High-speed Waveform Metrology

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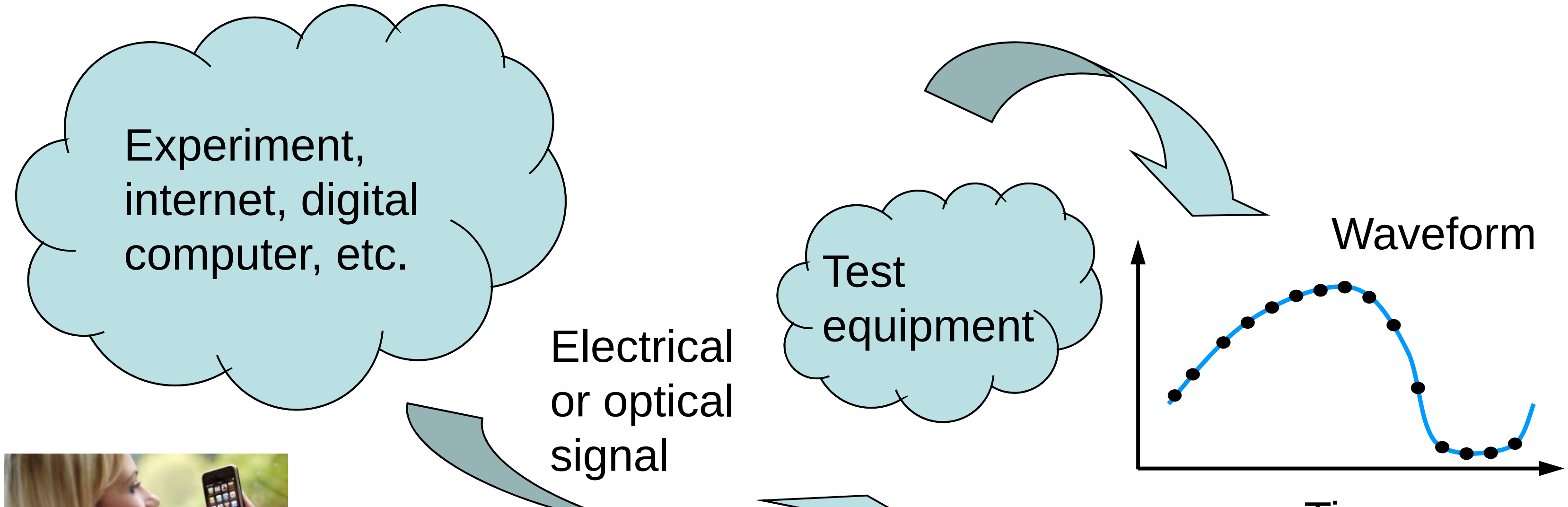
What are waveforms and who cares?



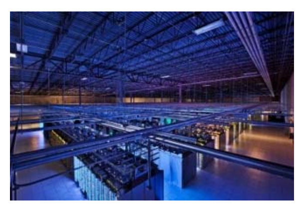
Smart phones

Fiber-optic communications and the internet

Force, torque, and pressure measurements

Wireless and satellite communications

Computers



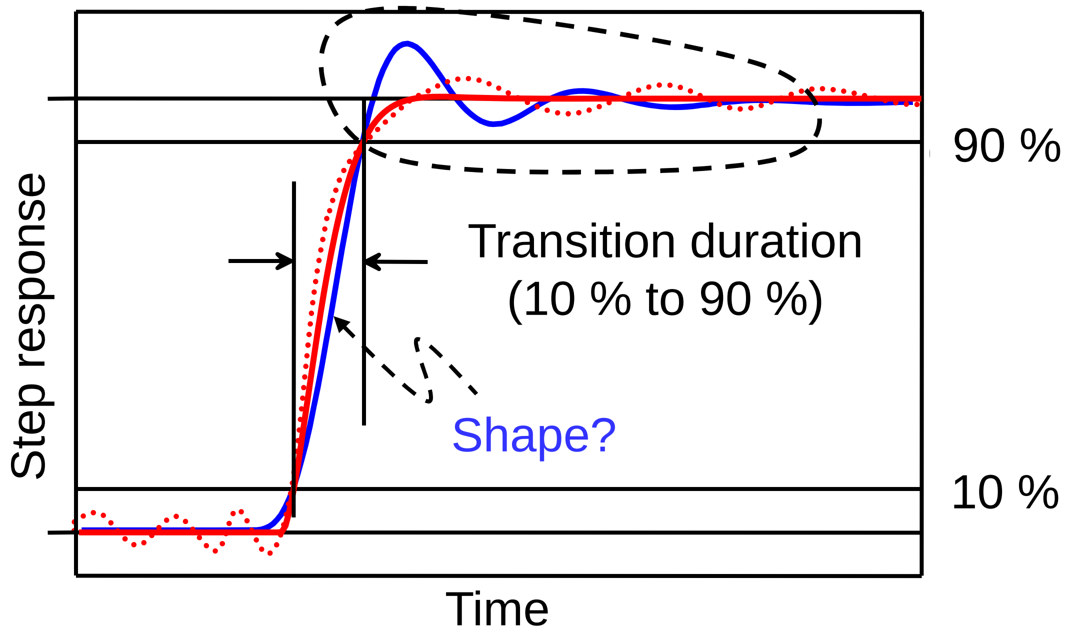
Data centers

Basic research

What is full waveform metrology?
Example: Oscilloscope response calibration

Old way: A few numbers (parameters) to describe response

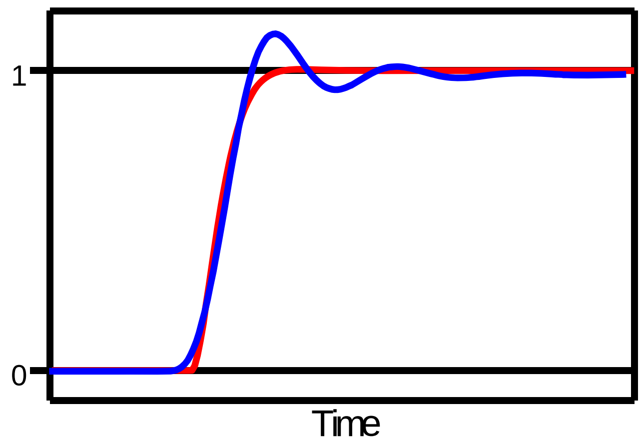
⇒ Bandwidth, amplitude, transition duration, overshoot



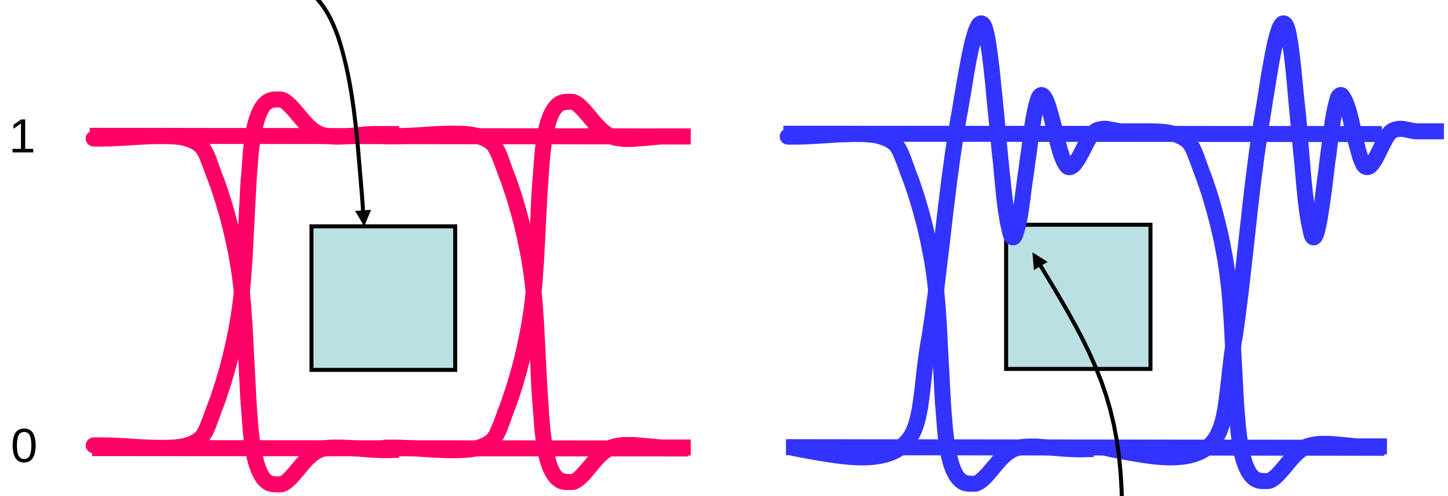
One or a few parameters do not uniquely describe response function

Application: Digital signal test

Different responses yield different results!



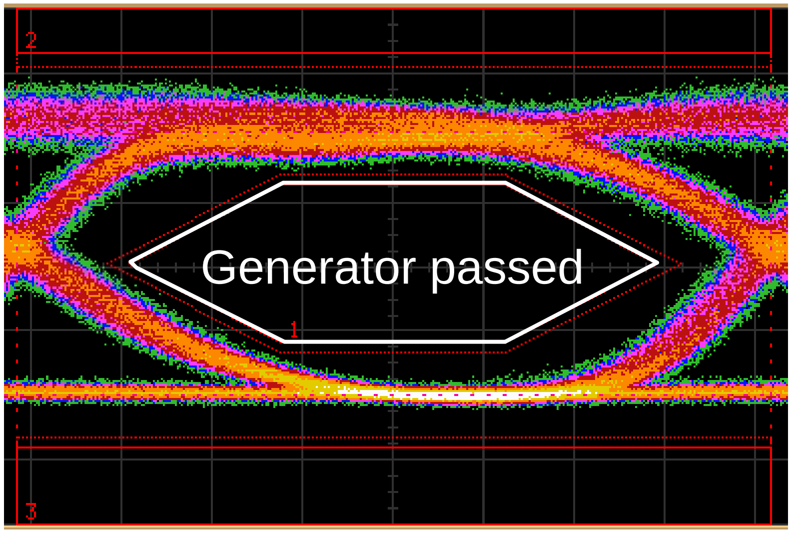
Forbidden region

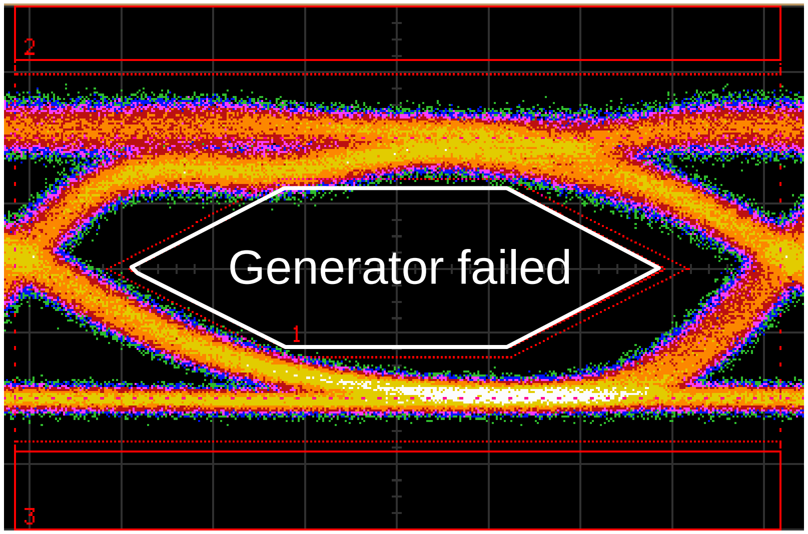


Passes test

Fails test

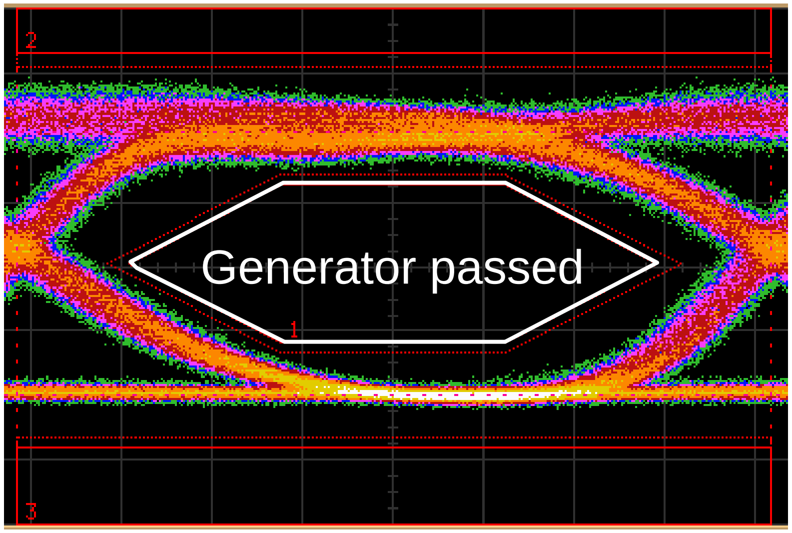
Why is full waveform metrology important?

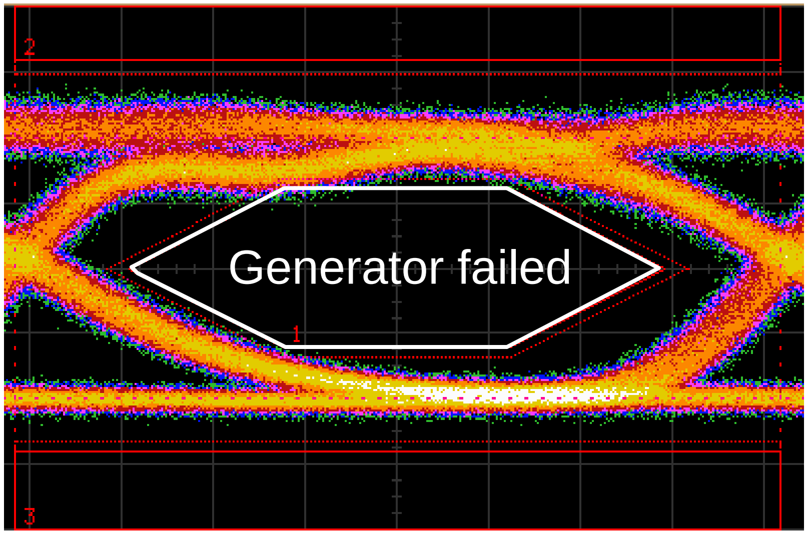




- Same device
- Two different oscilloscopes
- Same oscilloscope manufacturer specification (bandwidth)
- Which measurement is correct?
- By one estimate 10% to 20% of 10 Gbit/s Ethernet transceivers erroneously rejected due to measurement errors, costing industry $200M/yr to $400M/yr on this product alone.

Why is full waveform metrology important?



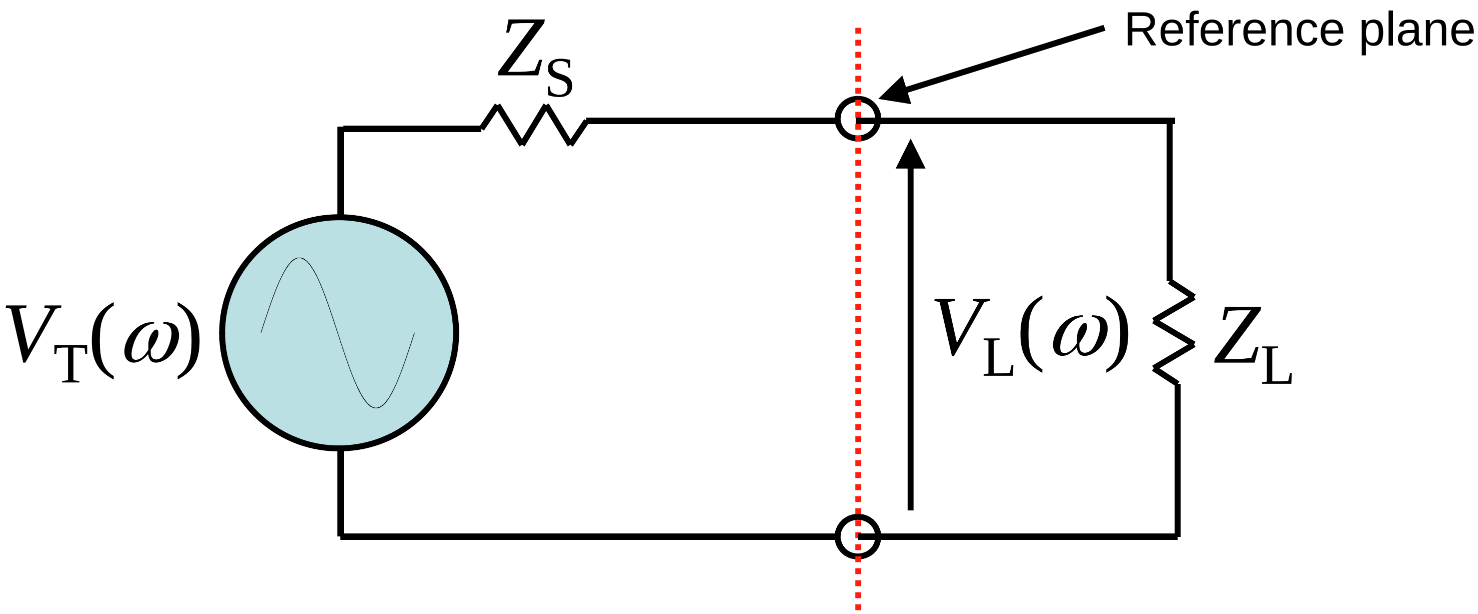


- A fundamental measurement is needed to separate the effect of the source from that of the receiver

Full waveform metrology includes:

1. Response function traceability to fundamental physics
   – Well understood and characterized measurement model
2. Impedance effects
3. Timing errors
4. Principled deconvolution
5. Errors are correlated $\Rightarrow$ Covariance matrix-based or Monte-Carlo uncertainty analysis
   – Analysis of the waveform at each point in the measured epoch, along with uncertainty at each point
   – Allows propagation of uncertainty through a linear transformation
   – Fourier transforms, pulse parameters, etc.

Effect of impedance on measurement



Thévenin equivalent circuit

$$V_L(\omega) = V_T(\omega)\left(\frac{Z_L(\omega)}{Z_L(\omega)+Z_S(\omega)}\right)$$

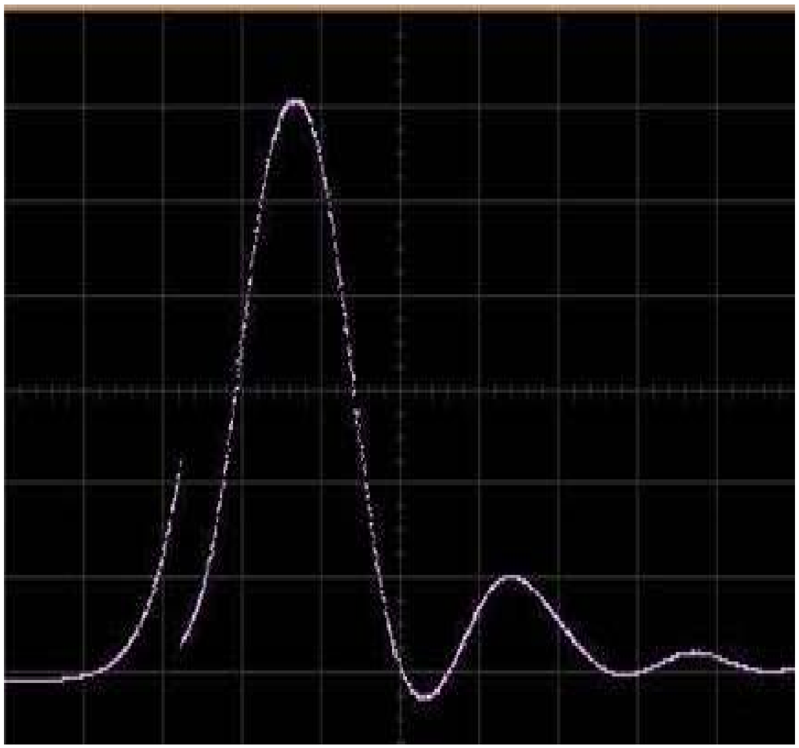
Quantities are generally complex and frequency dependent

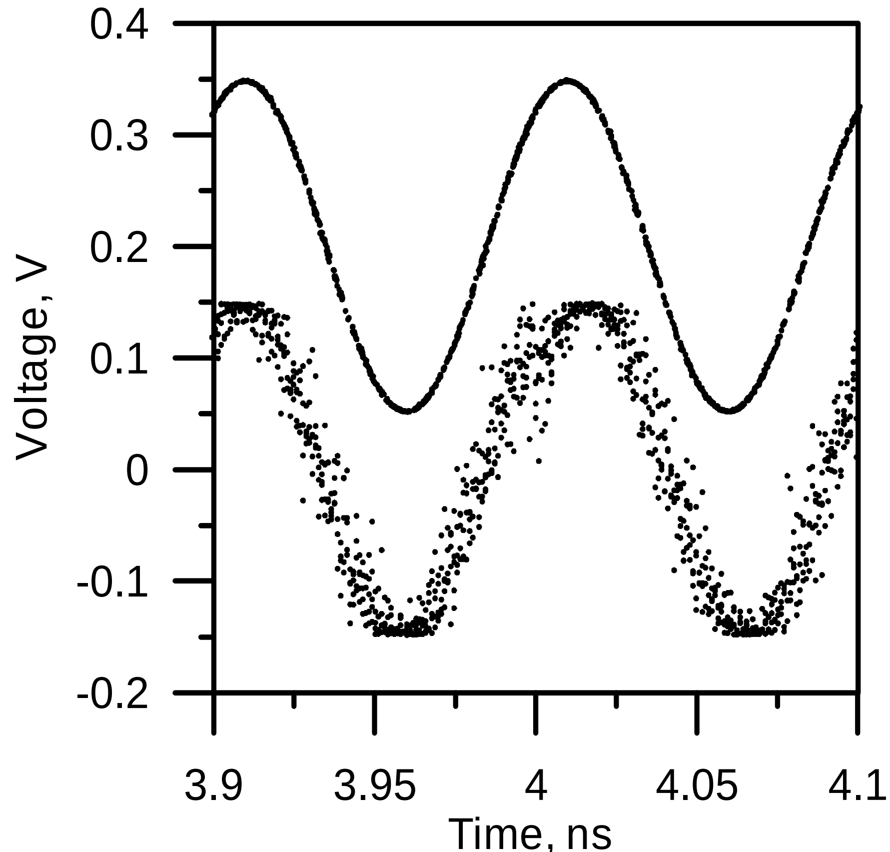
D.F. Williams, *et al.*, "Terminology for High-Speed Sampling-Oscilloscope Calibration," ARFTG, Nov. 30-Dec. 1, 2006.

Timebase errors

Evenly spaced time samples 1 2 3 4 5 6 7 8 9 10……

Actual sample timing 1 2 3 45 6 7 8 9 10 11 12 13…

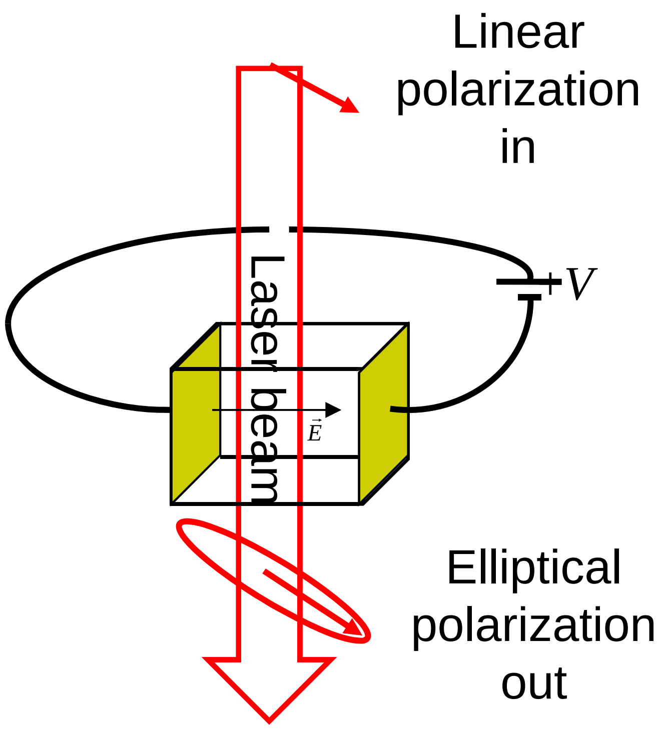




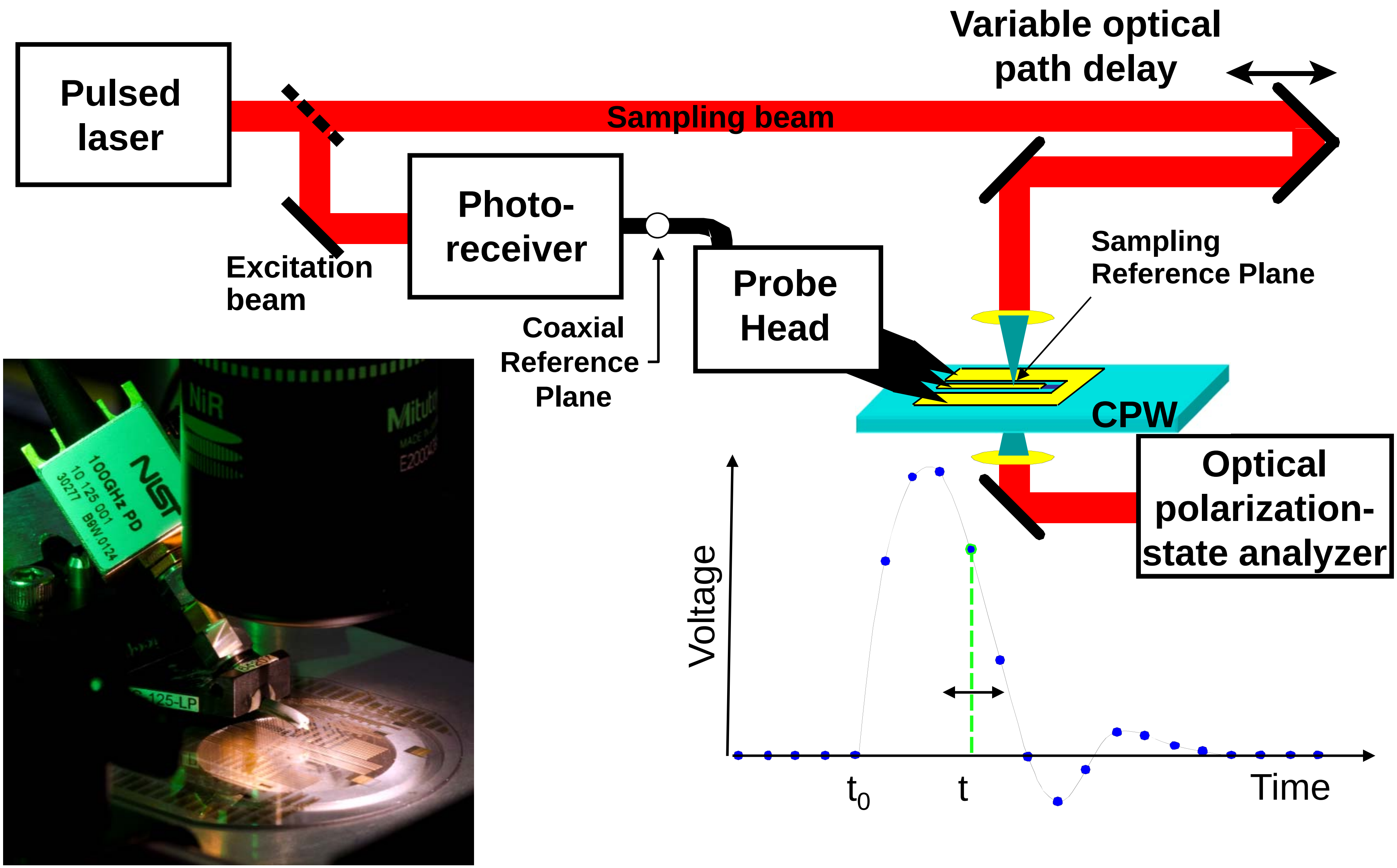
P. D. Hale, *et al.*, “Compensation of random and systematic timing errors in sampling oscilloscopes,” *IEEE Trans. Instrum. Meas.*, vol. 55, no. 6, pp. 2146-2154, Dec. 2006.

Response traceability: Electro-optic sampling

- NIST, PTB, and NPL have EOS systems for waveform traceability, others in development
- Use electro-optic (Pockels) effect in $LiTaO_3$ or GaAs, but other materials possible
- Phase delay between linear polarization states is proportional to the electric field
- Response time limited by phonon resonances and propagation effects
- Laser pulse duration and spatial extent also are limiting factors



NIST electro-optic (EO) sampling system: A THz sampling oscilloscope



Oscilloscope response function

Calibrate a photodiode impulse source

Use calibrated source to calibrate oscilloscope

$$M(t) = \left[\text{Photo-diode}\right] * \left[\text{Oscillo-scope}\right](t) \Leftrightarrow M(f) = \left[\text{Photo-diode}\right](f) \bullet \left[\text{Oscillo-scope}\right](f)$$

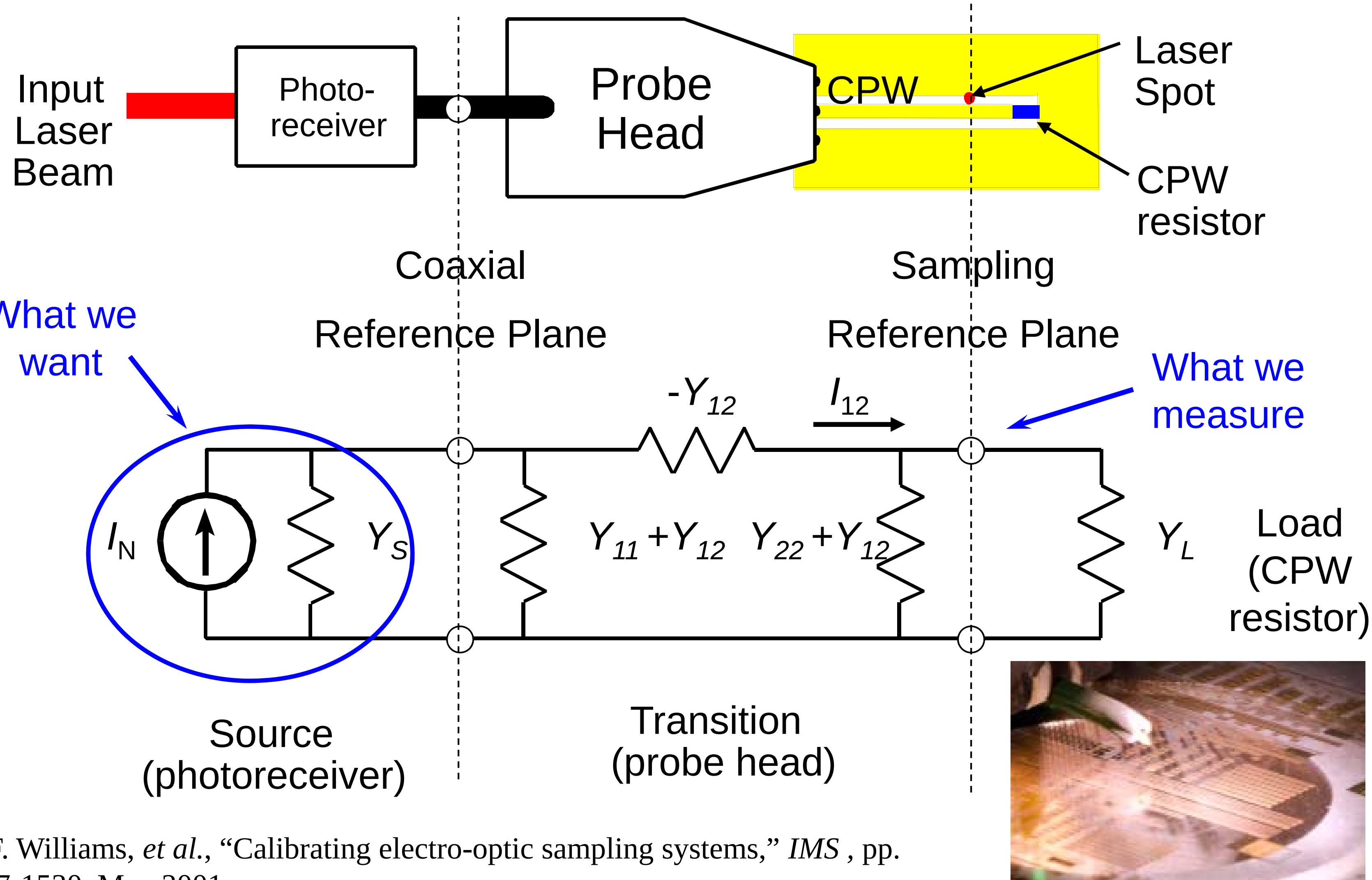
Convolution

Solve by division, but often not that simple

NIST

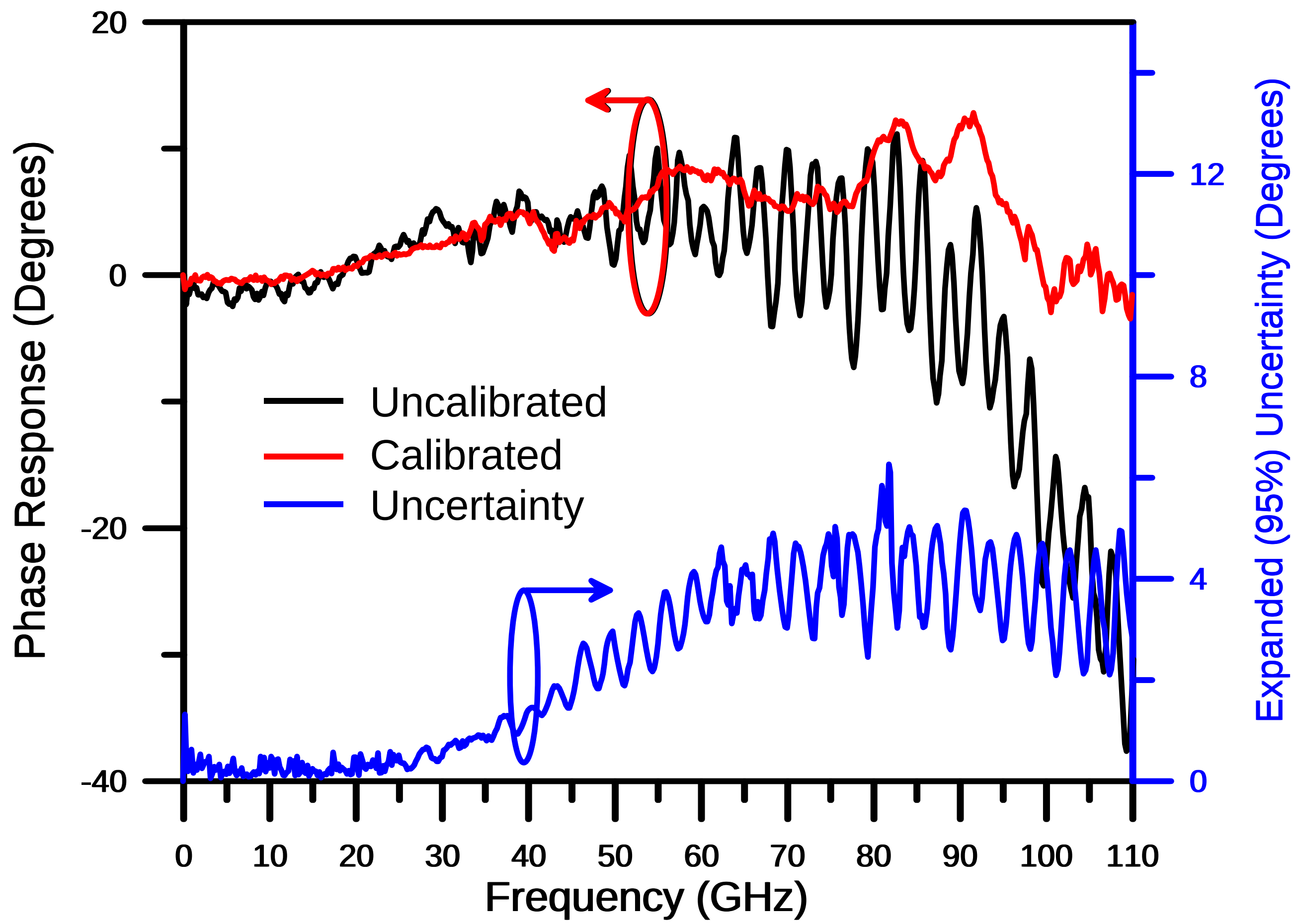
T. S. Clement, et al., “Calibration of sampling oscilloscopes with high-speed photodiodes, ” *IEEE Trans. Microwave Theory Tech.*, Vol. 54, pp. 3173-3181 (Aug. 2006).

Putting frequency domain corrections together: Equivalent circuit model



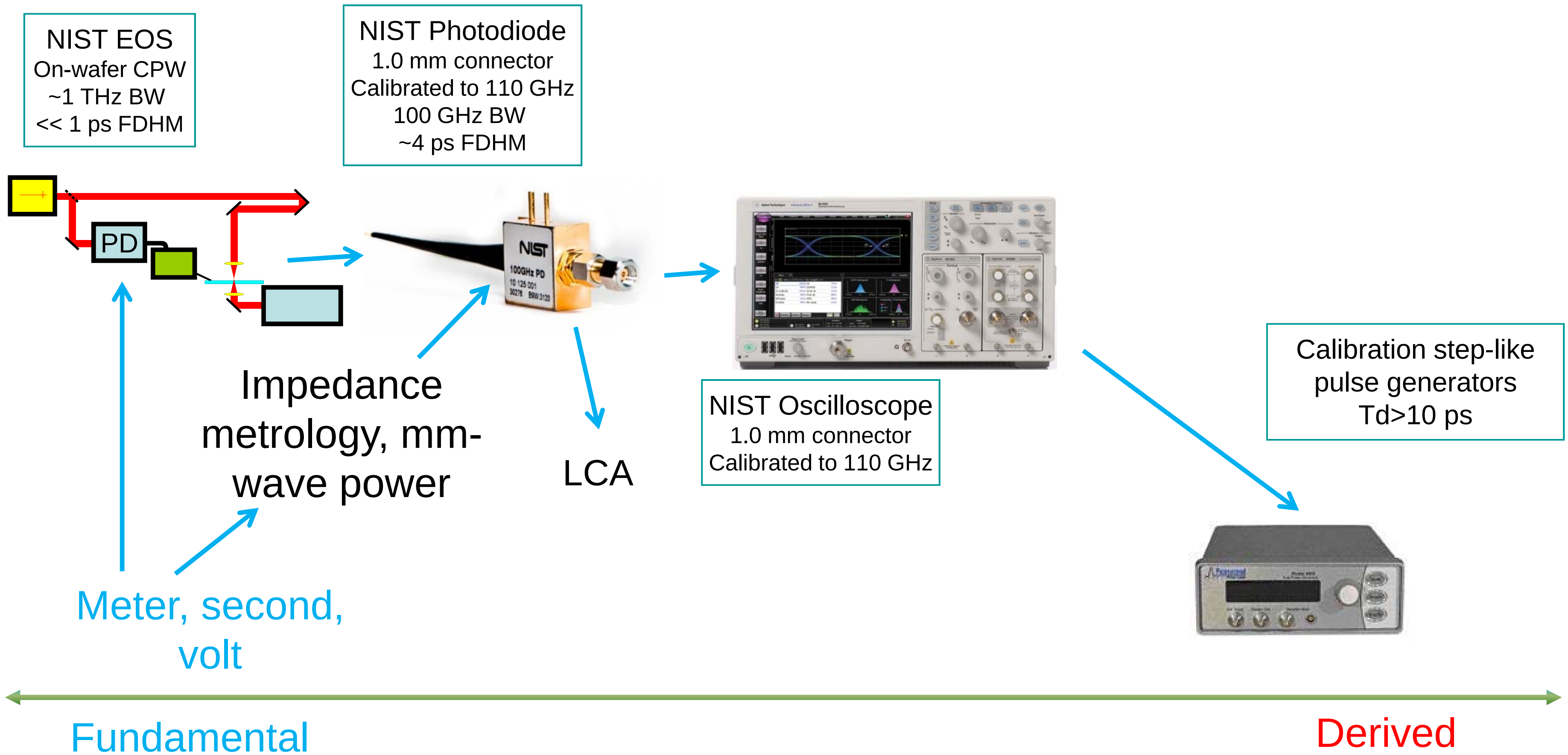
- D. F. Williams, *et al.*, "Calibrating electro-optic sampling systems," *IMS* , pp. 1527-1530, May 2001.
- D. F. Williams, *et al.*, "The impact of characteristic impedance on waveform calibrations," ARFTG, June 2013

Typical photodiode phase response



T. S. Clement, *et al.*, “Calibrated photoreceiver response to 110 GHz,” *IEEE LEOS*, Nov. 10-14, 2002, Glasgow, Scotland.

NIST traceability path for pulse measurements



Uncertainties must be propagated for each step.
We do this with the NIST Microwave Uncertainty framework.

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Dynamic measurement

Pulse source $x(t)$ → Oscilloscope $a(t)$ → Measurement $y(t)$

Dynamic measurement: One in which the physical quantity that is measured varies with time or space and where this variation has a significant effect on the estimate of the measurand and the associated uncertainty.

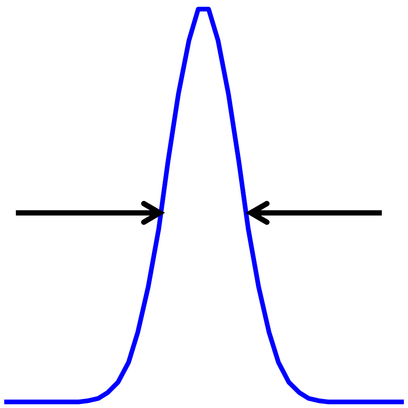
- Forward problem: $y(t) = [a * x](t) = \int a(s)x(t-s)ds$ or $\mathbf{y} = \mathbf{A}\mathbf{x}$
- Inverse problem: $\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$
- Inverse problem is not an "easy" problem because small fluctuations

in y give large changes in x; least squares solutions typically fail

- Typical solutions balance amplification of noise with bias

$\Rightarrow$ Regularized deconvolution $\mathbf{x}_\lambda = \mathbf{A}_\lambda^{-1}\mathbf{y}$.

If we are just interested in pulse duration…



Full duration at half maximum (FDHM)

Simplification for Gaussian pulses: Root sum of squares (RSS), also known as quadrature sum

$$\tau^2_{\mathrm{FDHM}}(y) = \tau^2_{\mathrm{FDHM}}(a) + \tau^2_{\mathrm{FDHM}}(x)$$

$$\Rightarrow \quad \tau^2_{\mathrm{FDHM}}(x) = \tau^2_{\mathrm{FDHM}}(y) - \tau^2_{\mathrm{FDHM}}(a)$$

- Not true for general pulse shapes
- Used by most NMIs and third party calibration labs ☹

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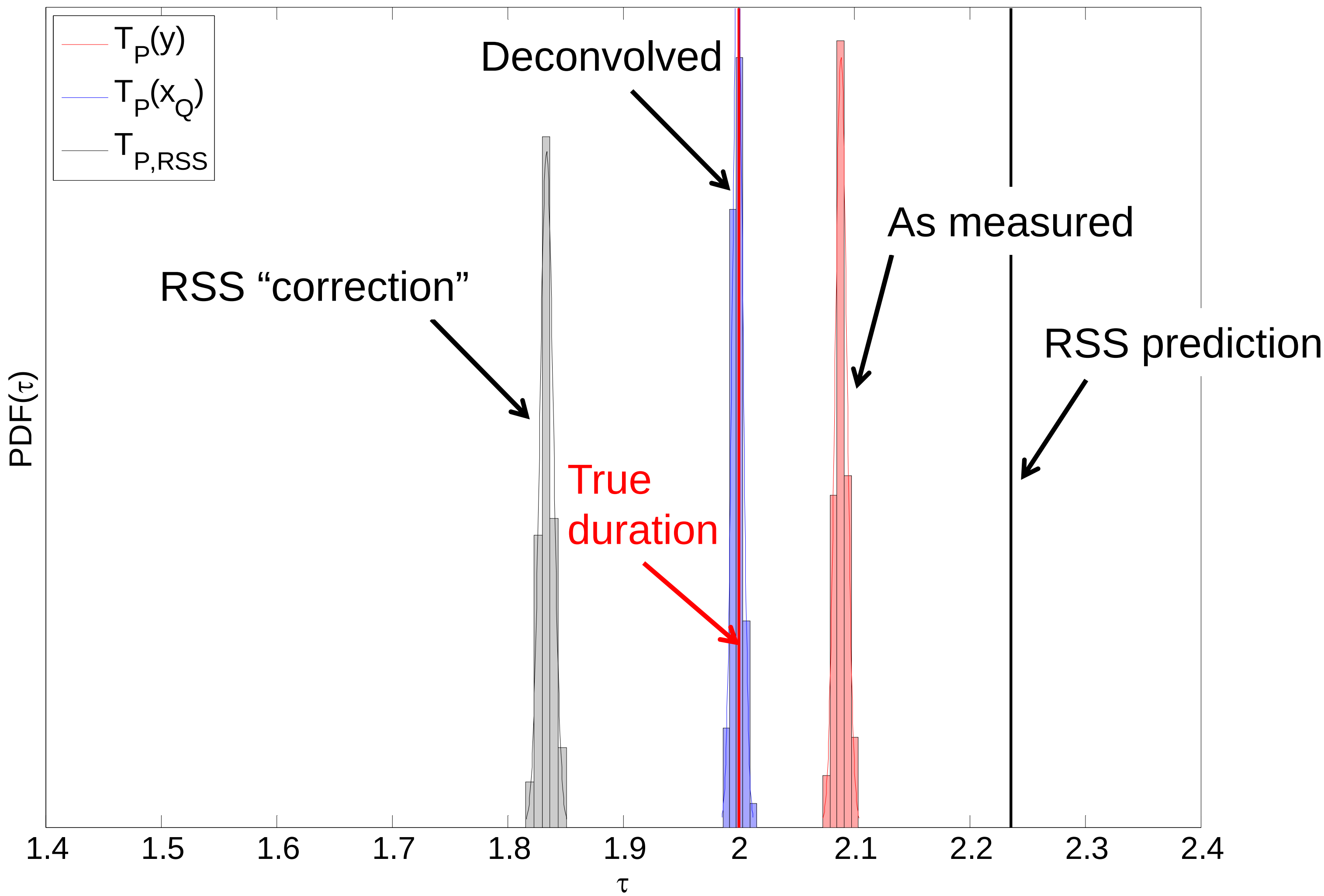
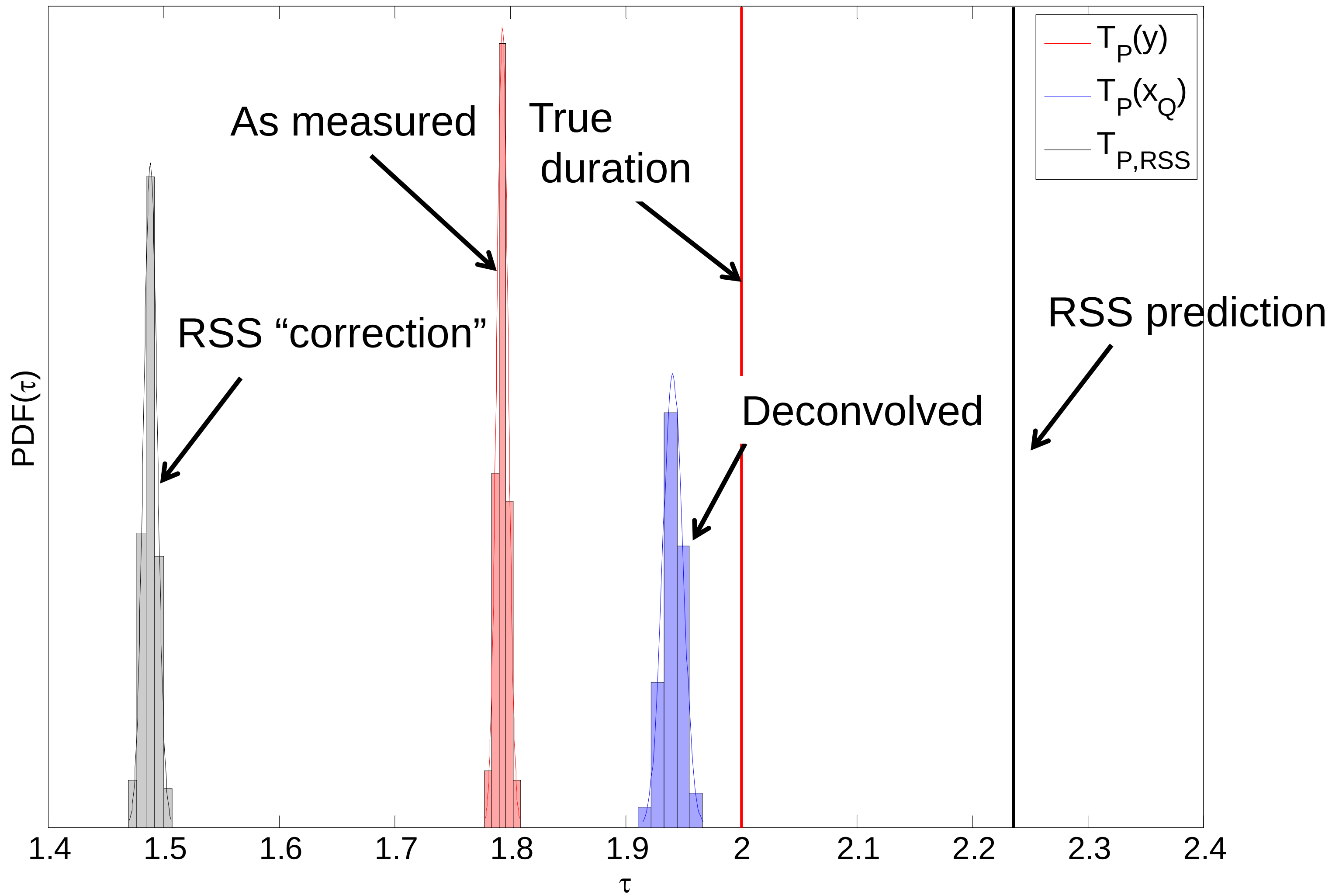
RSS can be quantitatively incorrect…

input = Chebyshev 4th order, duration=2
system = Butterworth 2nd order, duration=1

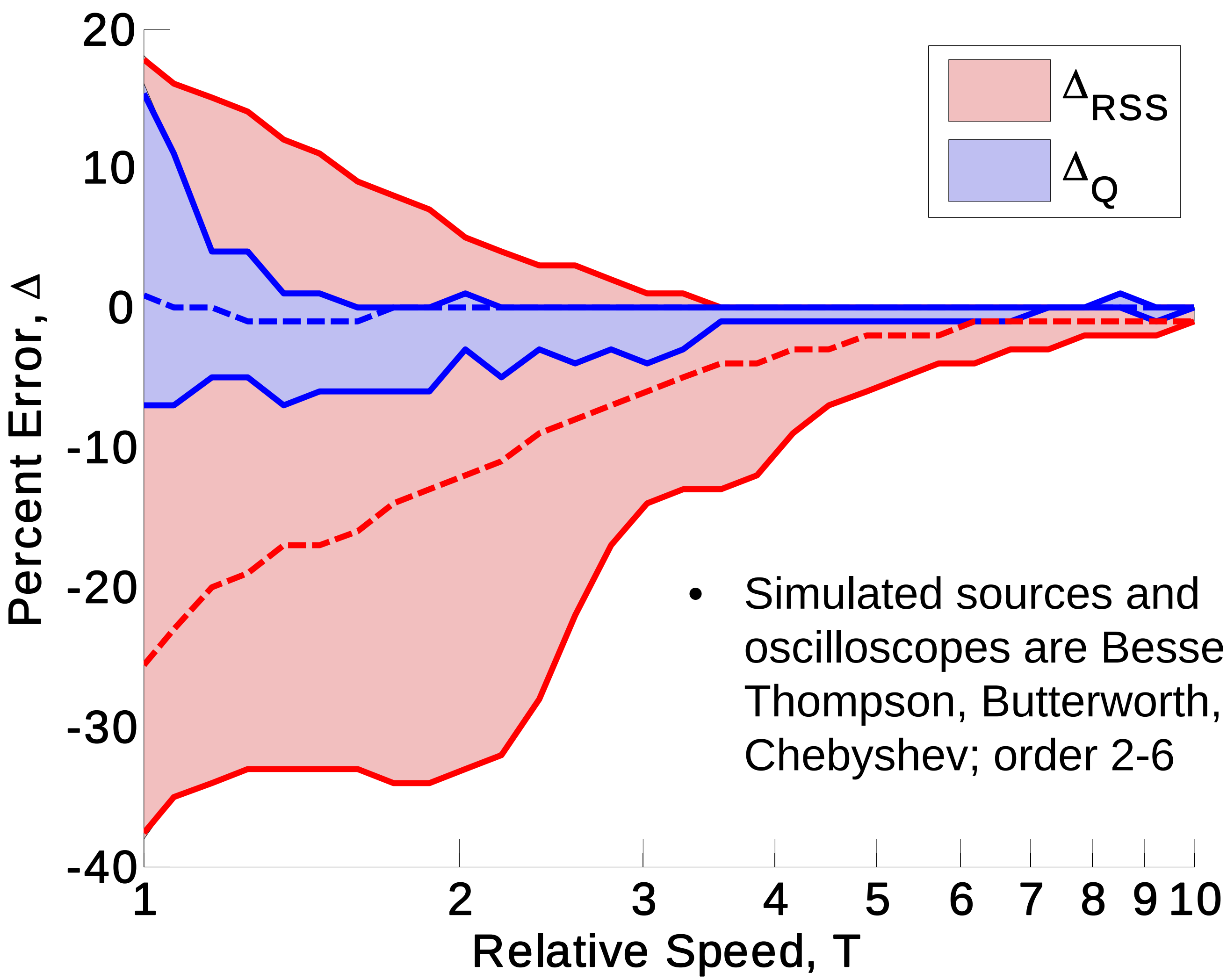


…or qualitatively wrong!

input = Butterworth 2nd order, duration=2
system = Chebyshev 4th order, duration=1



Estimation of τ_F: Deconvolution and RSS



- Simulated sources and oscilloscopes are Bessel-Thompson, Butterworth, and Chebyshev; order 2-6

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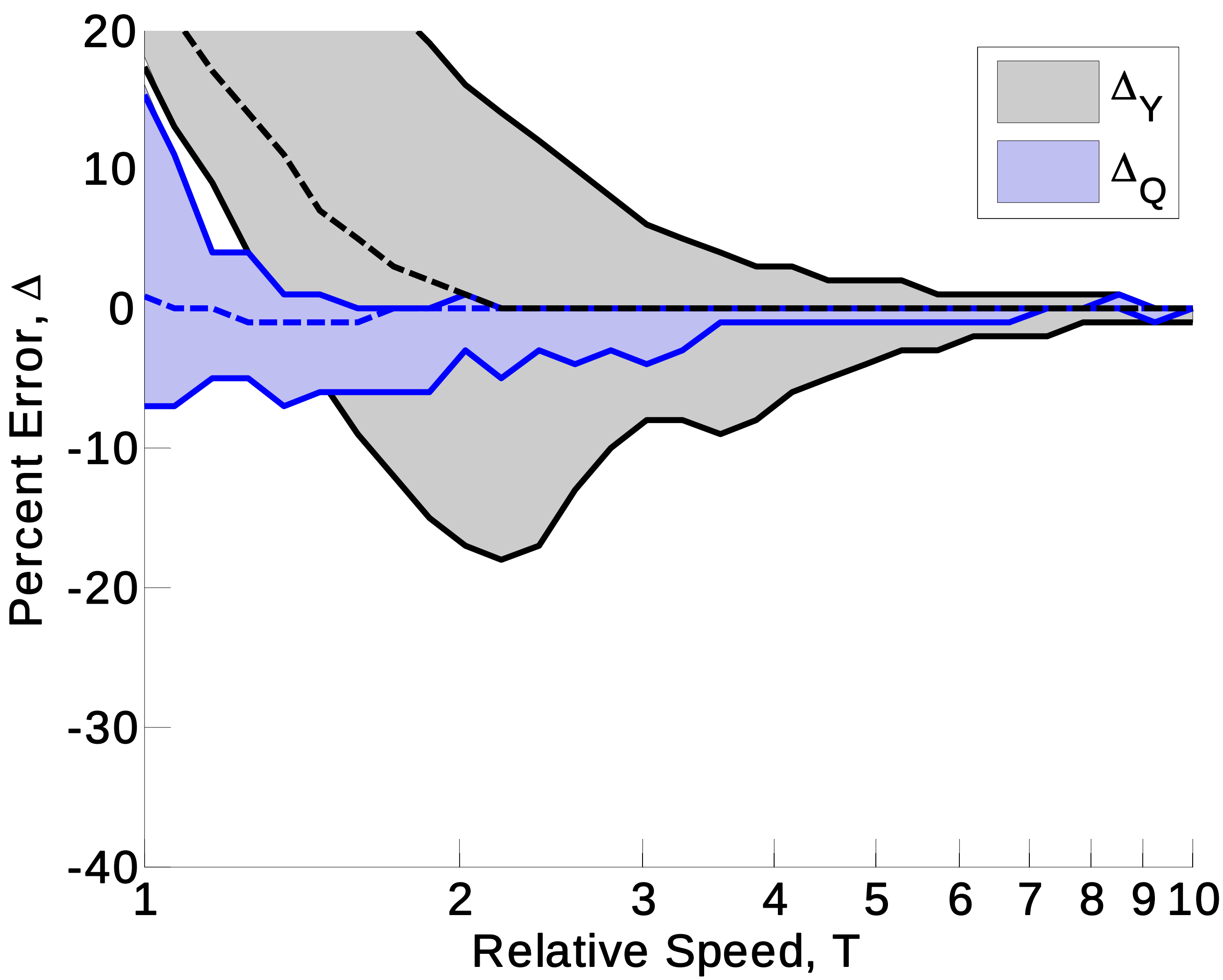
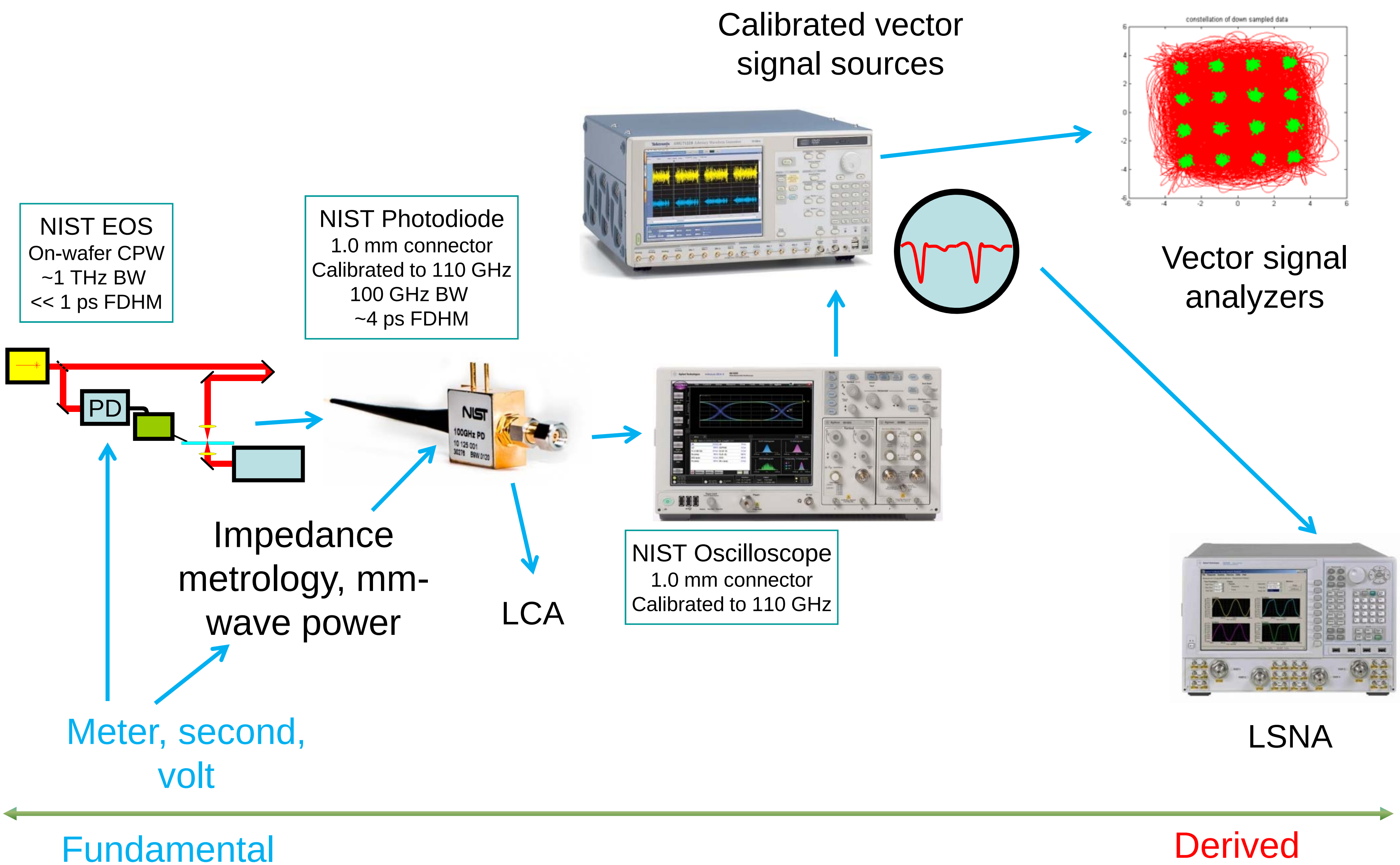
A. Dienstfrey and P. D. Hale, "Analysis for dynamic metrology," *Meas. Sci. Technol.*, **25 (**2014) 035001.

Estimation of τ_F: Deconvolution and as-measured



A. Dienstfrey and P. D. Hale, “Analysis for dynamic metrology,” *Meas. Sci. Technol.*, **25 (**2014) 035001.

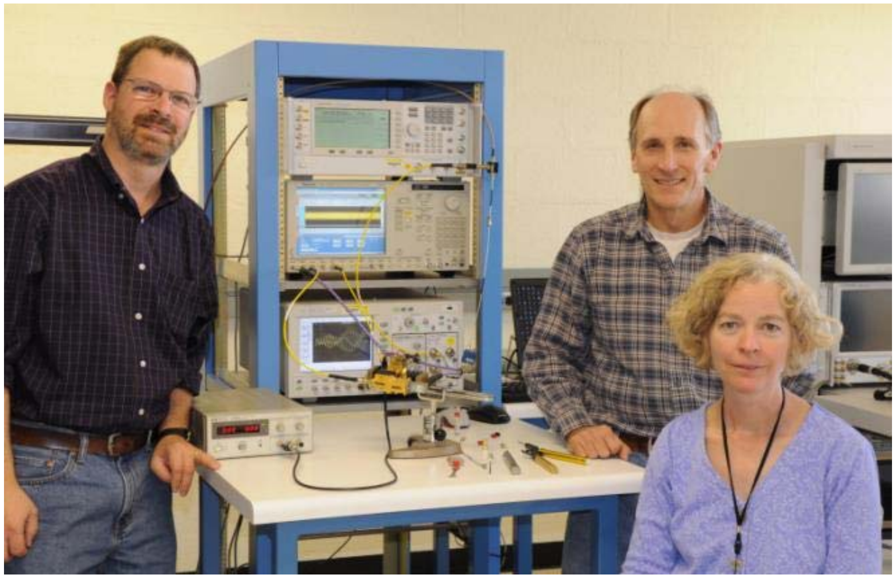
NIST traceability path for modulated-signal measurements



Uncertainties must be propagated for each step.
We do this with the NIST Microwave Uncertainty framework.

Broadband Modulated-Signal Source

- Millimeter-wave signal generation
  - New broadband arbitrary waveform generators, fast SiGe technology
- NIST techniques to calibrate generators with oscilloscope
  - Internal response corrected, traceable to EOS
  - Also correct time-base distortion and impedance effects



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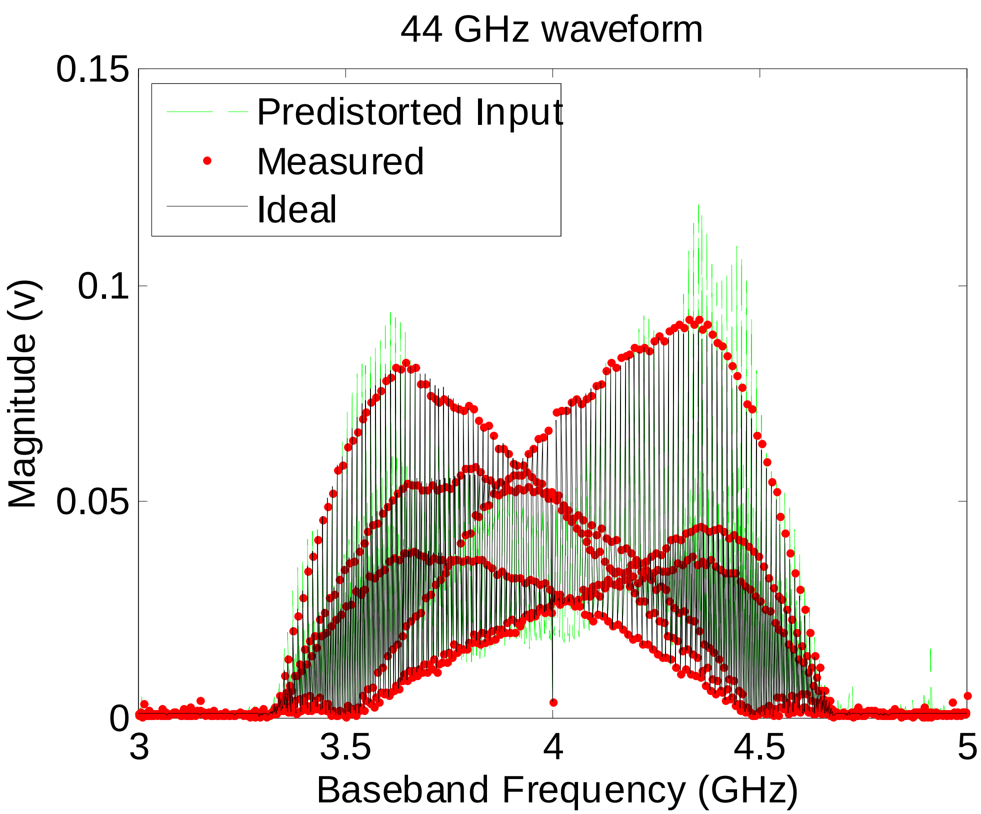
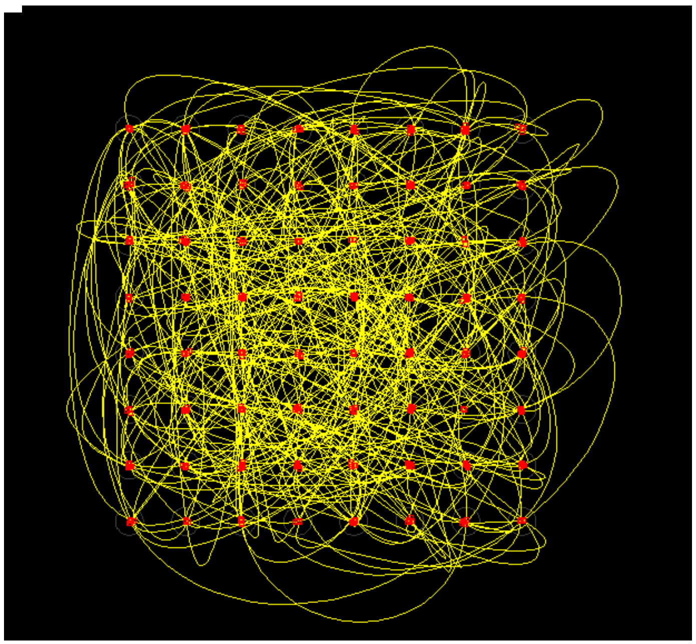
Millimeter-Wave Modulated Signals at 44 GHz

- Non-ideal AWG and upconverter
- Iteratively predistorted to make a source with low EVM



Original:
EVM=8.54%

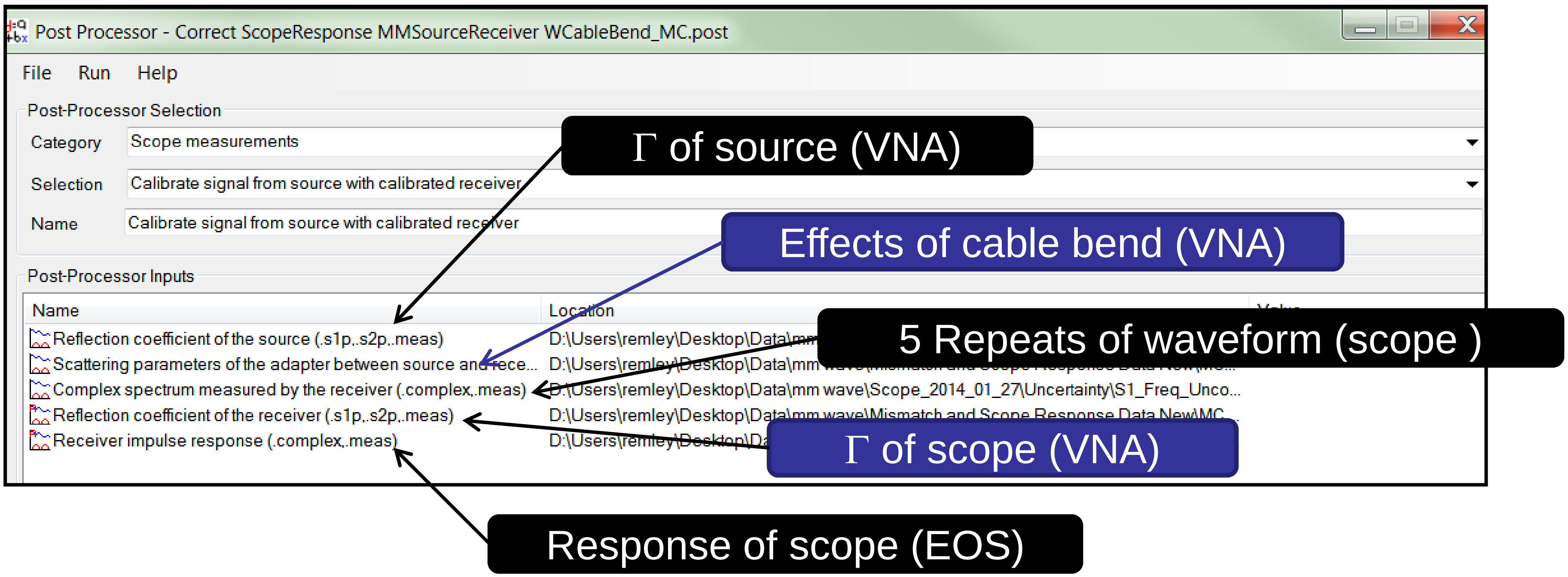


44 GHz, 64 QAM, 1 GS/s

K. A. Remley, *et al.*, “Millimeter-Wave Modulated-Signal and Error-Vector-Magnitude Measurement with Uncertainty,” submitted to *IEEE Trans. Microwave Theory Tech.*

0.74% EVM: How do we Know it is Correct?

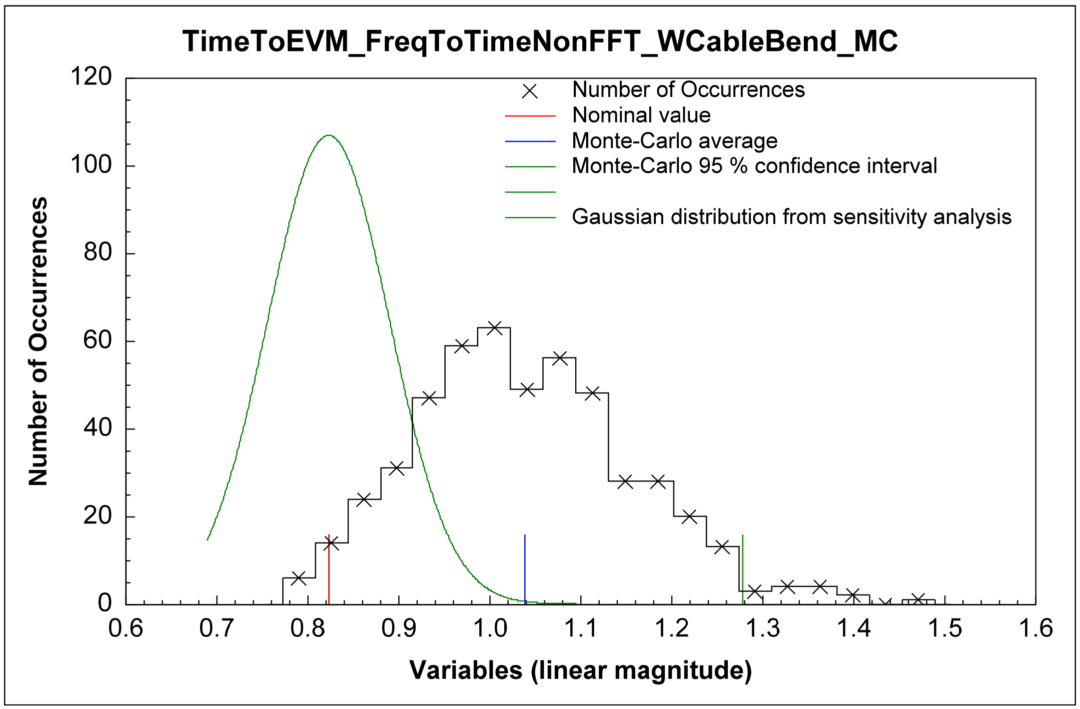
The NIST Microwave Uncertainty Framework will tell us!



Drag and Drop measurement files to incorporate errors

Errors in EVM Measurement of Source

- NIST Microwave Uncertainty Framework finds uncertainty
- Asymmetric distribution



- **Histogram:** Monte Carlo analysis of error mechanisms for 1000 simulations
- **Continuous curve:** Sensitivity analysis for each error mechanism separately

K. A. Remley, D. F. Williams, P. D. Hale, C.M. Wang, J.A. Jargon, and Y.C. Park, “Modulated-Signal Measurements and Uncertainty in Error Vector Magnitude at Millimeter-Wave Frequencies,” submitted to *IEEE Trans. Microwave Theory Tech*.

Why is waveform metrology NMI worthy?

- Waveform measurements used in all areas of engineering and science
- Effects of source and measurement system cannot be separated without <u>fundamental</u> standards
- Full waveform metrology is multidisciplinary, requiring skills in microwave electronics, optoelectronics, microcircuit fabrication, statistical signal processing, and inverse problems
- Complicated system, considerable investment
- Opportunity to unify industry through standardized and traceable metrology

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EOS comparison between NIST, PTB, and NPL

- Will be first comparison of ultrafast, full-waveform metrology
- Although using electro-optic sampling, the three systems use different approaches
  - $\Rightarrow$Better validation
- Photodiode is being used as transfer artifact
- First step towards CMC in this area

P. D. Hale, D. F. Williams, A. Dienstfrey, J. Wang, J. Jargon, D. Humphreys, M. Harper, H. Füser, and M. Bieler, "Traceability of High-Speed Electrical Waveforms at NIST, NPL, and PTB," *Precision Electromagnetic Measurements (CPEM), 2012 Conference on*, pp.522-523, 1-6 July 2012.

NIST

Conclusions

- Full/complete waveform measurements are needed in all aspects of science and technology
- Fundamental traceability for high-speed electrical measurements is available through EOS
- Impedance and time errors must be included to obtain meaningful results
- A multivariate covariance-matrix and Monte-Carlo based uncertainty analysis allows for transformation between time and frequency domains, calculation of pulse parameter uncertainties, and propagation through multiple steps

NIST

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Time-base errors, jitter, and drift

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NIST Microwave Uncertainty Framework

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