Best Measurement Practice in VNA Measurements - Hints for the Practitioner

VNA Tools II course

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Once upon a time… in a National Metrology Institute…

The HP 8510C was the state of the art in VNA metrology and representing the best accuracy and performance!

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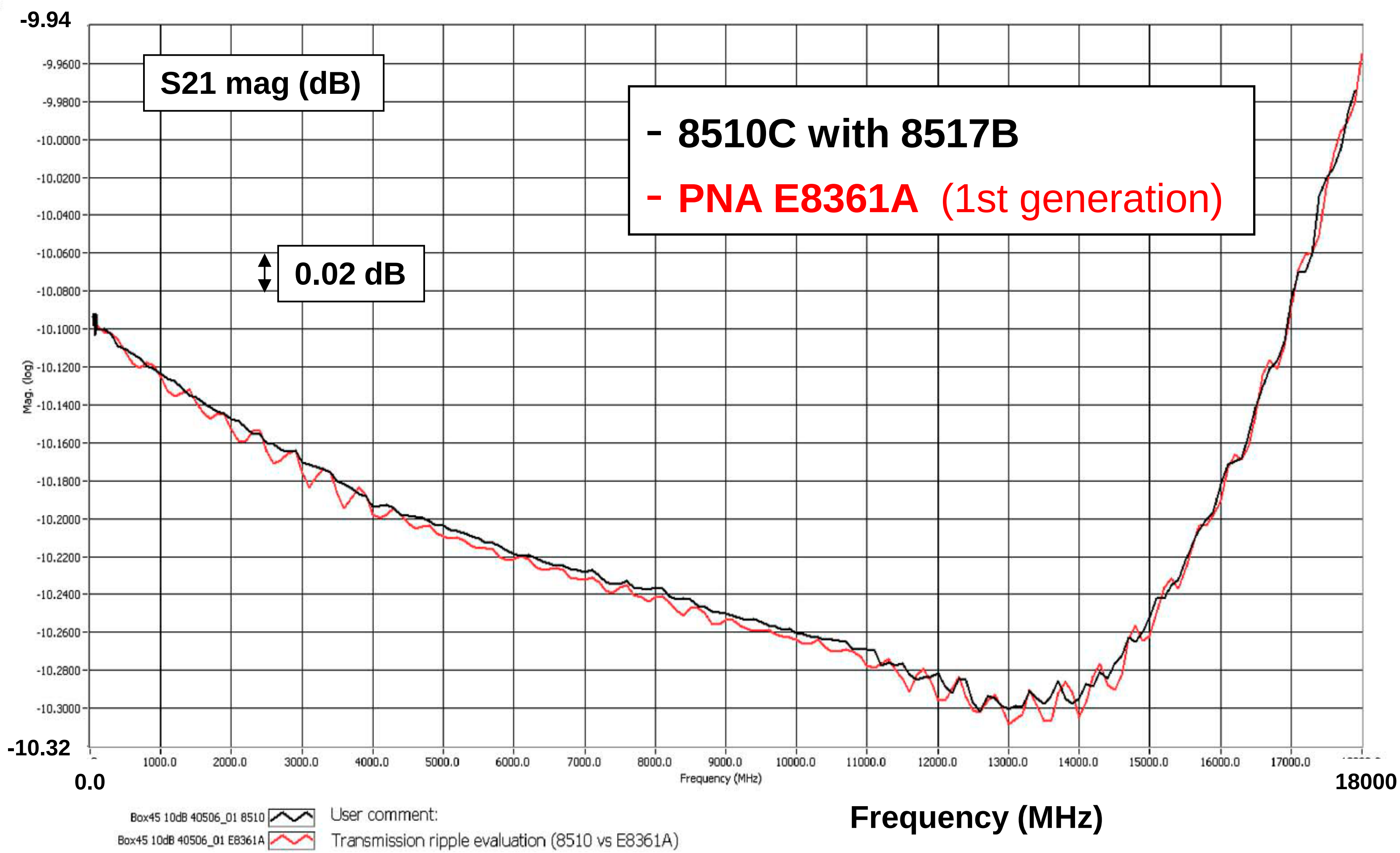
New VNAs: S21 measurement ripple of a Type-N 10 dB atten.

New VNA accuracy issue:
Using exactly the same set-up on both VNAs:
- cables
- port adapters
- cal kit and standard definitions.

Why is more ripple present?



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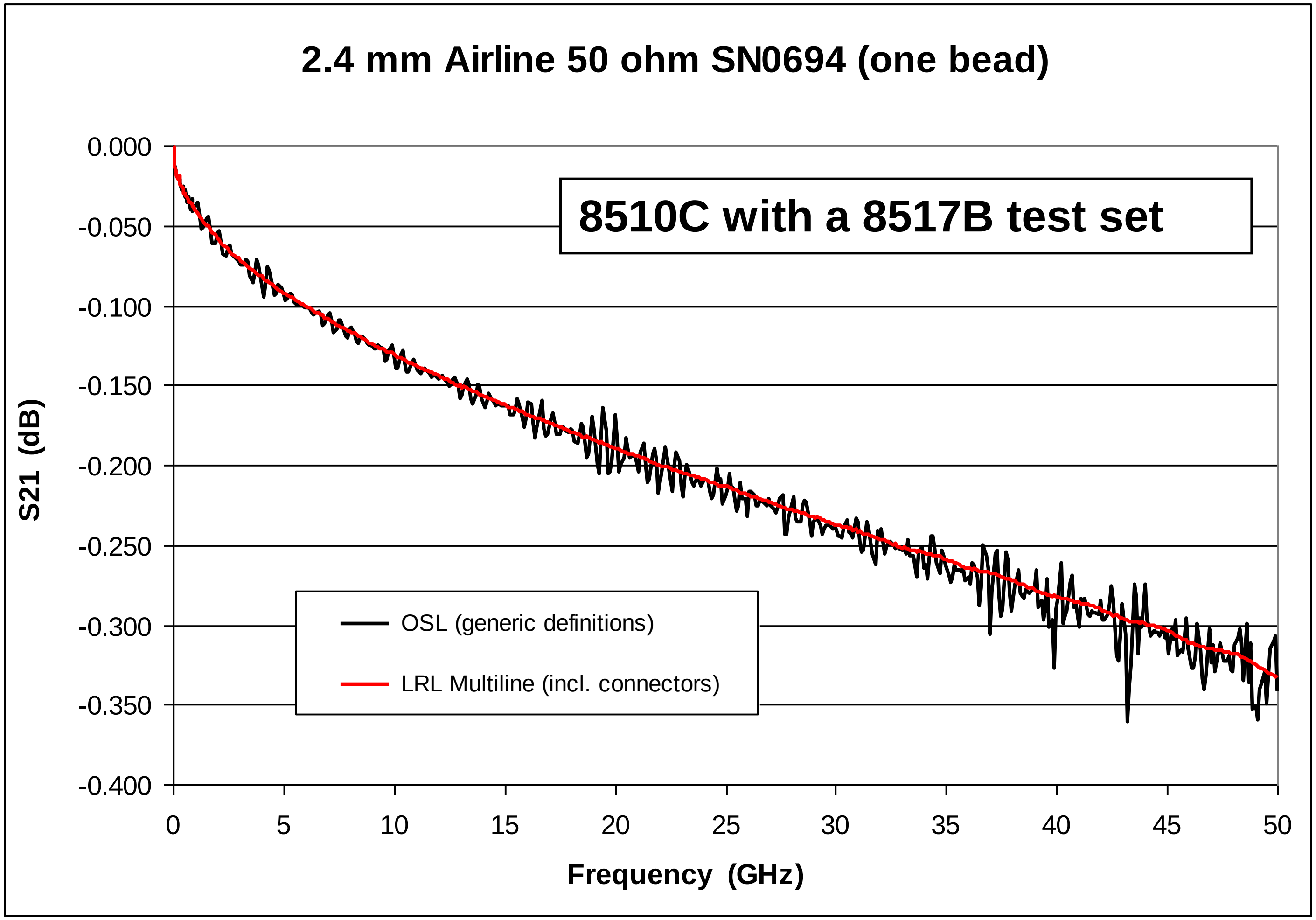
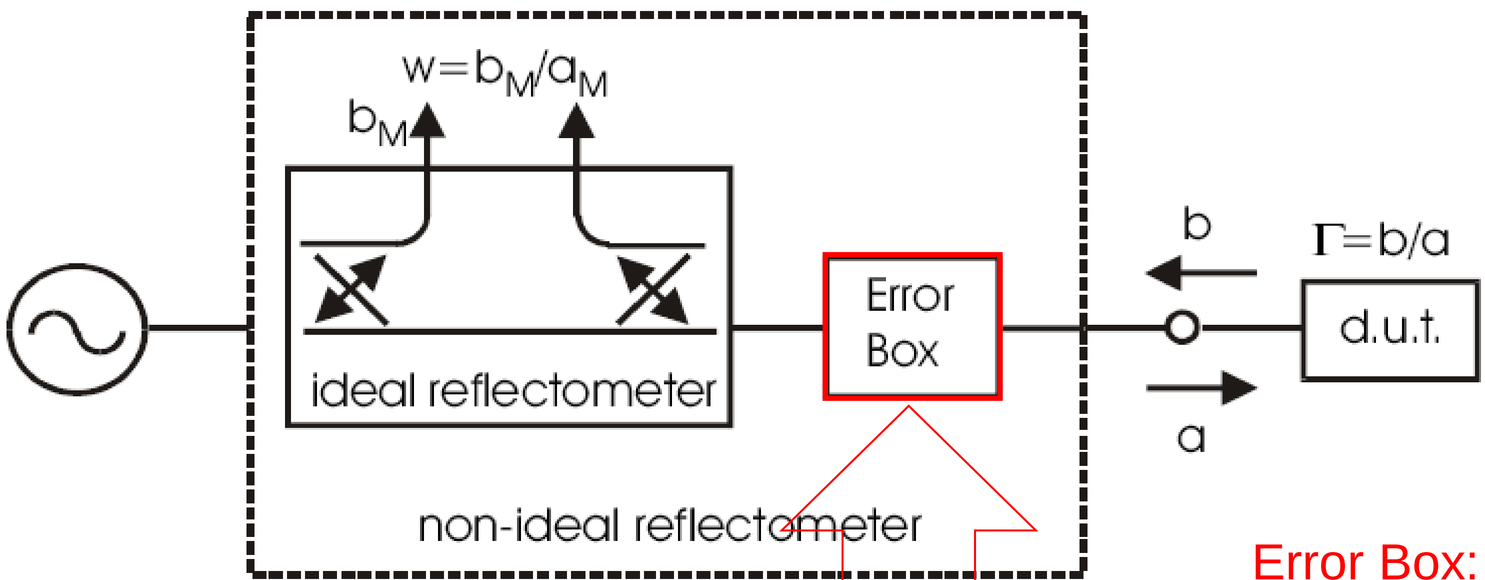
Introducing the systematic connector effects in the calibration standard definitions: The S21 ripple disappeared!

Improved accuracy:
Including the connector effects in the cal standard definitions allows to determine a more accurate reference plane!

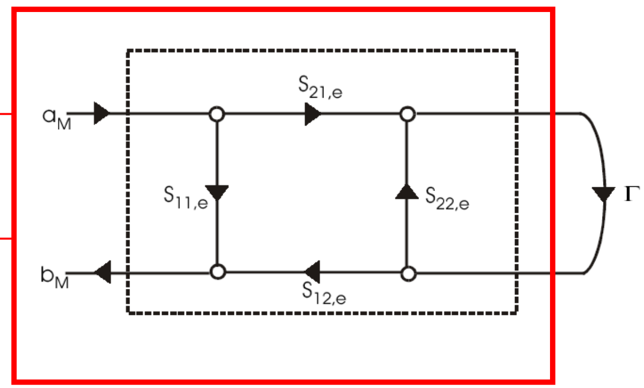
This results in a more accurate calculation of the:
- tracking terms and
- match terms



Error box model of the VNA (one port): *minimize the impacts!*



Error Box:



- ***VNA hardware and used measurement setup.***
- ***Cal standards: stability and traceability.***
- ***Used calibration method.***
- ***Operator (settings, handling, meas. order).***

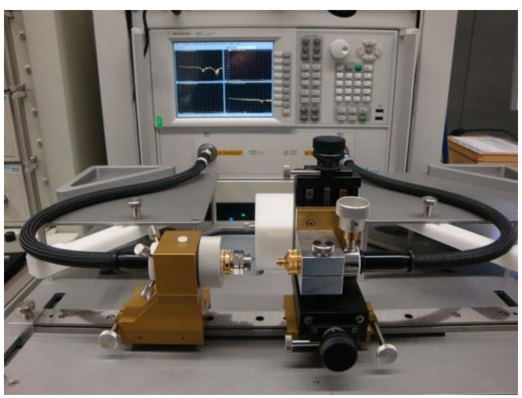
Best VNA measurement practice topics:

- **How to identify the dominant error sources?**
- **VNA measurement setup (pimp my VNA)**
- **Accuracy and S-parameter traceability chain**
- **Mating techniques and connector handling hints**
- **Practice and experience**

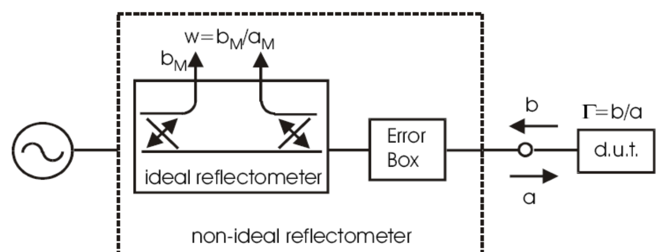
1st Topic

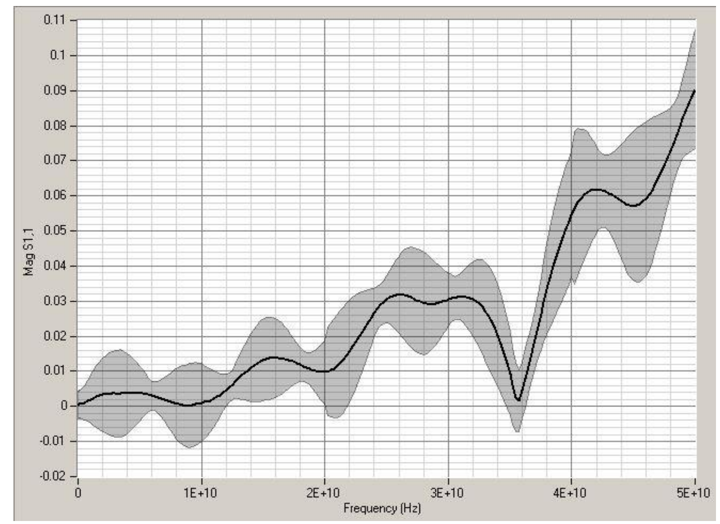
- **How to identify the dominant error sources?**

Basic influence parameters with uncertainties



VNA measurement model

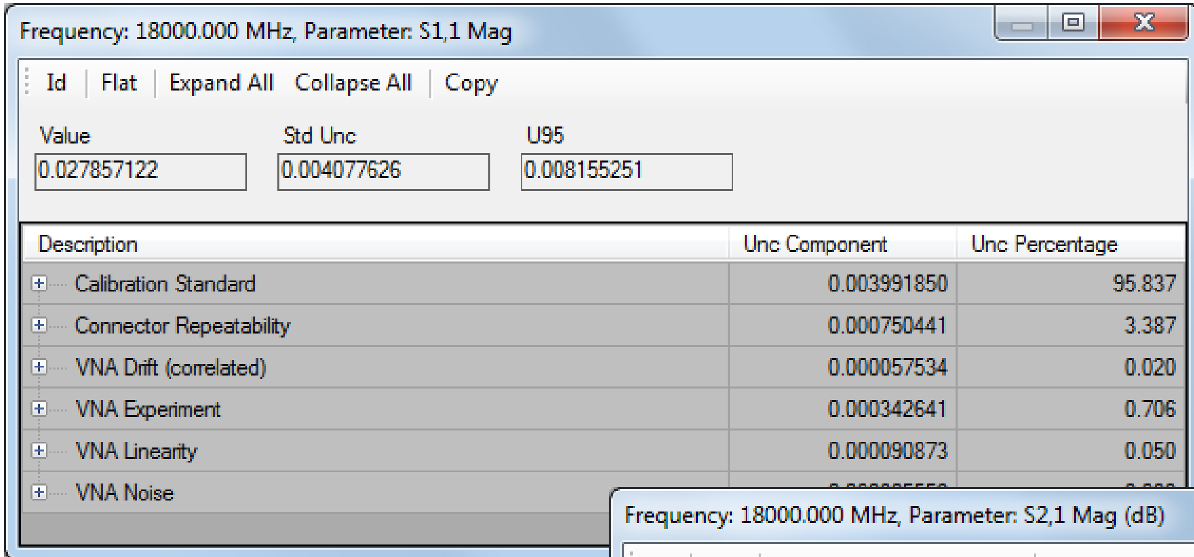




S-parameter data with uncertainties

GUM compliant VNA uncertainty budget per frequency point

Uncertainty budget:
S11 mag (lin) @ 18 GHz

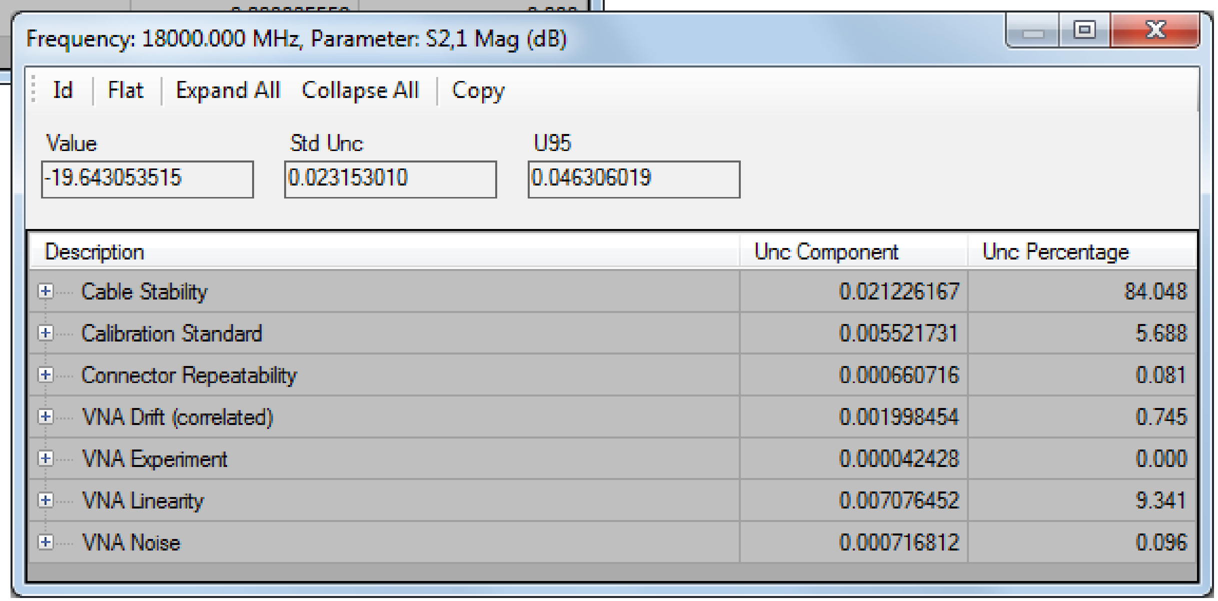


Frequency: 18000.000 MHz, Parameter: S1,1 Mag

Id | Flat | Expand All | Collapse All | Copy

Value	Std Unc	U95
0.027857122	0.004077626	0.008155251

Description	Unc Component	Unc Percentage
Calibration Standard	0.003991850	95.837
Connector Repeatability	0.000750441	3.387
VNA Drift (correlated)	0.000057534	0.020
VNA Experiment	0.000342641	0.706
VNA Linearity	0.000090873	0.050
VNA Noise		



Frequency: 18000.000 MHz, Parameter: S2,1 Mag (dB)

Id | Flat | Expand All | Collapse All | Copy

Value	Std Unc	U95
-19.643053515	0.023153010	0.046306019

Description	Unc Component	Unc Percentage
Cable Stability	0.021226167	84.048
Calibration Standard	0.005521731	5.688
Connector Repeatability	0.000660716	0.081
VNA Drift (correlated)	0.001998454	0.745
VNA Experiment	0.000042428	0.000
VNA Linearity	0.007076452	9.341
VNA Noise	0.000716812	0.096

Uncertainty budget:
S21 mag (dB) @ 18 GHz

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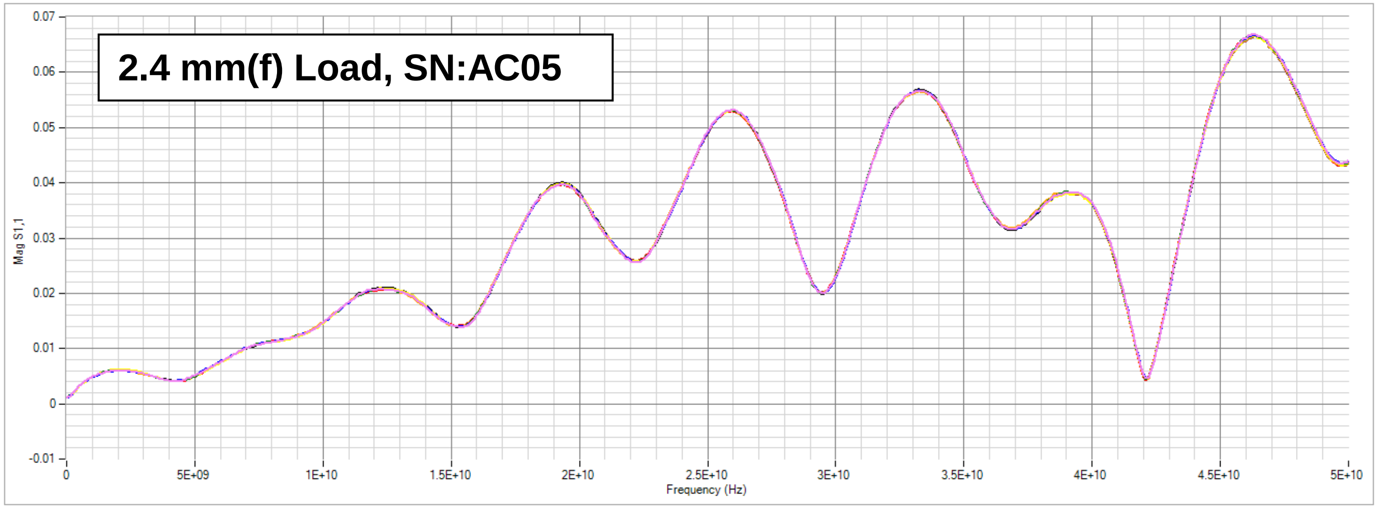
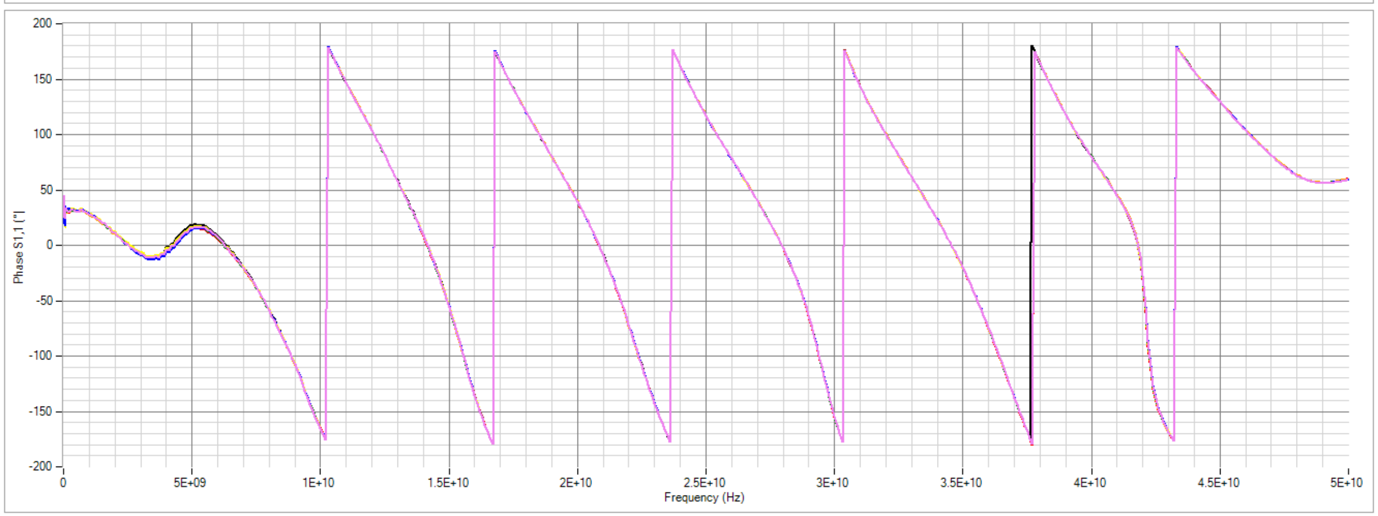
VNA uncertainty budget over all frequencies: no unc.

- S11 of a load measured at 8 different connector orientations

S11 mag (lin)



S11 phase (deg)



First example: DUT showing a good repeatability behaviour when measured at 8 different connector orientations.

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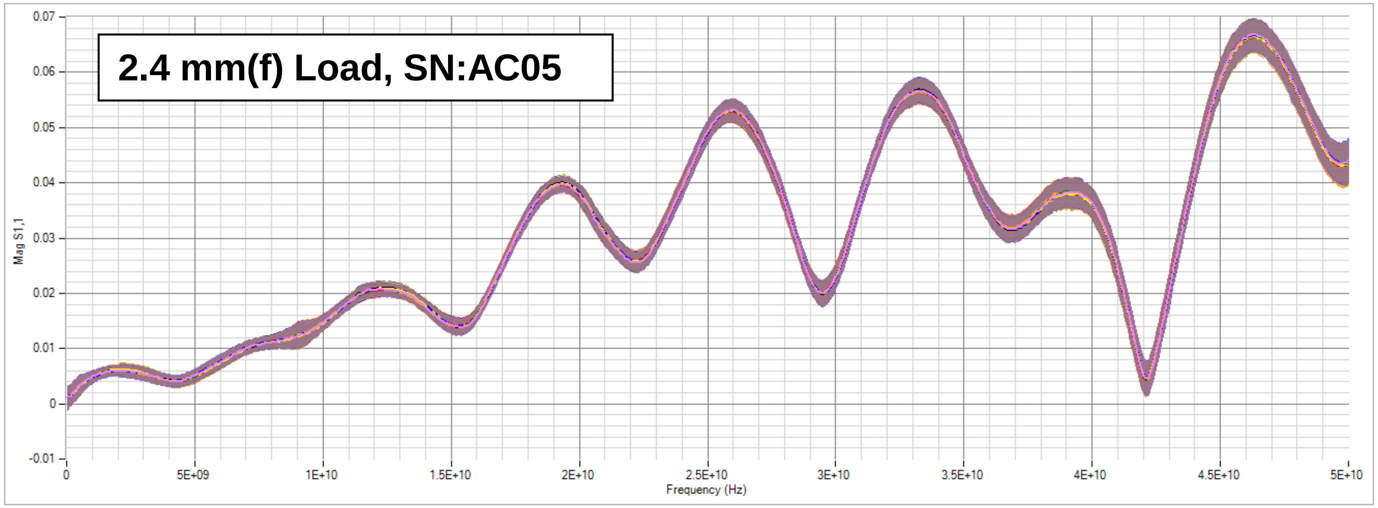
VNA uncertainty budget over all frequencies: with all unc.

- S11 of a load measured at 8 different connector orientations

0.070

S11 mag (lin)

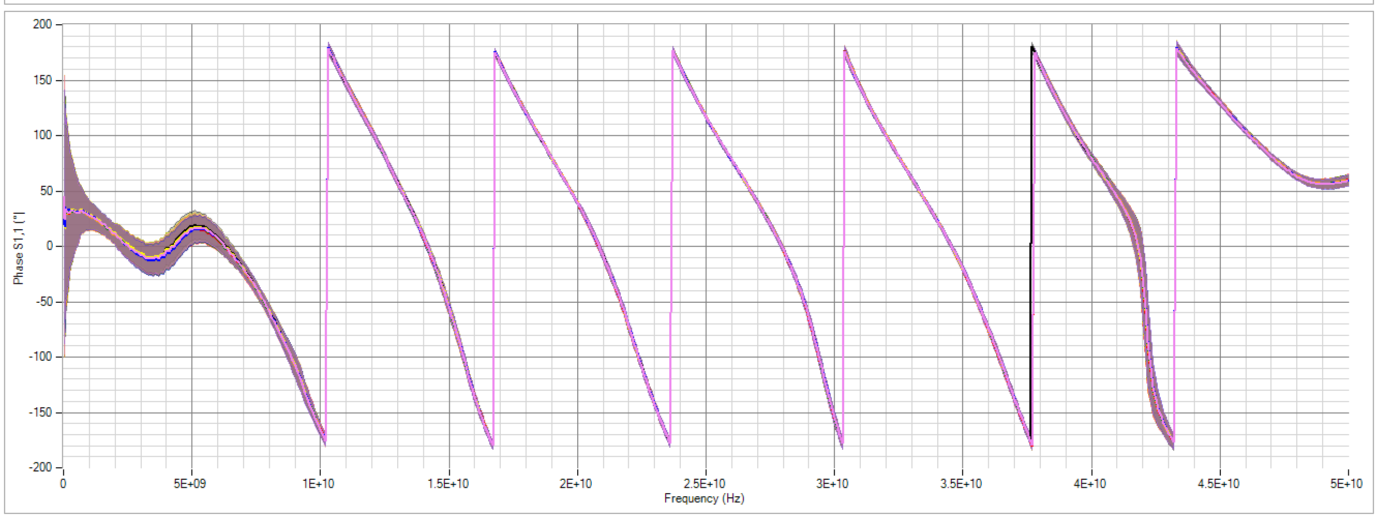
0.000



200

S11 phase (deg)

-200



First example: DUT showing a good repeatability behaviour when measured at 8 different connector orientations.

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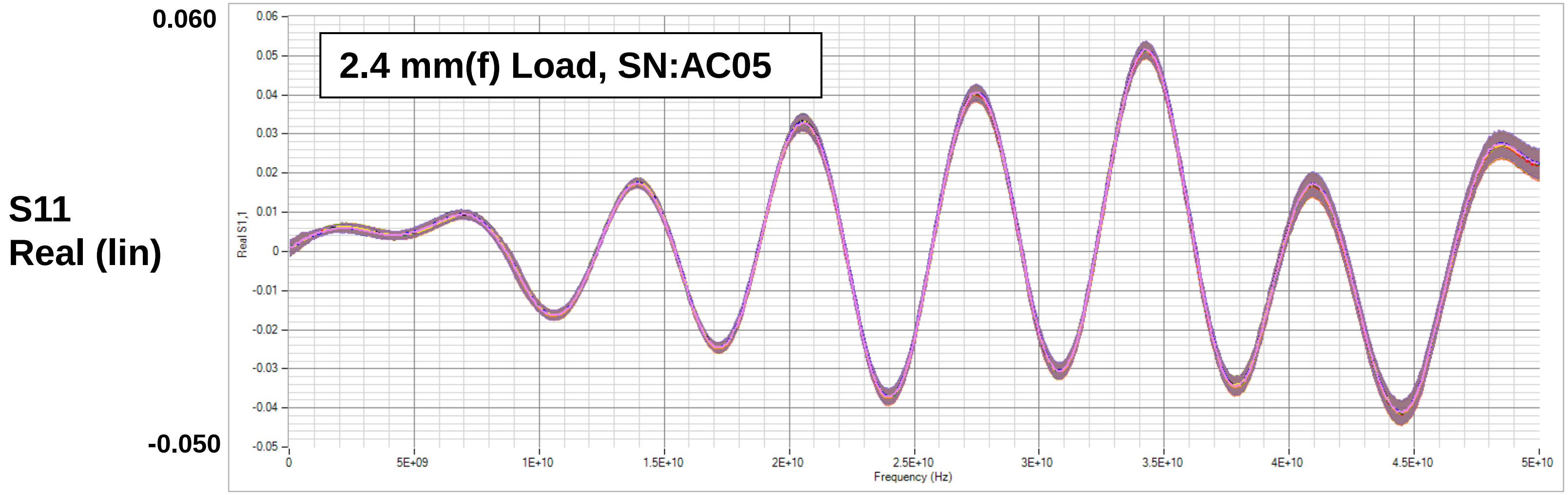
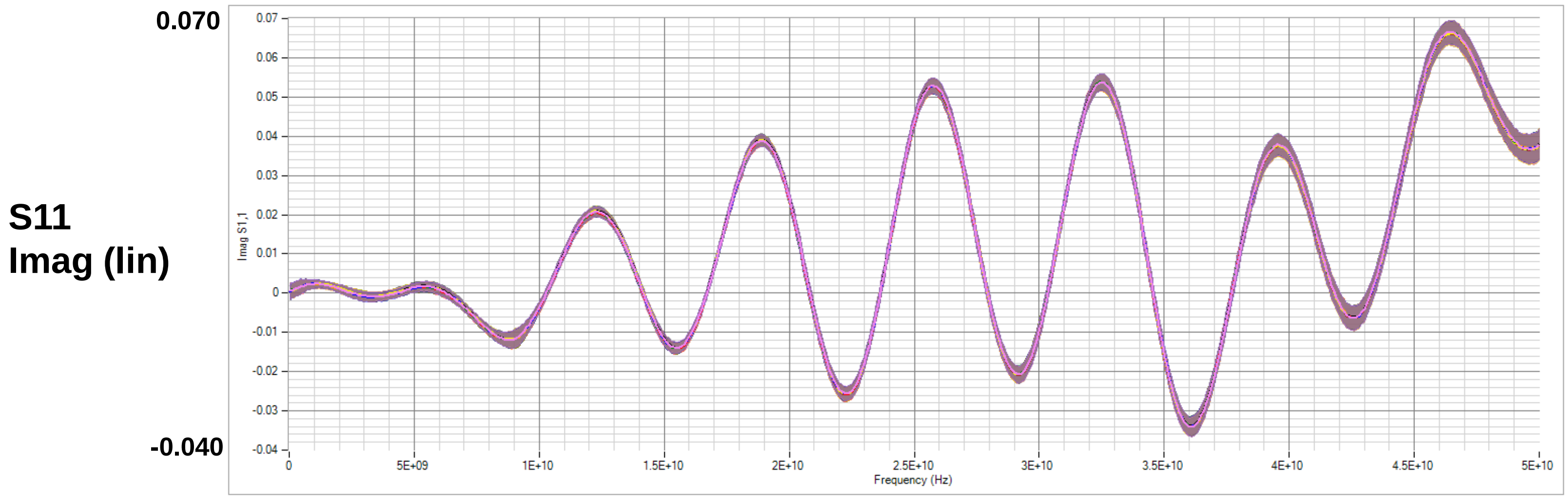
VNA uncertainty budget over all frequencies: with all unc.

- S11 of a load measured at 8 different connector orientations





First example: DUT showing a good repeatability behaviour when measured at 8 different connector orientations.

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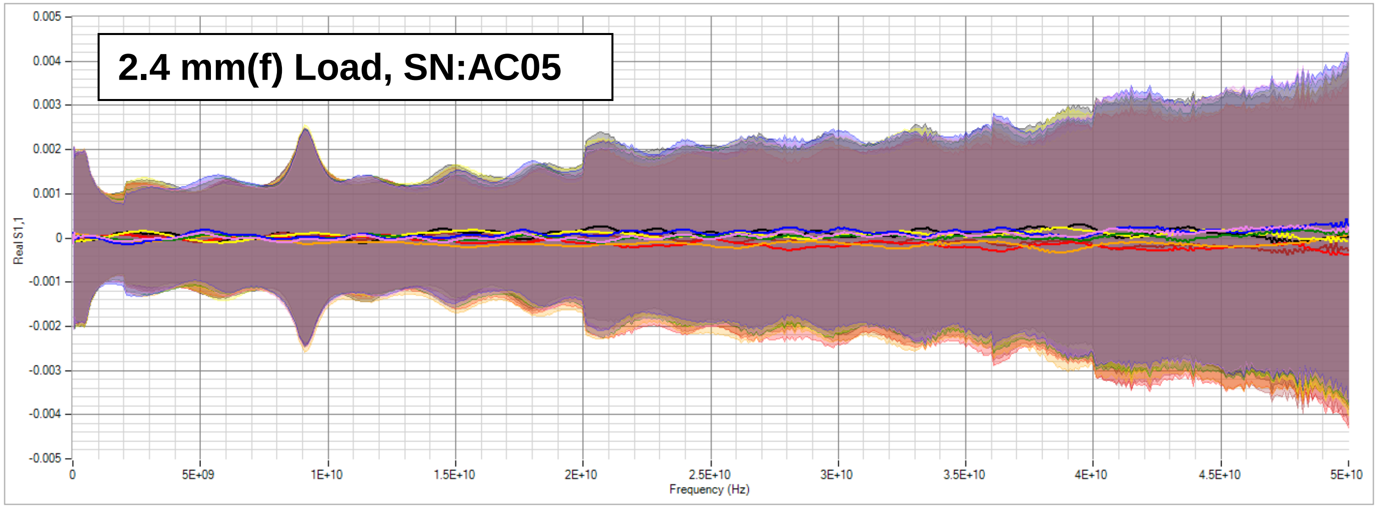
VNA uncertainty budget over all frequencies: with all unc.

- S11 normalized to the mean value (all influence parameters)

0.005

S11
Real (lin)

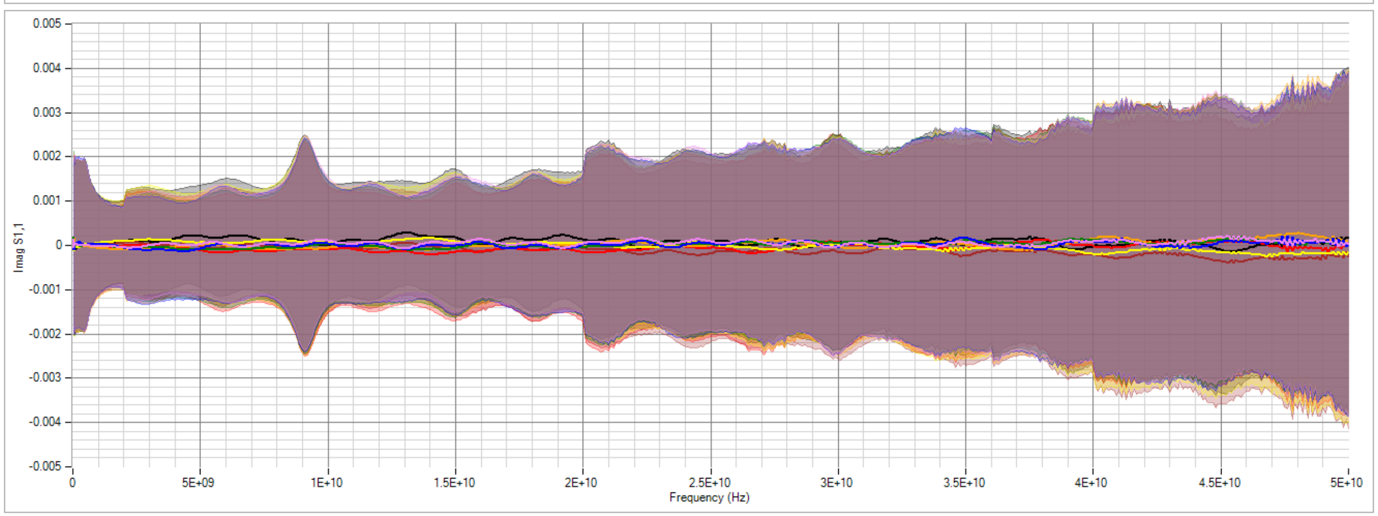
-0.005



0.005

S11
Imag (lin)

-0.005



First example:
DUT showing a good repeatability behaviour when measured at 8 different connector orientations.

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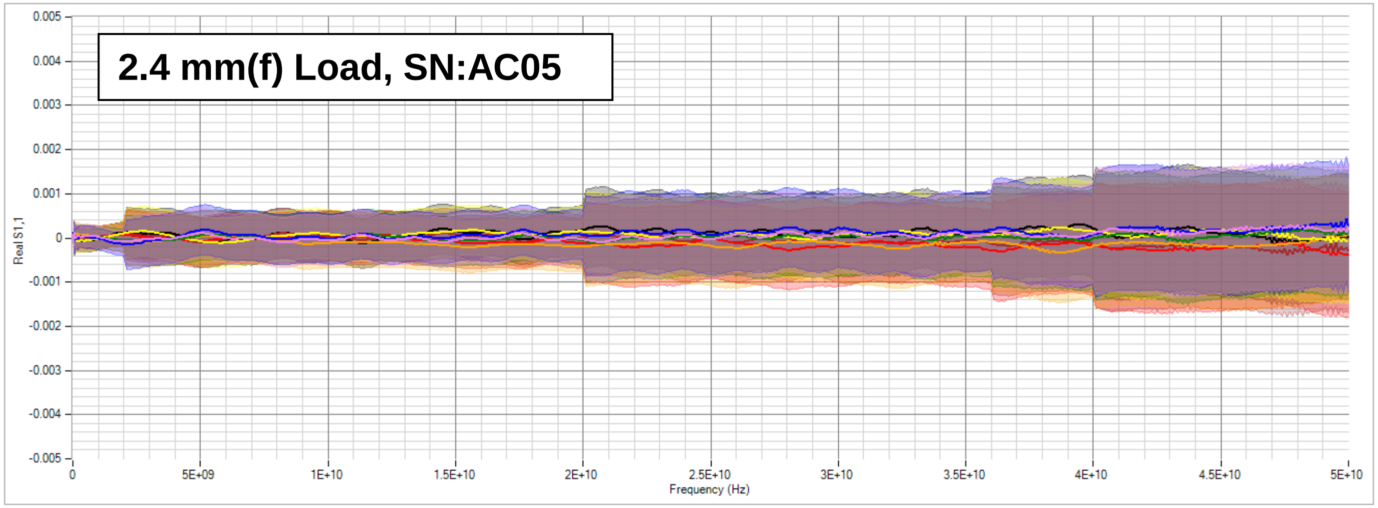
VNA uncertainty budget over all frequencies: single unc.

- S11 normalized to the mean value (connector repeatability unc. only)

0.005

S11
Real (lin)

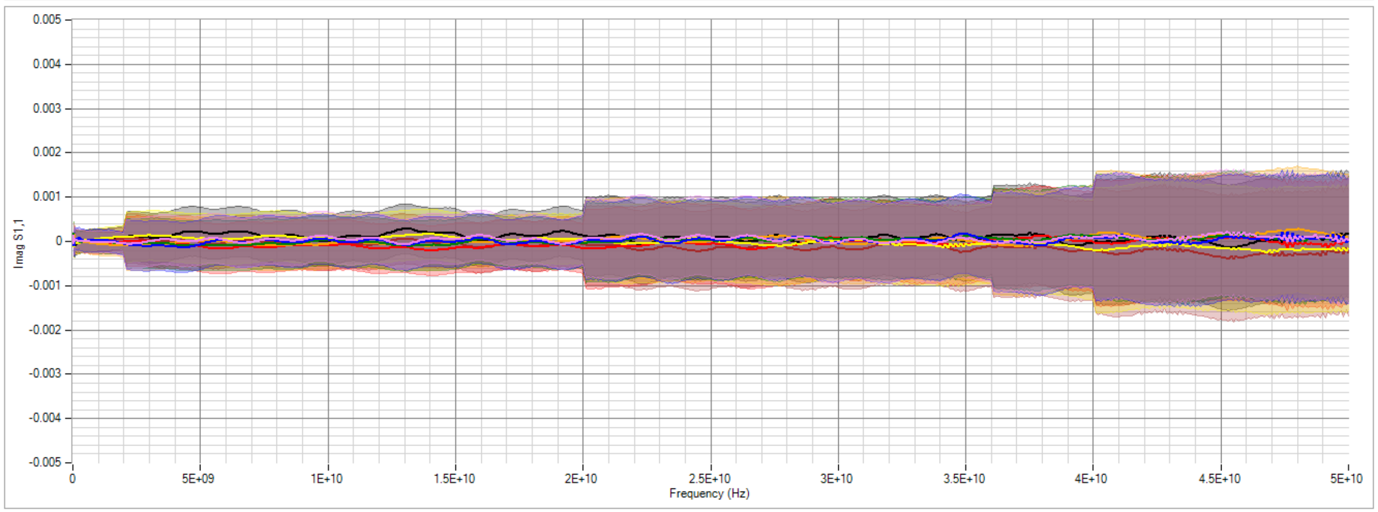
-0.005



0.005

S11
Imag (lin)

-0.005



First example:
DUT showing a good repeatability behaviour when measured at 8 different connector orientations.

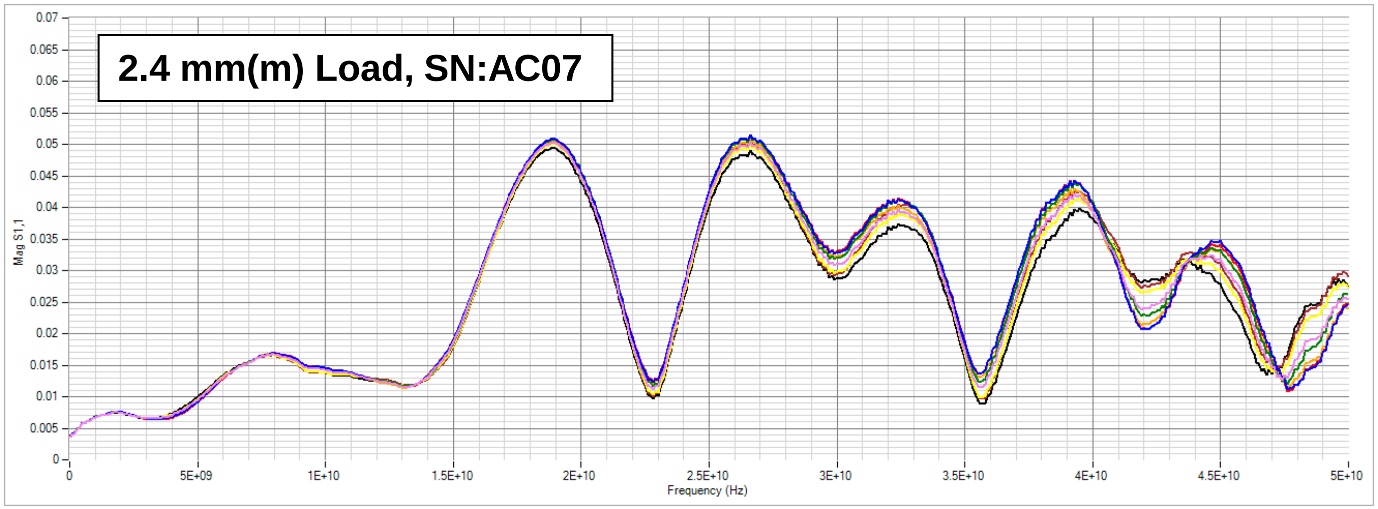
VNA uncertainty budget over all frequencies: no unc.

- S11 of a load measured at 8 different connector orientations

S11 mag (lin)

0.070

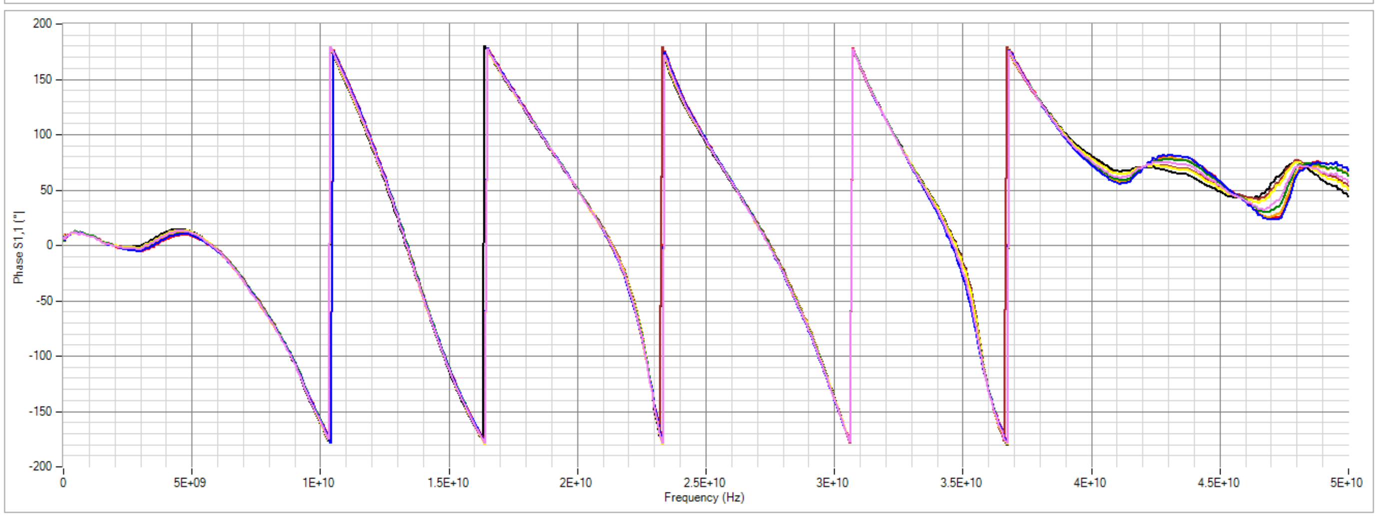
0.000



S11 phase (deg)

200

-200



Second example:
DUT showing a bad repeatability behaviour when measured at 8 different connector orientations.

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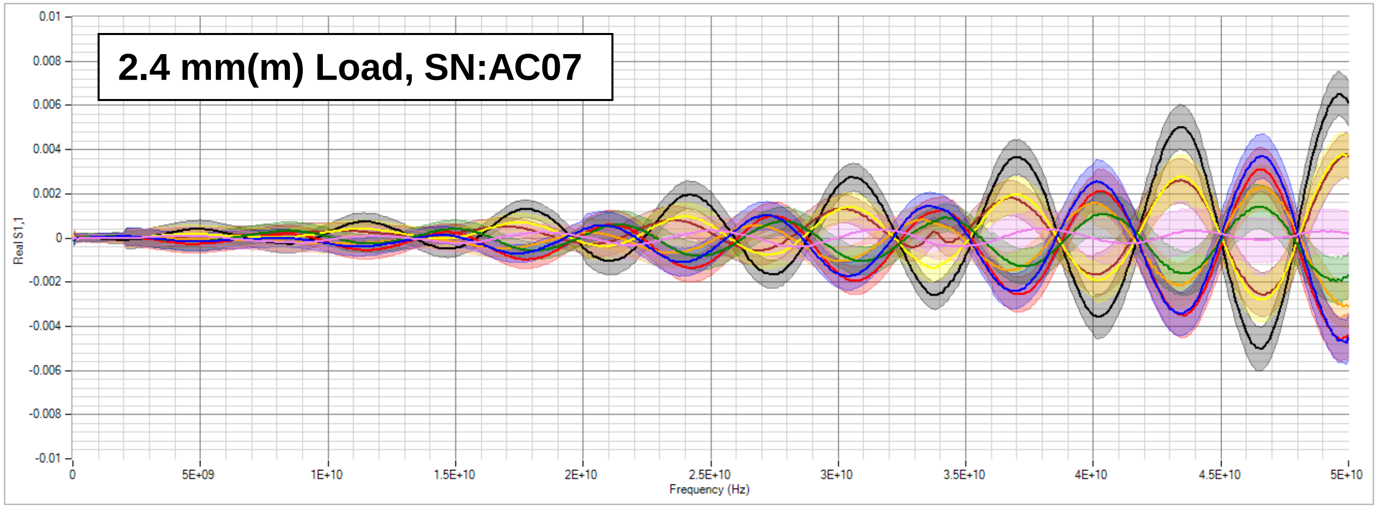
VNA uncertainty budget over all frequencies: single unc.

- S11 normalized to the mean value (connector repeatability unc. only)

0.010

S11
Real (lin)

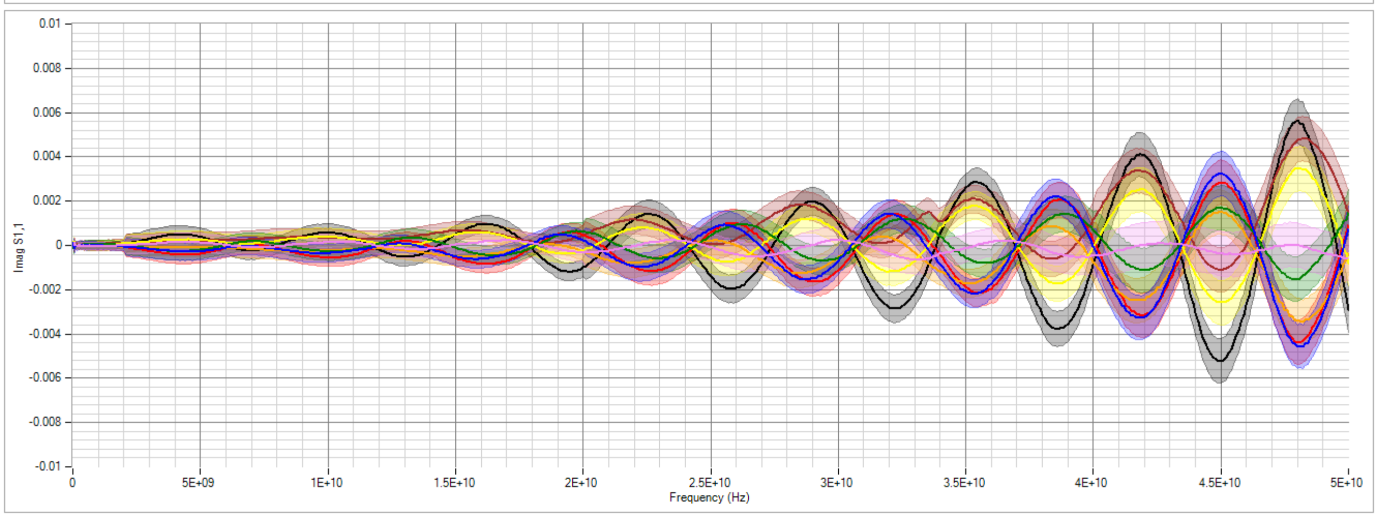
-0.010



0.010

S11
Imag (lin)

-0.010



Second example:
DUT showing a bad repeatability behaviour when measured at 8 different connector orientations.

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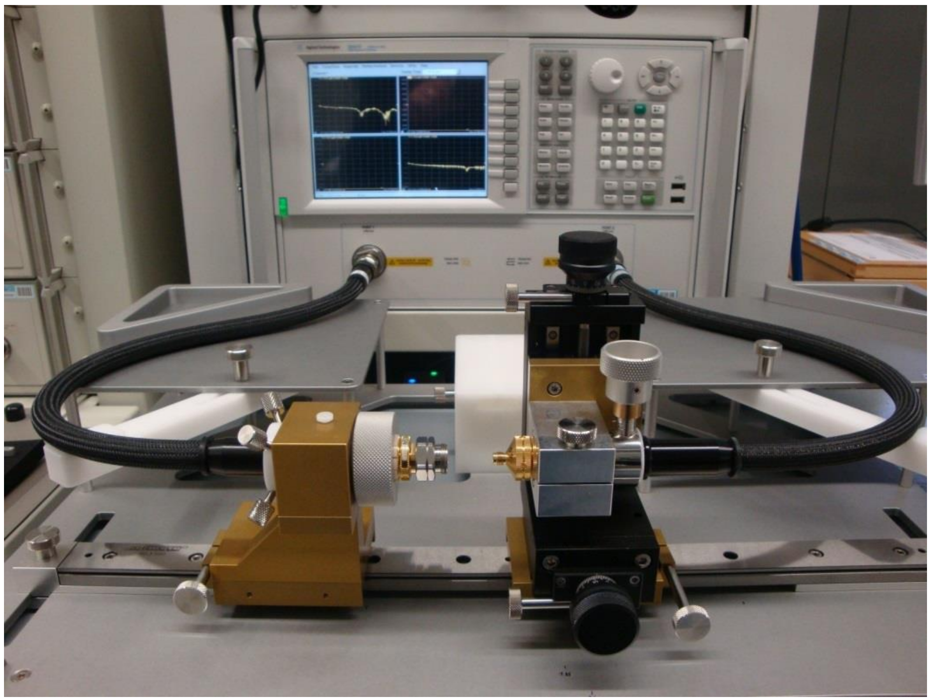
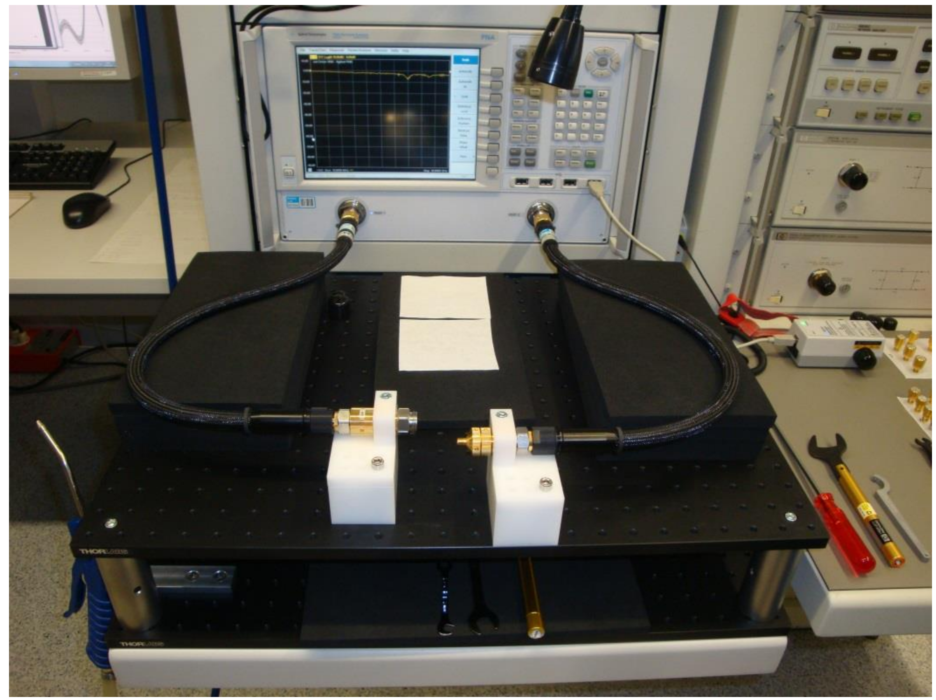
2nd Topic

- **VNA measurement setup (pimp my VNA)**





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VNA architecture, performance and settings

- **VNA hardware**

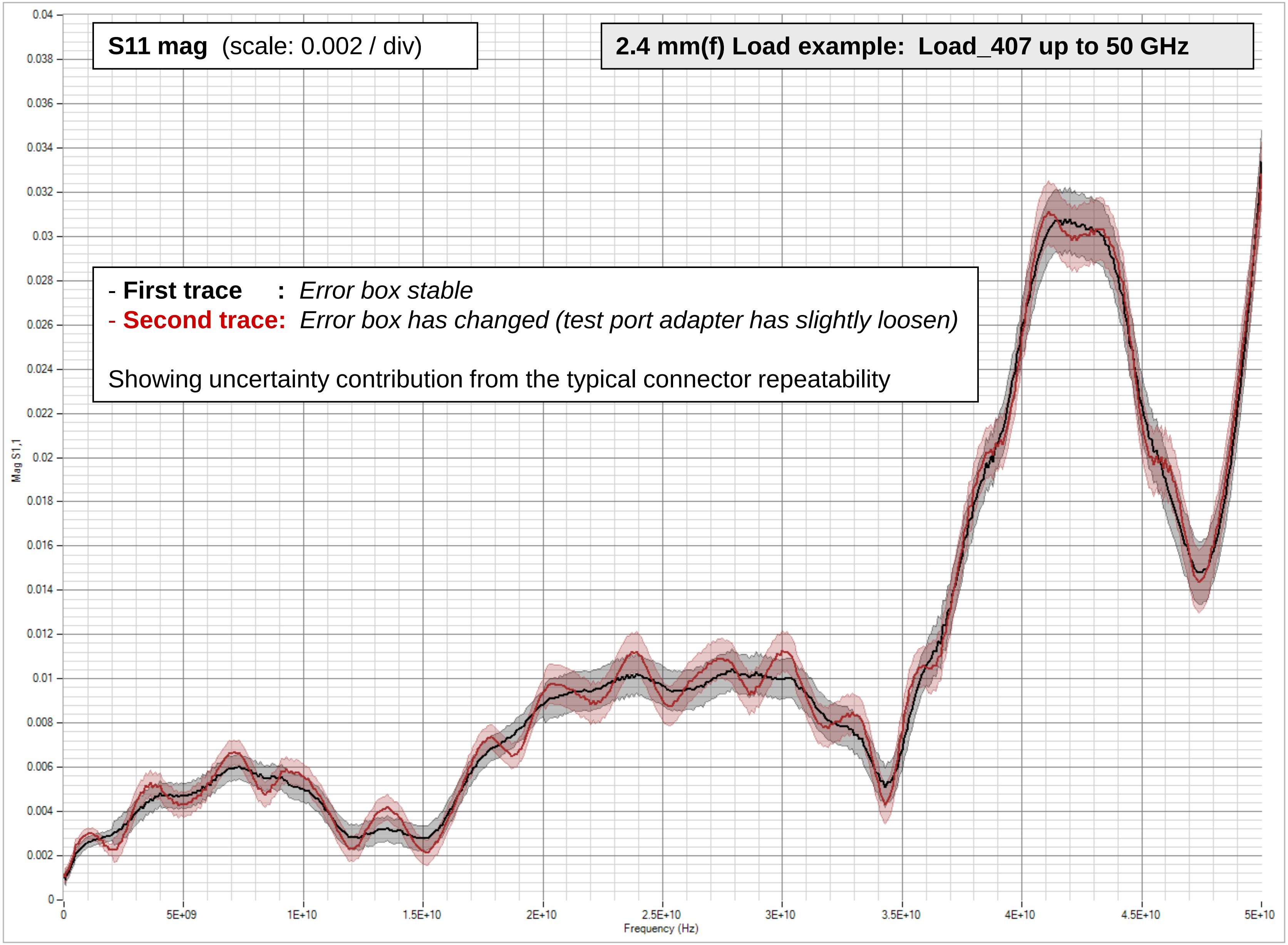
  - **4 receiver architecture** (possible to measure the switch terms).
  - **VNA errors** (note: it is not possible to error correct for all VNA errors)
    - **Systematic** (directivity, tracking terms, match terms, …),
    - **Random** (noise floor and trace noise),
    - **Drift** (S-parameters, switch and error terms)

- **VNA box performance**

  - **Raw match performance, receiver ratio linearity, S21-S12 symmetry** (specifications)**.**
  - **Metrology grade VNA (option): drift, raw performance, symmetry, temperature monitor.**
  - **Additional thermal isolation of the VNA** (box mounted in a rack cabinet)**.**

- **VNA settings**

  - **Source power** (receiver compression, DUT effects).
  - **Frequency resolution** (better information using more frequency points).
  - **Sweep time versus accuracy** (sweep types: swept vs. stepped sweep, frequency list).
  - **VNA accuracy:** reduce the IF BW instead of averaging.
  - **Avoid to stay in the HOLD mode** (VNA dependant, *VNA Tools II*: use measurement series).


S11 mag (scale: 0.002 / div)
2.4 mm(f) Load example: Load_407 up to 50 GHz
- First trace : Error box stable
- Second trace: Error box has changed (test port adapter has slightly loosen)
Showing uncertainty contribution from the typical connector repeatability
Mag S1,1
0.04
0.038
0.036
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5E+09
1E+10
1.5E+10
2E+10
2.5E+10
3E+10
3.5E+10
4E+10
4.5E+10
5E+10
Frequency (Hz)

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VNA test port cables (goal: to minimize the cable effects)

- **Test port cable styles**

  - Semi-Rigid versus flexible cables.
  - Short versus long test port cables.

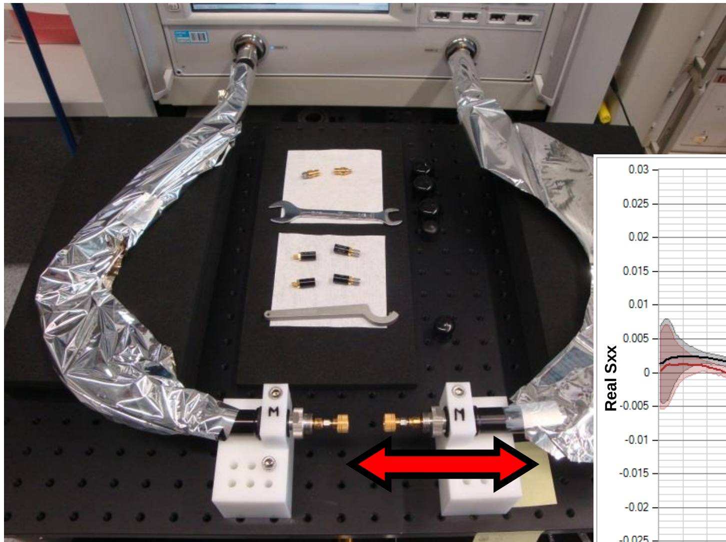
- **Test port cable layout**

  - Avoid: an unsupported cable setup, cable twisting, minimize any cable movements.
  - Commercial breadboard based fixture with clamps and foam pads support.
  - Special cable fixtures (most important: mechanically not over-determined → flush mating)**.**
  - Thermal isolation (thin rescue blanket foil, foam, etc.)**.**

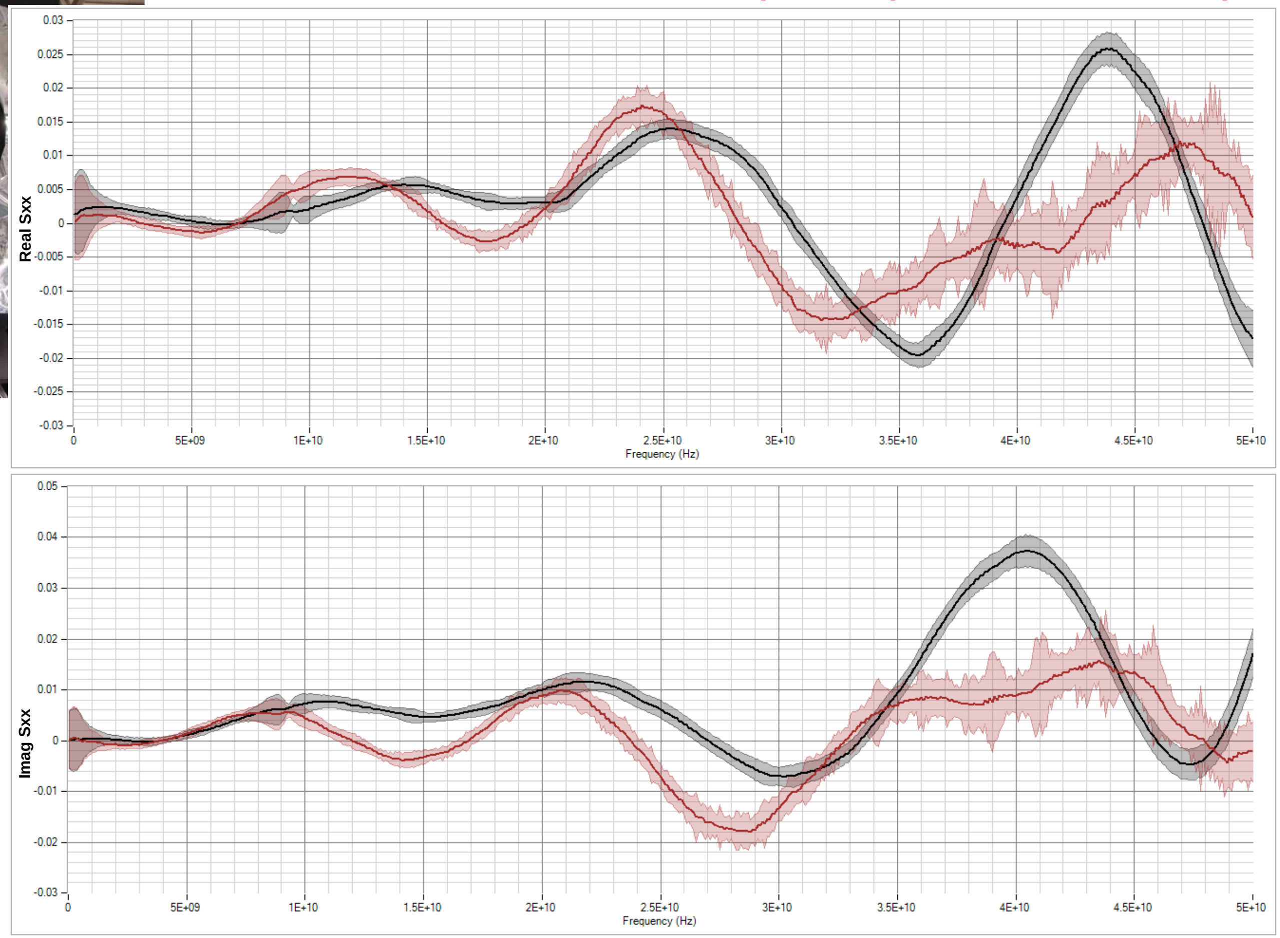
- **Practical cable handling hints**

  - Respect the natural bending of the cable (adaptive fixture design)**.**
  - Install the cables on the previous evening (time for the thermal and mechanical settling)**.**
  - Or if the needed time is not available: first warm up the cold cable connector interface.
  - Each cable has a settling time.
  - Some cables are showing hysteresis effects (mechanically and thermally)**.**
  - Using cables or perform the measurement direct on the VNA test ports (adapters)?
  (thermal effects: sensitive load designs, change of the dimensional properties → phase)
  - Cable storage boxes: avoid any stress to the 'cable – connector interface' section.

VNA test port cables (fixed port: female or male?)



Black trace : female load measurement (using a fixed port).
Red trace : male load measurement (the test port cable was moved).



Optimise the cable layout for minimal cable movements.

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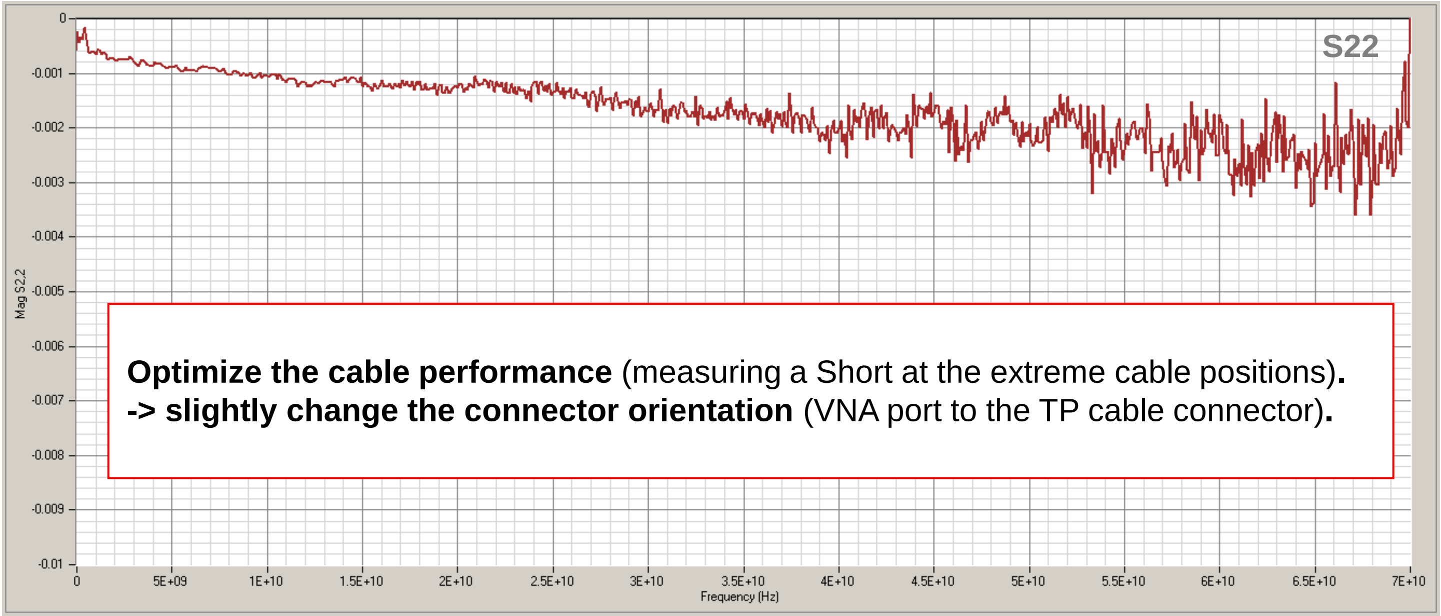
0.000

S22 mag (lin)

-0.010



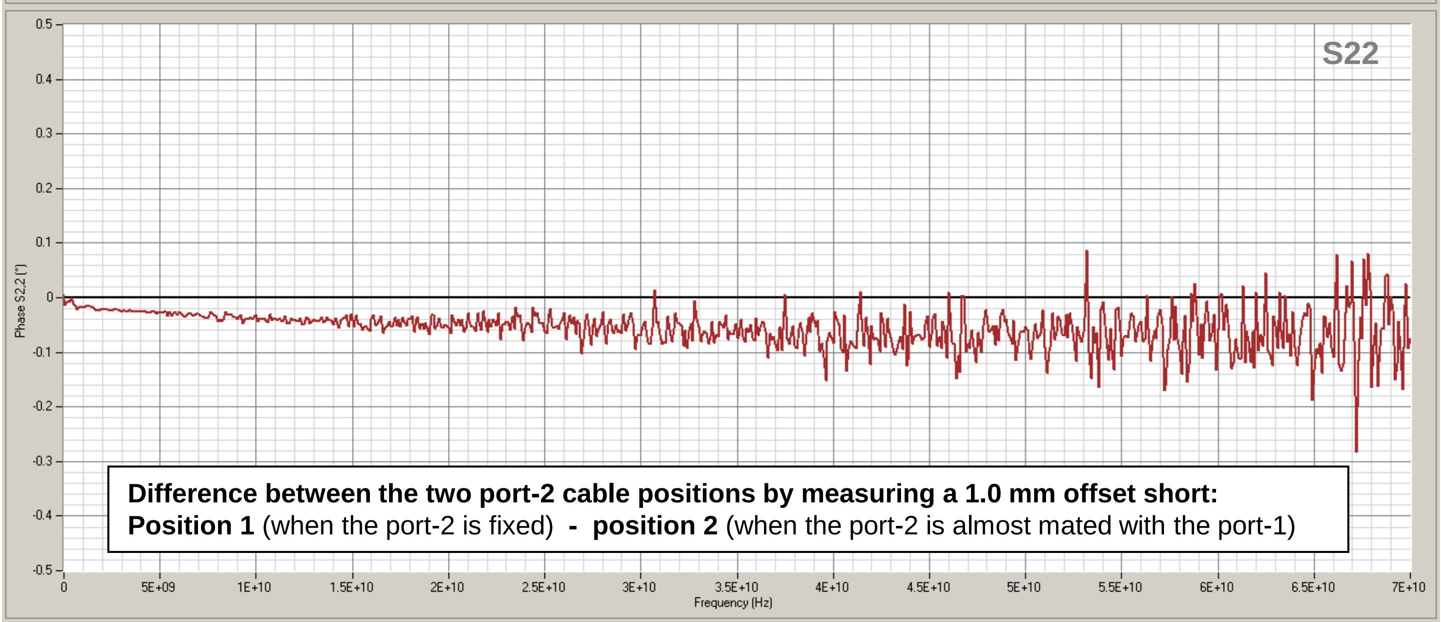
raw data normalized to 1st trace

Note:
raw data versus error corrected data?

0.5

S22 phase (deg)

-0.5



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VNA test port adapters (goal: to improve the repeatability)

- **Test port adapter styles**

  - Metrology versus lab precision type adapters.
  - Slotless versus slotted type.

- **Important features of a best test port adapter**

  - Mechanical specification: pin-depth, pin diameter, no eccentricity, surface finish.
  - Select a pin-depth which avoids to provoke the unpredictable near field effects.
  - Shows a good repeatability behaviour → low connector orientation sensitivity.
  - Does not change the characteristics of a cal standard or DUT (e.g.: nominal pin diameter)**.**

- **Practical test port adapter handling hints**

  - Always clamp at least one Test Port (TP) side (keep the VNA error box stable)**.**
  TP clamping: be careful with multistage adapters (centre conductor not from one piece)**.**
  - First run a TP repeatability test using a short (the open is less stable) → **burn in effect.**
  - Check the repeatability behavior of each possible connection pair.
  - Be careful with mechanical compatible connector families:
  Example: 2.92 mm vs K, 3.5 mm and SMA, etc.
  - Cleaning of the connector interfaces → most important for the small connectors.
  - Use a dielectric disc to control the center conductor position of a beadless airline.

Calculated minimal distances to avoid near field effects

based on the Agilent connector blue prints:

- **1.0 mm (slotted) : 5 µm**
- **1.85 mm (slotted) : 5 µm**
- **2.4 mm (slotless) : 15 µm**
- **2.92 mm (slotted) : 10 µm**
- **3.5 mm (slotless) : 15 µm**
- **Type-N (slotless) : 12 µm**

General: a slotless design needs more distance!

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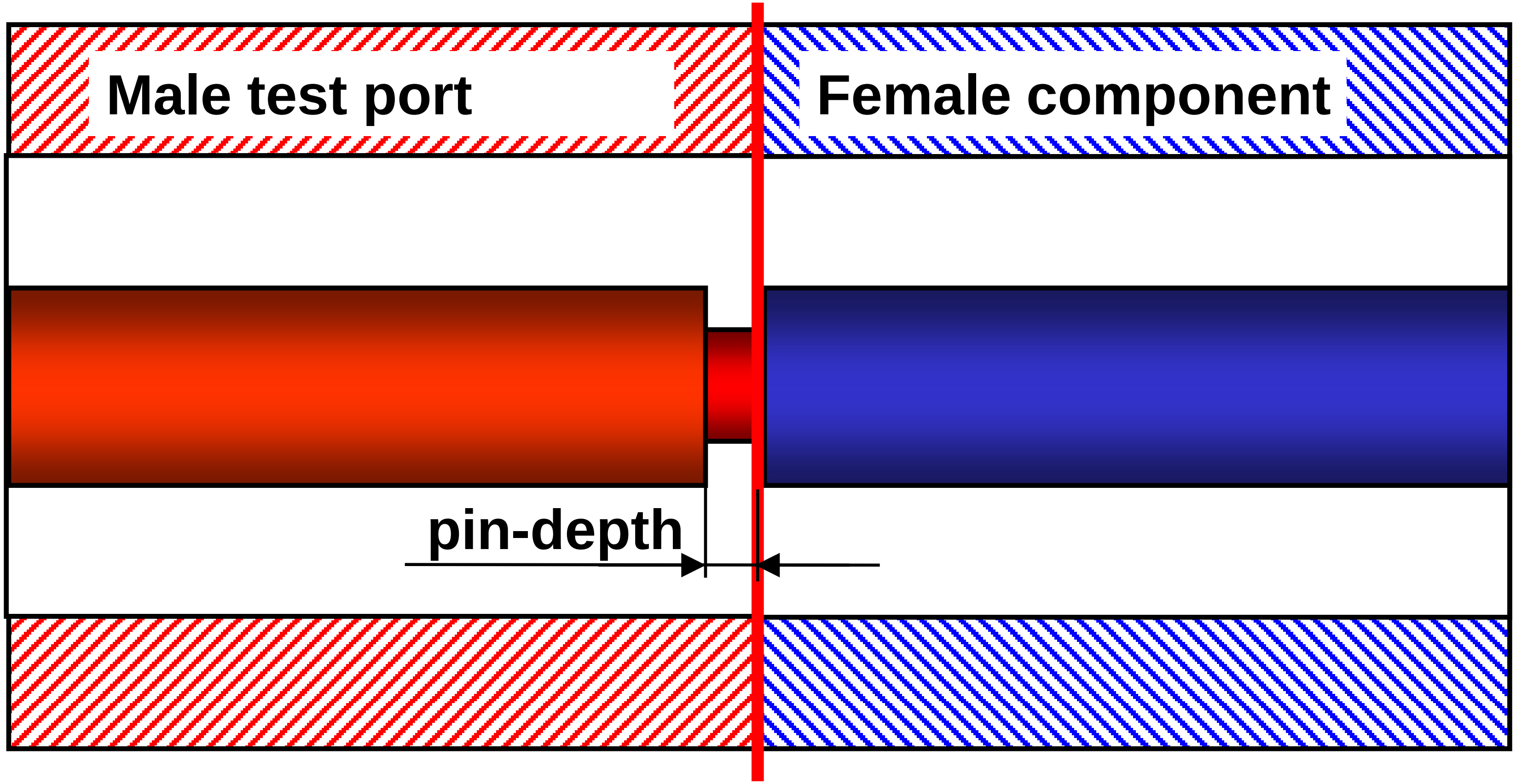
Tolerance on component side allows a flush pin-depth value



Conclusion: minimal gap must be realised at the test port side!

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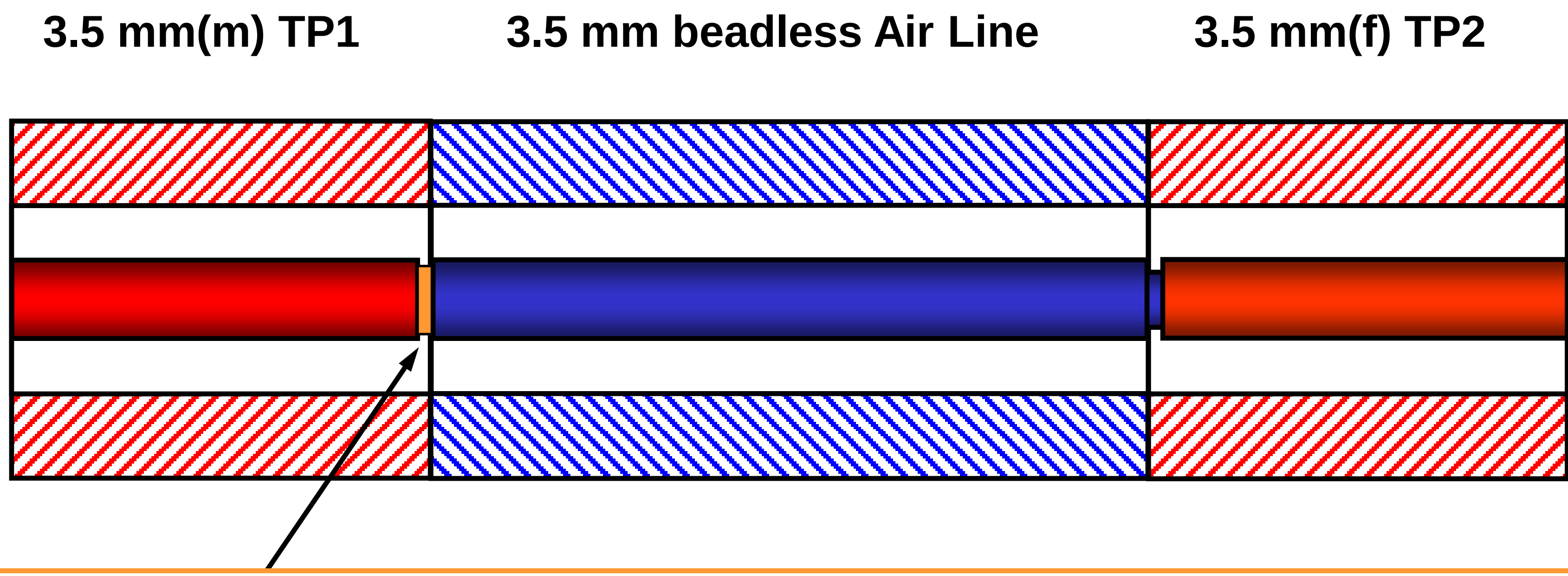
TP1 mounted with Kapton disc to avoid near field effects and to control a flush centre conductor position



Kapton disc sizes used at METAS: 12.7 µm or 19 µm

Example: optimal CC pin-depth recession for the 3.5 mm line system = 15 µm

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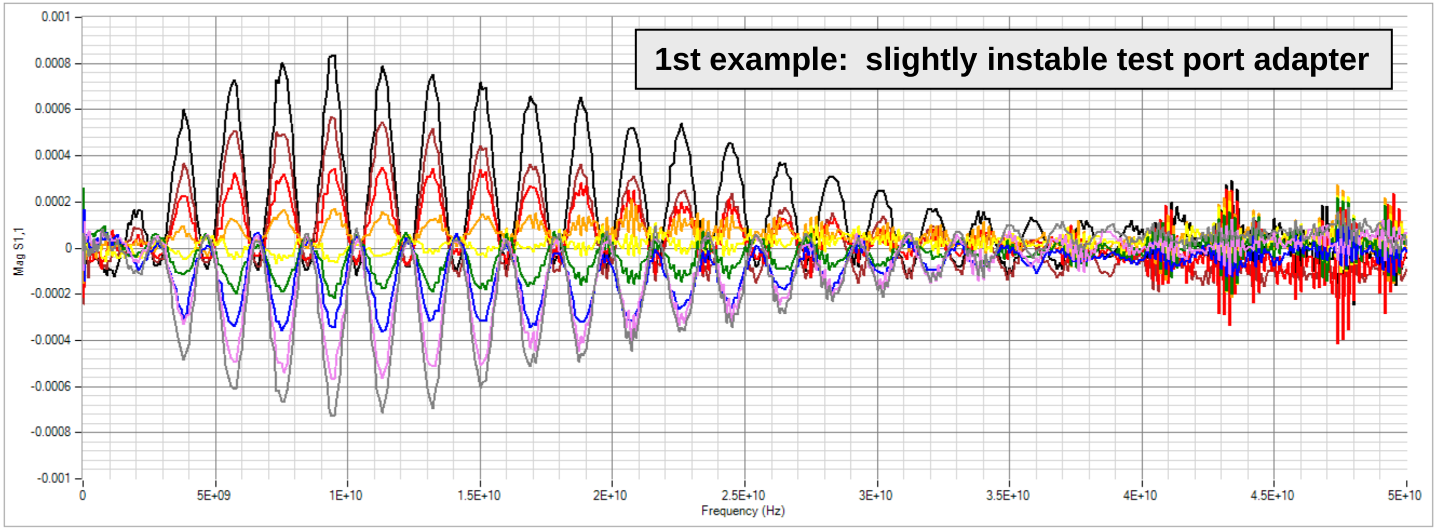
2.4 mm(f) test port adapter repeatability test using a short

0.001

S11 mag (lin)

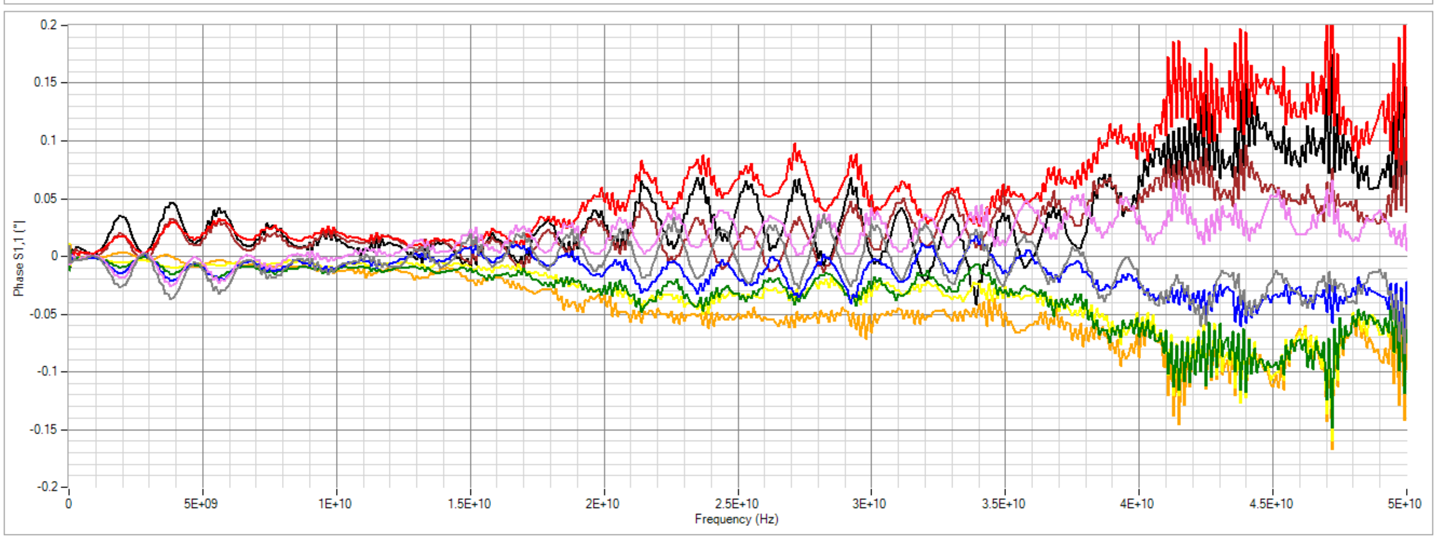
-0.001



0.2

S11 phase (deg)

-0.2



raw data normalized to mean

First: Evaluate the test port repeatability by measuring a Short at different connector orientations!

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2.4 mm(f) test port adapter repeatability test using a short

S11 mag (lin)

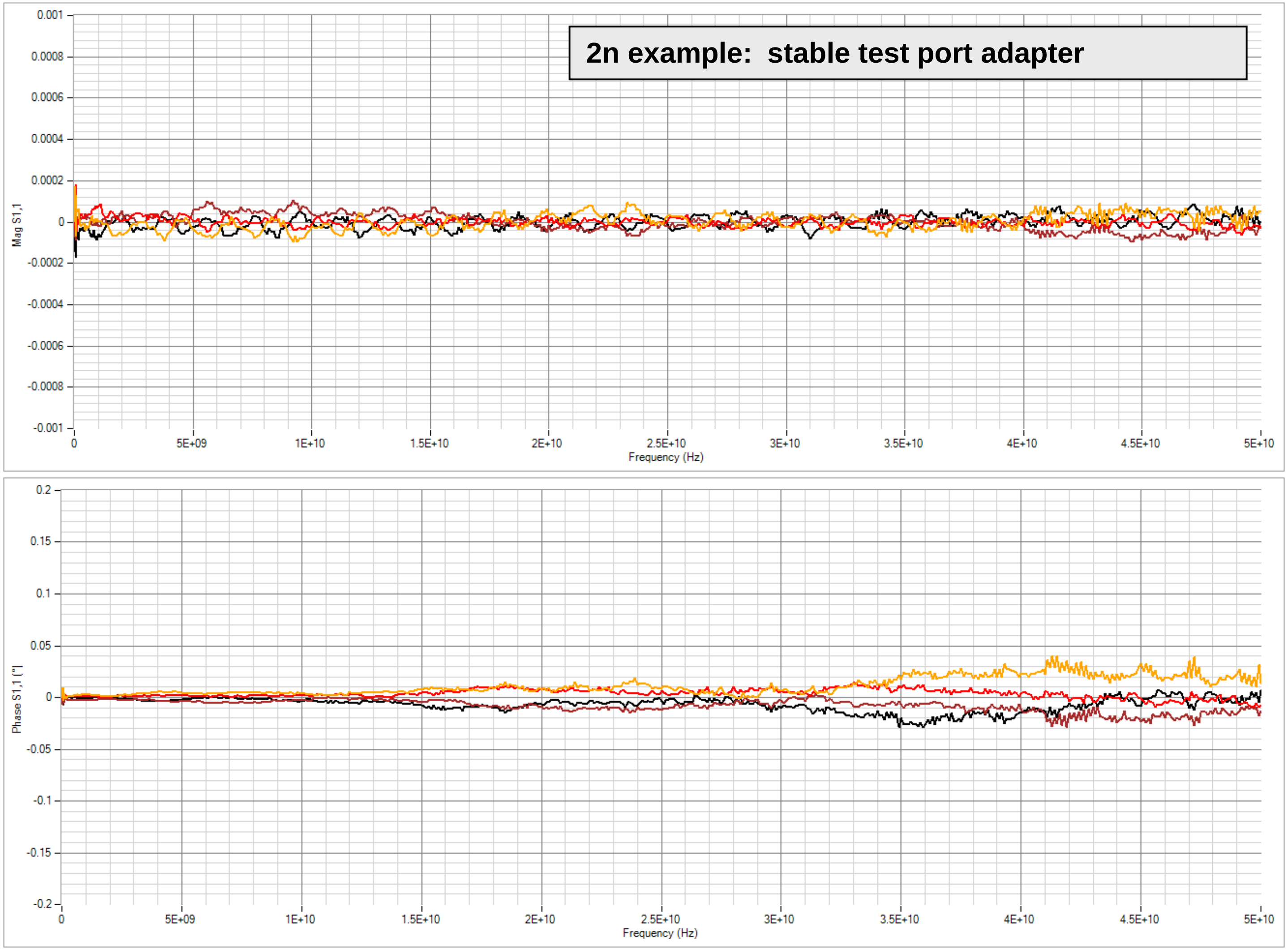
0.001

-0.001

S11 phase (deg)

0.2

-0.2



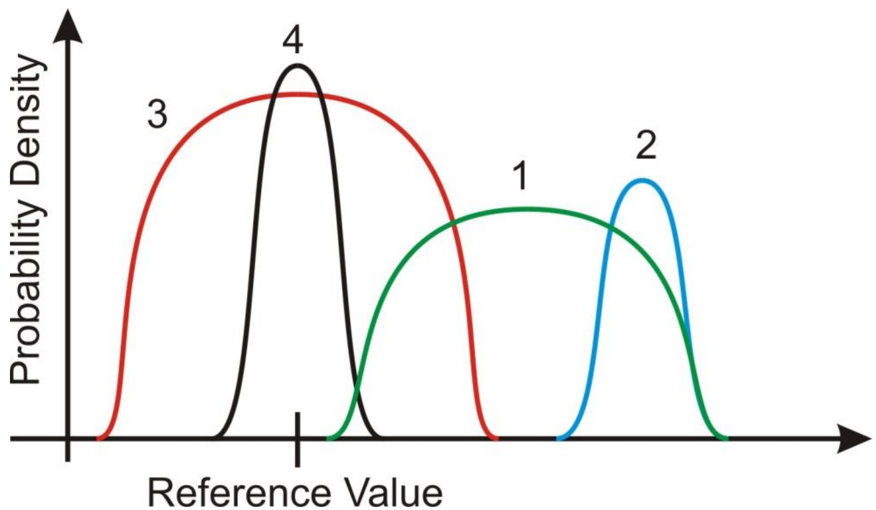
raw data normalized to mean

First:
Evaluate the test port repeatability by measuring a Short at different connector orientations!

3rd Topic

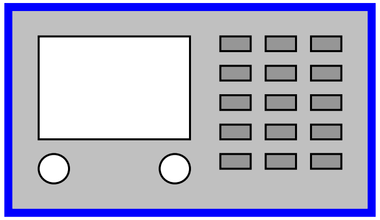
inaccurate: using a non-traceable calibration kit
imprecise : unstable VNA hardware and set-up

- **Accuracy and S-parameter traceability chain**

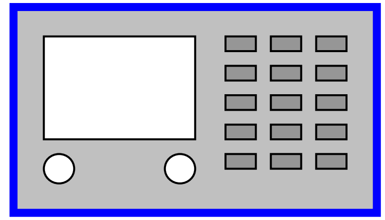


1. inaccurate and imprecise
2. inaccurate but precise
3. accurate but imprecise
4. accurate and precise

VNA 1



VNA 2



Cal Kit 1 (generic and/or polynomial data)

Open: polynomial data (C-terms)
Short: polynomial data (L-terms)
Load: assumed to be perfect 50+j0 ohm

Specs: O / S: **phase deviation from nominal**
Load: **RL better than 36 dB**

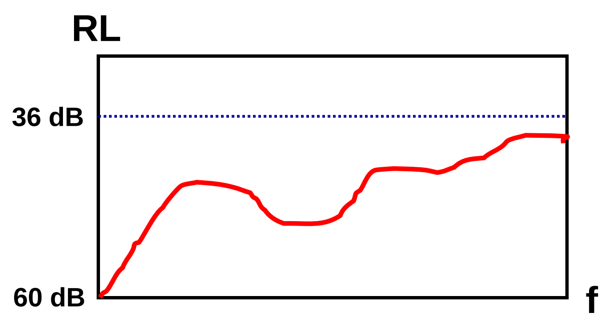
Cal Kit 2 (data base data with unc.)

Open:
Short:
Load:

VRC f(frequency)

freq.	real	imag
1	1.23	3.47
2	1.23	3.47
3	1.23	3.47
4	1.23	3.47
5	1.23	3.47

As an example: assumption that we have two identical loads in both calibration kits.



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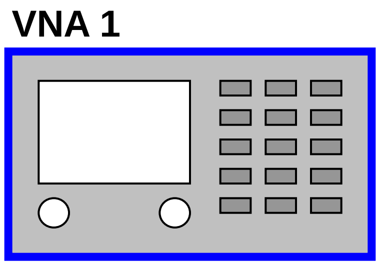
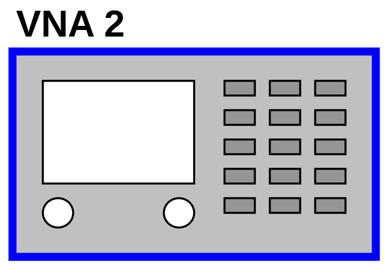
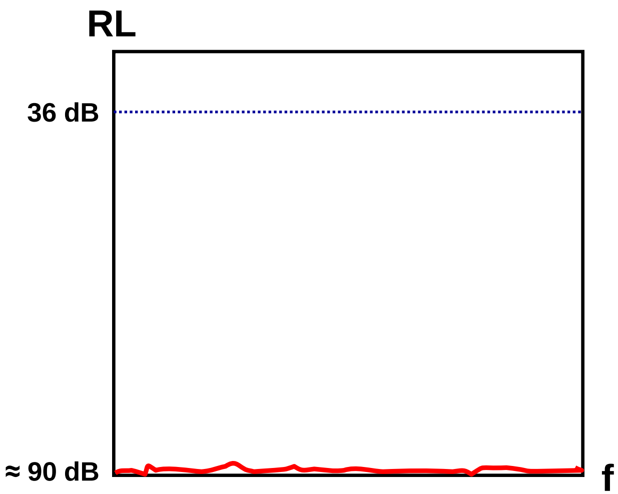
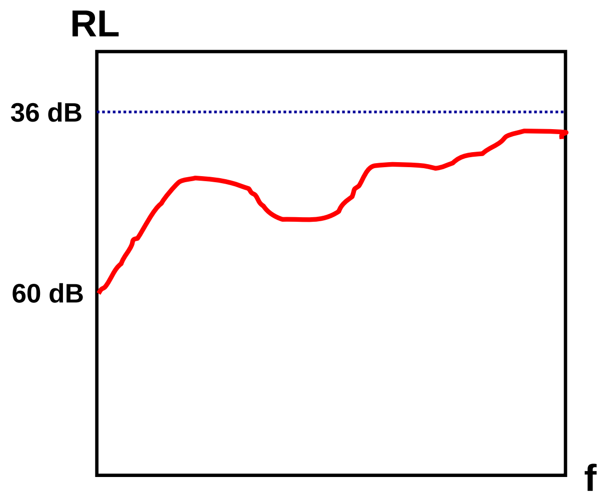




1st step: Perform a One Port cal and measure directly the used cal load (without a new connection)





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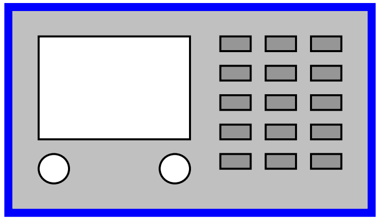
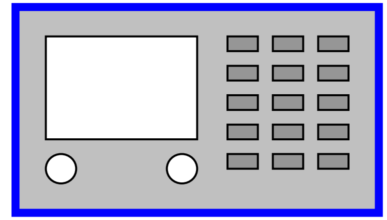
Traceability?

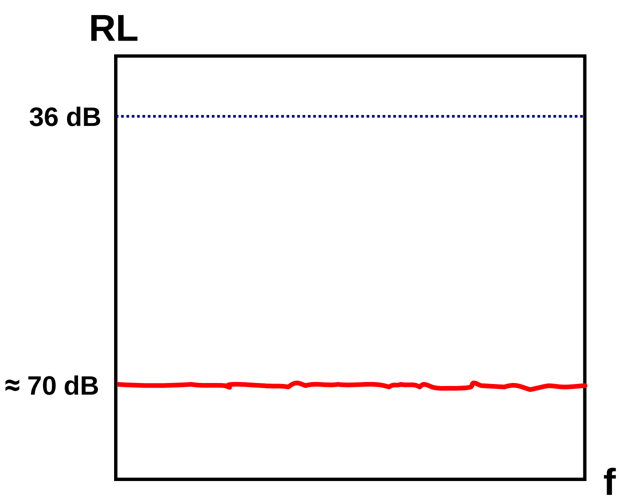
VNA 1

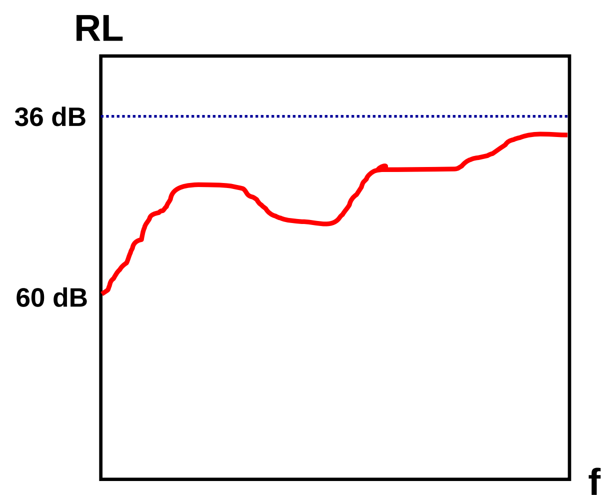


VNA 2



2nd step: Re-measure the used cal load (new connection – now including the connector repeatability)





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How to further improve the accuracy in VNA metrology?

- **Start with traceable calibration kits - not with the verification kits!**
  - **Use the best known standards for the VNA calibration** (cal or verification standards)**.**
  - **A verification standard must be: appropriate, transferable, repeatable and stable.**

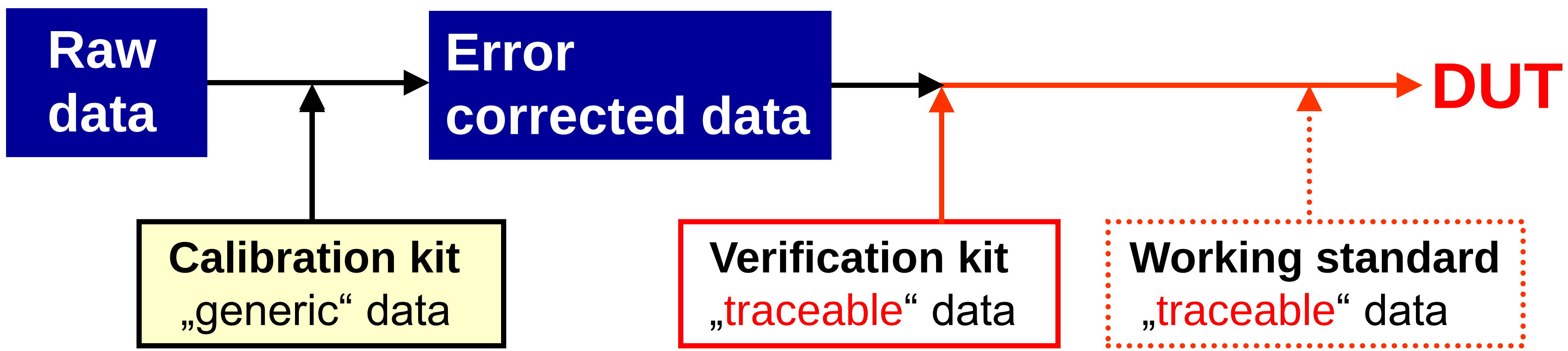
- **GUM compliant uncertainty calculation process**
  - **Identify the input quantities with their uncertainty definitions.**
  - **Define an appropriate VNA measurement model.**
  - **Uncertainty propagation through the defined VNA measurement model.**

- **Still widely used in VNA metrology**
  - **EURAMET/cg-12/v.01 (formerly: EA10/12): *Guidelines on the evaluation of VNA*:**
  - **Starts after applying the 'VNA calibration' by analysing the residuals.**
  - **Only for magnitude (no phase information) and uses outdated or wrong assumptions.**
  - **Airline based ripple assessments (ignoring connector effects and line losses).**

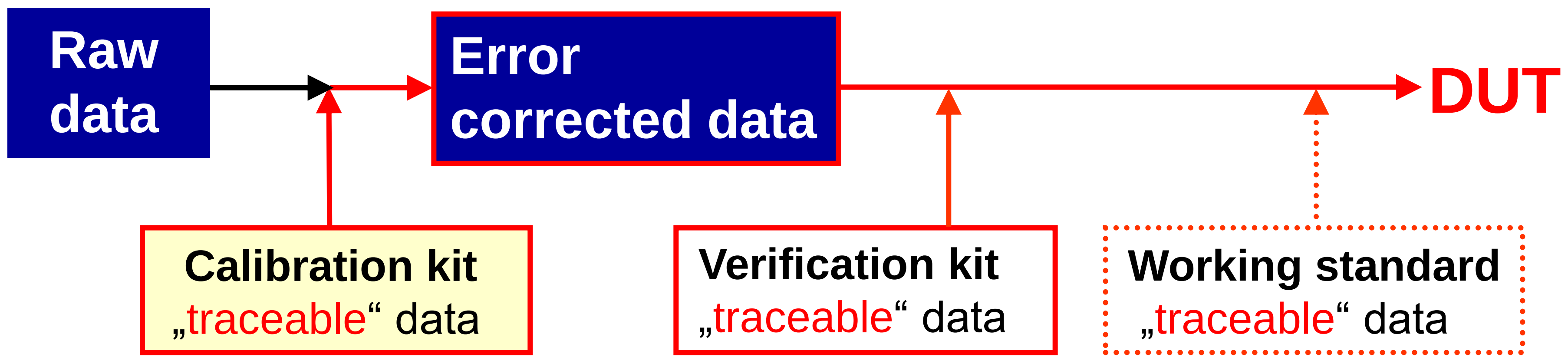
→ HF-Circuits (WP5): New guidelines on the evaluation of VNA and the uncertainties

Traceability

Traditional VNA calibration approach:



Direct “traceable” VNA calibration approach:



Accurate and traceable calibration kits and methods

- **Primary coaxial calibration standards**

  - Beadless airlines

  - Flush Shorts and Offset Shorts

  - Offset Opens? Only accurately calculable using an air dielectric design - but issues with small coaxial families:
  Near field coupling and the control of the center conductor position (longitudinal and angular).

Accuracy: mechanical characterisation, material knowledge, modelling capabilities, handling.
Issues : beadless airlines (position of the CC), determination of the propagation constants.

- **Traceable characterized coaxial calibration standards**

  - Offset Opens

  - Offset Shorts

  - Loads

Accuracy: quality of the uncertainty information, short and long term stability (design), handling, avoid center conductor coupling effects (use appropriate test ports).
First selection criteria: showing a good connector orientation repeatability behaviour!

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Accurate and traceable calibration kits and methods

- **Traceable characterized calibration standards – what is important:**
  - **The systematic connector effects must be included** (accurate reference plane definition)**.**
  - **Repeatability of the used standards** (short and long term stability, connector orientation)**.**
  - **S-parameter data format must include the uncertainty and correlation information.**
  - **Calibration standard definitions: data based versus polynomial data?**
  - **…**

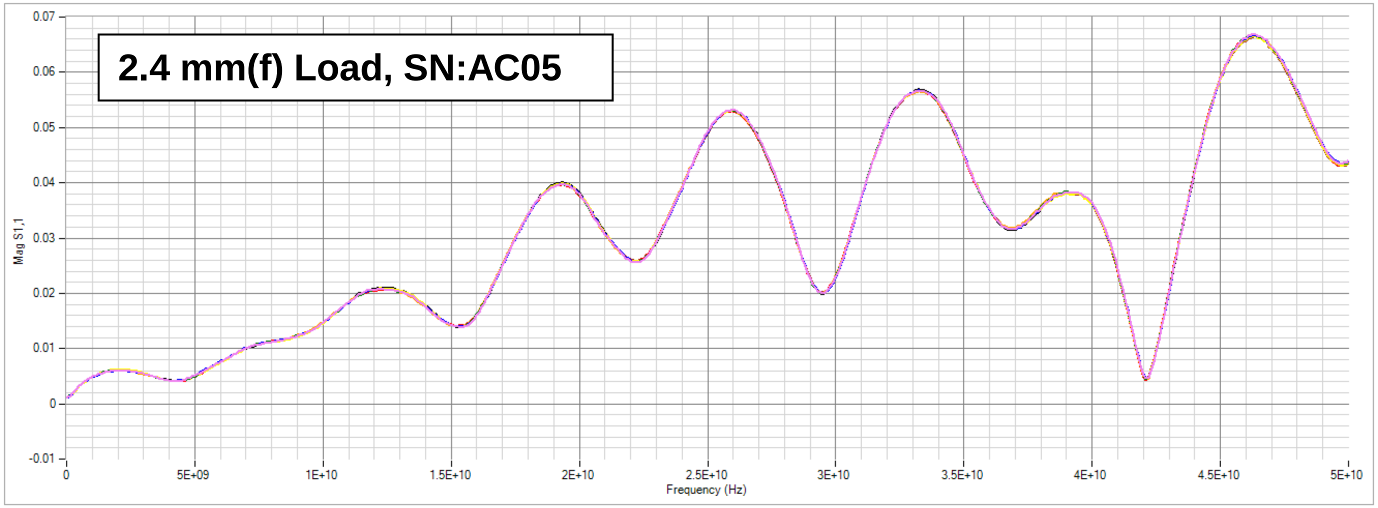
A stable calibration standard is a must for data based def.

- S11 of a load measured at 8 different connector orientations

0.070

S11 mag (lin)

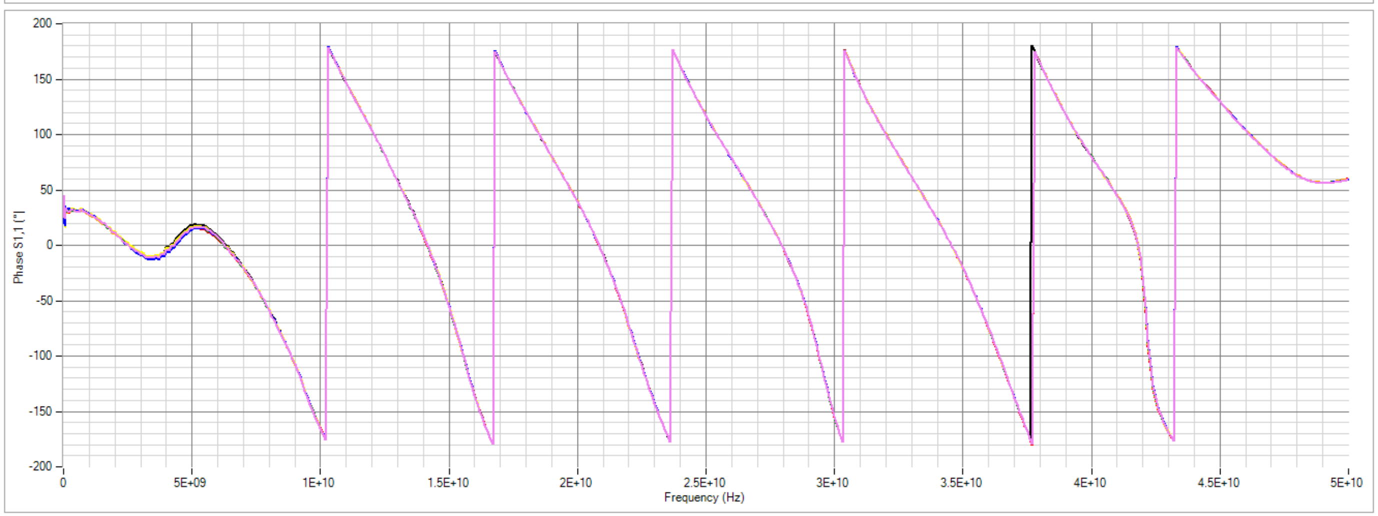
0.000



200

S11 phase (deg)

-200



First example:
Calibration standard showing a good repeatability behaviour.

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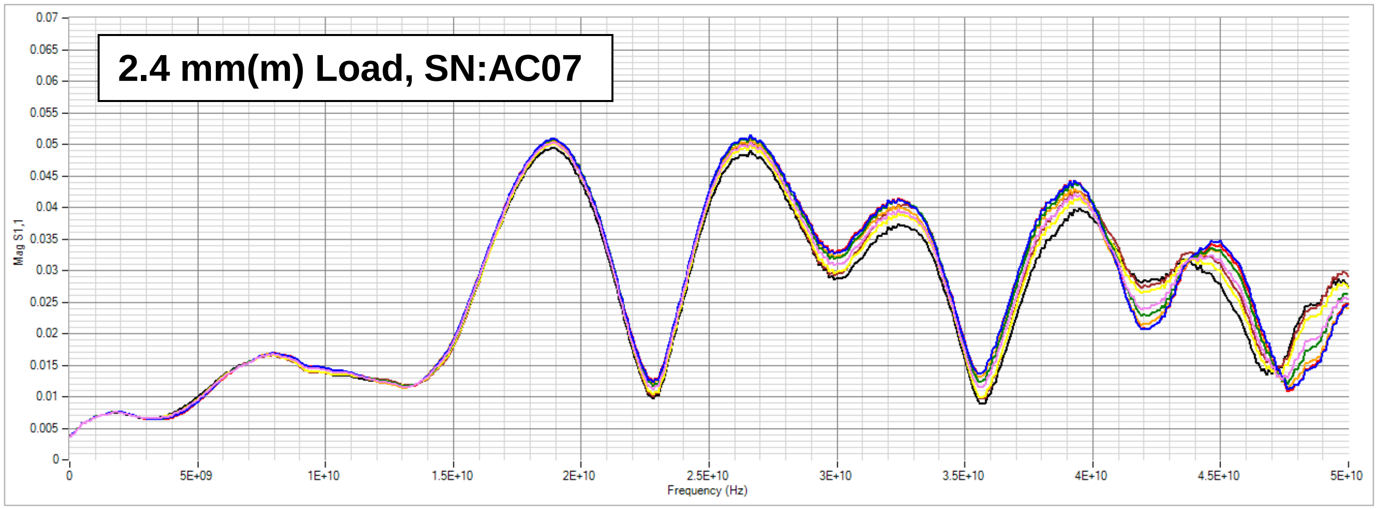
A stable calibration standard is a must for data based def.

- S11 of a load measured at 8 different connector orientations

0.070

S11 mag (lin)

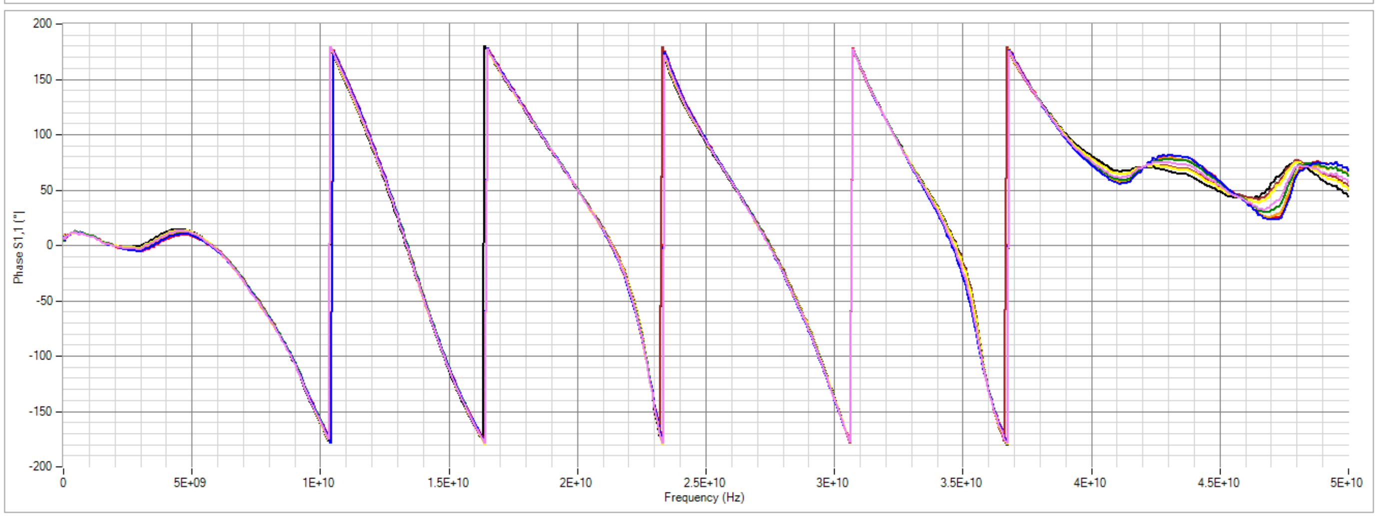
0.000



200

S11 phase (deg)

-200



Second example:
Calibration standard showing a bad repeatability behaviour.

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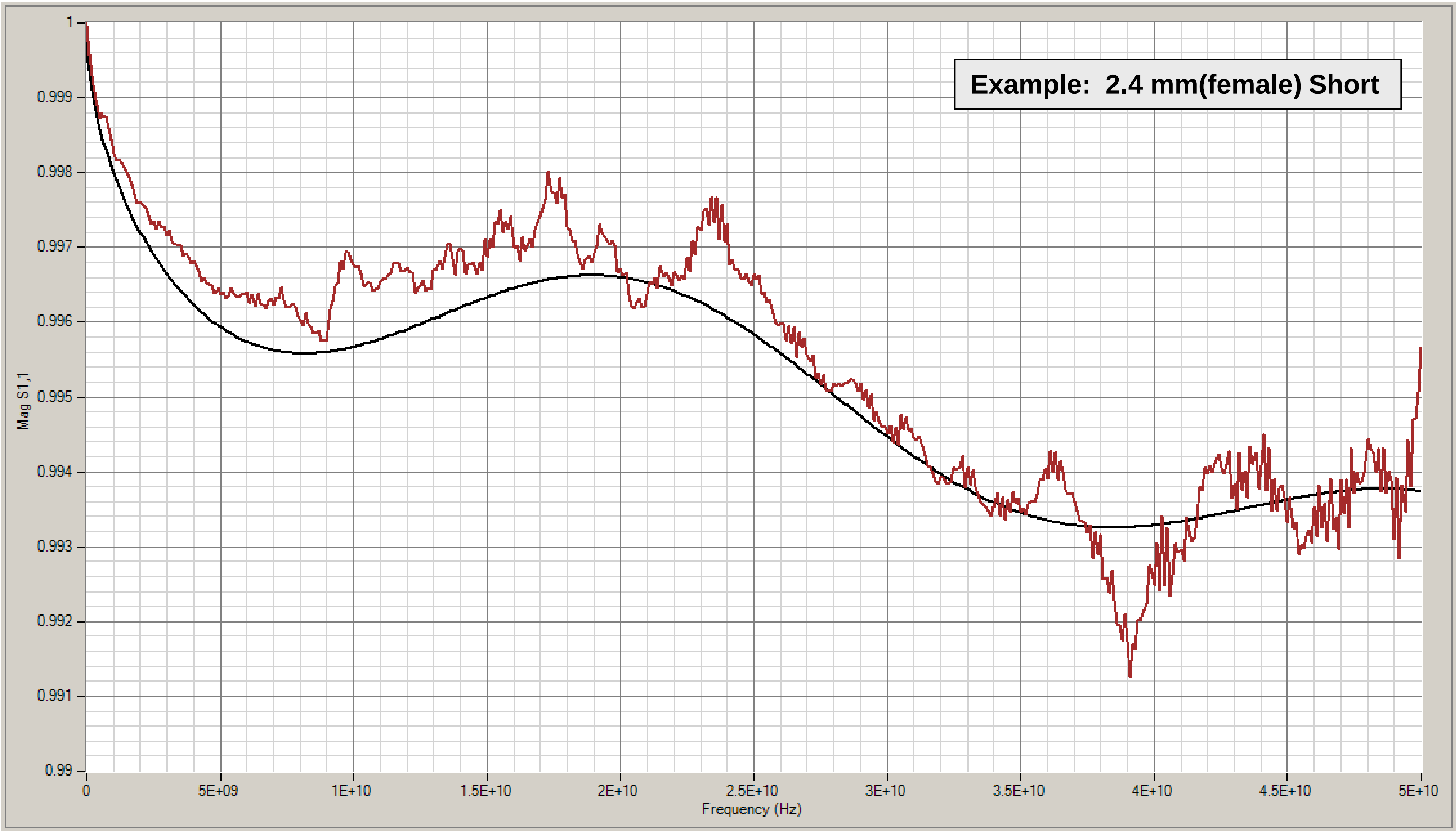
Standard definitions: data based versus polynomial data?



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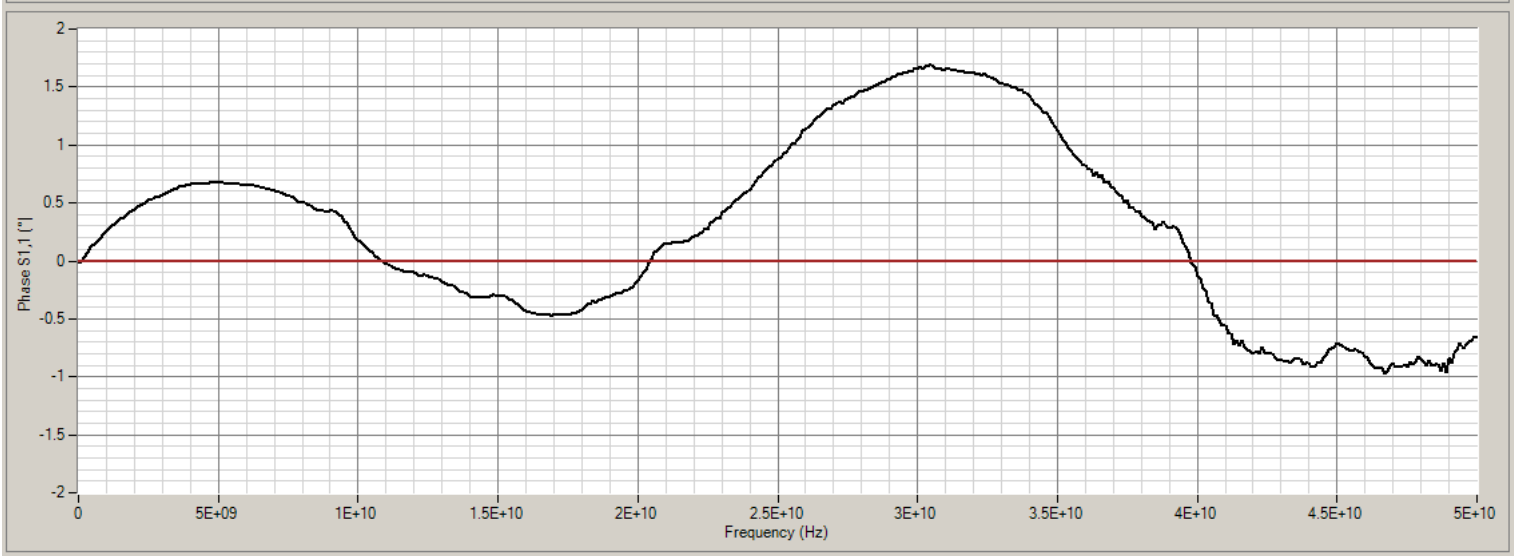
Data based versus polynomial data: fitting losses !

S11 mag (lin)

Normalized to the data based value

S11 phase (deg)



Accurate and traceable calibration kits and methods

- **Traceable characterized calibration standards – what is important:**
  - The systematic connector effects must be included (accurate reference plane definition)**.**
  - Repeatability of the used standards (short and long term stability, connector orientation)**.**
  - S-parameter data format must include the uncertainty and correlation information.
  - Calibration standard definitions: data based versus polynomial data.
  - …

- **Select the most appropriate cal method** (SOLT, Unknown Thru, etc.)
  - One Port (no cable movements)**.**
  - SOLT (insertable test port configuration, Thru connection is assumed to be perfect)**.**
  - Unknown Thru (Opens and Shorts are the dominant uncertainty contributors)**.**
  - Optimization calibration (over-determined: more cal standards than error terms)**.**

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4th Topic

- **Mating techniques and connector handling hints**

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Connector cleaning and specifications (preparation)

- **Consult connector guides**

  (see the references on the last slide)

- **Connector cleaning**

  - Stereo microscope → a must for the small coaxial families.
  - Use appropriate cleaning tools and solvents.
  - Cleaning techniques: → avoid any stress to the center conductor and contact fingers.
  → first mating areas, threads, protection caps.

- **Check for the connector specifications**

  - Mechanical or optical pin-depth measurements (mean pin-depth and compression effect)**.**

- **Practical cleaning hints for best measurements**

  - Cleaning process just before an electrical measurements (dry air with 23 deg)**.**
  - Special storage boxes (particles from the female connector protection caps)**.**

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Special storage boxes for the data base standards

Best mating techniques (goal: to improve the repeatability)

- **Good measurement guides and** (old) **cal kit operating manuals.**

- **Use a high quality torque wrench with the right setting and procedure.**
  - Avoid to use warm wrenches (from body heat).
  - Minimal thermal impact: alternately use two different wrench sets (load and long DUT).

- **Practical handling hints for best mating performance (repeatability):**
  - Avoid to rotate the coaxial components in respect to the test port (wear and contact)**.**
  For all components: keep the DUT body orientation fixed with a counter wrench.
  Coaxial families with thin contact fingers are very sensitive to rotational stress.
  (1 mm and 2.92 mm: finger bending will result in a change of the contact point.
  - First optimize the performance of the test port (see slide 22: test port handling hints)**.**
  - Perform at least one test connection (removal of oxide layers and contact finger settling)**.**
  - Do not push the DUT connector during the mating process (only for the thread mating)**.**
  - Mating speed controlled by the thread lead (slightly pull back the DUT component)**.**
  - Always minimize the cal standard and DUT warm up effects from the body heat.
  - Avoid a fast loosening process (reduce any impact forces to the center conductors: 'click')**.**
  - Cleanliness!

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Best mating techniques (S-parameters analysis)

- **Monitor and analyze the S-parameter data information**

  - Critical connections: check for the direct response on the VNA display (e.g.: beadless airline mating process, sliding load mating process)**.**

  - Measure each component at least at 4 different connector orientations (90 deg)**.**

  - VNA Tools II: use the add measurement series (evaluate the normalized raw data)**.**

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Raw data, normalized to mean

Real (lin) S11, S22

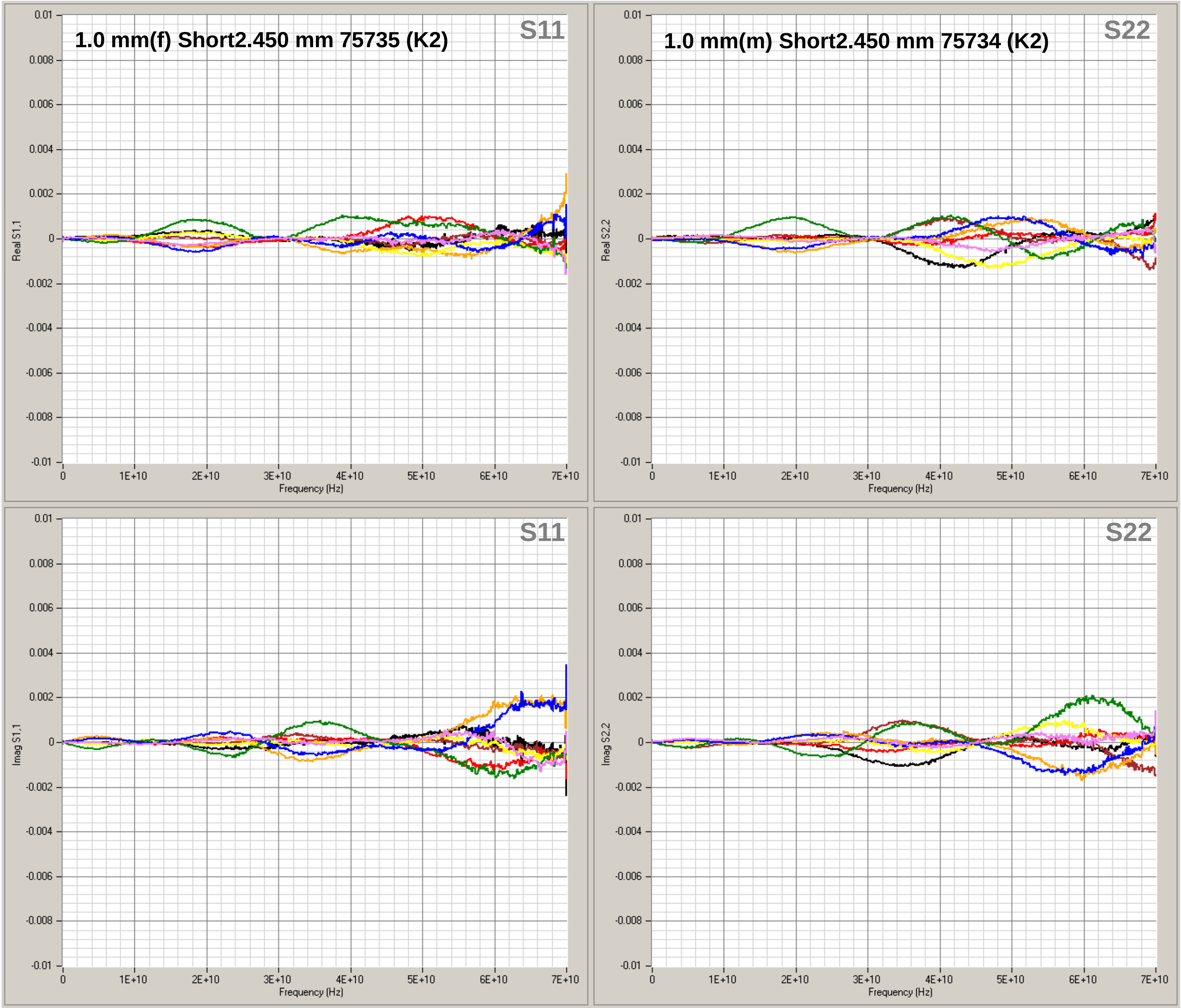
0.010

-0.010

Imag (lin) S11, S22

0.010

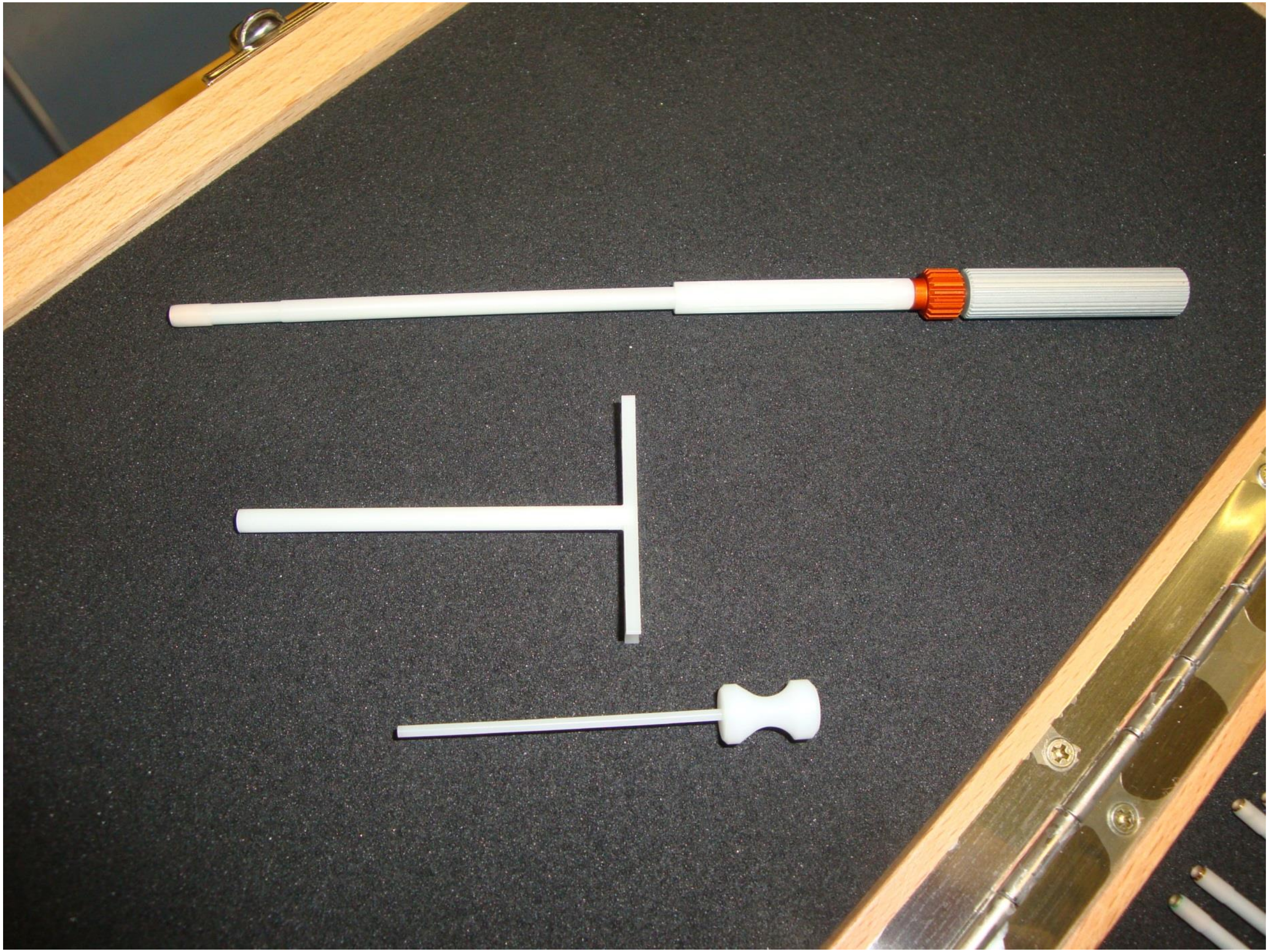
-0.010



Best mating techniques (S-parameters analysis)

- **Monitor and analyze the S-parameter data information**
  - Critical connections: check for the direct response on the VNA display
  (e.g.: beadless airline mating process, sliding load mating process)**.**
  - Measure each component at least at 4 different connector orientations (90 deg)**.**
  - VNA Tools II: use the add measurement series (evaluate the normalized raw data)**.**

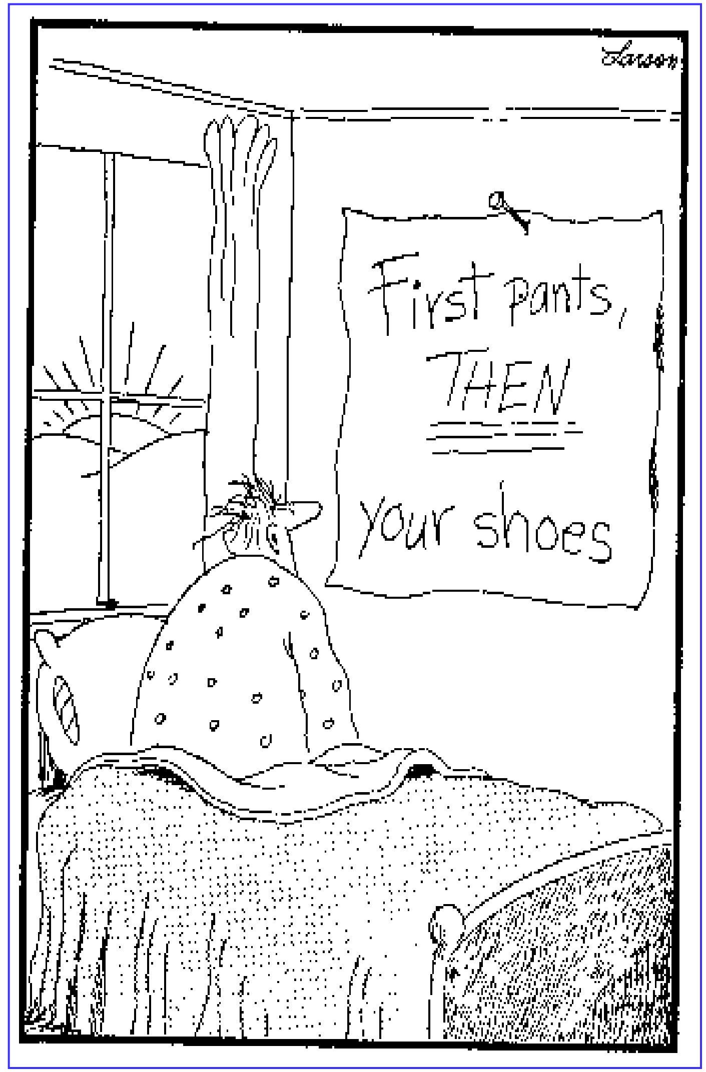
- **Practical handling hints for best mating performance (accuracy):**
  - A fixed test port allows a controlled and more precise mating process.
  - Use finger cots instead of gloves: does offer a better fine motor sensitivity!
  - Use a head loop with the small coaxial line systems: both hands are free!
  - For the initial connection process of a beadless airline:
  - use an outer conductor inner diameter (OCID) alignment tool for the first connection.
  - use an center conductor (CC) alignment tool to control the mating process.



OCID alignment tool (shown example: Type-N)

5th Topic

- **Practice and experience**



Quality management documents, metrology grade hardware and traceable kits are only the first steps towards the best accuracy…

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VNA Tools II - best calibration and measurement hints

- **Evaluate for the best possible performance for each specific VNA:**
  - **VNA settings (source power, IF-BW, average, sweep time and dwell time).**
  - **Roll-off characteristic (reliable start frequency – not what is written on the VNA!).**

- **Evaluation of the best cal standard measurement data:**
  - **Measure each component at least at 4 different connector orientations** (90 deg)**.**
  - **Identify outliers and select the measurement closest to the mean as reference data.**
    Note: pay attention to the measuremnt order (identify contact or temperature effects).
  - **Or: use more measurements with the over-determined optimization calibration.**

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Mag (lin)
S11, S22

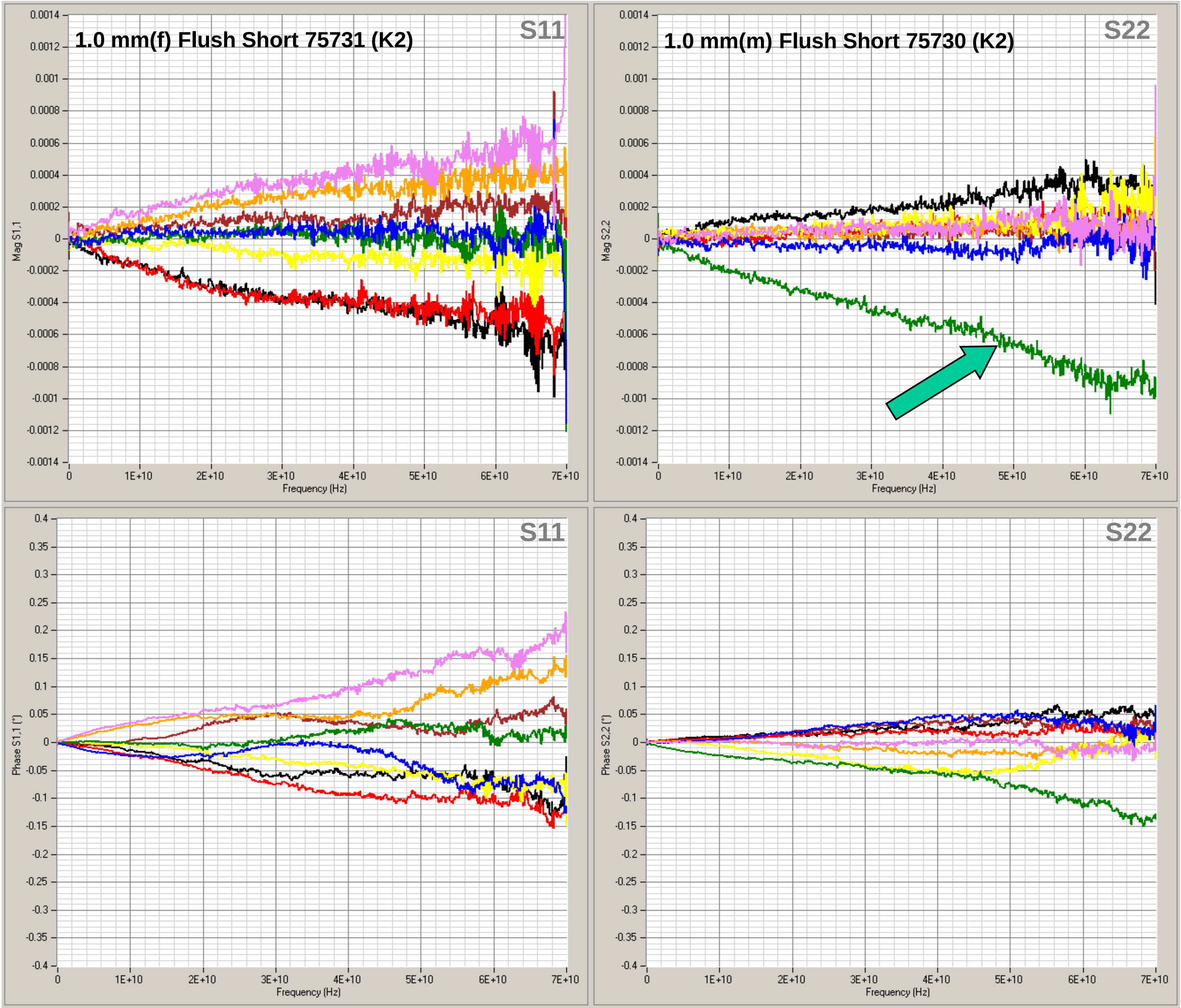
0.0014

-0.0014

Phase (deg)
S11, S22

0.4

-0.4



8 different connector orientation measurement data, normalized to the mean.

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VNA Tools II - best calibration and measurement hints

- **Best calibration standard and DUT measurement order:**
  - **Minimize the drift effects from the VNA setup** (try to keep the project time short)**.**
  - **One port measurements with the fixed ports: -> best measurement order?**
    - **Measure similar components together (showing a similar receiver ratio).**
    - **Use the following measurement order** (cal and DUT together)**: Loads, Opens then Shorts.**

- **Verification process:**
  - **For long measurement series: periodically re-measure a stable component.**
  - **For 2-port measurements: periodically re-measure the Thru connection (cable & drift).**
  - **A stable and traceable verification standard can also be used for the calibration.**
  - **Create a comparison folder to save the reference data.**
  - **If more cal standards available than needed: compare the different One port cal results.**
  - **For passive devices: reciprocal transmission response** (use the display function S/S‘)**.**
  - **SOLT: check for the Thru measurement response which was used during the calibration.**
  - **Compare SOLT with an 'Unknown Thru' cal: Check for the Thru measurement response.**
  - **Always re-measure the verification standard at the end of a measurement project.**
  - **…**

Conclusions : “best VNA performance”

- **Optimize and characterize the VNA measurement setup.**
- **Use traceable calibration kits – not only verification kits.**
- **Choose appropriate and stable verification standards.**
- **Mating techniques and connector handling.**
- **Determine the main uncertainty contributors** (investment)**.**
- **No way around more “practice and experience”.**

Thank you very much for your attention !

More information: *www.metas.ch/hf*

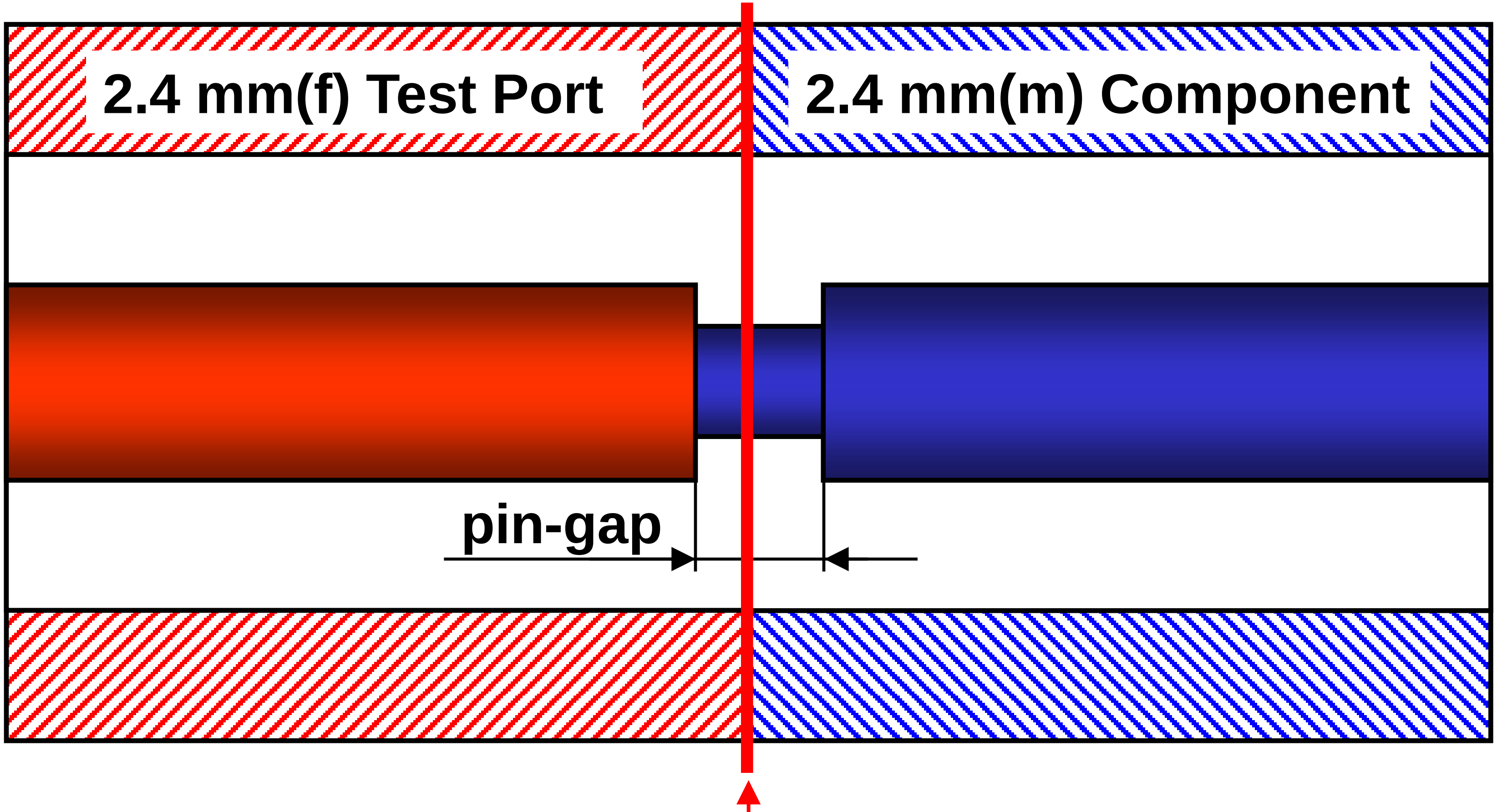
www.metas.ch/vnatools

Some connector handling guides:

- **Hewlett Packard (now Agilent), “Microwave connector care”, Manual Part No. 0851-90064, April 1986**
- **Hewlett Packard (now Agilent), “Connector care for RF & microwave coaxial connectors”, Manual Part No. 0851-90064 Edition 2, 1991**
- **Hjipieris, G., “RF and Microwave connector care”, Technical information, Marconi Instruments publication No. 46889-505, 1997**
- **Skinner, A.D., “ANAMET connector guide”, 3rd edition, August 2007.** (available for free, from: http://www.npl.co.uk/anamet-connector-guide)
- **http://na.tm.agilent.com/pna/connectorcare/Connector_Care.htm**
- **http://na.tm.agilent.com/pna/help/latest/Tutorials/Connector_Care.htm**

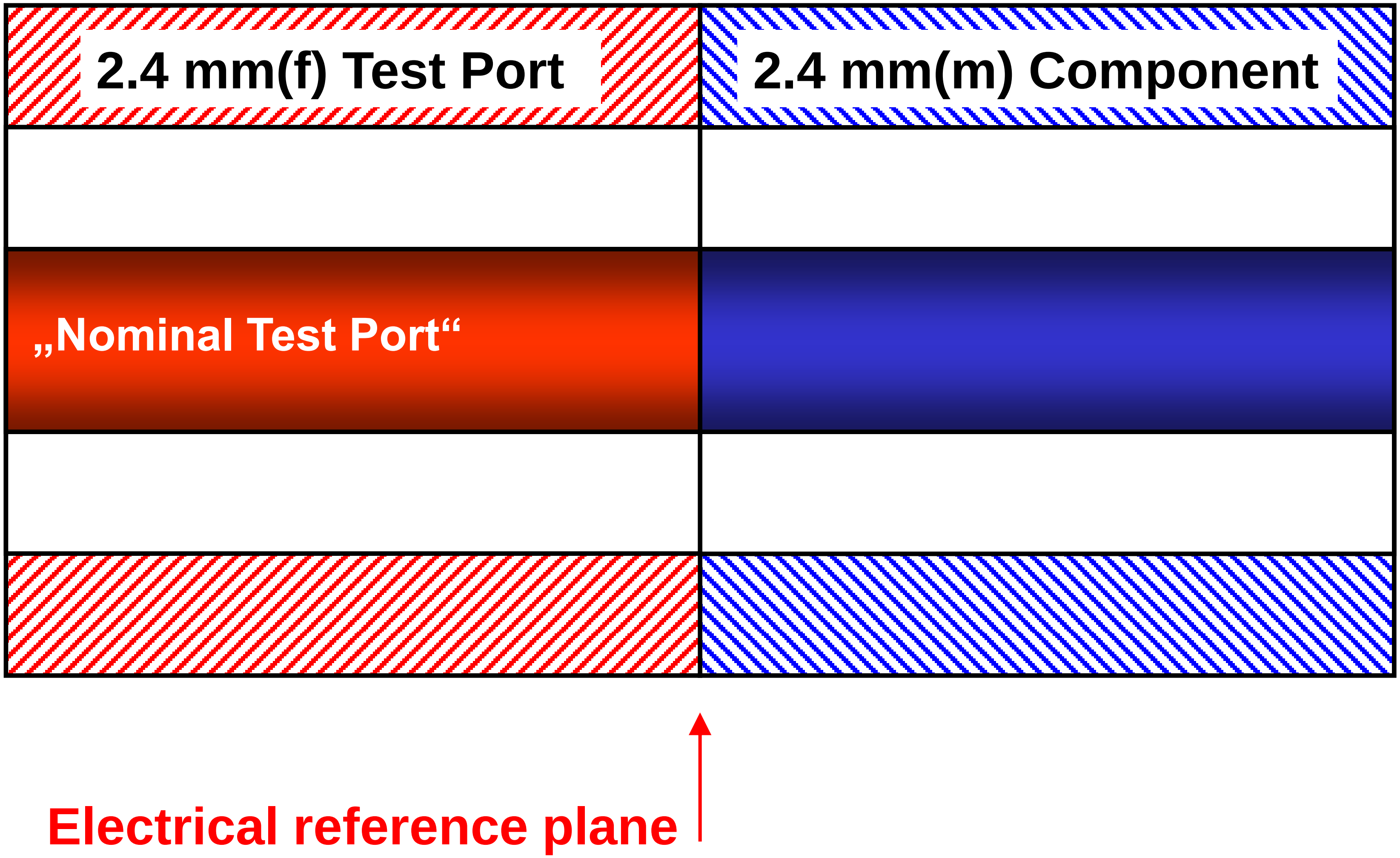
Hewlett Packard (now Agilent) „Microwave connector care“ (manual out of print)

- Typical connection
- Pin-depth on both sides



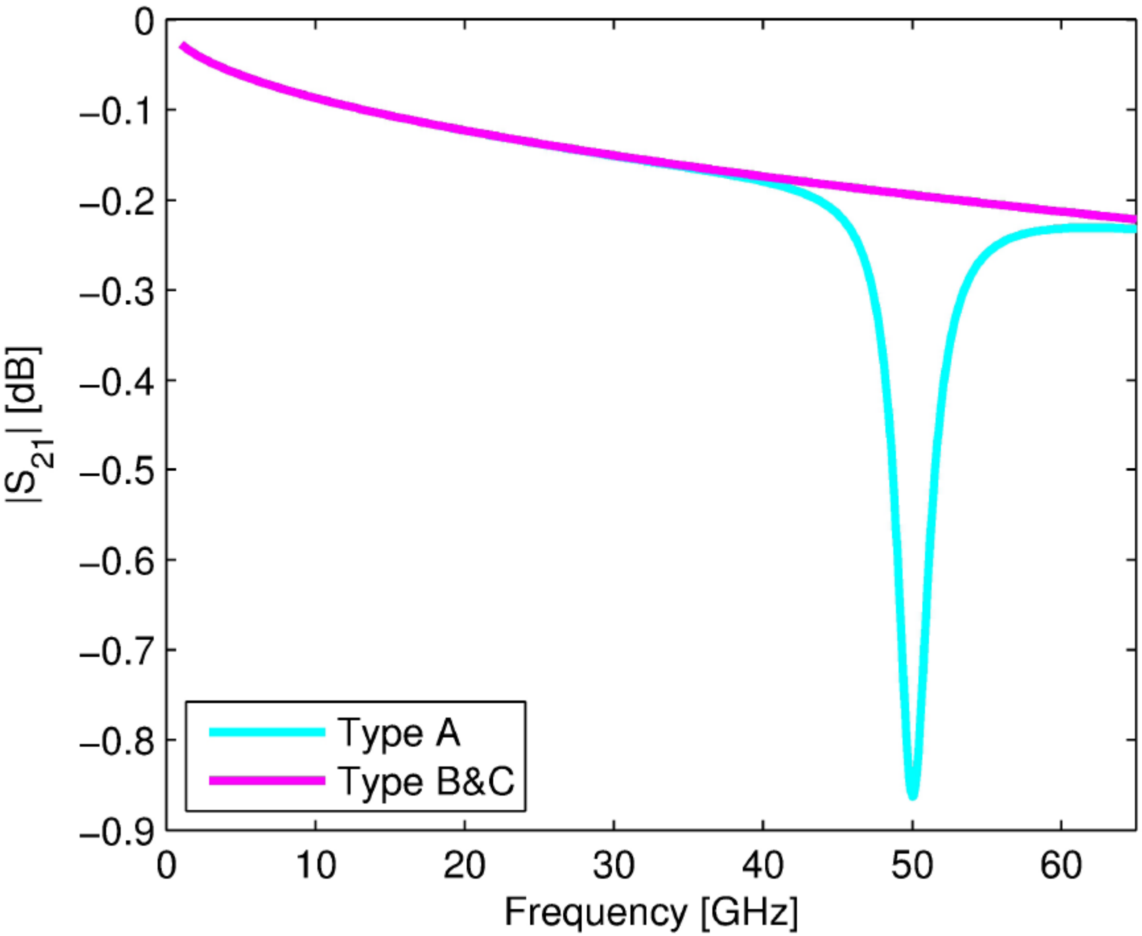
Electrical reference plane

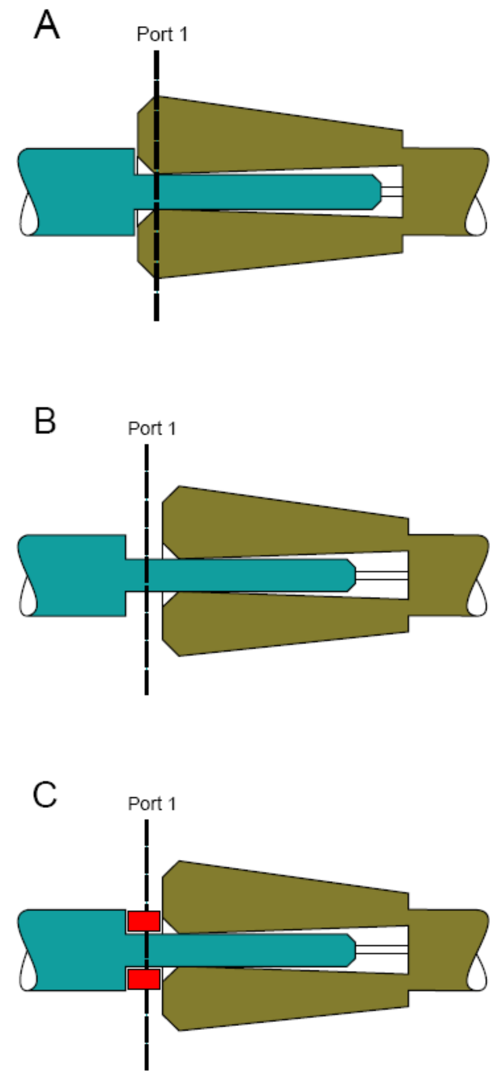
Old dogma: - Mind the pin-gap
- Ideal connection (50 ohm)



Issue: with small pin-gaps

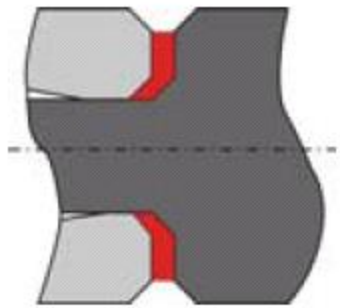
Typical coupling effects when measuring beadless air lines

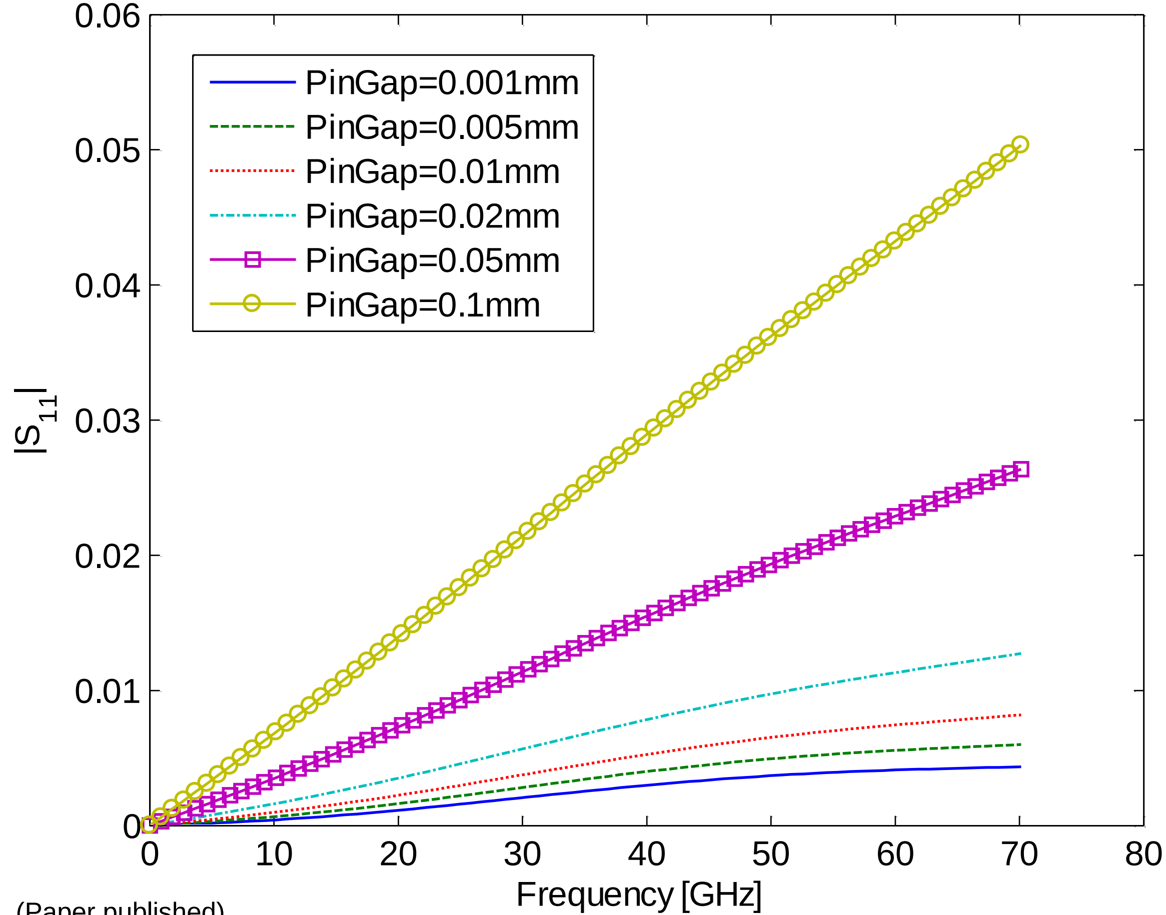




Resonance due to zero pin gap

1.85 mm connector: S11 with small female chamfer



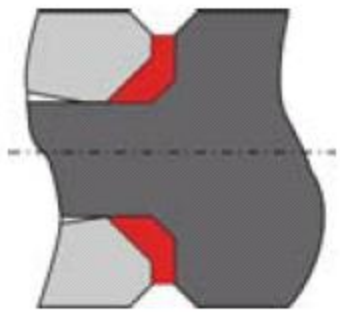


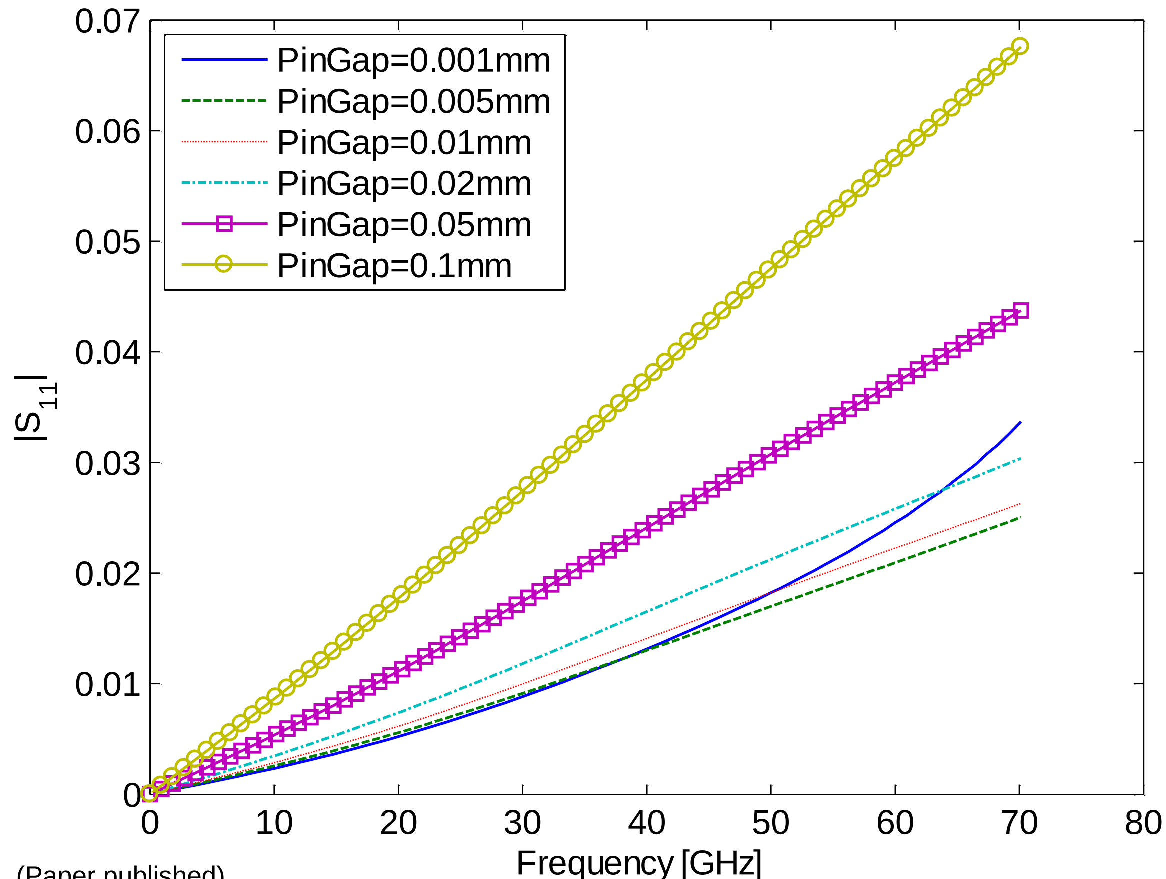
CoMo70 outcomes:

Johannes Hoffmann, ETHZ, CoMo70 project (Paper published)

Issue: with small pin-gaps

1.85 mm connector: S11 with big female chamfer





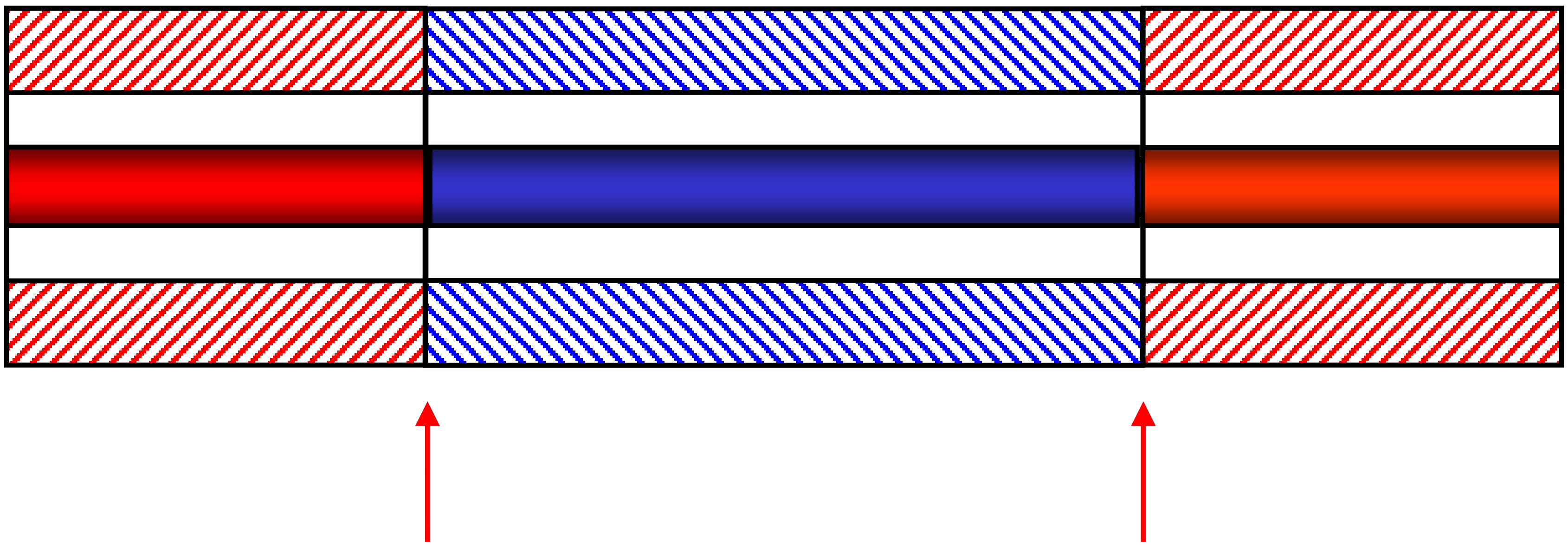
CoMo70 outcomes:

Johannes Hoffmann, ETHZ, CoMo70 project (Paper published)

Old paradigm: Test Port Adapters pin-depth set close to zero

Advantage: Centre Conductor position can be controlled

3.5 mm(m) TP1 **3.5 mm beadless Air Line** **3.5 mm(f) TP2**

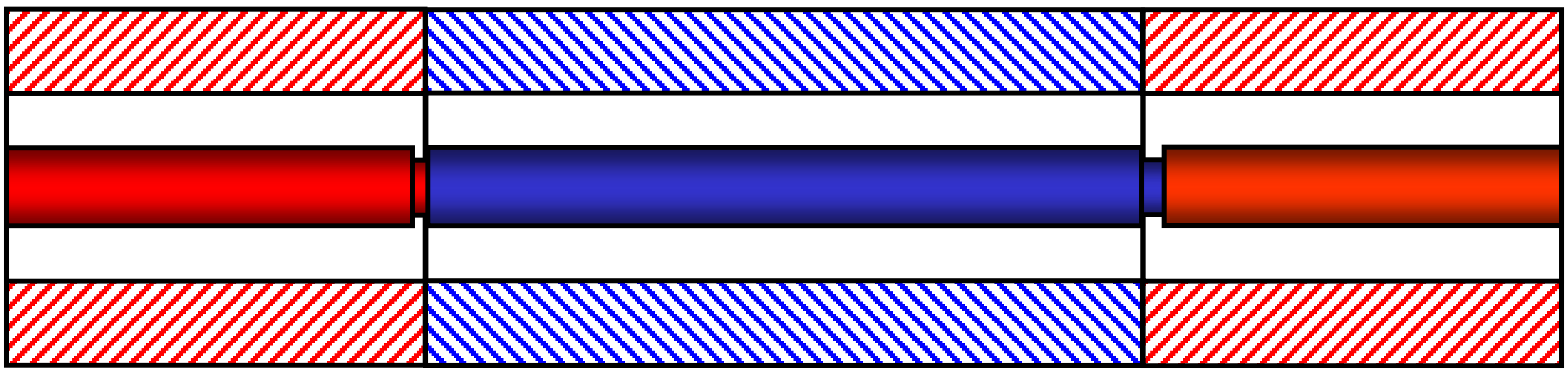


Electrical reference plane TP1

Electrical reference plane TP2

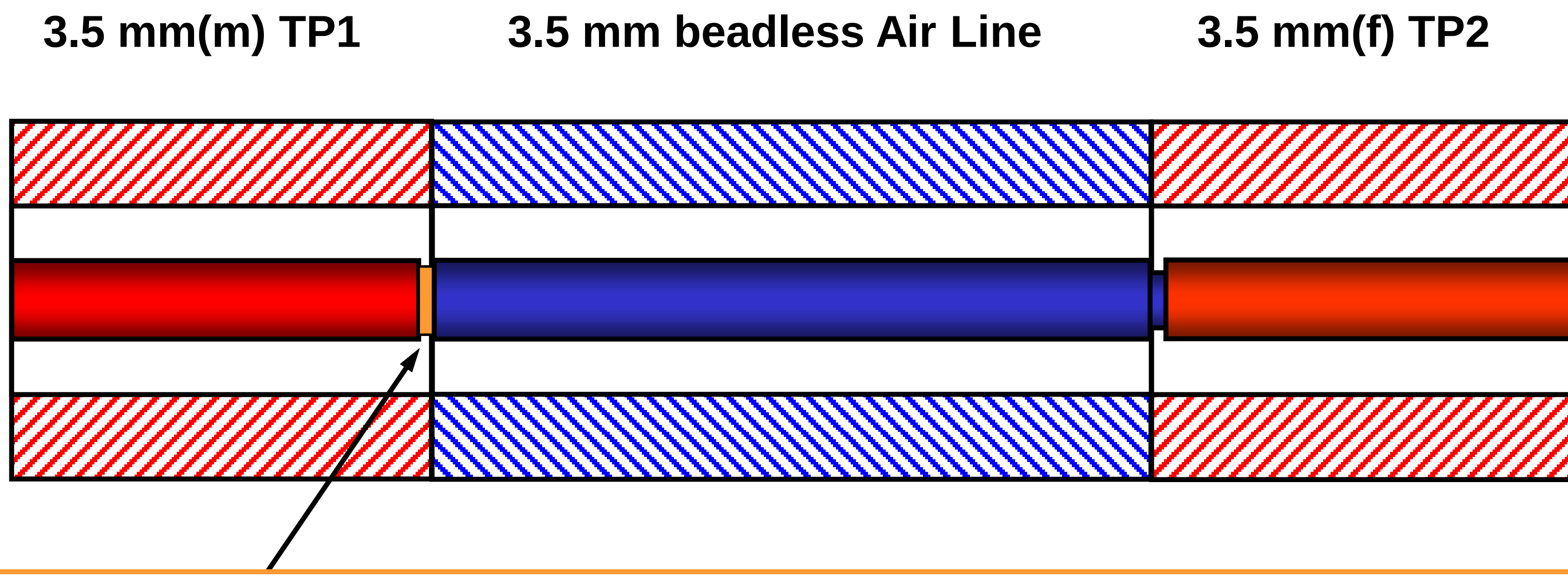
New paradigm: TP's recessed to avoid near field effects

3.5 mm(m) TP1 | 3.5 mm beadless Air Line | 3.5 mm(f) TP2



Problem: undefined Centre Conductor position

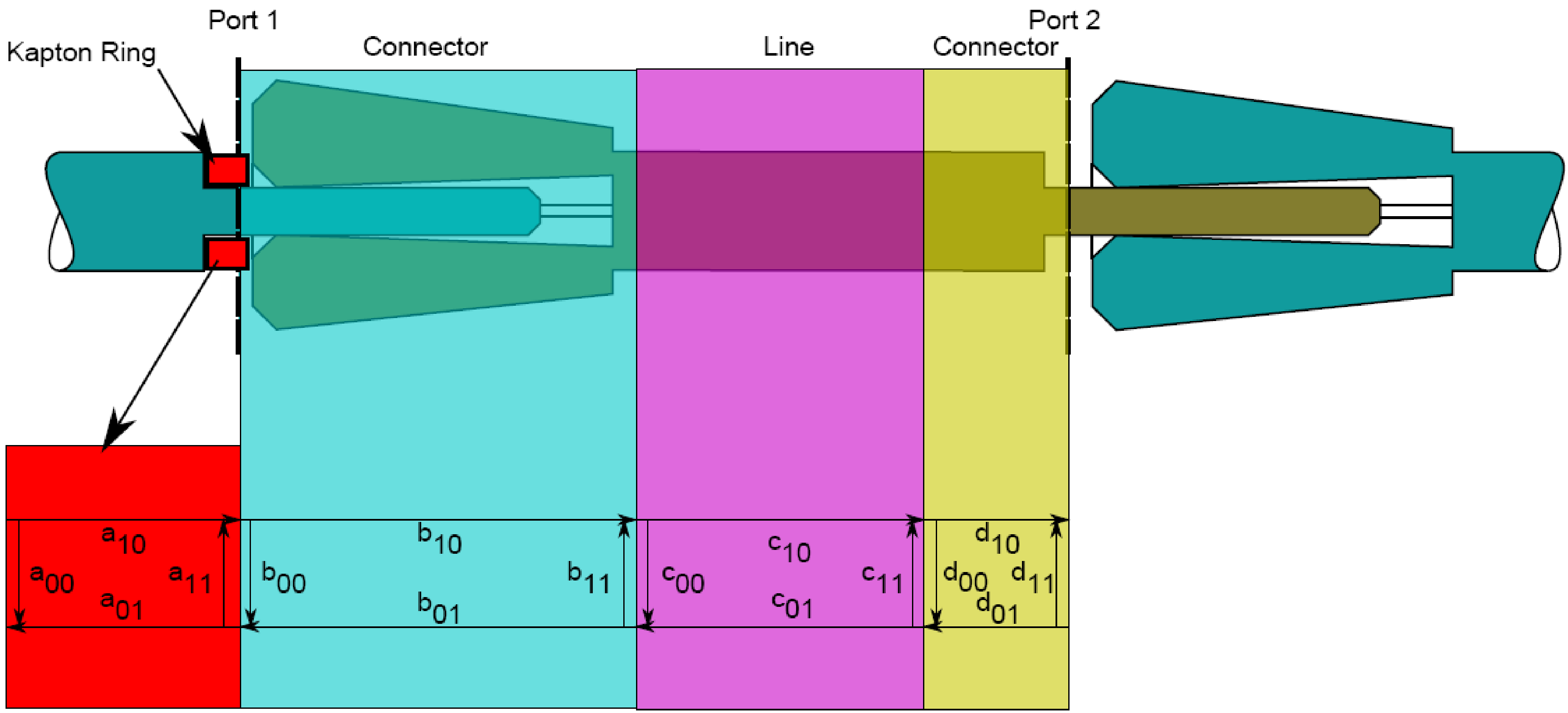
TP1 mounted with Kapton disc to avoid near field effects and to control a flush centre conductor position



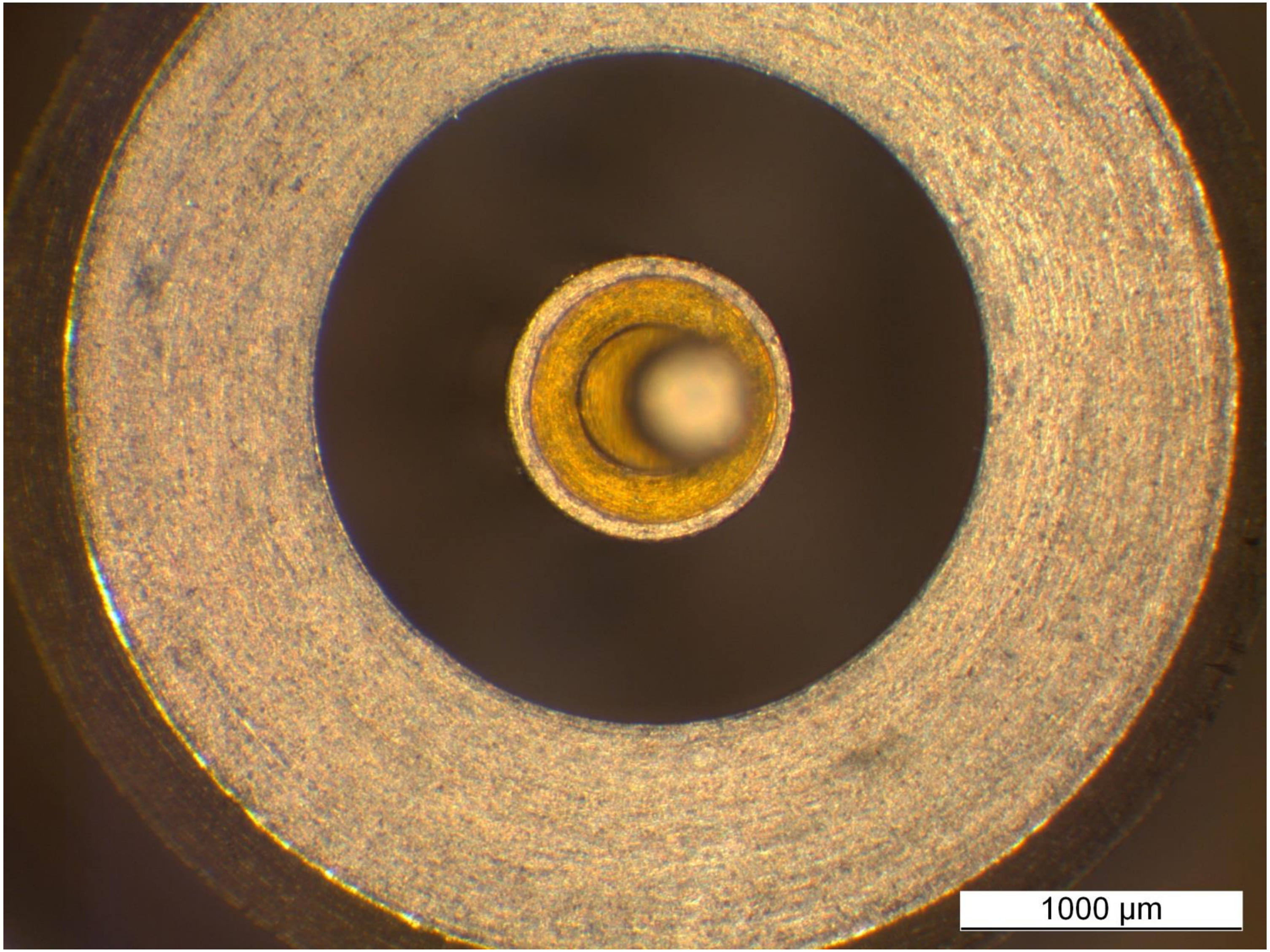
Kapton disc sizes used at METAS: 12.7 µm or 19 µm

Note: optimal CC pin-depth recession for the 3.5 mm line system = 15 µm

Airline model with a mounted Kapton disc



Kapton disc mounted on a 2.4 mm test port male pin



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S21 mag (dB)