

# Welcome to

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*Santa Clara Convention Center*



# VNA Calibration Essentials for Practicing Engineers

Travis Ellis, Samtec

*Jason Sia Samtec, Istvan Novak Samtec, Pete Pupalaikis Nubis, Julian Lechner Samtec, Gustavo Blando Samtec*



# SPEAKER

## Travis Ellis

*Signal Integrity Engineer, Samtec*

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*Travis Ellis* is a signal integrity practitioner working with customers to successfully deliver their systems to market. He believes signal integrity is critical for success. He has delivered many innovative solutions across multiple industries. He holds a mechanical engineering degree from Portland State University. Travis also enjoys the outdoors and the opportunity to work with many talented peers.



# Outline

## Introduction

- About the Nomenclature

- Instrumentation used

- Summary of SOLT and SOLR calibration processes

- Typical misconceptions and false expectations about calibrations

- Some calibration errors

- External calibration

- Summary and conclusions



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Summary of SOLT and SOLR Calibration Processes

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External calibration

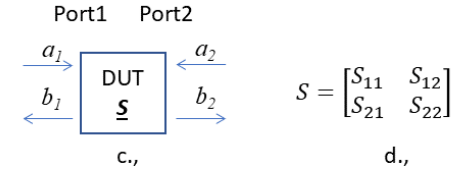
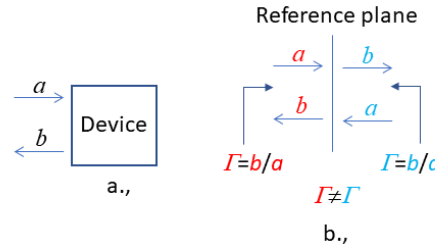
Summary and conclusions



# Introduction - About the Nomenclature

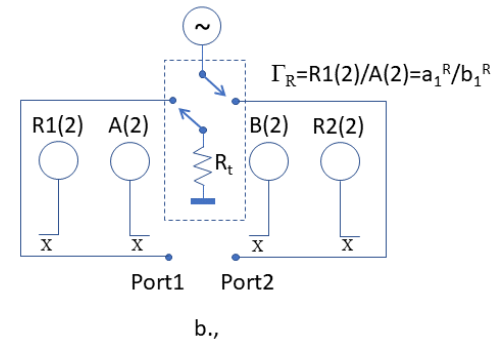
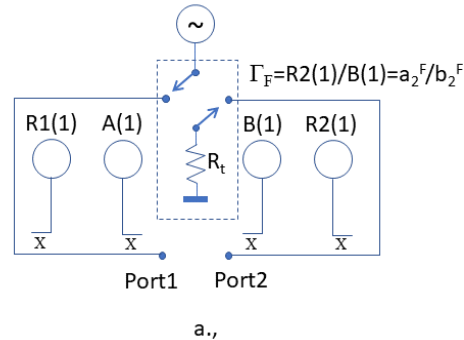
- SOLT

- Short, open, load, thru (known thru)



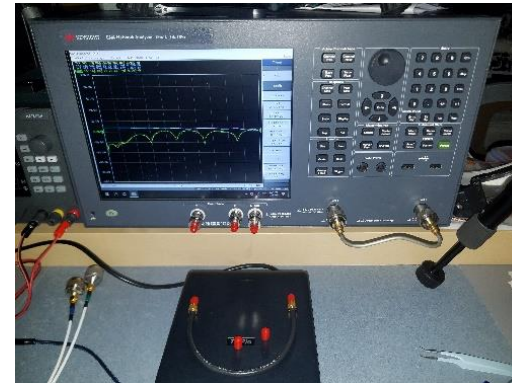
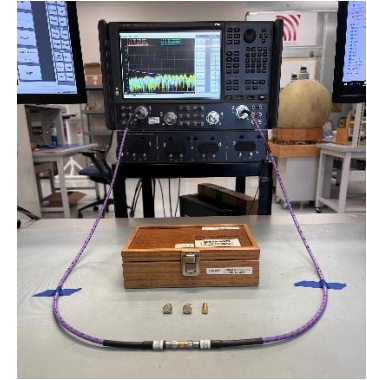
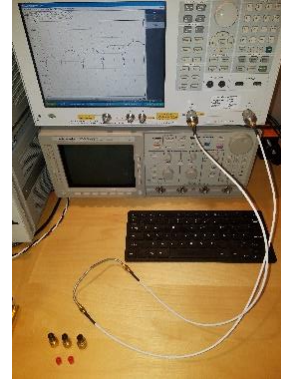
- SOLR

- Short, open, load, reciprocal thru (unknown thru)



# Introduction - Instrumentation & Software Used

- VNA
  - Keysight
    - *Economy series - E5061B (2MHz – 3GHz, 1500pts)*
    - *PNA series – N5227B (10MHz – 67GHz, 6700pts)*
- Calibration kit
  - Keysight
    - *85052C (with E5061B)*
    - *85056D (with N5227)*
    - *85058B (with N5227)*
- Phase-stable cables
- *SignalIntegrity* software



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# VNA Calibration and DUT Calculation

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} \frac{\hat{S}_{11}-E_{D1}}{E_{R1}} & \frac{\hat{S}_{12}-E_{X12}}{E_{T12}} \\ \frac{\hat{S}_{21}-E_{X21}}{E_{T21}} & \frac{\hat{S}_{22}-E_{D2}}{E_{R2}} \end{pmatrix} \cdot \begin{pmatrix} 1 + E_{S1} \frac{\hat{S}_{11}-E_{D1}}{E_{R1}} & E_{L12} \frac{\hat{S}_{12}-E_{X12}}{E_{T12}} \\ E_{L21} \frac{\hat{S}_{21}-E_{X21}}{E_{T21}} & 1 + E_{S2} \frac{\hat{S}_{22}-E_{D2}}{E_{R2}} \end{pmatrix}^{-1}$$

Term	Name
$E_{Dp}$	directivity term for port p
$E_{Sp}$	source-match term for port p
$E_{Rp}$	reverse-transmission term for port p
$E_{Xop}$	crosstalk term for port o when port p driven
$E_{Top}$	forward-transmission term for port o when port p driven
$E_{Lop}$	load-match term for port o when port p driven

The goal of calibration is to determine the 12 *error terms* so that raw s-parameters ( $\hat{S}$ ) can produce the correct DUT s-parameters ( $S$ )



# VNA Calibrations and Raw S-parameters

$$\hat{\mathbf{S}} = \begin{pmatrix} b_{1f} & b_{1r} \\ b_{2f} & b_{2r} \end{pmatrix} \cdot \begin{pmatrix} a_{1f} & 0 \\ 0 & a_{2r} \end{pmatrix}^{-1} = \begin{pmatrix} \frac{b_{1f}}{a_{1f}} & \frac{b_{1r}}{a_{2r}} \\ \frac{b_{2f}}{a_{1f}} & \frac{b_{2r}}{a_{2r}} \end{pmatrix}$$

This is what the VNA wants to give you

$$\hat{\mathbf{S}} = \begin{pmatrix} b_{1f} & b_{1r} \\ b_{2f} & b_{2r} \end{pmatrix} \cdot \begin{pmatrix} a_{1f} & a_{2f} \\ a_{1r} & a_{2r} \end{pmatrix}^{-1} = \begin{pmatrix} \frac{b_{1f}}{a_{1f}} & \frac{b_{1r}}{a_{2r}} \\ \frac{b_{2f}}{a_{1f}} & \frac{b_{2r}}{a_{2r}} \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{a_{1r}}{a_{2r}} \\ \frac{a_{2f}}{a_{1f}} & 1 \end{pmatrix}^{-1}$$

This is what is actually going on

Switch-term correction

When performing your own VNA calibrations, you need to be careful in interpreting what the VNA is providing

# SOLT and SOLR

- Eight of the twelve error terms are determined by application of the short, open and load standard.
- The final four are determined by application of the thru standard.
- For SOLT, the error terms don't depend on switch-term correction.
- SOLR Does!

In SOLR, the remaining error terms are determined from a raw measurement of the thru with no knowledge of the standard (other than it is reciprocal)

$$\hat{\mathbf{S}}_t = \begin{pmatrix} \hat{S}_{tpp} & \hat{S}_{tpo} \\ \hat{S}_{top} & \hat{S}_{too} \end{pmatrix} \quad \frac{\hat{S}_{tpo} - E_{Xpo}}{\hat{S}_{top} - E_{Xop}} = p$$

$$E_{Top} = \frac{\sqrt{E_{Rp}} \cdot \sqrt{E_{Ro}}}{p} \quad E_{Tpo} = \sqrt{E_{Rp}} \cdot \sqrt{E_{Ro}} \cdot p$$
$$E_{Lop} = E_{So} \quad E_{Lpo} = E_{Sp}$$



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**Typical Misconceptions and False Expectations about Calibrations**

Some Calibration Errors

External Calibration

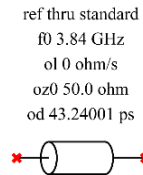
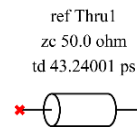
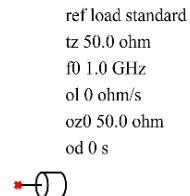
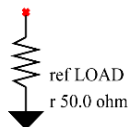
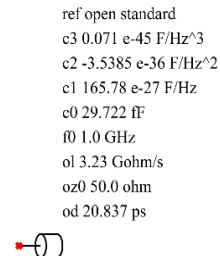
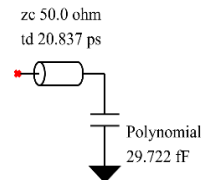
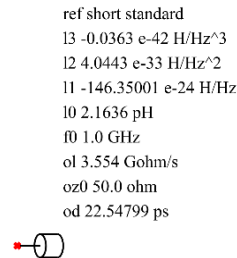
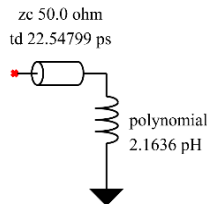
Summary and Conclusions



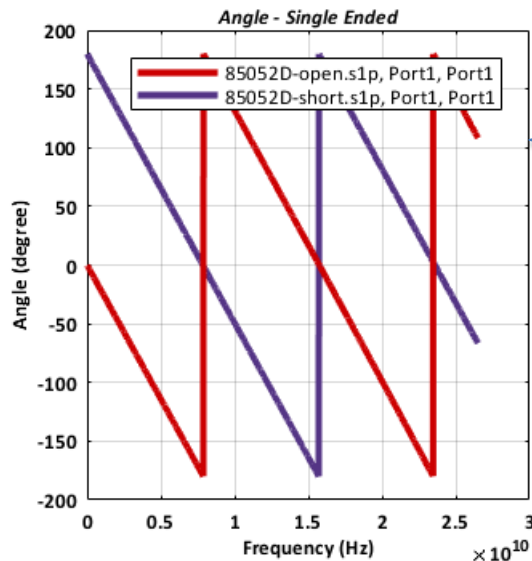
# Typical Misconceptions and False Expectations about Calibration

- No calibration standard are ideal
  - Non-ideal nature is specified in the calibration standard definitions supplied with the calibration kits
- Remeasuring the calibration standards after calibration will produce the calibration standard as defined
  - The reproduction of the calibration standard is not enough to guarantee a proper calibration

The load is usually specified as perfect

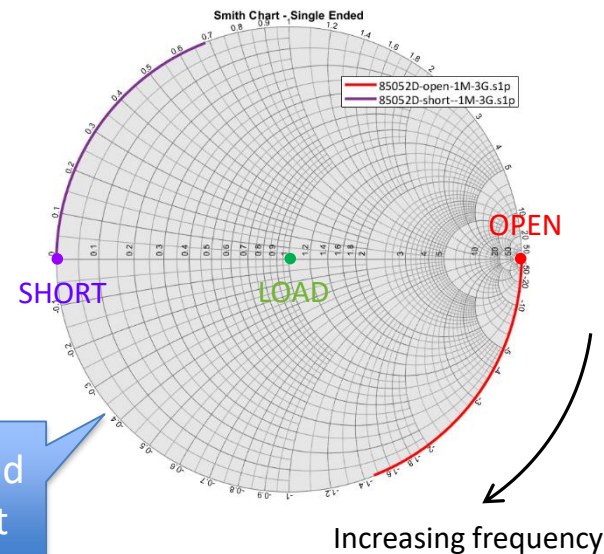


# Typical Misconceptions and False Expectations about Calibration

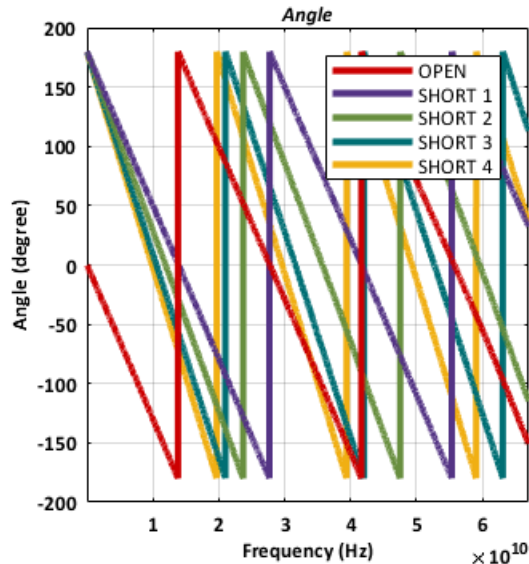


Calculated phase of 85052C open and short standards

Calculated 85052C open and short standard Smith chart

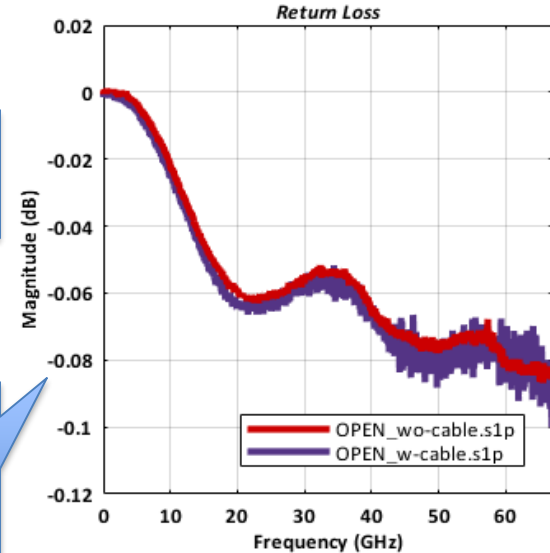


# Typical Misconceptions and False Expectations about Calibration



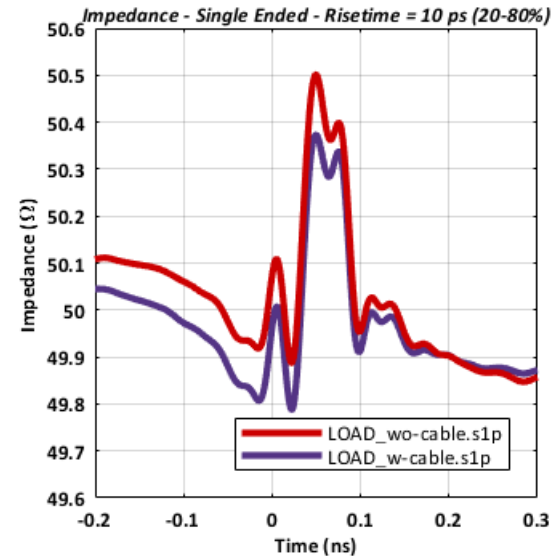
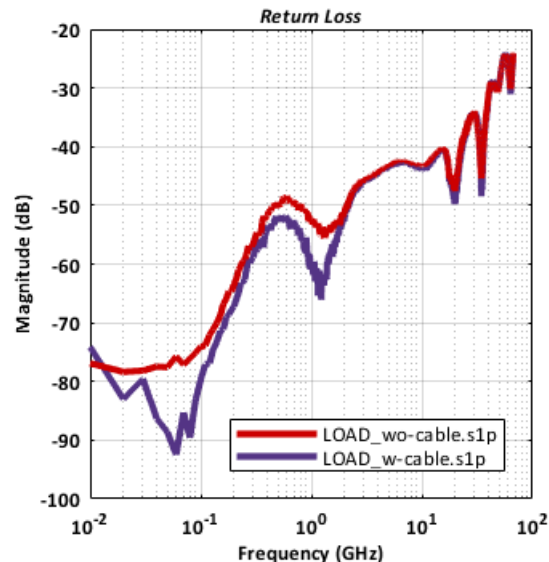
Measured phase of open standard and four short standards from 85058B

Measured return loss comparison of open standard at the VNA port and at the end of the VNA cable



# Typical Misconceptions and False Expectations about Calibration

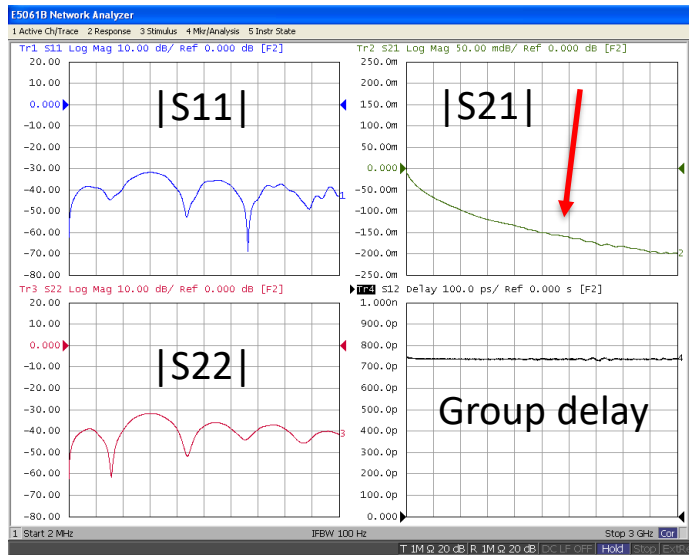
A file-defined load measured as DUT after calibration with and without cable in the calibration loop.



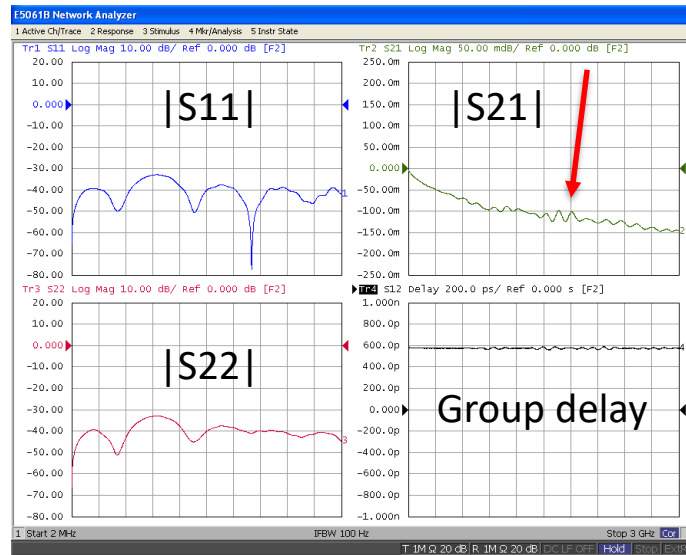


# Typical Misconceptions and False Expectations about Calibration

Measured S parameters of a well-matched DUT



Calibrated with correct thru definition

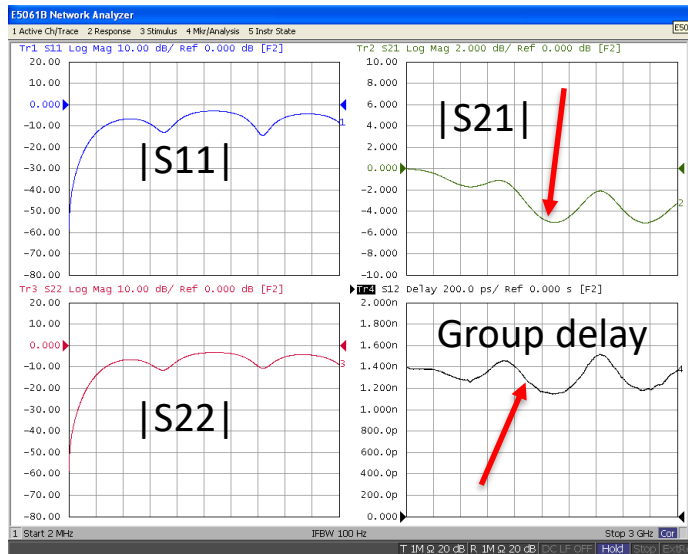


With incorrect thru definition

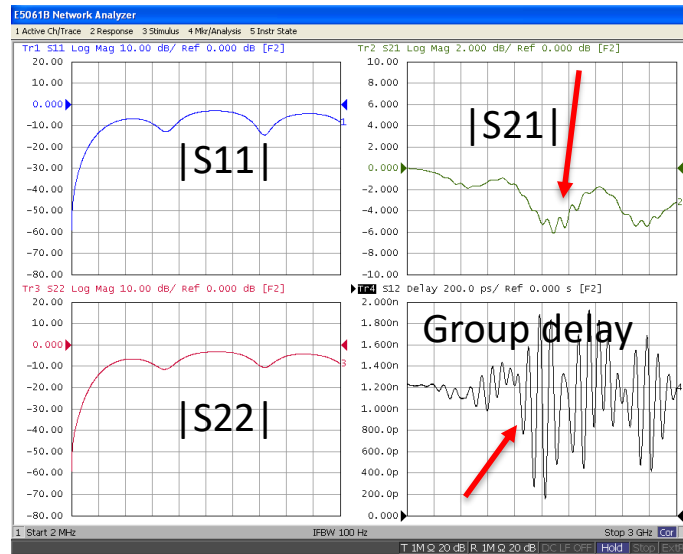


# Typical Misconceptions and False Expectations about Calibration

Measured S parameters of a highly reflective DUT



With the correct thru definition

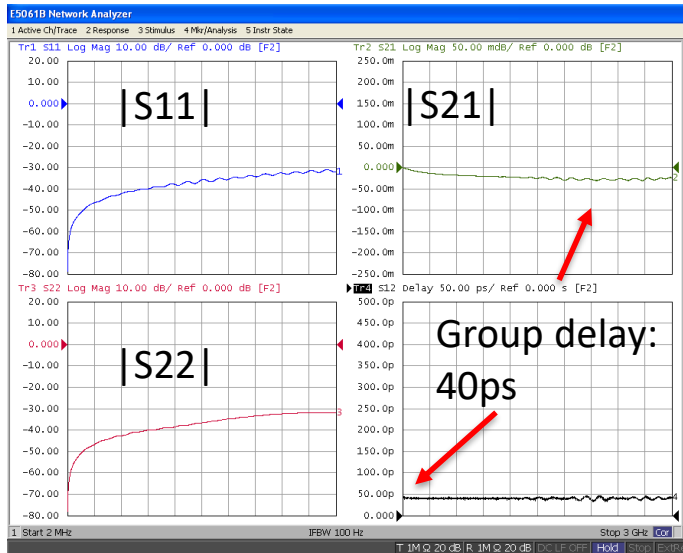


With the incorrect thru definition

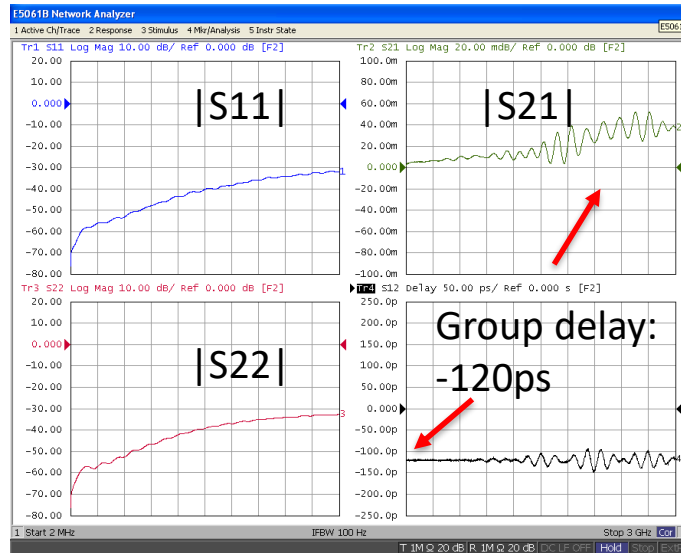


# Typical Misconceptions and False Expectations about Calibration

Measured S parameters of a female-female adaptor with 40ps delay



With the correct thru definition

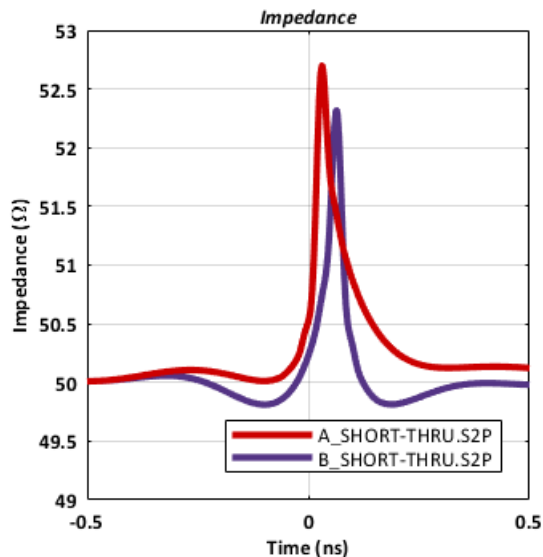


With the incorrect thru definition

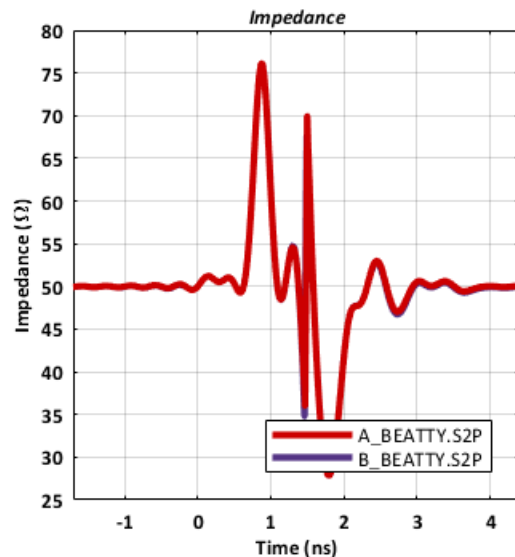


# Typical Misconceptions and False Expectations about Calibration

TDR response of a 40ps female-female adapter with correct (red) and incorrect (purple) THRU definition



TDR response of a highly reflective trace with correct (red) and incorrect (purple) THRU definition



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## **Some Calibration Errors**

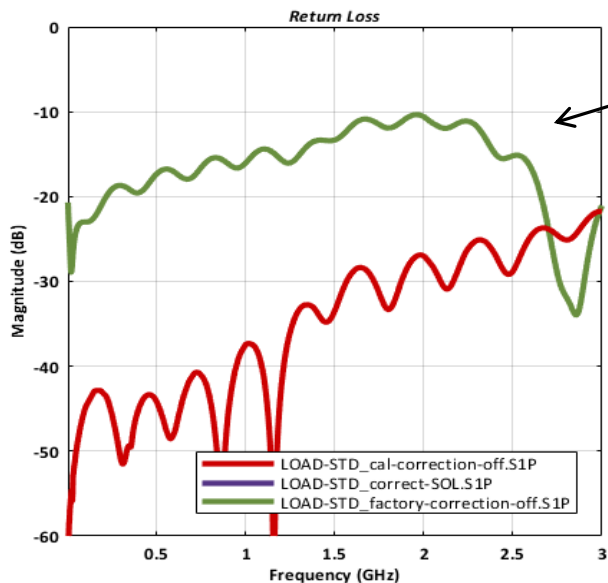
External Calibration

Summary and Conclusions



# Calibration Errors: Reflection

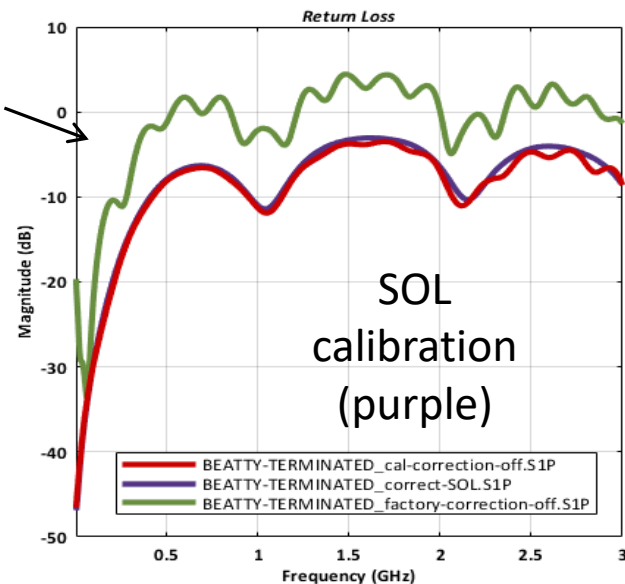
Load standard remeasured



Factory  
correction  
off (green)

Calibration  
correction  
off (red)

Reflective trace measured

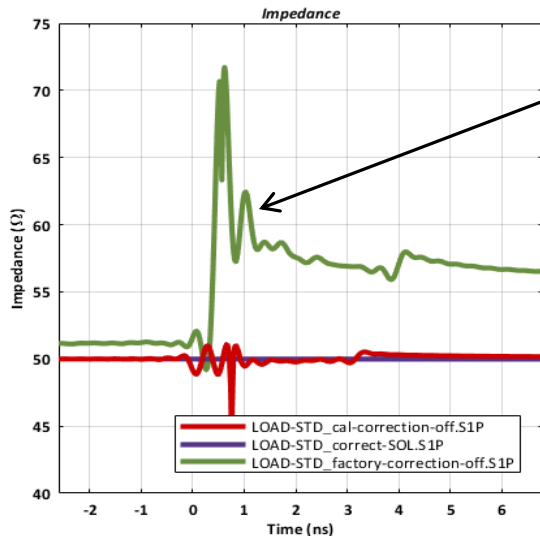


SOL  
calibration  
(purple)



# Calibration Errors: Reflection

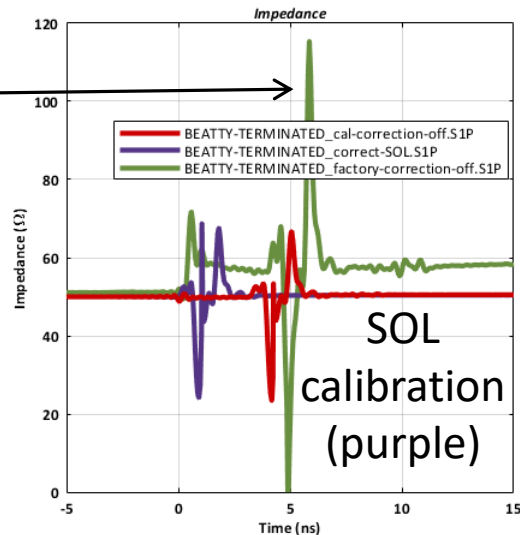
TDR of load standard



Factory  
correction  
off (green)

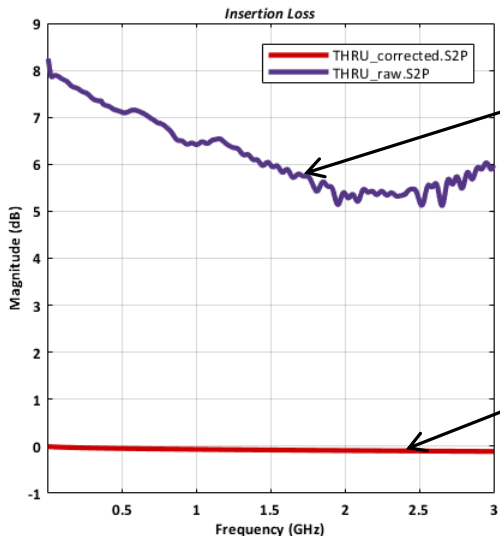
Calibration  
correction  
off (red)

TDR of reflective trace



# Calibration Errors: Two-port IL

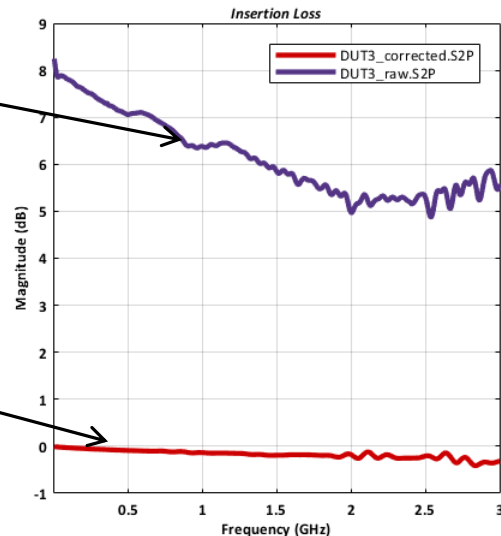
IL of THRU standard



Factory  
correction  
off (purple)

SOLT  
calibration  
(red)

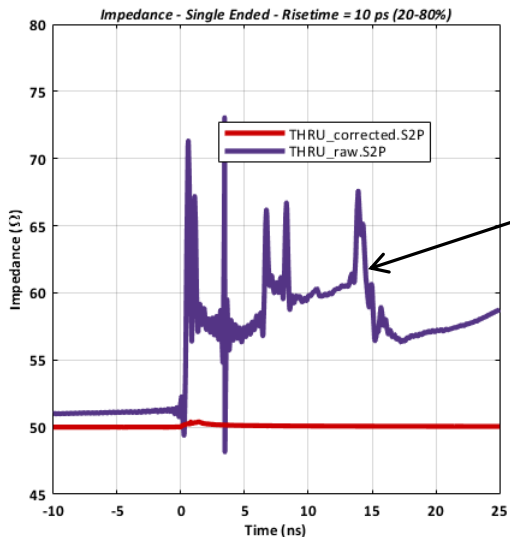
IL of 10" semirigid coax





# Calibration Errors: Two-port TDR

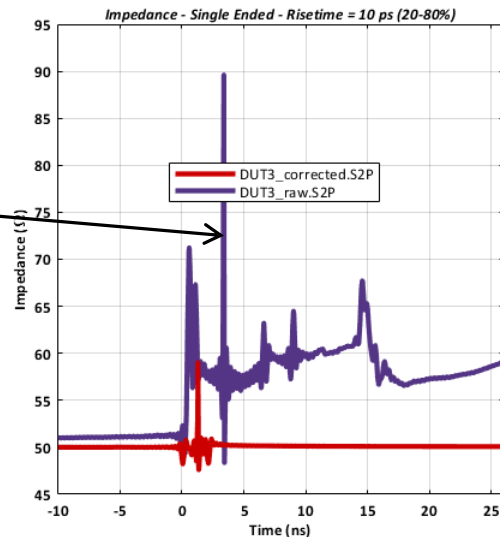
TDR of THRU standard



Factory  
correction  
off (purple)

SOLT  
calibration  
(red)

TDR of 10" semirigid  
coax



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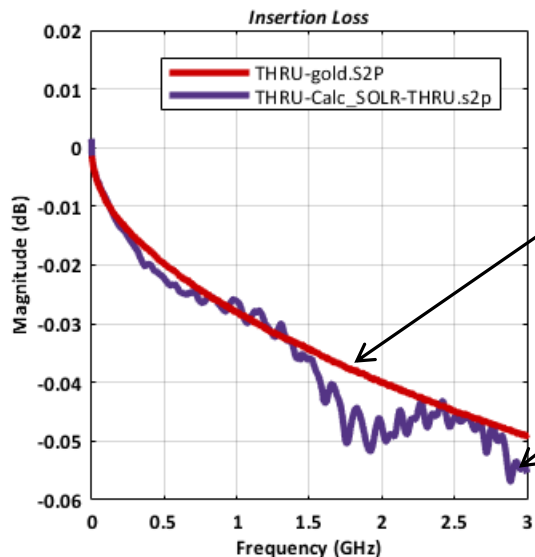
## **External Calibration**

Summary and Conclusions



# External Calibration: 2MHz – 3GHz

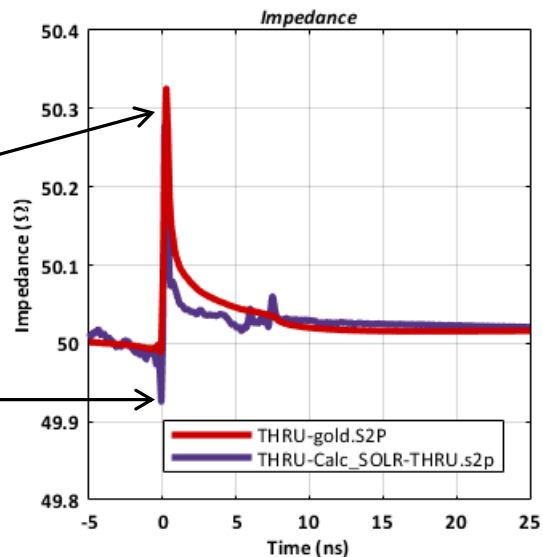
IL of THRU standard



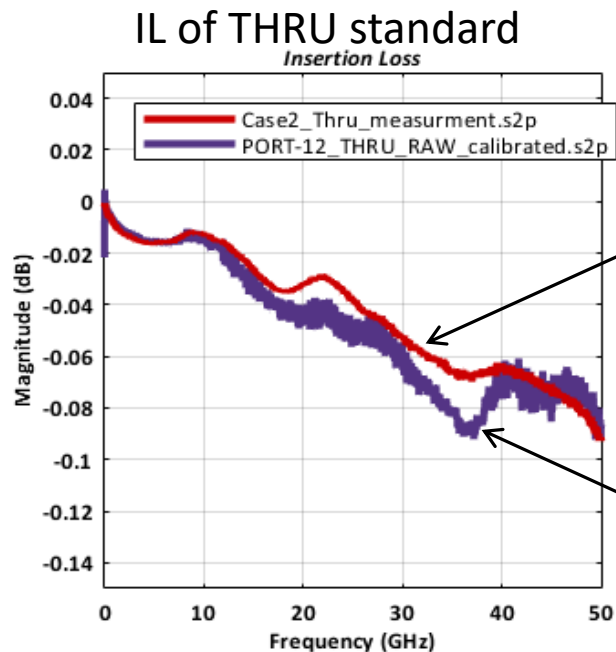
Internal SOLT (red)

External SOLR (purple)

TDR of THRU standard

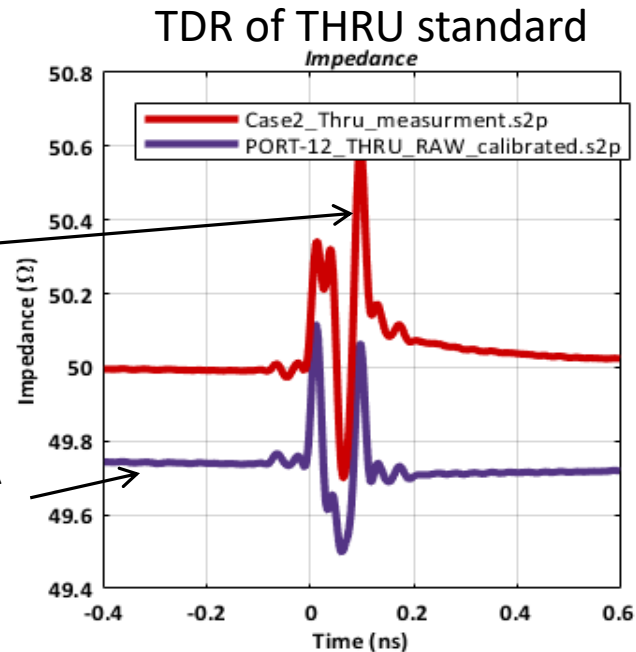


# External Calibration: 10MHz – 50GHz



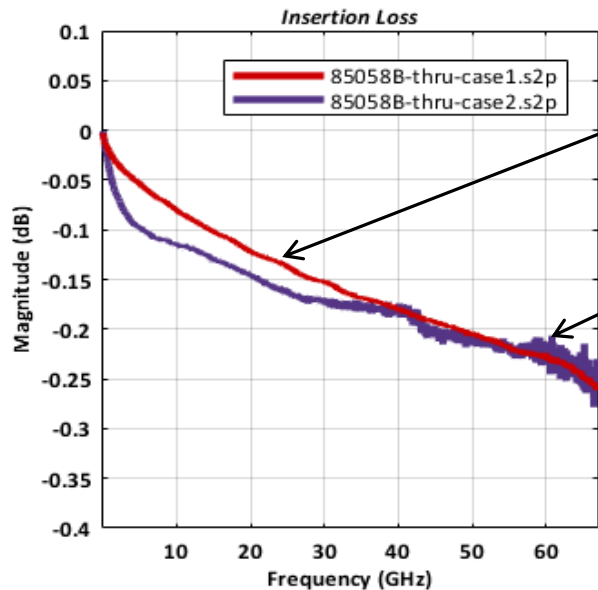
Internal  
SOLT (red)

External SOLR  
(purple)



# External Calibration: 10MHz – 67GHz

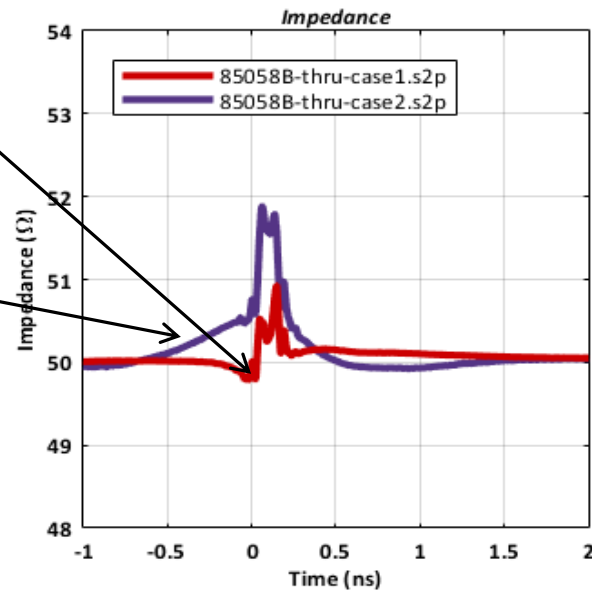
IL of THRU standard



Internal SOLT (red)

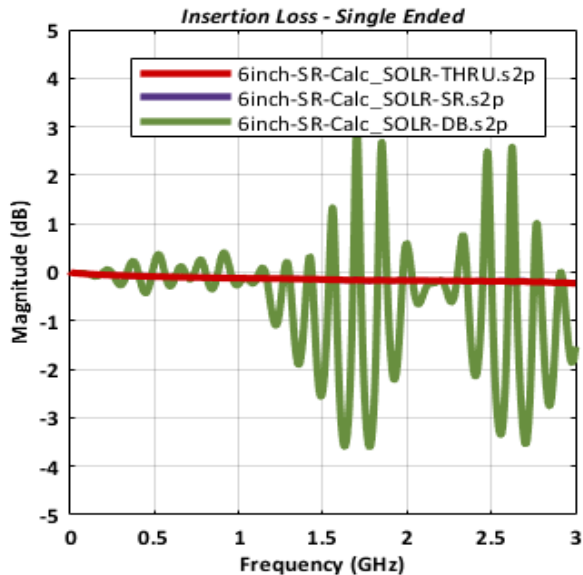
External SOLR (purple)

TDR of THRU standard



# External Calibration: 2MHz – 3GHz

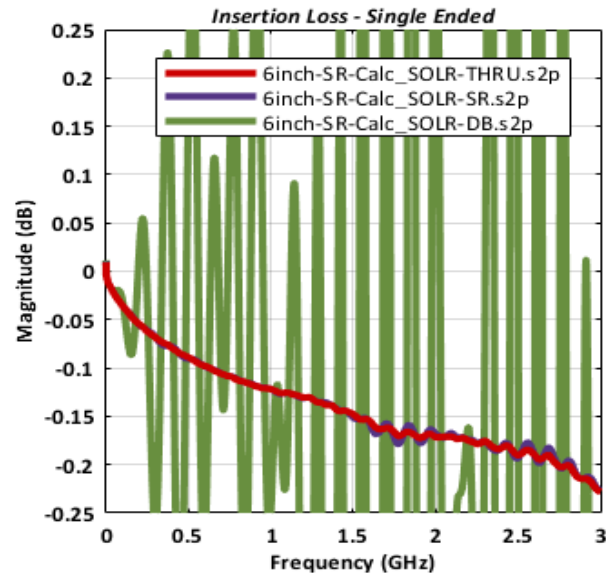
Measured IL of 6" semirigid coax with different unknown THRU standards



THRU:  
reflective  
trace (green)

THRU: 6"  
semirigid  
coax (purple)

THRU: THRU  
standard (red)



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# Summary and Conclusions

- Remeasuring calibration standards after calibration echoes the calibration standard definitions and therefore it is an indication of the stability and repeatability of the measurement setup, not an indication of the quality of calibration
- To check the quality of calibration we need to measure a known golden standard that was not part of the calibration
- Wrong thru standard definition in SOLT calibrations results in non-causal and potentially non-passive results. It tends to manifest itself as random fluctuation in the frequency-domain response
- Professional network analyzers tend to have two layers of corrections: a factory correction and a user calibration. To get raw data from the network analyzer, we need to turn off all corrections
- There are two possible definitions of raw S parameters: one as the actual network acquires the data, with no switch-term correction, and one based on the S-parameter definitions, which assumes and requires the correction for the switch terms. Switch terms do not matter in one-port measurements
- SOLT and SOLR calibrations can be done externally on the appropriate raw data read out from the instrument





# Acknowledgments

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- Al Neves *Wild River Technologies*
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- Brian Walker and John Hollowell *Copper Mountain Technologies*
- Jon Martens *Anritsu*



# MORE INFORMATION

- **Websites:**
  - <https://www.samtec.com>
  - <https://www.nubis-inc.com/>
- *SignalIntegrity tool*; <https://pypi.org/project/SignalIntegrity/>
- Who to contact with more questions?
  - [istvan.novak@samtec.com](mailto:istvan.novak@samtec.com)
  - [pete.pupalaikis@nubis-communications.com](mailto:pete.pupalaikis@nubis-communications.com)



# Thank you!



## QUESTIONS?

