Notice for UVNA-63 Application Notes

Application Notes for the UVNA-63 are provided as a guide to help our customers obtain a better understanding of the theory and math behind building a VNA. Each Application Note will provide examples and experiments that describe the functionality and calibration methods to make accurate measurements using a VNA.

Not all technical details are covered in these notes; however customers can find these details in the references mentioned at the end of each Application Note. These notes are not intended to replace technical textbooks.

Each Application Note will state functions that our customers can code using Python/MATLAB with the guidance of the same Application Note. Further details or function descriptions can be found at the following links:

Python: https://www.minicircuits.com/uvnadocs/Python/index.html

MATLAB: https://www.minicircuits.com/uvnadocs/MATLAB/index.html

Also, API commands are available in our Software manual:

https://www.minicircuits.com/pdfs/UVNA-63_Software_and_Programming_Guide.pdf

There may be some prerequisites or knowledge required in order to understand the Application Note. We recommend learning the prerequisites mentioned in the Application Notes before proceeding.

Learning Objectives will be mentioned clearly for particular Application Notes.

UVNA-63 Application Note

Calibration Standards and the SOLT Method

by Nikola Janjušević and Jack Langner
Applications Department

VNA Kit Functions:

`prompt1PortSOL()`, `prompt2PortSOLT()`, `readSNP()`

Module Prerequisites: Error Correction

Learning Objectives

- To understand the purpose of a calibration kit.
- To understand what a calibration method is.
- To understand the difference between data-based and model-based standards.
- To understand the transmission line theory behind the model-based standards.

Introduction

The various error models used to describe a VNA, results in a system of equations that involve using measured and *actual* S-parameters to obtain the model's error terms. Measured S-parameters are obtained at the time of calibration, and are the result of the DUT's parameters, as well as the parameters of each component of the network analyzer. *Actual* S-parameters are the parameters obtained if the DUT was measured with a perfect, error-free measurement tool. It should be noted by the reader that it is impossible to obtain *actual* S-parameters of any component. Any attempt at characterization will result in some degree of inaccuracy and uncertainty due to errors. We settle for using **listed S-parameters** instead of **actual S-parameters**. Listed S-parameters are provided by the supplier of a calibration standard. They may be defined either directly, through data-based standards, or indirectly through model-based standards. The differences between data-based and model-based calibration will be addressed in a later section. A calibration method defines how we use the calibration standards to obtain enough system information to solve for our error correction models.

1 The SOLT Method

A calibration method is a procedure in which a set of standardized components (a calibration kit) are measured and used to construct an error correction model. Before diving into standards definitions, it is important to be familiar with how the standards are used. As mentioned in the *Error Correction Application Note*, common grouping of calibration standards are the short, open, load, and thru components. The short, open, and load (SOL) components are one-port devices that canonically have reflection coefficients of $\Gamma_{short} = -1$, $\Gamma_{open} = 1$, $\Gamma_{load} = 0$. These three components are measured to solve for the 3-term one-port model during vector error correction (VEC). Though any characterized components may be used to solve the error model system of equations, the SOL standards are generally used as they cover a wide range of magnitude and phase. Furthermore, SOL standards are easy to manufacture and, as we'll see shortly, are relatively simple to model.

The ideal thru standard is a zero-length transmission line with no reflection and full transmission. But a real thru standard will have a finite length, impedance mismatch, and transmission loss. This standard is used to obtain most transmission parameters for error models. Other standard groupings (which are used in other calibration methods) opt to employ a fixed length transmission line called a "line" standard.

The SOLT method asks to measure the SOL standards on each portalong with the thru standard between each port. If the ports can be mated together directly, a thru standard is not required. Often times a Network Analyzer will prompt for an optional **isolation measurement**. The isolation measurement is a 2-port measurement of a matched load connected to each port which directly measures the leakage terms of the vector error correction model. This measurement is often listed as optional since the use of the leakage terms can be detrimental when their presence is negligible/beyond the dynamic range of the current measurement setup. These measurements are then used to construct a two-port VEC model (as discussed in the Error Correction Application Note). An example of the SOLT method procedure is provided below. It is taken from the UVNA-63 example code demonstrating Data-Based 2-Port SOLT calibration. The user is prompted to make 7 measurements in order to construct a 12-term VEC model.

```
-- 2-Port Calibration --

>> Measure OPEN @ Port-1:
Recording...Done.

>> Measure SHORT @ Port-1:
Recording...Done.

>> Measure LOAD @ Port-1:
Recording...Done.

-- Switch to Port-2 --
```

```
>> Measure OPEN @ Port-2:
Recording...Done.

>> Measure SHORT @ Port-2:
Recording...Done.

>> Measure LOAD @ Port-2:
Recording...Done.

>> Measure THRU:
Recording...Done.

Constructing 12-Term Error Model...
>> Measure DUT:
```

2 Data Based Standards

Data-based standards are defined by an S-Parameter file. To use a data-based standard, interpolation is performed on the provided data to obtain S-parameter values at measurement frequency points. The interpolated values may then be plugged directly into the error correction model equations. Data-based standards are most effective when individual components are characterized rather than averaging the characterization of a batch of components as the individual characterizations will more accurately reflect the subtle differences of each device. However, if there is trace noise present in the listed S-Parameter file, it could transfer over to your measurement as a static source of trace noise.

2.1 Example: Data Based Standards vs. *Ideal* Standards

We here at Mini-circuits performed a small experiment to develop our own data-based standards. We used previously uncharacterized open, short, and load terminations, as well as a female to female adapter (thru) to calibrate our UVNA-63, (assuming these as *ideal* standards where $\Gamma_{open} = 1$, $\Gamma_{short} = -1$, $\Gamma_{load} = 0$, $S_{thru} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$). We measured a Mini-circuits' VBF-2435+ bandpass filter (DUT) using this calibration on the UVNA-63. Then we used a Keysight calibration standard kit to calibrate on a Keysight PNA-X VNA. Using a resolution-bandwidth (RBW) of 100 Hz, 5 averages on each measurement, and an electronic calibration kit, we obtained S-parameter files for each of the uncharacterized standards that were previously used (open, short, load and thru) from 500-6000 MHz. We again calibrated the UVNA-63 using these characterized standards and measured our DUT. To test the quality of our new data-based standards, we looked at the qualitative differences between performing a two-port calibration with the SOLT component parameters listed as *ideal* vs. S-parameters obtained in the lab (Data-based). Figure 1 shows the UVNA-63 kit measurements with ideal and data-based SOLT calibration.

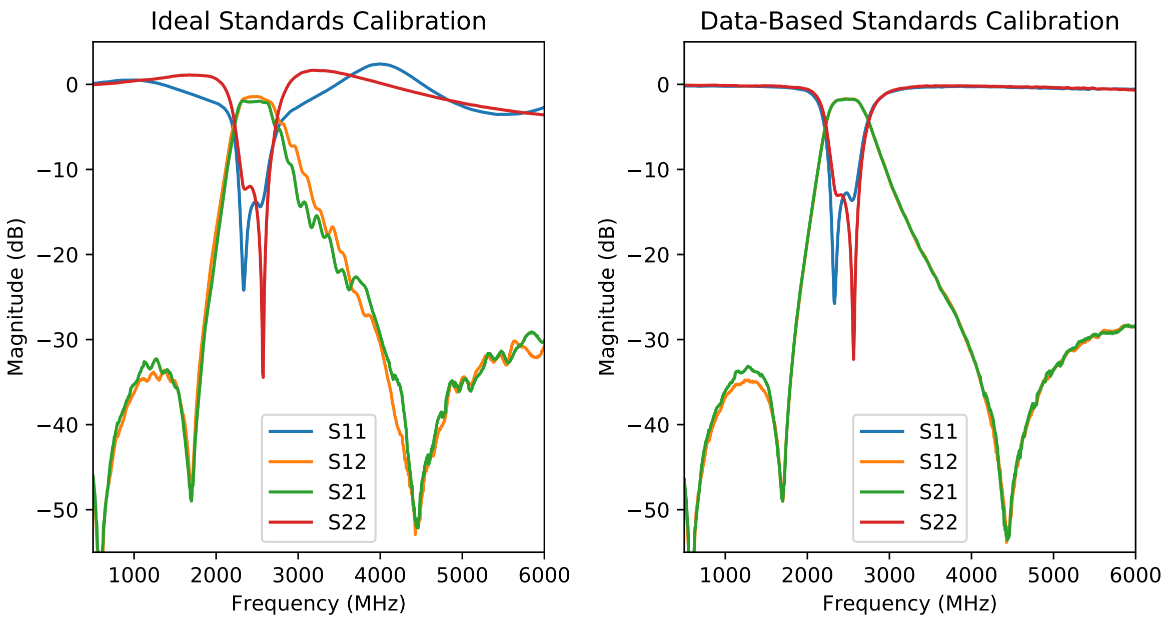

Figure 1: UVNA-63 kit measurement of a 2.5 GHz bandpass filter with ideal SOLT calibration (left) and data-based SOLT calibration (right)

Figure 1 clearly illustrates the difference between using characterized components for calibration vs using components listed as ideal. For reference, the maximum squared-difference between the magnitude of the data-based standards and their canonical *ideal* parameters is 2.4×10^{-4}, 2.9×10^{-4}, and 26×10^{-4} for the short, open, and load respectively. In other words, it doesn't take much of a deviation for ideal S-parameters to make the difference between inaccurate measurements to acceptably accurate measurements (mostly based off the presence of fictitious gain in the ideal SOLT cal.).

3 Model Based Standards

Model-based standards involve using transmission line theory to provide a compact way of characterizing the cal. kit components. Open, short, and load standards are modeled by lossy transmission lines with capacitive, inductive, or resistive loads (as shown in Figure 2). Parasitics and other imperfections are further taken into account by modeling the capacitors and inductors as having a value that changes over frequency.

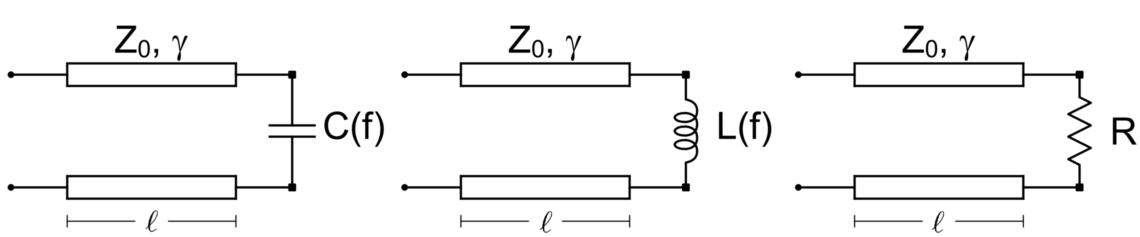

Figure 2: Transmission line model for open, short, and load terminations

With the characteristic impedance of the line, Z_0, the propagation constant, γ, the length of the transmission line ℓ, and the load impedance of Z_L, the input impedance Zin of the lumped element may be solved for by the transmission line impedance-transformation formula, provided in Equation 1. The input reflection coefficient, Γ_{in}, may then be solved for via the standard reflection coefficient formula, provided by Equation 2.

$$Z_{in} = Z_0 \frac{Z_L + Z_0 tanh(\gamma\ell)}{Z_0 + Z_L tanh(\gamma\ell)} \tag{1}$$

$$\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{2}$$

A model-based SOL calibration standard's job is to provide terms that can be used to solve these transmission line equations for reflection coefficients, Γ_{in}. However, from transmission line and circuit theory, we know every term in this model is, by definition, variable over frequency. Standards overcome this by providing the following frequency-independent constants:

- **Offset impedance**, Z_{off} [Ω]: The lossless characteristic impedance of the component's model transmission line
- **Offset delay**, $Delay_{off}$ [s]: The one-way delay from propagation through the transmission line
- **Offset loss**, $Loss_{off}[\frac{\Omega}{s}]$: A term used to account for energy loss through the transmission line due to the skin effect [1]
- $\mathbf{C_0}[F], \mathbf{C_1}[\frac{F}{Hz}], \mathbf{C_2}[\frac{F}{Hz^2}], \mathbf{C_3}[\frac{F}{Hz^3}]$: The coefficients for a 3rd degree polynomial definition of the open's capacitive load over frequency: $C(f) = C_0 + C_1 f + C_2 f^2 + C_3 f^3$
- $\mathbf{L_0}[H], \mathbf{L_1}[\frac{H}{Hz}], \mathbf{L_2}[\frac{H}{Hz^2}], \mathbf{L_3}[\frac{H}{Hz^3}]$: The coefficients for a 3rd degree polynomial definition of the short's inductive load over frequency: $L(f) = L_0 + L_1 f + L_2 f^2 + L_3 f^3$

These terms were chosen to be used in cal. kit standardization by studying approximations of several lossy transmission line formulas, and picking out measurable, frequency-independent terms. The final piece of the puzzle, connecting the calibration standards' listed information to our transmission line model, is in the form of the following two equations [2]:

$$Z_C = \left[Z_{off} + \left(\frac{loss}{2\omega}\right)\sqrt{\frac{f}{10^9}} \right] - j\left[\left(\frac{loss}{2\omega}\right)\sqrt{\frac{f}{10^9}} \right] \tag{3}$$

$$\gamma\ell = \left[\frac{(loss)(delay)}{2Z_{off}} \sqrt{\frac{f}{10^9}} \right] + j\left[\omega(delay) + \frac{(loss)(delay)}{2Z_{off}} \sqrt{\frac{f}{10^9}} \right] \tag{4}$$

These equations allow us to go directly to the impedance transformation formula and reflection coefficient formula to obtain the effective input reflection coefficient of the calibration standards. The reflection coefficients obtained are now labeled either as calibration standards ideal, or calibration standards listed, and are used to solve for the error terms of the VEC models.

3.1 Example: Model-Based Open Standard

To help further understand the coefficient model, the following is an example of how the model of an open would be used to calculate the corresponding S-parameters. Here, the Keysight 85033D/E 3.5 mm Calibration Kit is used. Table 1 lists the model parameters of the open standard from this cal kit.

$C_0[F]$	$C_1[\frac{F}{Hz}]$	$C_2[\frac{F}{Hz^2}]$	$C_3[\frac{F}{Hz^3}]$	Delay [sec]	Loss [GΩ/sec]	$Z_0[\Omega]$
49.433×10^{-15}	-310.13×10^{-27}	23.168×10^{-36}	-0.15966×10^{-45}	2.92×10^{-11}	2.2	50

Table 1: 85033D/E Cal. Kit. Open Standard Model Parameters

The load capacitor of the model's transmission line is described by,

$$C = C_0 + C_1 f + C_2 f^2 + C_3 f^3$$

From circuit theory, we know that the impedance given by this load capacitor is $Z_L = \frac{1}{j\omega C}$. Next, the transmission line is described with its characteristic impedance, Z_C, and propagation term, $\gamma\ell$ using equations 3 and 4. Note that our model describes the characteristic impedance of the line as Z_C, whereas the impedance transformation formula (Equation 1) calls for Z_0. This impedance transformation is calling for the actual characteristic impedance of the line, so we must use Z_C as follows,

$$Z_{in} = Z_C \frac{Z_L + Z_C tanh(\gamma\ell)}{Z_C + Z_L tanh(\gamma\ell)}$$

For finding the reflection coefficient of the lumped element we use Equation (2). Note that the Z_0 used in this equation is the characteristic impedance of the line used for connection (most commonly 50Ω or 75Ω). Performing these calculations for the open standard listed in Table 1, we can obtain the following plots (Figure 3)

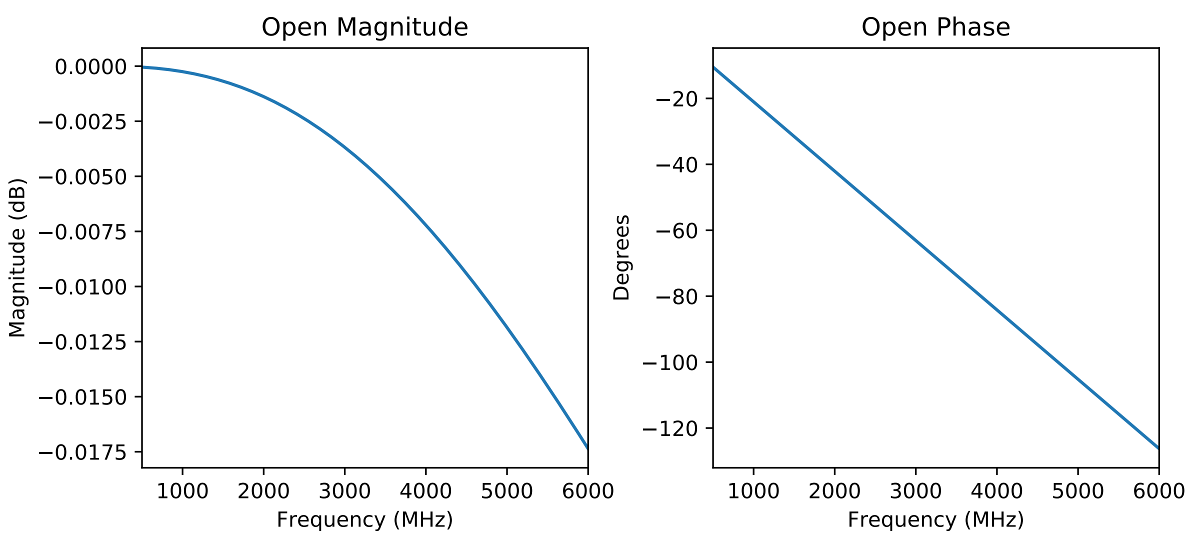

Figure 3: Model for the 85033D/E Cal. Kit Open Standard, Magnitude (left), Phase (right)

Notice that the open standard does not maintain anything close to a phase of 0°, though it has a phase of 0° at DC. The lack of maintenance is due to the non-zero length of the transmission line in the model causing an increasing phase delay over frequency. Approximating SOL standards by their canonical/ideal reflection coefficients will undoubtedly incur significant inaccuracies in phase measurements as the phase *cannot* be treated as static due to the 'line' in the transmission line model.

Summary

- Calibration standards and calibration standard models are required to obtain *measured* and *listed* S-Parameters.
- A group of measured and listed S-Parameters (usually 3 or more) allow us to solve for Network Analyzer error models over a specified frequency band.
- Data-based standards directly provide listed S-parameters, though they may need to be interpolated for use in a specific calibration.
- Model-based standards provide listed S-parameters indirectly through a set of model parameters for each standard.

VNA Kit Functions

The VNA kit API may be referenced for documentation on the format of inputs and outputs of all functions.

1. **SOLT Prompts**:
   Using the knowledge gained from Section 1, write your own version of the following UVNA-63 kit API functions:

```
prompt1PortSOLT(vnakit,settings,ports,tx)
    Prompts the user to measure SOL parameters at chosen port (tx)
    input:
        vnakit: (the board) object,
        settings: vnakit settings object,
        ports: mapping dictionary,
            possible keys: ['Tx1','Tx2','Rx1A','Rx1B','Rx2A','Rx2B']
            possible values: [1, 2, 3, 4, 5, 6]
        tx: port number of transmitter
    output:
        Gm: measured reflection coefficients array [num_pts, 3] in order of OSL

prompt2PortSOLT(vnakit,settings,ports,isolation=False):
    Uses prompt1PortSOLT to get SOL measurements at each port, and an additional
    thru measurement
    input:
        vnakit: (the board) object,
        settings: vnakit settings object,
        ports: port mapping dictionary,
        tx: port number of transmitter
    output:
        Gm1: [num_pts,3] port 1 measured reflection coefficients in order OSL
        Gm2: [num_pts,3] port 2 measured reflection coefficients in order OSL
        Tm: [num_pts,2,2] measured thru S-parameters
        (optional) Im: [num_pts,2,2] measured isolation S-parameters
```

   These functions will allow you to obtain measured SOLT data required for building your error models. Interface them with the error correction functions written at the end of the Error Correction module. See the `skeleton.py or skeleton.m` scripts for example prompts on how these functions interface with the rest of the calibration process.

2. **Touchstone File Interpolation**:
   Using the knowledge gained from Section 2, write your own version of the following UVNA-63 kit API functions:

```
readSNP(path,freq_desired=None)
```

```
Reads a touchstone file, returning a frequency vector and S-parameter matrix.
If freq_desired is provided, S-parameter data is interpolated and then returned
Units of freq_desired must be in Hz. The python API uses the scikit-rf module
for reading in raw touchstone data.
input:
    path: [string] path/to/filename of touchstone file (*.sNp)
    freq_desired: (optional) [num_pts] frequency vector (in Hz)
        for interpolation
output:
    S: [num_pts,1] or [num_pts,n,n] S-Parameter matrix
    f: (optional) [num_pts] frequency vector (in Hz) of file.
        Only returned if no freq_desired is given.
```

This function will allow you to obtain interpolated S-parameter data. As pertaining to this section, it is most useful for using data-based standards in your VNA Kit calibration. See the `skeleton.py or skeleton.m` scripts for examples of its usage.

References

[1] *Modifying Calibration Kit Definition*, Keysight, web: `http://ena.support.keysight.com/e5072a/manuals/webhelp/eng/measurement/calibration/advanced_calibrations/changing_the_calibration_kit_definition.htm`

[2] Monsalve Raul, *Effect of Loss on VNA Calibration Standards*, SESE Arizona State University, August 7th 2013, web: `http://loco.lab.asu.edu/loco-memos/edges_reports/report_20130807.pdf`