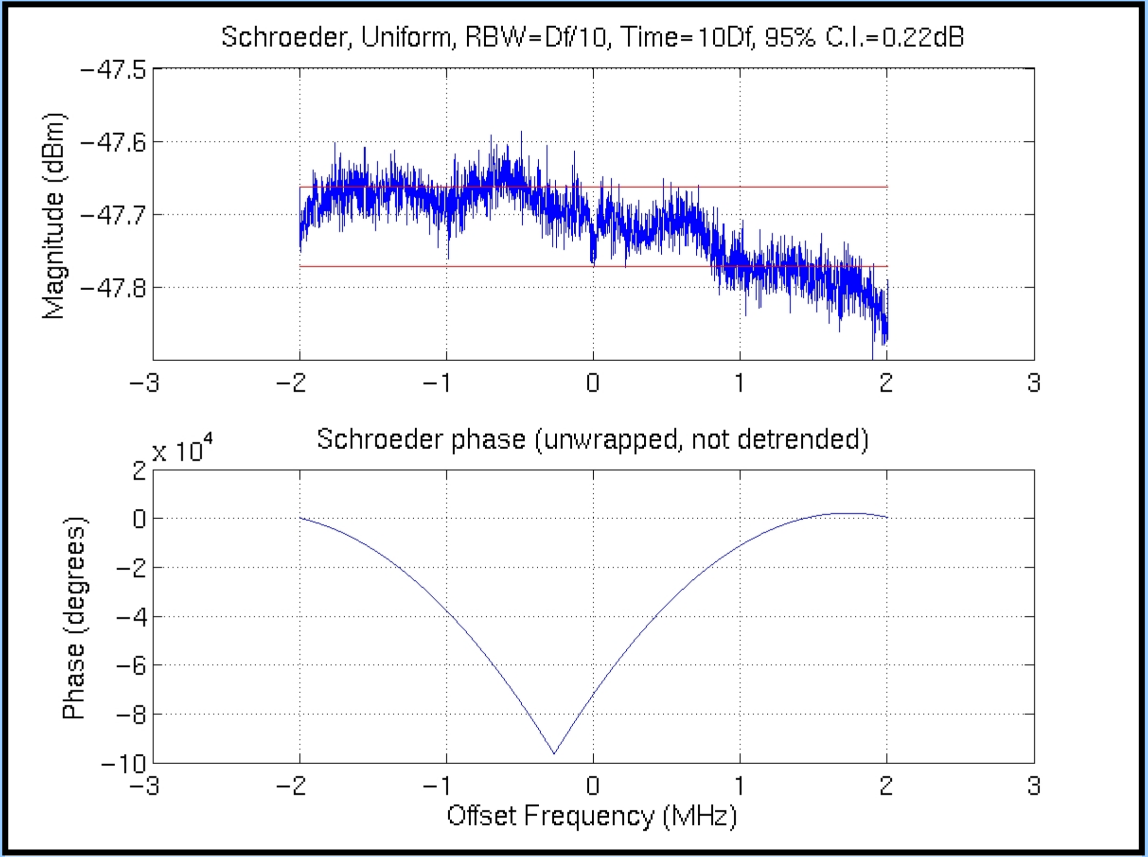
A multisine is used for the “IF Cal” of the LSNA:



- “Known spectrum”: 2000-component Schroeder multisine, VSG-generated, VSA-measured (VSA previously calibrated)
- Measure same multisine on LSNA
- Differences between VSA-measured and LSNA-measured are correction coefficients

# Multisine Calibration Example

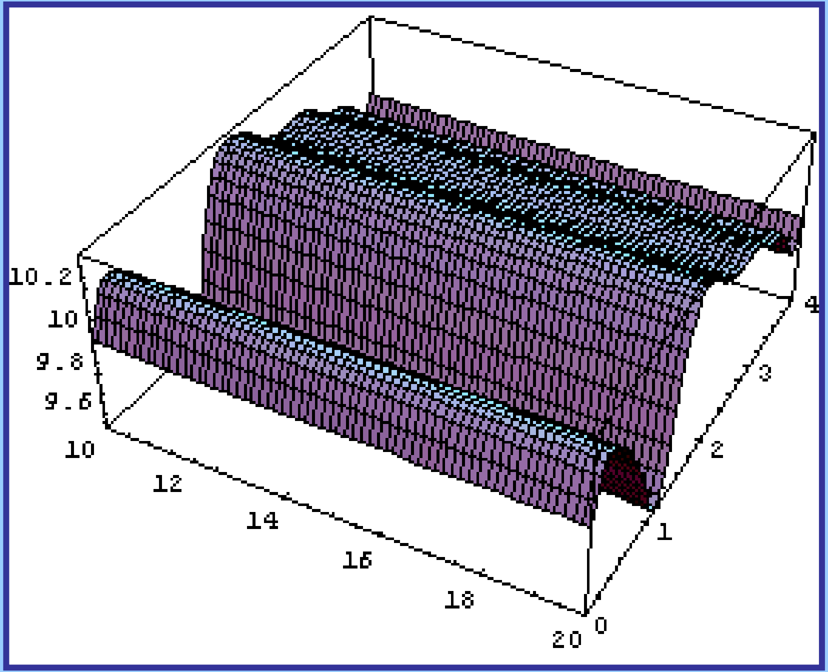
**"Known Spectrum":** 2000-component Schroeder multisine measured on the VSA



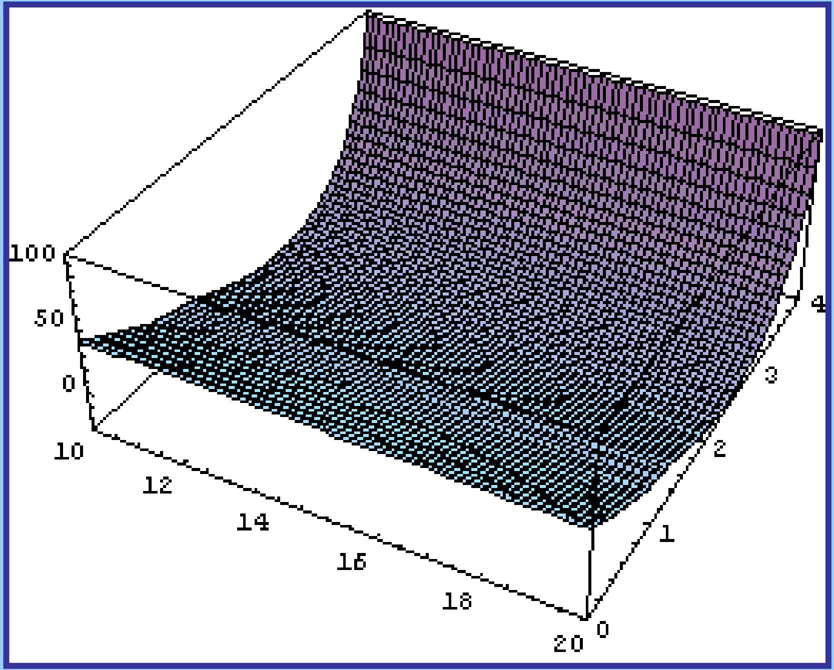
- Center frequency is 2 GHz, 4 MHz modulation bandwidth
- Measured uncertainty is ~0.11dB, LSNA resolution is ~0.2 dB

# Multisine Calibration Example

## Typical IF Cal Results:



Magnitude



Phase

- ~0.2 dB magnitude variation, ~110° phase variation over 4 MHz
- Negligible variation with LO sweep
- Measured by Don DeGroot and Jan Verspecht

It is obvious that the downconverter does need calibration!

# Calibration of Instruments for Vector Modulated-Signal Measurements

## Example I: NIST oscilloscope calibration

Present capability:

- FD to 110 GHz
- TD to 15 ps
- 60 dB dynamic range

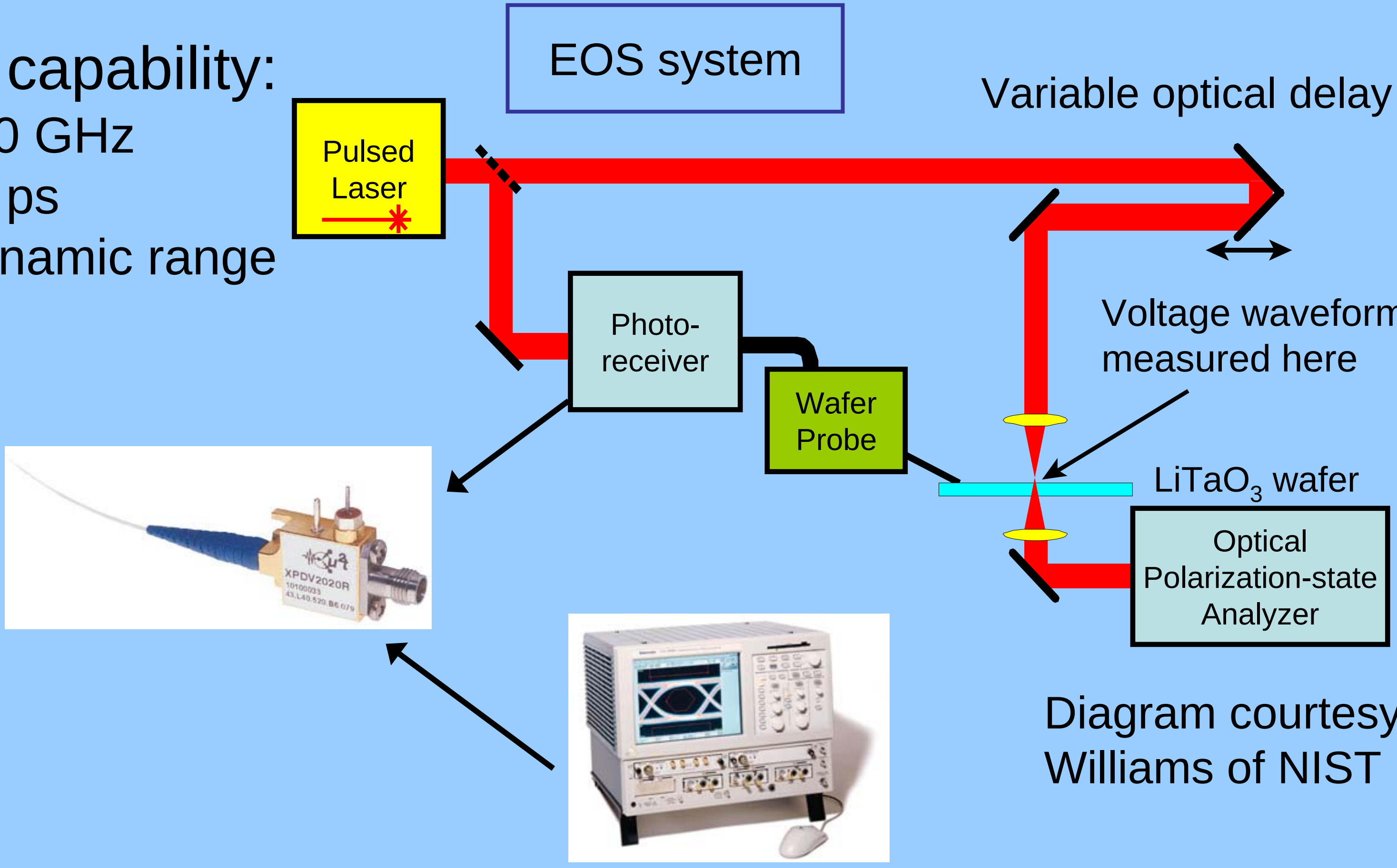
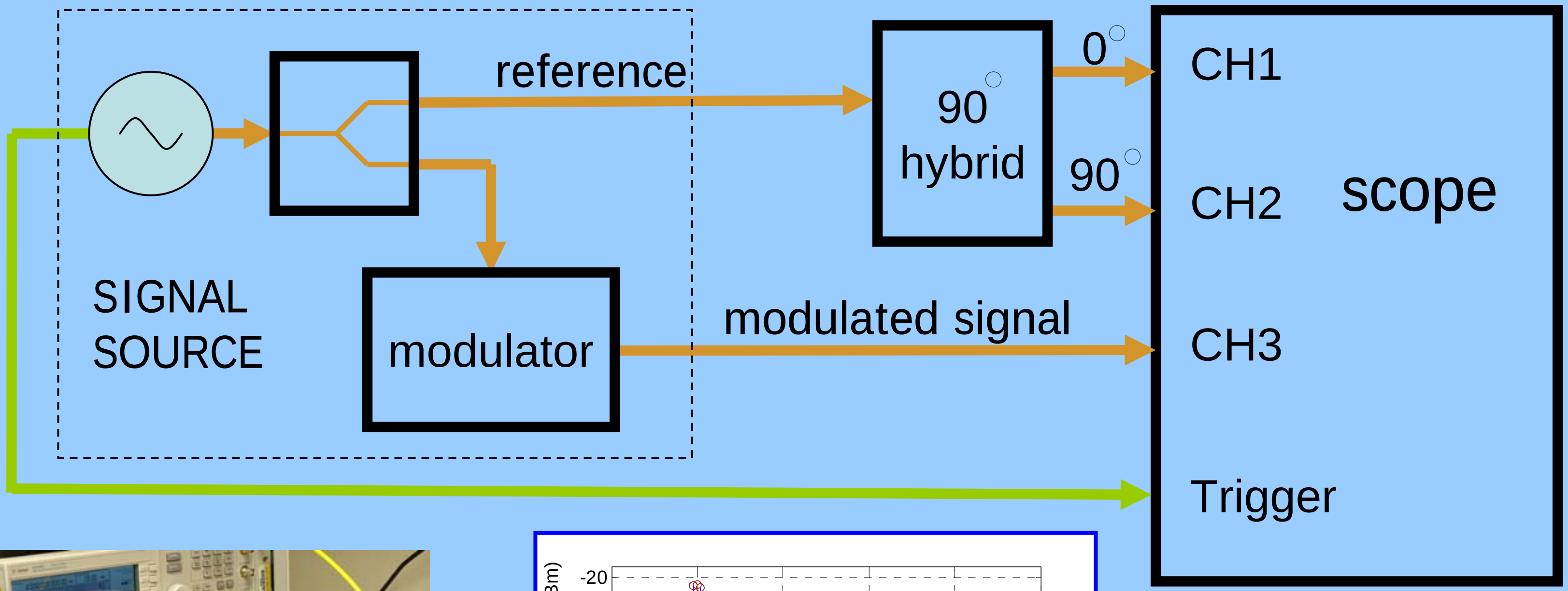


Diagram courtesy Dylan Williams of NIST

Photodiode is transfer standard for oscilloscope calibration

# Example I: NIST Oscilloscope Calibration

In-phase/quadrature reference signals create new time base



reference

SIGNAL
SOURCE

modulator

90°
hybrid

0°

90°

modulated signal

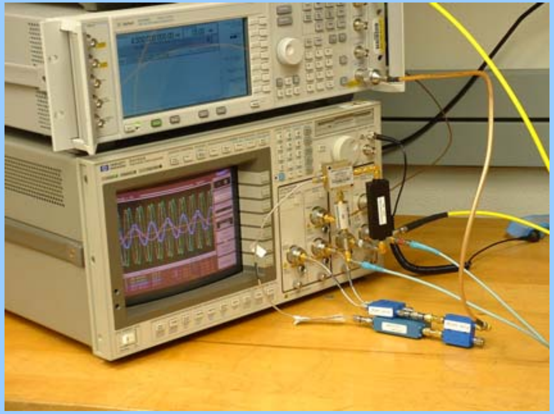
CH1

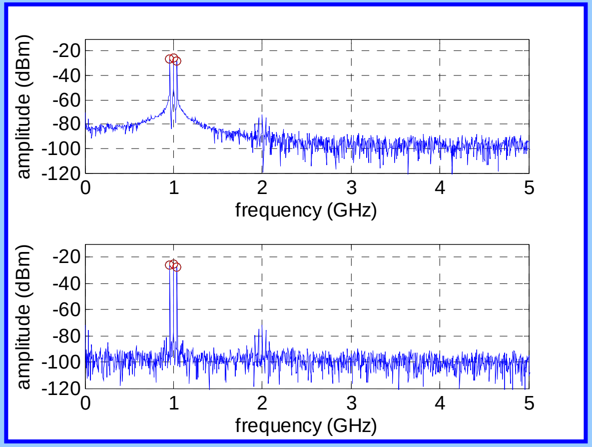
CH2

CH3

Trigger

scope

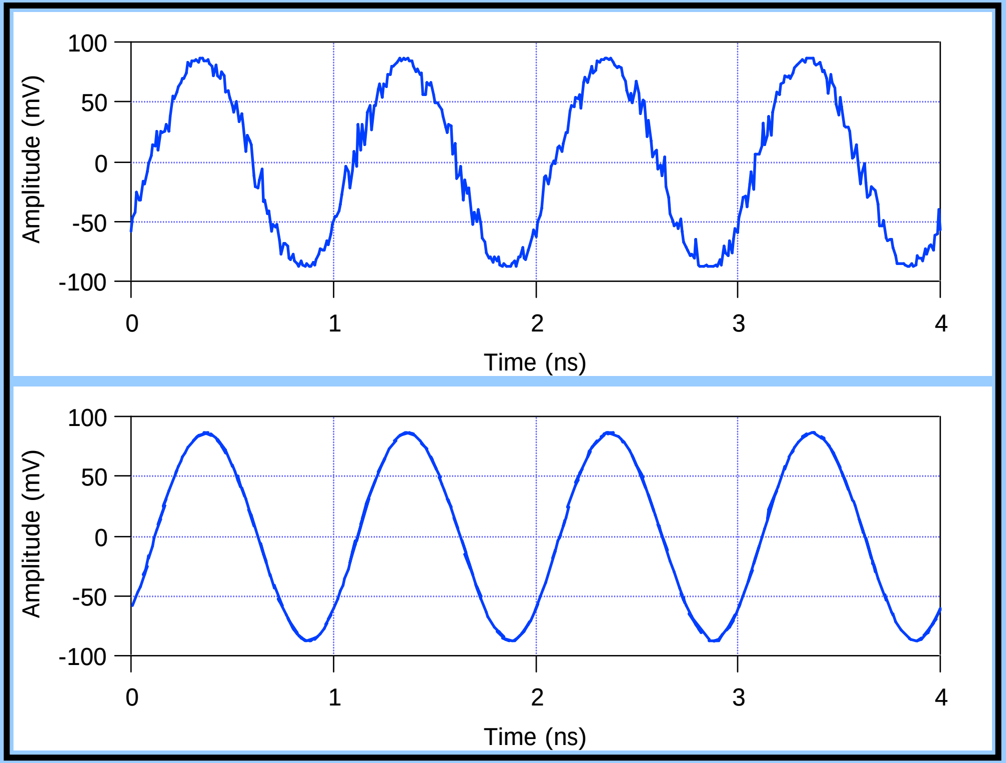




# Example I: NIST Oscilloscope Calibration

## Jitter Correction

The relationship between the sine and cosine is known.
Correct the timebase for jitter, then correct the multisine.

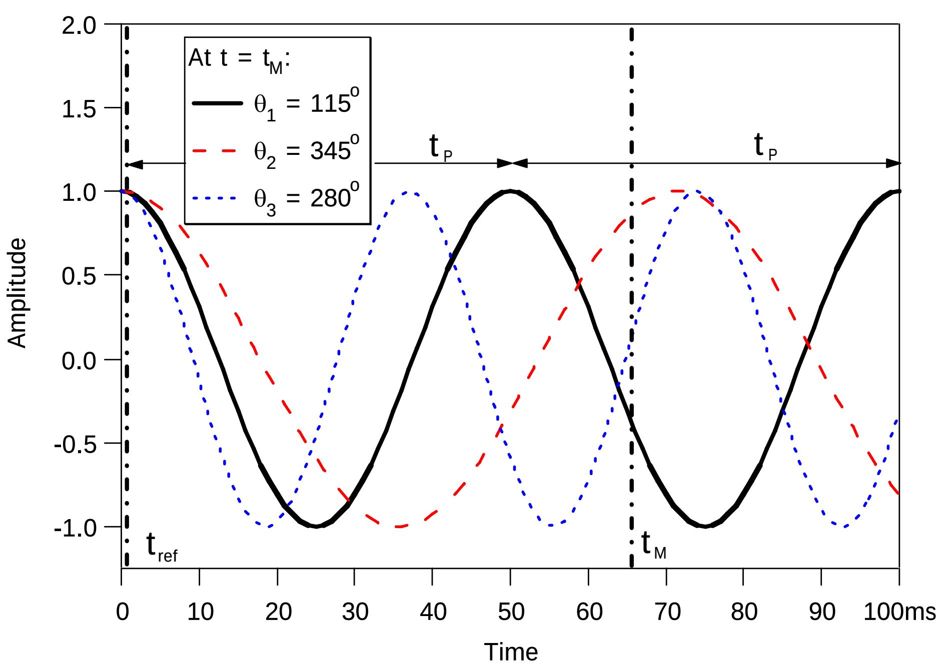


A calibrated VSG could be used to independently calibrate
VSAs, receivers, mixers, other sources

# Example II: Determining Phase

- Characterized comb generators are often used to calibrate measurements of signals consisting of a fundamental and harmonics.

- Post-processing methods often used for finding the relative of bandpass signals.



Graph from [detrendo]

# Example II: Determining Phase

- Approaches when fundamental tone is present:
  - Fundamental alignment

    = fundamental is aligned to an arbitrary phase
  - Time-domain signal alignment

    = estimate time shift between measured and target signal by maximising cross-correlation of measured and target signal
  - Frequency-domain alignment (= phase detrending)

    = estimate time shift by minimizing least-squared error between measured and target phases
  - Time-zero cancellation

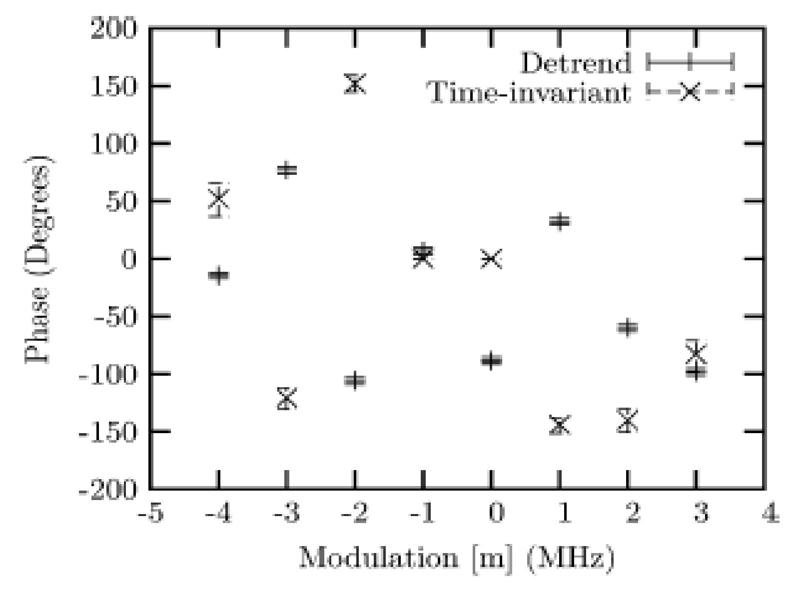
    = a linear transform is applied to the phases such that the new phases are independent of time zero

$$\phi'_{k,m} = \phi_{k,m} - \left(k\phi_c + m\phi_0\right) \qquad f_{k,m} = kf_c + mf_0$$

From [Blockley2]

# Example II: Determining Phase

Experiment: 41-tone multitone, 172 measurement repeats

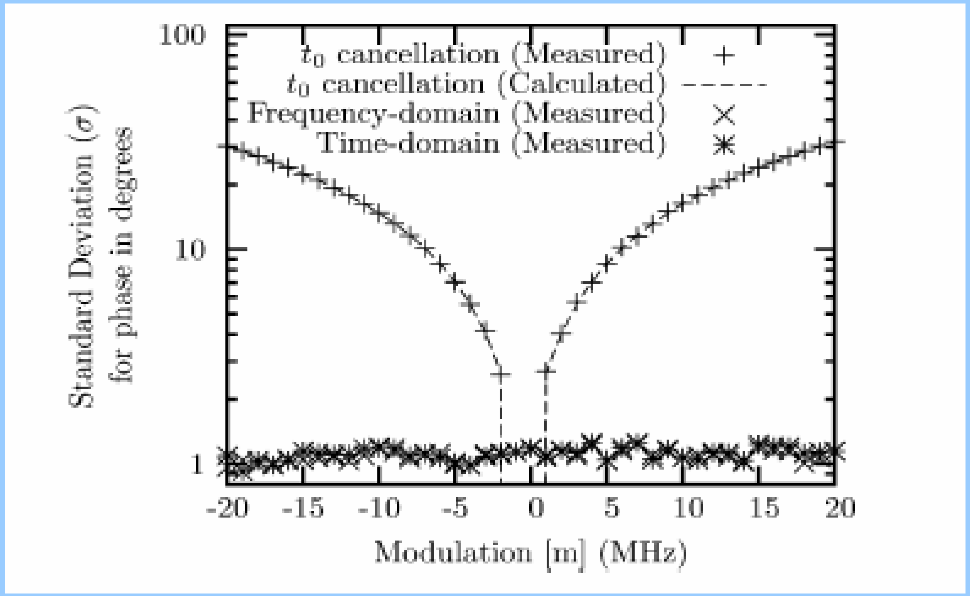


+: frequency-domain alignment: error bar size is fairly constant

x: time-zero cancellation approach: error bar size increases

From [Blockley2]

# Example II: Determining Phase



- time-zero cancellation approach:
  - standard deviation increases for frequencies further away
  - only arbitrary target phases are required

- time- and frequency alignment approaches:
  - standard deviation is lower and fairly constant across bandwidth
  - target time domain signal or target phases have to be known

From [Blockley2]

# Summary: Traceable Modulated Signal Measurements

**Similarities to uncertainties for single frequencies:**

- Repeatability, reproducability found in same way as for CW signals

**Differences unique to modulated signals:**

- Multistage derived traceability path
- Difficulty separating source response from receiver response (absolute calibrations required)
- Baseband effects can occur when nonlinear detectors and receivers are used

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- [NIST2]: P. D. Hale, C. M. Wang, D. F. Williams, K. A. Remley, and J. Wepman, “Compensation of random and systematic timing errors in sampling oscilloscopes,” IEEE Trans. Instrum. Meas., vol. 55, no. 6, pp. 2146-2154, Dec. 2006.
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- [Blockley2]: P.S. Blockley, J.B. Scott, D. Gunyan, A.E. Parker, “Noise considerations when determining phase of large-signal microwave measurements,” IEEE Trans. Microwave Theory Tech., vol. 54, no. 8, pp. 3182-3190, Aug. 2006.