Traceability for Oscilloscopes and Oscilloscope Calibrators

…in relation to RF Voltage measurements

Paul C. A. Roberts
Fluke Precision Measurement

Introduction

- Scope cal was typically part of DCLF, but nowadays average scope is 1GHz bandwidth
  - Bandwidth of several GHz common
- Scope cal moving into RF & Microwave domain!
- Metrologists & Calibration Technicians have to deal with variety of high frequency considerations
  - Loading, Impedance matching, VSWR, etc
- Understanding how results are influenced and how scope cal methods address them can…
  - Simplify the task
  - Reduce errors
  - Improve uncertainty analysis

Topics

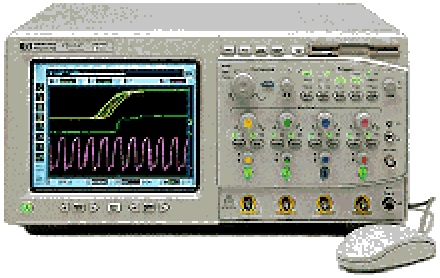
- Oscilloscope Architecture & Calibration Requirements Overview

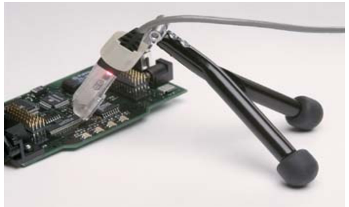
- Oscilloscope Vertical Accuracy & Bandwidth Calibration

- Oscilloscope Calibrator Calibration

Oscilloscopes

- Bandwidth from <100MHz to 70GHz
- Analog, Digital, Sampling
  - High impedance and matched inputs.
  - Waveform displays, cursor measurements, and signal analysis.
- Variety of high frequency probes available





LeCroy Active Probe

±8V - <2.5GHz

TekConnect probe

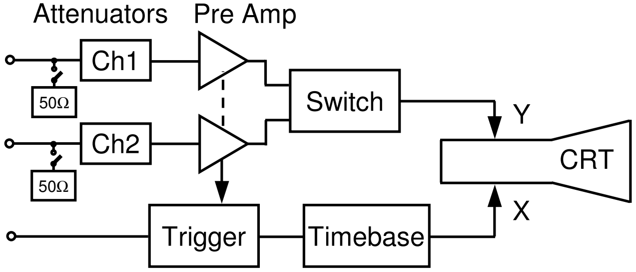
±1.75V - <4GHz

Agilent probe

±5V - <2.5GHz

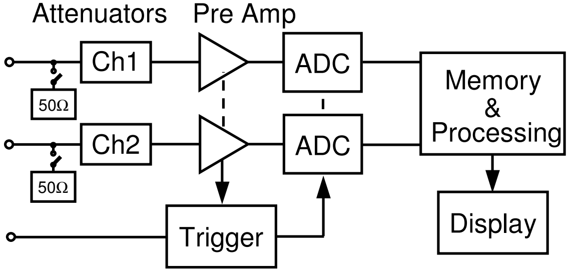
Architectures

- Analog 'Real Time': BW to 500MHz
  - Switched 1MΩ/50Ω inputs
  - 50Ω VSWR frequency dependence



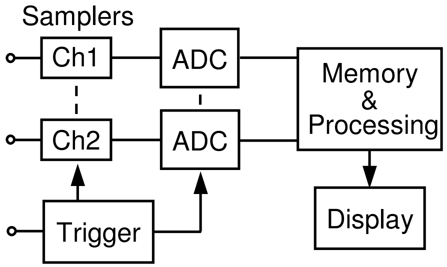
Block diagram of Analog Scope.

- Digital: BW to >10GHz
  - Switched & dedicated 50Ω inputs
  - Avoid aliasing!



Block diagram of Digital Scope.

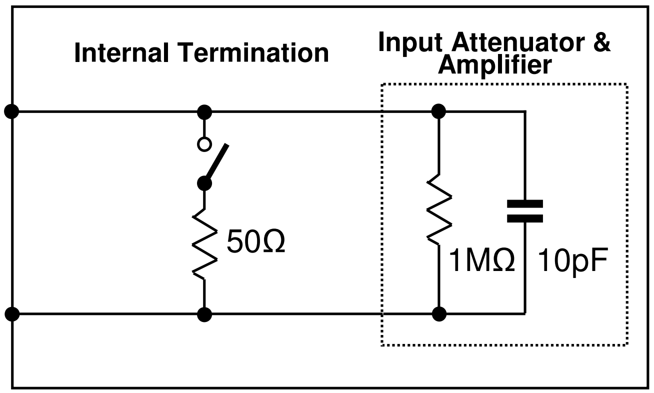
- Sampling: BW to 70GHz
  - 50Ω inputs
  - Reduced input signal range

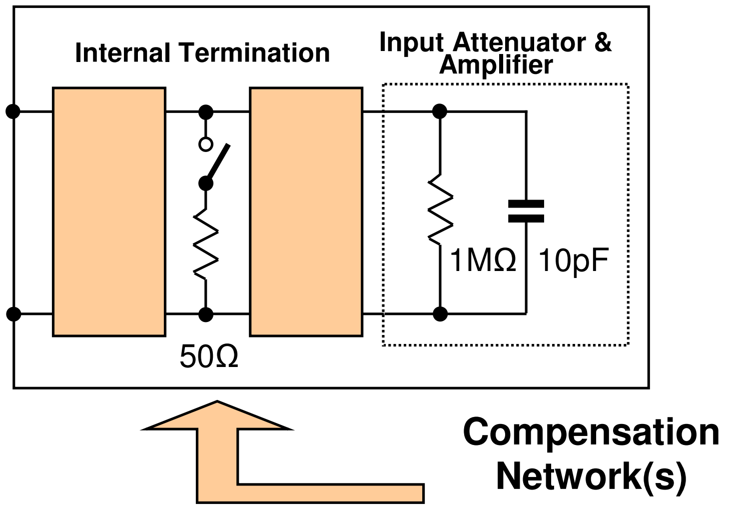


Block diagram of Sampling Scope.

Switched Input Impedance Scopes

- Scopes with 1MΩ and 50Ω input impedance
  - Single BNC connector, internal switching

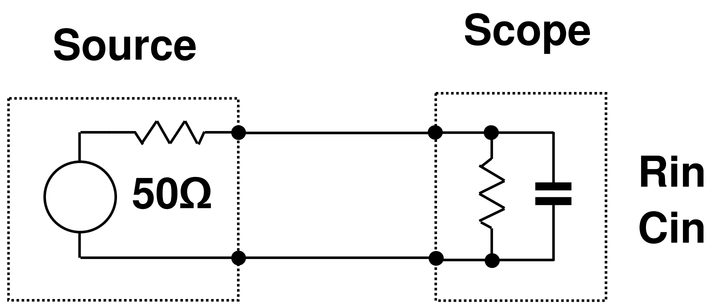


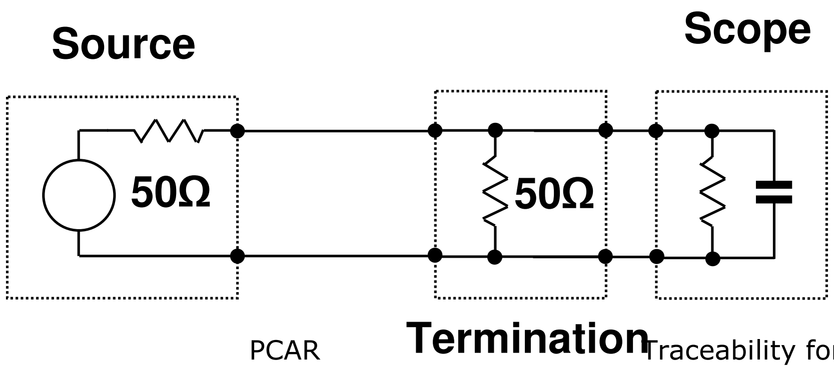


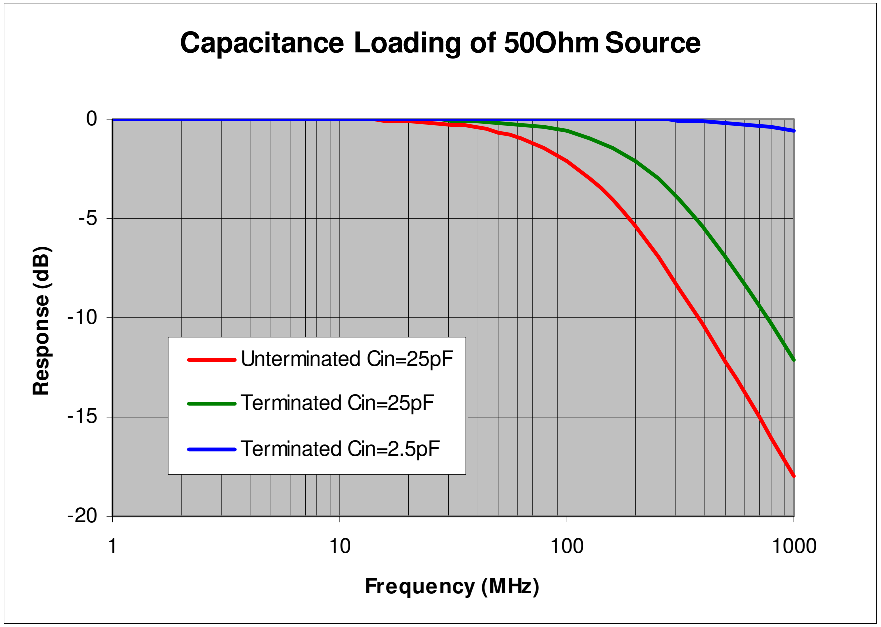
- **Input capacitance compromises 50Ω impedance**
- **Scope designs typically employ compensating networks, often inductive, to improve 50Ω**
  - **Some peaking/ringing may be observed**

Loading Effects

- Scope input impedance
  - Rin >>100kΩ, so negligible
  - Cin affects apparent BW





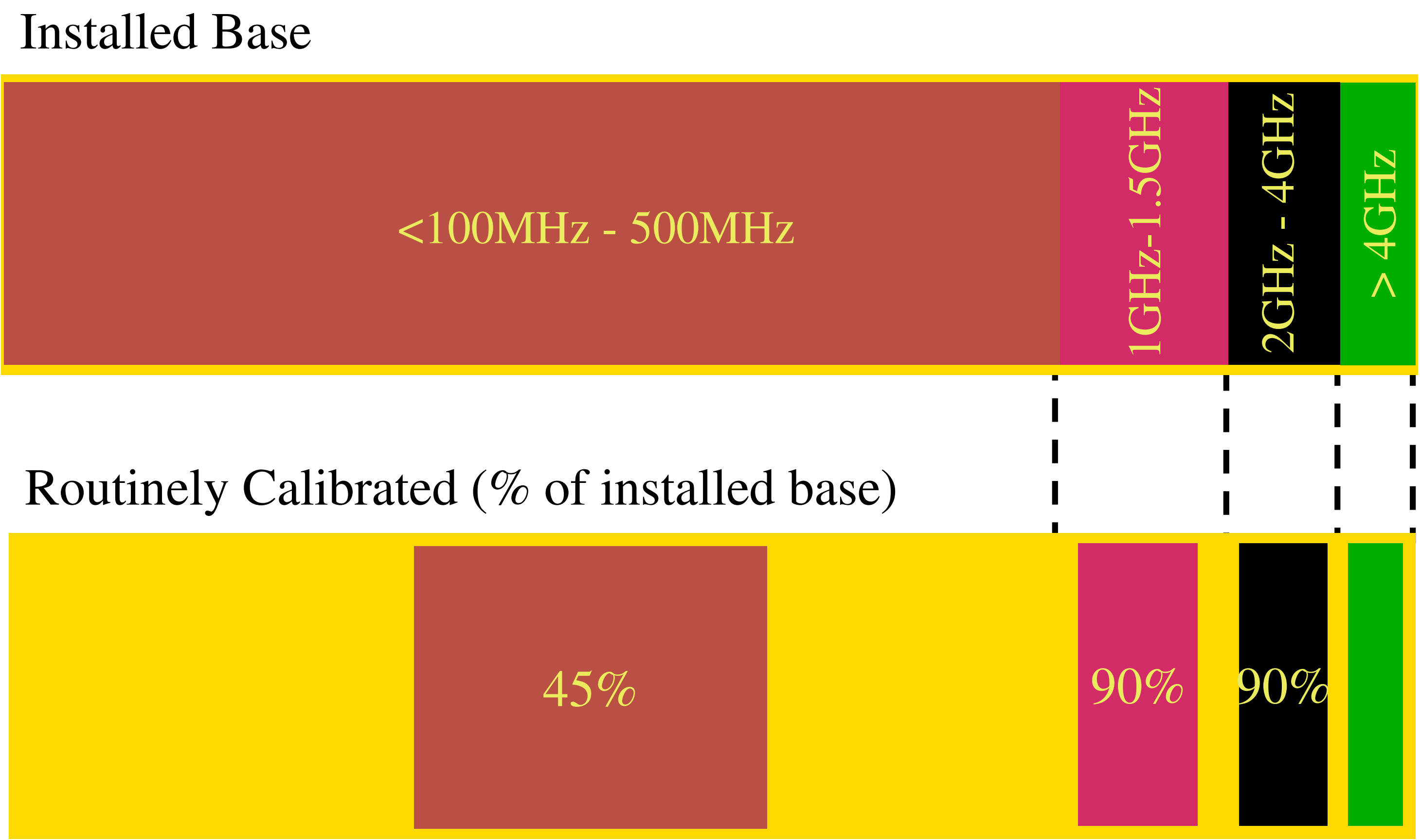


Unterminated with Cin = 25pF: BW 129MHz
(And voltage 2x expected value)

Terminated with Cin = 25pF: BW 257MHz

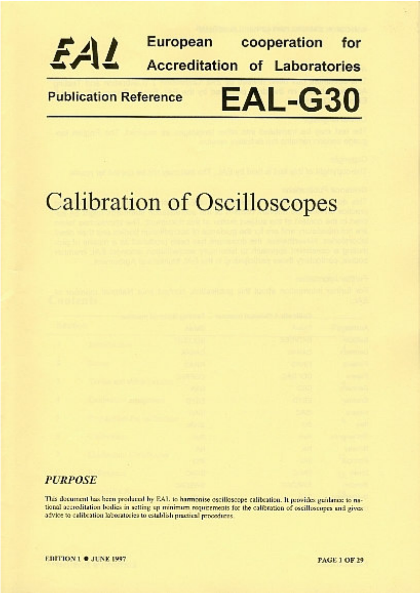
Terminated with Cin = 2.5pF: BW 2.6GHz

Oscilloscope Calibration Workload



Calibration Requirements

- Vertical deflection
- Bandwidth
- Rise-time/Aberration
- Horizontal/timebase
- Trigger
- Input Impedance
- Interchannel delay
- Jitter Analysis
- Effective Bits


EAL European cooperation for Accreditation of Laboratories

Publication Reference EAL-G30

Calibration of Oscilloscopes

PURPOSE

EDITION 1 • JUNE 1997

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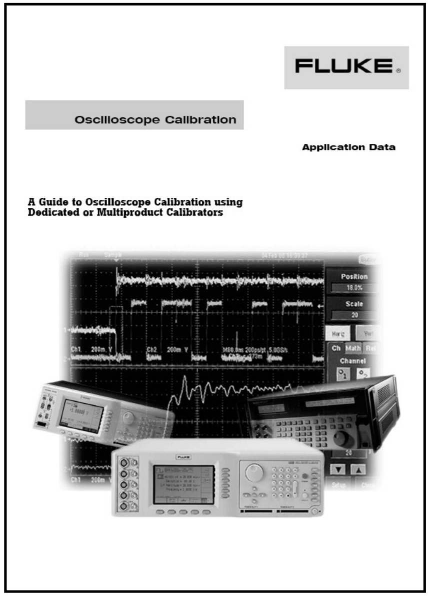
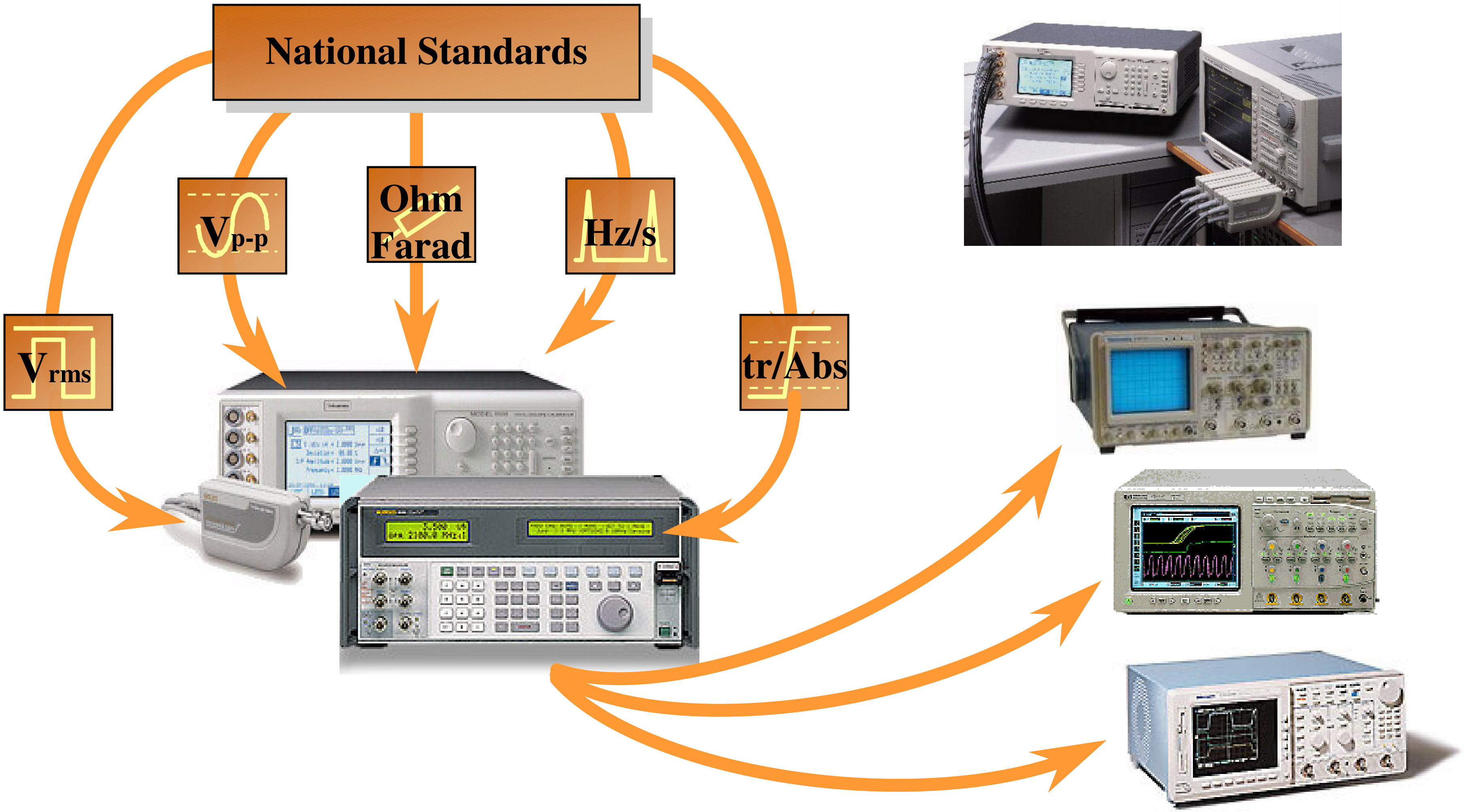


Calibration Solutions & Traceability



Oscilloscope Calibration Solutions

Bandwidth/Accuracy

6.4GHz
25ps/14GHz

2.1GHz

Dedicated Scope Calibrators
(Multi Channel)

Multi-Product Calibrators with scope cal options
(Single Channel)

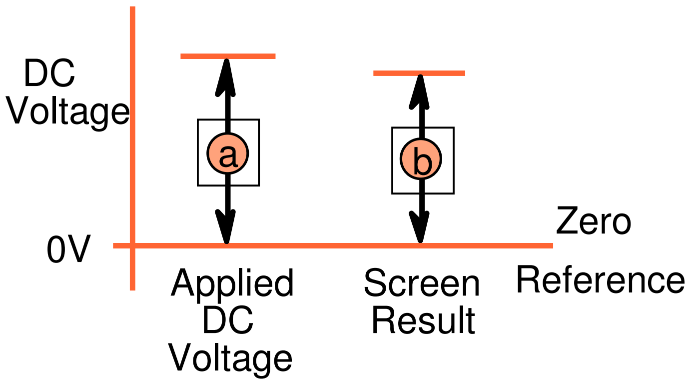
300/600/1100MHz

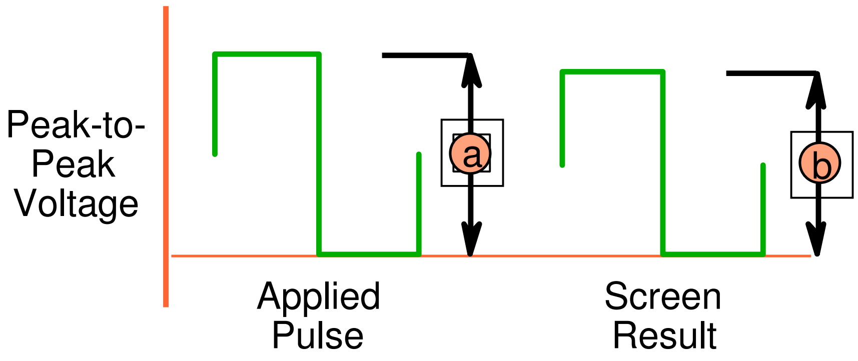
300/600MHz

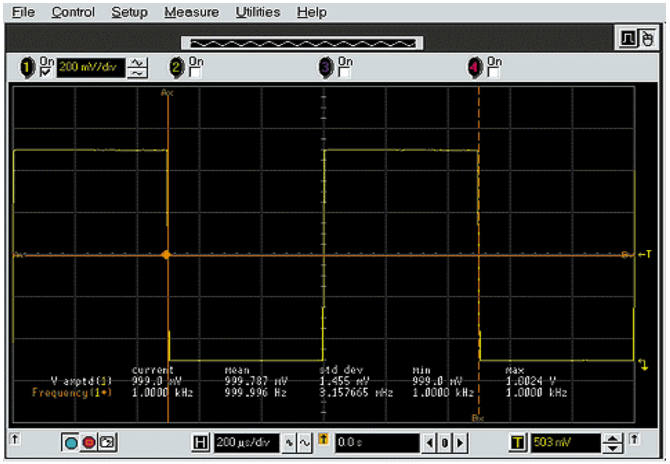
250/600MHz

Vertical Channel(s) - amplitude accuracy

- **Vertical Amplitude**
  - Vertical (Y) Gain Calibration
    1M Ohm & 50 Ohm
  - DC Level or LF Square



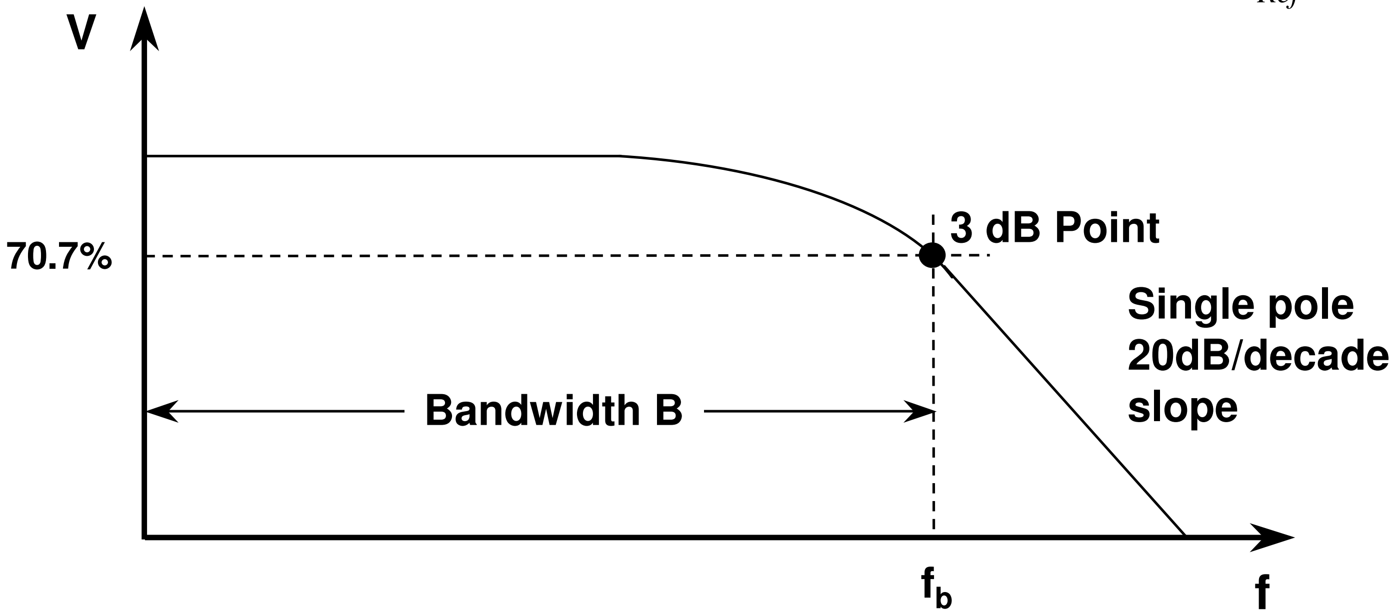




Vertical Channel(s) - Bandwidth

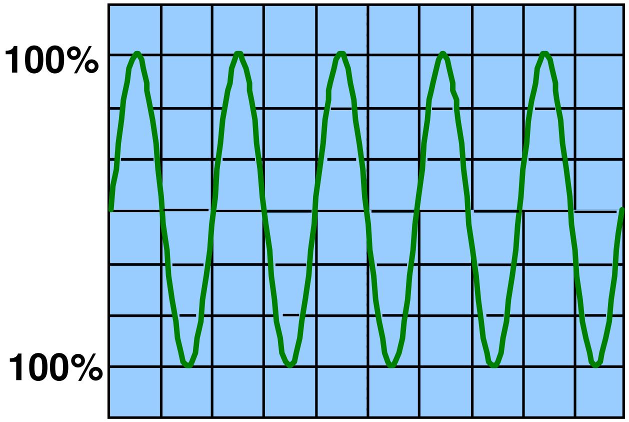
- Bandwidth definition:

Definition of -3dB Point: $$-3dB = 20\log_{10}\frac{V_{BwFreq}}{V_{Ref}}$$

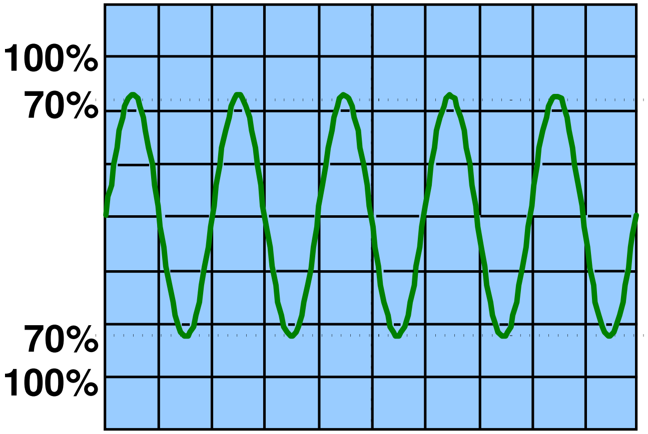


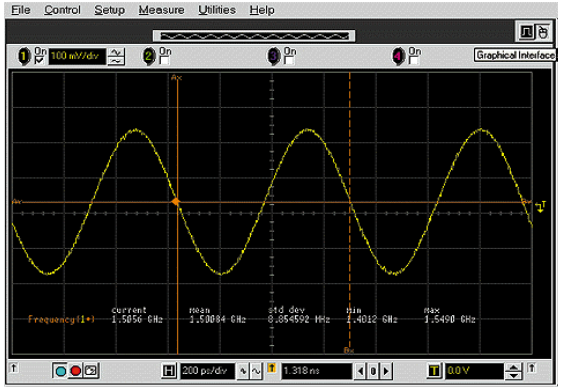
Bandwidth Testing - Leveled Sinewave

- Apply reference frequency



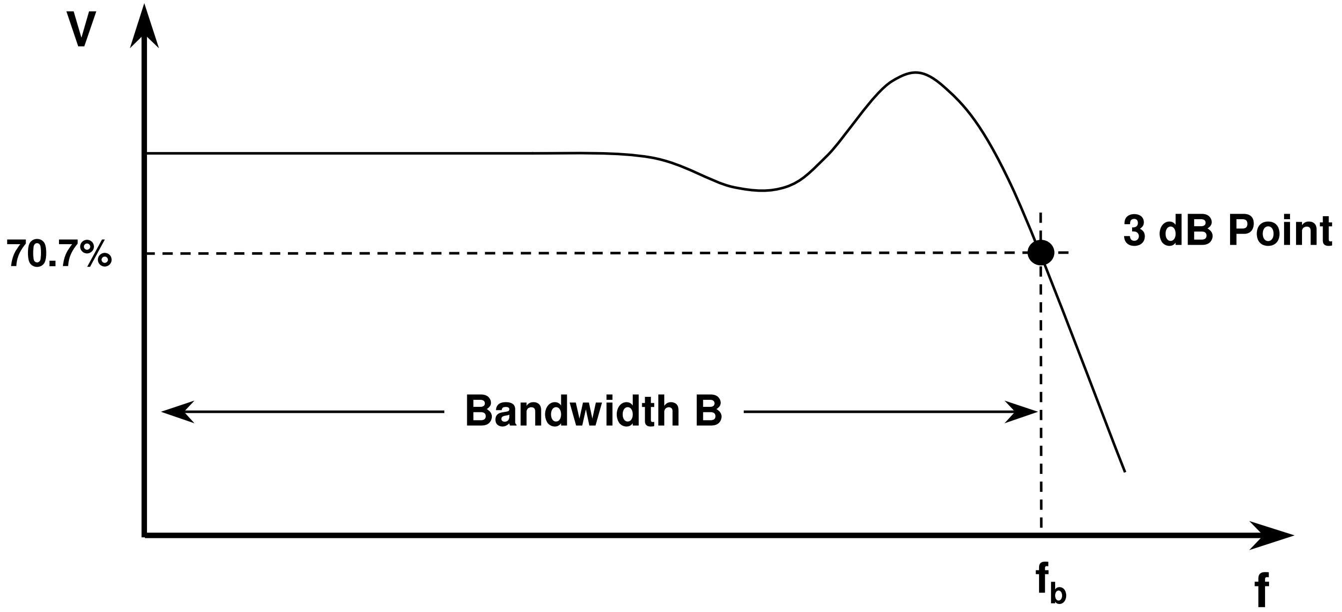
- Determine -3dB frequency
  - or check amplitude >-3dB at nominal BW frequency





Frequency Response

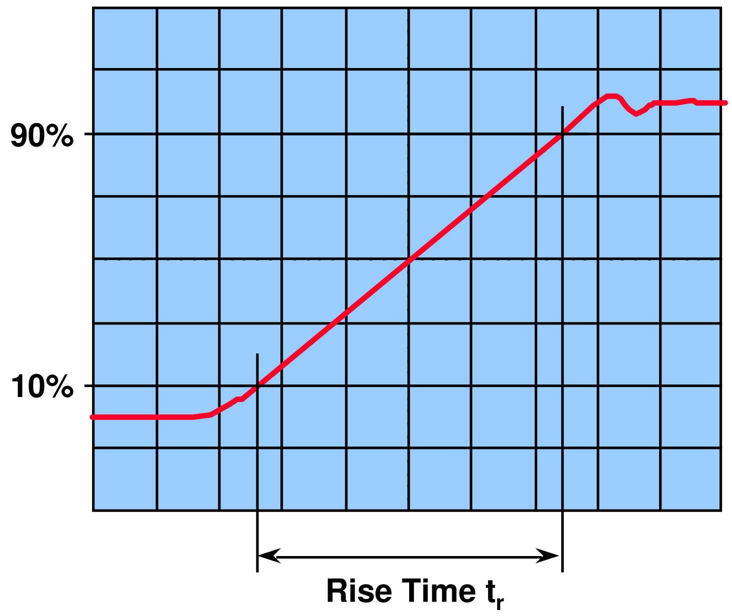
- Sinewave testing allows examination of peaks, dips and changing slopes



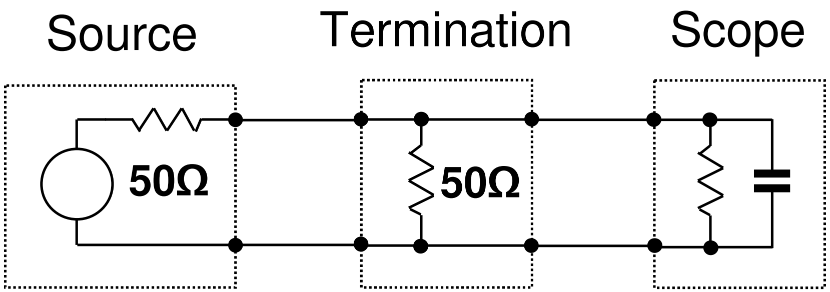
Bandwidth and Risetime

Bandwidth imputed from pulse response test:

- Bandwidth is related to risetime:
  - BW (MHz) = $350/t_r$ (ns)
  - If response is Gaussian
- Displayed risetime depends on applied edge risetime:
  - $t_r\,\text{display}^2 = t_r\text{uut}^2 + t_r\text{pulse}^2$

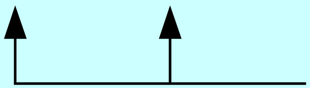


Non-50Ω Input Scopes

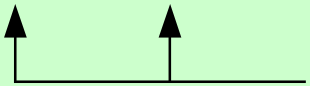


R_{IN} = 1MΩ, C_{IN} = 10pF – 25pF

Higher BW scopes tend to have lower C_{IN}



95XX calibrator heads: Short line and internal termination



58XX, 55XX & 9100 calibrators: Cable and external termination

- Scope input capacitance C_{IN} causes mismatch at high frequency
- Higher frequencies attenuated by C_{IN}
  - Reduces apparent bandwidth
  - Slows apparent risetime, generates reflections
- C_{IN} can also interact with transmission line
  - Other effects possible depending on line length, frequency, etc

Voltage Mismatch Uncertainty

Typical instrument VSWR performance

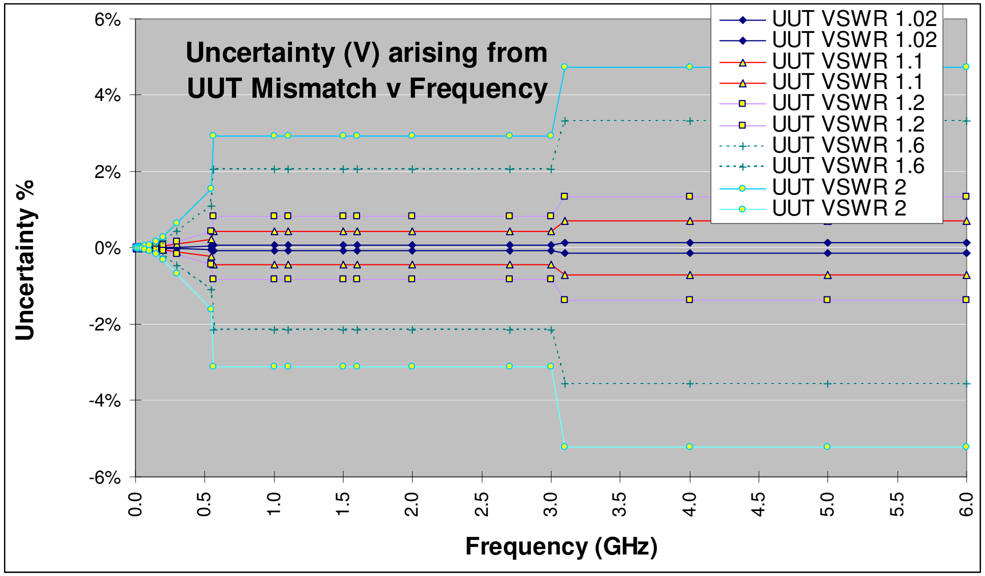
Calibrator:

- **Eg: Fluke 9500B with 9560**
  - **VSWR: <1.1 to 550MHz, <1.2 550MHz to 3GHz, <1.35 3GHz to 6GHz**
  - **Chart shows mismatch error with various UUT VSWRs**

Scopes:

- **Typical 1GHz scope**
  - **VSWR <1.5 to 1GHz**
- **Typical 4-6GHz scopes**
  - **VSWR <1.1 to 2GHz**
  - **<1.3 4GHz to 6GHz**
  - **some <2.0 at 4GHz**
- **Can be worse on more sensitive ranges**

  Eg: TDS6604 typical VSWR specs
  - **1.3 at 6GHz for >100mV/div**
  - **2.5 at 6GHz for <100mV/div**



Note: Plots are slightly asymmetric – use larger value as worst case ± uncert.

Uncertainty Analysis Considerations

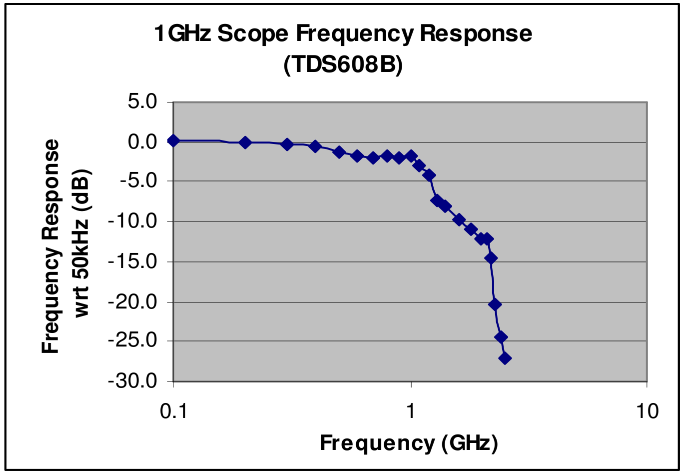
- Scopes are calibrated in terms of voltage not power, so express mis-match error in terms of voltage

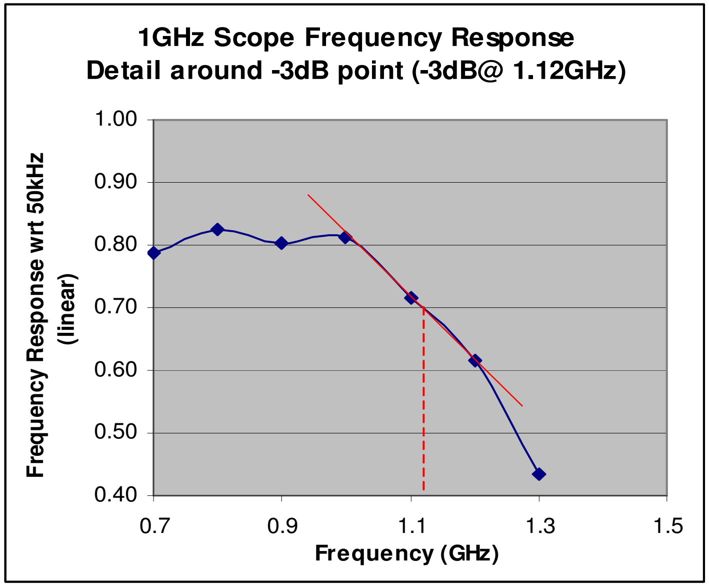
$$Voltage\ Error = \left\{ 1 - \frac{1}{\left(1 \pm |\Gamma_S||\Gamma_L|\right)} \right\} \times 100\%$$

- Alternatively, if errors are small use half the power error
  - Voltage proportional to square root of power
  - Sensitivity coefficient is ½
- Treat mis-match errors as one of the Type B (systematic) contributions
- Mis-match errors have U-shaped distribution
- Divide by √2 to express at standard uncertainty

Converting to BW Uncertainty

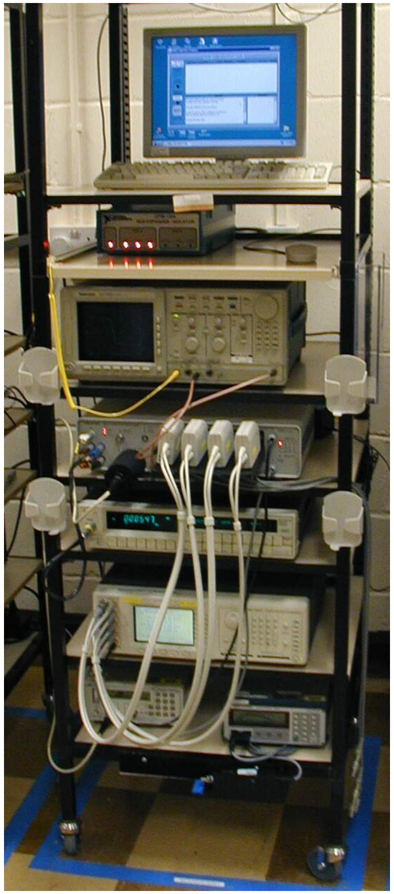
- Example of typical 1GHz scope measured with 9500B and 9530
- Plot opposite shows frequency response
- Displayed amplitude reduces to 0.707 of LF value at 1.121GHz = 3dB BW freq

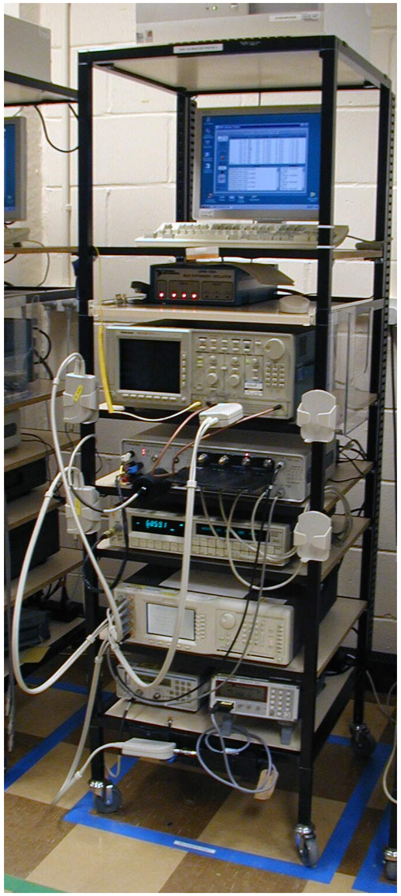




- Slope of response at 1.1GHz is 1.02/GHz
  - From slope of tangent drawn on linear plot opposite at -3dB point
- More simply, calculate slope from frequencies either side of 3dB point
  - Say 1.0 and 1.2 GHz, giving slope = 1.00/GHz
- Convert amplitude uncertainty into frequency uncertainty
  - Divide the amplitude uncertainty by the frequency response slope

Scope Calibrator Cal Systems





9500 Product Series

Factory Calibration Systems

Scope Calibrator Calibration

- Calibrating levelled sine Peak to Peak voltage up to 6GHz

- Conversion from RMS to pk-pk
- Absolute RMS voltage measurement up to 100kHz with AC Voltage measurement standard
- Flatness measurement from 100kHz up to 6GHz with RF power meter & sensor

Example flatness uncertainties for 2.5Vp/p to 5Vp/p at 1GHz				
Power Meter	Calibration*	B	95%CL	1.5%
	1Yr Stability	B	Rect	0.5%
	±3°C Tempco	B	95%CL	0.015%
	Linearity & Resolution	B	Rect	0.501%
Mismatch		B	U	0.2%
Distortion		B	Rect	1.0%
Combined Noise		A	1σ	0.075%
Connector Repeatability		A	1σ	0.1%
TOTAL (Expanded Unc)			95%CL	1.62%

Tables shows individual type A and B uncertainty contributions. Total is expanded uncertainty after combination in accordance with UKAS M3003.

* Power Meter Cal contribution is power uncertainty from cal cert.

Photograph showing setup for up to 3.2GHz levelled sine calibration against power meter. 6GHz head has SMA connector, and is calibrated with different sensor.

Conclusions

The design of dedicated oscilloscope calibration solutions minimise the effect of impedance mis-matches, but calibration technicians and metrologists should be aware of their impact:

- The effect of scope input VSWR can easily be assessed and included as an uncertainty contribution when making bandwidth tests.
- Mis-match effects should be considered as having a U-shaped distribution for uncertainty analysis purposes, and be treated with a coverage factor of $\sqrt{2}$ when converting to standard uncertainty.
- Mis-match effects can also influence pulse testing results by causing reflections, and excessive observed aberrations or anomalies may be indicative of scope input damage.

Useful references

- Fluke Application Note
  - **A Guide to Oscilloscope Calibration using Dedicated or Multiproduct Calibrators**

    Produced by Fluke to accompany the oscilloscope calibrator products Provides guidance for users covering common oscilloscope calibration requirements and calibration procedures.

  Go to www.fluke.com/us/usen/products/9500B, select application notes to download.

- European Cooperation for Accreditation Of Laboratories Publication
  - **EAL Guide EA-10/07 Calibration of Oscilloscopes (previously EAL-G30)**

    Produced by EAL to harmonise oscilloscope calibration... Provides guidance to national accreditation bodies setting up minimum requirements for oscilloscope calibration and gives advice to calibration laboratories to establish practical procedures... Published June 1997.

  Go to www.european-acceditation.org, select documents menu to download.

- Aeroflex/IFR Booklet
  - **RF Datamate Booklet**

    Produced by the signal sources group… A 76-page guide to commonly used RF data, measurement methods, power measurement uncertainties, etc.….

  Go to www.Aeroflex.com/rfdatamate to order free copy online.

- Agilent Technologies Application Note
  - **Fundamentals of RF and Microwave Power Measurements (Part 3)**
    Power Measurement Uncertainty per International Guides
    AN 1449-3, literature number 5988-9215EN

    Part 3 discusses the all-important theory and practice of expressing measurement uncertainty, mismatch considerations, signal flowgraphs, ISO 17025, and examples of typical calculations……

  Go to www.agilent.com, search for AN1449-3 to download.