On-wafer residual error correction through adaptive filtering of verification line measurements

Uwe Arz[1], Aleksandr Savin[2]

[1]*Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany*
[2]*Tomsk State University of Control Systems and Radioelectronics, 634050, Tomsk, Russia*
uwe.arz@ptb.de

***Abstract*— In this paper we compare the performance of a residual error correction algorithm against the performance of its predecessor and investigate its ability to second-order correct on-wafer calibrations which are widely used in industry. Independent of the calibration standard definition and the calibration method used, consistent results are obtained after applying the residual error correction.**

I. Introduction

We investigate the performance of an algorithm for the estimation of complex residual errors of a calibrated two-port vector network analyzer (VNA) requiring only one planar transmission line as verification device. The algorithm is applied to correct calibrations on a commercially available on-wafer calibration substrate (CS-5 from GGB Industries, Inc.) in a frequency range up to 110 GHz. Several calibration schemes, including Short-Open-Load-Thru (SOLT), Line-Reflect-Match (LRM) and Line-Reflect-Reflect-Match (LRRM), have been examined with both manufacturer-provided and characterized definitions of the calibration standards.

II. Residual Errors Determination

The original algorithm for estimating the frequency characteristics of the complex residual error model was developed using the Markov theory of nonlinear filtering and based on the unscented transformation, also known as Unscented Kalman Filter [1], [2]. The method presented in [3] proposes residual error correction by performing a second-order calibration to a pre-calibrated VNA, as shown in Fig. 1.

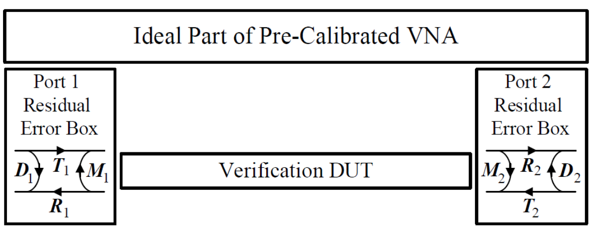


Fig. 1. Model of a pre-calibrated 2-port VNA.

The estimation of the residual errors D_i, T_iR_i, M_i ($i = 1, 2$) can be completed using only one verification element, such as a sufficiently long transmission line with known characteristic impedance and propagation constant . The measurement sequence consists of three steps (see Fig. 2): a two-port measurement with both microwave probes contacting the verification line, and two one-port measurements with only one probe contacting at either end of the line, leaving the respective other end of the line open.

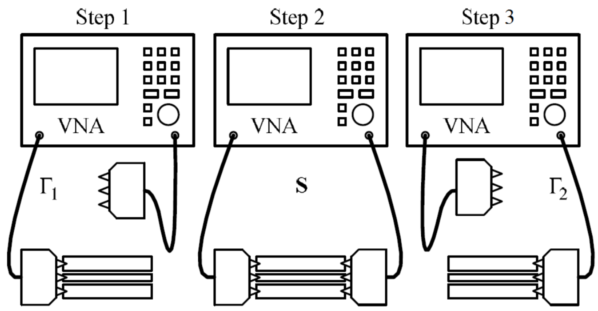


Fig. 2. Verification measurement steps.

Here, we used a coplanar line with a length of 6600 μm built on the CS-5 substrate as verification element. For the measurements, GGB probes with 100 μm pitch width and ground-signal-ground footprint were employed. To investigate the performance of the algorithm after second-order correction of the residual errors, a different line with a length of 1500 μm was utilized as device under test (DUT).

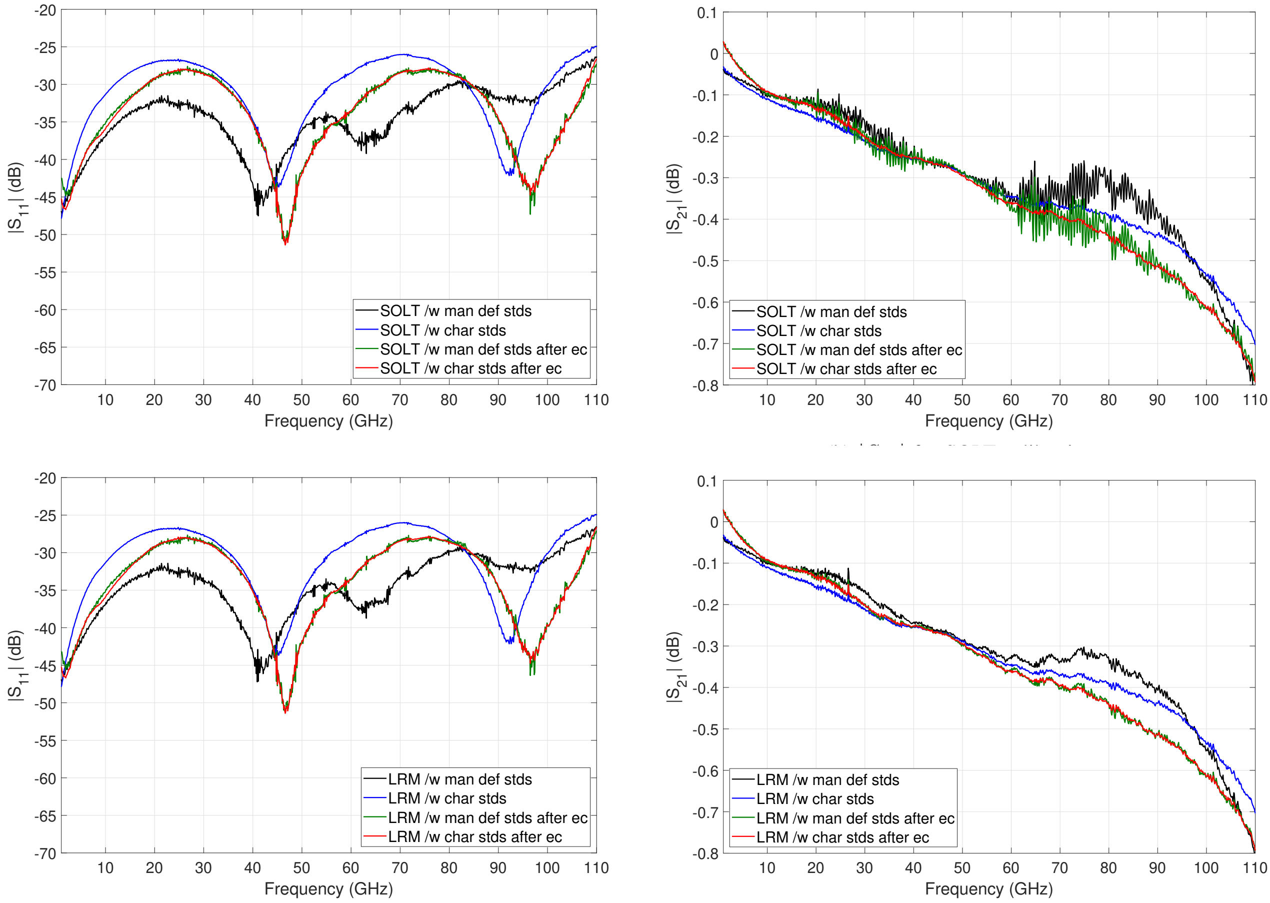
A newer and much faster version of [3] based on solving a linear model with the least-square-method (LMS) was introduced in [4]. In addition to filtering in the time domain, adaptive post-processing is applied as described in [3].

III. Computational Aspects

For simplicity, the algorithms of [3] (UKF) and [4] (LMS) were evaluated for only one residual error (directivity). The number of frequency points was 1000. The simulation was performed on a PC with the following characteristics: Intel Core i7-2630QM (2 GHz, 6 MB cache), 6 GB RAM. The results are given in the following.

- UKF: 54.2 s for measurements processing, 62.3 s total
- LMS: 0.57 ms for measurements processing, 346 ms total

Hence, the LMS algorithm processes the measurements approximately 100k times faster. The total time is the processing time plus the time for the formation of all necessary matrices. Matrices can be generated in advance and used for processing of subsequent data. When changing the number of residual errors or the number of points in frequency, the calculation time varies proportionally.



(c) $|S_{11}|$ for LRM calibrations.

(d) $|S_{21}|$ for LRM calibrations.

Fig. 3. Magnitude of corrected S-parameters of 1500 μm long line built on commercial CS-5 substrate.

IV. Results and Discussion

Figure 3 demonstrates the performance of the algorithm of [4] for SOLT and LRM calibrations when using both manufacturer-defined calibration standards (in black) and characterized calibration standards (in blue) for correcting the raw S-parameter measurements of the DUT. The results after second-order correction are shown in green for the manufacturer-defined calibration standards, and in red for the characterized calibration standards, respectively.

In all four cases shown in Fig. 3, the results after applying the second-order correction are in very good agreement. The results are almost independent of the calibration standard definition and the type of calibration used (LRRM not shown here for the sake of brevity), which proves the consistency of the algorithm. It should be noted that at the edges of the frequency range (ca. 5% of the frequency band), the error of the filtering algorithm increases. This applies to measurements of both transmission and reflection coefficients. The effect can be reduced by applying a verification line with a longer length.

V. Conclusions

In summary, we have demonstrated that the adaptive algorithm for second-order correction can be used to further improve on a variety of calibration algorithms and calibration standard definitions, yielding consistent results only perturbed by the noise in the original data. Compared to its predecessor, the current LMS-based algorithm is several orders of magnitude faster.

Acknowledgment

The authors acknowledge support by the European Metrology Programme for Innovation and Research (EMPIR) Project 14IND02 “Microwave measurements for planar circuits and components”. The EMPIR program is co-financed by the participating countries and from the European Union’s Horizon 2020 research and innovation program.

References

[1] S. Julier, J. Uhlmann, and H. Durrant-Whyte, “A new approach for filtering nonlinear systems,” *Proceedings of the American Control Conference*, vol. 3, pp. 1628–1632, Jun. 1995.

[2] S. Julier and J. Uhlmann, “Unscented filtering and nonlinear estimation,” *Proceedings of the IEEE*, vol. 92, no. 3, pp. 401–422, Mar. 2004.

[3] A. A. Savin, V. G. Guba, A. Rumiantsev, B. D. Maxson, D. Schubert, and U. Arz, “Adaptive estimation of complex calibration residual errors of wafer-level S-parameters measurement system,” in *84th ARFTG Microwave Measurement Conference*, Boulder, USA, 2014, pp. 1–4.

[4] A. A. Savin, “Second-order error correction of a pre-calibrated vector network analyzer for wafer-level measurements,” in *Proceedings of the 47th European Microwave Conference*, Nuremberg, Germany, 2017, pp. 743–746.