Calibration and error correction

- Why and how?

The need for calibration

Why do we have to calibrate?

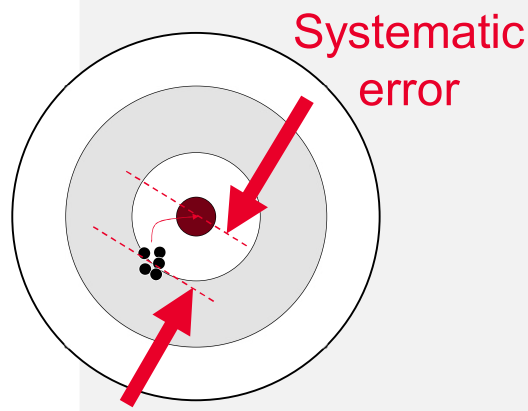
- It is impossible to make perfect hardware
- It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction

How do we get accuracy?

- With vector-error-corrected calibration
- Not the same as the yearly instrument calibration

What does calibration do for us?

- Removes the largest contributor to measurement uncertainty: systematic errors
- Provides best picture of true performance of your device under test



Why is calibration so important to network analysis? The reason is that it is impossible to make perfect test hardware, and too difficult and/or too expensive to make the network analyzer hardware so good that the need for error correction is entirely eliminated. Vector error correction is a cost effective way to improve the performance of test systems comprised of good but not perfect hardware. The right balance between hardware performance, cost, and system performance (including error correction) must be achieved. If the RF performance of the hardware is poor, then vector error correction will not be able to overcome all the deficiencies, and the overall system performance will suffer compared to that obtained from a system using better hardware.

VNAs provide high measurement accuracy by calibrating the test system using a mathematical technique called vector error correction (this type of calibration is different than the yearly calibration done in a cal lab to ensure the instrument is functioning properly and meeting its published specifications for things like output power and receiver noise floor). Vector error correction accounts for measurement errors in the network analyzer itself, plus all of the test cables, adapters, fixtures, and/or probes that are between the analyzer and the DUT.

Calibrating a VNA-based test system removes the largest contributor to measurement uncertainty, which are systematic errors. Systematic errors are repeatable, non-random errors that can be measured and removed mathematically. A vector-error-corrected VNA system provides the best picture of the true performance of the device under test (DUT). A network analyzer is really only as good as its calibration, so Keysight spends a great deal of effort to provide the most complete and highest-quality choices for calibration.

Calibration does not remove random or drift errors.

Measurement error modeling

Systematic errors

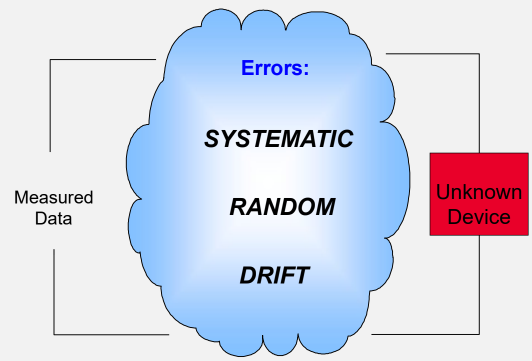
- Generally, are largest sources or error
- Due to imperfections in the analyzer and test setup
- Assumed to be time invariant (predictable)

Random errors

- Vary with time in random fashion (i.e. unpredictable)
- Main contributors: instrument noise, switch and connector repeatability

Drift errors

- Primarily caused by temperature variation
- Due to system performance changing after a calibration has been done



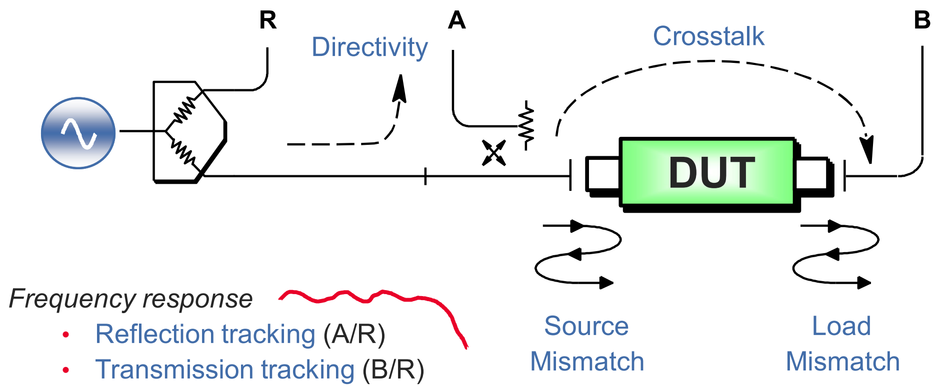
Let's look at the three basic sources of measurement error: systematic, random and drift.

Systematic errors are due to imperfections in the analyzer and test setup. They are repeatable (and therefore predictable), and are assumed to be time invariant. Systematic errors are characterized during the calibration process and mathematically removed during measurements.

Random errors are unpredictable since they vary with time in a random fashion. Therefore, they cannot be removed by calibration. The main contributors to random error are instrument noise (source phase noise, sampler noise, IF noise).

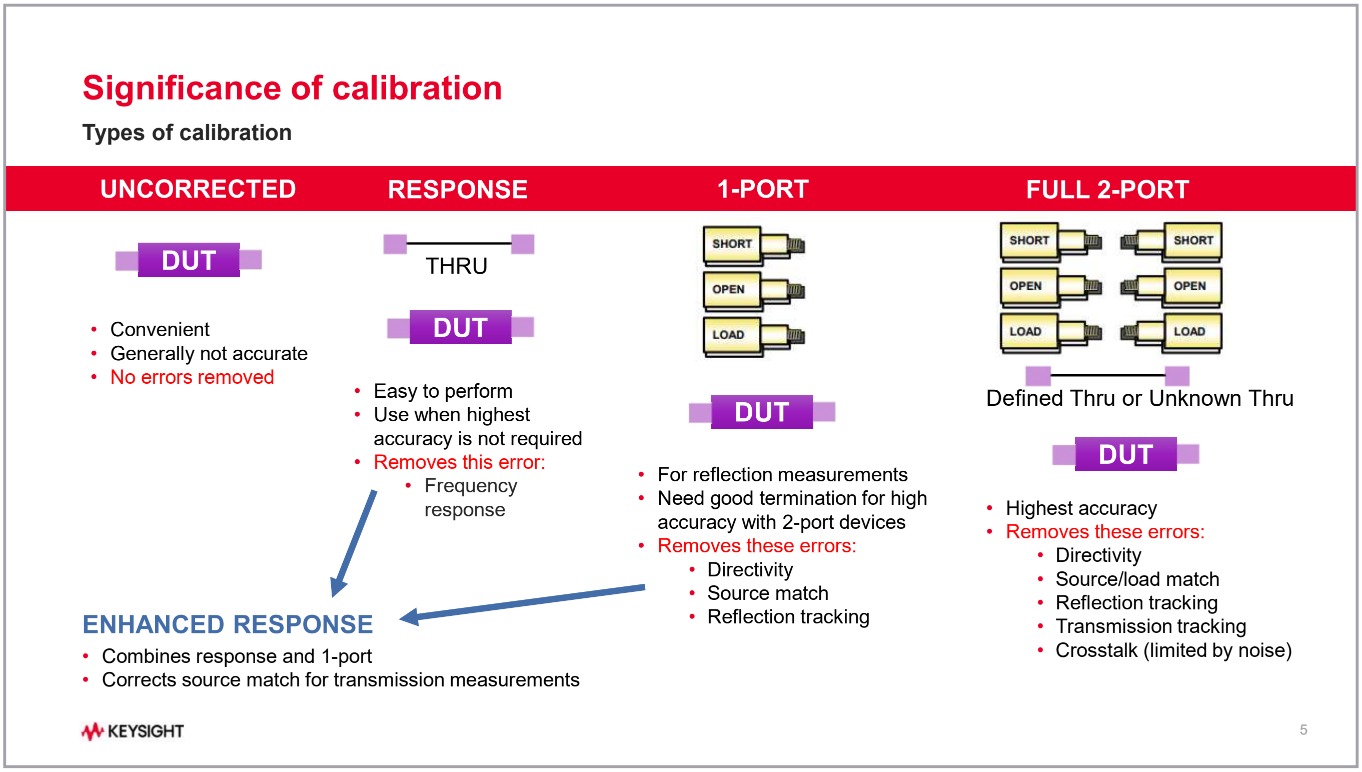
Drift errors are due to the instrument or test-system performance changing *after* a calibration has been done. Drift is primarily caused by temperature variation and it can be removed by further calibration(s). The timeframe over which a calibration remains accurate is dependent on the rate of drift that the test system undergoes in the user's test environment. Providing a stable ambient temperature usually goes a long way towards minimizing drift.

Systematic measurement errors

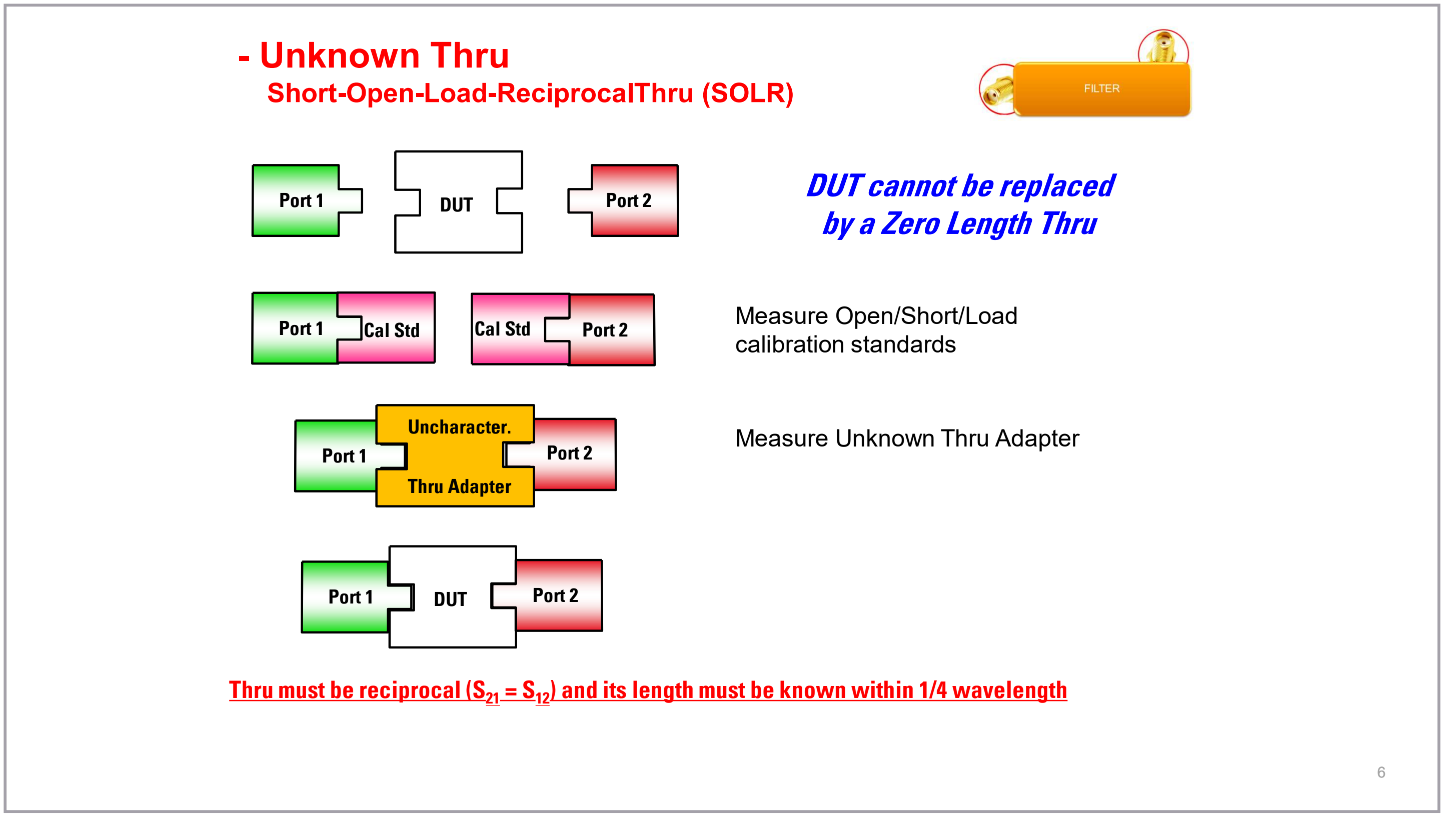


Six forward and six reverse error terms yields 12 error terms for two-port devices

Shown here are the major systematic errors associated with network measurements. The errors relating to signal leakage are directivity and crosstalk. Errors related to signal reflections are source and load match. The final class of errors are related to frequency response of the receivers, and are called reflection and transmission tracking. The full two-port error model includes all six of these terms for the forward direction and the same six (with different data) in the reverse direction, for a total of twelve error terms. This is why we often refer to two-port calibration as twelve-term error correction



Uncorrected measurements give results without removing any systematic errors. A response cal is simple but only corrects for frequency response errors. In a 1-port cal, directivity, source match, and reflection tracking is measured and removed. Vector Error Correction is the process to characterize all major sources of systematic error, like directivity and crosstalk, by measuring known calibration standards. You will need to perform a 2-port cal to remove all 12 sources of error for forward and reverse measurements. This is done by performing 12 measurements on 4 standards (short, open, load, and thru, or SOLT)



The unknown thru calibration technique is used when a "flush" (zero-length or mate-able) thru cannot be used or when using a flush thru would cause measurement impairment from cable movement. It is a refinement of SOLT calibration, and is also called short-open-load-reciprocal-thru (SOLR) calibration. The unknown thru technique eliminates the need for matched or characterized thru adapters, and largely eliminates the need to move or bend test cables. It works great for many component-measurement challenges such as non-insertable devices, mechanically difficult situations, and for multiport devices.

The requirements for the unknown thru calibration are first, the normal reflection error terms (directivity, source match, and reflection tracking) can be acquired for each test port. This is accomplished by measuring shorts, opens, and loads, or by using ECal. The only constraint of the "unknown" thru standard is that it is reciprocal (i.e., S21=S12) and it's insertion phase must be known to within a quarter wavelength of the highest frequency of the measurement (i.e., the approximate group delay of the thru must be known). Other than that, the thru can have and arrangement of connectors, can be any length and shape, and can be very lossy (more on this later). One final constraint on the test system is that it must be capable of measuring the difference between the source match and load match on each test port, which is a normal TRL constraint. These differences in port match are due to the internal transfer switch within the analyzer, and they are used to calculate switch-correction terms that are a part of the TRL algorithm. The switch error terms can be directly measured with most two-port analyzers with two reference receivers, or by a two-tier calibration for analyzers with a single reference receiver (like the 4-port PNA-L) or for systems with external test sets. More discussion of this topic is in the section “TRL Calibration for Single-Reference Receiver VNAs”.

Using known standards to correct for systematic errors

Response calibration *(normalization)*

- Only 1 systematic error term measured
- Reflection tracking

1-port calibration *(reflection measurements)*

- Only 3 systematic error terms measured
- Directivity, source match, and reflection tracking

Full 2-port calibration *(reflection and transmission measurements)*

- 12 systematic error terms measured
- 10 measurements on four known standards (SOLT)
- 7 measurements using Unknown Thru; 4 measurements using QSOLT

Standards defined in cal kit definition file

- **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
- Network analyzer contains standard cal kit definitions
- User-built standards must be characterized and entered into user cal-kit

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Vector-error correction is the process of characterizing systematic error terms by measuring known calibration standards, and then removing the effects of these errors from subsequent measurements.

One-port calibration is used for reflection measurements and can measure and remove three systematic error terms (directivity, source match, and reflection tracking). Full two-port calibration can be used for both reflection and transmission measurements, and all twelve systematic error terms are measured and removed. Two-port calibration usually requires twelve measurements on four known standards (short-open-load-through or SOLT). Some standards are measured multiple times (e.g., the through standard is usually measured four times). The standards themselves are defined in a cal-kit definition file, which is stored in the network analyzer. Keysight network analyzers contain all of the cal-kit definitions for our standard calibration kits. In order to make accurate measurements, the cal-kit definition MUST MATCH THE ACTUAL CALIBRATION KIT USED! If user-built calibration standards are used (during fixtured measurements for example), then the user must characterize the calibration standards and enter the information into a user cal-kit file. Sources of more information about this topic can be found in the appendix.

ECal: Electronic Calibration

- Variety of two- and four-port modules cover 300 kHz to 67 GHz
- Nine connector types available, 50 and 75 ohms
- Single-connection calibration
  - dramatically reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated characterized terminations provide excellent accuracy

Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

Although the previous slides have all shown mechanical calibration standards, Keysight offers a solid-state calibration solution which makes two-port calibration fast, easy, and less prone to operator errors. A variety of calibration modules are available with different connector types and frequency ranges. The calibration modules are solid-state devices with programmable, repeatable impedance states. These states are characterized at the Keysight factory using a network analyzer calibrated with coaxial, airline-TRL standards (the best calibration available), making the ECal modules transfer standards (rather than direct standards).

For the microwave calibration modules, the various impedance states are achieved by PIN-diode switches which shunt the transmission line to ground. The number of diodes and their location vary depending upon the module's frequency range. A multitude of reflection coefficients can be generated by applying various combinations of the shunts. With no shunts, the network acts as a low loss transmission line. High isolation between the ports is obtained by driving several of the PIN shunts simultaneously. Four different states are used to compute the error terms at each frequency point. Four states are used because this gives the best trade-off between high accuracy and the time required for the calibration. With four reflection states, we have four equations but only three unknowns. To achieve the best accuracy from this over-determined set of equations, a least-squares-fit algorithm is used. Adding more impedance states at each frequency point would further improve accuracy but at the expense of more calibration time.

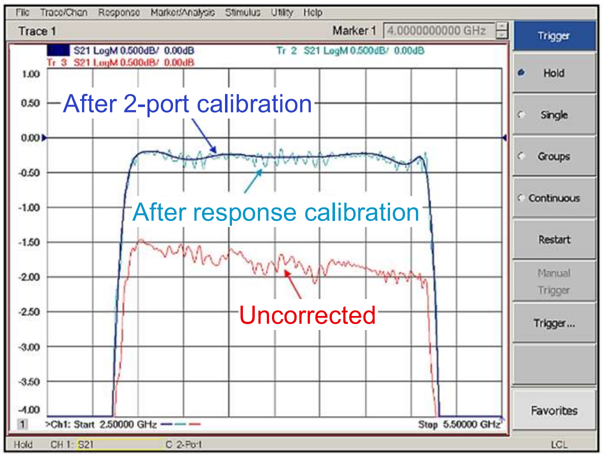
The RF module uses the more traditional short, open, and load terminations, and a through transmission line.

For more information about these products, please order Keysight literature number 5963-3743E.

VNA showing band pass filter

Uncalibrated, response cal and full 2-port cal

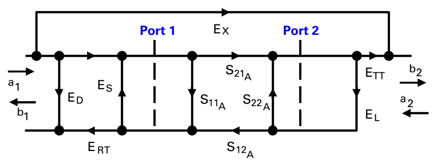
Measuring filter insertion loss



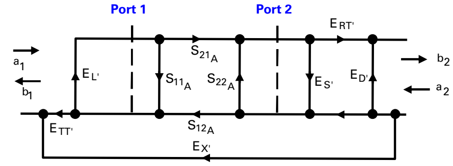
NA screen showing S21 if Bandpass Filter, one trace is uncalibrated, one trace after response CAL and one trace after full 2-port CAL

Two-Port Error Correction

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking
E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** a network analyzers!!!

$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D'}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{R.}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

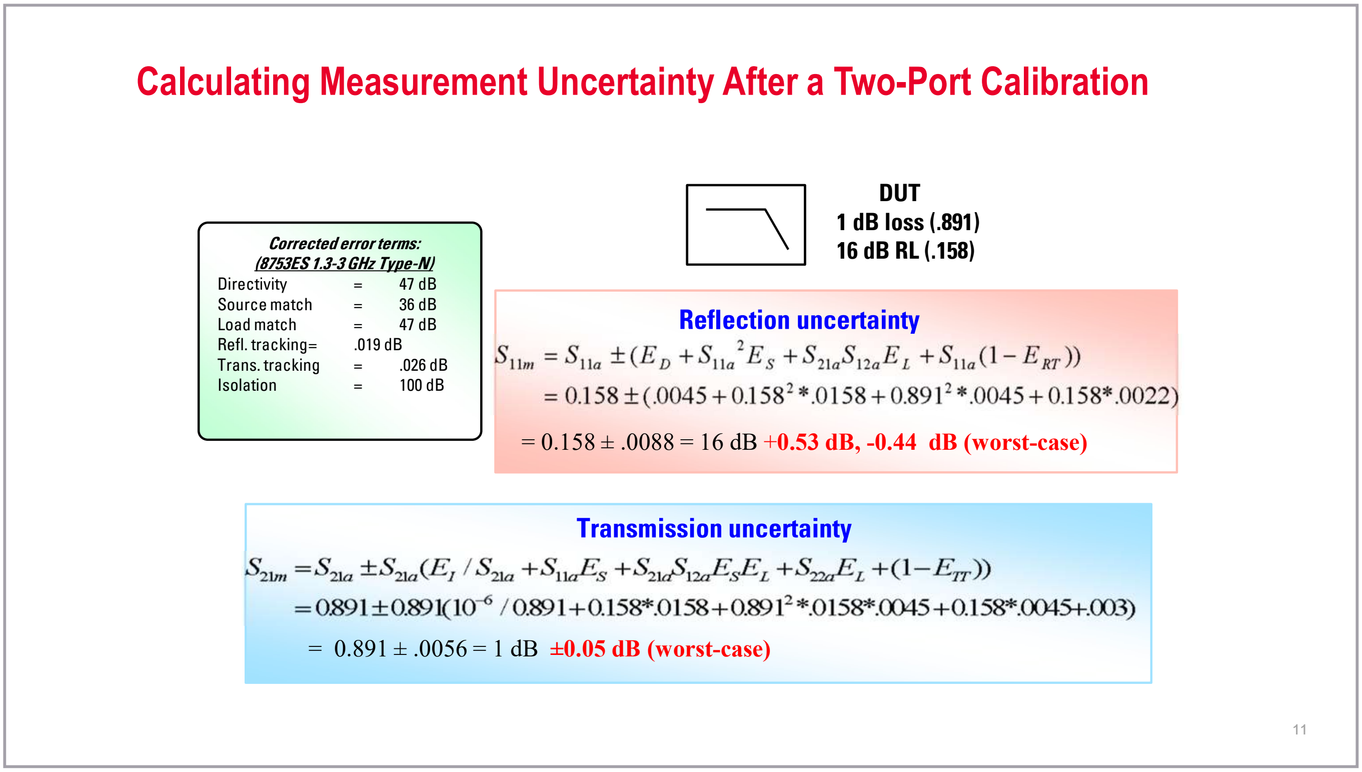
Two-port error correction is the most accurate form of error correction since it accounts for all of the major sources of systematic error. The error model for a two-port device is shown above. Shown below are the equations to derive the actual device S-parameters from the measured S-parameters, once the systematic error terms have been characterized. Notice that each actual S-parameter is a function of all four measured S-parameters. The network analyzer must make a forward and reverse sweep to update any one S-parameter. Luckily, you don't need to know these equations to use network analyzers!!!

$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D'}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$



Slide 69

Here is an example of calculating measurement error after a two-port calibration has been done. Agilent provides values on network analyzer data sheets for effective directivity, source and load match, tracking, and isolation, usually for several different calibration kits. The errors when measuring our example filter have been greatly reduced (±0.5 dB reflection error, ±0.05 dB transmission error). Phase errors would be similarly small.

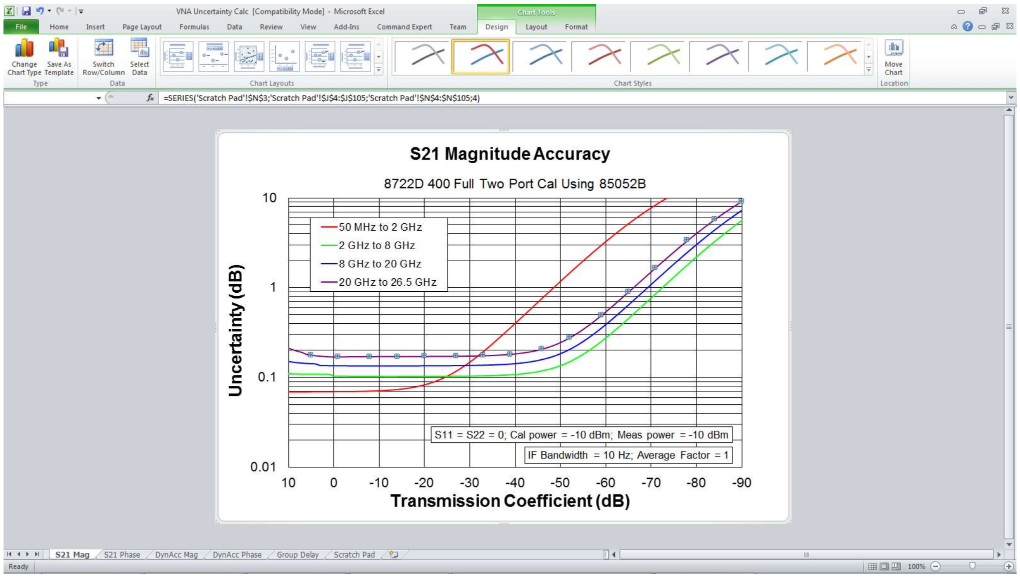
Note that this is a worst-case analysis, since we assume that all of the errors would add in-phase. For many narrowband measurements, the error terms will not all align with one another. A less conservative approach to calculating measurement uncertainty would be to use a root-sum-squares (RSS) method. The best technique for estimating measurement uncertainty is to use a statistical approach (which requires knowing or estimating the probability-distribution function of the error terms) and calculating the ± 3σ (sigma) limits.

The terms used in the equations are forward terms only and are defined as:

E_D	= directivity error
E_S	= source match
E_L	= load match
E_{RT}	= reflection tracking
E_{TT}	= transmission tracking
E_I	= crosstalk (transmission isolation)
a	= actual

m	= measured

Use VNA Uncertainty Calculator for Uncertainty calculations



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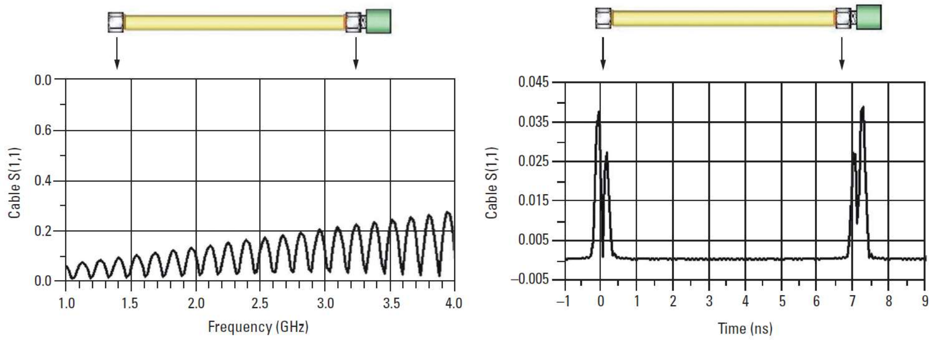
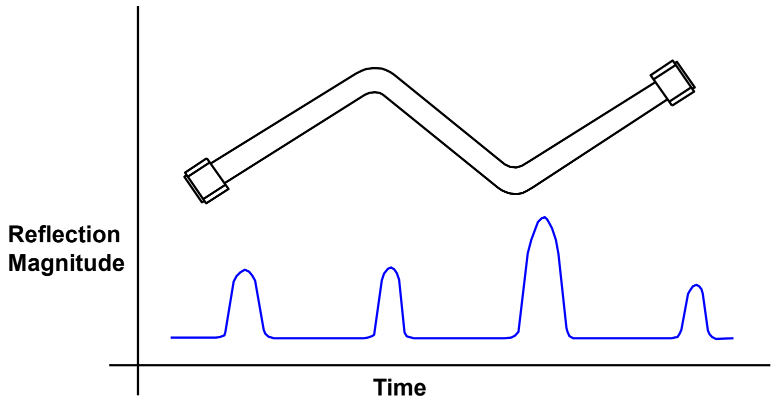
Time Domain Measurements

Basics of Time Domain Measurements



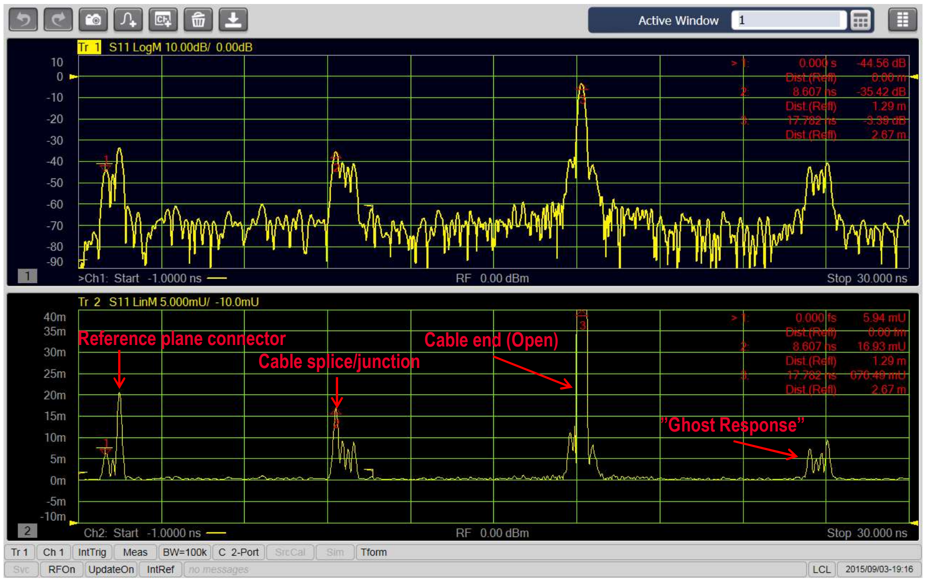
Frequency Domain **Time Domain**

Time Domain S_{11} Response of Semi-rigid Coax Cable



After selecting the time domain and the inverse Fourier transform has been computed, a time domain trace is displayed. When compared to the physical cable, it is easy to see the reflection responses of the connectors and bends of the cable. On the vertical axis is the reflection coefficient and on the horizontal axis is time (proportional to distance to reflection). In this case, the largest reflection is coming from the second bend (left to right). Now we have an idea of where to concentrate our troubleshooting efforts.

Reflection Time Domain Measurements (S11 Open)



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Reflection Time Domain Measurements (S11 Term.)

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Reflection Time Domain Measurements (S11 bad cable)

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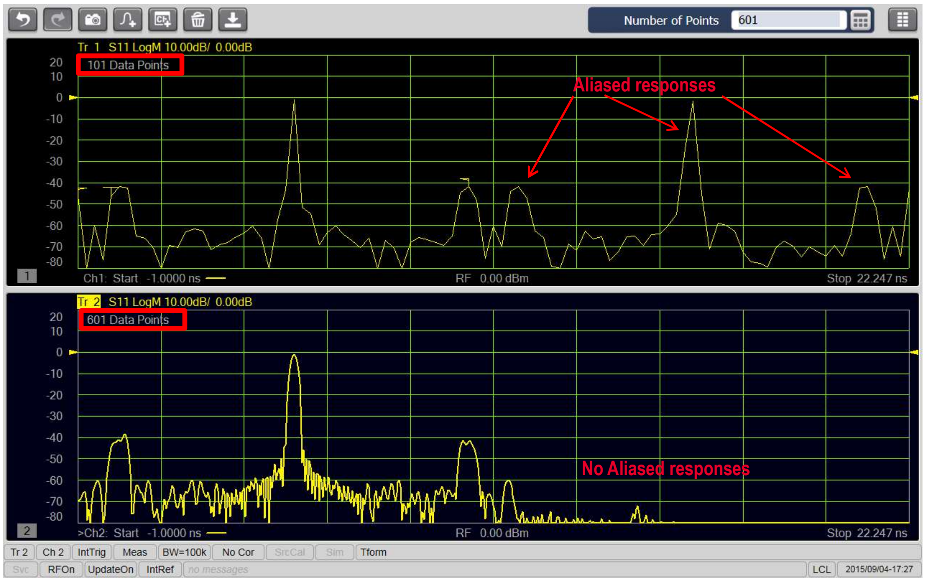
Aliased Responses In Time Domain (S11)



If you double the number of measurement points the alias free measurement range is also doubled!

Maximum Alias Free Measurement Range

$\boxed{\text{Range (m)} = (1/\Delta f) \times V_f \times c}$

Where:

Δf = frequency step size (which is frequency span/number of points)
V_f = the velocity factor in the transmission line
c = speed of light = 3×10^8 m/s (2.997925×10^8 m/s to be precise)
(Most cables have a relative velocity of 0.66 for polyethylene dielectric or 0.7 for PTFE dielectric)

For a measurement with 401 points and a span of 2.5 GHz, using a polyethylene cable, the time domain range must be 32 meters or less.

Above calculation is for transmisson measurement (s21, S12)
Divide maximum range by 2 for reflection measurements (S11, S22)

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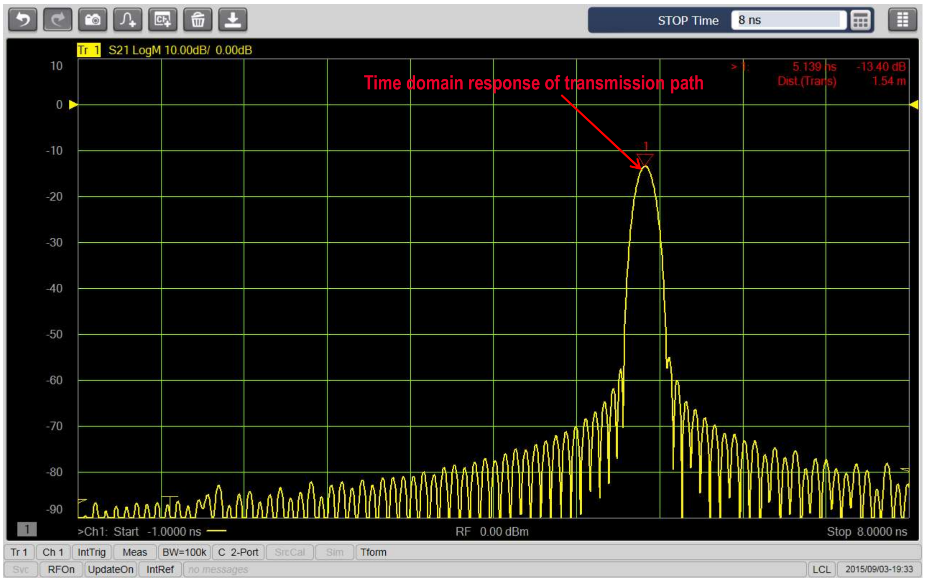
Transmission Time Domain Measurements (S21)



Measured response thru a network with only one transmission path

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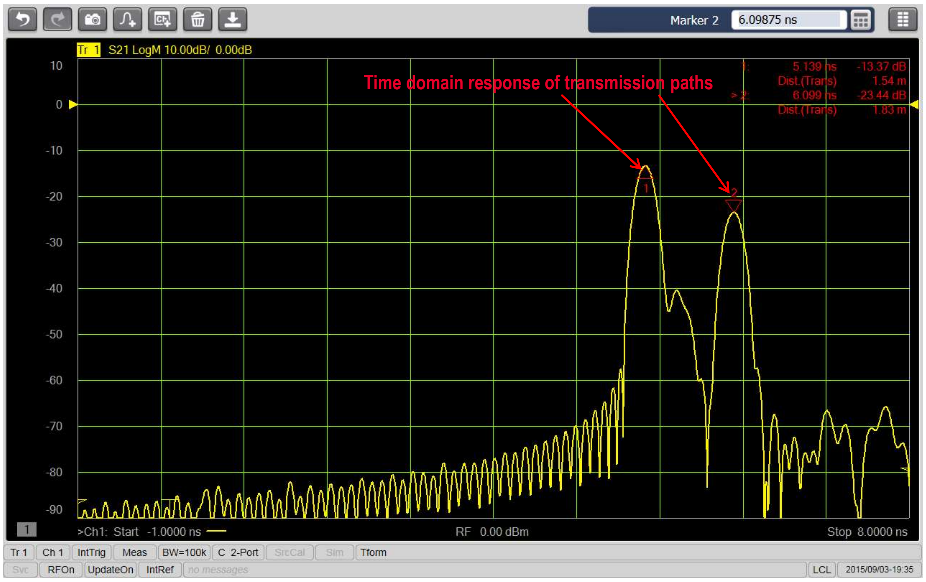
Transmission Time Domain Measurements (S21)



Measured response thru a network with two transmission paths

Thank you