# VNA ERROR TERMS AND CALIBRATION KITS

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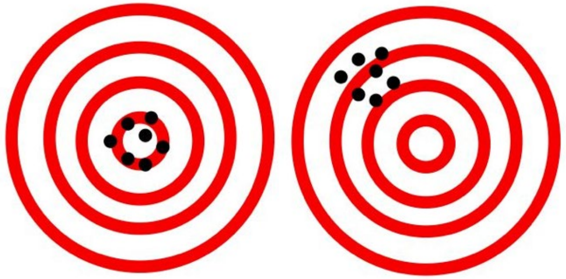
# VNA ACCURACY, PRECISION, UNCERTAINTY, ERRORS

- Let's start by defining terms:
  - Accuracy – an estimation of how close a measurement is to the true value.
  - Precision – a measure of how close a series of readings are to each other. The effect of random factors.
  - The first target has high accuracy and a certain precision
  - The second has the same precision with lower accuracy



# VNA ACCURACY, PRECISION, UNCERTAINTY, ERRORS

- Defining terms (cont’d):
  - **Uncertainty** – an argument accompanying a measurement defining a range around it, within which the true value should lie with a specific statistical expectation.
  - **Errors** – factors which cause the measurement to be different from the true value. Errors can be systematic or random.
    - **Systematic Errors** – errors which are built into a measurement, which may be significantly reduced by calibration
    - **Random Errors** – errors, usually environmental, which cannot be improved by calibration

# AN EXAMPLE MEASUREMENT

- A metrologically-sound measurement looks like this:
  - <Value><Units><Uncertainty><Confidence Interval>
- For example:
  - 5.684 V ± 0.005 V with 99.73% confidence ($3\sigma$ for Gaussian Distribution)
  - With 99.73% confidence, we can say that the true value must lie between 5.679 and 5.689 V.
- To complicate matters, the confidence interval is often not stated, but a *standard uncertainty* is taken to mean a one sigma, 68% confidence interval

# MAKING THE MOST ACCURATE MEASUREMENT

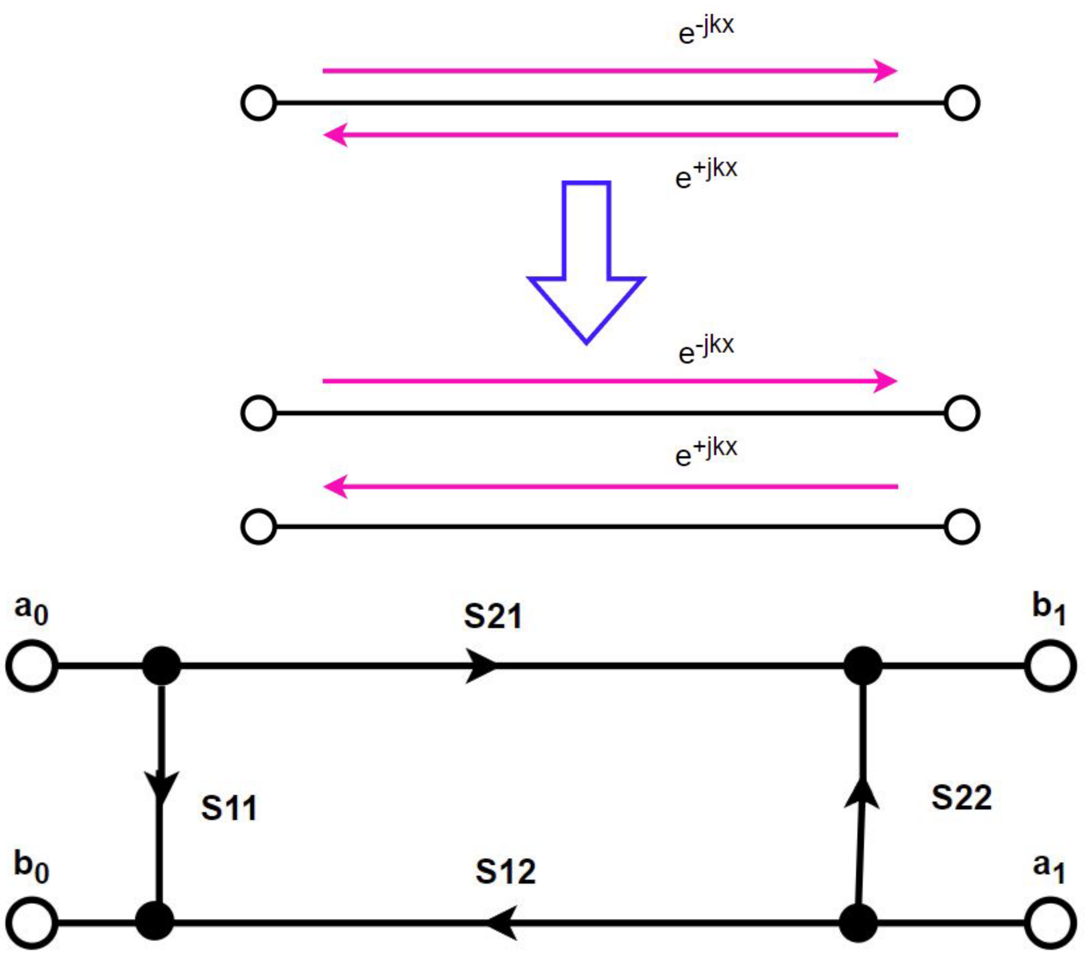
- To make the most accurate measurement, we must reduce errors as much as possible.
  - **Random errors**:
    - **Thermal** – reduce temperature fluctuations in the lab as much as possible. Use low loss cables, high stimulus power output, and a VNA with a low receiver noise floor to reduce thermal noise error.
    - **Connector variance** – use a torque wrench and precision connectors.
    - **Cable flexure** – minimize cable flexure, tape to bench, use a trapeze, and attach cables with natural curvature toward the DUT

# MAKING THE MOST ACCURATE MEASUREMENT

- Accurate measurements (cont'd)
  - **Systematic errors**:
    - Choose the best calibration method and kit for the measurement setup
    - For a DUT with N-Female connectors, use an N-Female calibration kit, eschew adapters.
    - Use an Automatic Calibration Module for best results

# WHAT ARE THE SYSTEMATIC ERRORS?

- The systematic errors for VNA measurement are best presented using S-parameter network diagrams
- These are diagrams which separate signals that move from left to right from those moving in the other direction on a transmission line

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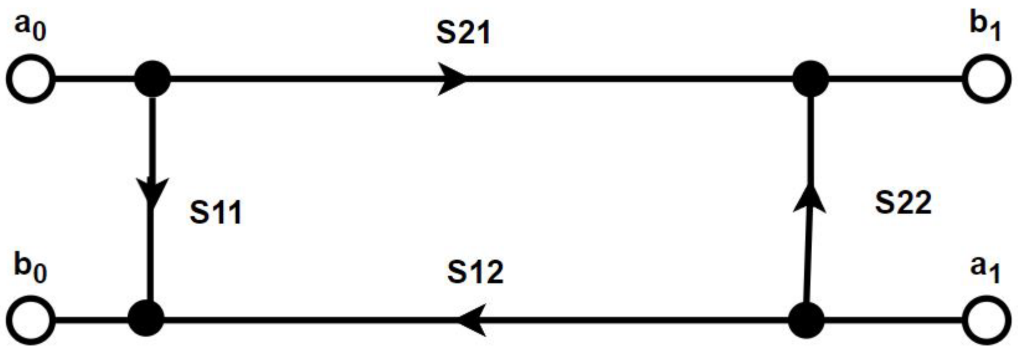
# NETWORK DIAGRAM REVIEW

- If a signal enters the transmission line at $a_0$, some will pass through $S_{21}$ and some will be reflected through $S_{11}$ and exit at $b_0$.
- After passing through S21, the signal can only leave through $b_1$.
- If this network were loaded there could be another reflection from $b_1$ down to $a_1$

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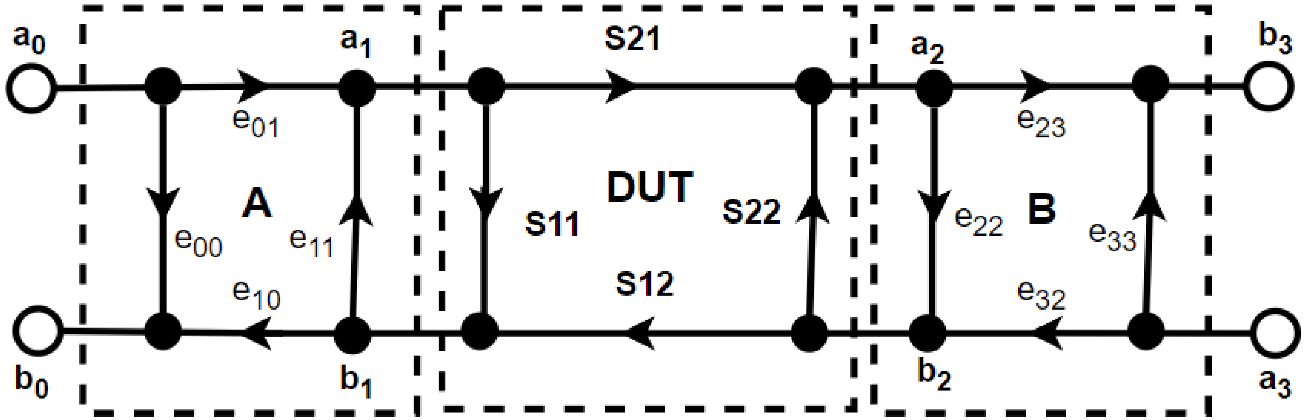
# THE 8-TERM ERROR MODEL

- For the 8-Term Model, two error boxes, A and B, are applied to each side of the DUT.
- We assume that a perfect VNA is attached to the left and right sides
- We need only find the values of the error terms and then de-embed A and B to find the actual S-parameters of the DUT

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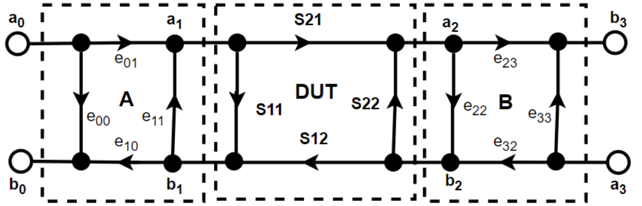
# THE 8-TERM ERROR MODEL

Mathematically the de-embedding works like this:




$$S_M = \begin{vmatrix} e_{00} & e_{10} \\ e_{01} & e_{11} \end{vmatrix} * \begin{vmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{vmatrix} * \begin{vmatrix} e_{22} & e_{32} \\ e_{23} & e_{33} \end{vmatrix} = S_A * S_{DUT} * S_B$$

But you can't multiply S-parameters like this, so they are converted into transfer parameters:

$$T_A = \frac{1}{e_{10}} \begin{vmatrix} -\Delta_{eA} & e_{00} \\ -e_{11} & 1 \end{vmatrix}$$

$$\Delta_{eA} = e_{00}e_{11} - e_{12}e_{21}$$

$$T_B = \frac{1}{e_{32}} \begin{vmatrix} -\Delta_{eB} & e_{22} \\ -e_{33} & 1 \end{vmatrix}$$

$$\Delta_{eB} = e_{22}e_{33} - e_{23}e_{32}$$

$$T_{DUT} = \frac{1}{S_{21}} \begin{vmatrix} -\Delta_S & S_{11} \\ -S_{22} & 1 \end{vmatrix}$$

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

Then: $T_M = T_A * T_{DUT} * T_B$ and $T_{DUT} = T_A^{-1} * T_M * T_B^{-1}$

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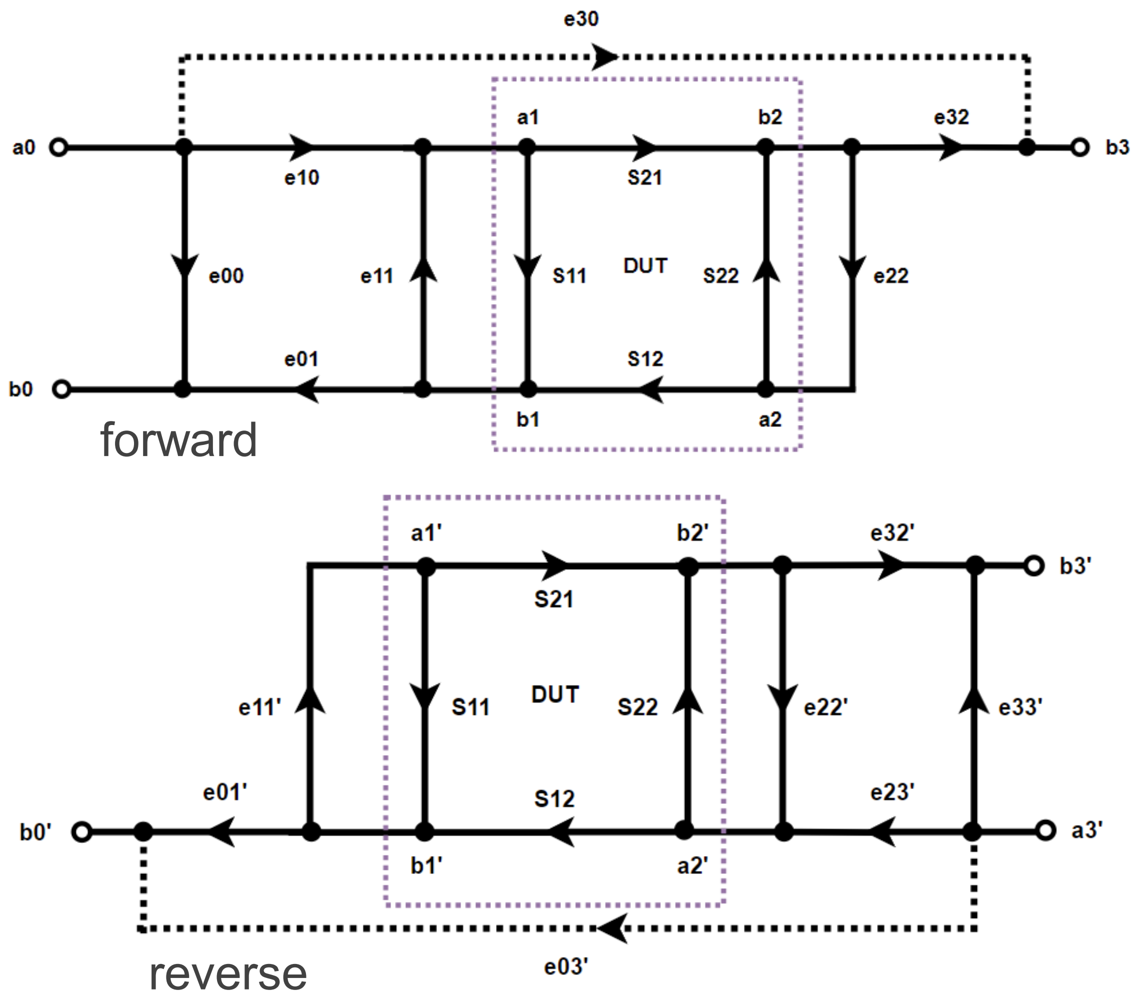
# THE 8-TERM ERROR MODEL

- Now we need only find all the error terms and do the math
- But how do we find all eight of those error terms?
  - Apply Open, Short and Load standards on the right side of A then the left side of B, then install a thru between them measure and do the math.
  - See *Introduction to the Metrology of VNA Measurement*, Appendix B for the gory details.
- What do each of those error terms physically mean?
  - Physical meaning is best described with the 12-Term Model

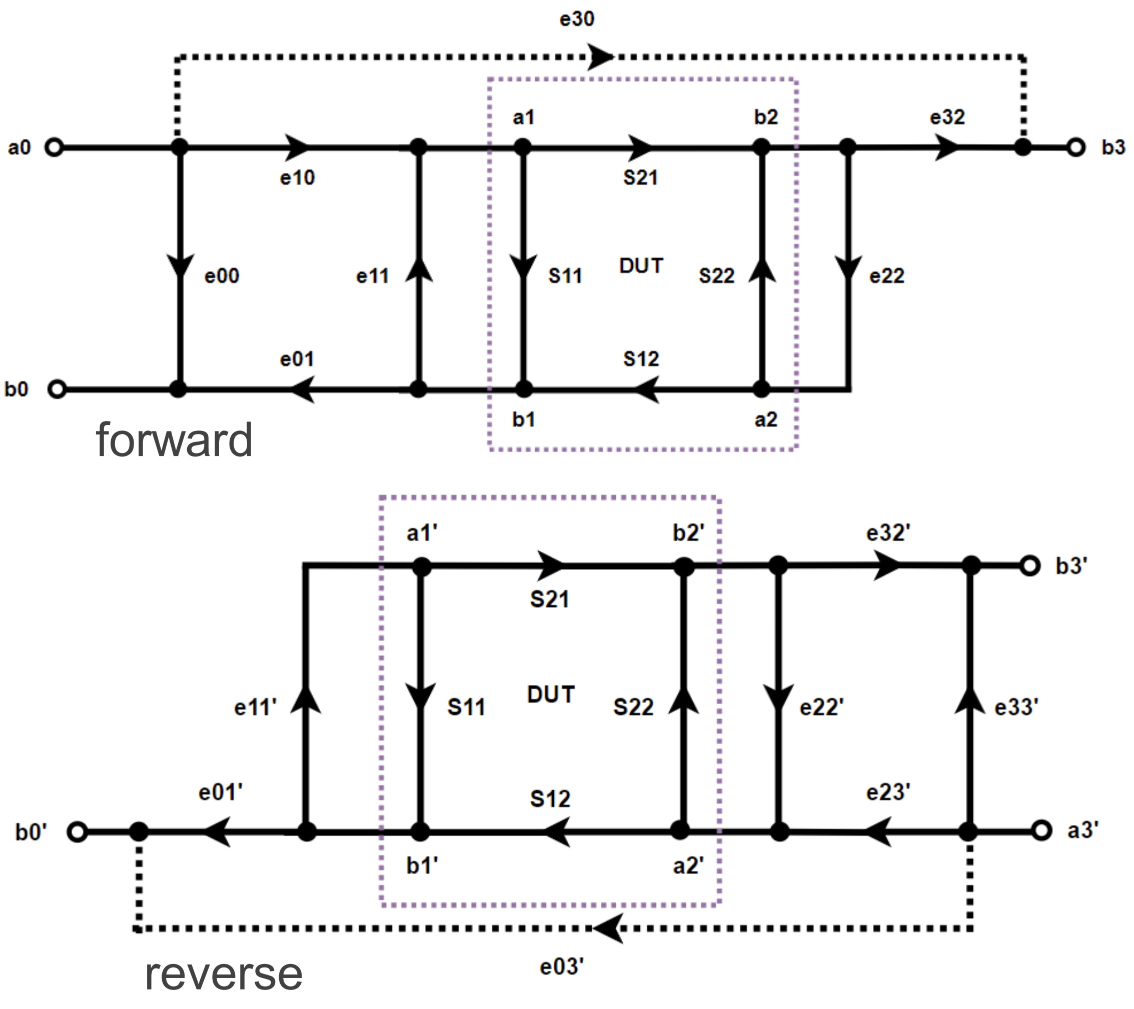
# THE 12-TERM ERROR MODEL

- The 12-Term Model is similar to the 8-Term, but the forward and reverse models are considered separately.
- The forward model with driven $a_0$ is shown on the top, and the reverse with driven $a_3$ is shown on the bottom.
- It is only necessary to understand one of them.
- Note the Isolation terms $e_{30}$ and $e_{03}'$, which should actually have appeared in the 8-Term model.



# THE 12-TERM ERROR MODEL

- These error terms relate to real-world phenomena:
- *e00, e33'* Directivity Error
- *e10e01, e23'e32'* Ref Tracking Error
- *e11, e22'* Source Match Error
- *e10e32, e23'e01'* Trans Tracking Error
- *e22, e11'* Load Match Error
- *e30, e03'* Isolation Error

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# THE 12-TERM ERROR MODEL

- The **Directivity Error**, *e00*, is due to the leakage in the VNA directional bridge. The two ports on the bridge should produce two pure signals. One, a sample of the incident signal leaving the port, and two, a sample of the reflected signal entering the port. In practice, there is some leakage of the incident signal into the reflection port.
- **Reflection Tracking**, *e10e01* accounts for the indignities suffered by an incident signal leaving the port, passing through cables and connectors, *e10*, and being reflected by the DUT, to go through them once again, *e01*.
- **Source Match Error**, *e11*, accounts for the complex error in the source impedance of the incident signal as it appears at the input of the DUT. Even if the source impedance of the stimulus of the VNA is a perfect 50 Ohms, small variations in the characteristic impedance of cables and connectors will alter it somewhat.

# THE 12-TERM ERROR MODEL

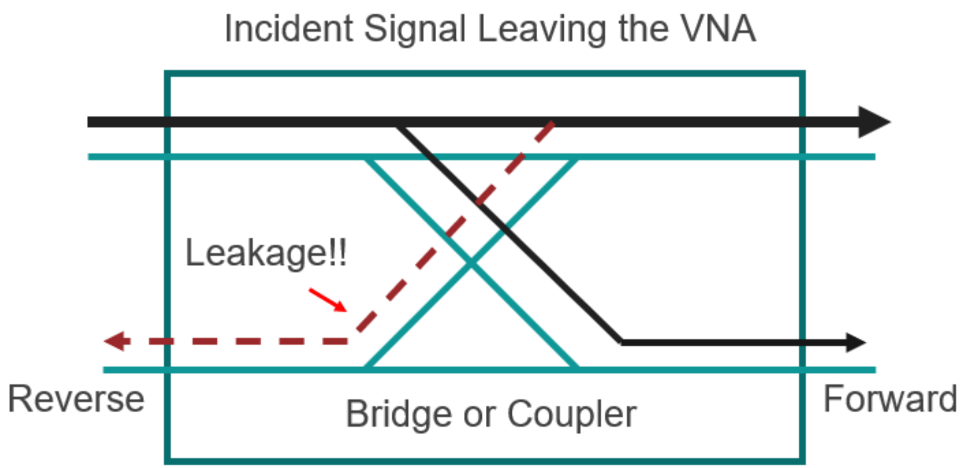
- **Transmission Tracking**, *e10e32*, is similar to **Reflection Tracking** and includes the first part of it, *e10*, but also includes the errors in the path to the other VNA port, *e32*.
- **Load Match Error**, *e22*, is the load impedance error from 50 Ohms as seen at the output of the DUT and includes impedance variations caused by the output cable and connectors and any small load impedance error through the bridge of the VNA itself.
- **Isolation Error**, *e30*, accounts for any signal which bypasses the DUT entirely. Either through leakage within the VNA itself, which is uncommon, or from the electromagnetic coupling between the two DUT connections, such as that experienced between the probes within a probe station measurement.

# THE 12-TERM ERROR MODEL

- We use these error terms to represent two things.
- Before calibration, $e_{00}$ represents ***Raw* Directivity**.
- After calibration, $e_{00}$ represents ***Residual* Directivity**.
- Errors are never completely eliminated, just greatly reduced.

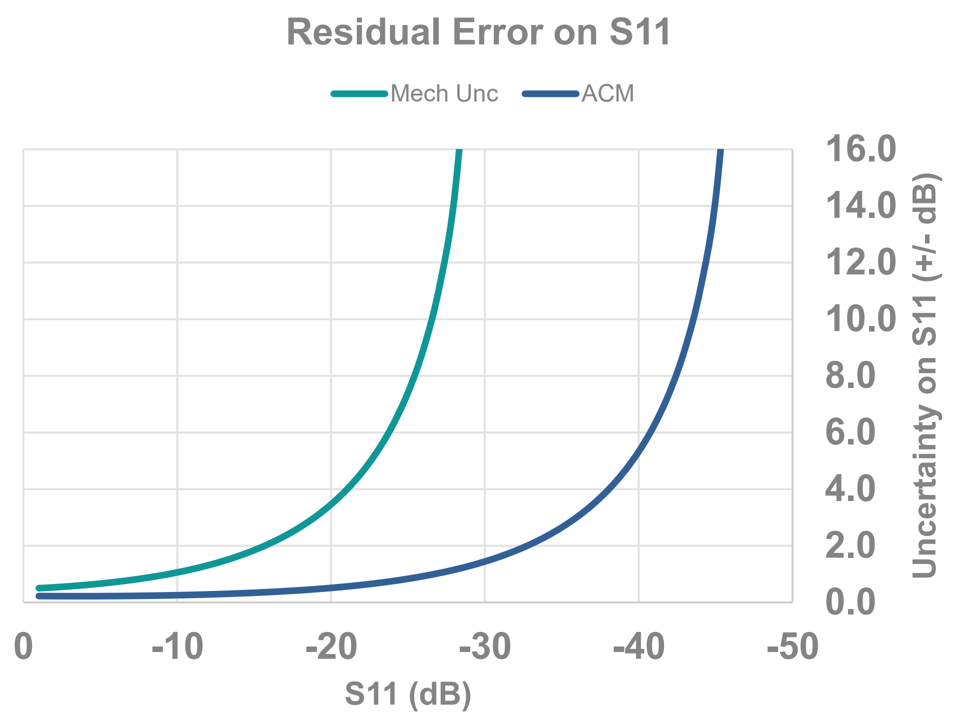
# HOW ARE ERRORS CORRECTED?

- **Directivity Error** is due to the leakage in the directional bridge
- If the output is terminated with a perfect load, then the leakage can be measured and completely eliminated, making $e_{00} = 0$
- Unfortunately, the calibration load may have a worst-case return loss of 30 dB
- The 30 dB signal sets the floor for reflection measurement uncertainty.



# HOW ARE ERRORS CORRECTED?

- The chart on the right shows how the uncertainty on a 1-port measurement is affected by the uncertainty (RL) of the calibration load
- The green curve is uncertainty with a 30 dB mechanical cal kit load, and the blue curve is the uncertainty with a 47 dB ACM calibration
- The uncertainty of the calibration load is the most important factor

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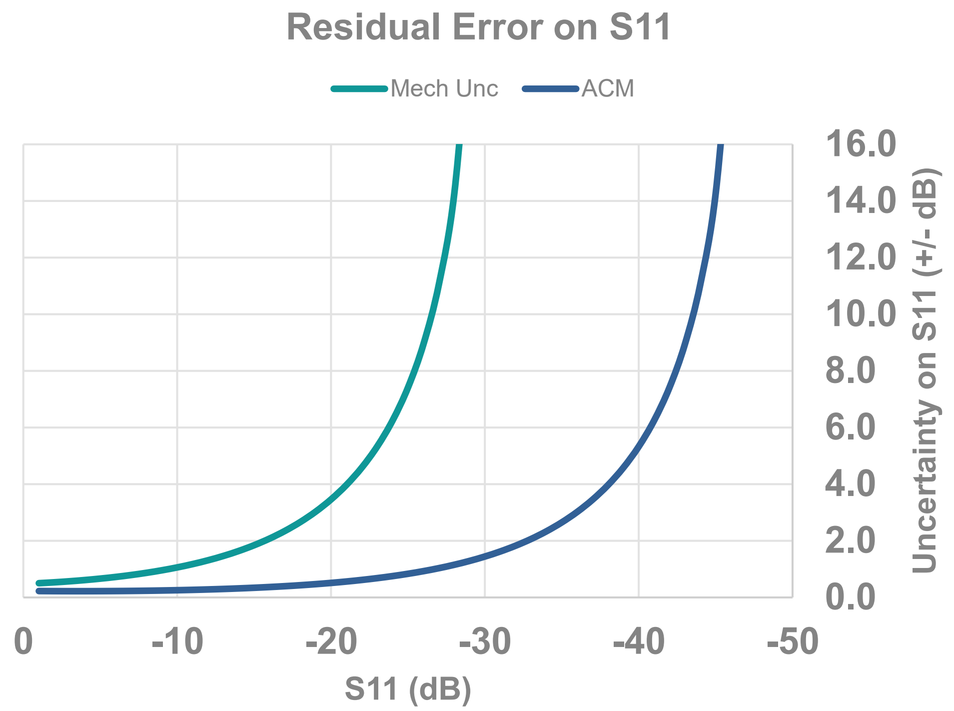


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# THE CALIBRATION KIT

- The specifications for the calibration kit are loaded into the VNA
- The calibration load is assumed to be perfect
- The calibration short is defined by a delay followed by a small inductance
- The calibration open is defined by a delay followed by a small capacitance
- The calibration thru does not need to be defined if “Unknown Thru” is chosen in the calibration process. Otherwise, its delay and loss must be specified.
- A typical cal kit definition is shown below

| | Standard | | Frequency | | Offset | | | | | Terminal Impedance | C0·1e-15 F | C1·1e-27 F/Hz | C2·1e-36 F/Hz² | C3·1e-45 F/Hz³ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | Type | Label | F min | F max | Delay | Z0 | Loss | Media | H/W | | L0·1e-12 H | L1·1e-24 H/Hz | L2·1e-33 H/Hz² | L3·1e-42 H/Hz³ |
| 1 | Open | Open | 0 Hz | 999 GHz | 33.356 ps | 50 Ω | 2.2 GΩ/s | Coax | | | -17.5 | -2000 | 140 | -2.7 |
| 2 | Short | Short | 0 Hz | 999 GHz | 33.356 ps | 50 Ω | 2.36 GΩ/s | Coax | | | -44 | 3700 | -250 | 5 |
| 3 | Load | Load | 0 Hz | 999 GHz | 0 s | 50 Ω | 0 Ω/s | Coax | | 50 Ω | | | | |
| 4 | Thru/Delay | Thru | 0 Hz | 999 GHz | 84.058 ps | 50 Ω | 2.51 GΩ/s | Coax | | | | | | |
| 5 | Unkn Thru | Unknown Thru | 0 Hz | 999 GHz | AUTO | | | Coax | | | | | | |

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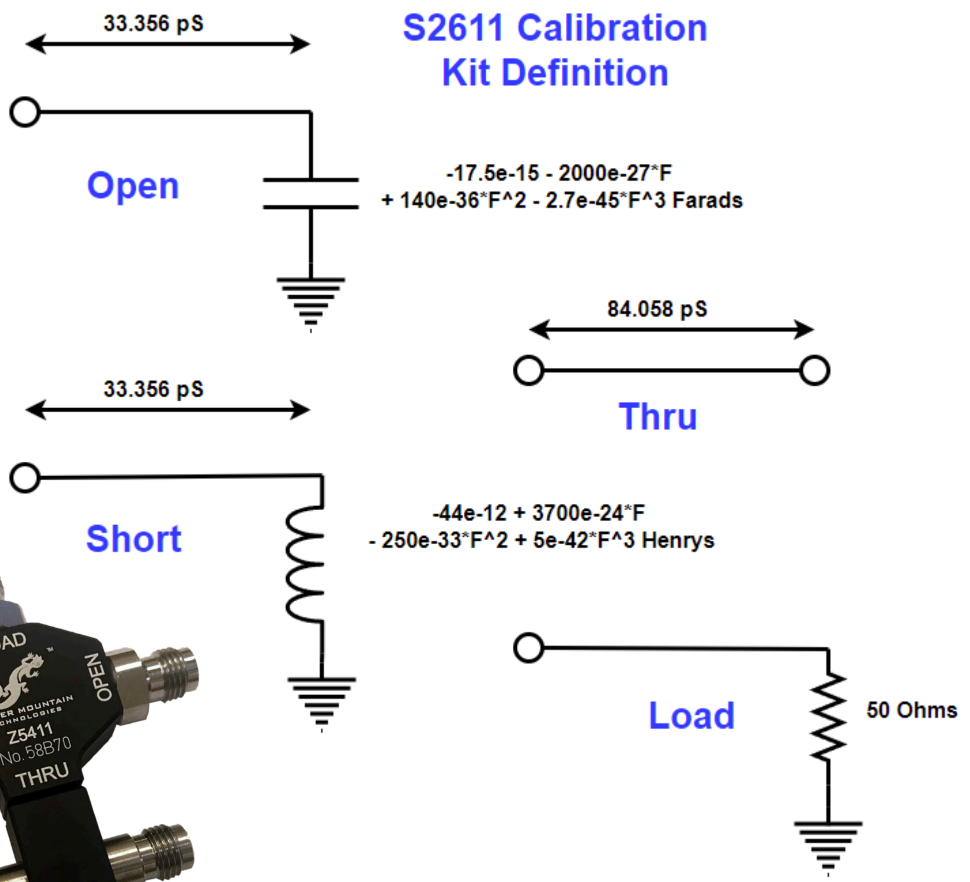
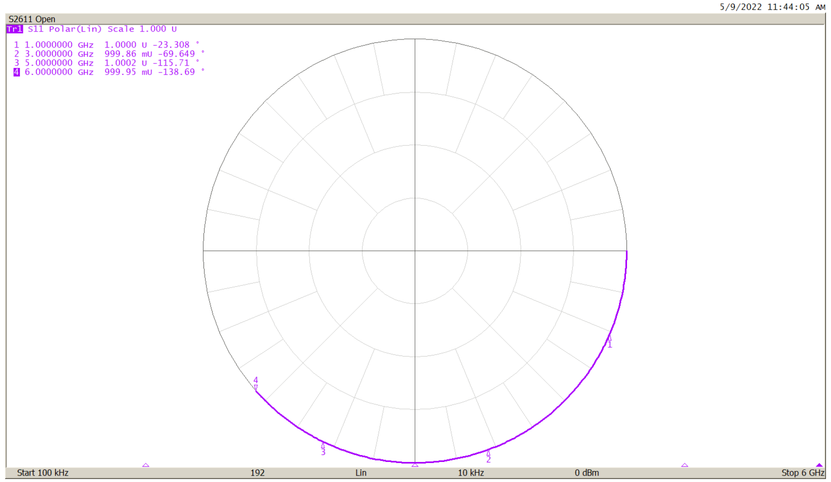
# THE CALIBRATION KIT

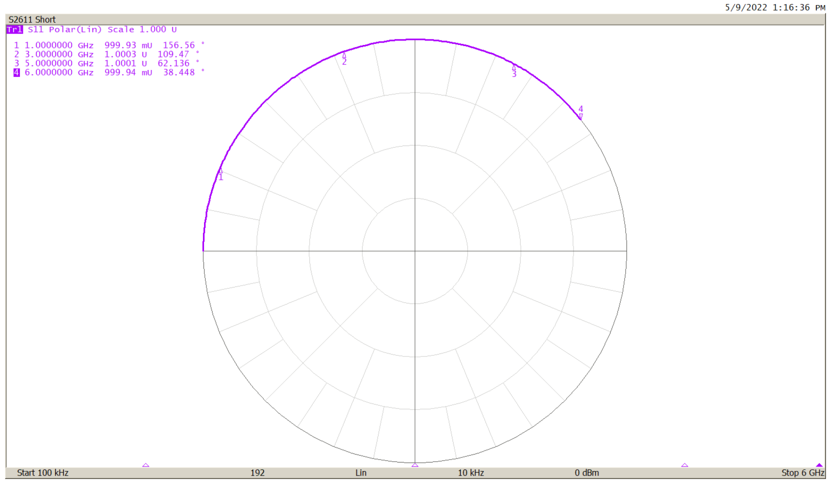
- The parts of the calibration kit are modeled as shown on the right.
- Because of the Open and Short delays, the reflection as seen on the Smith chart is not a “dot” at 0 and 180º, but a clockwise arc, increasing with frequency
- The Open capacitance and Short inductance are calculated from the third order function vs frequency as shown.




# THE CALIBRATION KIT

- After calibration is complete, the Open and Short standards will look like the measurements on the right.
- Errors in the stated vs actual Open and Short delay will result in phase errors in the correction matrix resulting in measurement ripple over frequency
- Databased standards can be much more accurate

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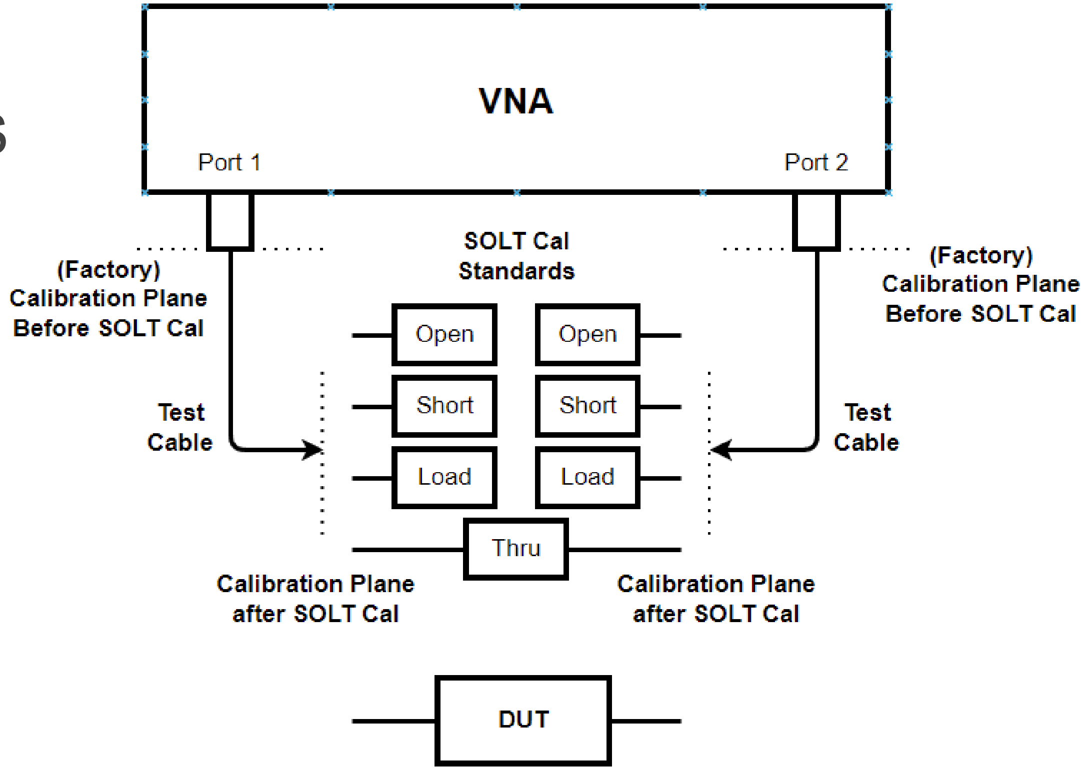
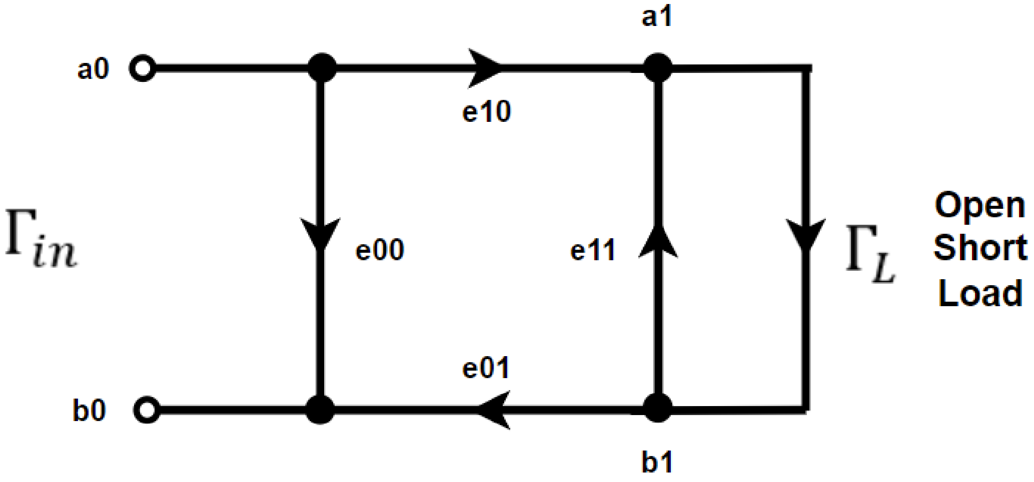
# THE CALIBRATION PROCESS

- To calibrate the VNA, the Open, Short, Load, and Thru standards are applied as shown.
- The measured reflections are used along with the known reflections of each calibration standard to generate a correction matrix at each frequency point.



# 1-PORT CALIBRATION

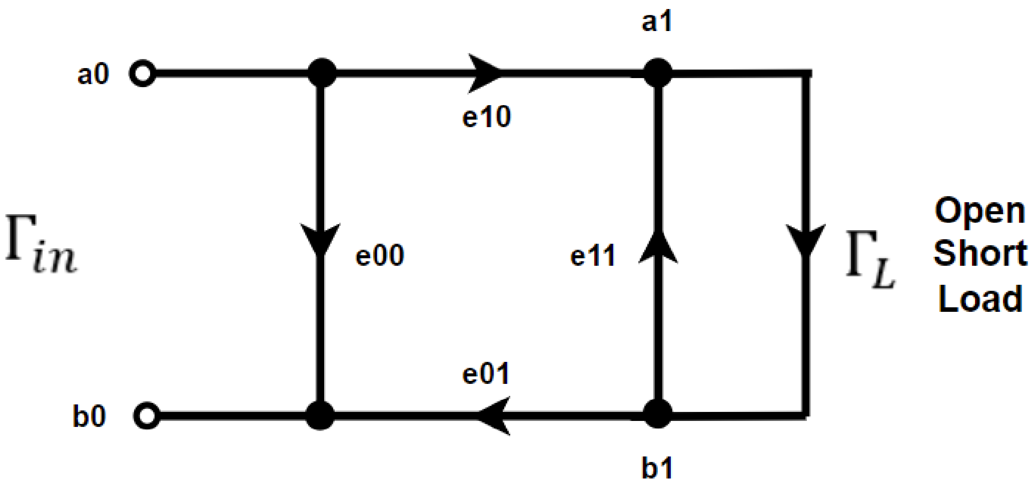
- 1-port calibration is straightforward
- Measure the three known standards
- Solve for raw **Directivity**, $e_{00}$, **Reflection Tracking**, $e_{10}e_{01}$, and **Source Match**, $e_{11}$, using the equation shown (Mason's Rule), where $\Gamma_L$ is the Open, Short, and Load standard in turn.




$$\Gamma_{in} = e_{00} + \frac{e_{10}e_{01}\Gamma_L}{1 - e_{11}\Gamma_L}$$

# 1-PORT CALIBRATION

- The true reflection, Γ, can be found from the measured reflection $\Gamma_m$ using the formula to the right.
- For more on this, including a convenient matrix solution technique, see:
  - B. Walker, "One-Port VNA Calibration: A Look Under the Hood", Microwaves & RF, Jan 2021




$$\Gamma = \frac{\Gamma_m - e_{00}}{e_{10}e_{01} + e_{11}(\Gamma_m - e_{00})}$$

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# 2-PORT CALIBRATION

- 2-port calibration is not as simple and intuitive as the 1-port case.
- The formulas are tedious and don't provide much enlightenment
- Suffice to say that the process starts with a 1-port calibration on each side followed by the thru measurement.
- If the 1-port calibration provides **Directivity**, **Source Match**, and **Reference Tracking** terms, the **Load Match** and **Transmission Tracking** may thus be derived after attaching the Thru.

# TRL AND LRL

- Besides the SOLT or SOLR (Unknown Thru) calibration techniques, one can use TRL or LRL
- TRL stands for Thru-Reflect-Line and LRL stands for Line-Reflect-Line for a non-zero length Thru
- Both methods solve for the eight terms of the 8-Term error model, see:
  - B.Walker, "Introduction to the Metrology of VNA Measurement", Appendix B, May 2022, CMT Website

# TRL AND LRL

- TRL does not include a Load standard
- Instead, the characteristic impedance of the line must be pristine or meticulously characterized, often with the use of an expensive air line.
- You can attain **Residual Directivity** in excess of 60 dB if you use a sufficiently precise line.