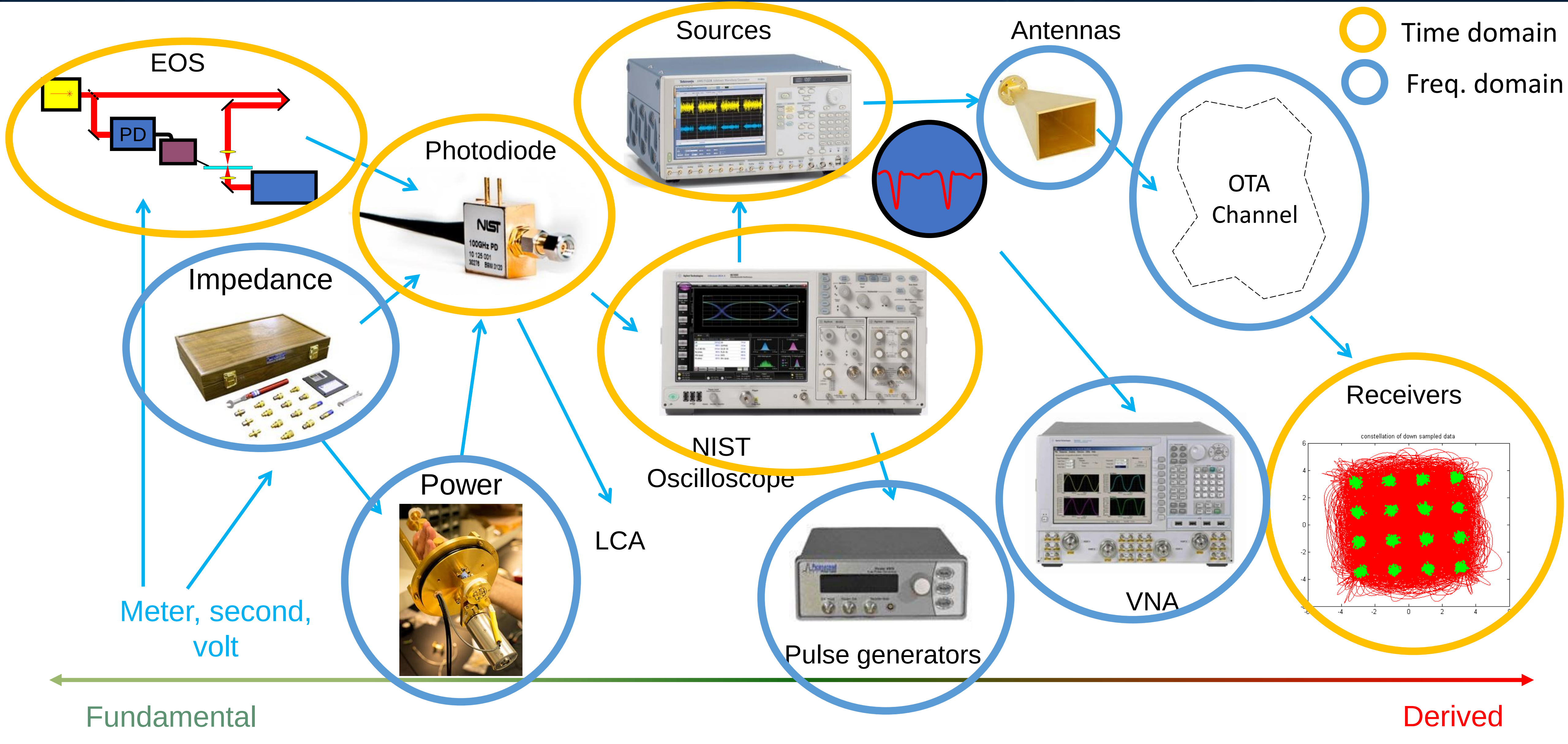
The NIST Microwave Uncertainty Framework

National Institute of Standards and Technology
U.S. Department of Commerce

CTL Communications Technology Laboratory

Traceable Measurements are Complicated!



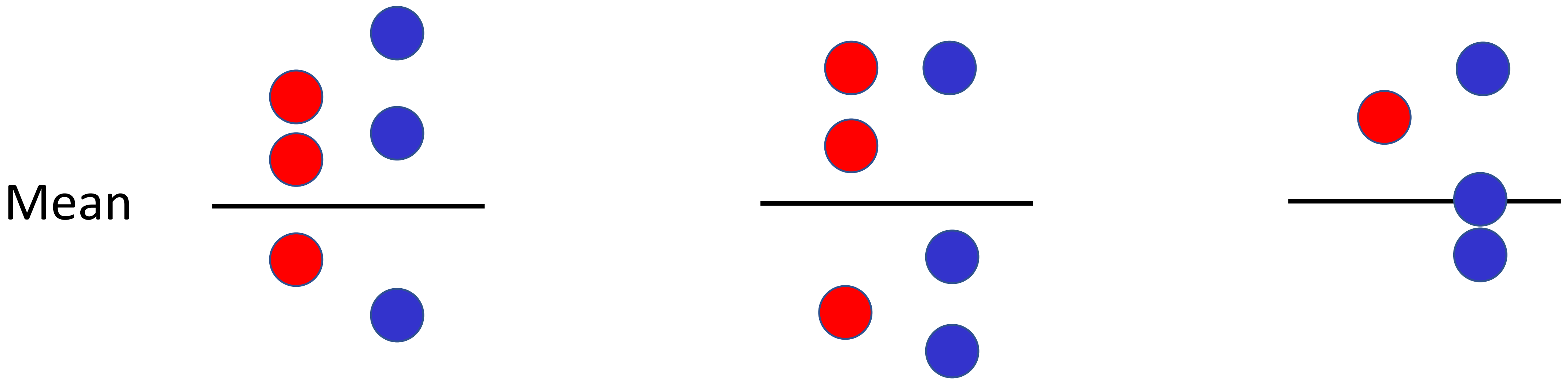
Correlated Uncertainties

Correlations: A linear relationship between variations

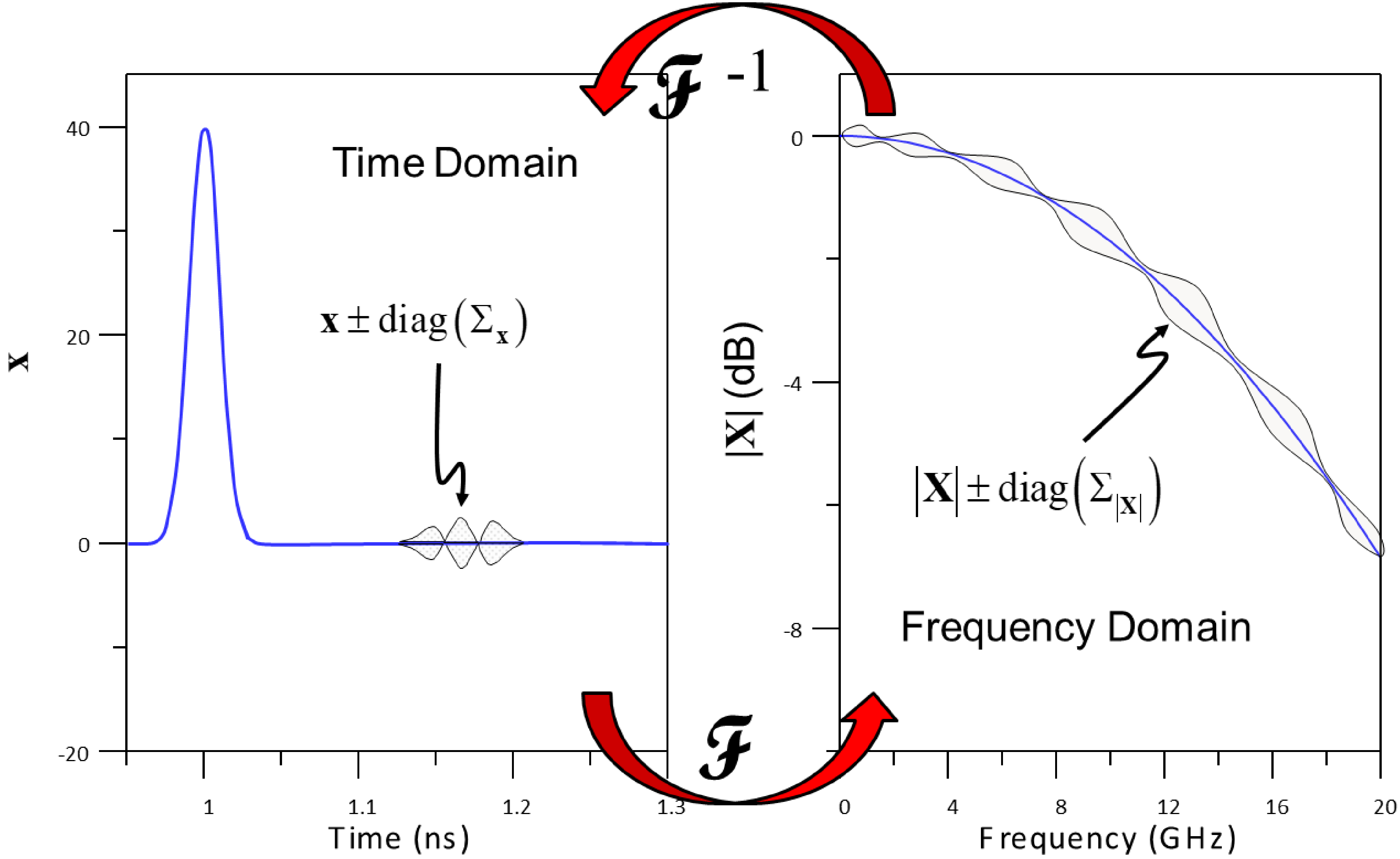
Perfectly correlated
$(\rho = 1)$
Move together

Negatively correlated
$(\rho = -1)$
Move oppositely

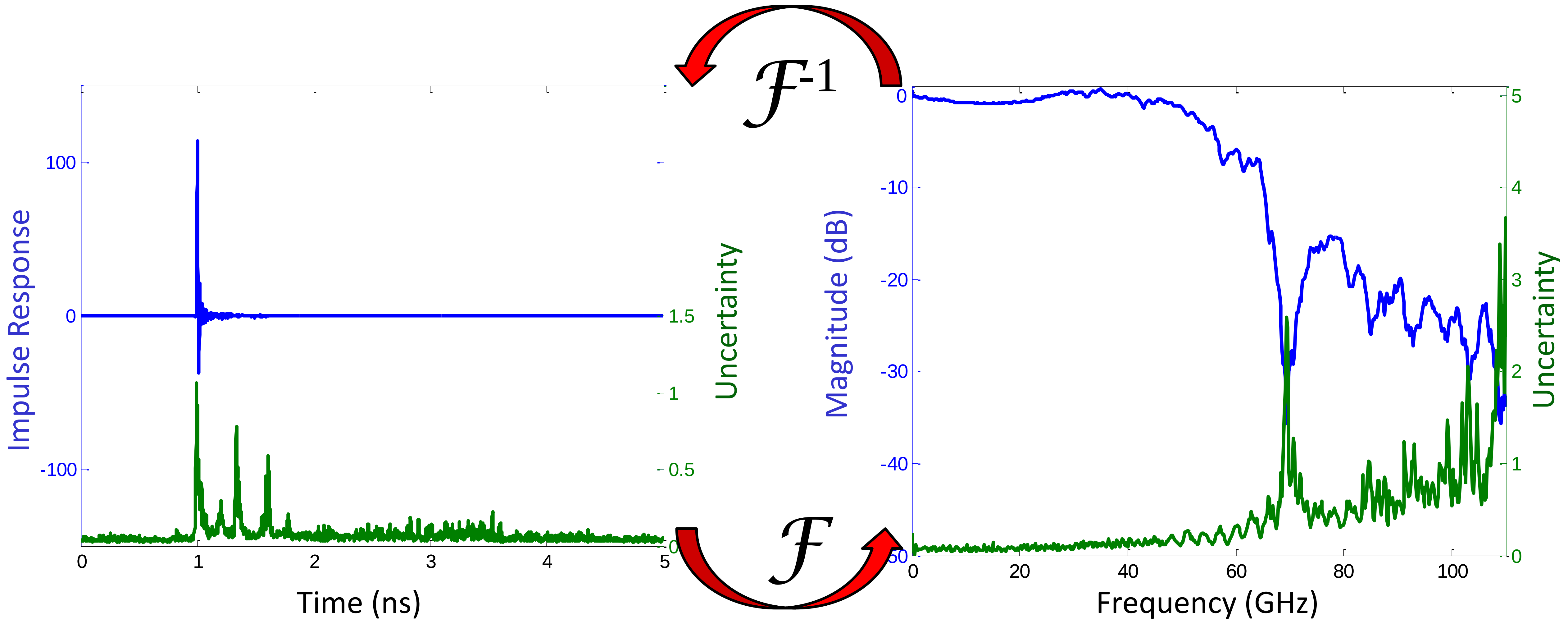
No correlation
$(\rho = 0)$
No linear relationship



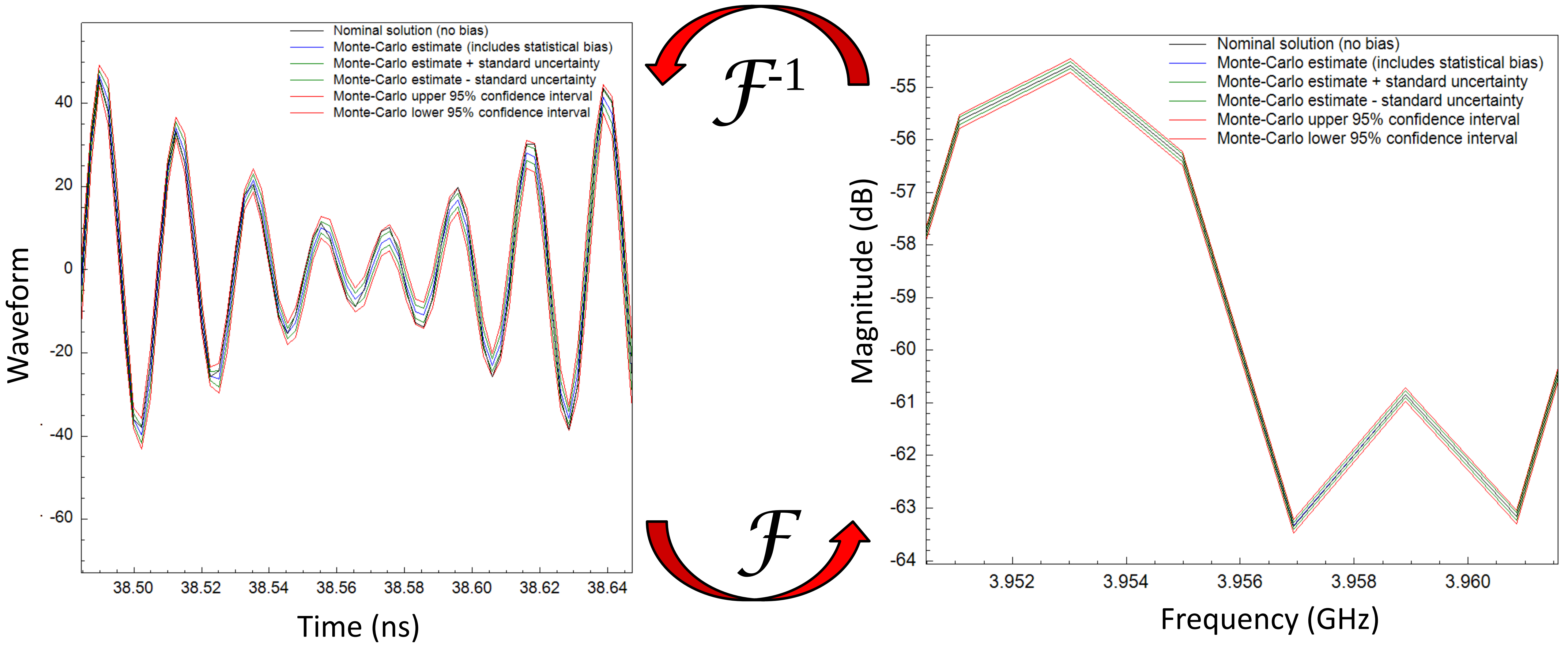
Correlated Uncertainty Analysis



Oscilloscope Response



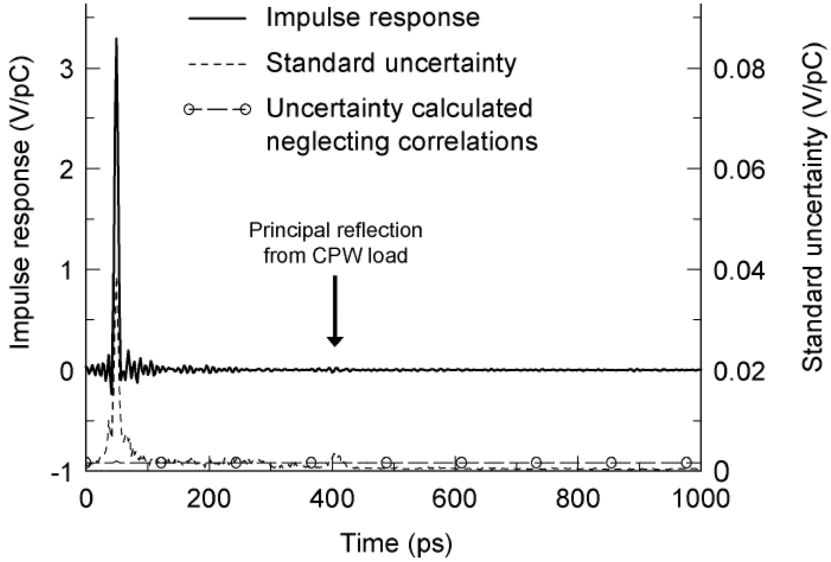
Wide Bandwidth Modulated Signals



Correlated Uncertainty Analysis

- Classic uncertainty analysis
  - No structure
  - Unable to consistently propagate uncertainties
- Correlated uncertainty analysis
  - Captures uncertainty structure across records
  - Allows transformations between domains
  - More important at higher frequencies
- NIST leader in correlated uncertainty analysis
  - Electro-Optic Sampling 2004 (time and frequency)

	UNKNOWN TARGET UNCERTAINTIES	dB
3.1	Average Illumination	0.4
3.2	Background-Target Interactions	0.1
3.3	Cross Polarization	0.6
3.4	Drift	1.0
3.5	Frequency	neg.
3.6	Integration	neg.
3.7	I-Q Imbalance	neg.
3.8	Near Field	1.0
3.9	Noise-Background	0.9
3.10	Nonlinearity	1.0
3.11	Range	neg.
3.12	Target Orientation	n.a.
3.13	Calibration Target (4.14)	0.9
3.14	Overall Uncertainty (RSS)	**1.7**

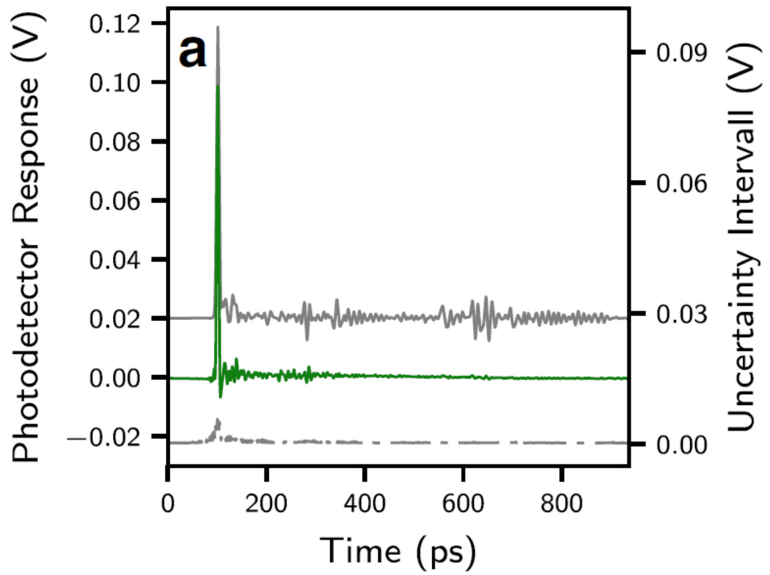


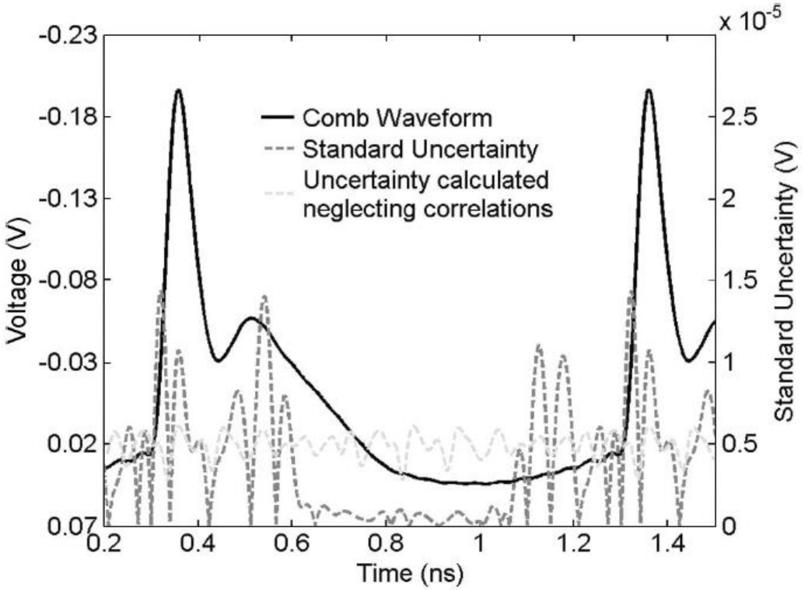
Correlated Uncertainty Analysis - NMIs

Other NMIs now following NIST's lead:

- PTB Germany:
    - Characterization of photodetectors
- Harbin I.T./NIM China:
    - NVNA measurements
- NPL UK
    - Time ↔ frequency domains

- Instrument makers beginning to follow suit



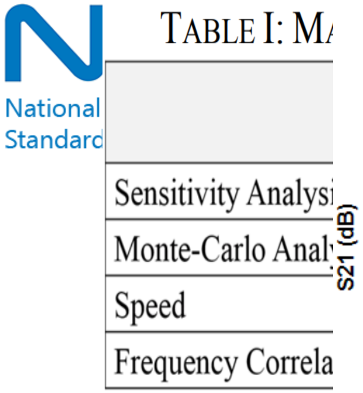


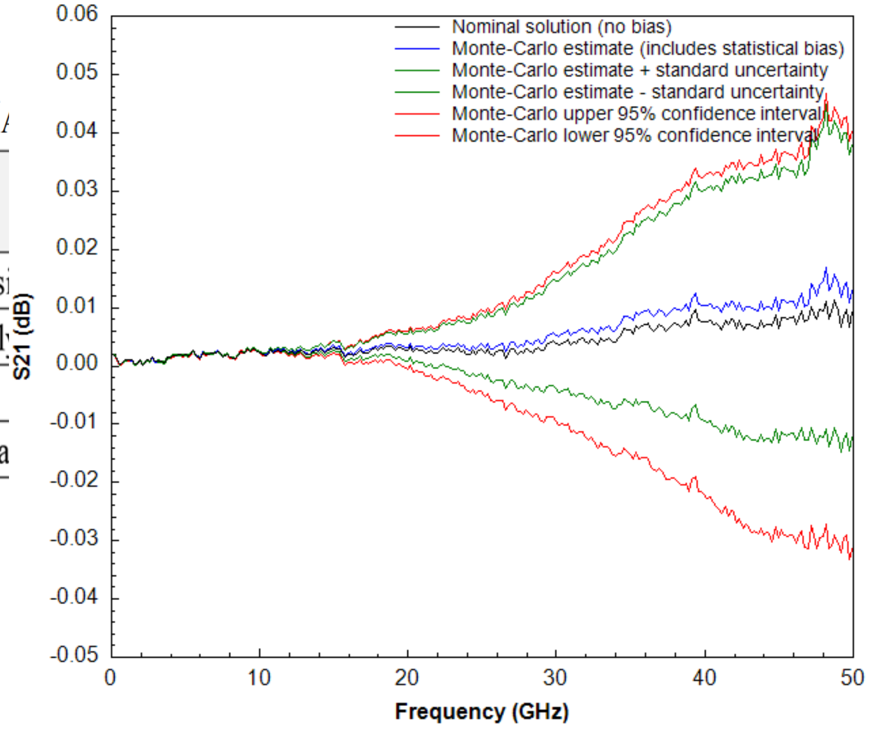
Everybody has Recognized the Need for Software

- PyDynamic (PTB and NPL)
  - Uncertainty of FIR filters
- VNATools (METAS)
  - Limited to VNA-related routines
- Keysight option 015 – SW3
  - Real time on VNA
  - Extensibility?

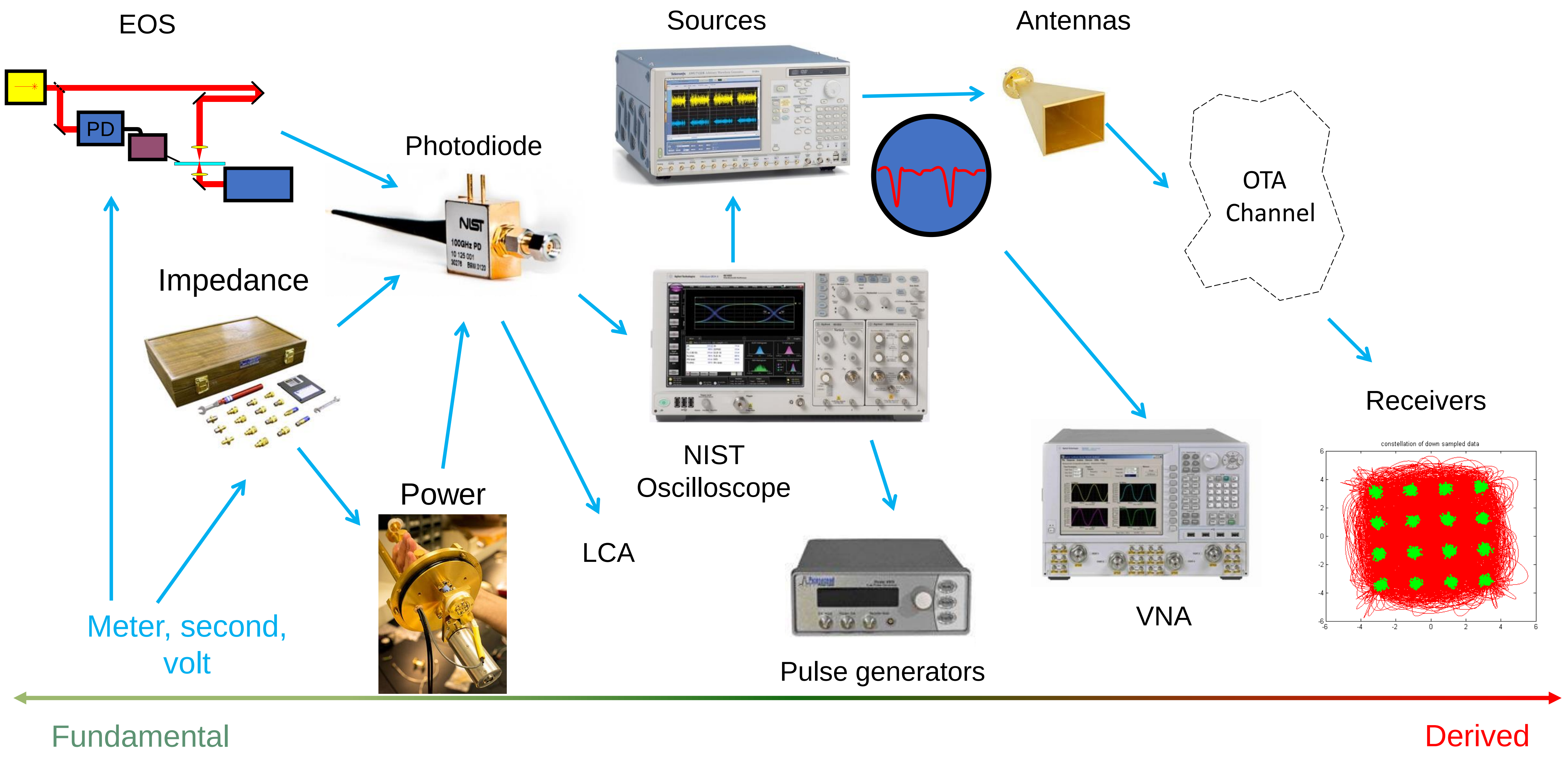
Microwave Uncertainty Framework

- NIST Microwave Uncertainty Framework
  - Correlated uncertainty analysis
- Many RF applications
  - VNAs, scopes, sources, receivers, etc.
  - Fourier transform, EVM, many others
- Uncertainty from multiple measurements
- Common framework for CTL measurements
  - Uniformity of metrology
  - Consistent uncertainty analyses across distributed measurements



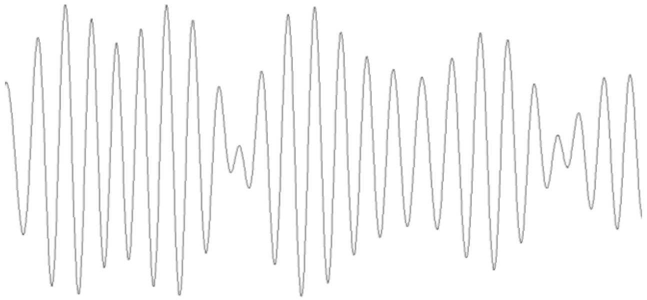


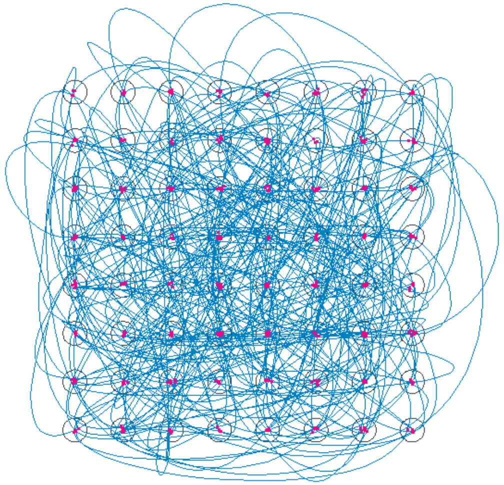
Traceable Measurements are Complicated!

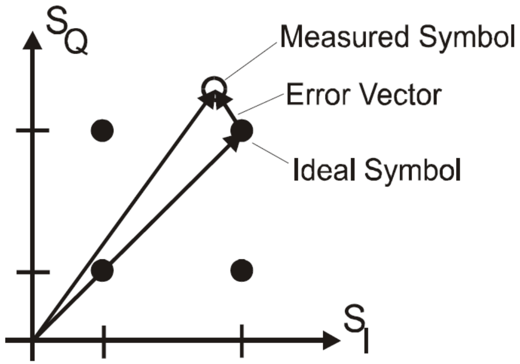


Error Vector Magnitude

- EVM common figure of merit
  - Industry: Use EVM to characterize
  - IEEE P1765: Uncertainty in EVM
- Need correlated uncertainty analysis
  - VNA, Oscilloscope
  - Frequency → time domain
- Typically EVM applies a time correction
  - Align sampling times to symbol/data





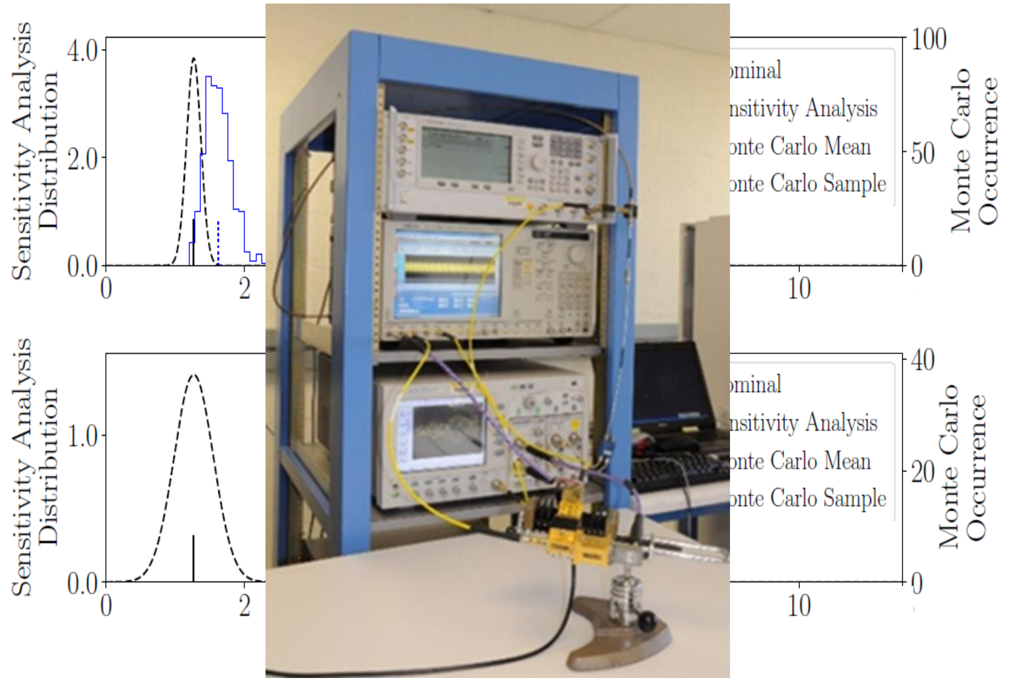


Error vector magnitude

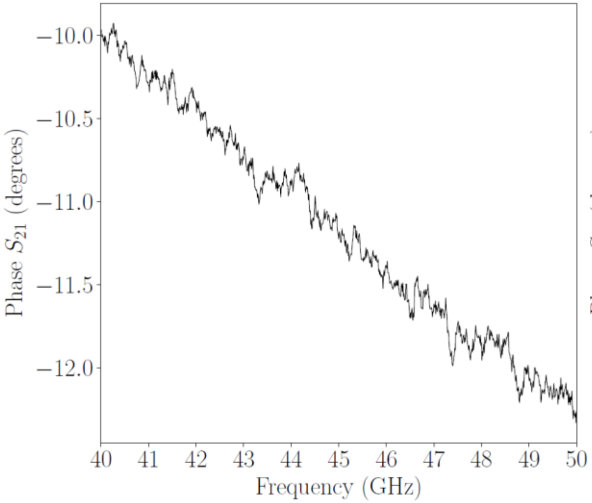
IEEE
IEEE STANDARDS ASSOCIATION

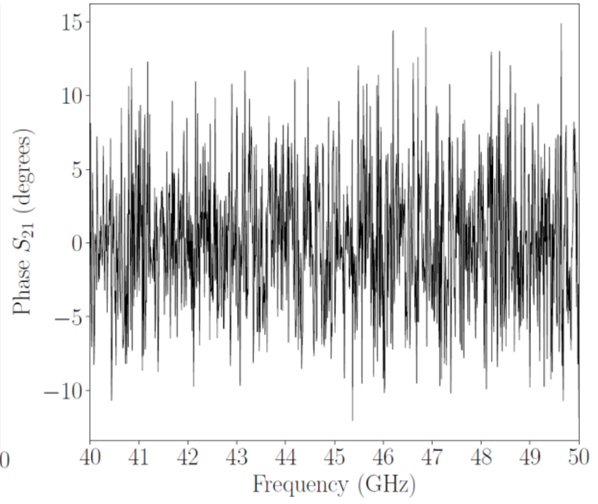
Importance of Correlations in EVM

- Precision source 4, 44, 92.4 GHz, 1 GHz BW
  - Calibrations: source, scope, VNA
  - Including bending a cable (delay)
  - Microwave Uncertainty Framework
  - [Remley et al. 2015]



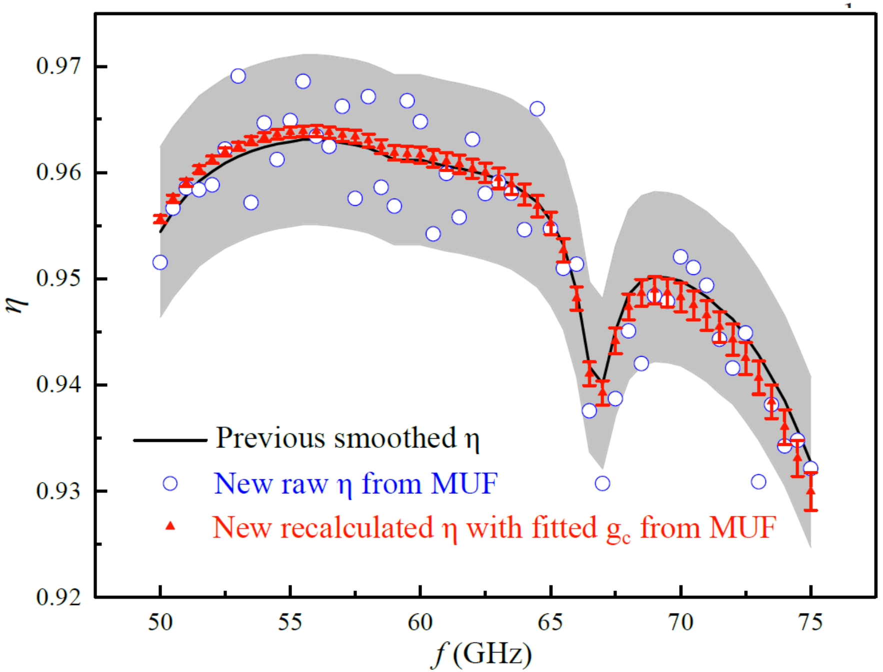
- Cable response uncertainty
  - Correlated → time delay (corrected)
  - Noise → distortion → higher EVM
  - [Jamroz et al. 2018]





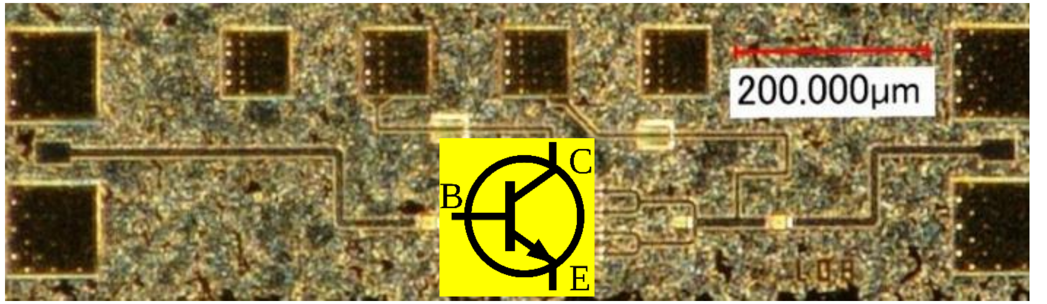
New Method for Traceable Power

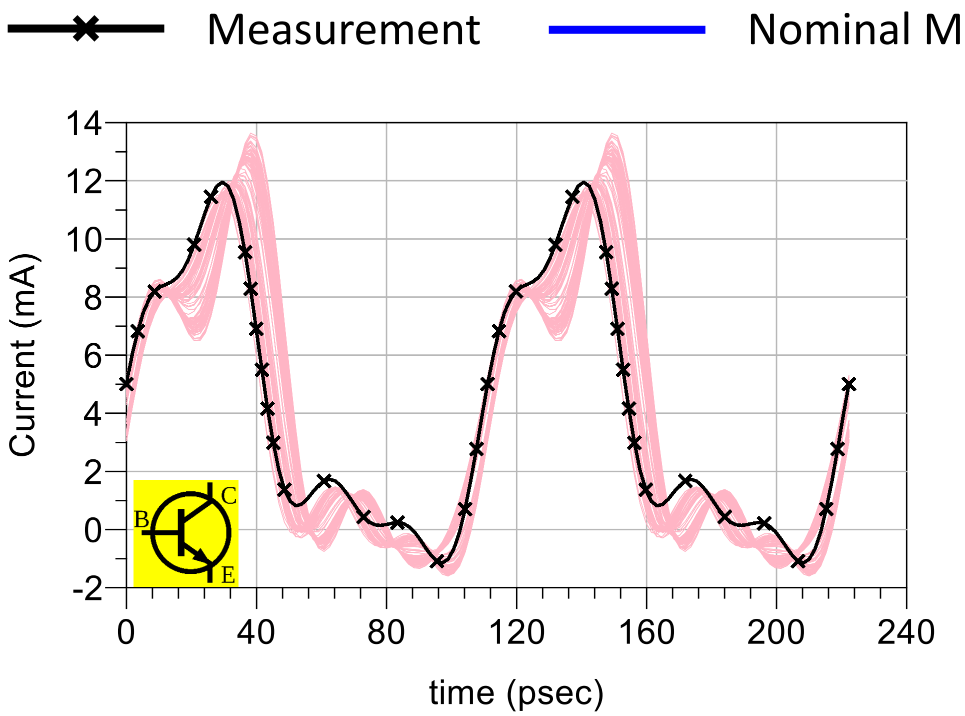
- Traceable power with correlated uncertainties [Gu et al. 2019]
  - Use Vector Network Analyzer to calibrate a calorimeter
- Consistent correlated uncertainties
  - Effective efficiency, correction factor
  - Previously: constant uncorrelated uncertainty
- Correlations are important for modulated signals



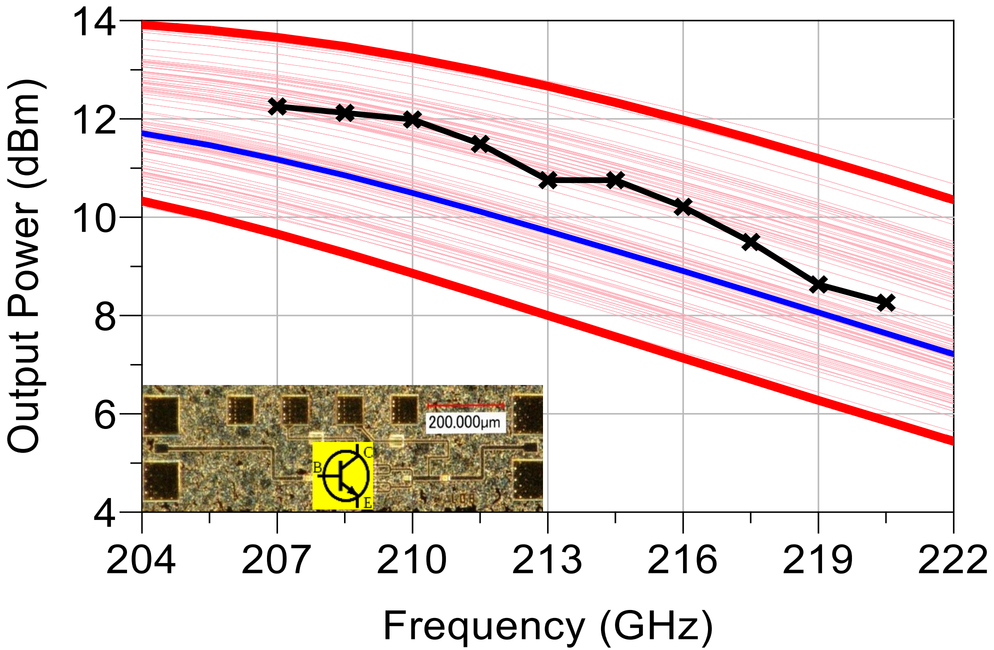
mm-Wave Power Amplifier Design

- mm-Wave Power Amplifier (PA) design
  - Critical aspect of mm-Wave communications
- Uncertainties in transistor model
- Embed transistor uncertainty in PA design at mm-Wave [Cheron et al. 2019]



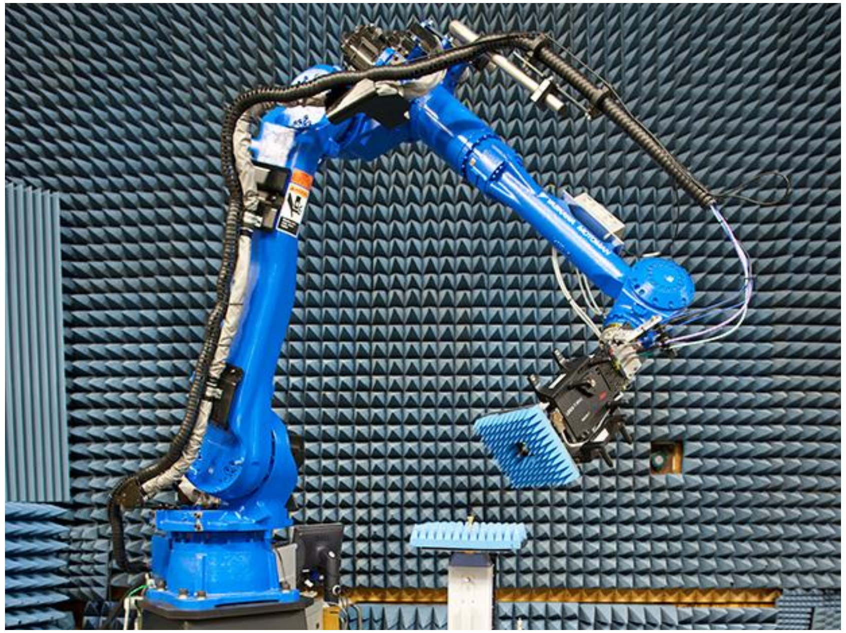


1st pass design success



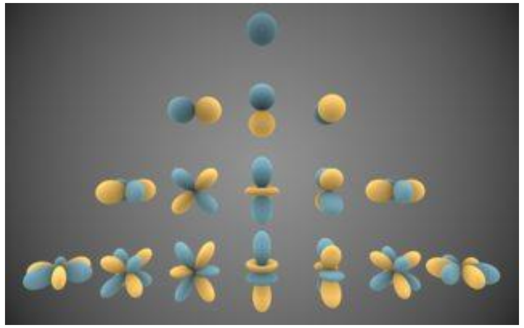
Antenna Pattern Characterization

- Antenna Patterns
  - Large Antenna Positioning System (LAPS)
  - Antenna Communication and Metrology Lab (ACML)
  - Sampling fields in space using VNA (frequency domain)



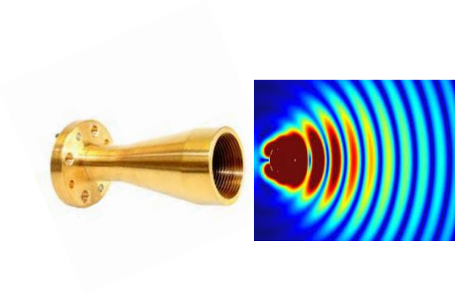
- Uncertainties
  - Calibration standards, impedances of components
  - Positioning errors, alignment errors, etc.

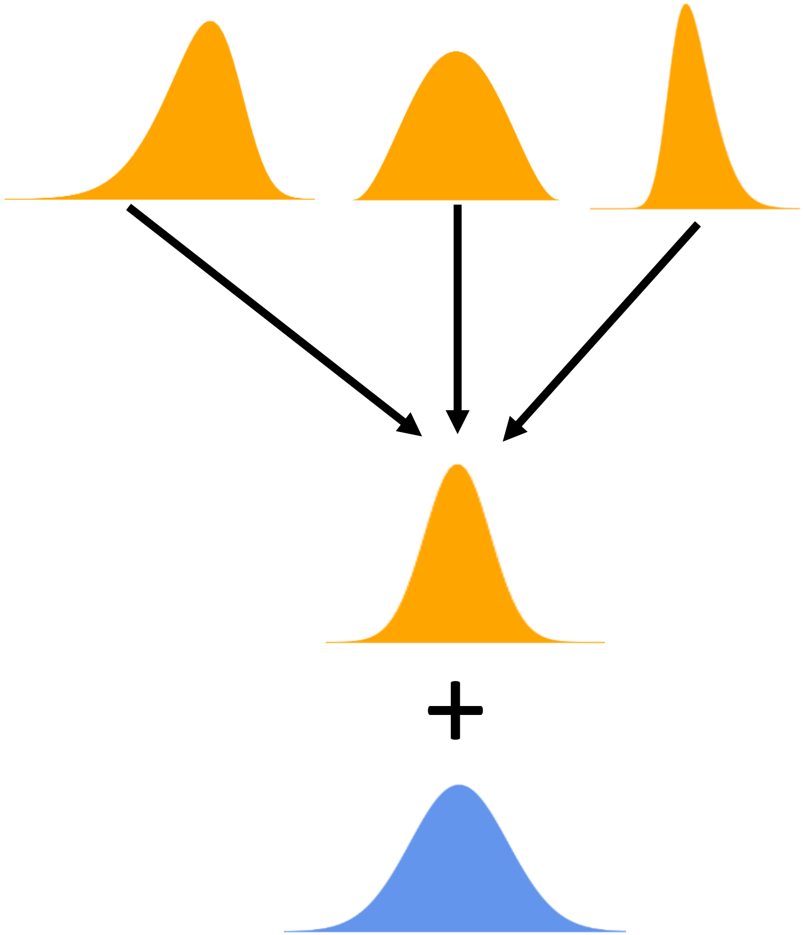
- OTA metrology requires antenna responses



Uncertainty From Repeated Measurements

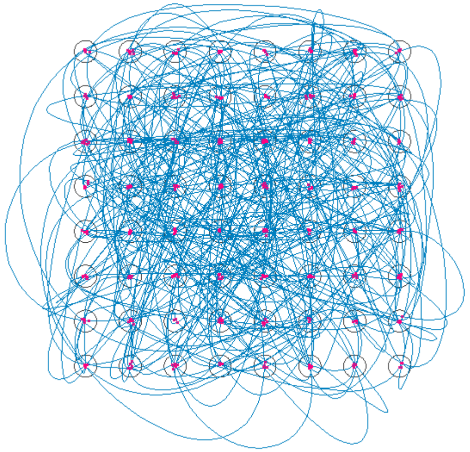
- Estimate uncertainty from multiple equivalent measurements
  - Capture uncertainties for which we don't have a model
  - Multiple different but equivalent measurements
  - Algorithm development with statisticians
    - [Frey et al. 2019, Jamroz et al. 2019]
- E.g. Channel characterization





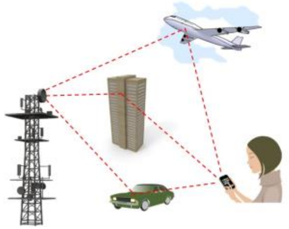
When Correlations Matter

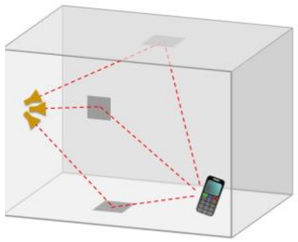
- When do you need to track correlations?
  - Debate in microwave engineering community
- Many cases of if/when/how correlations matter
  - Sometimes it won’t matter (EVM: Delay corrected)
  - Sometimes it will (Digital: Delay matters)
- Tracking correlations always handles these cases
  - IEEE Standard P1765
  - “Recommended Practice for Uncertainty in EVM”



Uncertainty Framework - Applications

- OTA multipath testbed
  - Prescribed multipath environment
  - 5G angle verification
- Customer photodiode calibrations
  - Correlated uncertainty data included
- Air Force oscilloscope calibrations
  - Provide with uncertainties

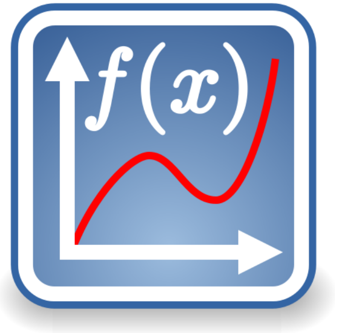




5G Millimeter-Wave Channel Model Alliance

Challenges for Uncertainty Analysis in CTL

- Complicated/unique systems
- Greater complexity in measurements
  - 1D → 3D or higher
  - Modeling/statistics/mathematics
  - Lots of data, computational resources, time
- Intuition for high-dimensional uncertainties
  - What does it mean?

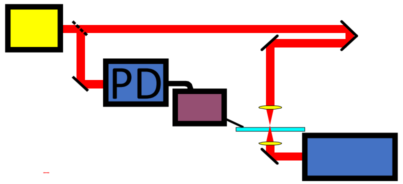


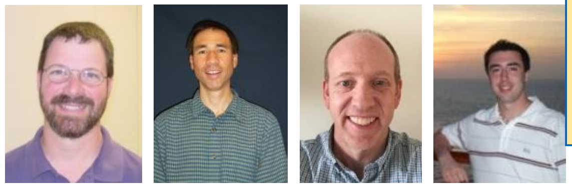
Final Thoughts

- Uncertainty analysis required for metrology
  - Quantifies how well we know measurement
  - Is an enabling technology
- Correlated uncertainty analysis → propagation through measurement chain
  - Maintain traceability and consistent uncertainties
  - NMIs around the world now recognize importance - following NIST lead
- Microwave Uncertainty Framework
  - Tracks correlated uncertainties through complicated transformations
  - CTL resource calculate uncertainties in RF measurements

Correlated Uncertainty Analysis

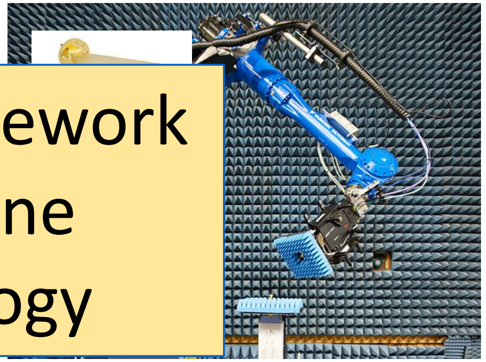
NIST Waveform Services





Vector Network Analyzer

Antennas



The Microwave Uncertainty Framework ties CTL measurements into one consistent package for metrology

Microwave Power

Download the Microwave Uncertainty Framework at https://www.nist.gov/services-resources/software/wafer-calibration-software