A Review of VNA Calibration Methods

Andrej Rumiantsev

SUSS MicroTec Test Systems GmbH
Sussstr. 1, Sacka, D-01561, Germany
a.rumiantsev@ieee.org

Outline

- What is VNA Calibration?
- Measurement Errors
- Error Models: from 1 to N Ports
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

What is VNA calibration?

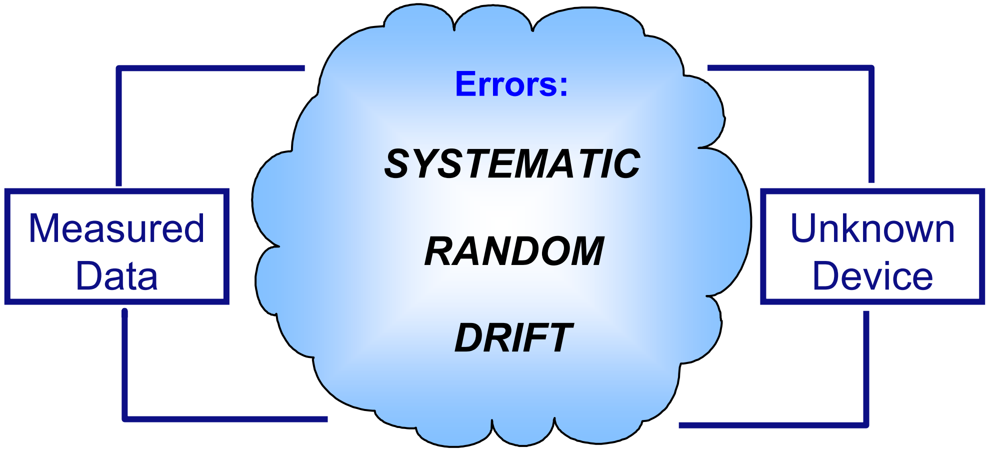
- Calibration (by ISO) is the:
  - *"…set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards."* [1]
- Two meanings of the VNA calibration are typically in use:
  - Instrument calibration at the manufacturer's side
    - once in two years or so
  - Definition and removing of systematic measurement errors before measurement session
    - once a day or more often

Outline

- What is VNA Calibration?
- Measurement Errors
- Error Models
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

Measurement Errors

- Can be grouped as:
  - Systematic
  - Random
  - Drift



- Drift and systematic errors can be defined by (re-)calibration
- Error correction procedure removes these errors from measurement results

Picture: Agilent Technologies

Outline

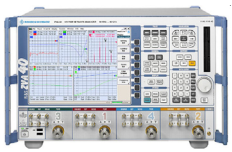
- What is VNA Calibration?
- Measurement Errors
- Error Models
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

EuMIC 2008
SÜSS MicroTec
38TH EUROPEAN MICROWAVE CONFERENCE 2008

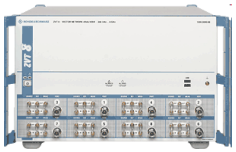
Error Models: Influencing Factors

- Number of ports

2 ports



4 ports

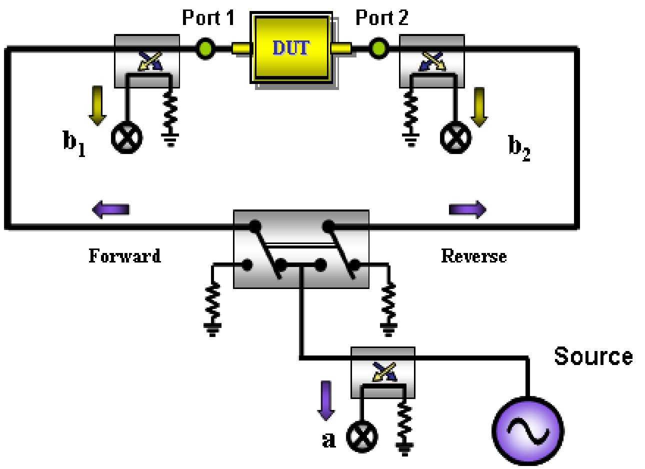


8 ports

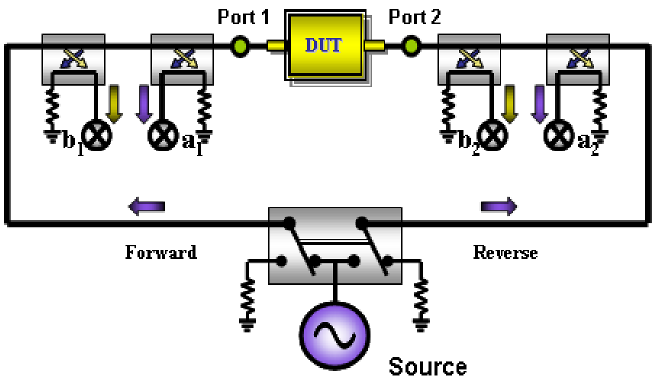
≤16 ports

- Receiver concept

Reference channel: N=n+1 receivers



Double reflectometer: N=2n receivers



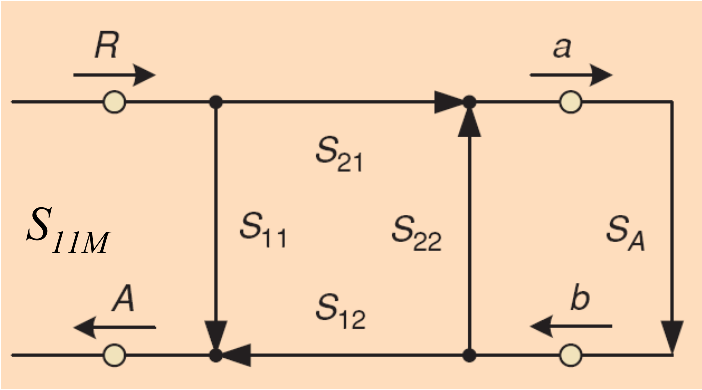
where :
N - number of receivers
n - number of ports

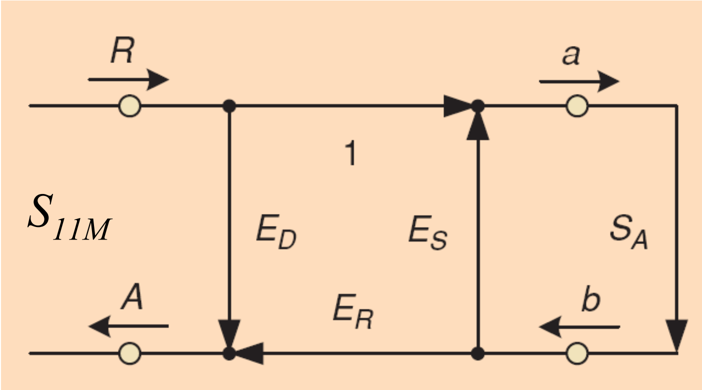
EuMIC 2008
SÜSS MicroTec
38TH EUROPEAN MICROWAVE CONFERENCE 2008

Error Models: One Port

- Over four error S-parameters
- Over three error terms [2]
  - Directivity, E_D
  - Source match, E_S
  - Reflection tracking, E_R
- Error correction:

$$S_{11A} = \frac{S_{11M} - E_D}{E_S\left(S_{11M} - E_D\right) + E_R}$$



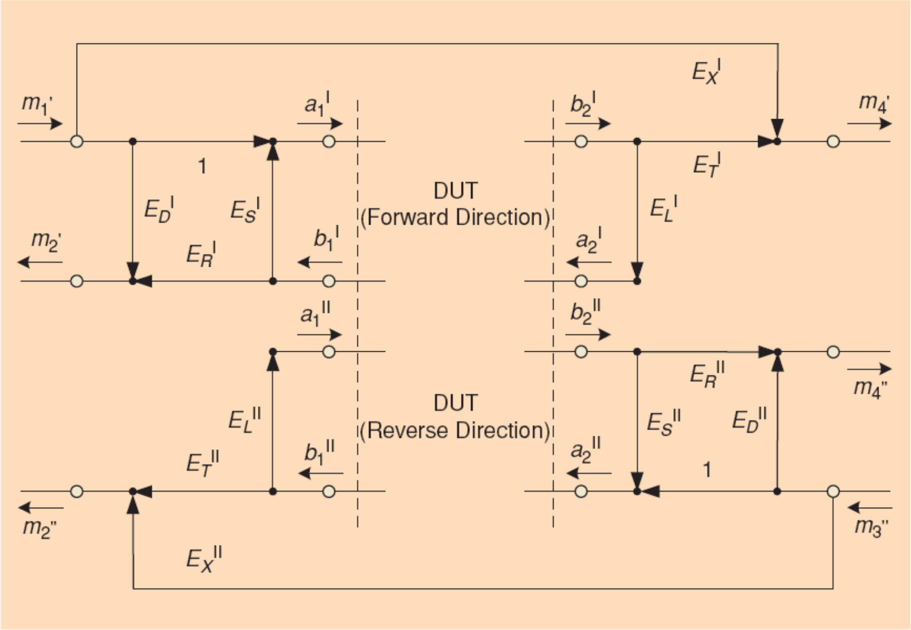


where:
S_{11A} – actual DUT parameter
S_{11M} – measured DUT parameter

EuMIC 2008
SÜSS MicroTec
38th European Microwave Conference 2008

Error Models: Two Port

- Contains 10(12) error terms
- Additional terms:
  - Transmission tracking, E_T
  - Load match, E_L
  - Crosstalk, E_X
- Crosstalk (Isolation) E_X is typically omitted
- Error correction [3]:



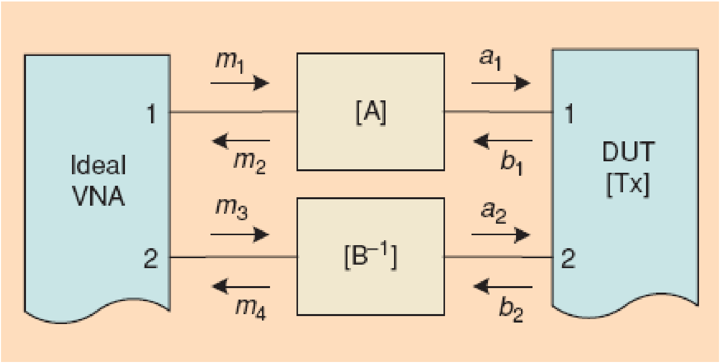
$$a_1^I = m_1^I + \frac{E_S^I}{E_R^I}\left(m_2^I - E_D^I m_1^I\right), \quad b_1^I = \frac{1}{E_R^I}\left(m_2^I - E_D^I m_1^I\right), \quad b_2^I = \frac{m_4^I}{E_T^I}, \; a_2^I = \frac{E_L^I m_4^I}{E_T^I},$$

$$\begin{pmatrix} b_1^I & b_1^{II} \\ b_2^I & b_2^{II} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}\begin{pmatrix} a_1^I & a_1^{II} \\ a_2^I & a_2^{II} \end{pmatrix}, \; [K]=[Sx][L], \quad [Sx]=[K][L]^{-1}$$

where:
m – waves measured by the ideal VNA receivers;
a, b – incident, transmitted/reflected waves, at the DUT plane;
prime, double-prime parameters correspond to the forward and reverse measurement directions respectively.

Two Port Double Reflectometer

- Built off the transmission [*T*] parameters [4]
- Two matrices [*A*] and [*B*]
- 7 Error terms are in use:
  - Normalized to one term (A_{22})
- Error correction:



$$\begin{pmatrix} m_1' & m_1'' \\ m_2' & m_2'' \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}^{-1} \begin{pmatrix} m_3' & m_3'' \\ m_4' & m_4'' \end{pmatrix},$$

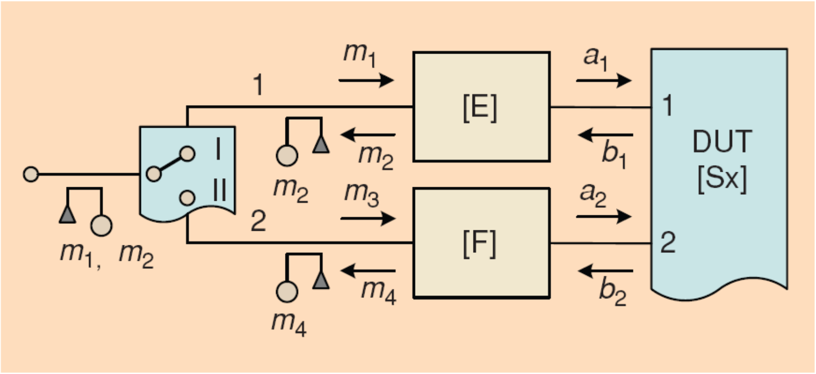
$$M = ATB^{-1}, \quad M = \begin{pmatrix} m_1' & m_1'' \\ m_2' & m_2'' \end{pmatrix} \begin{pmatrix} m_3' & m_3'' \\ m_4' & m_4'' \end{pmatrix}^{-1}, \quad T_X = A^{-1} M_X B$$

where:
T_X – T-parameters of DUT;
prime, double-prime parameters correspond to the forward and reverse measurement directions respectively.

EuMIC 2008
SÜSS MicroTec
38th European Microwave Conference 2008

Error Models: Multiport Cases

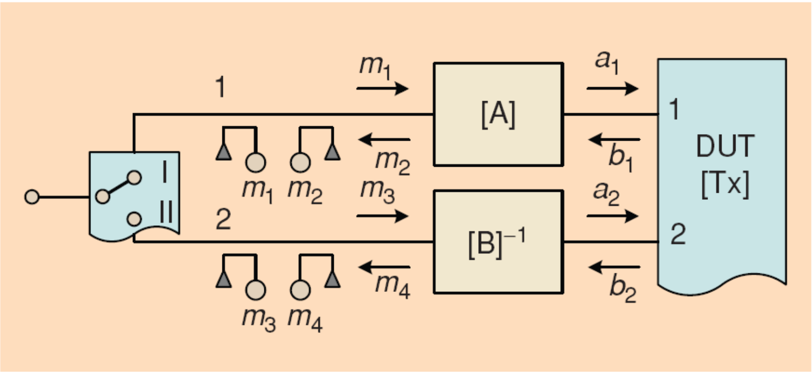
- Reference channel [4]



  - Model can be extended by matrices [G], [H], …
  - Number of error terms is:

$$N = 2n^2 - 1$$

- Double reflectometer [5]



  - Model can be extended by matrices [B_{II}], [B_{III}], …
  - Number of error terms is:

$$N = 4n - 1$$

EuMIC 2008
SÜSS MicroTec
38th European Microwave Conference 2008

Outline

- What is VNA Calibration?
- Measurement Errors
- Error Models
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

Calibration: One Port

- Three unknowns have to be defined

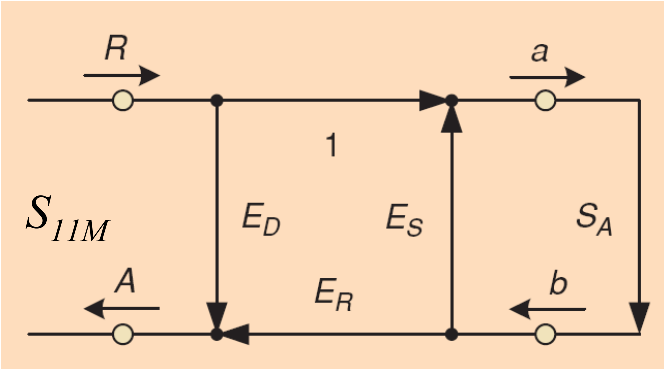
$$S_{11A} = \frac{S_{11M} - E_D}{E_S\left(S_{11M} - E_D\right) + E_R}$$

- Three independent measurement conditions are required

1: $E_D + S_{11A}^{I} S_{11M}^{I} E_R - S_{11A}^{I}\left(E_D E_S - E_R\right) = S_{11M}^{I}$

2: $E_D + S_{11A}^{II} S_{11M}^{II} E_R - S_{11A}^{II}\left(E_D E_S - E_R\right) = S_{11M}^{II}$

3: $E_D + S_{11A}^{III} S_{11M}^{III} E_R - S_{11A}^{III}\left(E_D E_S - E_R\right) = S_{11M}^{III}$



- Commonly used standards:
  – Short, Open, Load (SOL)

Calibration: Two Ports

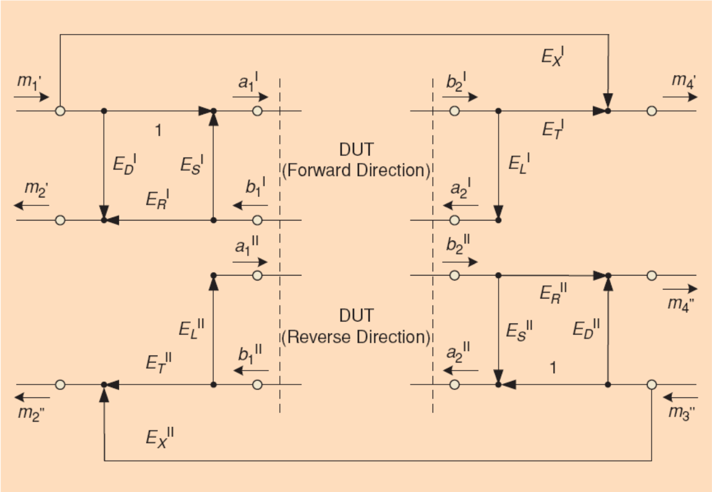
10 Unknowns have to be defined

- Step 1. One-port SOL for Port 1:

$$E'_D\ ,\ E'_S\ ,\ E'_R$$

- Step 2. One-port SOL for Port 2:

$$E''_D\ ,\ E''_S\ ,\ E''_R$$



- Step 3. Connect two ports together (“Thru”):

$$E'_L = \frac{S'_{11M} - E'_D}{S_{11M}E'_S - \left(E'_D E'_S - E'_R\right)}, \qquad E'_T = S_{21M}\left(1 - E'_S E'_L\right)$$

- Step 4. Same as Step 3 but in reverse direction: $E''_L\ ,\ E''_F$

prime, double-prime parameters correspond to the forward and reverse measurement directions respectively.

Calibration SOL and SOLT

- Advantages
  - Can be applied on both reference channel and double reflectometer VNAs
  - Robust
- Drawbacks
  - All standards have to be either known or ideal
  - Not self-consistent

Outline

- What is VNA Calibration?
- Measurement Errors
- Error Models
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

Self-Calibration Algorithms: TRL [6]

Standards	Requirements	Unknown	Error Terms	Self-Calibration Product
THRU	Known: S_{11}, S_{21}, S_{12}, S_{22}	---	4	---
LINE	Known: S_{11}, S_{22}; length	S_{21}, S_{12},	2	Propagation constant γ
REFLECT	S_{11}=S_{22} S_{11}(S_{22}) known within +/- 90 degree	S_{11} (S_{22})	1	S_{11} (S_{22})

EuMIC 2008 SÜSS MicroTec 38TH EUROPEAN MICROWAVE CONFERENCE 2008

Self-Calibration Algorithms: TRL

- Advantages
  - Traceable calibration and measurements (for air-lines)
  - Does not require ideal Open or Short
  - Self-consistent
- Drawbacks
  - Frequency limited. Many lines required for broadband measurements (e.g. multiline TRL)
  - Difficulties in on-wafer application
  - Sensitive to Reflect asymmetry

Self-Calibration Algorithms: LRM [7]

Standards	Requirements	Unknown	Error Terms	Self-Calibration Product
LINE (Thru)	Known: S_{11}, S_{21}, S_{12}, S_{22}	---	4	---
MATCH (Load)	Known: S_{11}, S_{22} $S_{11}=S_{22}$ Z_{MATCH}=50 Ohm	---	2	---
REFLECT	$S_{11}=S_{22}$ $S_{11}(S_{22})$ known within +/- 90 degree	S_{11} (S_{22})	1	S_{11} (S_{22})

Self-Calibration Algorithms: LRM

- Advantages
  - Broadband
  - Self-consistent
- Drawbacks
  - Requires 50 Ohm Load
  - Sensitive to Load asymmetry and Reflect asymmetry

Self-Calibration Algorithms: SOLR [8]

Standards	Requirements	Unknown	Error Terms	Self-Calibration Product
SHORT	Known: S_{11}, S_{22}	---	2	---
OPEN	Known: S_{11}, S_{22}	---	2	---
LOAD	Known: S_{11}, S_{22}	---	2	---
RECIPROC	$S_{21}=S_{12}$ $S_{21}(S_{12})$ known within +/- 90 degree	S_{11}, S_{21}, S_{12}, S_{22}	1	S_{11}, S_{21}, S_{12}, S_{22}

Self-Calibration Algorithms: SOLR

- Advantages
  - Does not require known Thru
  - Self-consistent
- Drawbacks
  - All lumped standards (Open, Short, Load) should be either ideal or known

Self-Calibration Algorithms: QSOLT [9, 10]

Standards	Requirements	Unknown	Error Terms	Self-Calibration Product
SHORT	Known: S_{11}, S_{22}	---	1	---
OPEN	Known: S_{11}, S_{22}	---	1	---
LOAD	Known: S_{11}, S_{22}	---	1	---
THRU	Known: S_{11}, S_{21}, S_{12}, S_{22}	---	4	---

Self-Calibration Algorithms: QSOLT

- Advantages
  - Reduced calibration time
  - Improved quality of transmission measurements (vs. SOLT)
- Drawbacks
  - Poor measurement accuracy on the “virtually” calibrated port
  - Not self-consistent

Self-Calibration Algorithms: LRRM [11]

Standards	Requirements	Unknown	Error Terms	Self-Calibration Product
THRU	Known: S_{11}, S_{21}, S_{12}, S_{22}	---	4	---
REFLECT (as Open)	$S_{11}=S_{22}$ $S_{11}(S_{22})$ known within +/- 90 degree	S_{11} (S_{22})	1	S_{11} (S_{22})
REFLECT (as Short)	$S_{11}=S_{22}$ $S_{11}(S_{22})$ known within +/- 90 degree	S_{11} (S_{22})	1	S_{11} (S_{22})
MATCH (Load)	Known: S_{11} Not measured on the second port	---	1	---

Self-Calibration Algorithms: LRRM

- Advantages
  - Not sensitive to the Load asymmetry (only one Load is measured)
  - Does not require known Open and Short
  - Impedance element can be used as Load
  - Self-consistent
- Drawbacks
  - Poor measurement accuracy on second port
  - Sensitive to the measurement setup asymmetry
  - Requires known Load
  - Sensitive to the Reflect asymmetries

Self-Calibration Algorithms: LRM+ [12]

Standards	Requirements/ Conditions	Unknown	Error Terms	Self-Calibration Product
LINE (Thru)	Known: S_{11}, S_{21}, S_{12}, S_{22}	---	4	---
MATCH (Load)	Known: S_{11}, S_{22} $S_{11} \neq S_{22}$ Arbitrary impedance	---	2	---
REFLECT	$S_{11}=S_{22}$ S_{11}(S_{22}) known within +/- 90 degree	S_{11} (S_{22})	1	S_{11} (S_{22})

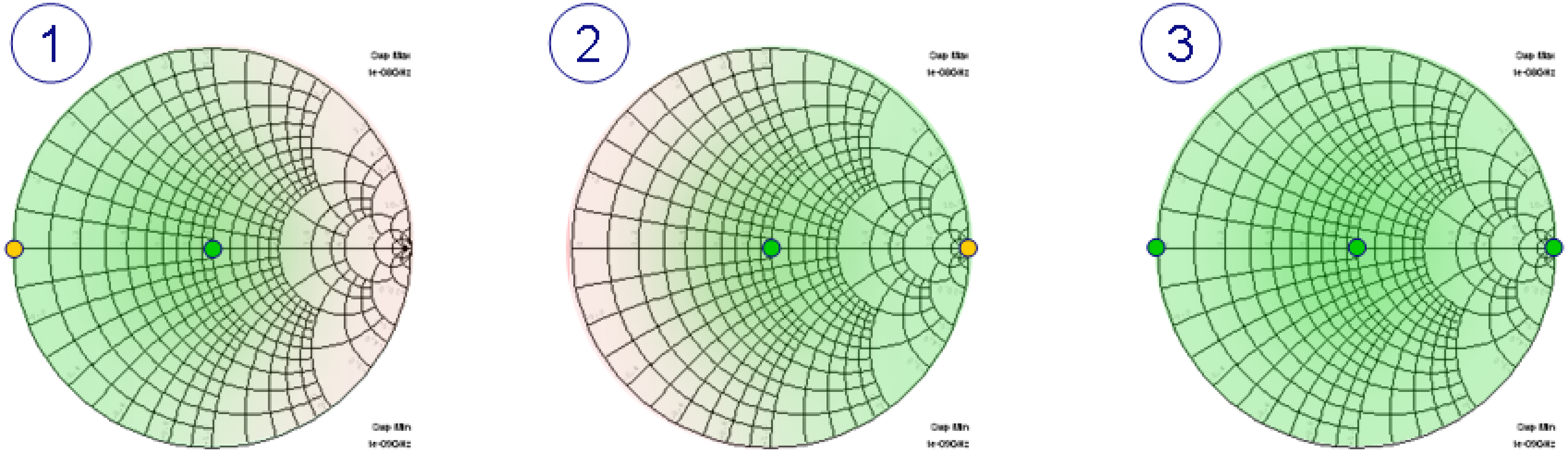
EuMIC 2008
SÜSS MicroTec
38TH EUROPEAN MICROWAVE CONFERENCE 2008

Self-Calibration Algorithms: LRM+

- Advantages
  - Not sensitive to Load asymmetry
  - Arbitrary impedance elements can be used as Loads
  - Does not require known Open or Short
  - Self-consistent
- Drawbacks
  - Requires known Loads
  - Sensitive to Reflect asymmetry

Self-Calibration Algorithms: RRMT [13]

- RRMT concept: merge the best from 10- and 7-Term calibration in one



7-Term step: LRM+ with Short:
→ Model of the Short

7-Term step: LRM+ with Open:
→ Model of the Open

10-Term step: calibration with fully known standards

Self-Calibration Algorithms: RRMT

Standards	Requirements	Unknown	Self-Calibration Product
THRU	Known: S_{11}, S_{21}, S_{12}, S_{22}	---	---
REFLECT (as Open)	$S_{11}=S_{22}$ $S_{11}(S_{22})$ known within +/- 90 degree	S_{11} (S_{22})	S_{11} (S_{22})
REFLECT (as Short)	$S_{11}=S_{22}$ $S_{11}(S_{22})$ known within +/- 90 degree	S_{11} (S_{22})	S_{11} (S_{22})
MATCH (Load)	Known: S_{11}, S_{22} $S_{11} \neq S_{22}$ Arbitrary impedance	---	---

Self-Calibration Algorithms: RRMT

- Advantages
  - Robust 10-Terms calibration algorithm
  - Not sensitive to the Load asymmetry
  - Arbitrary impedance elements can be used as Loads
  - Does not require known Open or Short
  - Self-consistent
- Drawbacks
  - Requires known Loads
  - Sensitive to Reflect asymmetry

Outline

- What is VNA Calibration?
- Measurement Errors
- Error Models
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

Residual Calibration Errors

- Calibration standards should fit requirements:

THRU	LINE*	OPEN	SHORT	LOAD (MATCH)	REFLECT	RECIPROC
Known: S_{11}, S_{21}, S_{12}, S_{22}	Known: S_{11}, S_{22}; length	Known: S_{11} (S_{22})	Known: S_{11} (S_{22})	Known: S_{11}** (S_{22})	$S_{11}=S_{22}$ $S_{11}(S_{22})$ known within +/- 90 degree	$S_{21}=S_{12}$ $S_{21}(S_{12})$ known within +/- 90 degree

- Standard fabrication tolerances, as well as insufficient models lead to residual calibration errors [14]

*For TRL

**50 Ohm for conventional LRM

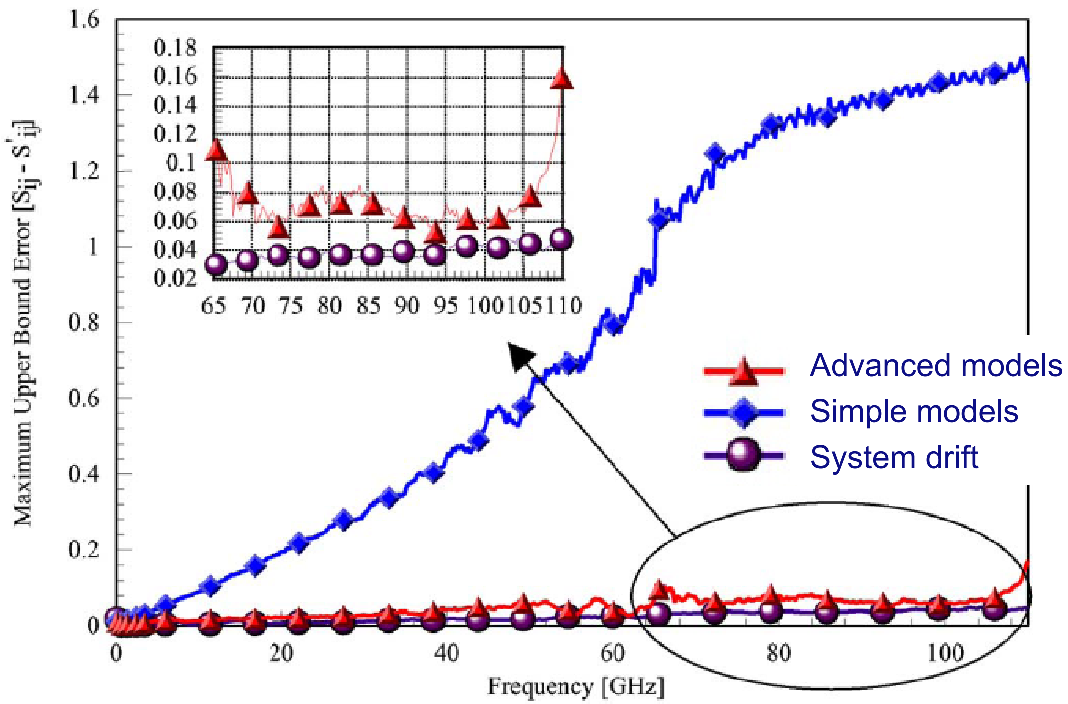
EuMIC 2008

SÜSS MicroTec

38th European Microwave Conference 2008

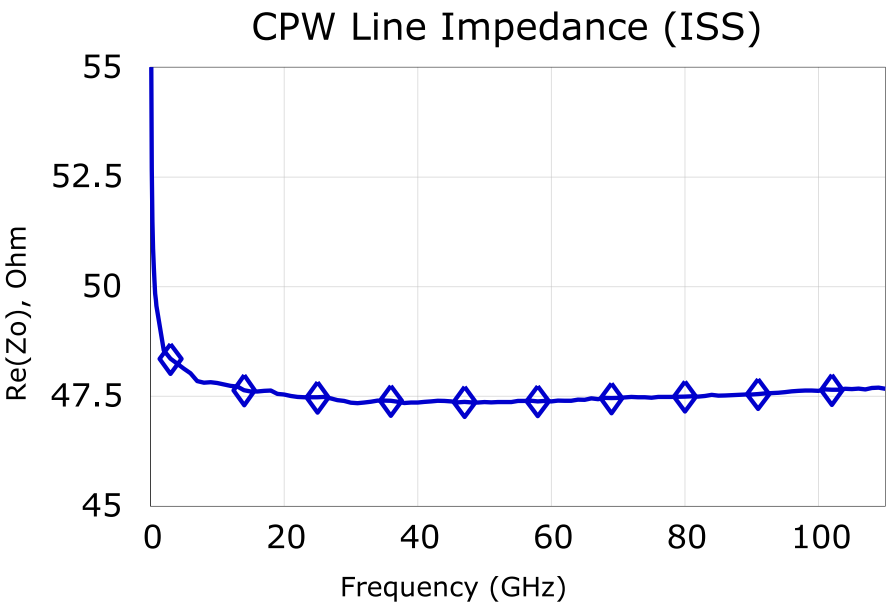
Residual Calibration Errors: SOLT

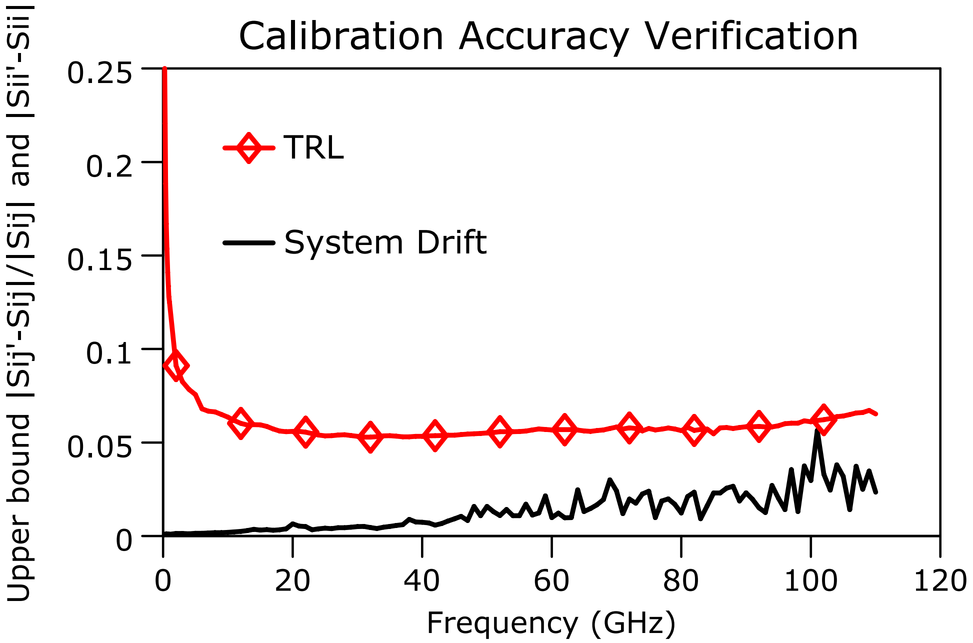
- SOLT on GaAs with simplified and advanced models for Open, Short and Load [15]



Residual Calibration Errors: TRL

- CPW TRL (4 Lines) on ISS with respect to the 50 Ohm calibration [16, 17]

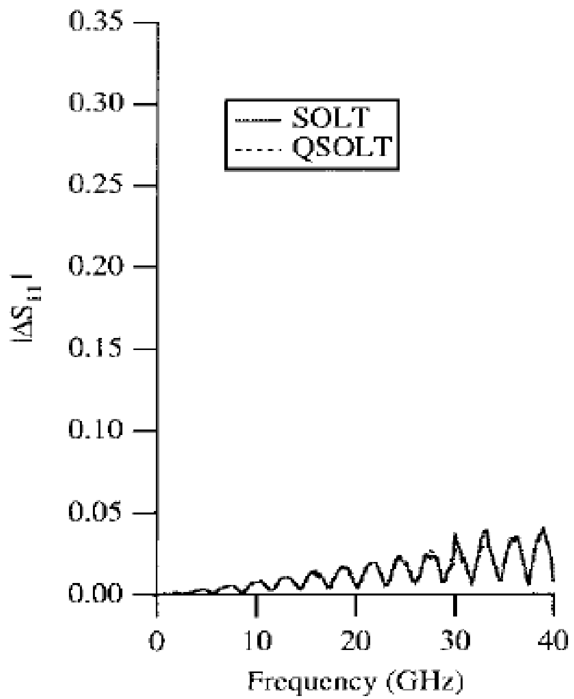




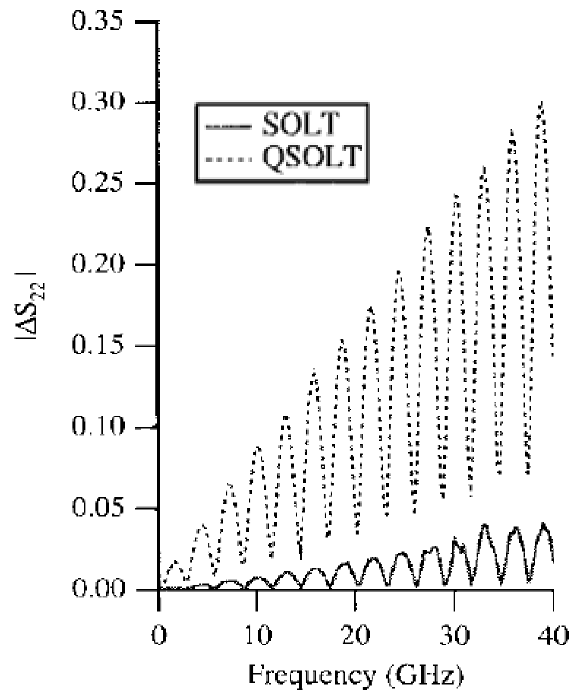
Residual Calibration Errors: QSOLT

- QSOLT and SOLT with the same set of coaxial standards [18]

Port 1, Calibrated

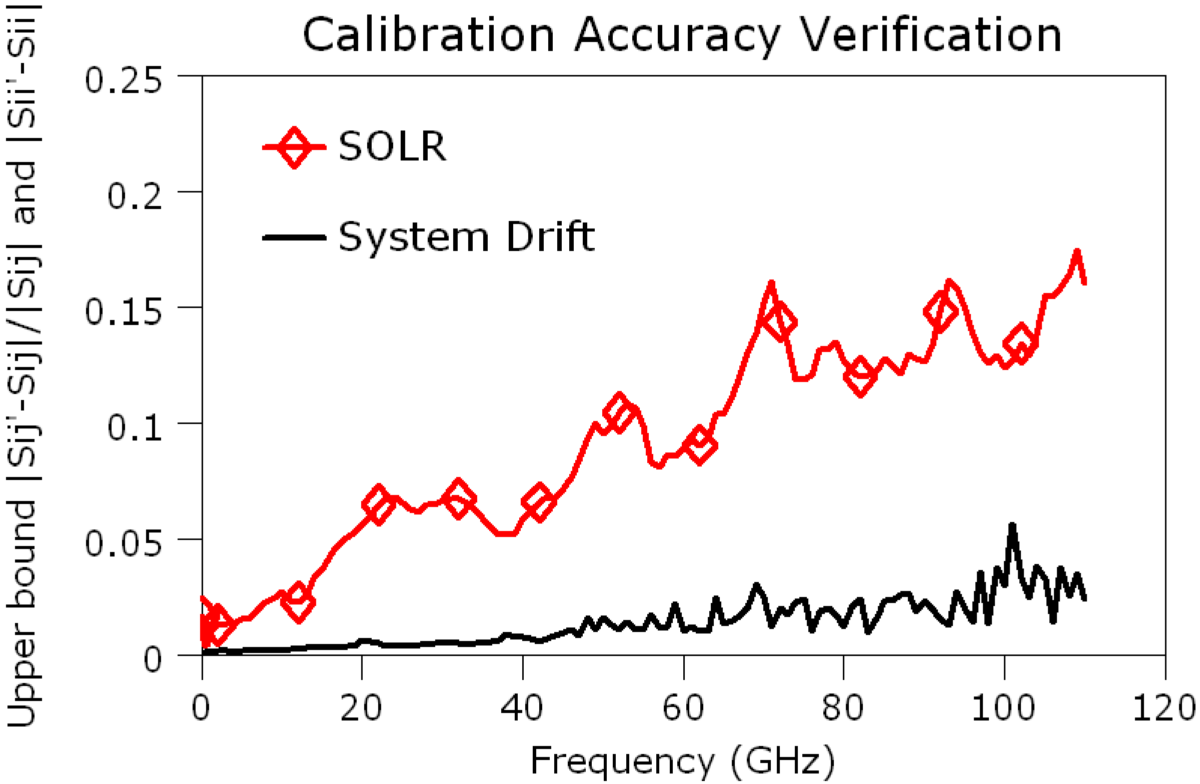


Port 2, "Virtually" Calibrated



Residual Calibration Errors: SOLR

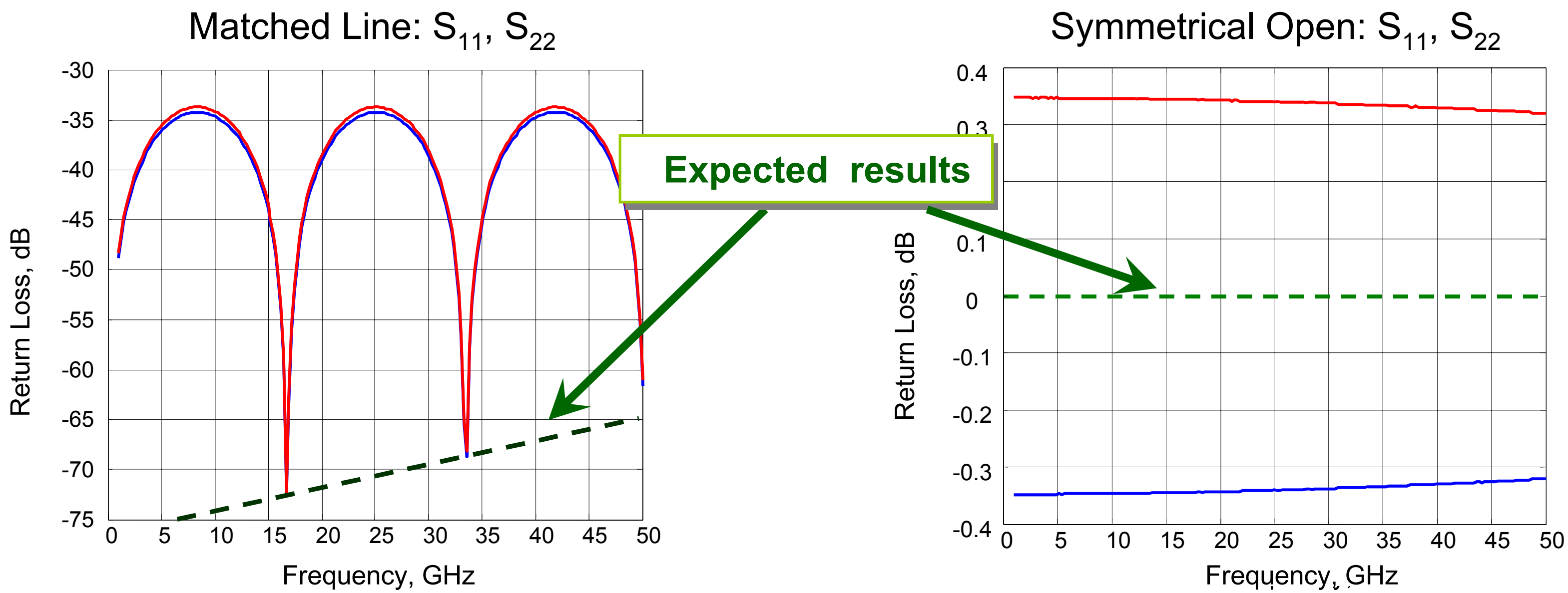
- SOLR on alumina with respect to 50 Ohm multiline TRL [17]



EuMIC 2008
SÜSS MicroTec
38TH EUROPEAN MICROWAVE CONFERENCE 2008

Residual Calibration Errors: LRM

- Load's asymmetry for LRM* with:
  - Load, Port 1: R=51 Ohm, X=0
  - Load, Port 2: R=49 Ohm, X=0
  - Short as reflect



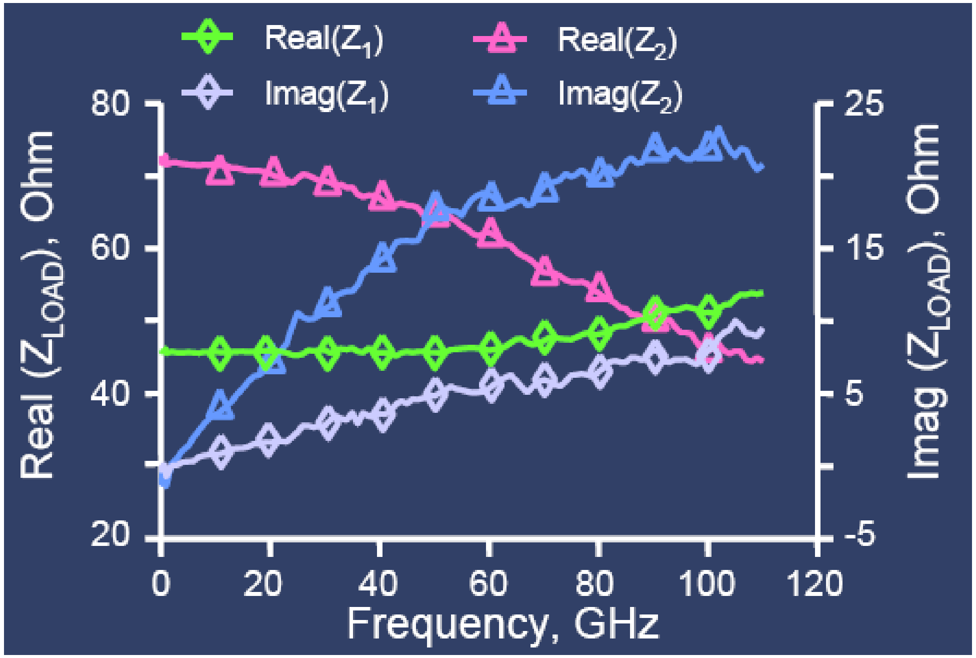
*Simulated results

EuMIC 2008
SÜSS MicroTec
38TH EUROPEAN MICROWAVE CONFERENCE 2008

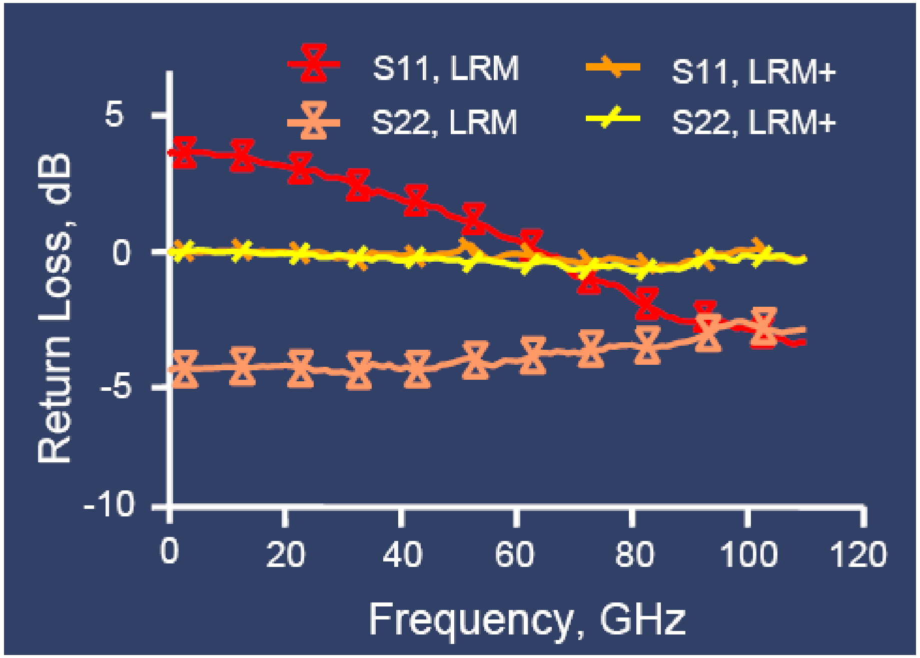
Residual Calibration Errors: LRM, LRM+

- Load's asymmetry for LRM and LRM+ (Short as reflect) on GaAs RM8130 [19]

Load Impedance



Symmetrical Open



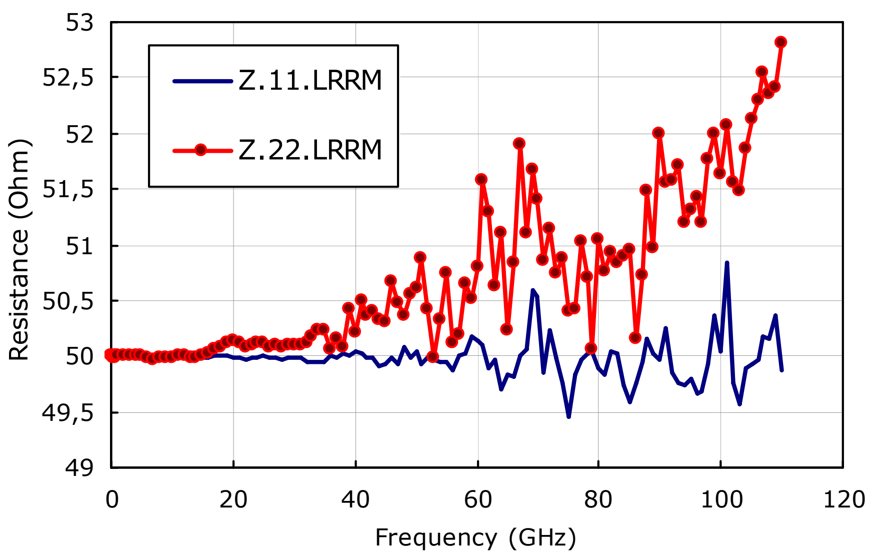
EuMIC 2008

SÜSS MicroTec

38TH EUROPEAN MICROWAVE CONFERENCE 2008

Residual Calibration Errors: LRRM

- System reference impedance Z_0 after enhanced LRRM* (with the Load measured on the VNA Port 1) on ISS [20]
- Verification measurements:
  - the same matched (50 Ohm) DUT, measured at Port 1, Port 2



$$S = \frac{Z_{DUT} - Z_0}{Z_{DUT} + Z_0}$$

$$Z_{0,PORT\,2} \neq 50$$

$$S_{DUT,PORT\,2} = ?$$

EuMIC 2008 SÜSS MicroTec 38th European Microwave Conference 2008

Outline

- What is VNA Calibration?
- Measurement Errors
- Error Models
- Calibration
- Self-Calibration Algorithms
- Residual Calibration Errors
- Conclusion

Conclusion

- VNA calibration removes systematic measurement errors and instrument drift
- Difficulties in standard realization and modeling can be solved by self-calibration procedures
- “Virtual” calibration leads to poor measurement accuracy
- All VNA port should be calibrated using real standards
- Optimal calibration algorithm can be found for each measurement applications and system configuration

References

[1] "International vocabulary of basic and general terms used in metrology," 2ed: International Organization for Standardization, 1993.

[2] A. Rumiantsev and N. Ridler, "VNA calibration," Microwave Magazine, IEEE, vol. 9, pp. 86-99, 2008.

[3] H. Heuermann, "GSOLT: the calibration procedure for all multi-port vector network analyzers," in *Microwave Symposium Digest, MTT-S International*, 2003, pp. 1815-1818.

[4] H. J. Eul and B. Schiek, "A generalized theory and new calibration procedures for network analyzer self-calibration," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 39, pp. 724-731, 1991.

[5] H. Heuermann, "Multi-port calibration techniques for differential parameter measurements with network analyzers," in European Microwave Conference, 33rd, Rohde and Schwarz Workshop, 2003, pp. 1-6.

[6] G. F. Engen and C. A. Hoer, "Thru-Reflect-Line: an improved technique for calibrating the dual six-port automatic network analyzer," Microwave Theory and Techniques, IEEE Transactions on, vol. 27, pp. 987-993, 1979.

[7] H. J. Eul and B. Schiek, "Thru-Match-Reflect: one result of a rigorous theory for de-embedding and network analyzer calibration," in *European Microwave Conference, 18th*, B. Schiek, Ed., 1988, pp. 909-914.

[8] A. Ferrero and U. Pisani, "Two-port network analyzer calibration using an unknown `thru'," Microwave and Guided Wave Letters, IEEE, vol. 2, pp. 505-507, 1992.

References (cont).

[9] A. Ferrero and U. Pisani, "QSOLT: a new fast calibration algorithm for two port S parameter measurements," in ARFTG Microwave Measurements Conference-Fall, 38th, 1991, pp. 15-24.

[10] H. J. Eul and B. Schiek, "Reducing the number of calibration standards for network analyzer calibration," Instrumentation and Measurement, IEEE Transactions on, vol. 40, pp. 732-735, 1991.

[11] A. Davidson, K. Jones, and E. Strid, "LRM and LRRM calibrations with automatic determination of load inductance," in ARFTG Microwave Measurements Conference-Fall, 36th, 1990, pp. 57-63.

[12] R. F. Scholz, F. Korndorfer, B. Senapati, and A. Rumiantsev, "Advanced technique for broadband on-wafer RF device characterization," in ARFTG Microwave Measurements Conference-Spring, 63rd, 2004, pp. 83-90.

[13] H. Heuermann, A. Rumiantsev, and S. Schott, "Advanced on-wafer multiport calibration methods for mono- and mixed-mode device characterization," in ARFTG Microwave Measurements Conference-Spring, 63rd, 2004, pp. 91-96.

[14] A.Rumiantsev, “Calibration uncertainty estimation for the S-parameter measurements at the wafer level”, MTT-S International Microwave Symposium Workshop WMN “Applications and misapplications of measurement uncertainty”, Atlanta, Juni 2008.

[15] S. Padmanabhan, L. Dunleavy, J. E. Daniel, A. Rodriguez, and P. L. Kirby, "Broadband space conservative on-wafer network analyzer calibrations with more complex load and thru models," Microwave Theory and Techniques, IEEE Transactions on, vol. 54, pp. 3583-3593, 2006.

References (cont).

[16] A. Rumiantsev, R. Doerner, and S. Thies, "Calibration standards verification procedure using the calibration comparison technique," in 36th European Microwave Conference, 2006, pp. 489-491.

[17] "RF & microwave test solutions," in Application overview OT Thiendorf, Germany: SUSS MicroTec Test Systems GmbH, 2006.

[18] J. A. Jargon, R. B. Marks, and D. K. Rytting, "Robust SOLT and alternative calibrations for four-sampler vector network analyzers," Microwave Theory and Techniques, IEEE Transactions on, vol. 47, pp. 2008-2013, 1999.

[19] R. Doerner and A. Rumiantsev, "Verification of the wafer-level LRM+ calibration technique for GaAs applications up to 110 GHz," in ARFTG Microwave Measurements Conference-Spring, 65th, 2005, pp. 15-19.

[20] R. Doerner, "Evaluation of wafer-level LRRM and LRM+ calibration techniques," in ARFTG Microwave Measurements Conference-Spring, 69th, 2007, pp. 86-89.