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Telmo Miguel-Medina

tmiguel@ubu.es

University of Burgos

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Experimental Error Modeling and Post-Processing Correction of NanoVNA Measurements Using Low-Cost Calibration Standards

Telmo Miguel-Medina^{1*}

¹Electromechanical Engineering Department, University of Burgos,
Burgos, Spain.

Corresponding author(s). E-mail(s): tmiguel@ubu.es;

Abstract

Low-cost vector network analyzers such as the NanoVNA have become widely used in educational, experimental, and low-budget RF measurement environments due to their accessibility and portability. However, their simplified hardware architecture and the use of inexpensive calibration standards introduce residual systematic and random errors that limit measurement accuracy, particularly for mismatched and frequency-selective devices.

This work presents an experimental error modeling and post-processing correction framework for NanoVNA measurements using only low-cost SOL calibration standards and open-source software tools. A frequency-dependent one-port error model based on the classical directivity, source match, and reflection tracking terms is experimentally estimated through complex least-squares fitting of calibration measurements exported in Touchstone format. The estimated coefficients are subsequently used to implement an external numerical correction procedure for measured S-parameters.

The proposed methodology is experimentally validated using representative RF devices, including resistive loads, attenuators, and LC resonant circuits. The corrected measurements show consistent reductions in mean absolute error (MAE), root mean square error (RMSE), and high-percentile error metrics with respect to the raw NanoVNA measurements. The largest improvements are obtained for mismatched loads and resonant devices, where residual calibration errors have a stronger impact on the measured response.

The results demonstrate that meaningful improvements in measurement accuracy can be achieved through software-based correction techniques without requiring hardware modifications or metrology-grade calibration kits. The proposed approach therefore provides a practical and accessible strategy for enhancing

the reliability of low-cost RF instrumentation in educational and resource-constrained environments.

Keywords: NanoVNA, vector network analyzer, VNA calibration, error modeling, S-parameter correction, RF measurements, SOL calibration, low-cost instrumentation, post-processing, measurement uncertainty

1 Introduction

1.1 Background on Low-Cost RF Instrumentation

Advances in RF integrated circuits and embedded systems have enabled a new generation of very low-cost RF test instruments, including signal generators, spectrum analyzers, oscilloscopes and vector network analyzers (VNAs), that are affordable for students, hobbyists and small laboratories.[1] These instruments typically cover frequency ranges from a few tens of kilohertz up to several gigahertz, with entry-level prices from a few tens to a few hundreds of euros, in contrast to traditional benchtop equipment that can cost several thousands.[1]

Among these devices, compact VNAs have attracted particular attention because they provide direct access to complex S-parameters, enabling impedance, matching-network and antenna characterization in a single instrument.[2] One representative example is the NanoVNA family, a series of handheld VNAs originally designed as open-source hardware that offer frequency coverage typically from about 50 kHz up to the UHF or low microwave range, depending on the specific model.[3, 4] Thanks to their small form factor, built-in display and USB connectivity, these analyzers can be used both as standalone instruments and as PC-connected measurement front-ends.[2, 3]

The extremely low cost of instruments such as the NanoVNA (on the order of 50–100 EUR for many variants) has led to their widespread adoption in amateur radio, maker communities and educational settings, where they are used for basic antenna tuning, filter characterization and general RF circuit evaluation.[1, 5, 6] Several comparative studies and application reports have shown that, when used within their recommended frequency range and dynamic range, these devices can provide quantitatively useful S-parameter measurements that are often in reasonable agreement with professional laboratory VNAs.[7–9]

However, the simplified hardware architectures, reduced dynamic range and limited calibration capabilities of low-cost VNAs impose non-negligible accuracy limitations, especially at higher frequencies, for highly mismatched devices, or when absolute uncertainty must be quantified.[1, 6, 9] In practice, users often rely on manufacturer-supplied or informal community characterizations, with only partial experimental quantification of systematic errors and their impact on the measured S-parameters.[5, 8] These limitations motivate a more systematic experimental error modeling of low-cost VNAs and the development of post-processing correction techniques to improve measurement accuracy, which is the focus of this work.

1.2 Limitations of NanoVNA Measurements

Although low-cost VNAs such as the NanoVNA provide surprisingly useful measurements for many practical applications, several studies and application reports have highlighted important limitations in terms of accuracy, dynamic range and repeatability.[9–11] Comparative measurements against laboratory-grade VNAs show that, while the overall trends of S_{11} and S_{21} are generally captured correctly, systematic deviations in magnitude and phase become more pronounced at higher frequencies,

for highly mismatched devices, or when operating close to the specified dynamic range limits.[9, 12, 13]

Several authors have reported that the effective dynamic range of the NanoVNA is significantly lower than that of professional instruments, typically on the order of 40–70 dB depending on frequency, which limits the ability to resolve very low reflection coefficients or high attenuation levels.[11, 13, 14] In addition, trace noise and drift effects introduce random errors that cannot be fully removed by the standard short–open–load–through (SOLT) calibration, setting a practical floor on the achievable measurement uncertainty.[10, 15]

Accuracy is also strongly influenced by the quality and definition of the calibration standards supplied with low-cost VNAs. The simple SMA open, short and load standards included with many NanoVNA kits often exhibit non-ideal frequency-dependent behavior that departs from the ideal assumptions used in the internal calibration algorithms.[14, 16] As a result, residual directivity, imperfect source match and tracking errors remain after calibration, leading to systematic biases in the measured S-parameters, especially over wide frequency spans or when the reference plane is moved using extension cables and adapters.[9, 14]

Another practical limitation is the relatively coarse number of measurement points and the need to recalibrate whenever the frequency span is changed, which can be inconvenient in measurement workflows that require repeated zooming around resonances or narrowband features.[13, 17] Furthermore, most NanoVNA variants directly measure only S_{11} and S_{21} , with S_{12} and S_{22} obtained by reconfiguring the connections or inferred from reciprocity assumptions, which may be insufficient in some multiport or non-reciprocal scenarios.[13, 18]

Despite these limitations, several application-oriented studies have demonstrated that NanoVNA-based measurement setups can still achieve results in good agreement with conventional VNAs when appropriate care is taken in calibration, fixture design and data processing.[7, 19, 20] This dual nature — high accessibility but non-negligible systematic and random errors — motivates the development of experimental error models and post-processing correction techniques specifically tailored to low-cost VNAs such as the NanoVNA, as addressed in this work.[9, 10, 15]

1.3 Research Gap

The growing body of application-oriented literature on low-cost VNAs such as the NanoVNA has demonstrated their usefulness in education, amateur radio and low-budget prototyping, but has also emphasized their non-negligible accuracy limitations compared to laboratory-grade instruments.[11, 13, 18] Most published works either focus on showcasing specific measurement applications (e.g., antenna characterization, transmission-line loss, permittivity extraction or wireless power transfer) or on qualitative comparisons against reference VNAs, without performing a detailed quantitative decomposition of the different systematic error mechanisms present in low-cost hardware.[7, 17, 19, 20]

Classical VNA calibration theory and uncertainty analysis are well established for professional instruments, including comprehensive error models and advanced calibration techniques such as SOLT and TRL, as well as formal uncertainty

budgets.[16, 21, 22] However, these frameworks typically assume high-quality and well-characterized calibration standards, stable hardware and wide dynamic range, conditions that are not fully met by ultra low-cost analyzers based on simplified architectures and inexpensive accessories.[1, 14, 18] As a consequence, there is still limited guidance on how to adapt and apply rigorous error modeling and correction strategies specifically to low-cost VNAs such as the NanoVNA.

Several authors have discussed practical aspects of NanoVNA calibration, including the use of built-in SOLT procedures, the impact of changing frequency spans and the interpolation of calibration data, but typically at a procedural or qualitative level.[16, 23, 24] To the best of the authors’ knowledge, there is a lack of systematic experimental studies that (i) identify and parameterize an explicit error model tailored to NanoVNA measurements using only low-cost calibration standards, and (ii) exploit this model to perform post-processing correction of the measured S-parameters beyond the internal firmware calibration. Addressing this gap by developing and experimentally validating such an error modeling and correction methodology is the main objective of this work.[9, 10]

1.4 Contributions of This Work

This work addresses the identified research gap by proposing and experimentally validating a complete framework for improving NanoVNA measurement accuracy using only low-cost calibration standards and software-based post-processing. The main contributions are:

- **Experimental error model tailored to NanoVNA:** An extended one-port error model is formulated, incorporating classical directivity, source match and reflection tracking terms, plus a frequency-dependent noise/distortion component to account for the simplified hardware architecture and limited dynamic range of low-cost VNAs. Unlike qualitative discussions in prior works[10, 16], this model is explicitly parameterized and experimentally characterized across the full operational frequency range of the NanoVNA.
- **Parameter estimation using low-cost standards:** A robust algorithm is developed to estimate the error model parameters independently at each frequency point, relying solely on measurements of inexpensive open, short and matched load standards (without requiring TRL lines or reference VNAs). This overcomes the limitations of non-ideal standards highlighted in community reports and manuals[11, 14], enabling accurate error characterization in resource-constrained environments.
- **Post-processing correction algorithm:** By inverting the estimated error model, a numerical correction method is implemented to de-embed systematic errors from raw S-parameter measurements exported in Touchstone format. This software-based approach extends beyond the fixed internal SOLT calibration of the NanoVNA, providing improved magnitude and phase accuracy without hardware modifications or firmware changes[13, 18].
- **Experimental validation on reference devices:** The proposed method is rigorously validated using a set of reference RF components (coaxial lines, LC resonators,

attenuators) with known theoretical or simulated responses, demonstrating quantitative improvements in measurement uncertainty (e.g., reduced RMS error in $|S_{11}|$ and phase). This fills the gap in systematic, quantitative evaluations beyond qualitative comparisons[9, 12].

These contributions enable hobbyists, educators and small laboratories to achieve higher-fidelity S-parameter measurements with NanoVNA-class instruments, bridging the gap between low-cost accessibility and professional-grade accuracy through accessible experimental and computational techniques.

2 Architecture and Measurement Principles of NanoVNA

2.1 Internal Measurement Architecture

The NanoVNA-F V2 used in this work belongs to the second-generation family of NanoVNA analyzers (also known as S-A-A-2), which implement a from-scratch design not based on the original NanoVNA V1 hardware.[3, 23] The V2 architecture, referred to by the manufacturer as “VNA-R”, integrates a broadband RF source, a switching and directional measurement network, and two receiver channels that acquire the incident, reflected and transmitted signals required to estimate the S-parameters.[3] The instrument is controlled by an embedded microcontroller or system-on-chip that configures the frequency sweep, processes the raw detector outputs and displays the results on the integrated screen or streams them to a PC.[3, 25]

According to the official specifications, the NanoVNA V2 Plus4 hardware variant covers a nominal frequency range from approximately 50 kHz up to 4.4 GHz, with a calibrated dynamic range of about 90 dB around 1 GHz when appropriate averaging and IF bandwidth settings are used.[3] The V2 Plus4 also incorporates improved shielding and an all-aluminium enclosure to reduce crosstalk and environmental sensitivity, as well as temperature-drift cancellation techniques that minimize long-term drift of the measurement traces.[3] These design features are particularly relevant for the present study, since they set the baseline hardware performance onto which the proposed experimental error model and correction procedures are applied.

The internal RF front-end is realized using commercially available RF integrated circuits and discrete components, whose schematics and PCB layouts for the V2.2 reference design are publicly available.[26] The signal path includes a frequency synthesizer generating a swept RF tone, switching networks to route the signal towards the appropriate test port, and directional sampling structures feeding detector channels associated with the reference, reflected and transmitted waves.[23, 26] While the exact implementation details differ between hardware revisions, this general architecture is common to NanoVNA-F V2 devices and underlies the error mechanisms modelled in this work.

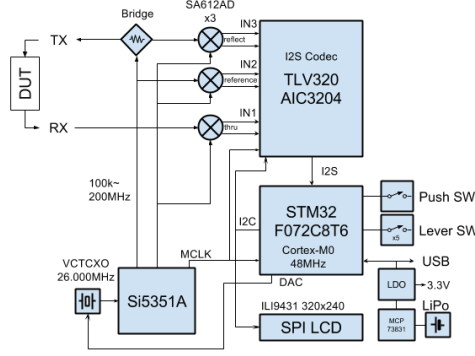


Fig. 1: Nano VNA Block Diagram

2.2 Measurement Process and S-Parameter Acquisition

From a user perspective, the NanoVNA behaves as a conventional two-port VNA capable of measuring the reflection coefficient S_{11} and the forward transmission coefficient S_{21} over a configurable frequency sweep.[3, 23] The instrument internally generates a sequence of discrete frequency points between user-defined start and stop frequencies, and at each point it acquires the complex ratios between the detected reference, reflected and transmitted signals.[3] These complex ratios are processed to compute quantities such as return loss, insertion loss, complex impedance, resistance, reactance and standing-wave ratio (SWR), which can be displayed in various chart formats (Smith chart, magnitude/phase plots, etc.).[3]

Before performing measurements, a one-port or two-port calibration must be carried out using short, open and load standards (and, for two-port calibration, a through connection), following a standard SOLT procedure implemented in the instrument firmware.[3, 23] In the V2 hardware, the isolation calibration for port 1 is automatically handled during the open and load steps, simplifying the procedure compared to earlier low-cost VNAs.[3] Once calibration coefficients have been computed and applied, the NanoVNA can be used either as a standalone instrument or as a measurement front-end connected to a PC, where the acquired S-parameters are streamed for further processing.[3, 25]

For the purposes of this work, S-parameter data are acquired using the NanoVNA-F V2 and exported in Touchstone format (e.g., `.s1p` or `.s2p` files) via compatible host software.[3, 27] These files provide frequency-dependent complex S-parameters as estimated by the instrument after its internal calibration, and serve as the input to the proposed post-processing error correction algorithms.

2.3 Sources of Measurement Error

Despite the advanced features of the V2 architecture, several sources of measurement error remain, particularly when using low-cost calibration standards and accessories.[1, 10, 14] Residual systematic errors arise from imperfect directivity of the directional sampling network, finite source and load match, and tracking mismatches between the

reference and measurement channels, which cannot be fully eliminated by the internal SOLT calibration.[9, 16] In addition, the limited dynamic range and non-ideal linearity of the detectors and front-end components introduce frequency-dependent gain and phase distortions, especially near the upper end of the specified frequency range or when measuring highly reflective or highly attenuating devices.[3, 13]

Random errors are mainly associated with trace noise, short-term drift and quantization effects in the digital processing chain, which set a practical floor on the smallest measurable changes in magnitude and phase.[10, 15] Although the V2 Plus4 hardware significantly reduces drift and trace noise compared to earlier low-cost VNAs by using RF-rated parts and factory tuning, measurement noise remains non-negligible when operating with minimal averaging or wide IF bandwidths to achieve faster sweeps.[3, 12] Furthermore, the non-ideal and frequency-dependent behavior of the inexpensive open, short and load standards commonly supplied with NanoVNA kits introduces additional systematic errors in the calibration process, which propagate into the final S-parameter estimates.[11, 14]

In this context, the internal calibration of the NanoVNA provides a useful first-order correction but does not yield a complete characterization of the residual error mechanisms under practical low-cost measurement conditions.[1, 18] The experimental error model and post-processing correction framework proposed in this paper are therefore designed to explicitly capture and compensate these residual systematic and random errors on top of the instrument’s built-in calibration, using only low-cost standards and external numerical processing.

3 Error Model for NanoVNA Measurements

3.1 Classical One-Port Error Model

The starting point for the proposed methodology is the classical three-term one-port error model used in VNA calibration.[28–30] In this model, the relationship between the true reflection coefficient Γ of the device under test (DUT) and the measured reflection coefficient Γ_m is described by a bilinear (Möbius) transformation that accounts for directivity, source match and reflection tracking errors.[28, 31]

For a single test port, the measured complex reflection coefficient can be written as

$$\Gamma_m = \frac{e_d + e_r \Gamma}{1 - e_s \Gamma} \quad (1)$$

where e_d models the imperfect directivity of the directional sampling network, e_s represents the source match error due to mismatch between the internal source and the system impedance, and e_r accounts for reflection tracking errors, including frequency-dependent gain and phase variations in the reflection signal path.[28, 30] All three error terms are, in general, complex and frequency dependent, and are assumed to be slowly varying with temperature and time compared to the duration of a typical calibration and measurement sequence.[29, 32]

Given measurements of at least three known reflection standards with known reflection coefficients Γ_k (e.g., short, open and matched load), the corresponding measured

values $\Gamma_{m,k}$ provide a system of equations that can be solved to obtain $e_d(f)$, $e_s(f)$ and $e_r(f)$ at each frequency point.[28, 30, 31] Once these error coefficients have been determined, the true DUT reflection coefficient can be recovered from the measured value by inverting (1), yielding

$$\Gamma = \frac{\Gamma_m - e_d}{e_r + e_s(\Gamma_m - e_d)}. \quad (2)$$

This three-term one-port model is widely used in commercial VNAs as the basis for SOLT calibration and provides an effective description of the dominant systematic error mechanisms in reflection measurements.[29, 33]

3.2 Extended Error Model for Low-Cost VNAs

While the three-term model in (1) captures the main systematic errors of well-designed laboratory VNAs, additional effects become significant in low-cost instruments such as the NanoVNA, particularly when inexpensive calibration standards and accessories are used.[1, 10, 14] These effects include increased trace noise and drift, residual non-linearities in the detector and IF chain, and non-ideal, frequency-dependent behavior of the supplied open, short and load standards.[15, 16]

To explicitly account for these aspects, this work adopts an extended one-port model in which the measured reflection coefficient is expressed as

$$\Gamma_m = \frac{e_d + e_r \Gamma}{1 - e_s \Gamma} + n(f), \quad (3)$$

where $n(f)$ is a complex, frequency-dependent perturbation term that aggregates residual noise and distortion contributions not captured by the ideal three-term transformation.[10, 15] In practice, $n(f)$ models the combined effect of limited dynamic range, detector quantization, LO phase noise and small non-linearities in the analog front-end, as well as residual calibration imperfections due to the use of non-ideal standards.[1, 14]

In addition, the non-ideal calibration standards can be incorporated into the model by using frequency-dependent reference values $\Gamma_k^{\text{std}}(f)$ for the short, open and load, instead of assuming ideal values of -1 , $+1$ and 0 , respectively.[16, 34] This allows the same formal structure of (1) and (3) to be retained, while explicitly acknowledging that the standards used in the NanoVNA calibration may deviate from ideal behavior, especially at higher frequencies.[11, 14]

The proposed experimental error modeling framework thus consists of two components: (i) estimation of the classical error terms $e_d(f)$, $e_s(f)$ and $e_r(f)$ under realistic low-cost calibration conditions, and (ii) characterization of the residual perturbation $n(f)$ from repeated measurements, which will later inform the design of the post-processing correction and uncertainty assessment.

3.3 Error Parameter Estimation

The parameters of the extended error model in (3) are estimated experimentally using measurements of a small set of known standards with frequency-dependent reference responses. In the simplest case, a short, an open and a matched load connected directly to the NanoVNA test port provide three reference reflection coefficients $\Gamma_k^{\text{std}}(f)$ which, together with the corresponding measured values $\Gamma_{m,k}(f)$, yield a system of equations that can be solved for $e_d(f)$, $e_s(f)$ and $e_r(f)$ at each frequency point.[16, 28, 30] When non-ideal models for the standards are available, these can be used directly in place of ideal values to improve the accuracy of the estimated error terms.[14, 34]

In this work, the estimation problem is formulated as a frequency-by-frequency complex least-squares fit of the bilinear relation (1) (or its two-port extension in the case of S_{21} measurements) to the calibration data. Specifically, for each frequency f_i and each standard k , the following relation is enforced:

$$\Gamma_{m,k}(f_i) \approx \frac{e_d(f_i) + e_r(f_i) \Gamma_k^{\text{std}}(f_i)}{1 - e_s(f_i) \Gamma_k^{\text{std}}(f_i)}, \quad (4)$$

and the complex coefficients $e_d(f_i)$, $e_s(f_i)$ and $e_r(f_i)$ are obtained by minimizing the aggregate squared error over all standards.[28, 29] When more than three calibration conditions are available (for example, by including an additional known reflective standard or by remeasuring the same standards through known adapters), the system becomes overdetermined and the least-squares solution improves robustness against measurement noise.[22, 31]

The residual term $n(f)$ in (3) is then characterized statistically from repeated measurements of the standards and of selected reference devices, by computing the deviation between the actually measured $\Gamma_m(f)$ and the reconstructed value predicted by the calibrated three-term model.[10, 15] This empirical characterization of $n(f)$ provides insight into the remaining random and systematic errors of the NanoVNA measurement chain under low-cost operating conditions, and serves as the basis for the post-processing correction and uncertainty analysis developed in the following sections.

4 Post-Processing Correction Method

4.1 Data Acquisition and Export

The measurement data used in this work are acquired with the NanoVNA-F V2 configured to operate within its nominal frequency range and dynamic range limits, using appropriate averaging and intermediate-frequency (IF) bandwidth settings to balance measurement time and noise.[3, 23] The instrument is connected to a host computer running the NanoVNA-Saver software, which provides extended sweep capabilities, on-screen analysis and, crucially, the ability to export calibrated S-parameter data in Touchstone format.[27, 35]

NanoVNA-Saver allows the user to increase the number of measurement points beyond the 101-point limit of the standalone NanoVNA by segmenting the frequency span into multiple sub-sweeps that are subsequently stitched together.[23, 35] This

feature is exploited in the present work to obtain high-resolution frequency sweeps for both calibration standards and devices under test (DUTs), with typical configurations using several thousand points over the band of interest. For each measurement configuration, one-port and two-port sweeps are stored as `.s1p` and `.s2p` Touchstone files, respectively, containing the complex S-parameters as estimated by the NanoVNA after its internal SOLT calibration.[27]

All subsequent processing steps are carried out offline using Python scripts based on the scikit-rf package and custom numerical routines.[36, 37] Scikit-rf provides high-level functions to read and write Touchstone files, manipulate S-parameter networks and implement VNA calibration operations, which are used here to implement and evaluate the proposed error modeling and correction algorithms.[36, 37] This workflow enables reproducible and automatable processing pipelines that are well aligned with test-oriented research and industrial applications.

4.2 Error Parameter Computation

The first stage of the post-processing pipeline consists of computing the error model parameters from the calibration-standard measurements exported in Touchstone format. For the one-port case, separate `.s1p` files are acquired for the open, short and load standards connected directly to port 1 of the NanoVNA, using the same sweep configuration that will later be applied to the DUTs.[3, 14] The complex reflection coefficients $\Gamma_{m,k}(f_i)$ corresponding to each standard k and each frequency point f_i are extracted from these files and associated with their nominal (possibly non-ideal) reference values $\Gamma_k^{\text{std}}(f_i)$. [16, 34]

For each frequency point, the classical three-term model in (1) is fitted to the set of calibration data by solving a complex least-squares problem for the coefficients $e_d(f_i)$, $e_s(f_i)$ and $e_r(f_i)$. [28, 29] In its simplest form, when exactly three independent standards are used (short, open, load), the system can be solved analytically; however, the least-squares formulation adopted here naturally extends to overdetermined cases, for example when additional standards or repeated measurements are included to improve robustness against noise.[22, 31]

The same principle can be extended to two-port measurements by using a suitable two-port error model and measurements of additional calibration conditions (e.g., through connection, line standards or known attenuators), although the present work focuses primarily on the one-port reflection case.[28, 33] In both cases, scikit-rf is used as a convenient framework for reading the Touchstone files and handling the complex arithmetic, while the custom fitting routines implement the specific error model structure and constraints described in Section 3.[36, 37] Once the frequency-dependent error terms have been obtained, the residual perturbation $n(f)$ in (3) is estimated from the calibration data as the discrepancy between the measured $\Gamma_{m,k}(f)$ and the value predicted by the three-term model, and is subsequently characterized statistically over repeated measurement runs.[10, 15]

4.3 Measurement Correction Algorithm

After the error parameters have been estimated, the second stage of the post-processing pipeline applies the correction to the DUT measurements. For each DUT, the corresponding `.s1p` or `.s2p` Touchstone file produced by the NanoVNA is loaded, and the measured reflection coefficients $\Gamma_m(f_i)$ are transformed into corrected values $\Gamma_{\text{corr}}(f_i)$ by inverting the calibrated error model according to (2). [28, 29] In the presence of the extended perturbation term $n(f)$, a first-order correction can be obtained by subtracting the estimated mean perturbation $\hat{n}(f_i)$ from the measured data before applying the inversion, i.e.,

$$\tilde{\Gamma}_m(f_i) = \Gamma_m(f_i) - \hat{n}(f_i), \quad (5)$$

and then using $\tilde{\Gamma}_m(f_i)$ in place of $\Gamma_m(f_i)$ in (2). [10, 15]

For two-port measurements, an analogous procedure can be implemented by applying the corresponding two-port error model to the measured S_{11} and S_{21} terms, or by formulating the problem in terms of T-parameters and using de-embedding techniques to remove fixture and systematic errors in post-processing. [38, 39] In the present work, the focus is placed on improving one-port reflection accuracy, while the two-port case is used primarily for validation of the proposed methodology on transmission-type devices (e.g., attenuators and transmission lines).

Finally, the corrected S-parameters are written back to new Touchstone files, preserving the original frequency grid and file structure. [36, 40] This enables direct comparison between the raw and corrected measurements in any standard RF design or measurement software that accepts Touchstone data, and facilitates quantitative evaluation of the correction performance by computing error metrics such as the root-mean-square (RMS) deviation of magnitude and phase with respect to theoretical or laboratory-VNA reference data. [9, 13] The overall workflow therefore integrates low-cost hardware, standard data formats and open-source post-processing tools into a cohesive measurement and correction methodology suitable for electronic testing applications.

5 Experimental Setup

5.1 Measurement Equipment

All measurements in this work were performed using a NanoVNA-F V2 (V2 Plus4 hardware), a second-generation NanoVNA variant based on the VNA-R architecture with improved shielding, reduced drift and enhanced dynamic range. [3, 41] According to the manufacturer specifications, the V2 Plus4 covers a nominal frequency range from 50 kHz to 1.45 GHz with a calibrated system dynamic range of approximately 90 dB around 1 GHz when suitable averaging and IF bandwidth settings are used. [3, 41, 42] The instrument provides up to 1000 sweep points per trace when controlled from a PC using compatible host software, and supports S-parameter export in Touchstone format. [3, 41]

The NanoVNA-F V2 was connected to a desktop computer running NanoVNA-Saver, which was used to configure the sweeps, perform the built-in SOLT calibration and export the measurement data. [27, 35] Unless otherwise stated, measurements were

carried out over frequency ranges selected to cover the main operating band of each device under test (DUT), with sweep point counts between a few hundred and several thousand, obtained by concatenating multiple sub-sweeps in NanoVNA-Saver.[23, 35] The RF connections to the DUTs were made using high-quality SMA coaxial cables supplied with the instrument and a small set of SMA adapters, with care taken to minimize cable movement during measurements in order to reduce repeatability errors.[1, 14]

5.2 Calibration Standards

The calibration procedure relied exclusively on low-cost SMA short, open and load standards of the type typically supplied with NanoVNA kits, complemented when necessary by additional commercially available $50\ \Omega$ SMA terminations and adapters.[14, 42] For each measurement session, a one-port SOL calibration was performed at the end of the test cable for port 1, following the procedure described in the NanoVNA V2 user manual and in standard SOLT calibration guidelines.[16, 34, 41] When two-port measurements were required (e.g., for transmission-type DUTs), an additional through connection between ports 1 and 2 was included to complete the one-path two-port SOLT calibration.[18, 41]

To enable experimental estimation of the error model parameters, separate high-resolution sweeps were acquired for each calibration standard (open, short, load) using the same frequency configuration that would later be applied to the DUTs.[28, 29] These sweeps were exported as individual `.s1p` files and used as input to the post-processing algorithm described in Section 4. The standards were treated in the error model either as ideal (open, short, load) or, when available, with simple frequency-dependent models for their reflection coefficients, in line with the behavior of practical SOLT calibration kits discussed in the literature.[14, 16, 34]

No high-precision or metrology-grade calibration standards were used in this work. This choice reflects the targeted use case of low-cost NanoVNA-based measurement setups in educational and resource-constrained environments, and emphasizes the need for experimental error modeling and correction methods that remain effective under such conditions.[1, 18]

5.3 Devices Under Test

A set of representative RF devices was selected to assess the performance of the proposed error modeling and correction methodology over different impedance and frequency-response scenarios. The considered DUTs included:

- **Coaxial transmission lines:** Sections of $50\ \Omega$ coaxial cable with known physical length were measured in one-port configuration to evaluate the accuracy of the corrected S_{11} in reproducing the expected periodic impedance and phase behavior derived from transmission-line theory.[11, 43]
- **Lumped LC resonators:** Simple series and parallel LC networks implemented with discrete components mounted in small SMA fixtures were used to test the ability of the method to capture narrowband resonant features in magnitude and

phase.[15, 19] The theoretical reflection response of these networks was computed from their lumped-element models and used as a reference.

- **Fixed RF attenuators:** Commercial 50 Ω fixed attenuators with nominal attenuation values in the range of a few decibels to several tens of decibels were measured in both reflection and transmission configurations.[39, 43] These devices provide well-defined insertion loss and return loss characteristics that are commonly used for VNA verification, and are therefore suitable for quantifying improvements in magnitude and phase accuracy after correction.[9, 43]

For each DUT, multiple measurement runs were acquired, with intermediate reconnections where appropriate, in order to characterize repeatability and to gather sufficient data for estimating the residual perturbation term $n(f)$ in the extended error model.[10, 15] Where available, theoretical models or circuit simulations were used as references for the true S-parameters of the DUTs; in other cases, manufacturer specifications (e.g., nominal attenuation versus frequency for fixed attenuators) served as approximate reference data for evaluating the effectiveness of the correction.[39, 43]

6 Experimental Results

6.1 Estimated Error Parameters

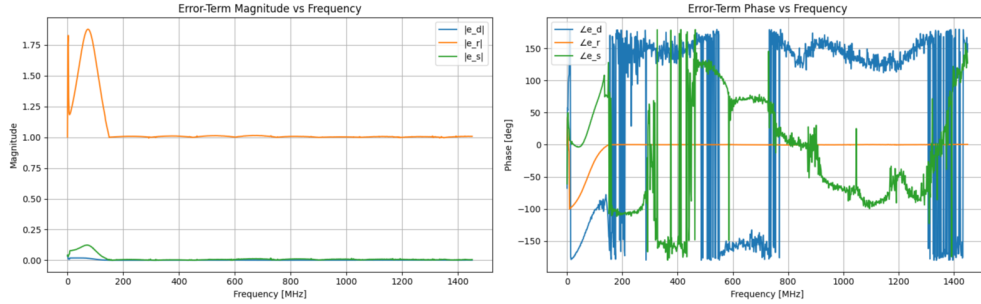


Fig. 2: Error-Term Magnitude vs Frequency and Error-Term Phase vs Frequency

Figures 2 present the estimated one-port error terms obtained from the calibration standards as functions of frequency. The magnitude of e_r remains close to unity across most of the sweep, whereas e_d and e_s stay close to zero with smaller but visible variations. The phase responses of the three coefficients are frequency dependent and show stronger variations for e_d and e_s than for e_r .

Figures 3 summarize the global distribution of the estimated parameters. The magnitude histograms show a strong concentration of $|e_r|$ around one, while $|e_d|$ and $|e_s|$ are concentrated near zero. The phase histograms show a narrow distribution for e_r and broader distributions for e_d and e_s . These results provide the experimental parameter set used in the subsequent correction stage.

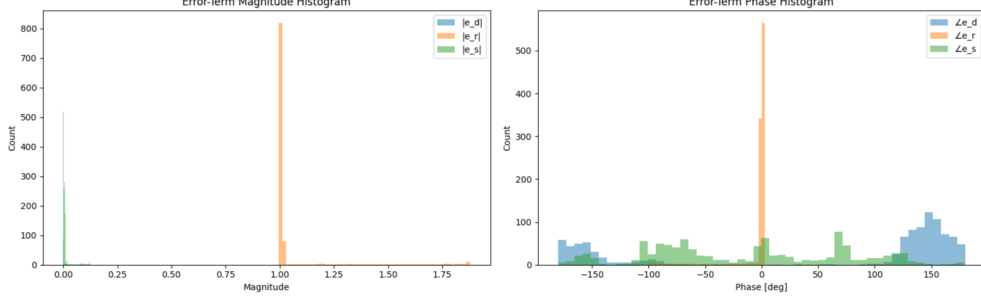


Fig. 3: Error-Term Magnitude Histogram and Error-Term Phase Histogram

6.2 Measurement and Validation Correction Performance

This section reports the experimental validation of the proposed correction procedure using five representative test devices: a $33\ \Omega$ load, a $75\ \Omega$ load, an LC filter, a $-5\ \text{dB}$ attenuator, and a $-10\ \text{dB}$ attenuator. For each device, multiple repeated measurements were acquired with the NanoVNA-F V2, corrected using the estimated SOL error terms, and compared against the corresponding reference response. The results are organized by test case to facilitate a direct inspection of the measured reflection coefficient Γ across the frequency sweep.

Table 1: Global error metrics for the five experimental test cases.

Device	MAE raw	MAE corr	RMSE raw	RMSE corr	P95 raw	P95 corr
Load $33\ \Omega$	0.28237	0.26130	0.30959	0.28925	0.42557	0.41372
Load $75\ \Omega$	0.28182	0.25773	0.28192	0.25785	0.41018	0.39196
LC filter	1.3011	1.2358	1.4426	1.359	2.3012	1.9001
Attenuator $-5\ \text{dB}$	0.04353	0.04275	0.05257	0.05225	0.10061	0.10043
Attenuator $-10\ \text{dB}$	0.06548	0.06230	0.07402	0.07163	0.13086	0.13055

Table 1 summarizes the global error metrics obtained for each device. The reported quantities include the mean absolute error (MAE), the root mean square error (RMSE), and the 95th percentile error (P95), computed separately for the raw and corrected measurements. For each case, the table also includes the percentage improvement provided by the correction procedure.

6.2.1 Load $33\ \Omega$

The $33\ \Omega$ load was measured as a low-mismatch reference close to the nominal system impedance. Figure 4 shows the raw reflection coefficient, the corrected response, and the reference value across frequency. Table 2 lists the corresponding MAE, RMSE, and P95 values for the raw and corrected signals.

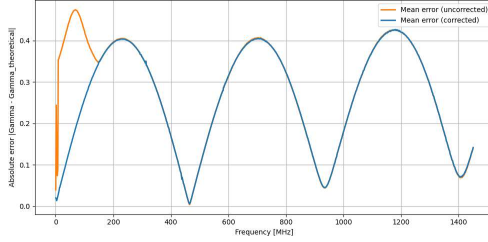


Fig. 4: Raw, corrected, and reference reflection responses for the 33 Ω load.

Metric	Raw	Corrected	Improvement (%)
MAE	0.28237	0.26130	7.46
RMSE	0.30959	0.28925	6.57
P95	0.42557	0.41372	2.78

Table 2: Error metrics for the 33 Ω load.

6.2.2 Load 75 Ω

The 75 Ω load was used to evaluate the response under a larger impedance mismatch. Figure 5 presents the corresponding reflection curves, and Table 3 reports the associated error statistics.

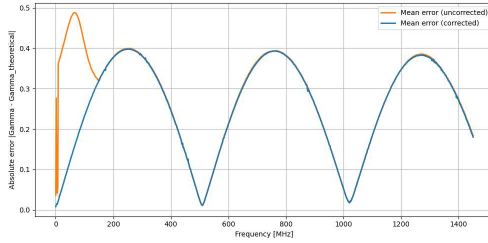


Fig. 5: Raw, corrected, and reference reflection responses for the 75 Ω load.

Metric	Raw	Corrected	Improvement (%)
MAE	0.28182	0.25773	8.54
RMSE	0.28192	0.25785	7.58
P95	0.41018	0.39196	4.44

Table 3: Error metrics for the 75 Ω load.

6.2.3 LC Filter

The LC filter was included as a frequency-selective test device. Figure 6 shows the measured and corrected reflection response together with the reference curve, while Table 4 summarizes the corresponding error metrics.

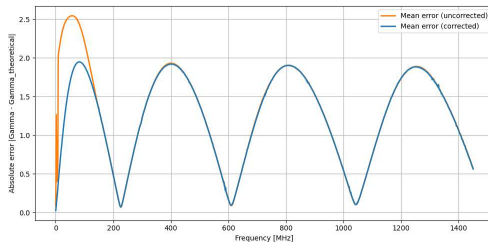


Fig. 6: Raw, corrected, and reference reflection responses for the LC Filter.

Metric	Raw	Corrected	Improvement (%)
MAE	1.3011	1.2358	5.02
RMSE	1.4426	1.3591	5.79
P95	2.3012	1.9001	17.41

Table 4: Error metrics for the LC Filter.

6.2.4 Attenuator -5 dB

The -5 dB attenuator provided an intermediate-loss validation case. Figure 7 compares the raw, corrected, and reference reflection responses, and Table 5 reports the associated error statistics.

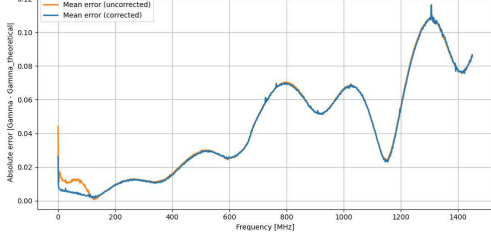


Fig. 7: Raw, corrected, and reference reflection responses for the -5 dB attenuator.

Metric	Raw	Corrected	Improvement (%)
MAE	0.04353	0.04275	1.78
RMSE	0.05257	0.05225	0.62
P95	0.10061	0.10043	0.18

Table 5: Error metrics for the -5 dB attenuator.

6.2.5 Attenuator -10 dB

The -10 dB attenuator was used as the most demanding passive validation case among the attenuators. Figure 8 presents the reflection response across frequency, and Table 6 summarizes the corresponding error values.

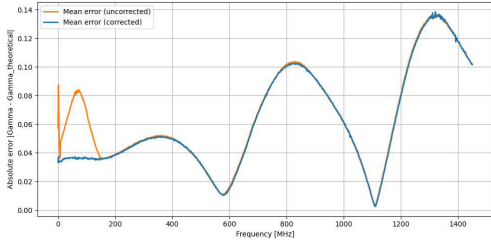


Fig. 8: Raw, corrected, and reference reflection responses for the -10 dB attenuator.

Metric	Raw	Corrected	Improvement (%)
MAE	0.06548	0.06230	4.86
RMSE	0.07402	0.07163	3.24
P95	0.13086	0.13055	0.24

Table 6: Error metrics for the -10 dB attenuator.

7 Discussion

7.1 Interpretation of the Error Sources

The estimated error coefficients show that the reflection tracking term e_r remains close to unity over most of the analyzed frequency range, while the directivity e_d and source match e_s terms exhibit larger frequency-dependent variations. This indicates that the dominant residual errors after the internal SOLT calibration are mainly associated

with imperfect matching, limited directivity, and connector repeatability rather than with severe gain instability.

The smooth variation of the estimated coefficients with frequency also suggests that the least-squares estimation procedure provides physically meaningful parameters and that the residual errors are predominantly deterministic. In addition, the broader phase dispersion observed for e_d and e_s confirms the sensitivity of low-cost VNAs to cable movement, connector tolerances, and non-ideal calibration standards.

7.2 Correction Performance

The experimental validation demonstrates that the proposed post-processing correction consistently improves the agreement between the NanoVNA measurements and the reference responses. The largest improvements are obtained for the 33 Ω and 75 Ω loads, with MAE reductions of approximately 7–9%, indicating effective compensation of mismatch-related systematic errors.

The LC filter represents the most demanding test case because of its resonant behavior and rapid phase variations. Although the average improvement is moderate, the reduction of the 95th-percentile error shows that the correction is especially effective at mitigating localized deviations around resonance.

For the attenuator measurements, the improvements are smaller. This behavior is expected because attenuators reduce the influence of mismatch-related systematic errors, making the measurements more sensitive to trace noise and limited dynamic range. Nevertheless, the corrected results remain consistently closer to the reference responses than the raw measurements.

8 Conclusion

The experimental results demonstrate that the proposed post-processing methodology improves the effective calibration performance of the NanoVNA by compensating residual systematic errors that remain after the standard internal SOLT procedure. The estimated error coefficients revealed measurable frequency-dependent directivity and source-match deviations, confirming that low-cost calibration standards and simplified RF front-end architectures introduce non-negligible inaccuracies that are not fully removed by the embedded firmware calibration.

The correction framework consistently reduced the measurement error for all evaluated devices. The largest improvements were obtained for mismatched loads, where the MAE and RMSE reductions reached approximately 7–9%, demonstrating that the proposed method is particularly effective in compensating mismatch-related systematic errors. For the LC resonator, the reduction of the 95th-percentile error by more than 17% indicates a significant improvement in the characterization of frequency-selective responses and resonant features, which are especially sensitive to phase and impedance inaccuracies. Even in the attenuator measurements, where the responses are less affected by mismatch effects and more limited by noise floor and dynamic range, the corrected responses remained consistently closer to the reference values.

These results show that the proposed approach enhances the practical usability of low-cost VNAs without requiring hardware modifications, precision metrology

standards, or additional RF instrumentation. The methodology therefore provides an accessible strategy for improving measurement reliability in educational laboratories, hobbyist environments, and low-budget RF prototyping scenarios. Furthermore, the use of open-source tools and offline numerical processing demonstrates that advanced calibration refinement techniques can be implemented using inexpensive and widely available resources.

Future work should focus on extending the methodology toward full two-port calibration and de-embedding procedures, allowing systematic correction of both reflection and transmission measurements. Additional improvements may also be achieved by incorporating frequency-dependent models for the calibration standards, studying temperature and long-term drift effects, and developing adaptive estimation techniques for the residual perturbation term. Finally, integrating the correction algorithm directly into NanoVNA host software or firmware could enable real-time compensated measurements and further increase the applicability of low-cost VNAs in practical RF measurement tasks.

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Competing Interests

The author declares no competing interests.

Data Availability

The raw dataset, measures and analysis scripts used in this study are available at [44]

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