VNA MASTER CLASS – VNA CALIBRATION, KITS, ERROR TERMS AND CALCULATION

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AGENDA

- SOLT Calibration
    - How are standards Defined?
    - What should an Open or Short look like after Calibration
    - Thru and Unknown Thru (SOLT vs SOLR)
    - Data-Based standards
- Error Terms
    - 2-Port and 1-Port models
    - What are these errors?
    - How is calibration performed mathematically?

SOLT/SOLR CALIBRATION

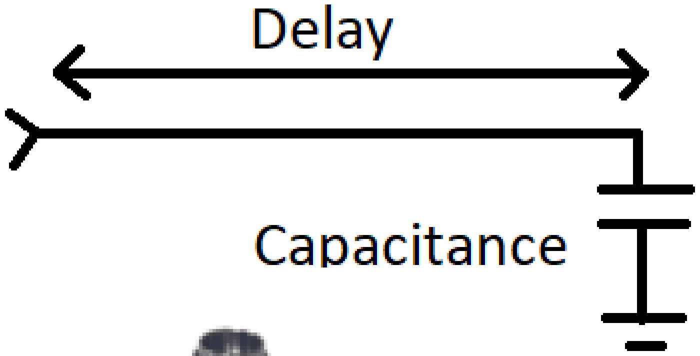
- SOLT uses Short-Open-Load-Thru standards.
  - Thru has defined Delay.
- SOLR is Short-Open-Load-Reciprocal.
  - Can utilize almost any “reciprocal” Thru, (S21 = S12).
- Calibration process is identical.

OPEN STANDARD

- An ideal Open standard would look like the cross-section of an ideal transmission line with radial electric fields which stop abruptly at the slice .
- In the real world, the electric fields “fringe” and curve out into the air before returning to ground and there is a small delay between the connector and the “Open”.
  - This looks like a delay followed by a small capacitor.

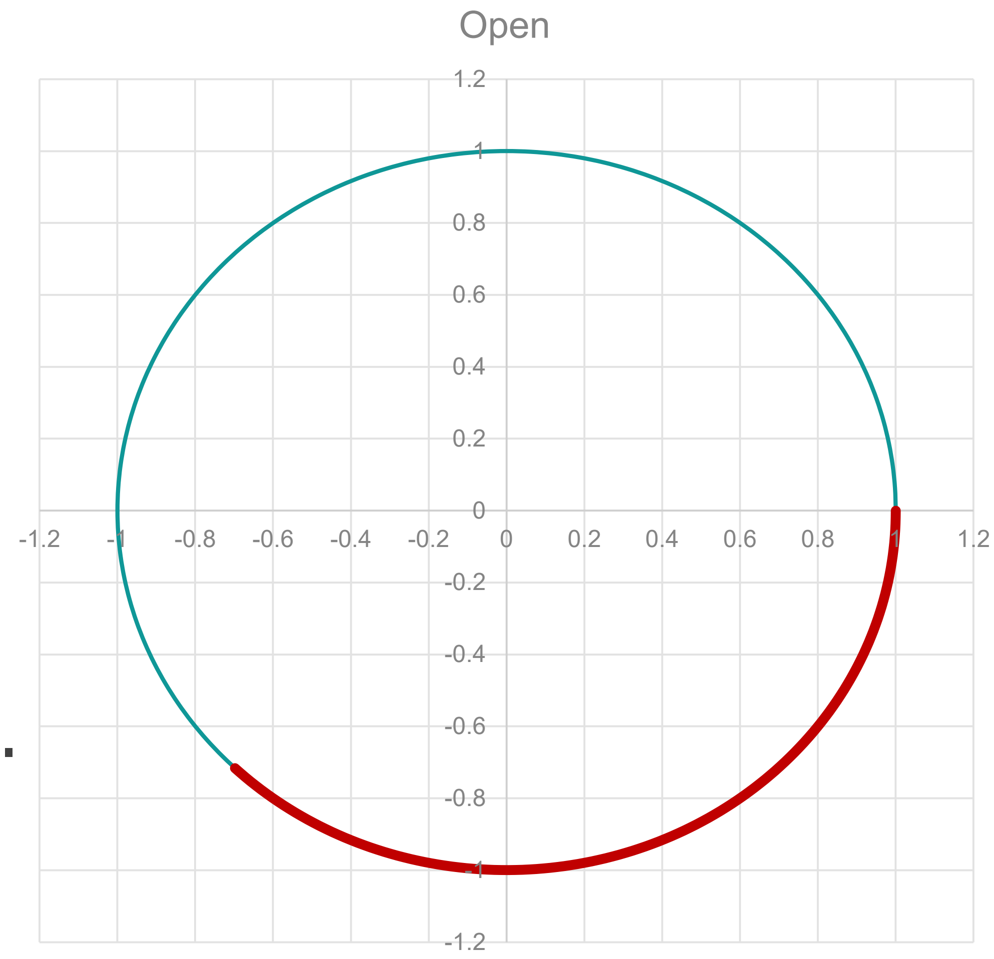
OPEN STANDARD

- The Open may defined by a short transmission line followed by a capacitance to ground which is characterized by a third order polynomial over frequency.
- $C = C_0 + C_1 * f + C_2 * f^2 + C_3 * f^3$
- A loss term which increases linearly with frequency may also be included.



OPEN STANDARD (WHERE'S MY DOT?)

- For the T4311 mechanical standard, the delay is 28.353 pS and the Capacitance is defined by:
- $C = -4.3e\text{-}15 - 431e\text{-}25 * f - 11.5e\text{-}35 * f^2 + 0.12e\text{-}46 * f^3$
- From 9 kHz to 6.5 GHz this will look like a curve from 0 degrees on the right to -132 degrees
- **A Real Open does NOT look like a "Dot" at 0 degrees.**



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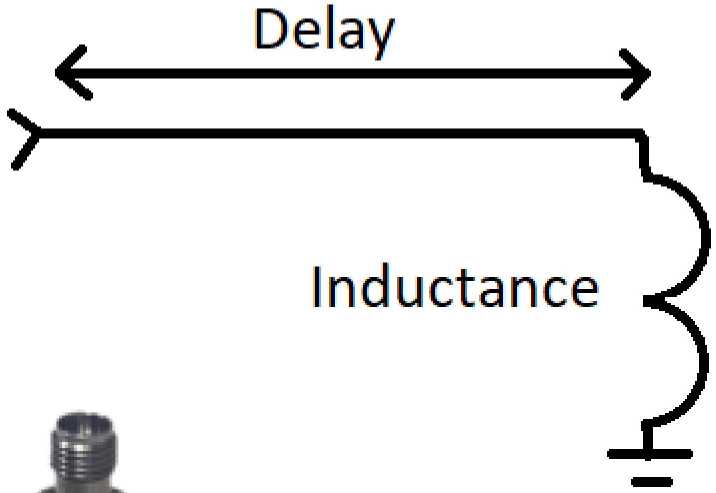
SHORT STANDARD

- An ideal Short standard would look like a perfect Short with no inductance.
- In the real world, there is a small delay between the connector and the Short and the Short has a finite inductance.

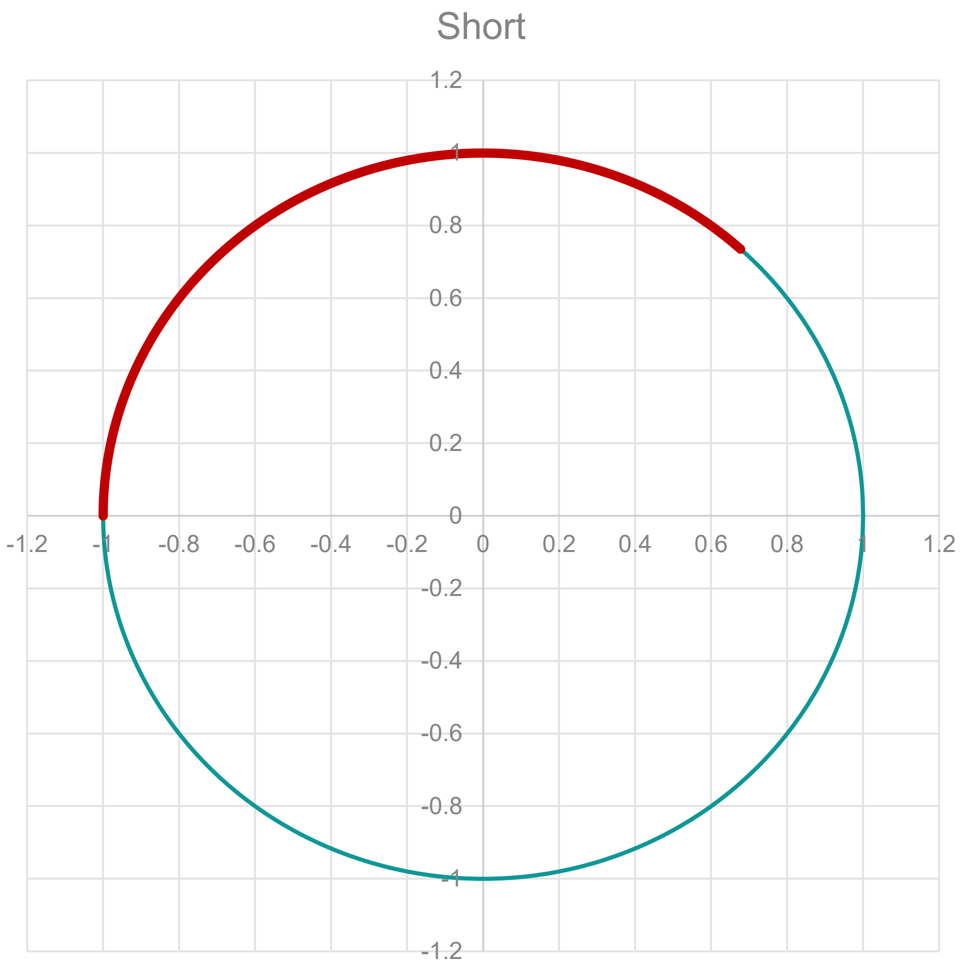
SHORT STANDARD

- The Short may defined by a Short transmission line followed by an inductance to ground which is characterized by a third order polynomial over frequency.
- $L = L_0 + L_1 * f + L_2 * f^2 + L_3 * f^3$
- A loss term which increases linearly with frequency may also be included.



SHORT STANDARD

- For the T4311 mechanical standard, the delay is 28.353 pS and the inductance is defined by:
    - $L = 0 + 0 * f + 0 * f^2 + 0 * f^3$
    - In this case the Inductance is negligible
- From 9 kHz to 6.5 GHz this will look like a curve from 180 degrees on the left to 48 degrees.
- **A real Short does NOT look like a “Dot” at 180 degrees.**



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THRU VS “UNKNOWN” THRU (SOLR)

- It is recommended to use “Unknown” Thru and perform SOLR calibration whenever possible.
- In SOLT the characterized Thru must be very high quality and properly characterized
- Errors in Thru definition result in ripples in an S21 or S12 measurement, ripples in the passband of a filter for example.
- “Unknown” Thru, SOLR calibration is free of this deficiency.
- See “Conducting Calibration with the SOLR (Unknown Thru) Method” April 19, 2018. (https://coppermountaintech.com/conducting-calibration-with-the-solr-unknown-thru-method/)

DATABASED CALIBRATION STANDARDS

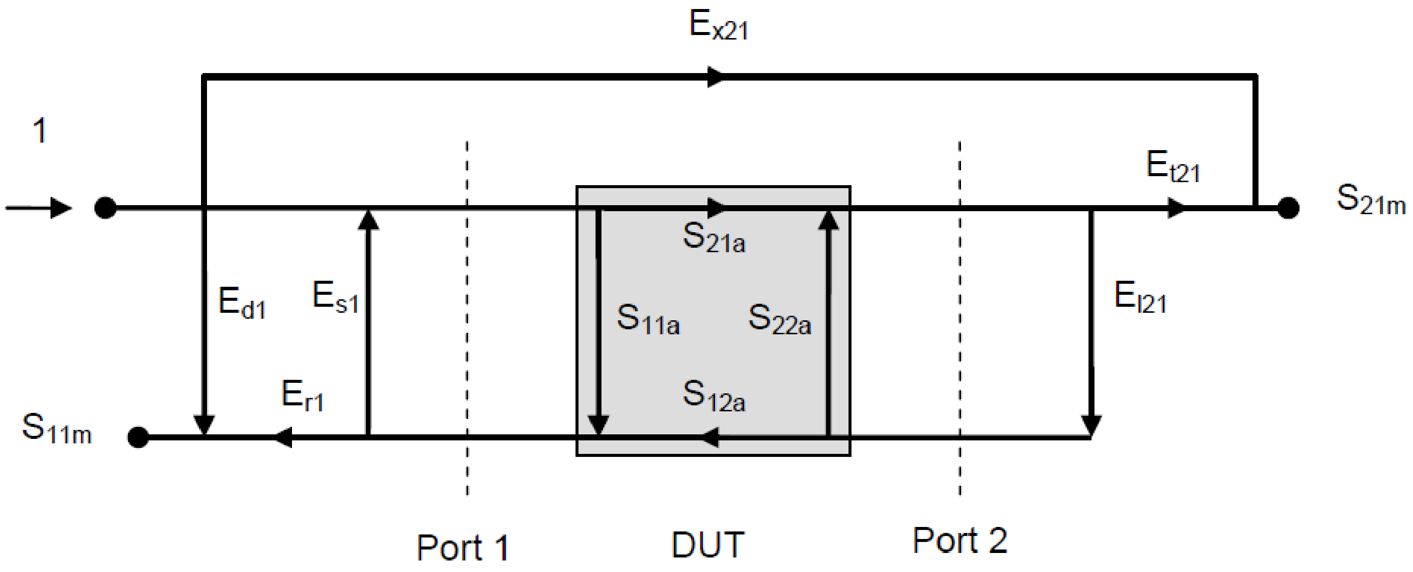
- In the earlier examples, the calibration standards were defined by third order polynomials.
- These polynomials are the same for every calibration piece of the same type from a manufacturer.
- Small differences in machining and fabrication will give rise to errors in the characterization.
- Loads are usually assumed to be perfect.

DATABASED CALIBRATION STANDARDS

- Databased standards are measured with a “Golden” VNA such that each piece has a unique S-Parameter characterization, including the load.
- This is more accurate than polynomial characterization but not quite as accurate as an electronic calibration using an Automatic Calibration Module (ACM).
- See: https://coppermountaintech.com/calibration-kits/

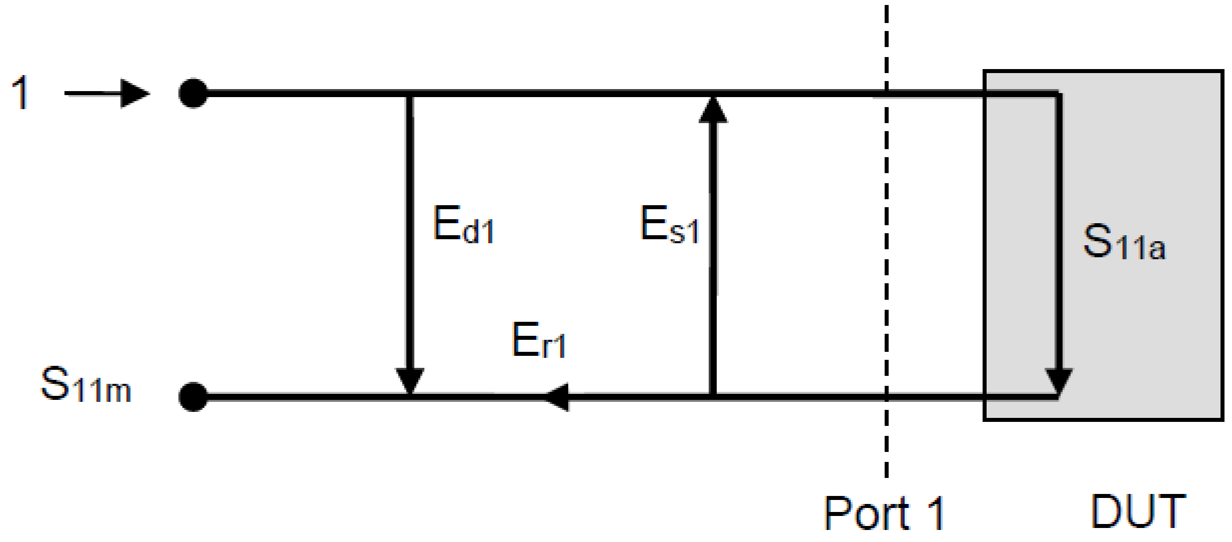
12 TERM ERROR MODEL (FULL 2-PORT)

- Six errors in the forward direction and six in the reverse.
- Directivity, Source Match, Ref Tracking, Load Match, Trans Tracking and Isolation
- For 1-Port calibration only the first three are used



1-PORT CALIBRATION

- It is easy to solve the flow graph and determine the value of S11m
- $S_{11m} = \frac{E_{d1} - \Delta_e S_{11a}}{1 - E_{s1} S_{11a}}$
- Where $\Delta_e = E_{d1} E_{s1} - E_{r1}$
- Then $S_{11a} = \frac{S_{11m} - E_{d1}}{S_{11m} E_{s1} - \Delta_e}$



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1-PORT CALIBRATION

- Using $S_{11m} = \frac{E_{d1} - \Delta_e S_{11a}}{1 - E_{s1} S_{11a}}$, we measure three known artifacts, Open, Short and Load (Or any known three artifacts) and solve the system of three equations with three unknowns.

- Then with those three complex unknowns in hand, E_{d1}, E_{s1} and E_{r1} we can compute the actual, calibrated reflection coefficient

- $S_{11a} = \frac{S_{11m} - E_{d1}}{S_{11m} E_{s1} - \Delta_e}$

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1-PORT CALIBRATION

- It is clear that one can use three knowns to perform calibration in this way, but one can also use more calibration artifacts and improve the result somewhat. Here is the matrix notation for the earlier equations:
- Form two matrices “C” and “V”

$$C = \begin{vmatrix} \Gamma_{a1} & 1 & \Gamma_{a1}\Gamma_{m1} \\ \Gamma_{a2} & 1 & \Gamma_{a2}\Gamma_{m2} \\ \Gamma_{a3} & 1 & \Gamma_{a3}\Gamma_{m3} \end{vmatrix} \text{ and } V = \begin{vmatrix} \Gamma_{m1} \\ \Gamma_{m2} \\ \Gamma_{m3} \end{vmatrix}$$

- Where the Gammas are actual and measured values as before

1-PORT CALIBRATION

- Now compute vector “E”:

$$E = (C^H * C)^{-1} * C^H * V \; = \begin{vmatrix} E_1 \\ E_2 \\ E_3 \end{vmatrix}$$

- Where “H” is the **Hermetian Operator**, the transpose of the complex conjugate of the matrix

- Finally, Ed1 = E2, Es1 = E3 and Er1 = E1+E2*E3

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REFERENCES

- Doug Rytting, *Network Analyzer Error Models and Calibration Methods*
- Doug Rytting, *Improved RF Hardware and Calibration Methods for Network Analyzers*
- Zhang Na, Zhang Guo Hua, Chen Ting and Liu Jie, *Study on the Unknown Thru Calibration Technique*
- Brian Walker, *Thru-Reflect-Line (TRL) Calibration*, Cal Lab Magazine, October 2020

REFERENCES - VIDEOS

- Fixture Removal Software
  - https://coppermountaintech.com/video-automatic-fixture-removal-plug-in-for-cmt-vnas/
- Reflection Measurement Uncertainty
  - *https://coppermountaintech.com/reflection-vs-transmission-accuracy-in-vector-network-analyzer-measurement/*
- *Transmission Measurement Uncertainty*
  - *https://coppermountaintech.com/video-vna-transmission-measurement-uncertainty/*

1-PORT CALIBRATION OVERDETERMINED

- To use more than three standards for an over-determined result, simply add more rows to the “C” and “V” matrices and a “Least-Squares” result automatically follows

$$C = \begin{vmatrix} \Gamma_{a1} & 1 & \Gamma_{a1}\Gamma_{m1} \\ \Gamma_{a2} & 1 & \Gamma_{a2}\Gamma_{m2} \\ \Gamma_{a3} & 1 & \Gamma_{a3}\Gamma_{m3} \\ \dots & 1 & \dots \;\; \dots \\ \dots & 1 & \dots \;\; \dots \end{vmatrix} \text{ and } V = \begin{vmatrix} \Gamma_{m1} \\ \Gamma_{m2} \\ \Gamma_{m3} \\ \dots \\ \dots \end{vmatrix}$$

$$E = \underbrace{(C^H * C)^{-1} * C^H}_{\text{This is the least Squares Computation}} * V = \begin{vmatrix} E_1 \\ E_2 \\ E_3 \end{vmatrix}$$

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QUESTIONS?

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