Automatic Fixture Removal (AFR) Training

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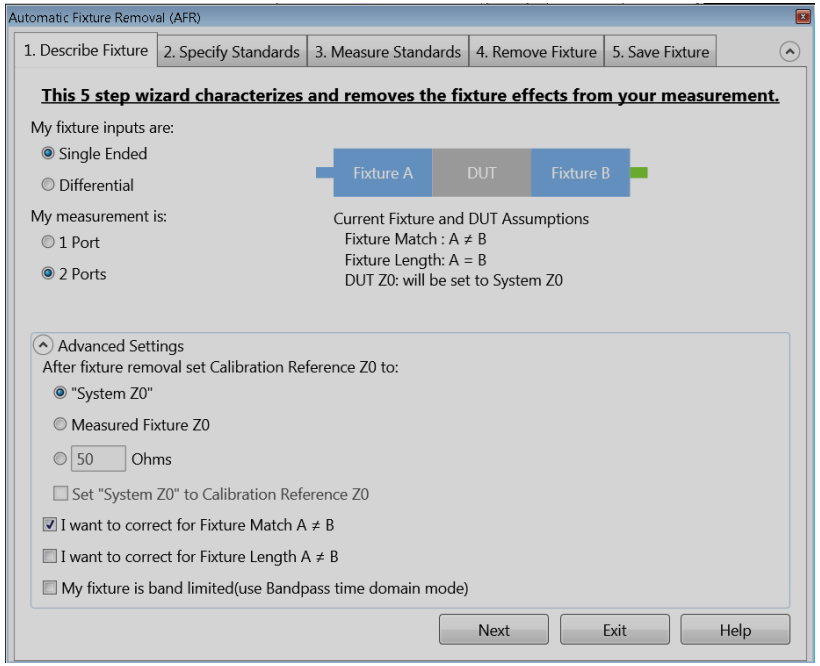
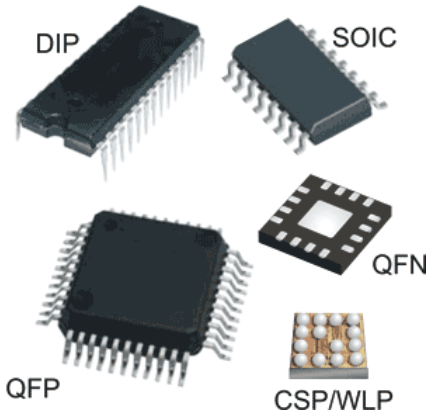
Agenda

- Automatic Fixture Removal (AFR) Overview
- Comparison
- Wizard Demonstration

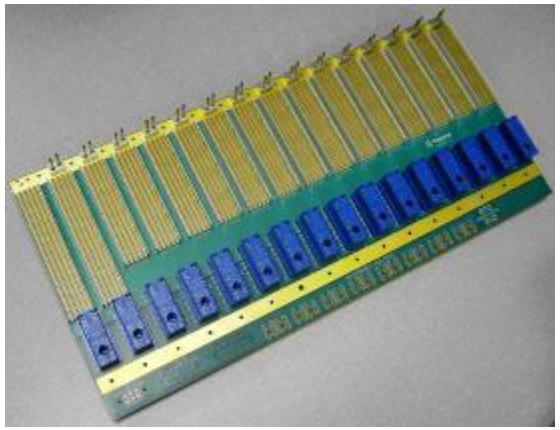


Measurement Challenges



IC packages

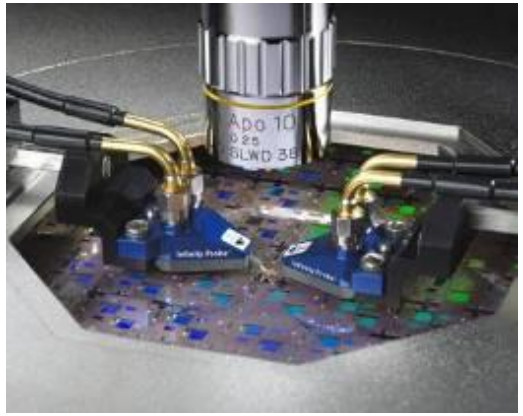
USB connector



Backplane

- Linear passive interconnect devices often have non-coaxial connectors, so they cannot be connected to test instruments with coaxial port connectors
- Accurately removing the effects of the fixture is required to get a good measurement of the device under test (DUT).
- Before AFR, commonly used fixture removal methods were complicated and time consuming.

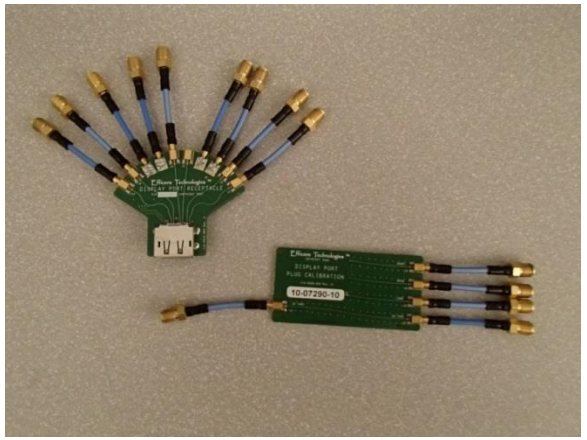
Traditional Methods of Measuring Non-coaxial Devices



Probing on the device for measurement

Drawback:

1. Probe station is expensive
2. Need probe cal kit and models for probe calibration



Building test fixtures for coaxial to microstrip/stripline transition

Drawback:

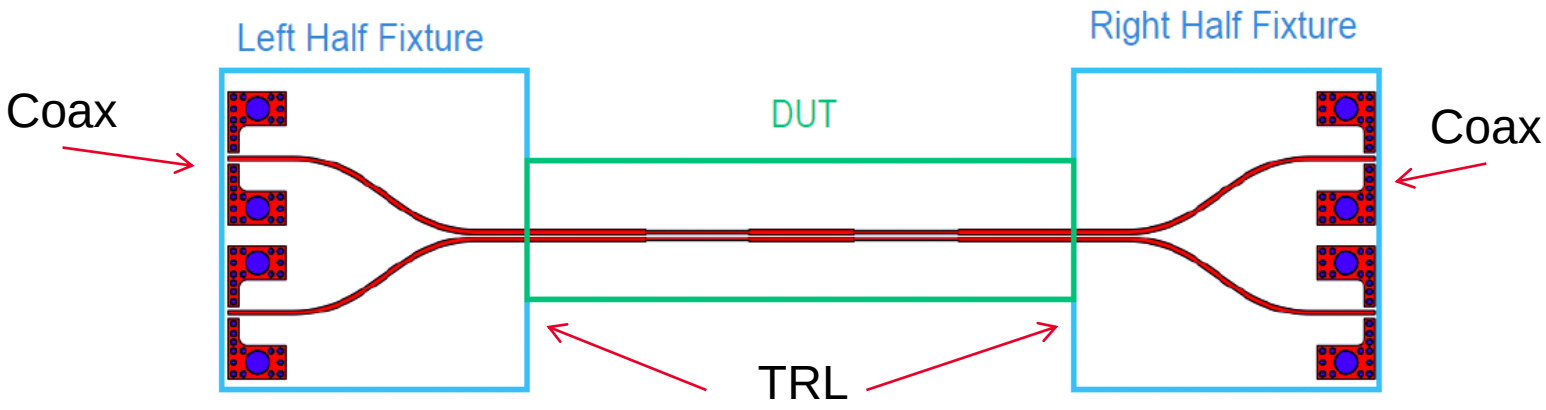
1. The fixtures are not electrically transparent, they have mismatch, loss and delay, they need to be characterized and removed from the DUT measurement
2. The fixtures also have non-coaxial connectors and cannot be measured directly

We'll focus on solving fixturing problem in this presentation

Traditional Fixture Removal Techniques

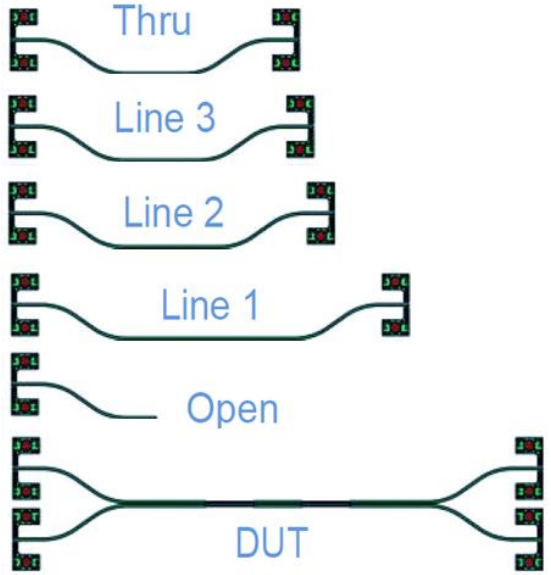
Historically – 2 methods:

- Model fixture using EM Simulation and de-embed the fixtures from the measurement
- Use a TRL calibration technique to move measurement reference planes to the DUT.

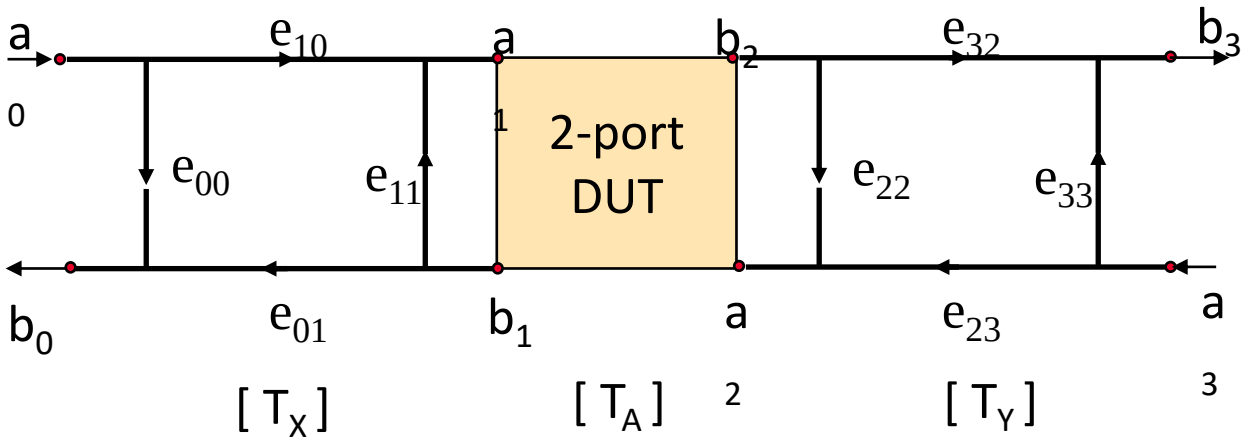


TRL Calibration (Single Ended)

- Assumptions for single ended TRL
  - Connectors and launches are identical
  - All lines have same Transmission Line characteristics
    - Impedance, loss, propagation
    - Only differ in length
  - Lines are usable 20 to 160 degrees relative to thru
  - Usually 2-4 lines depending on frequency range
  - For differential fixtures
    - No coupling in fixture is removed



By the way, why 20 to 160 degrees?



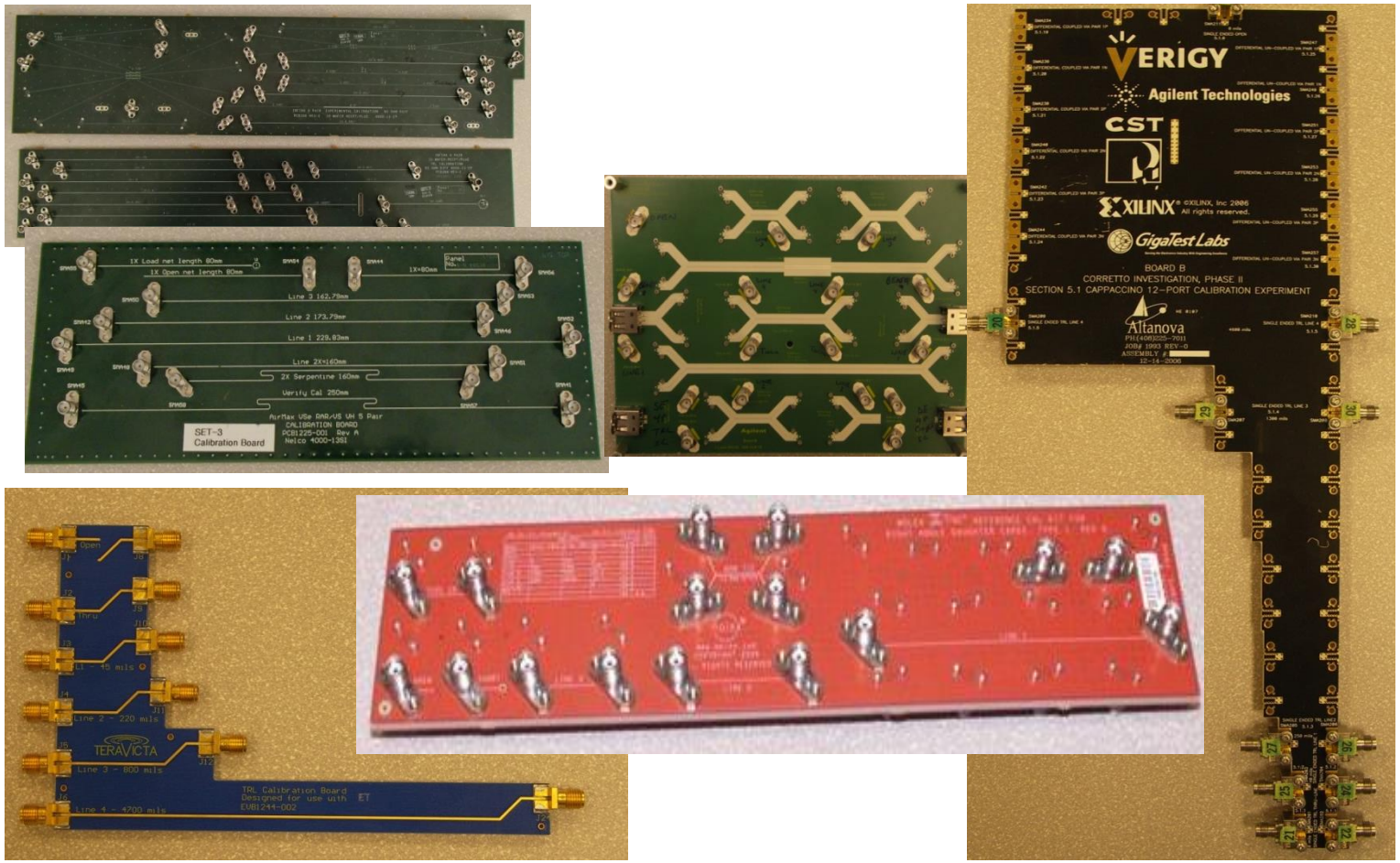
$$[T_m] = [T_X]\,[T_A]\,[T_Y]$$

Thru step: $[T_{mt}] = [T_X]\,[T_{At}]\,[T_Y] = [T_X]\,[T_Y]$, where $[T_{At}] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

Delayed line step: $[T_{md}] = [T_X]\,[T_{Ad}]\,[T_Y]$, where $[T_{Ad}] = \begin{bmatrix} e^{-\delta l} & 0 \\ 0 & e^{\delta l} \end{bmatrix}$

When the phase difference of Thru and Line (δl) is close to N * 180 degrees, delayed line matrix almost equals to Thru matrix, the measurement uncertainty is much bigger

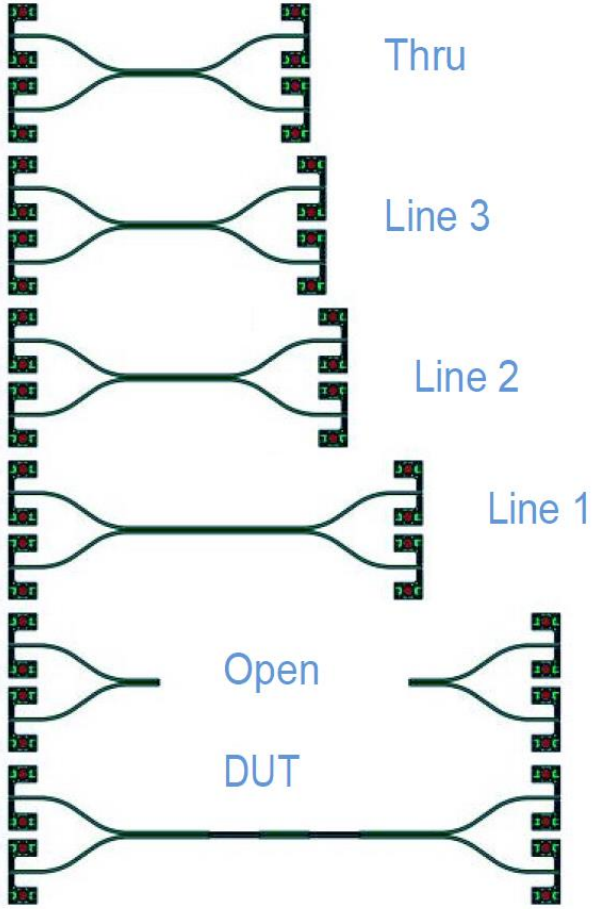
TRL Calibration (Single Ended)



A good TRL cal kit is difficult to design and fabricate due to launch repeatability, PCB impedance variations, and typical PCB manufacturing tolerances

Even more complicated - Differential Cross talk calibration

- 4-port TRL Calibration Technique
  - Available in Keysight PLTS software
- Fixture may be asymmetric
- Similar assumptions to single ended TRL
  - Repeatability of connector, launch, and line
  - lines are usable 20 to 160 degrees relative to thru
- Additional differential constraints
  - SDCnm and SCDnm < -30 dB
  - Skew between lines < 10 degrees
- Coupling in fixture is removed

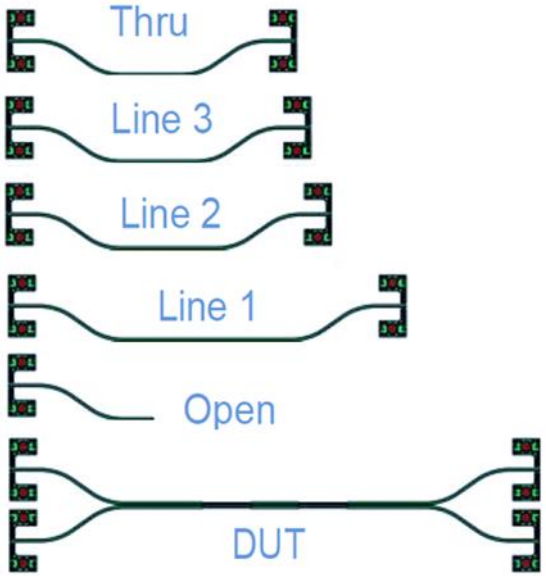


Automatic Fixture Removal

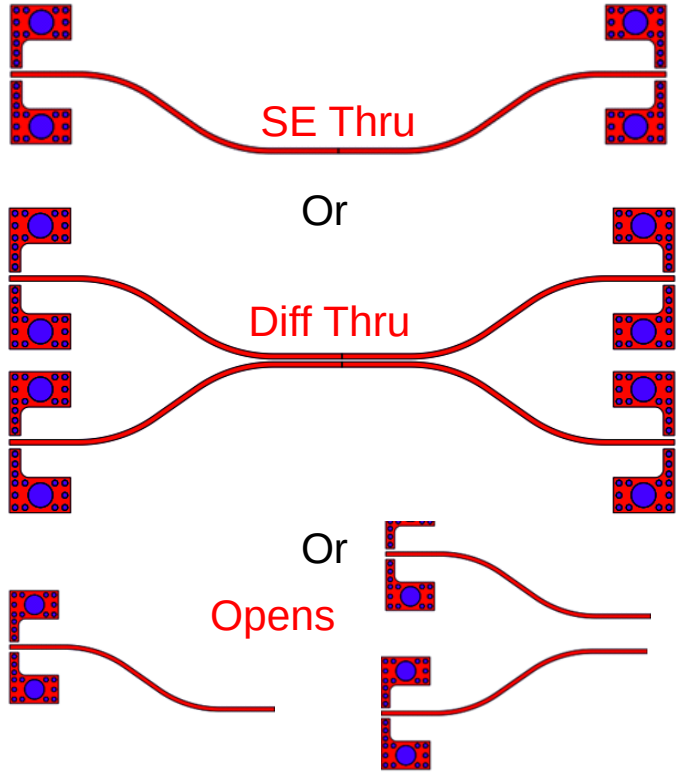
THE SOLUTION IS AFR

- AFR is the fastest and easiest way to de-embed a fixture from a non-coaxial device measurement.
- option S93007B the same powerful AFR in PLTS2019 software, now available for PNA, PNA-X and PNA-L
- Based on simple cal standards, using time domain gating and signal flow calculations to extract fixtures and do de-embedding.
- Much simpler but same accuracy as TRL calibration.

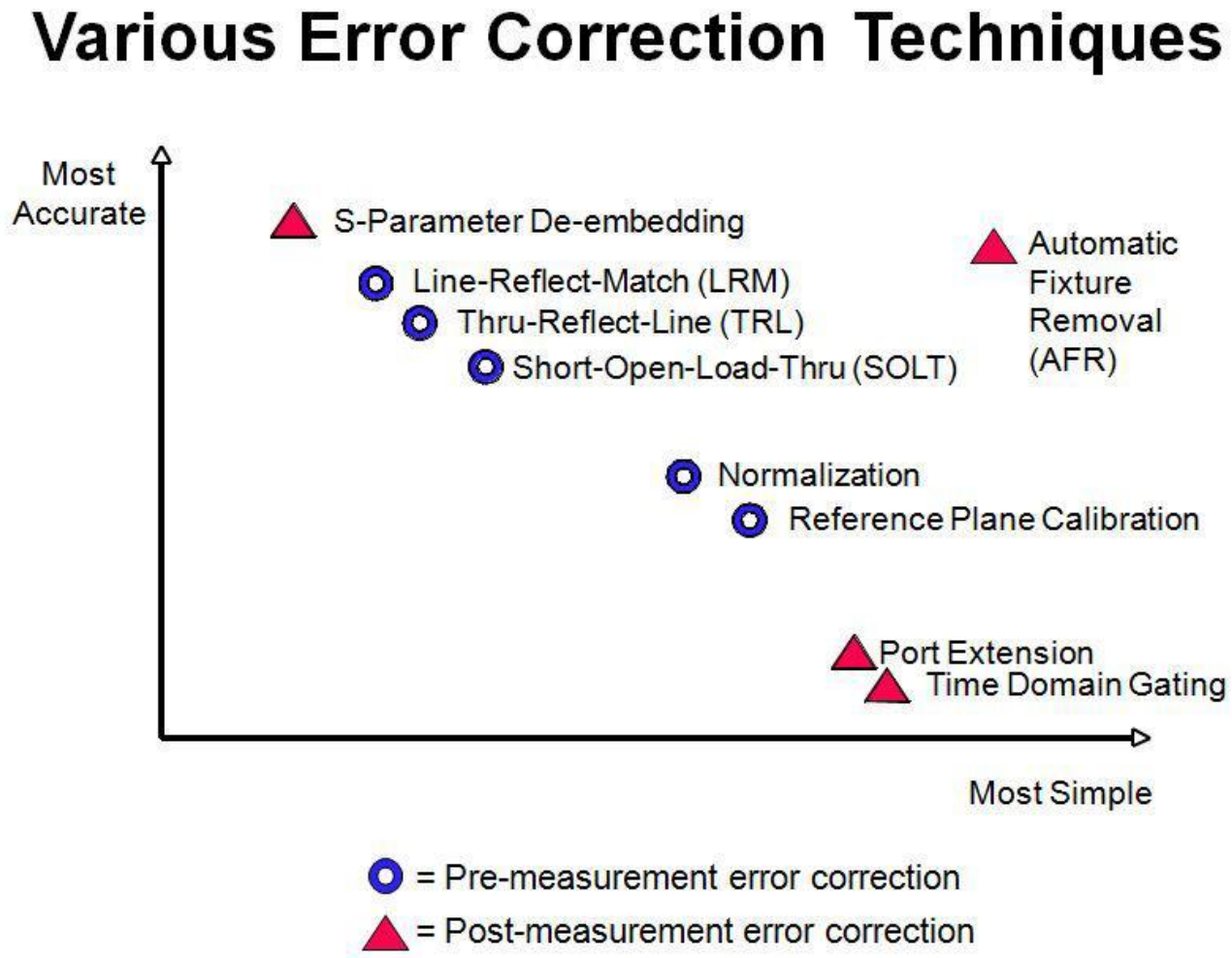
Yesterday's Method: TRL



Today's Method: AFR



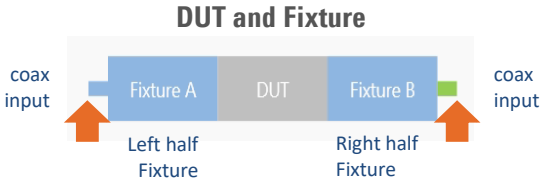
Various Error Correction Techniques



Automatic Fixture Removal Overview

Simple fixture characterization process

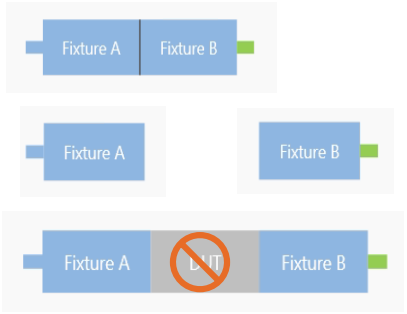
- Calibrate in coax with the reference planes at the inputs to your fixture



Measure one or more standards

- Replica of the fixture's 2 port thru
- Replica of fixture half terminated with an open or short.
- Or, even faster! Measure the fixture itself before the DUT is installed as an open standard.

Powerful features meet a variety of needs



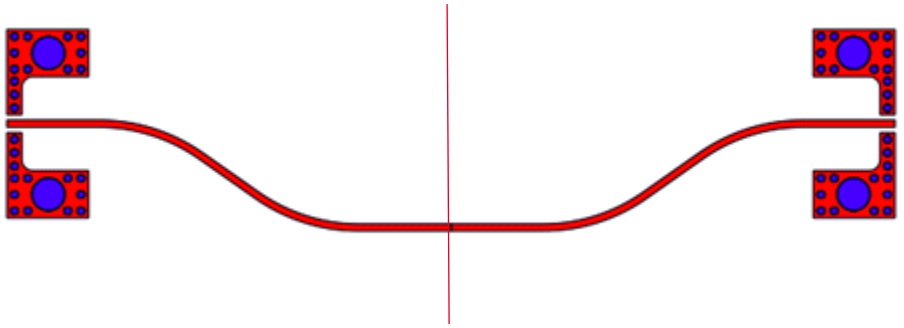
- Single ended and differential devices
- Fixture left and right side can be asymmetrical
- Thru lengths can be specified or determined from open or short measurements.
- Band Pass time domain mode for band limited devices.
- Frequency extrapolation to match DUT
- Power correction compensates for fixture loss vs. frequency
- De-embed files can be saved in a variety of formats for later use in PNA, ADS, & PLTS

Automatic Fixture Removal

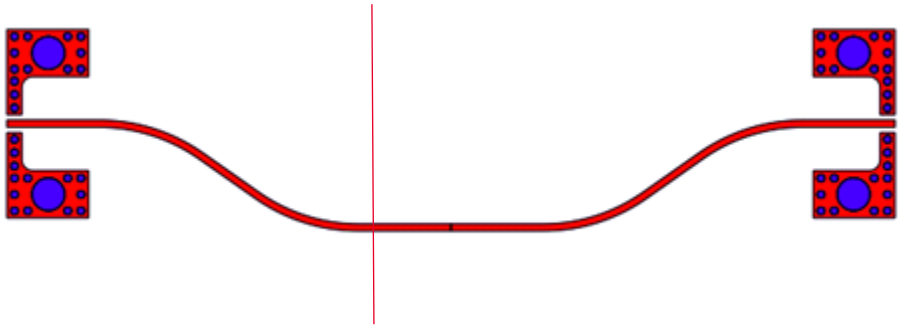
- Assumptions:
  - Originally had to be Symmetric right to left
  - Now it can be Asymmetric
    - in length (2 - 2X thrus required)
    - in match (advanced gating)

- Steps:
  - 1. Calibrate at the cable ends
  - 2. Measure fixture and save file
  - 3. Measure fixtured DUT
  - 4. Remove fixture

Symmetric



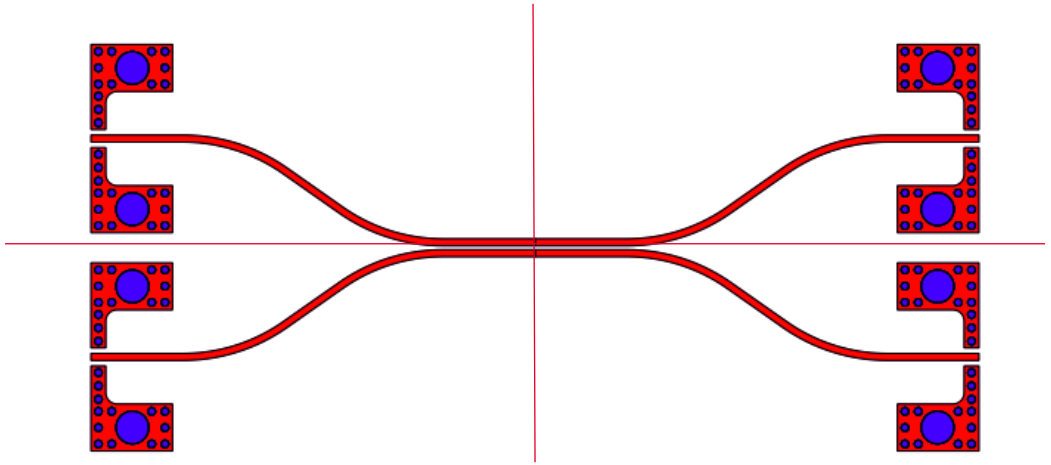
Asymmetric



Differential Automatic Fixture Removal

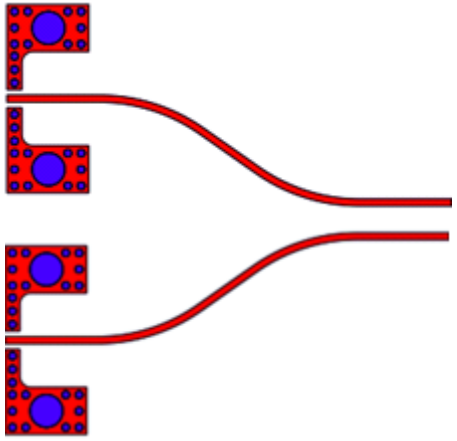
- Assumptions:
  - Originally had to be Symmetric right to left and top to bottom
  - Now it can be Asymmetric
    - in length and match
  - Still needs to b Symmetric top to bottom
    - No mode conversion

- Steps:
  - 1. Calibrate at the cable ends (4-port)
  - 2. Measure fixture and save file
  - 3. Measure fixtured DUT
  - 4. Remove fixture



Automatic Fixture Removal

WITH ONLY OPEN OR SHORT



Applications:

- Easy to fabricate
- Smallest footprint
- Probes – especially GSSG (coupling)
  - measure open and shorted
- Fixtured packages –

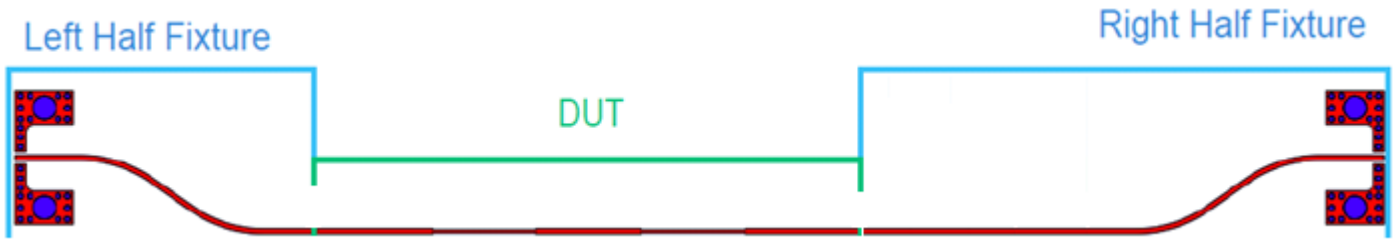
1. measure open fixture
2. measure loaded part

- PC board

1. measure unloaded board
2. load part and measure

Automatic Fixture Removal

- Unknown thru length and fixtured DUT
- Assumption – we can tell where the DUT starts vs. the line.

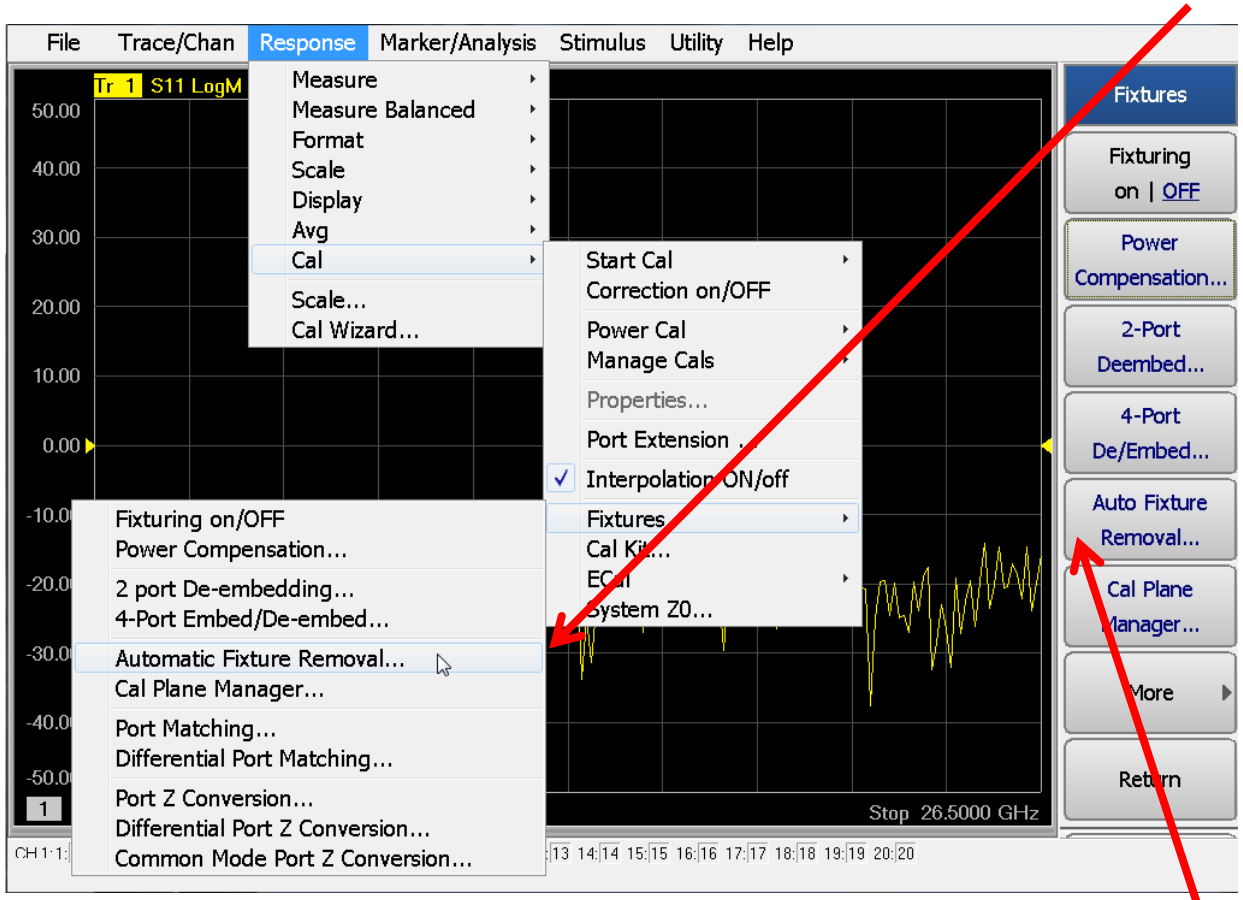


Application:

- Assymetric length fixtures
- Fixture lengths automatically computed
- Example:
  - 3” fixture + 1 “ DUT + 2” fixture
  - Simply copy above and replace DUT with a line and you now have a 6” thru.

Automatic Fixture Removal

Menu: Response\Cal\Fixtures\Automatic Fixture Removal …

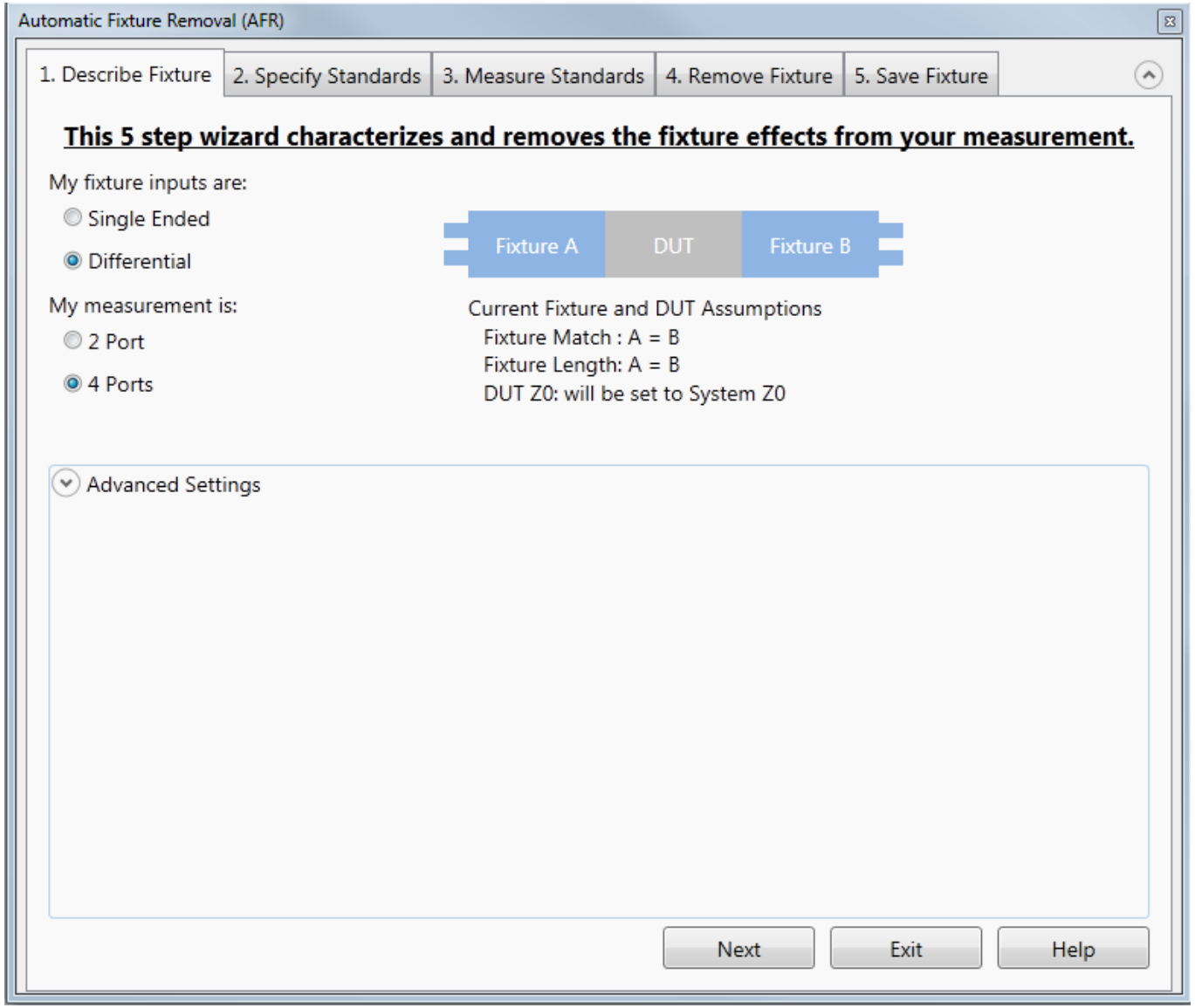


Soft key: Cal -> More -> Fixtures -> Auto Fixture Removal …

Automatic Fixture Removal

- 5 Step Wizard makes it easy to define your fixture and remove it from your measurement.

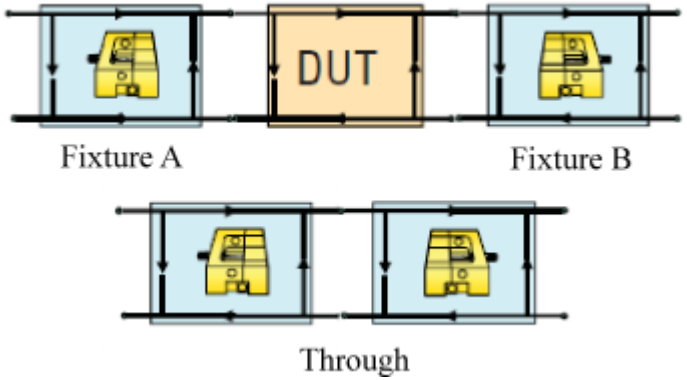
- Advanced selections are collapsed (blanked) by default to keep the wizard clean and simple for standard cases.



Automatic Fixture Removal

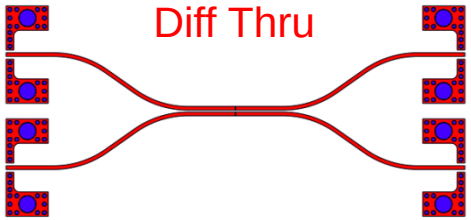
2X THRU

AFR with 2xThru



Concept:

1. Measure the 2xThru with VNA after coaxial calibration
2. Mathematically divide the 2xThru to two halves (based on Time Domain Gating and Signal Flow diagram calculations) to acquire the S-parameters of the two fixtures
3. De-embed the fixtures from the DUT measurement to achieve the real DUT characteristics



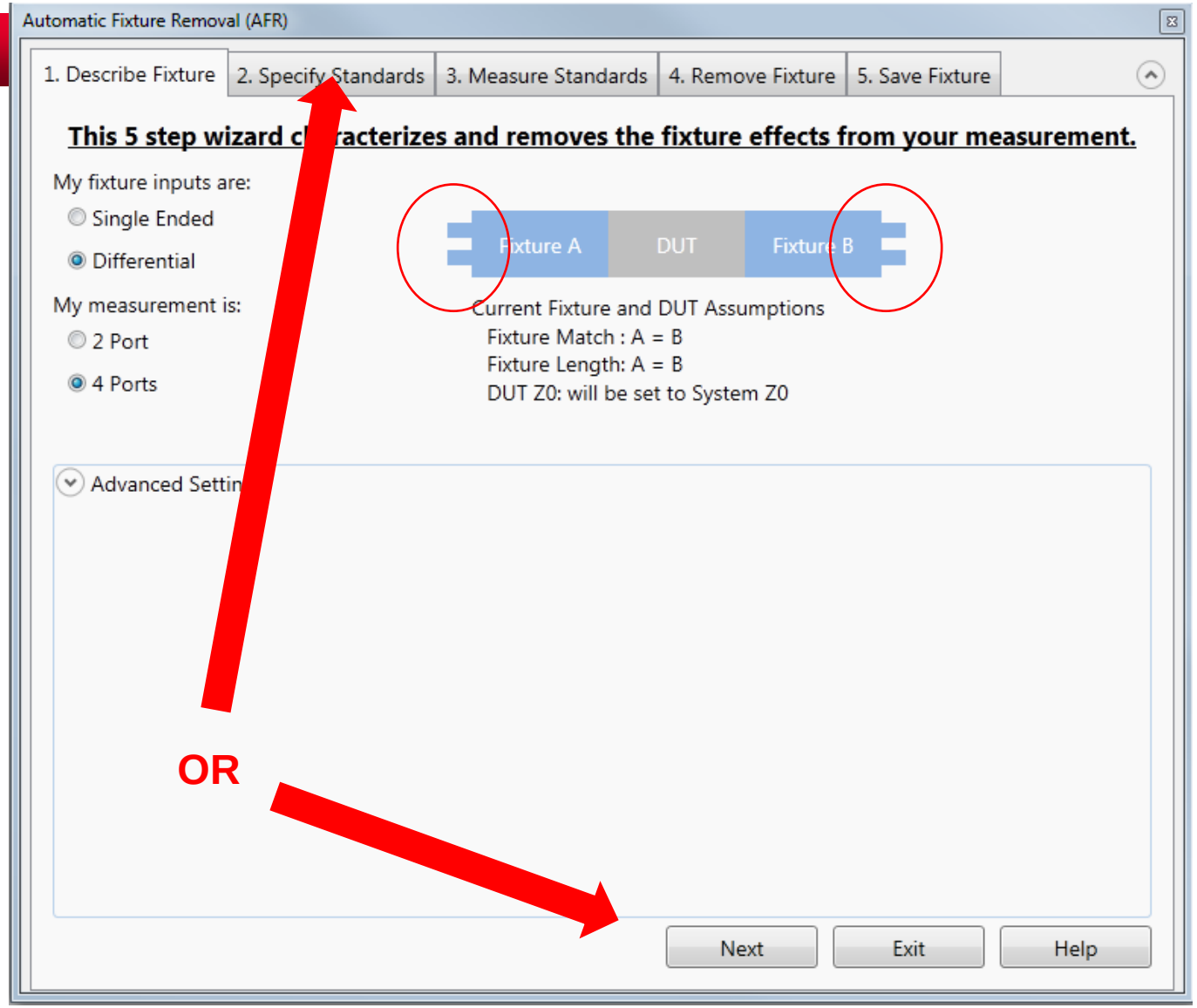
In Differential case: Coupling in fixture is removed

Automatic Fixture Removal

DEFAULT 2X THRU CASE

- Click to select differential measurements instead of single ended.

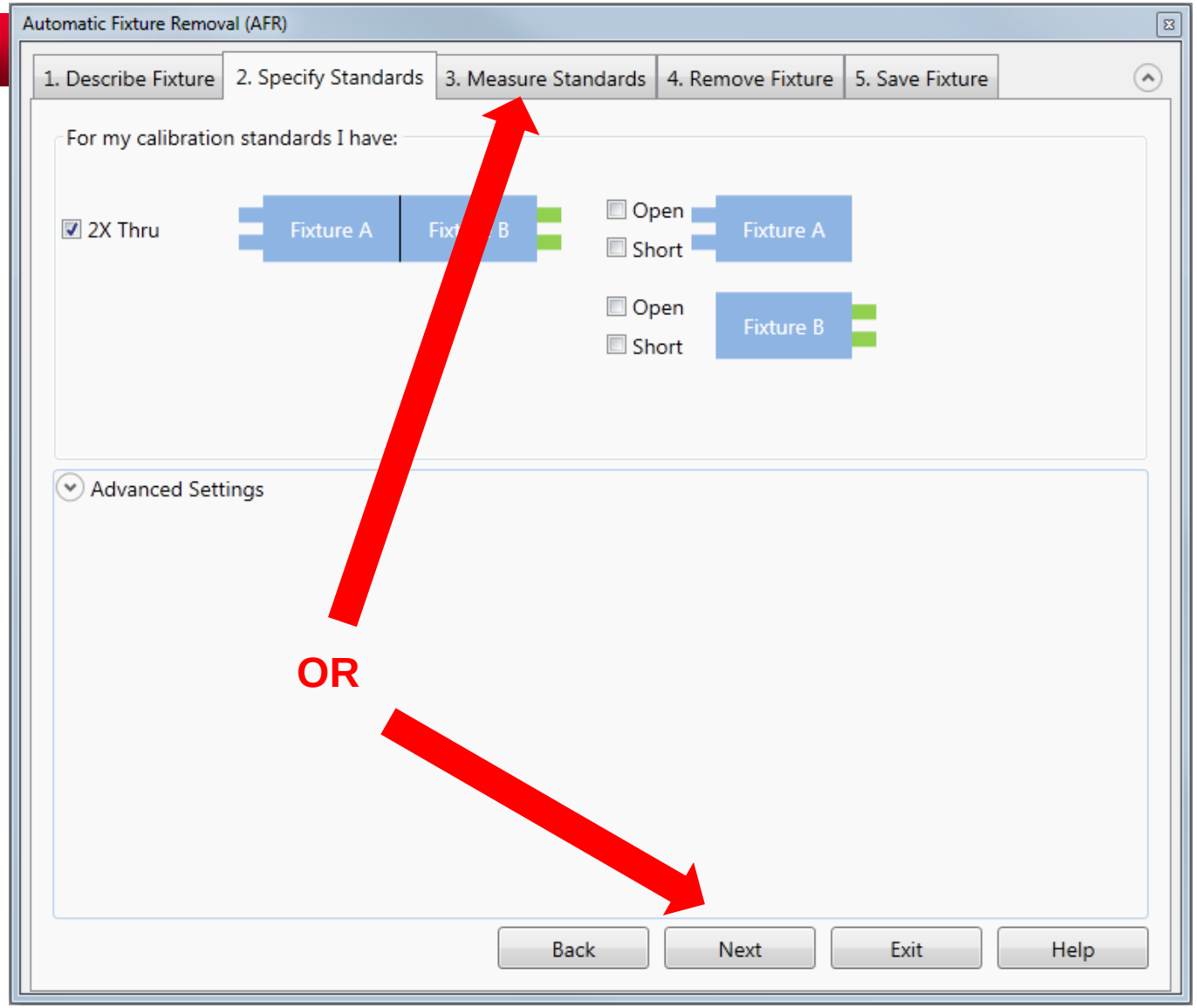
- Just click “Next” or tab 2 to continue.



Automatic Fixture Removal

DEFAULT 2X THRU CASE

- The 2X Thru is still is default for AFR.
- Just click “Next” or tab 3 to continue.



Automatic Fixture Removal

DEFAULT 2X THRU CASE

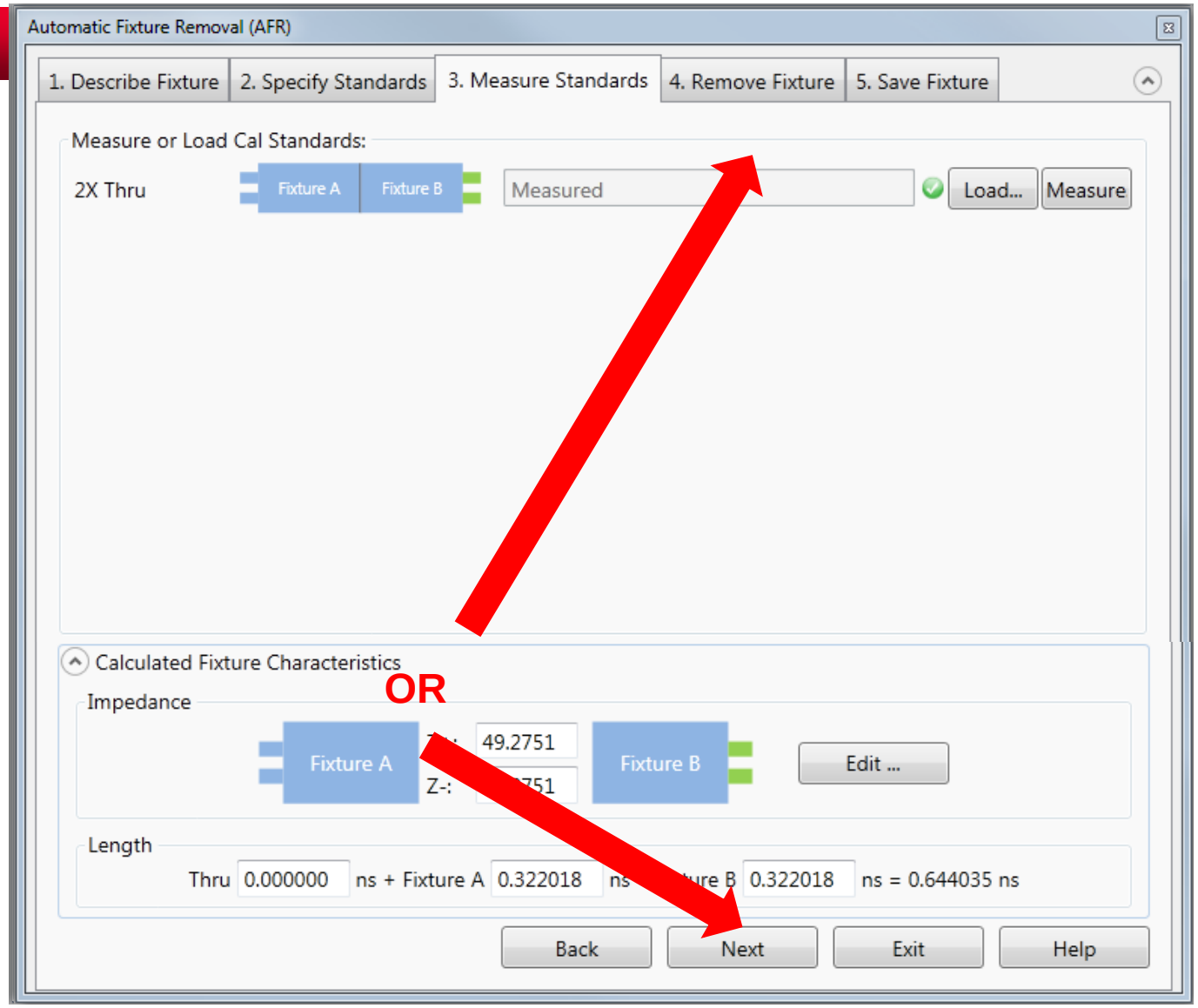
- Click Load …

to load a previously measured standard

- Or click Measure

to load the standard connected to the PNA

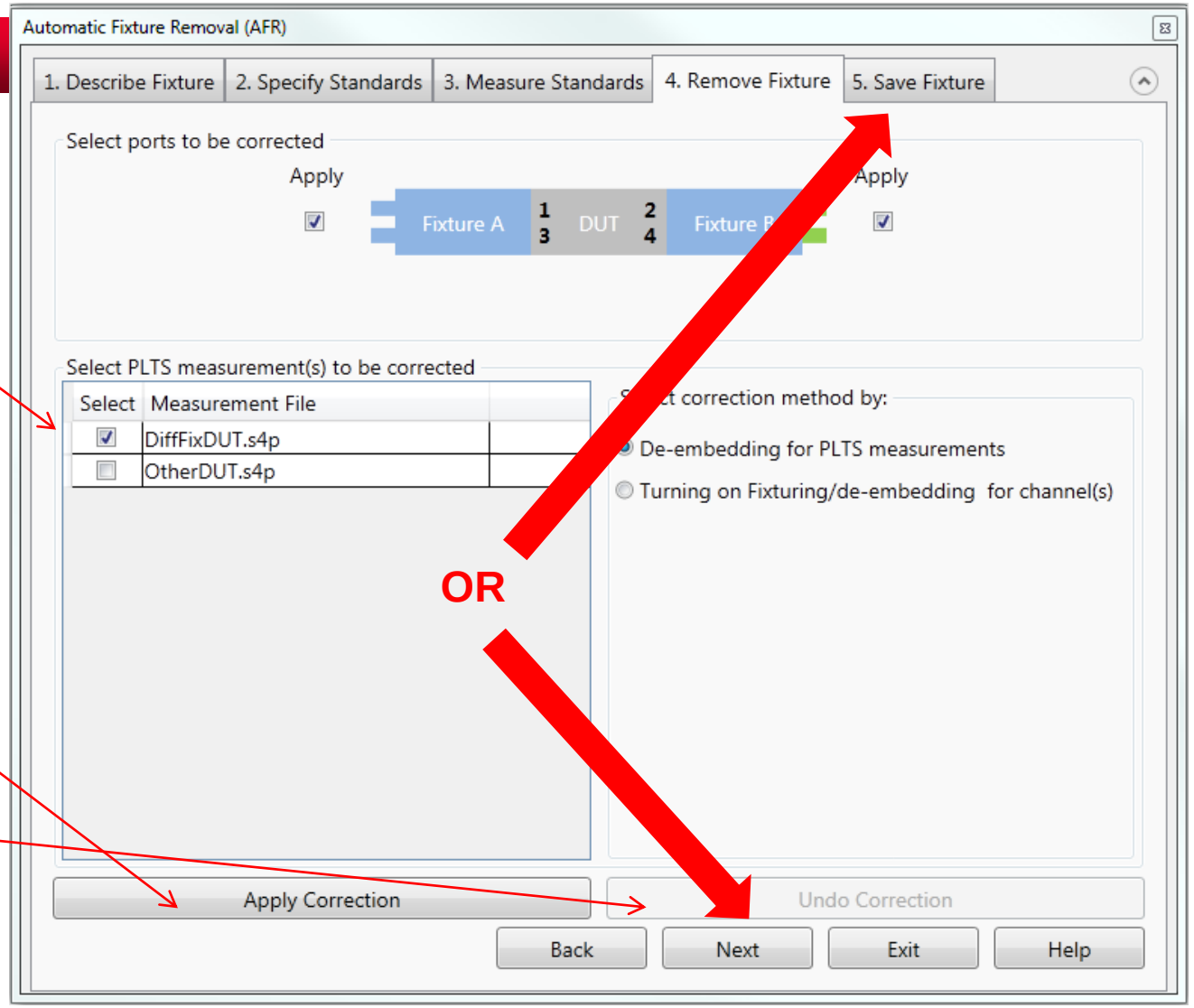
- Measured fixture impedance and length



Automatic Fixture Removal

DEFAULT 2X THRU CASE

- The Active DUT file is automatically selected. Click others if you want to remove fixtures from other files.
- Click “Apply Correction” to remove fixture from measurement(s)
- Click Undo Correction to add fixture back to measurement.



Automatic Fixture Removal

DEFAULT 2X THRU CASE

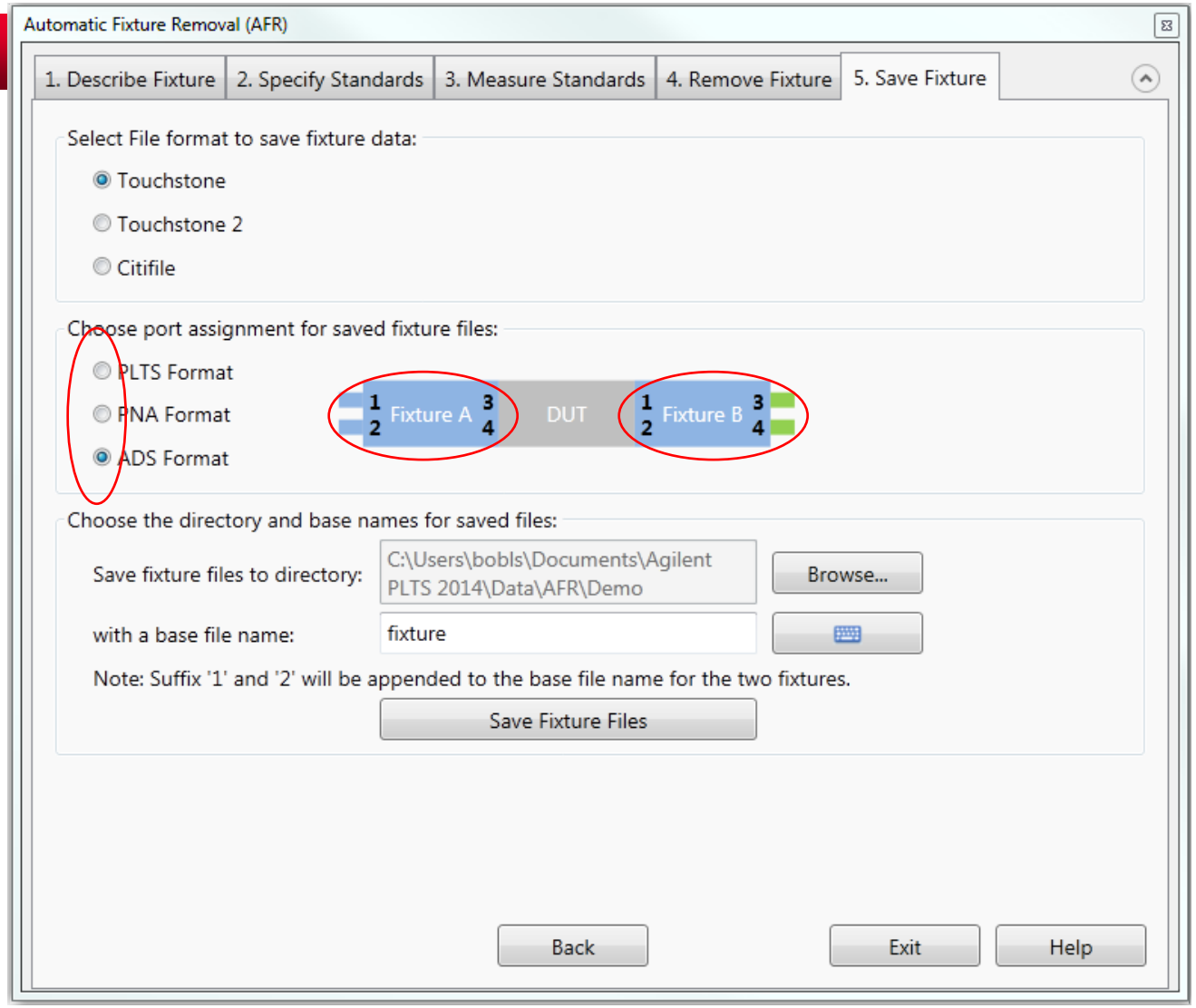
Select File Format

Note Touchstone (1) format has just 1 value for port

Choose Port assignment

Port numbers change with the different formats

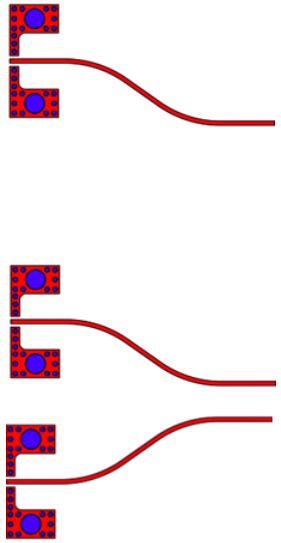
Specify directory and file name



Automatic Fixture Removal

1 PORT OPEN CASE

One-port AFR using Open or Short



Concept:

1. Measure the Open or Short fixture with VNA after standard coaxial calibration
2. Mathematically extract the fixture S-parameters from the Open / Short measurement (based on Time Domain Gating and Signal Flow diagram calculations)
3. De-embed the fixtures from the DUT measurement to achieve the real DUT characteristics

In Differential case: Coupling in fixture is removed

One-port AFR Applications

- Probes – especially GSGSG (coupling)
  - measure open and shorted
- Fixtured packages –
  - measure open fixture
  - measure loaded part
- PC board –
  - measure unloaded board
  - load part and measure

Automatic Fixture Removal

1 PORT OPEN CASE

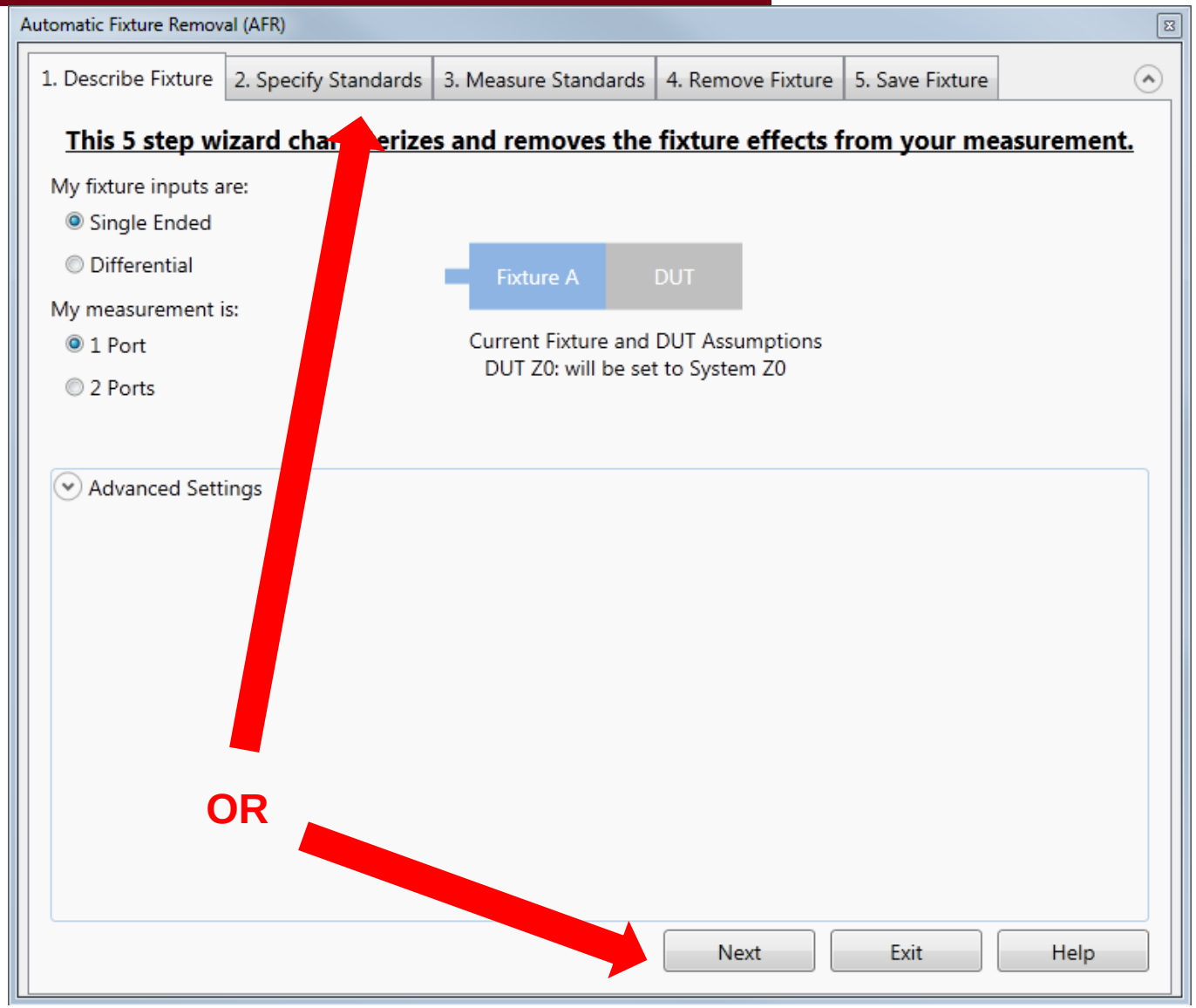
Select Fixture Inputs

PNA Default

Select DUT Ports

Select 1 port

This determines which port (s) to remove fixtures.



Automatic Fixture Removal

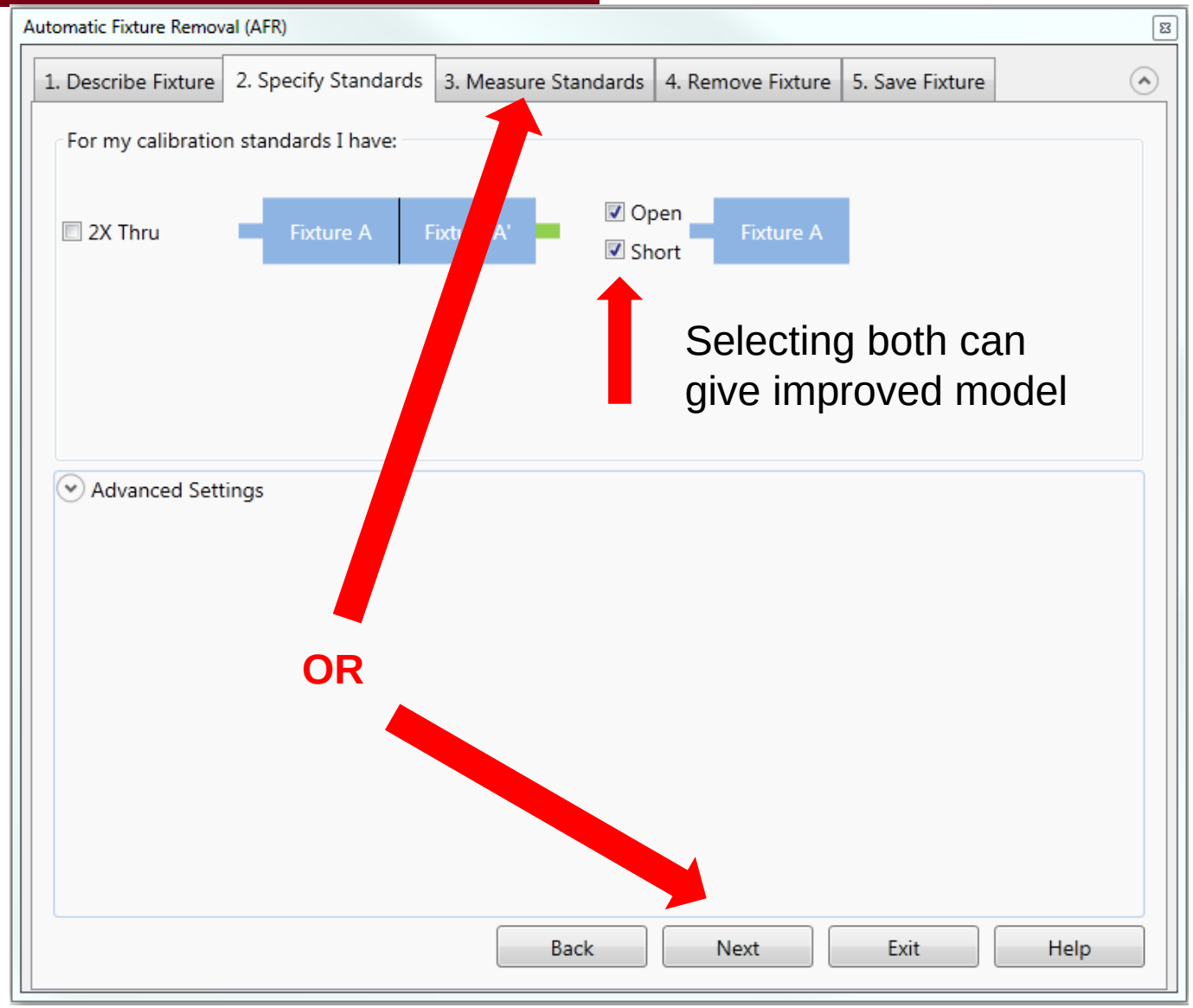
1 PORT OPEN CASE

Select Standards

Open is the default for 1 port measurements

Or select a Short

Or both



Automatic Fixture Removal

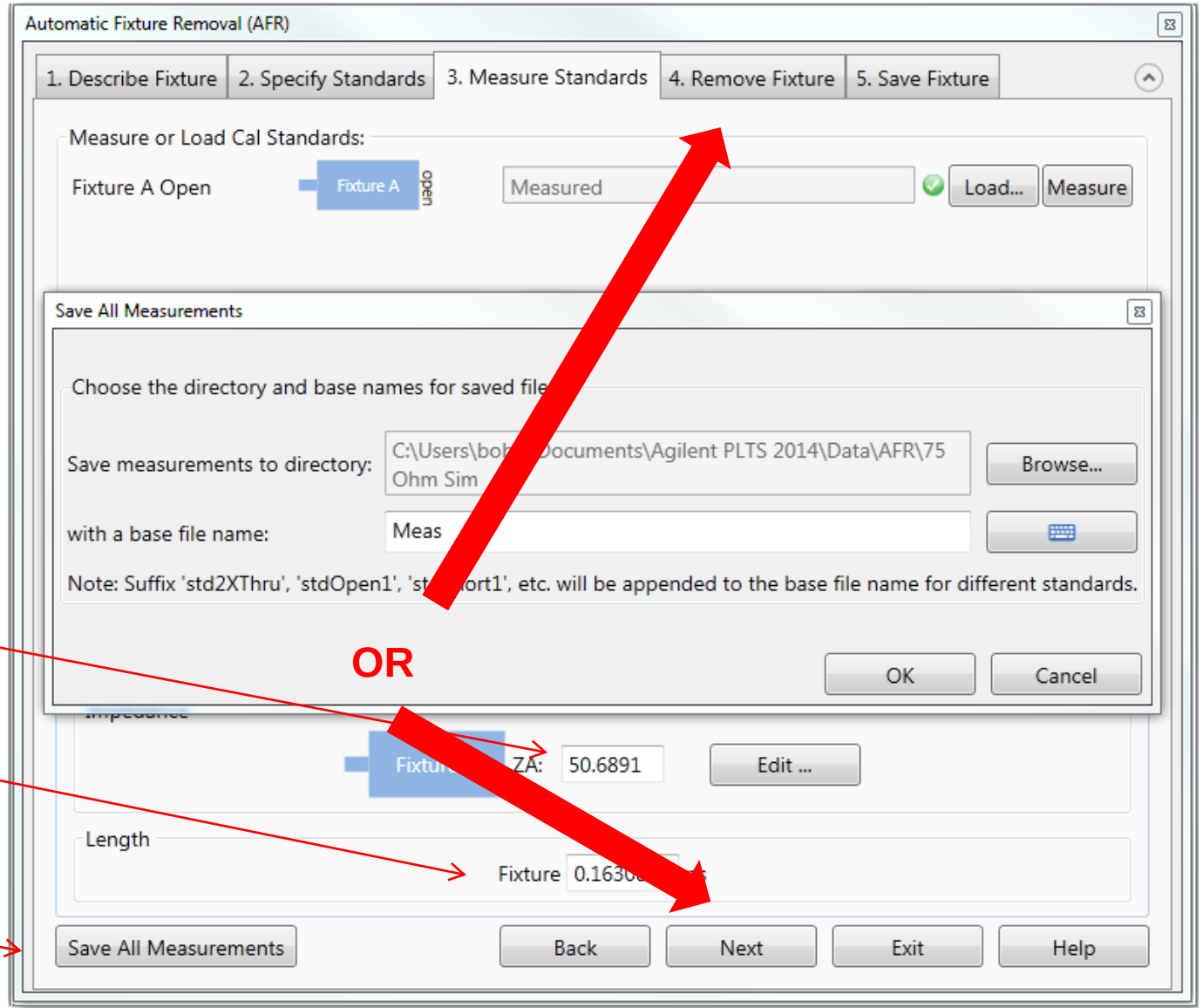
1 PORT OPEN CASE

Click Load …
to load a previously measured standard

Or click Measure to measure the standard connected to the PNA

Measured fixture impedance and length

Click to save measurements of standards

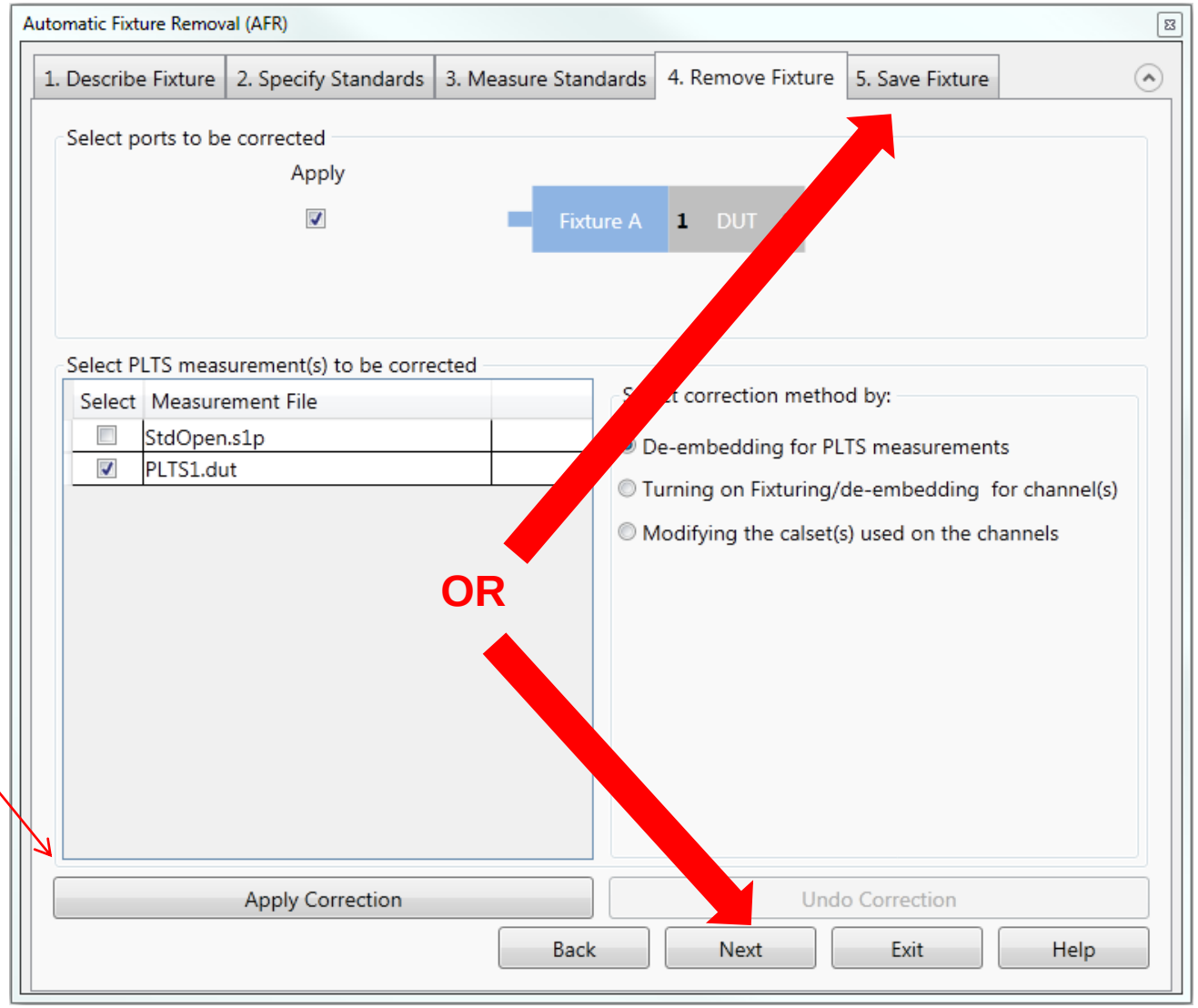


Automatic Fixture Removal

1 PORT OPEN CASE

Click “Apply Correction” to remove fixture from measurement(s)

Click Undo Correction to add fixture back to measurement.



Automatic Fixture Removal

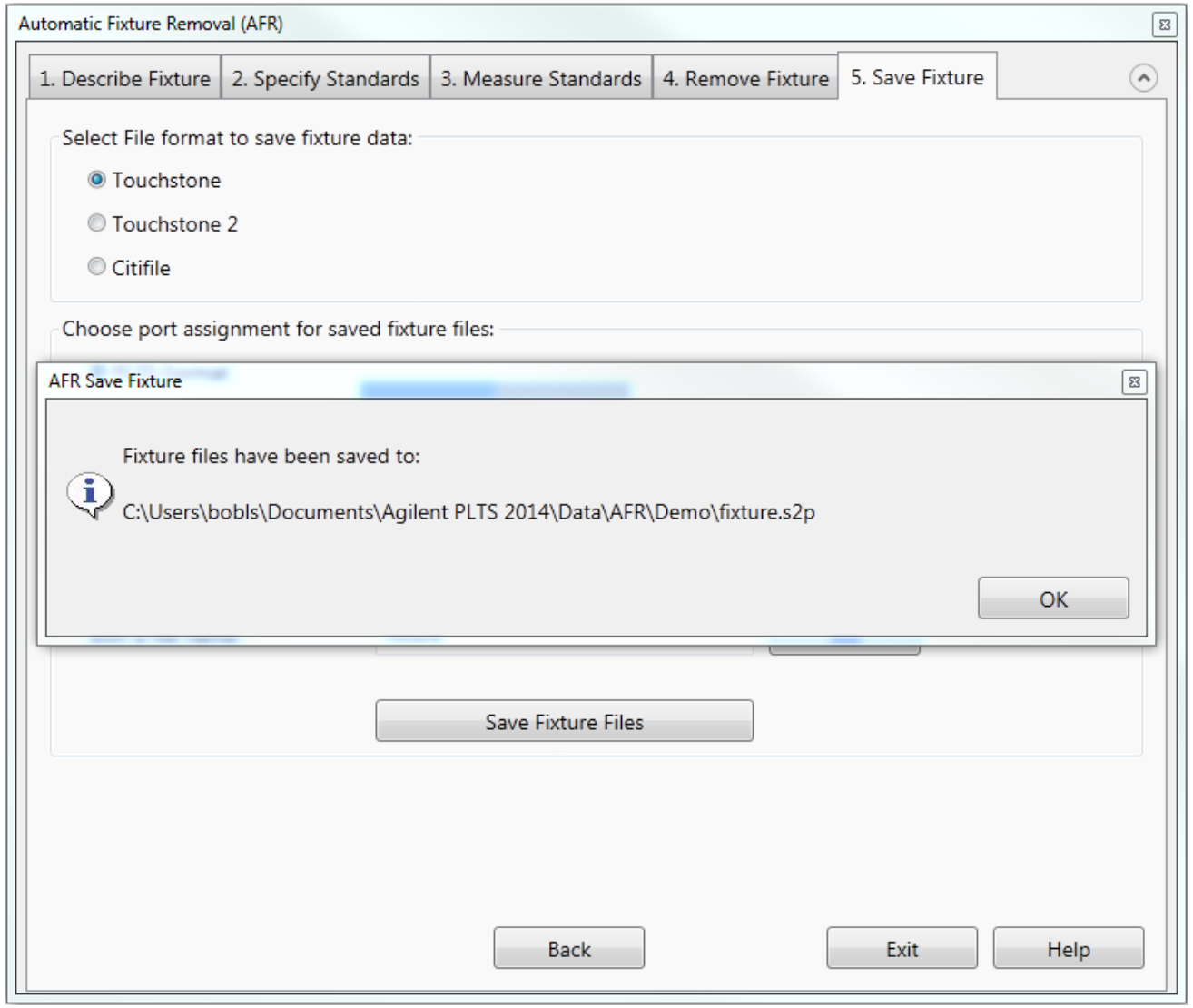
1 PORT OPEN CASE

Select File Format

Choose Port assignment

Specify directory and file name

Note: Only 1 fixture file is saved in this case.



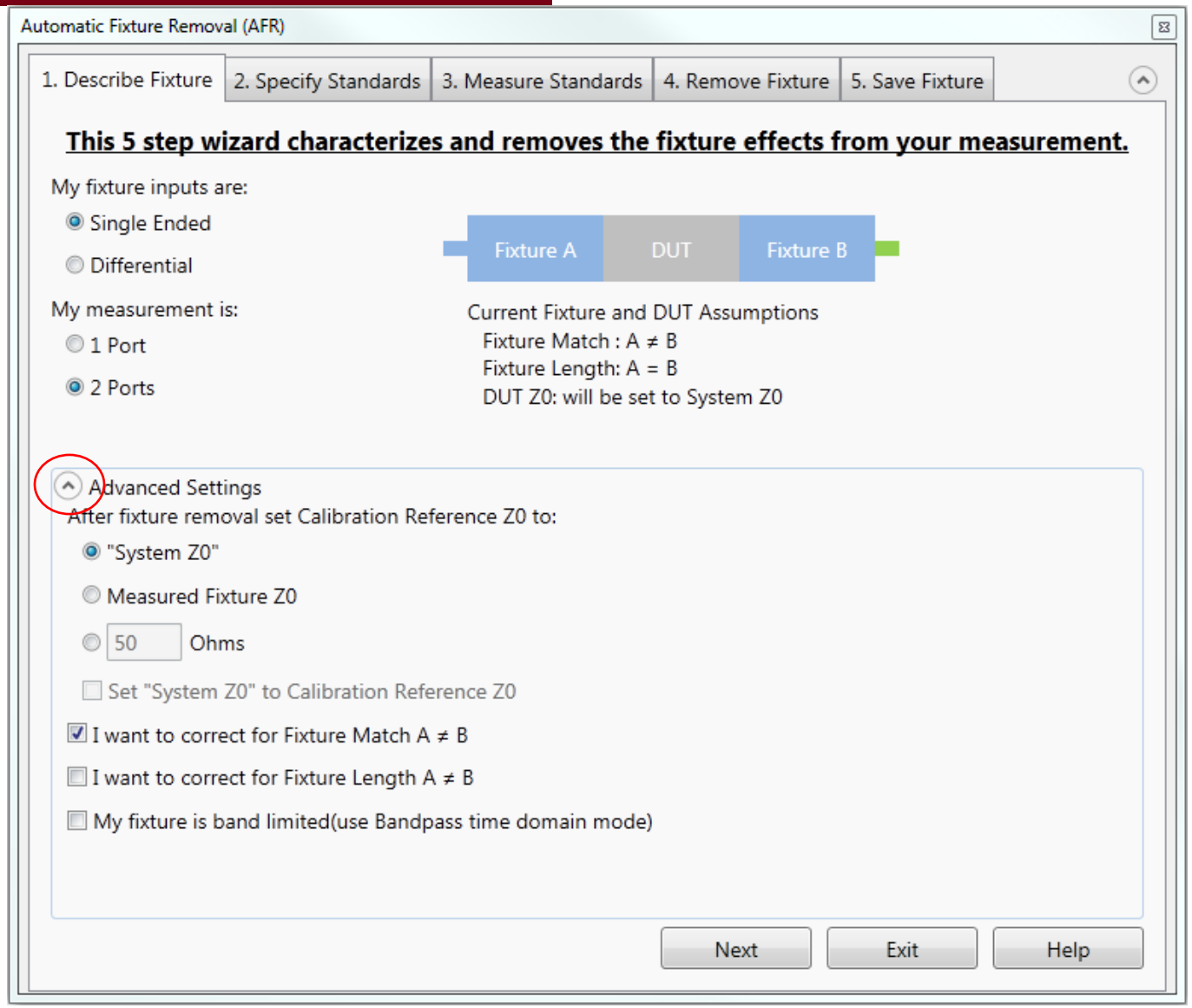
Automatic Fixture Removal

ADVANCED SETTINGS

Automatic Fixture Removal

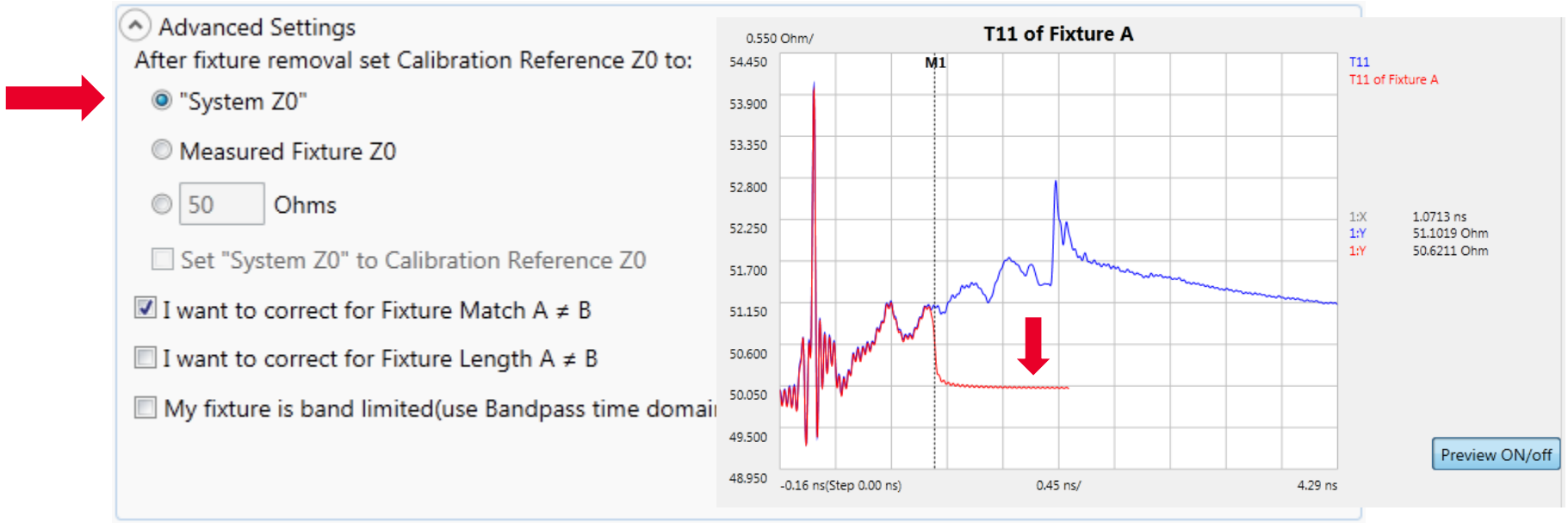
ADVANCED SETTINGS

Advanced Settings



Automatic Fixture Removal

ADVANCED SETTINGS

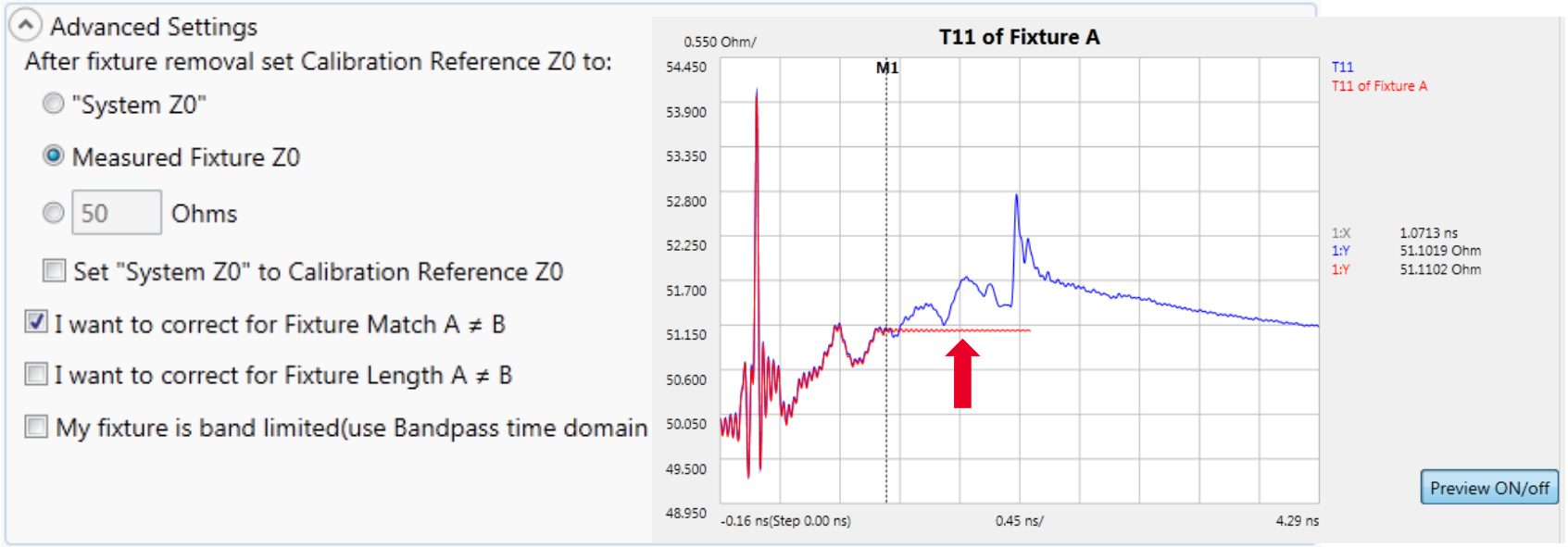


After the Fixtures are removed using AFR – there are three choices on setting the reference Z0:

1. “System Z0” will force the reference impedance to the current setting for System Z0 (default is 50 Ohms). For example if the fixture impedance was determined to be 51 Ohms, the fixture S parameters port 2 impedance will be converted back to 50 Ohms. In this case after the fixture is removed the DUT S parameters will have Z0=50 Ohms.

Automatic Fixture Removal

ADVANCED SETTINGS

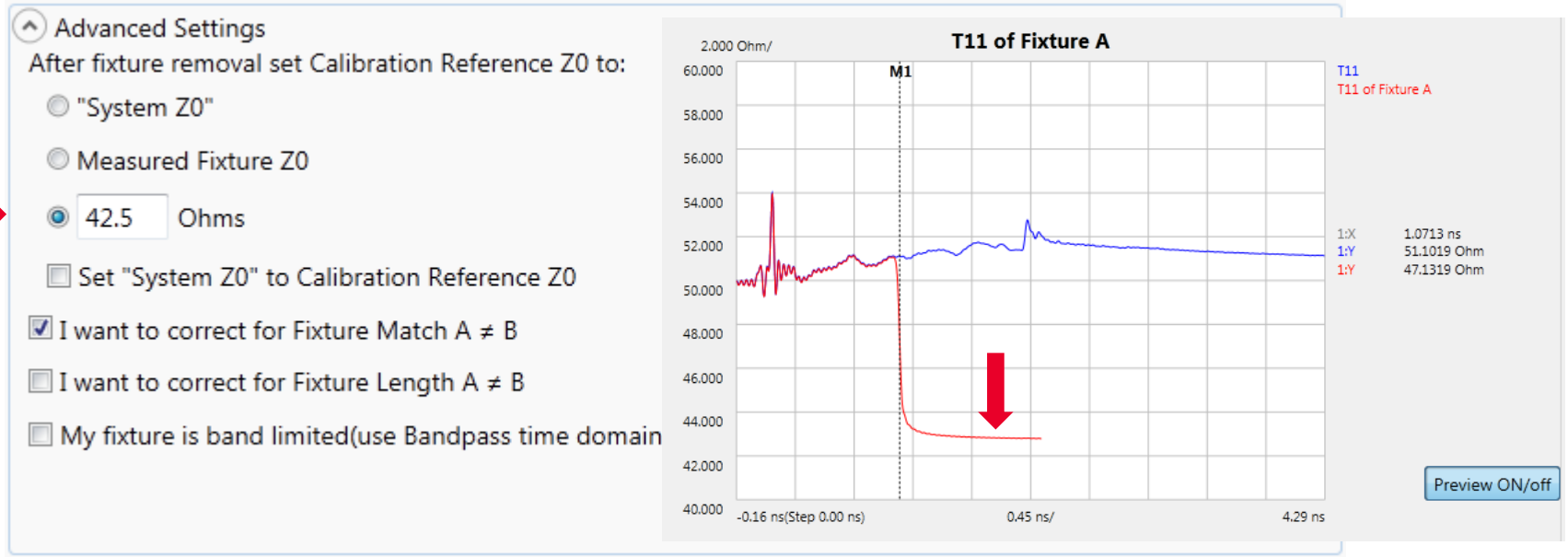


After the Fixtures are removed using AFR – there are three choices on setting the reference Z0:

2. Measured Fixture Z0 will set the reference impedance to the fixture impedance. For example if the fixture impedance was determined to be 51 Ohms, the fixture S parameters port 2 impedance will be left at 51 Ohms. In this case after the fixture is removed the DUT S parameters will have Z0=51 Ohms.

Automatic Fixture Removal

ADVANCED SETTINGS

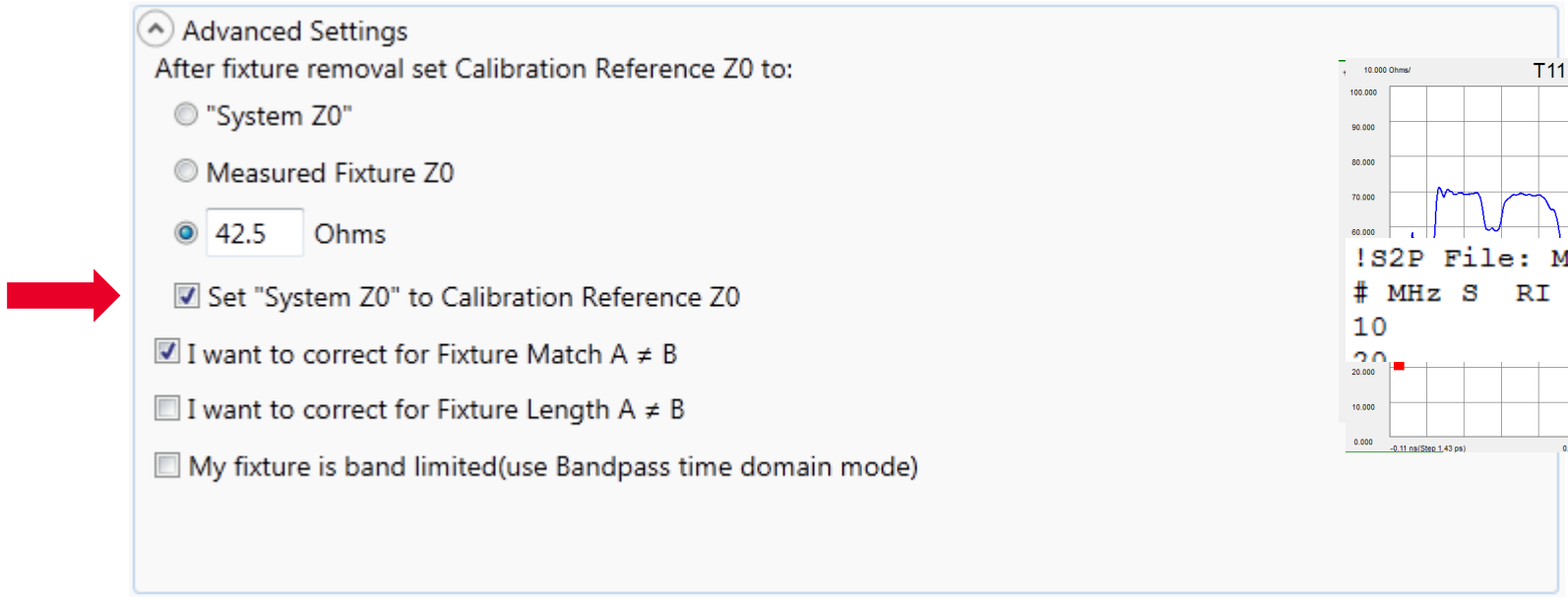


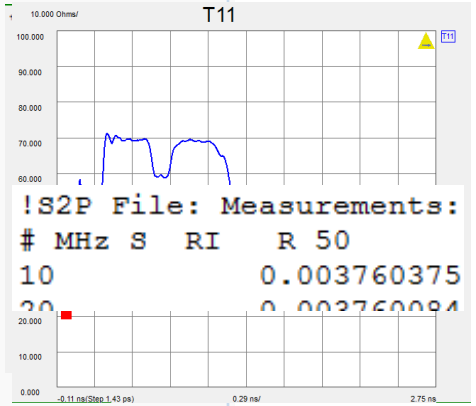
After the Fixtures are removed using AFR – there are three choices on setting the reference Z0:

3. Specified Z0 will force the reference impedance to the specified value. For example if the fixture impedance was determined to be 51 Ohms, the fixture S parameters port 2 impedance will be converted back to 42.5 Ohms. In this case after the fixture is removed the DUT S parameters will have Z0=42.5 Ohms.

Automatic Fixture Removal

ADVANCED SETTINGS



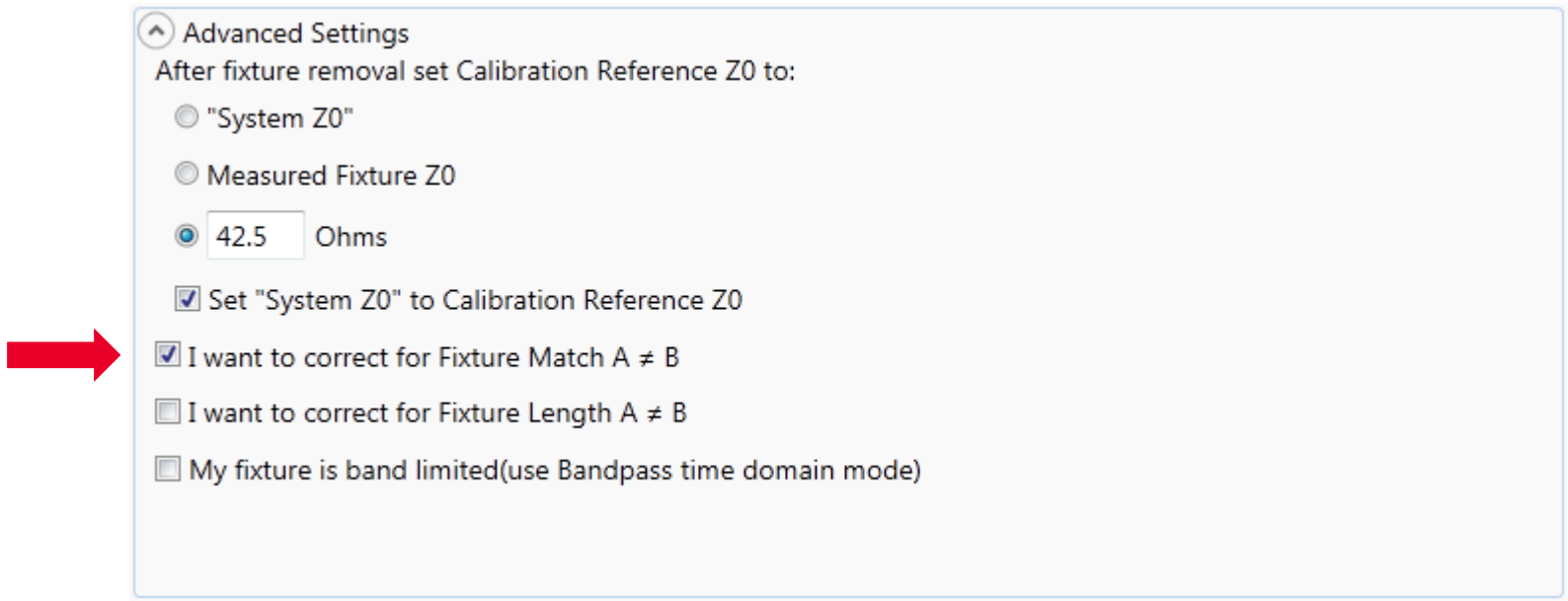


After the Fixtures are removed using AFR and the impedance setting is **Measured Fixture Z0** or **Specified Z0**, there is an option to set the “System Z0” to that value. In this case 42.5 Ohms.

Note: System Z0 defines the center of the Smith Chart (frequency domain) and the impedance of the TDR plots (time domain). When S parameters are exported this value for Z0 is saved in the file.

Automatic Fixture Removal

ADVANCED SETTINGS

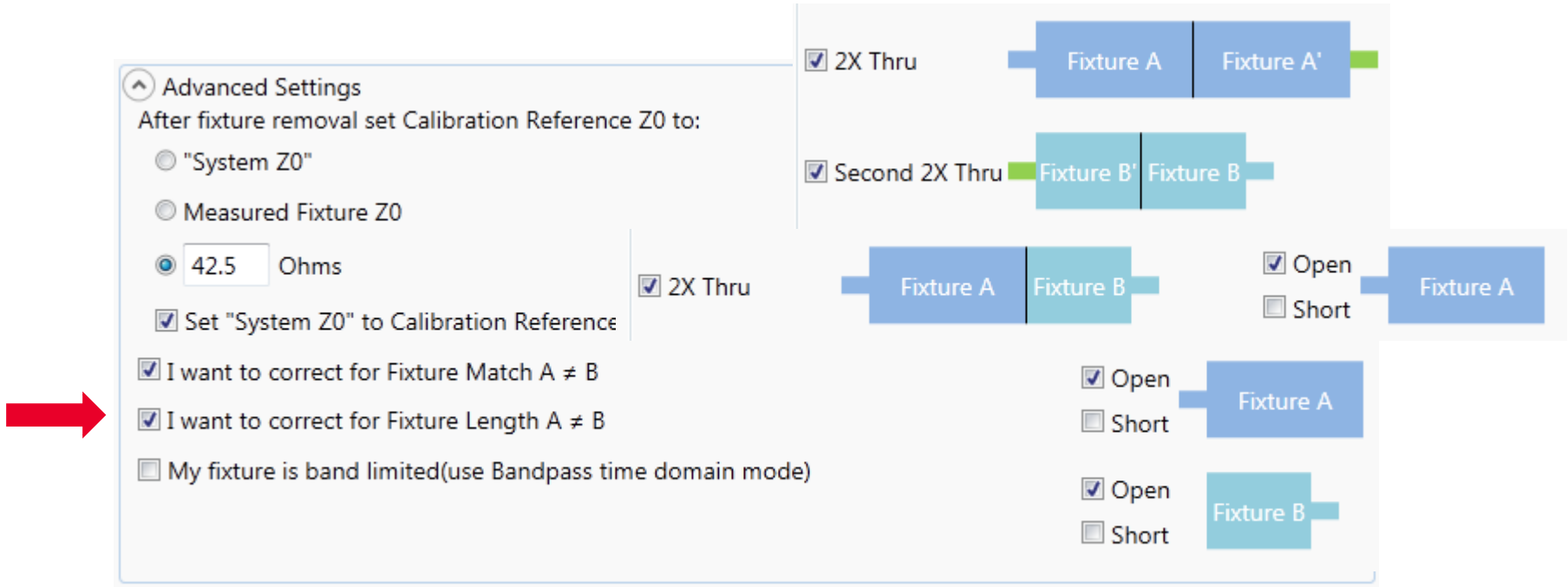


“I want to correct for Fixture Match A not equal to B” – this is the default setting. When cutting a 2X thru in half to create 2 fixture files, the process is done for each of the ports. Therefore Fixture A may be different from Fixture B.

If this is NOT checked then the assumption is both fixtures are identical and Fixture B is set to be the same as Fixture A.

Automatic Fixture Removal

ADVANCED SETTINGS

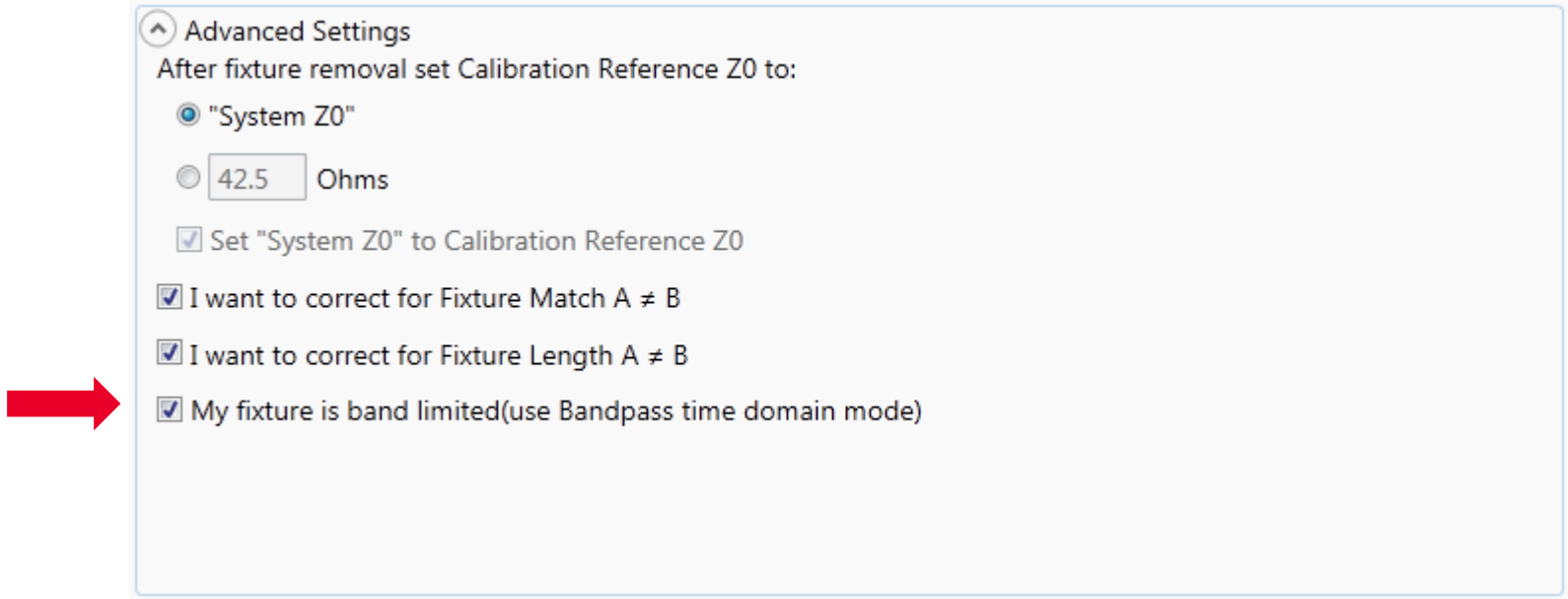


"I want to correct for Fixture Length A not equal to B" – in this case the fixtures are different lengths. This setup requires additional standards to determine both fixtures. The choices are:

1. 2X thru (Fixture A + Fixture A) and a second 2X thru (Fixture B + Fixture B)
2. 2X thru (Fixture A + Fixture B) and an open and/or short for (Fixture A or Fixture B)
3. Opens and/or shorts for (Fixture A or Fixture B)

Automatic Fixture Removal

ADVANCED SETTINGS



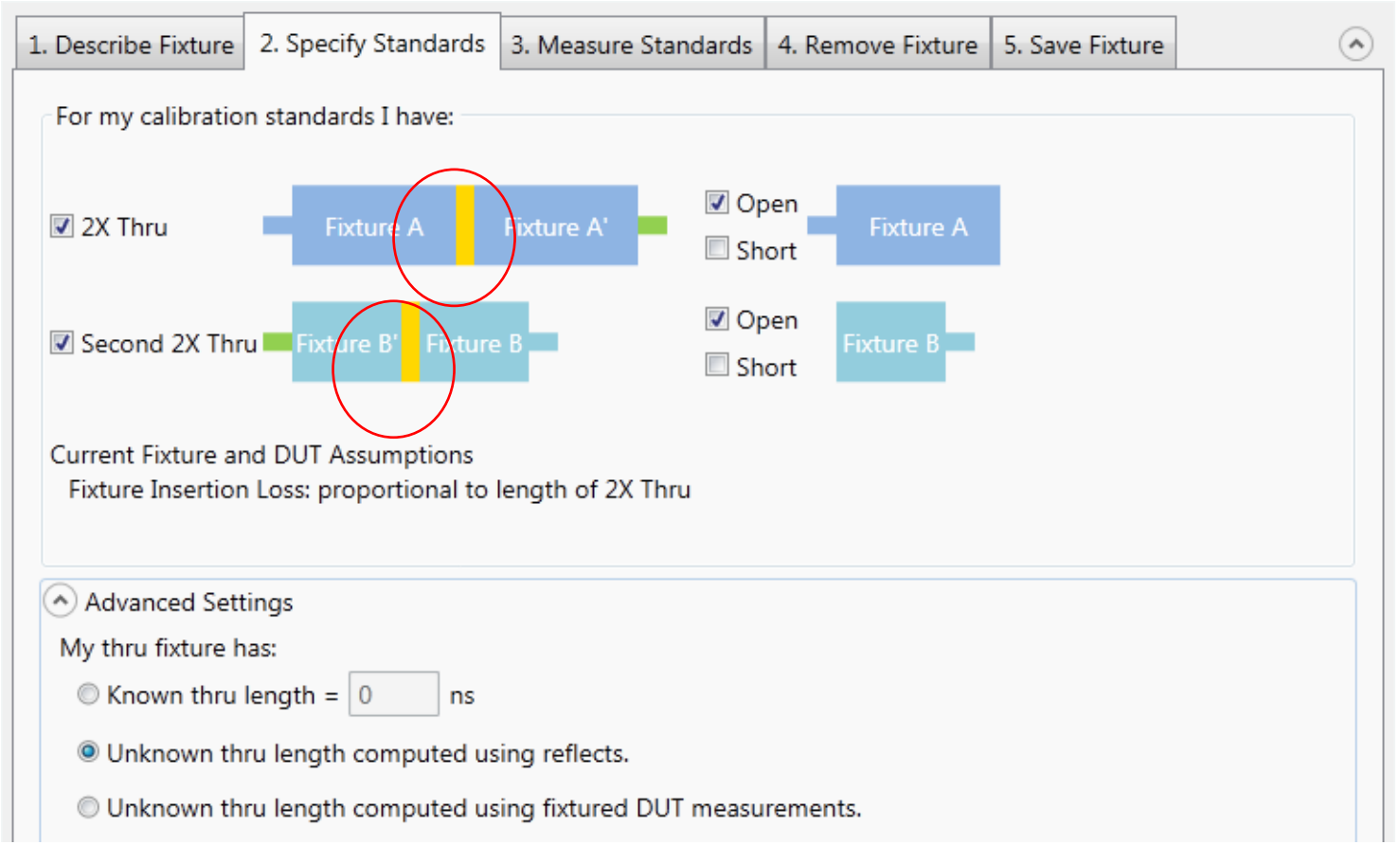
This selection does NOT require frequencies to low (near DC) values. This is good for band limited devices. In this mode the IFFT is Bandpass mode instead of Low Pass mode. In this case we cannot determine the actual impedance from the measurement so it is assumed to be “System Z0” or you can specify the value.

Automatic Fixture Removal

ADVANCED SETTINGS

On tab 2 the Advanced settings allow you to specify non-zero thru lengths. The thru length can be

1. specified or
2. unknown and computed from additional standards.

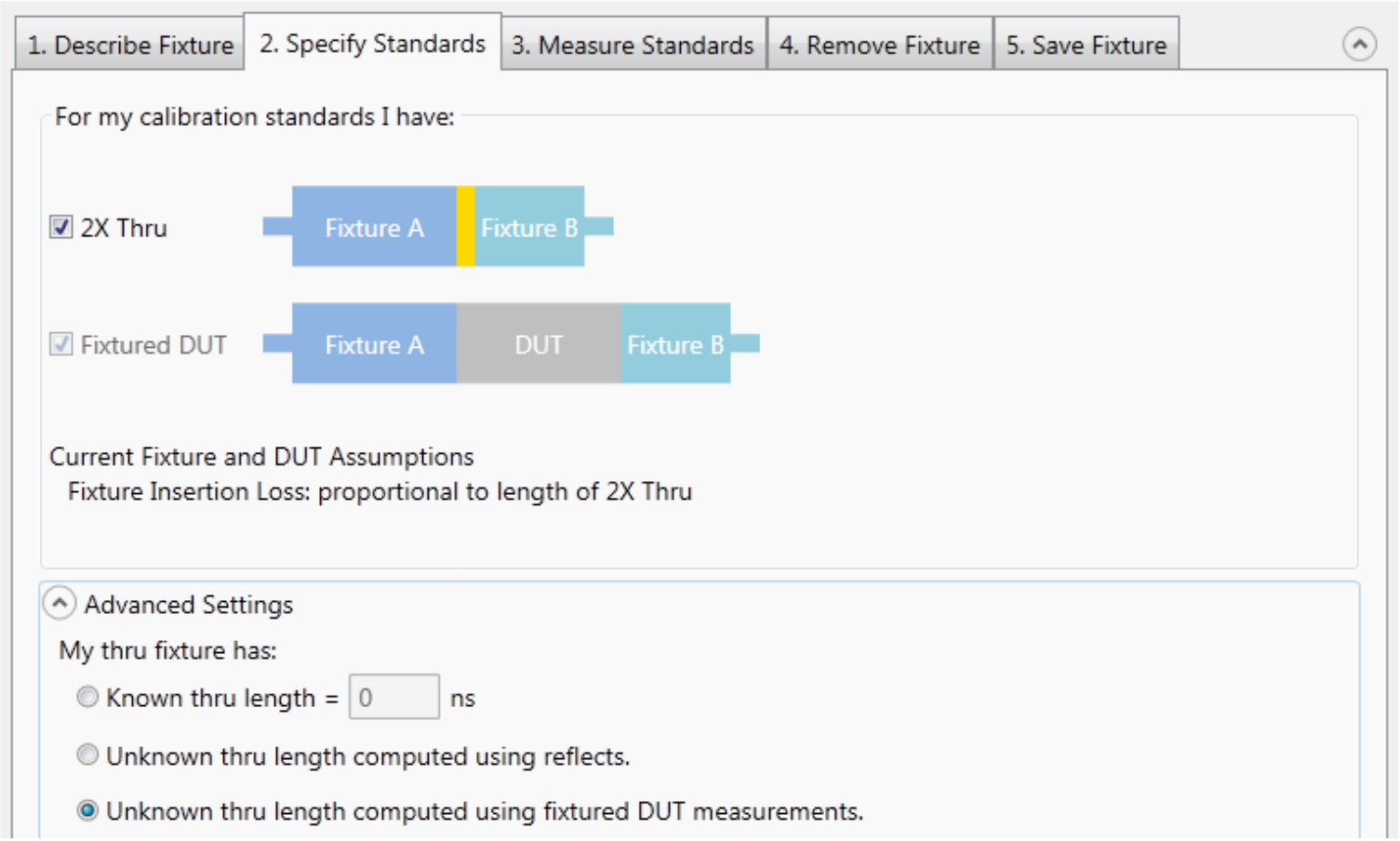


Automatic Fixture Removal

ADVANCED SETTINGS

On tab 2 the Advanced settings allow you to specify non-zero thru lengths.

The thru length can be specified or unknown and computed from additional standards or unknown and computed using fixtured DUT measurements.



Automatic Fixture Removal

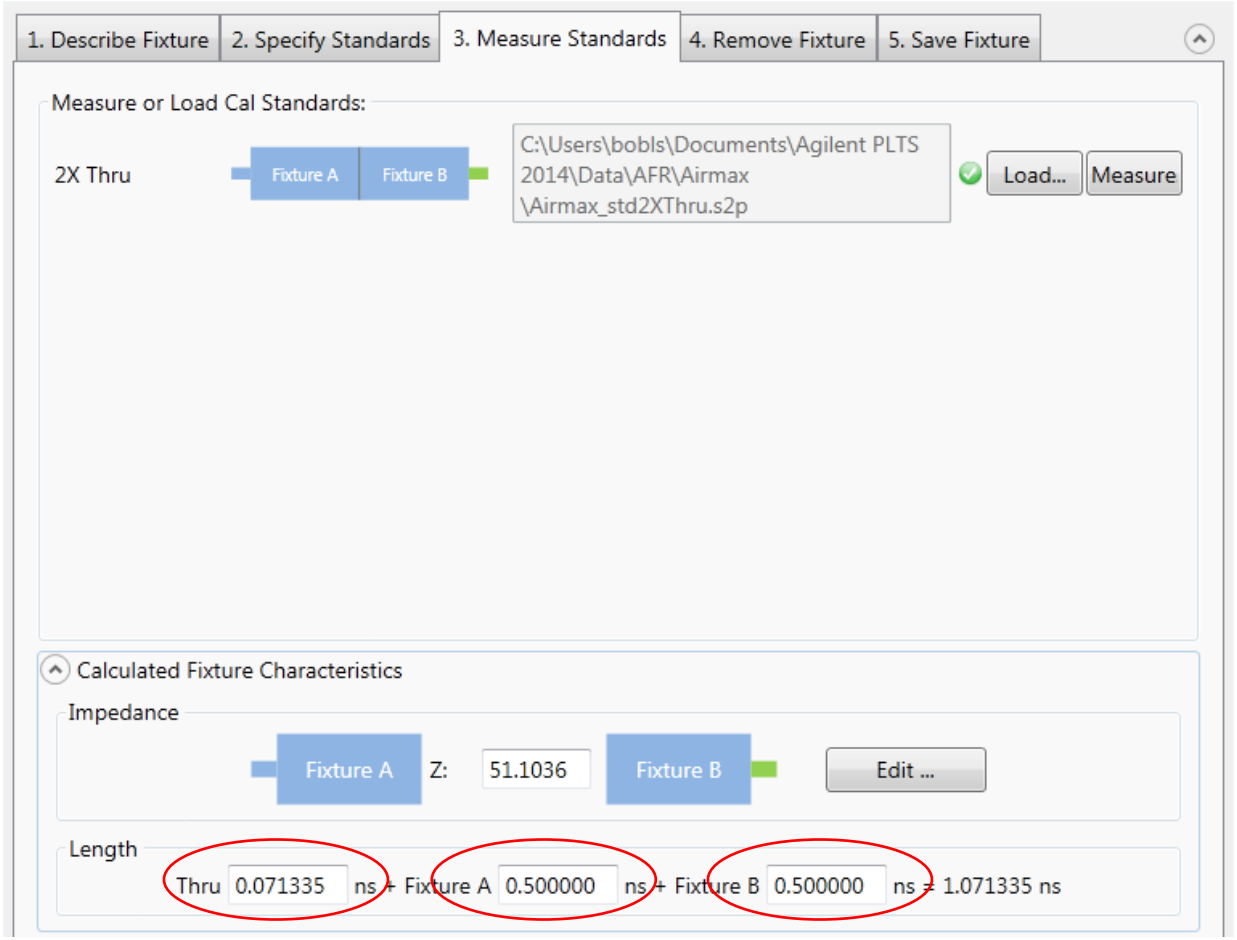
ADVANCED SETTINGS

On tab 3 you can click “Edit …” to view the measurement of the standard and extracted fixture and modify the “Measured Fixture Z0”.

Automatic Fixture Removal

ADVANCED SETTINGS

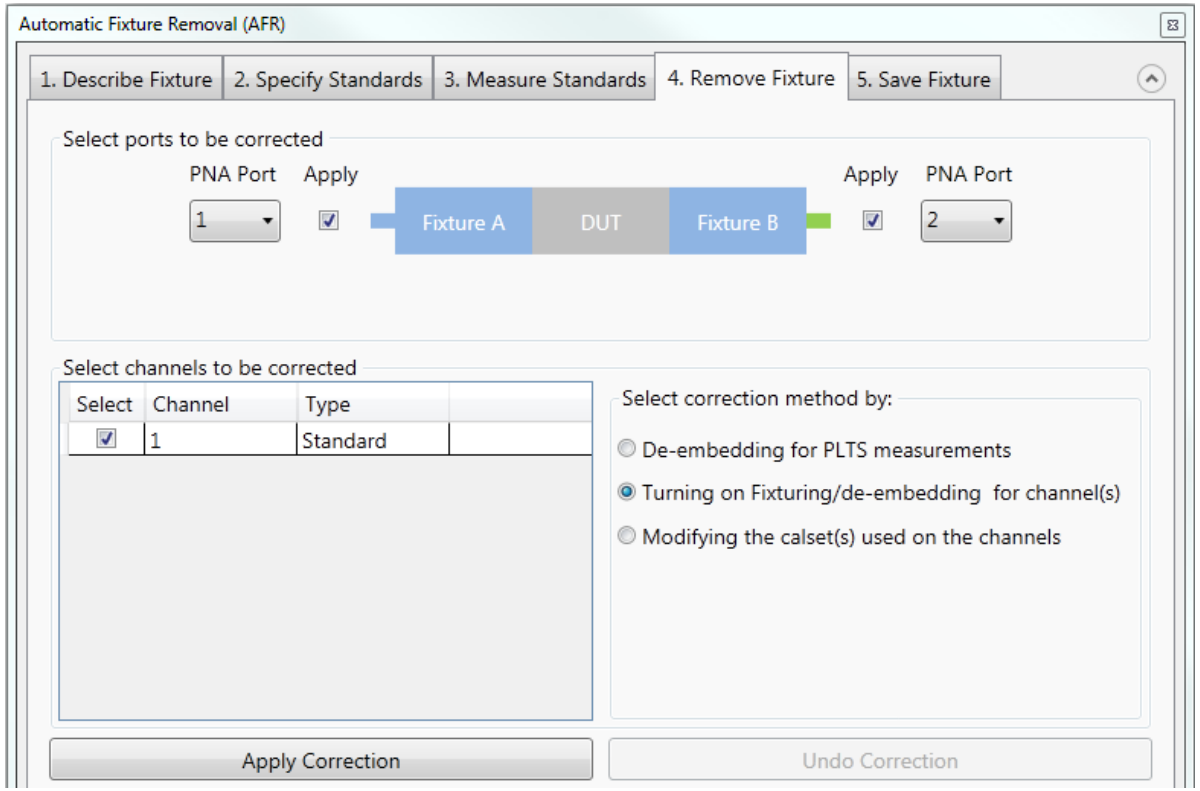
On tab 3 you can also modify the length of the fixtures and thru length.



Automatic Fixture Removal

ADVANCED SETTINGS

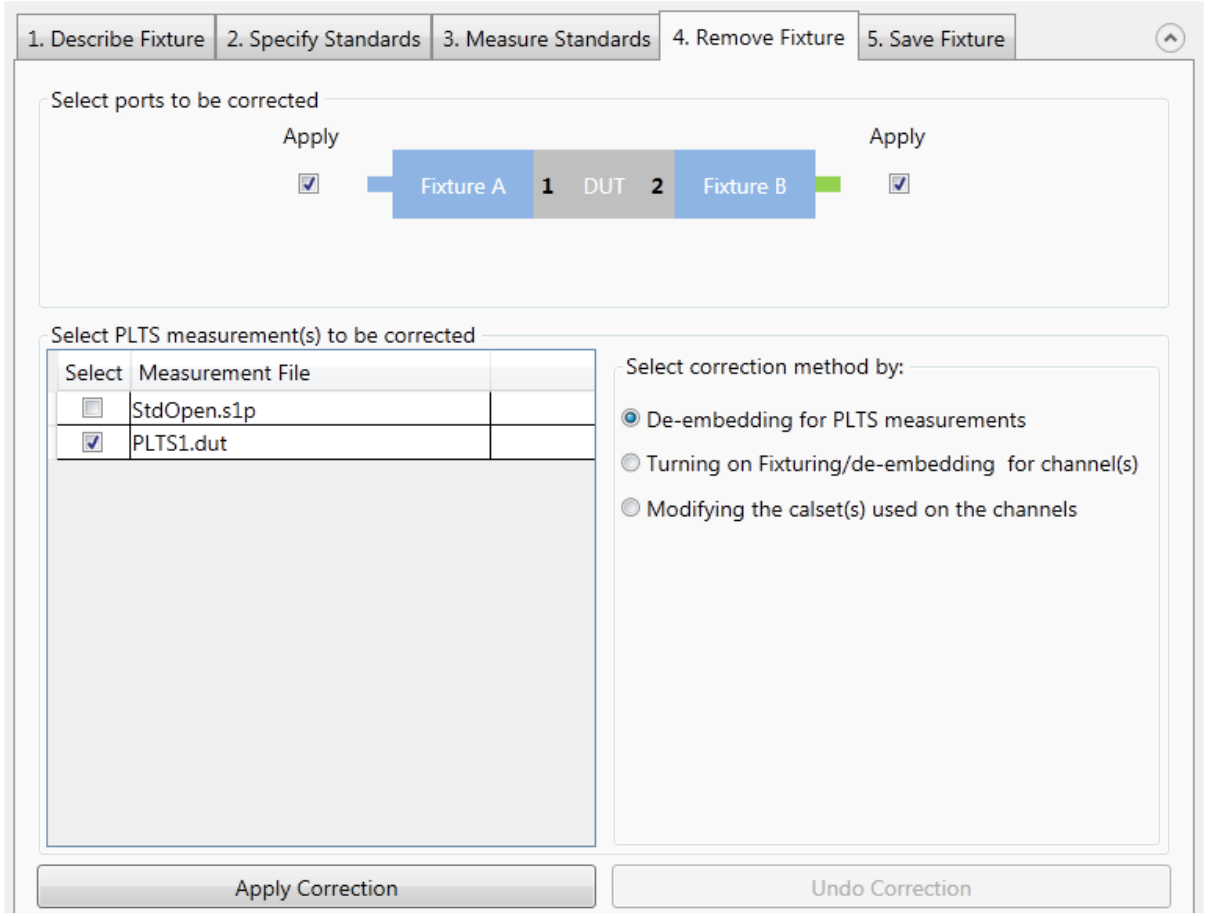
On tab 4 in addition to removing the fixtures from loaded DUT files you can also:
1. Turn on de-embedding on the PNA (all measurements will now have the fixtures removed automatically by using the fixturing feature.



Automatic Fixture Removal

ADVANCED SETTINGS

On tab 4 in addition to removing the fixtures from loaded DUT files you can also:
2. Turn on de-embedding on the PNA (all measurements will now have the fixtures removed automatically by modifying the calset. The calset can be used in the future.



Rule of Thumb for all AFR Techniques & Best practices

Rule of Thumb for all AFR techniques

- Always measure to the **widest** frequency range of the VNA to achieve **best time domain resolution** for fixture extractions (for example, to characterize a probe at 2 GHz, you may still measure from DC to 50 GHz because of the small size of the probe)
- Optimal measurement settings for AFR processing:
  - Low pass mode: Start Freq = Step Freq = 10 MHz (for example, 10 MHz to 50 GHz, 5000 points)
  - Band pass mode: also use 10 MHz freq step (for example, 75 GHz to 110 GHz, 3500 points)
- Use the extracted fixture for de-embedding in the DUT measurement frequency range
- The characterized fixture may show active result at high frequency, but if it is good in DUT measurement frequency range, it still can be used for de-embedding

Warning “RF line is 4 time shorter than the rising time”

→ Measurement parameters are not optimized for best fixture removal

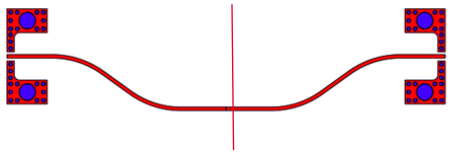
- The rough calculation for the risetime is 0.35/bandwidth of the measurement
- The warning doesn't mean that AFR will not work
- We recommend using the Edit dialog to see the response that AFR is going to generate.
  - This dialog will let you make some changes in how the data is processed and you can see the effects.
  - You could also measure to a higher frequency (if your system can go higher).

Fixture designing advice for best AFR result

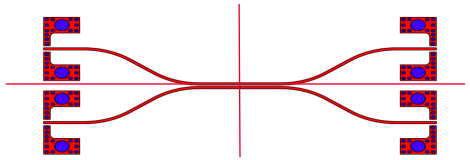
- Always design in a 2x thru ref fixture to be identical to the actual fixture to the DUT
- Always split the reference plane in a uniform transmission line region
  - Otherwise, the fringe fields are specific to the probe and intrinsic to the DUT
- Always design the fixture as transparent as possible
  - Short length, low loss
  - Uniform transmission lines matched to 50 Ohms
  - Short via stubs
  - Signal vias surrounded by return vias
  - Optimize barrel diameter, clearance holes to make 50 Ohm via
  - Minimum coupling between the lines
- What if the fixtures on the two ends are not the same?
  - Build two different 2x thru fixtures- both symmetric
  - Extract S-parameter files for each half fixture
  - Use a different de-embed files on each end
- Always compare T11, T22 of assembly,T11, T22 of fixture

AFR with 2xThru – limitations and best practices

SE Thru



Diff Thru

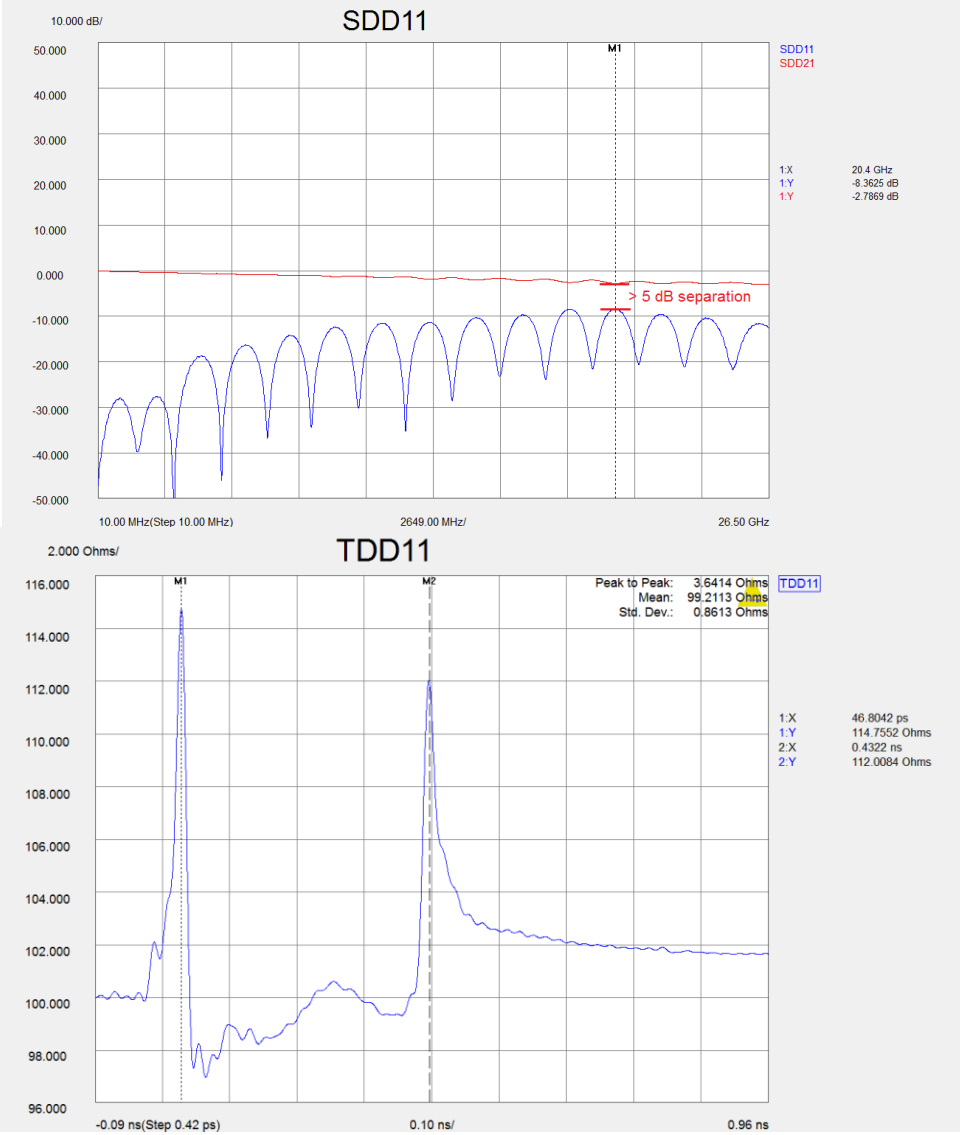


- The left and right fixtures do NOT need to have the same delay and insertion loss, but then two 2X THRU's will need to be fabricated (one for each length). The match (launch impedance) doesn't need to be the same
- The fixture length cannot be too short: should be at least 4x system step rise time
- The Thru cannot be too long: the fixture bandwidth should be higher than the DUT measurement bandwidth
  - the return loss and insertion loss of the 2xThru should not cross each other in **DUT** measurement frequency range, often **>5 dB** separation is best
  - Needs good control on the impedance mismatch on the connector, launch and PCB traces
  - New Feature: 2X THRU impedance and be slightly off from fixture and AFR will use fixture impedance

For Diff Thru:

- Top-bottom symmetric
  - SDCnm and SCDnm < -30 dB
  - Skew between lines < 10 degrees

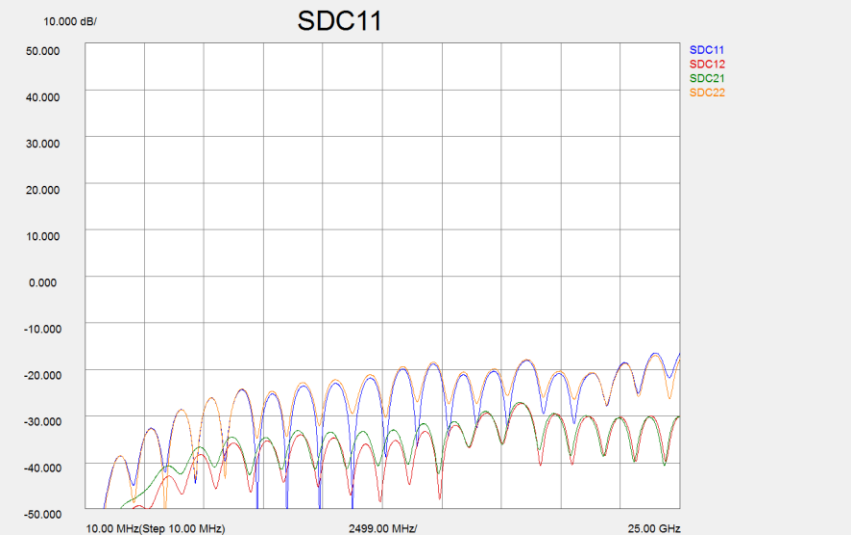
Investigate the 2xThru quality - bandwidth

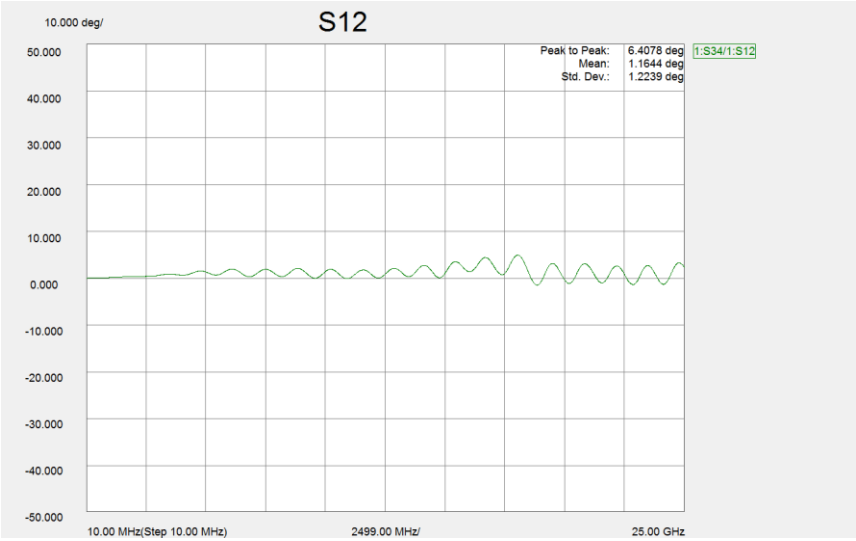


- SDD11 and SDD21 has >5 dB separation up to 20 GHz
- TDD11, Diff port 1 connector impedance is 114.7 Ohm
- TDD11, PCB trace impedance variation is 3.6 Ohm (peak to peak)

Here, the 2xThru and fixture are not so good, but usable up to 20 GHz

2xThru Top-bottom symmetry





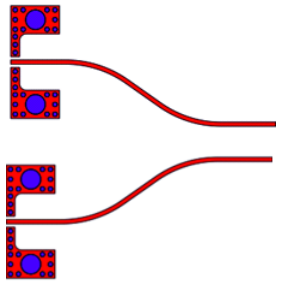
- Mode conversion is up to -20 dB
- Skew is less than 10 degrees

The mode conversion is -20 dB (linear 0.1),
But AFR assumes the fixture mode conversion SDC11 and SCD11 is 0. This error is transferred to the fixture S-parameters per this calculation:

$$S11 = 0.5 * (SDD11 + SCD11 + SDC11 + SCC11)$$

The effects of the mode conversion depends on how much it differs from the return loss

One-port AFR : Limitations and Best Practices

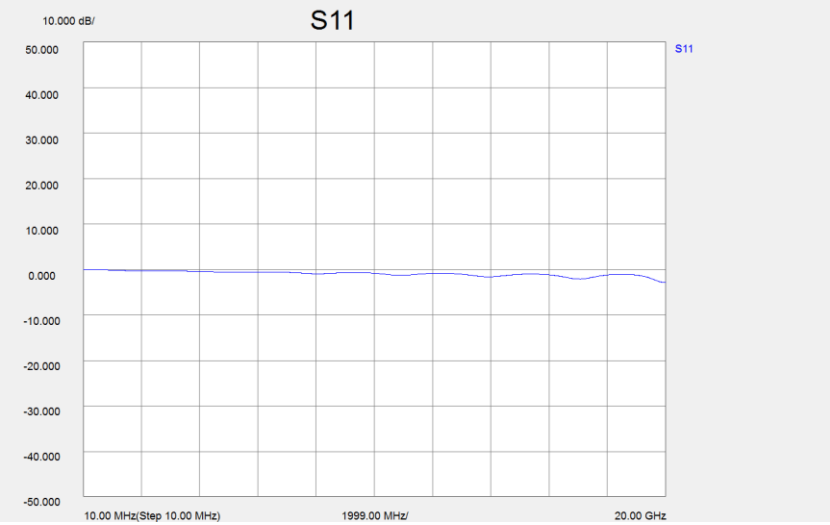


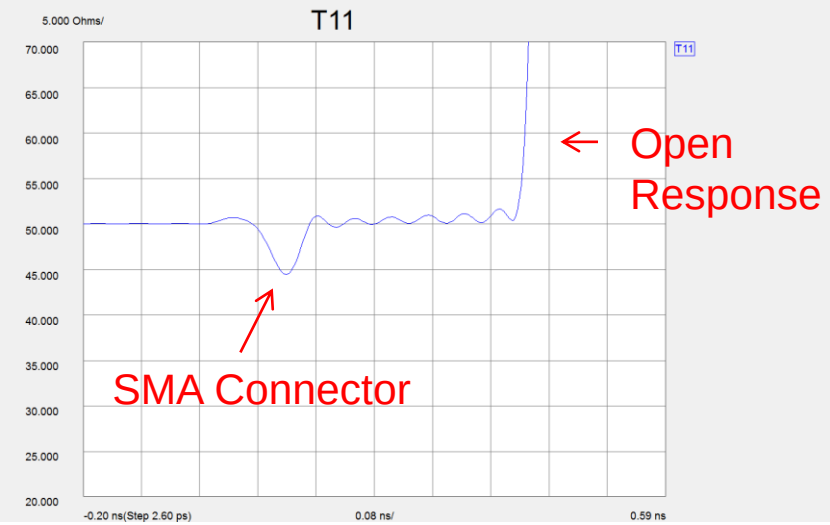
- No apparent radiation (open)
- Good reflect (for insertion loss accuracy)
- The open fixture should be consistent with that in the fixtured DUT. Typically, the same fixture can be used for both
- The fixture length should > 4x system rise time
- The fixture bandwidth should be higher than the **DUT** measurement bandwidth
  - Needs good control on the impedance mismatch on the connector, launch and PCB traces

For Diff Open:

- Top-bottom symmetric
  - SDC11 and SCD11 < -30 dB
  - Skew between lines < 10 degrees

Investigate Open Quality





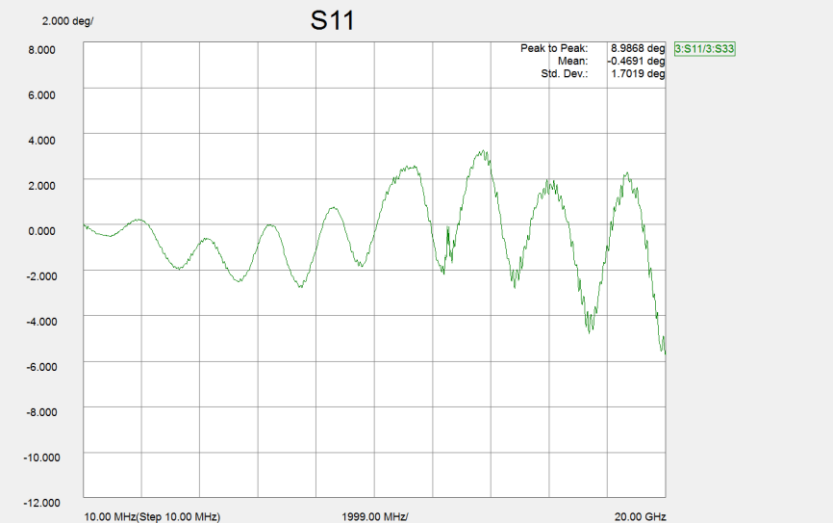
Frequency domain:

- No apparent resonance caused by radiation
- Return loss is close to 0 dB (good reflect)

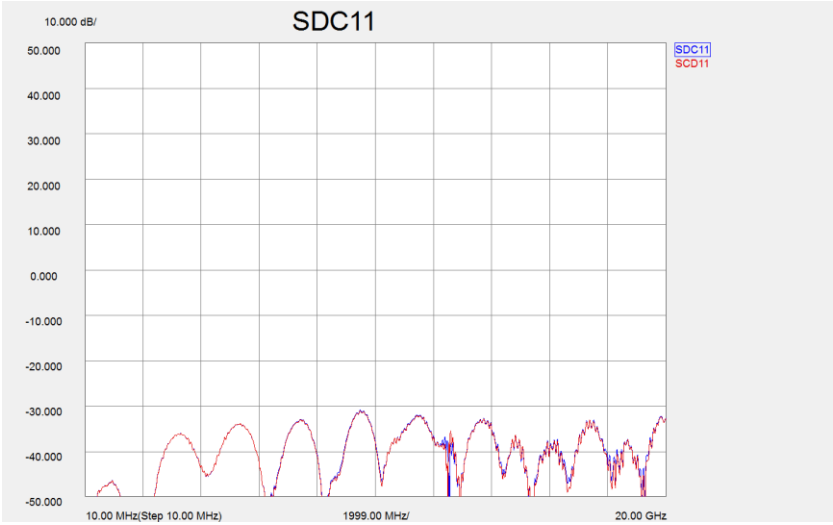
Time domain:

- Launch impedance variation is within 6 Ohm
- PCB trace impedance deviation is controlled within 2 Ohms

Differential Open Top-bottom symmetry

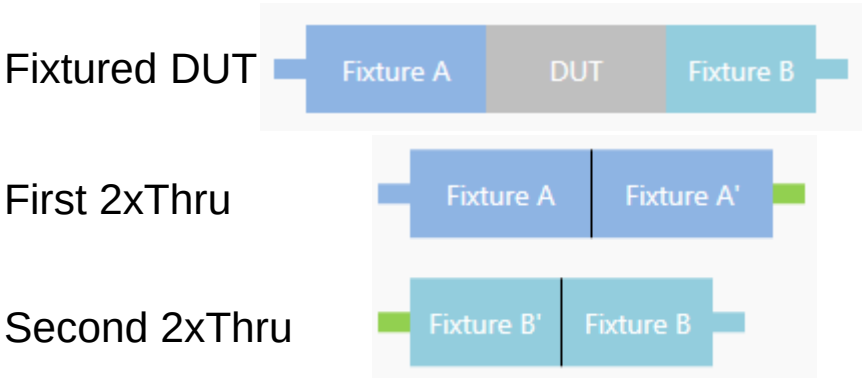


Skew is less than 10 degrees

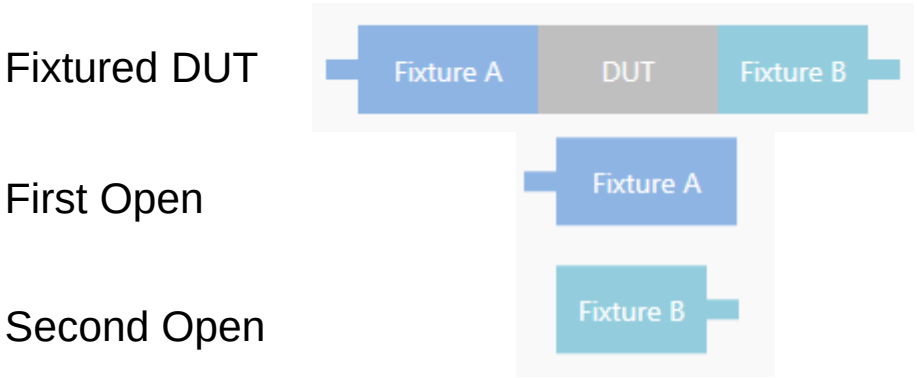


Mode conversion < -30 dB

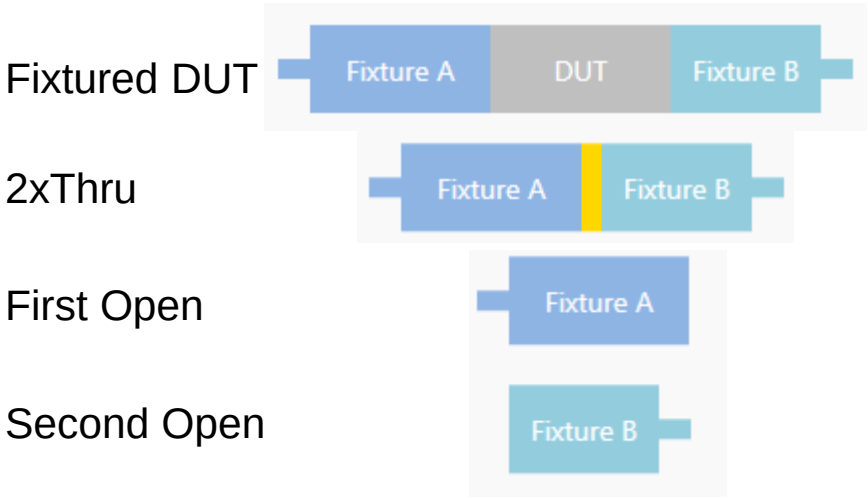
AFR for Asymmetric Fixtures – 3 methods



Using two 2xThrus, one for Fixture A, the other for Fixture B



Using two Open fixtures



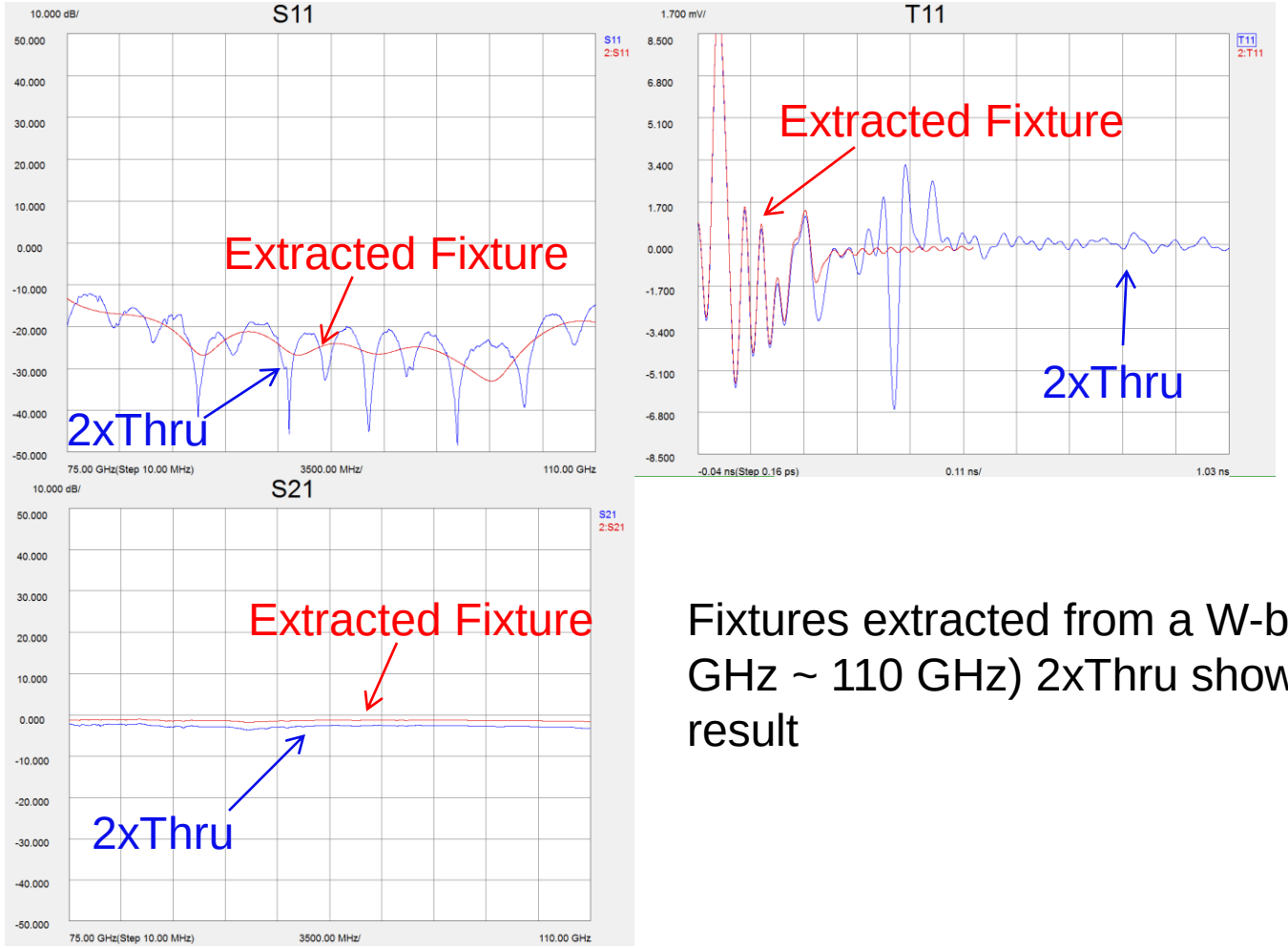
Using a Thru and two Open fixtures

- Open is used to determine the fixture electrical lengths
- Then the fixtures are extracted from the 2xThru

Limitation: the insertion loss and phase shift of the fixtures are proportional to that of the whole Through according to the electrical lengths

Bandpass AFR

- AFR algorithm works for bandpass devices with bandpass time domain gating
- Limitations are similar to those of low pass mode



Fixtures extracted from a W-band (75 GHz ~ 110 GHz) 2xThru show perfect result

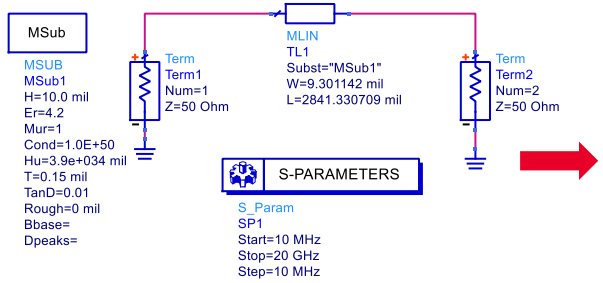
AFR for Non-50 Ohm Reference Impedance

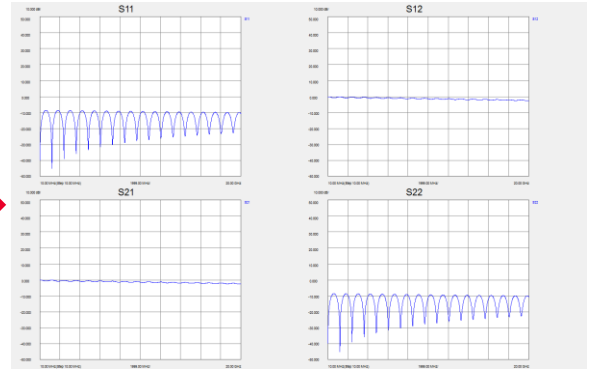
Can we use AFR for non-50 Ohm DUT reference impedance?

A similar question to

Can we use 50 Ohm VNA and cal kit to measure DUT with non-50 Ohm Z0?

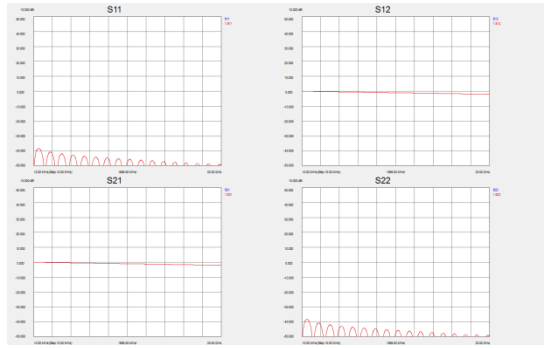
Example: measure a 75 Ohm device with 50 Ohm system

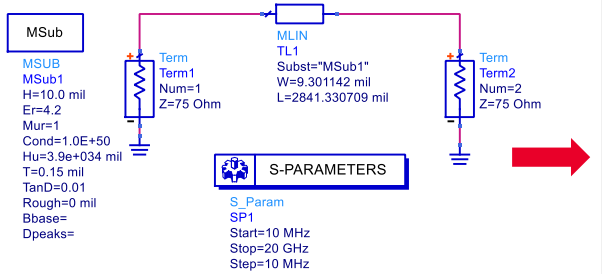


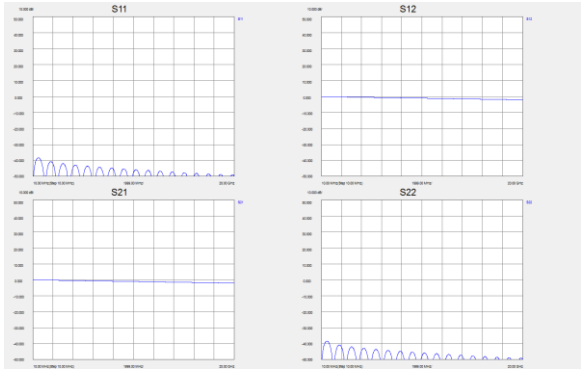


Measured with 50 Ohm system

Measured with 50 Ohm system and converted to 75 Ohm Z0 with Port impedance conversion, set System Z0 to 75 Ohm



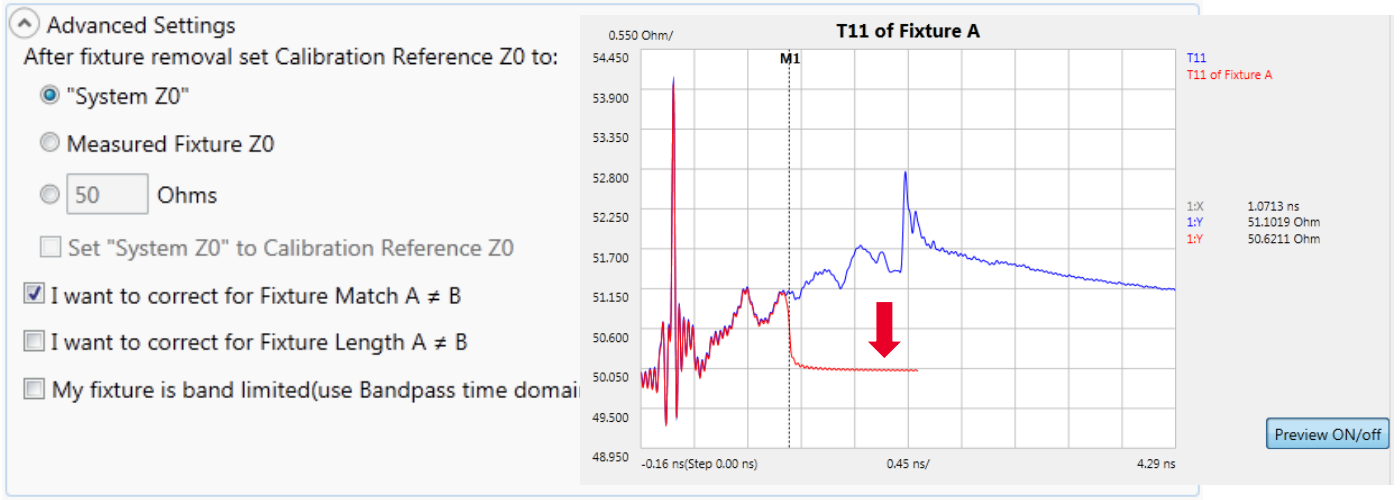




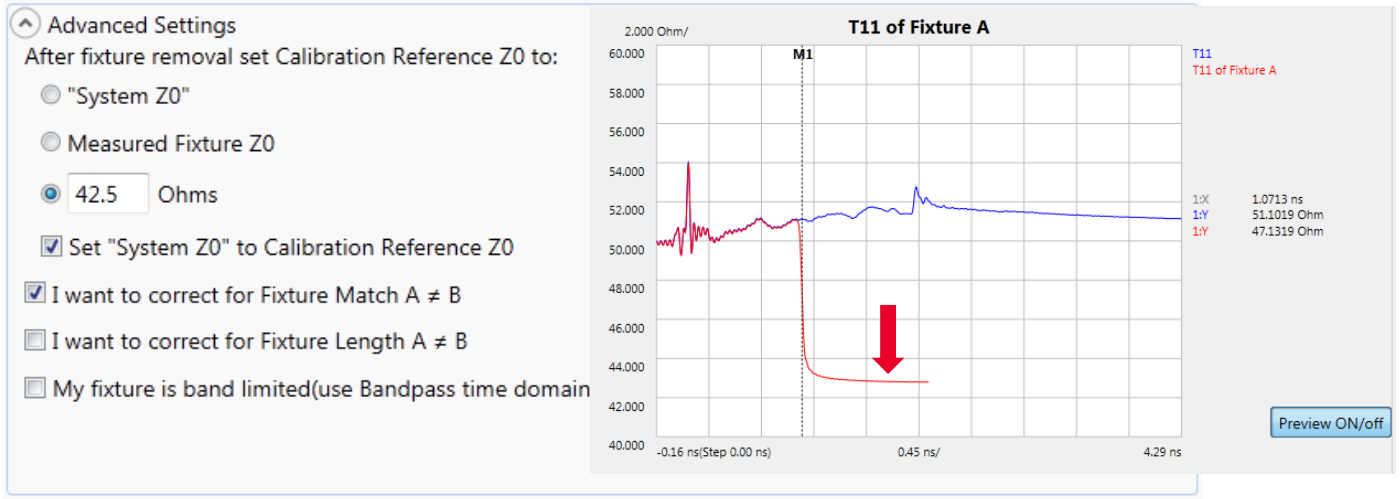
Same device, measured with 75 Ohm system

Exactly the same with the S-parameters measured with 75 Ohm system

AFR for non-50 Ohm Z0

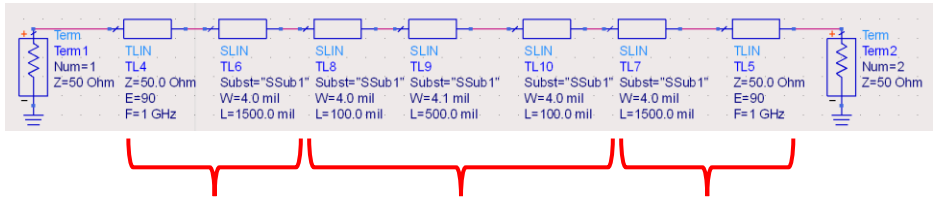


Re-normalize to System Z0 (default is 50 Ohm). For the 50 Ohm Z0 case.



Re-normalize to a new Z0 (42.5 Ohm here) and set System Z0 to 42.5 Ohm. For the non-50 Ohm Z0 case.

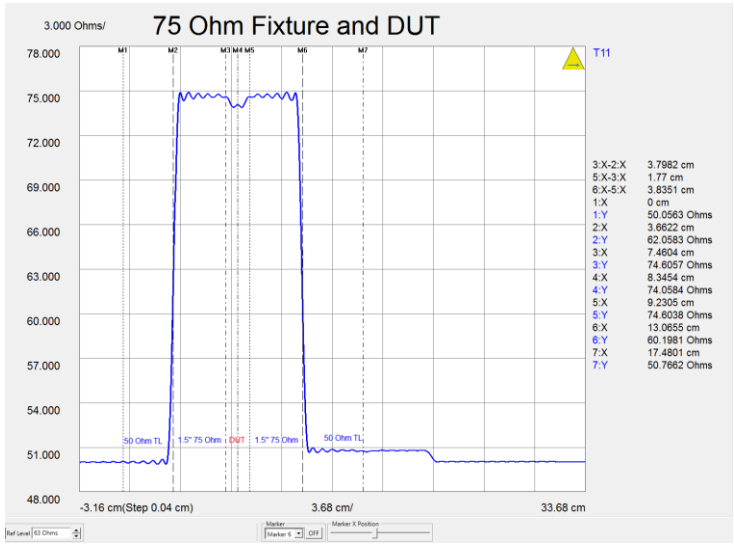
Case study with simulation



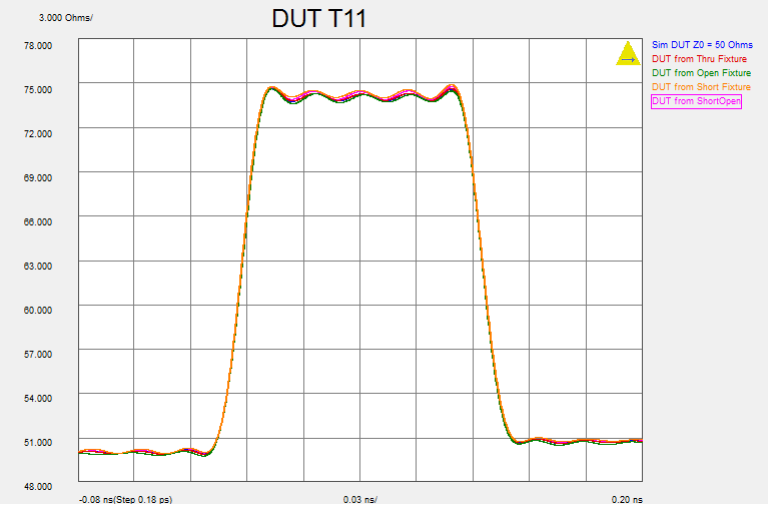
Fixture
Short 50 Ohm TL
+
1.5” 75 Ohm TL

DUT
100 mils 75 Ohm line
+
500 mils 74 Ohm Line
+
100 mils 75 Ohm line

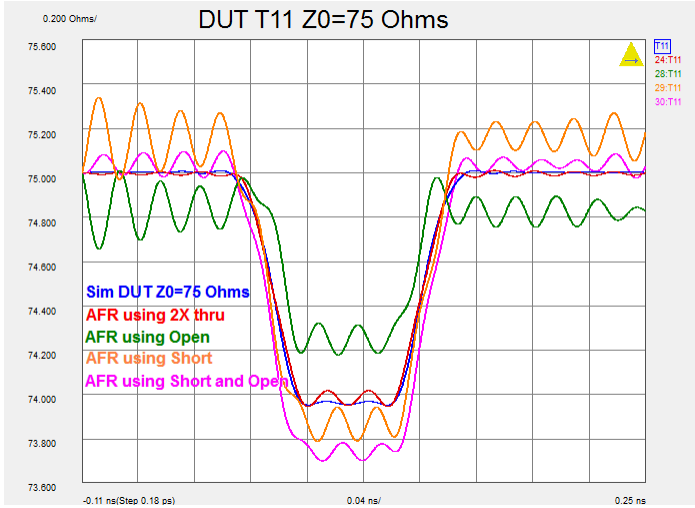
Fixture
Short 50 Ohm TL
+
1.5” 75 Ohm TL



AFR with DUT Z0 = 50 Ohm



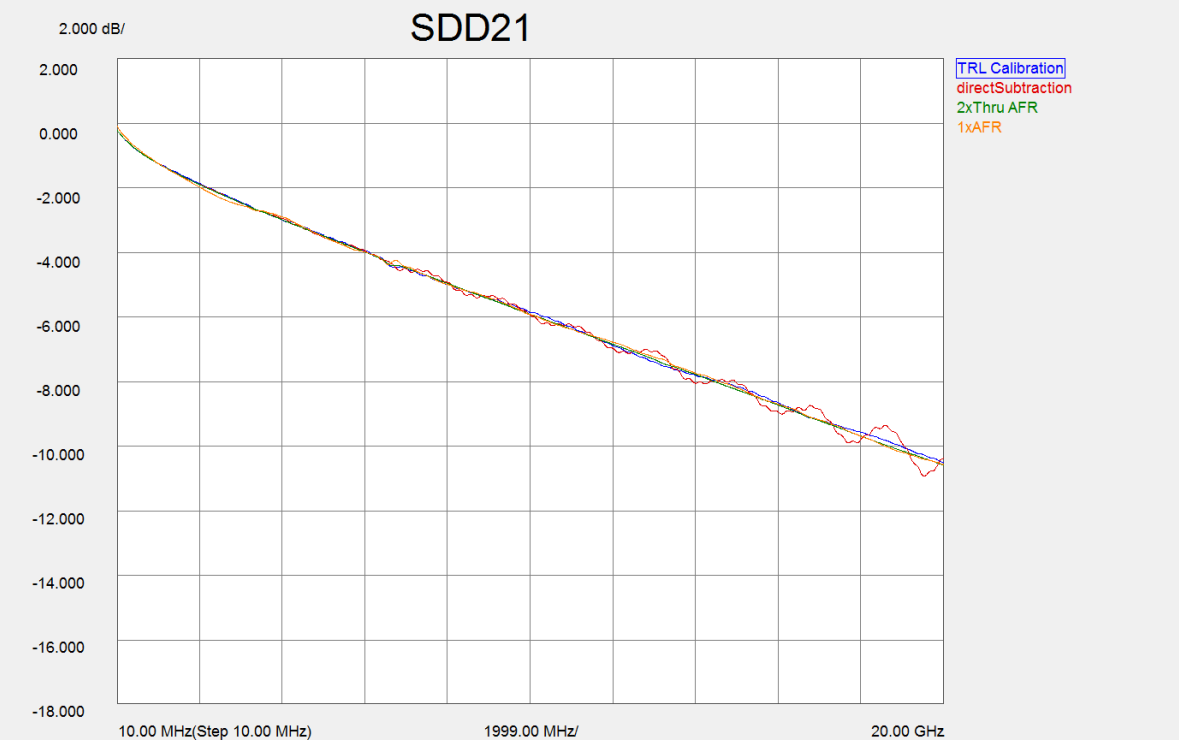
AFR with DUT Z0 = 75 Ohm



Case Study 1

PCB LOSS CHARACTERIZATION

Case study 1 – PCB loss characterization



Error compared to TRL:

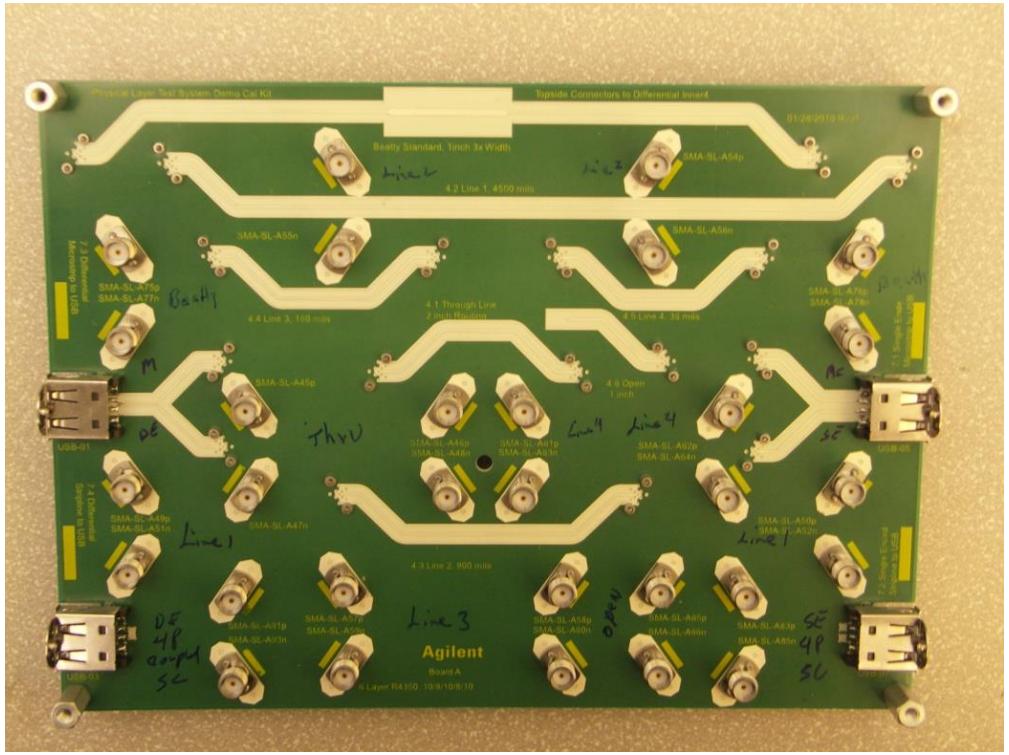
Char method	Error (dB/inch)
Direct Subtraction	0.06
2xThru AFR	0.016
One-port AFR	0.02

Case Study 2

RODGER 4350 PCB

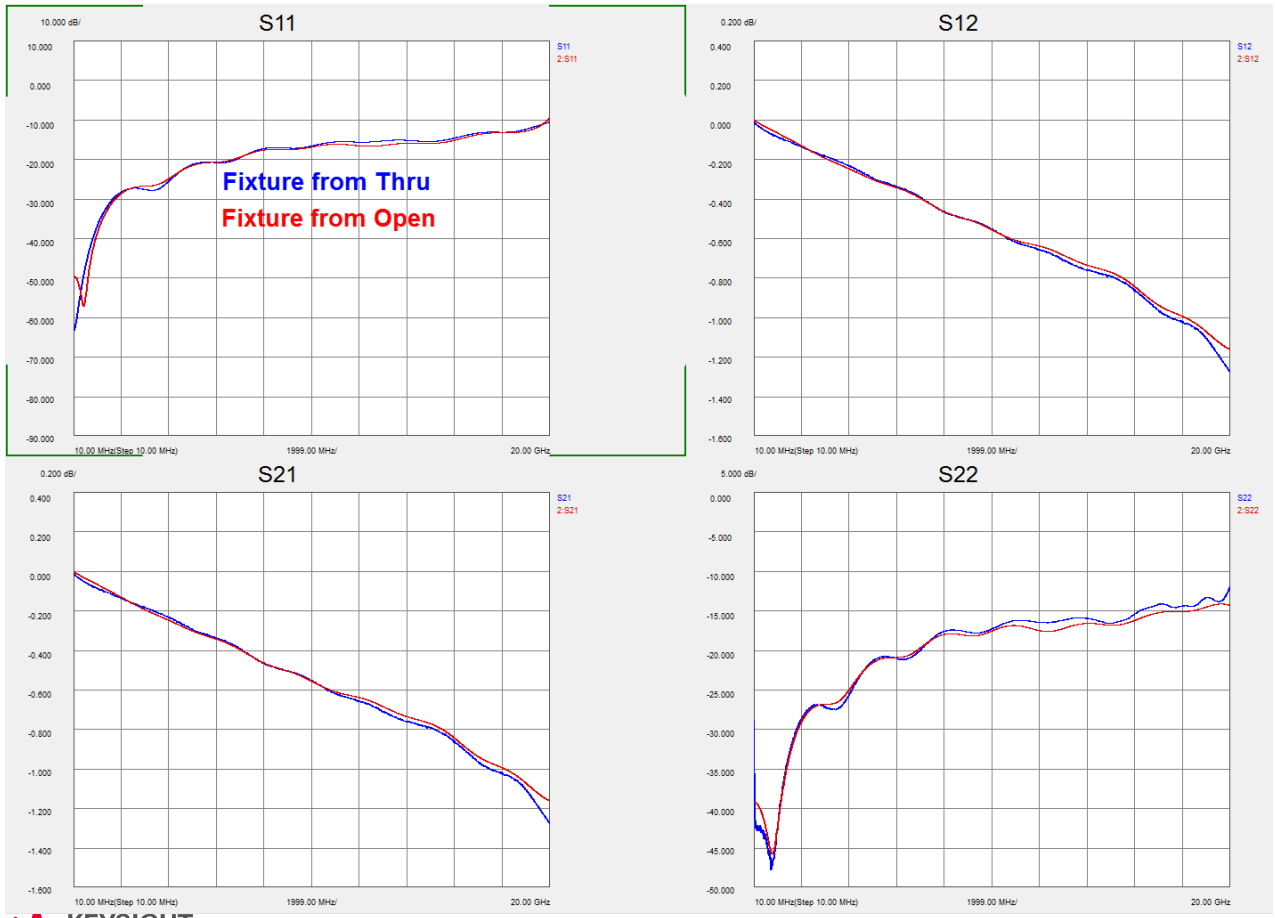
Case Study 2 – Rodgers 4350 PCB

- Low loss material
- Minimized weave variations
- Vias were not back drilled
- DUT is a mismatched line
- Compare AFR to TRL



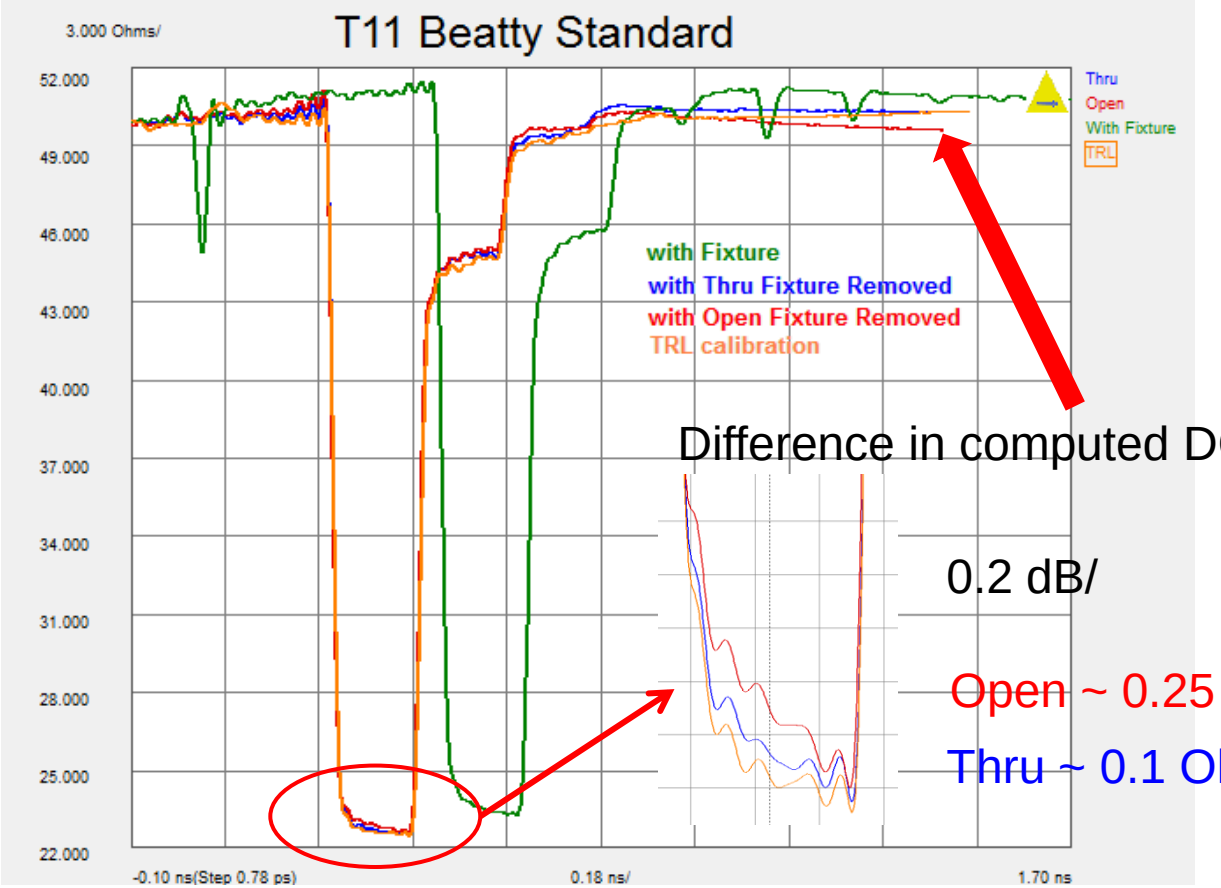
Rodgers 4350 Fixture

Comparing the fixture models from the 2X thru standard and the open standard, we see very good agreement.

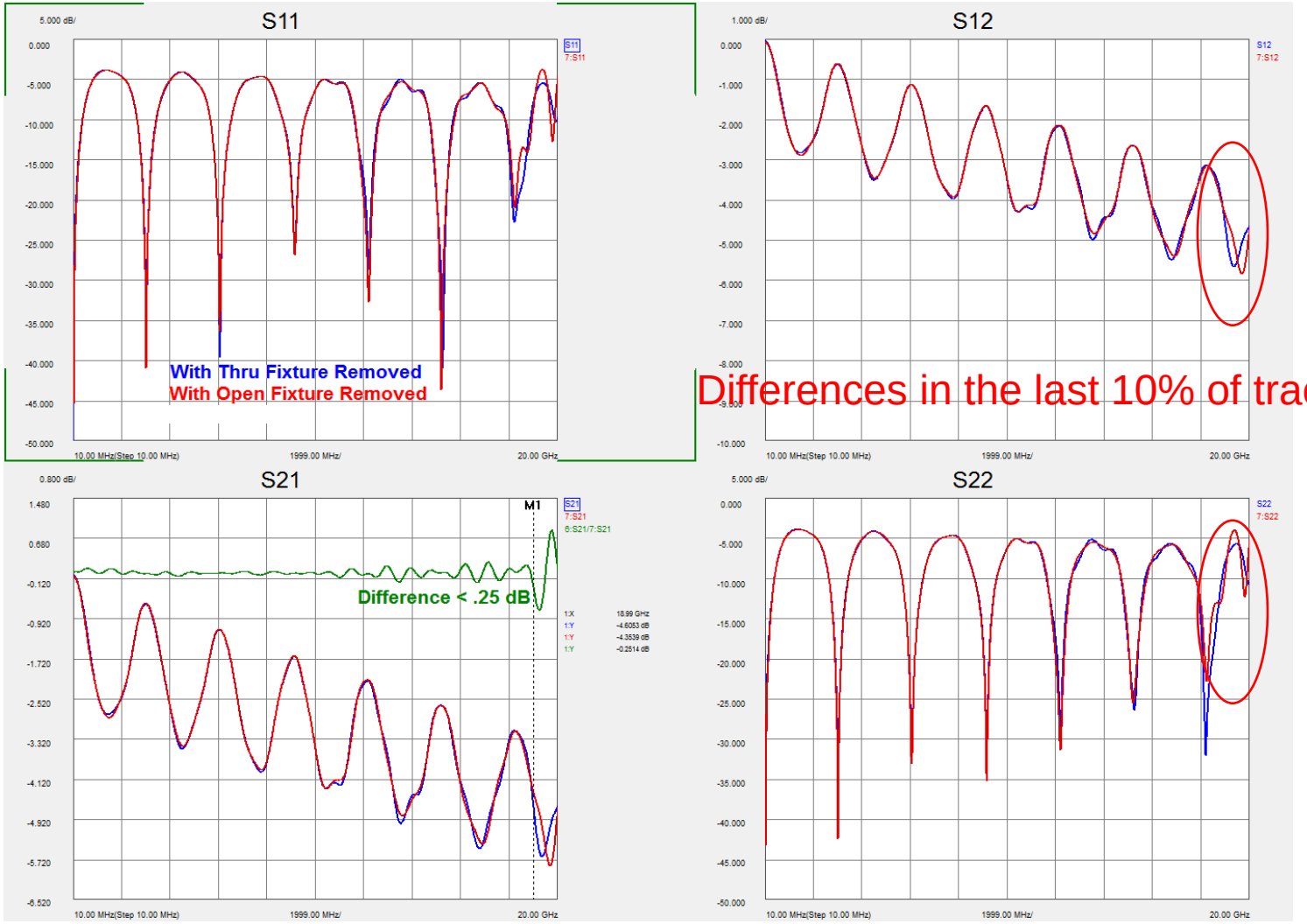


Rodgers 4350 Beatty DUT

Comparing DUT measurements after removing the fixtures from the 2X thru standard and the open standard, we see very good agreement.



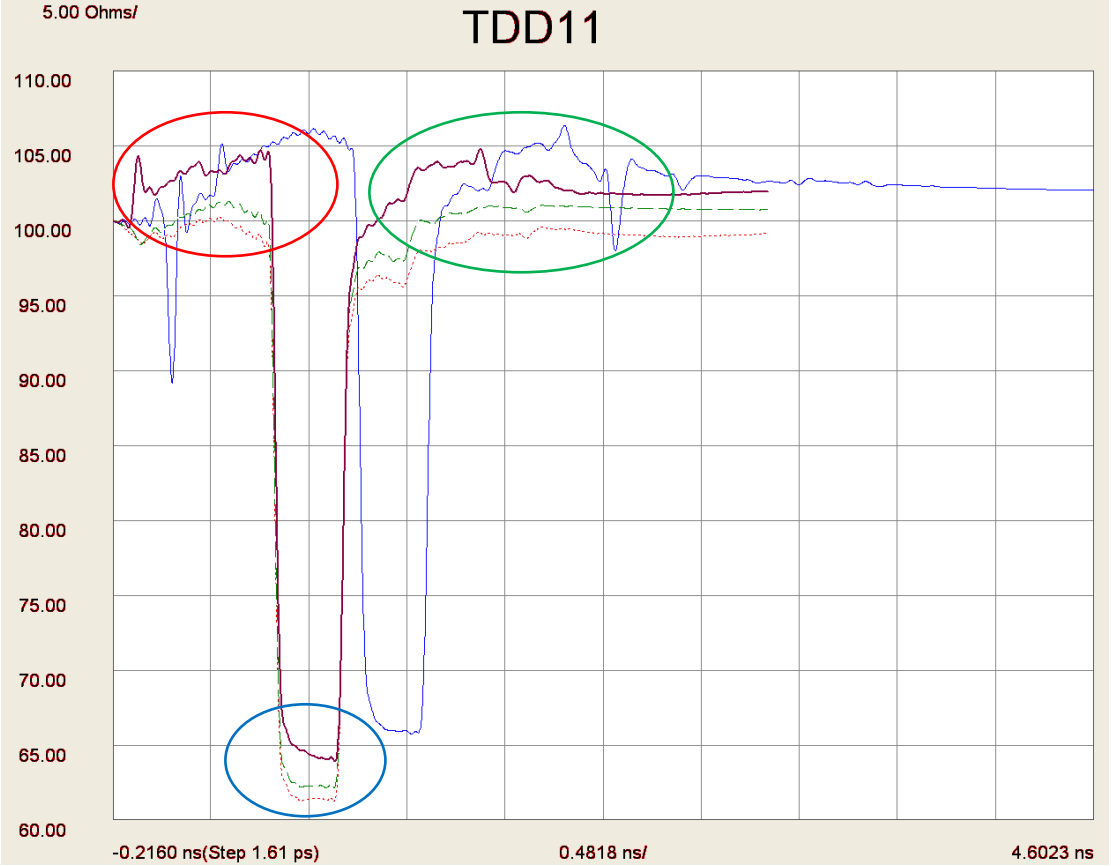
Rodgers 4350 Beatty DUT



Comparison

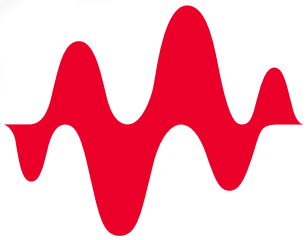
Comparing the 3 Fixture Removal Methods
USB Adapter With Differential Launch

- Original measurement
- Adapter + Fixtures
- TRL
- AFR
- SE TRL



Questions ?

KEYSIGHT TECHNOLOGIES



KEYSIGHT
TECHNOLOGIES