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The revision of EURAMET guide cg-12

M. Zeier

Outline

- Introduction
- Advances in VNA metrology
- Content of ‘new’ guide
- Rigorous uncertainty propagation
- Ripple Method
- Examples
- Summary

Introduction 1/3

Background

- Rewrite of VNA guide EURAMET cg-12 (formerly EA 10/12) in HF-Circuits project
- Almost complete draft was available beginning of March 2016
- Review (consortium, NMIs, calibration laboratories, selected individuals)
- Final draft will be submitted end of June to TCEM SC-RF&MW for further review.

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Introduction 2/3

Why a new guide?

- Remove some shortcomings of ‘old’ guide
- Implement advances in VNA metrology
- Make guide fit for higher frequencies
- Provide additional information to improve the quality of VNA measurements

Introduction 3/3

Major changes in new guide

- Promotion of rigorous uncertainty propagation as a new method, which is compatible with GUM methodology and widely applicable
- Keep Ripple Method, same procedure but improved analysis
- Additional information on VNA traceability, VNA calibration, VNA verification, characterization of uncertainty contributions, best measurement practice, S-parameter uncertainties, waveguide measurements, …

Advances in VNA metrology 1/3

Multivariate treatment of measurement uncertainty

- 2002: First paper by NPL
  on multivariate treatment
  of S-parameter uncertainties

N. M. Ridler and M. J. Salter

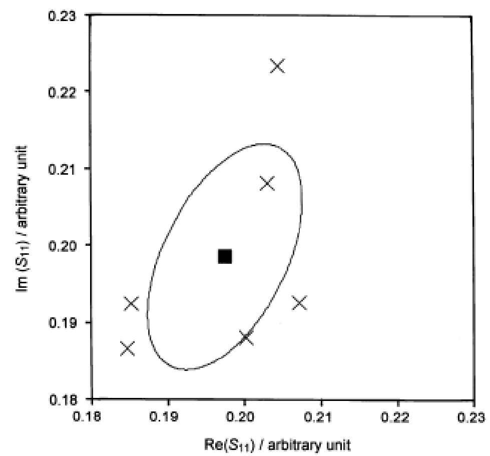

Figure 1. Elliptical region of uncertainty (95 % level of confidence) for the repeat measurements considered in the example given in the text. Measured values are shown as crosses and the mean value is shown as a square.

- 2011: GUM Supplement 2
  multivariate treatment of measurement uncertainty.

→ relevant standard for S-parameter uncertainties

Advances in VNA metrology 2/3

Connector effects

R&D work on VNA traceability since 2006 (METAS):
(picked up by *HF-Circuits* project in 2014)

→ Investigating role of coaxial connector interface

- Including connectors in the characterization of cal standards
  - better definition of the reference measurement plane
  - removes inconsistencies between different cal algorithms

  → Better accuracy, better consistency
- Beadless air lines
  - are not ideal, connector always causes reflections
  - are unstable, because of undefined position of inner conductor

  → As is, not suitable as a measurement standard

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Advances in VNA metrology 3/3

Software

- Software tools for generic multivariate and complex-valued uncertainty evaluation:
  - Measurement Software Toolkit (MSL, NZ) mst.irl.cri.nz
  - METAS UncLib www.metas.ch/unclib

- Specific software for the treatment of S-parameters in accordance with GUM Suppl 2
  - VNA Tools (METAS) www.metas.ch/vnatools
  - Microwave Uncertainty Framework (NIST) link
  - More to come…

Content of ‘new’ guide: Main body

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Content of 'new' guide: Appendix

Rigorous uncertainty propagation 1/6

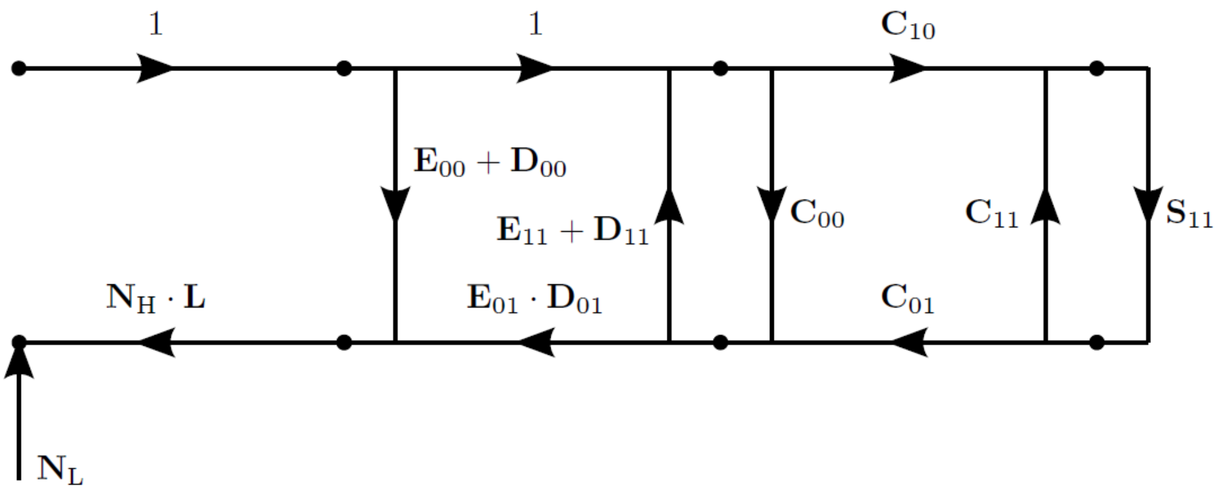
Triple rewarding:

“It should be noted that the migration from the ripple method to the rigorous approach is accompanied by a phenomenon that cannot be found in nature. Normally one has to pay for any convenience. Here, omitting the tedious ripple measurements is not only rewarded with the fact that all measurement errors remain unchanged but also with lower uncertainties (triple rewarding).”

T. Reichel (Review of draft 2)

Rigorous uncertainty propagation 2/6

One-port measurement model: Signal flow graph:



Influence factors:

$\mathbf{S}_{11}$: Calibration standards

$\mathbf{N}_{\mathrm{L}}$: Noise floor

$\mathbf{N}_{\mathrm{H}}$: Trace noise

$\mathbf{L}$: Linearity

$\mathbf{D}_{00}$, $\mathbf{D}_{01}$, $\mathbf{D}_{11}$: Drift in directivity, reflection tracking and source match

$\mathbf{C}_{\mathrm{ij}}$: Cable and connector

Rigorous uncertainty propagation 3/6

One-port measurement model: Equations

VNA calibration:

$$\mathbf{S}_{11}^{m} = \mathbf{N}_{\mathrm{L}} + \mathbf{N}_{\mathrm{H}}\mathbf{L}\left(\mathbf{E}_{00}' + \mathbf{k}\mathbf{C}_{00}\mathbf{E}_{01}' + \frac{\mathbf{k}^2\mathbf{C}_{10}\mathbf{C}_{01}\mathbf{E}_{01}'\mathbf{S}_{11}}{1-\left(\mathbf{C}_{11}+\mathbf{k}\mathbf{C}_{01}\mathbf{C}_{10}\mathbf{E}_{11}'\right)\mathbf{S}_{11}}\right)$$

$$\begin{aligned}
\mathbf{E}_{00}' &= \mathbf{E}_{00} + \mathbf{D}_{00} \\
\mathbf{E}_{01}' &= \mathbf{E}_{01}\mathbf{D}_{01} \\
\mathbf{E}_{11}' &= \mathbf{E}_{11} + \mathbf{D}_{11} \\
\mathbf{k} &= \frac{1}{1-\mathbf{E}_{11}'\mathbf{C}_{00}}
\end{aligned}$$

VNA error correction:

$$\mathbf{S}_{11} = \frac{\frac{\mathbf{S}_{11}^{m}-\mathbf{N}_{\mathrm{L}}}{\mathbf{N}_{\mathrm{H}}\mathbf{L}} - \mathbf{E}_{00}' - \mathbf{k}\mathbf{C}_{00}\mathbf{E}_{01}'}{\left(\mathbf{C}_{11}+\mathbf{k}\mathbf{C}_{01}\mathbf{C}_{10}\mathbf{E}_{11}'\right)\left(\frac{\mathbf{S}_{11}^{m}-\mathbf{N}_{\mathrm{L}}}{\mathbf{N}_{\mathrm{H}}\mathbf{L}} - \mathbf{E}_{00}' - \mathbf{k}\mathbf{C}_{00}\mathbf{E}_{01}'\right) + \mathbf{k}^2\mathbf{C}_{10}\mathbf{C}_{01}\mathbf{E}_{01}'}$$

Rigorous uncertainty propagation 4/6

Characterization of uncertainty contributions: e.g. noise

a) VNA settings: Leave the VNA uncalibrated and set the test port power, IF bandwidth and averaging to the values that are being used for measurements. Set the sweep type to CW (continuous wave).

b) Connect two shorts to port 1 and to port 2. Wait a few minutes.

c) Collect at least a few hundred measurement data points of $\mathbf{S}_{11}$ and $\mathbf{S}_{22}$ (for the calculation of the trace noise) and $\mathbf{S}_{21}$ and $\mathbf{S}_{12}$ (for the calculation of the noise floor) for each frequency point.

d) Calculate the standard deviations of the real and imaginary components of $\mathbf{S}_{21}$. Take the larger of both: $\max\left(\mathrm{s}(\mathrm{Re}\left[\mathbf{S}_{21})\right], \mathrm{s}(\mathrm{Im}\left[\mathbf{S}_{21}\right])\right)$ with $\mathrm{s}(\cdot)$ according to equation (B.7).

e) Define a reasonable envelope that encloses the calculated values over the whole frequency range. Typically, the whole frequency range is divided into frequency bands, each with a constant value that encloses the calculated values. The values can be taken as the standard uncertainties associated with the real and imaginary components of $\mathbf{N}_{\mathrm{L}2}$.

f) Calculate the standard deviation of the normalized magnitude of $\mathbf{S}_{11}$: $\mathrm{s}(|\mathbf{S}_{11}/\mathbf{m}(\mathbf{S}_{11})|)$ with $\mathbf{m}(\cdot)$ and $\mathrm{s}(\cdot)$ according to equations (B.9) and (B.7), respectively.

g) Calculate the standard deviation of the normalized phase of $\mathbf{S}_{11}$: $\mathrm{s}(\arg\left[\mathbf{S}_{11}/\mathbf{m}(\mathbf{S}_{11})\right])$ with $\mathbf{m}(\cdot)$ and $\mathrm{s}(\cdot)$ according to equations (B.9) and (B.7), respectively.

h) For the values defined in step f) and g), define envelopes according to step e) and assign the values as uncertainties associated with magnitude and phase of $\mathbf{N}_{\mathrm{H}1}$.

i) Repeat steps d) to h) for $\mathbf{S}_{22}$ and $\mathbf{S}_{12}$ to determine uncertainties associated with $\mathbf{N}_{\mathrm{L}1}$ and $\mathbf{N}_{\mathrm{H}2}$, respectively. Normally, this should give very similar results such that the same magnitude of uncertainties can be defined for both ports.

Rigorous uncertainty propagation 5/6

Uncertainty evaluation:

Propagate characterized uncertainties through measurement model using

- Linear uncertainty propagation
- Monte Carlo Method

Not feasible by hand (or in excel):

Requires software

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Rigorous uncertainty propagation 6/6

Pros:

- Multivariate treatment including correlations (following GUM Suppl 2)
- Results with uncertainties and correlations
- Measurement uncertainty budget w.r.t. basic influences
- Widely applicable (higher frequencies, multiport, non-linear, …)

Cons:

- Characterized calibration kit needed
- Explicit uncertainty equations are not given in the guide
- External software needed to master the elaborate equations

Ripple Method 1/8

Compared to ‘old’ guide:

- Experimental part remains the same → no need to buy new equipment
- Changes in analysis of the data
  - Safeguards to avoid underestimation of uncertainty
  - Addressing uncertainty of phase
  - Formally more clean
  - Origin of equations more clear
  - Taking additional uncertainty contributions properly into account
- Advanced Ripple Method → talk of Faisal

Ripple Method 2/8

Uncertainties

- ‘old’ guide:
  - Uncertainties just in magnitude
  - ***6.3 Uncertainty in phase***

    Still under consideration for inclusion in a future revision.

- ‘new’ guide:
  - Uncertainties as circular regions in complex plane

$$\mathrm{u}(\boldsymbol{S}_{11}) = \mathrm{u}\big(\mathrm{Re}(\boldsymbol{S}_{11})\big) = \mathrm{u}\big(\mathrm{Im}(\boldsymbol{S}_{11})\big)$$

Ripple Method 3/8

Measurement model 'old' guide:

One-port: $U_{VRC} = D + T\Gamma + M\Gamma^2 + R_{VRC}$

Two-port: $U_{VRC} = D + T\Gamma + M\Gamma^2 + R_{VRC} + S_{21}^2\Gamma_L$

$$U_{TM} = L + M_{TM} + I + R_{IB}$$

$$M_{TM} = 20\log_{10}\frac{1 + \left(|MS_{11}| + |\Gamma_L S_{22}| + |M\Gamma_L S_{11} S_{22}| + |M\Gamma_L S_{21} S_{12}|\right)}{1 - |M||\Gamma_L|}$$

If you can't make love with models, make at least models with love

Formally insufficient

Origin not always clear

Uncertainty contributions are missing

Ripple Method 4/8

Measurement model 'new' guide: uncertainty equations (based on calibrated VNA and simplifications)

One-port:

$$\left(\mathrm{u}(\mathbf{S}_{11})\right)^2 = \left(\mathrm{u}(\mathbf{E}_{00}) + |\mathbf{S}_{11}^m|\ \mathrm{u}(\mathbf{E}_{01}) + |\mathbf{S}_{11}^m|^2\ \mathrm{u}(\mathbf{E}_{11}) + |\mathbf{S}_{11}^m|\ \mathrm{u}(\mathbf{L})\right)^2 + \left(\mathrm{u}(\mathbf{R}_{S11})\right)^2$$

Two-port:

$$\begin{aligned}
\left(\mathrm{u}(\mathbf{S}_{11})\right)^2 =& \left(\mathrm{u}(\mathbf{E}_{00}^F) + |\mathbf{S}_{11}^m|\ \mathrm{u}(\mathbf{E}_{01}^F) + |\mathbf{S}_{11}^m|^2\ \mathrm{u}(\mathbf{E}_{11}^F) + |\mathbf{S}_{21}^m\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{E}_{22}^F) + \right. \\
& \left. |\mathbf{S}_{11}^m|\ \mathrm{u}(\mathbf{L})\right)^2 + \left(|\mathbf{S}_{21}^m\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{C}_{22})\right)^2 + \left(\mathrm{u}(\mathbf{R}_{S11})\right)^2 \\
\left(\mathrm{u}(\mathbf{S}_{21})\right)^2 =& \left(|\mathbf{S}_{11}^m\mathbf{S}_{21}^m|\ \mathrm{u}(\mathbf{E}_{11}^F) + |\mathbf{S}_{22}^m\mathbf{S}_{21}^m|\ \mathrm{u}(\mathbf{E}_{22}^F) + |\mathbf{S}_{21}^m|\ \mathrm{u}(\mathbf{E}_{32}^F) + \mathrm{u}(\mathbf{E}_{30}^F) + \right. \\
& \left. |\mathbf{S}_{21}^m|\ \mathrm{u}(\mathbf{L})\right)^2 + \left(|\mathbf{S}_{21}^m|\ \mathrm{u}(\mathbf{C}_{32})\right)^2 + \left(|\mathbf{S}_{21}^m\mathbf{S}_{22}^m|\ \mathrm{u}(\mathbf{C}_{22})\right)^2 + \left(\mathrm{u}(\mathbf{R}_{S21})\right)^2 \\
\left(\mathrm{u}(\mathbf{S}_{22})\right)^2 =& \left(\mathrm{u}(\mathbf{E}_{33}^R) + |\mathbf{S}_{22}^m|\ \mathrm{u}(\mathbf{E}_{32}^R) + |\mathbf{S}_{22}^m|^2\ \mathrm{u}(\mathbf{E}_{22}^R) + |\mathbf{S}_{21}^m\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{E}_{11}^R) + \right. \\
& \left. |\mathbf{S}_{22}^m|\ \mathrm{u}(\mathbf{L})\right)^2 + \left(|\mathbf{S}_{22}^m|\ \mathrm{u}(\mathbf{C}_{32})\right)^2 + \left(|\mathbf{S}_{22}^m|\ \mathrm{u}(\mathbf{C}_{23})\right)^2 + \\
& \left(|\mathbf{S}_{22}^m|^2\ \mathrm{u}(\mathbf{C}_{22})\right)^2 + \left(\mathrm{u}(\mathbf{C}_{33})\right)^2 + \left(\mathrm{u}(\mathbf{R}_{S22})\right)^2 \\
\left(\mathrm{u}(\mathbf{S}_{12})\right)^2 =& \left(|\mathbf{S}_{22}^m\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{E}_{22}^R) + |\mathbf{S}_{11}^m\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{E}_{11}^R) + |\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{E}_{01}^R) + \mathrm{u}(\mathbf{E}_{03}^R) + \right. \\
& \left. |\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{L})\right)^2 + \left(|\mathbf{S}_{12}^m|\ \mathrm{u}(\mathbf{C}_{23})\right)^2 + \left(|\mathbf{S}_{12}^m\mathbf{S}_{22}^m|\ \mathrm{u}(\mathbf{C}_{22})\right)^2 + \left(\mathrm{u}(\mathbf{R}_{S12})\right)^2
\end{aligned}$$

Ripple Method 5/8

Ripple assessment

Uncertainty in directivity ('old' guide): $u(\boldsymbol{E}_{00}) = \frac{1}{\sqrt{2}}\frac{A}{2}$

Uncertainty in directivity ('new' guide):

$$(\mathrm{u}(\mathbf{E}_{00}))^2 = \left(\frac{|\delta\mathbf{E}_{00}|}{\sqrt{2}}\right)^2 + 2\left(\frac{|\mathbf{\Gamma}_{\mathrm{CO}}|}{\sqrt{2}}\right)^2 + 2\left(\mathrm{u}(|\mathbf{\Gamma}_{\mathrm{CO}}|)\right)^2 + 2\left(\frac{|\mathbf{\Gamma}_{\mathrm{AL}}|}{\sqrt{2}}\right)^2 + 2\left(\mathrm{u}(|\mathbf{\Gamma}_{\mathrm{AL}}|)\right)^2 + \left(\mathrm{u}(|\mathbf{D}_{00}|)\right)^2 + \left(\mathrm{u}(\mathbf{R}_{\mathrm{E00}})\right)^2$$

$\mathbf{\Gamma}_{\mathrm{CO}}$: Reflection at connector interfaces of air line

$\mathbf{\Gamma}_{\mathrm{AL}}$: Characteristic impedance of air line

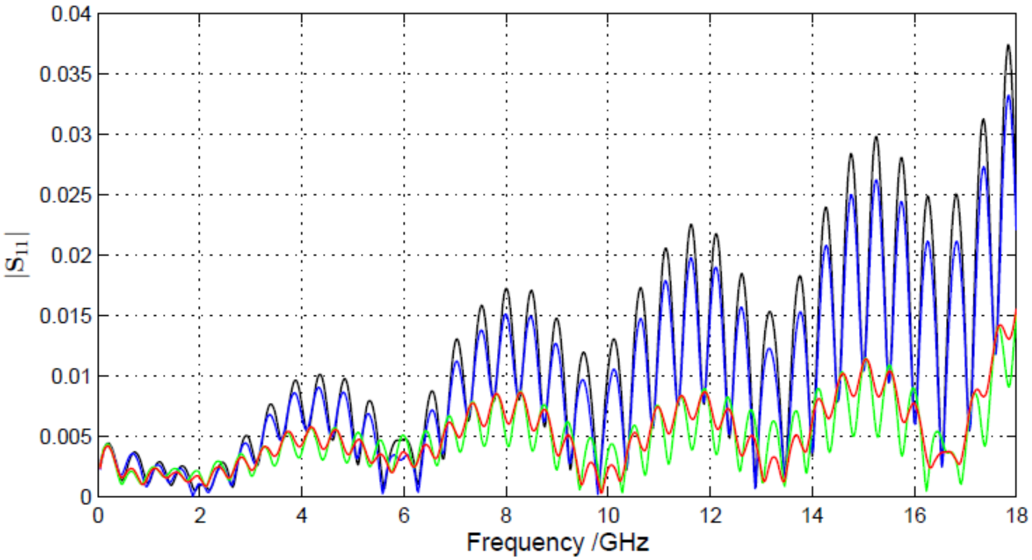
$\mathbf{D}_{00}$: Drift in directivity

$\mathbf{R}_{\mathrm{E00}}$: Repeatability in ripple evaluation

Ripple Method 6/8

Connector effect:

Different ripple amplitudes, depending on longitudinal position of center conductor



$$|\mathbf{\Gamma}_{\mathrm{CO}}| \simeq kf\,(1+0.1d_{\mathrm{pg}})$$

d_{pg}: maximum pin gap

Ripple Method 7/8

Tracking term

‘old’ guide:

6.2.4 Tracking

6.2.4.1 It is considered that the effect on the overall uncertainty for reflection measurements caused by imperfect tracking between the incident and reflected signals will be relatively small. An experimental estimate might be obtained from the repeatability of measuring high reflective devices. Usually it is satisfactory to use the manufacturer's value for this contribution, e.g. a relative uncertainty of 0.001 as half interval of a rectangular distribution.

‘new’ guide: Using measurement of cal short and propagating the uncertainties of directivity and source match

$$(\mathrm{u}(\mathbf{E}_{01}))^2 = \left(\left|\frac{1}{\boldsymbol{\Gamma}_s}\right| \mathrm{u}(\mathbf{E}_{00}) + |\boldsymbol{\Gamma}_s|\ \mathrm{u}(\mathbf{E}_{11})\right)^2 + \left(\left|\frac{1}{\boldsymbol{\Gamma}_s}\right| \mathrm{u}(\boldsymbol{\Gamma}_s)\right)^2 + (\mathrm{u}(|\mathbf{D}_{01}|))^2$$

Ripple Method 8/8

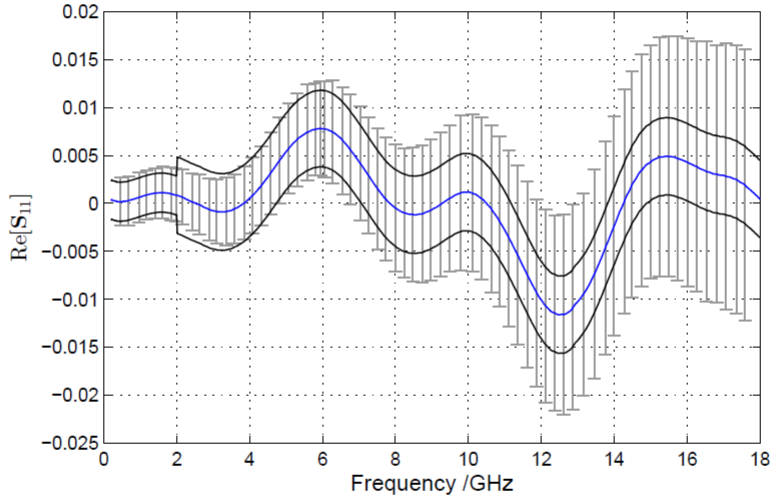
Pros:

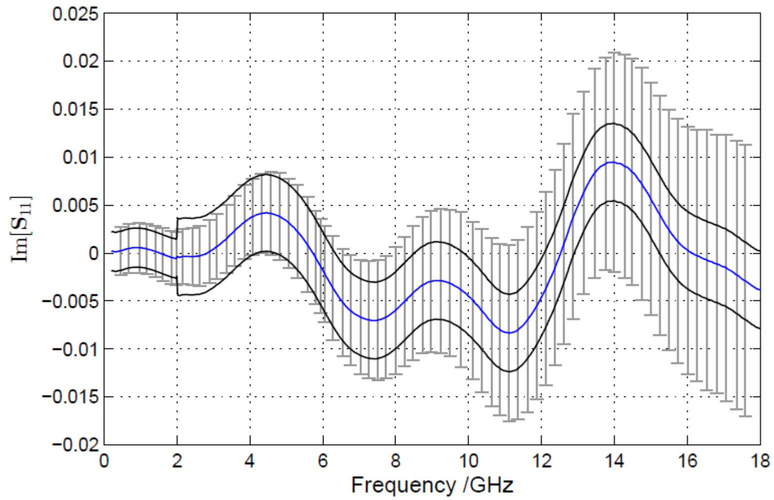
- No need to change experimental ripple evaluation
- Uncertainty equations are given in the guide
- Characterization of calibration kit is not necessary

Cons:

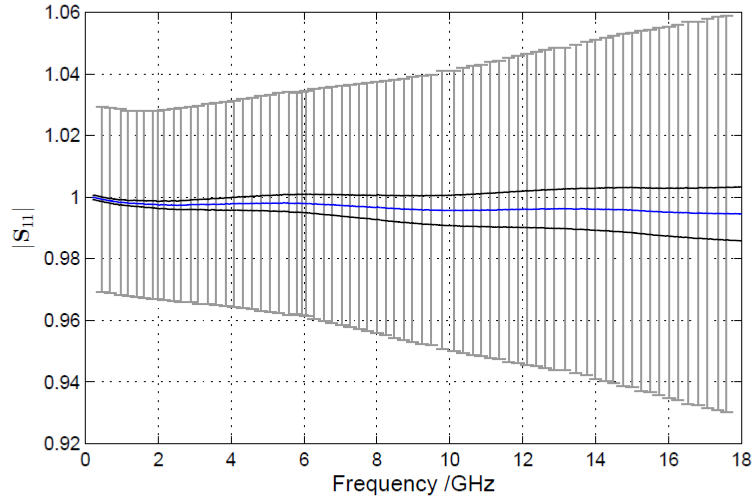
- Handling of air lines
- Limitations in application
- No correlations
- No differentiation between uncertainty in mag and phase
- Larger uncertainties than rigorous method due to safeguards

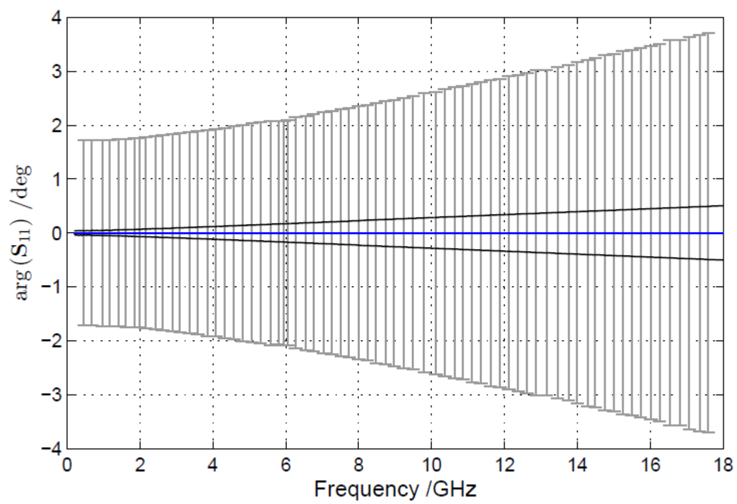
Examples: Matched load



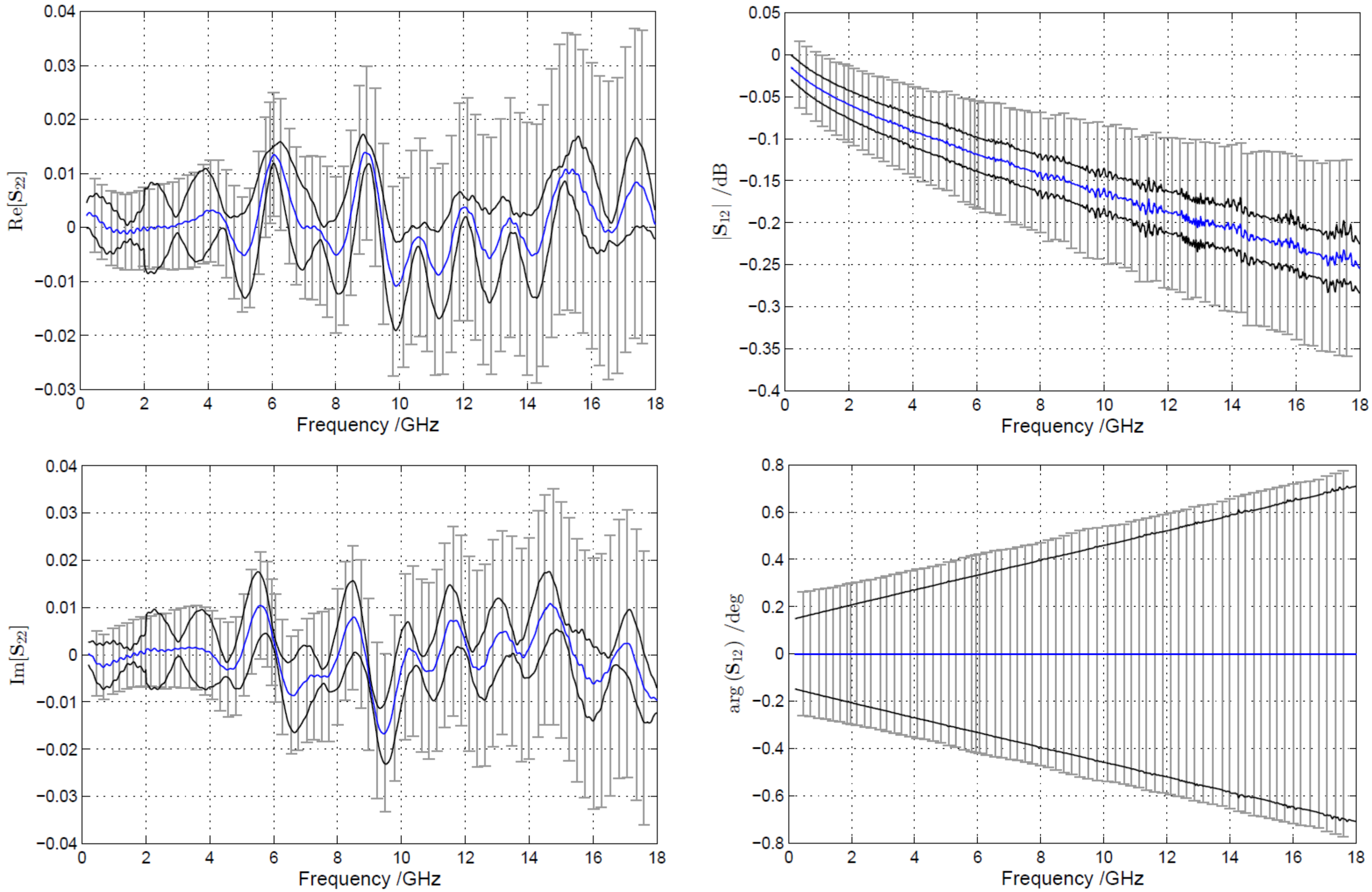


Examples: Short

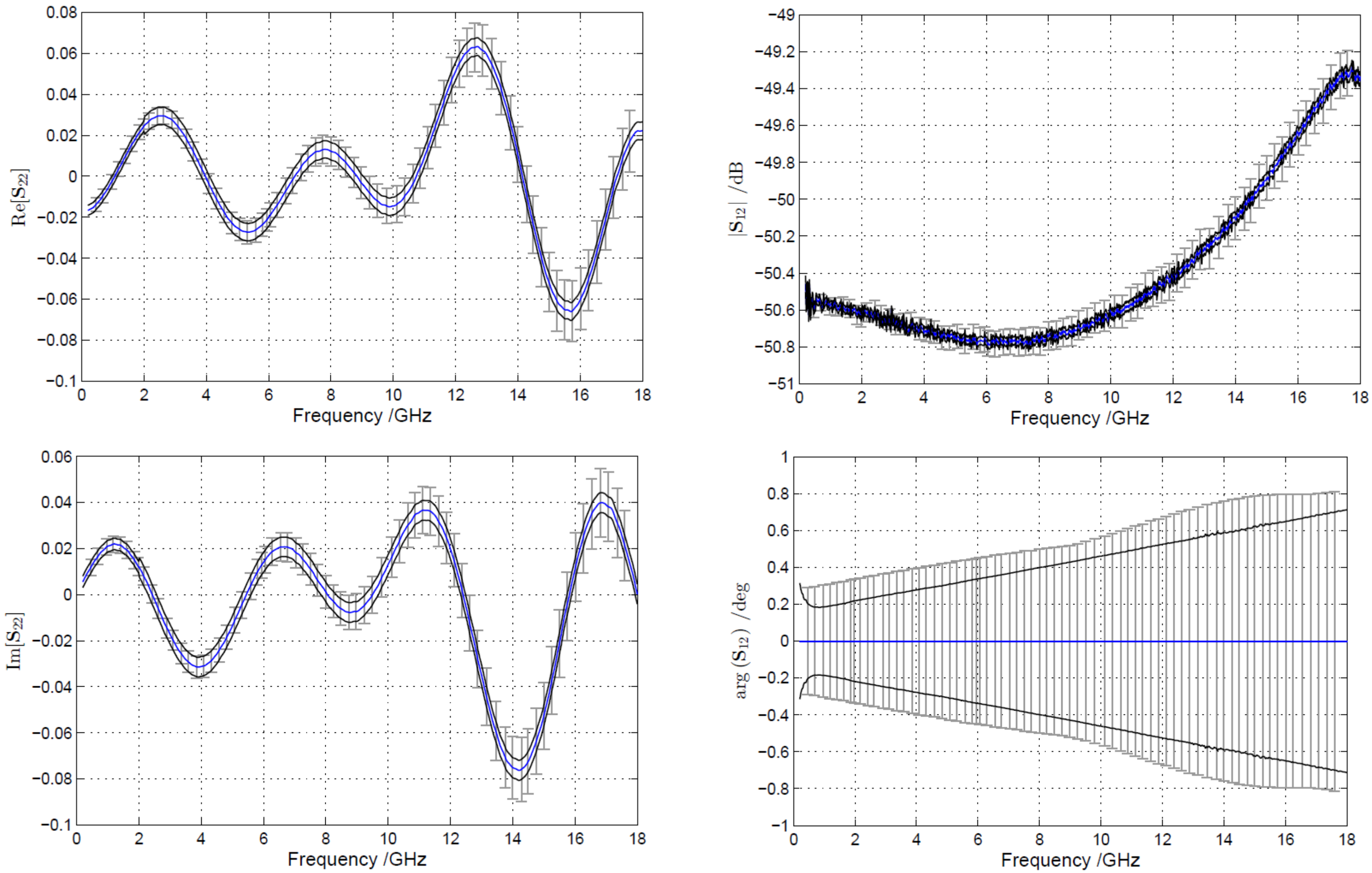




Examples: Adapter



Example: 50 dB attenuation device



Summary

The new EURAMET guide cg-12:

- promotes a modern, forward-looking and GUM compliant way to treat uncertainties associated with S-parameters
- provides continuity with an improved Ripple Method
- embraces developments of VNA metrology over the last years
- is not limited in applicability
- provides practical advice to enhance the quality of measurements
- Should become publicly available towards the end of 2016

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Thank you very much for your attention