"Factory" Calibration Considerations and Procedures for the NanoVNA

Preface

This document is an expansion of Message# 233 from the "NanoVNA-users" group at the groups.io website. It is a continued discussion of the Calibration Procedures for the NanoVNA Vector Network Analyzer. This document is mostly the work of Alan Victor, W4AMV and his colleague Gary O'Neil, N3GO. This re-write and the additional material is the work of Larry Goga, AE5CZ.

It is not within the scope of this document to be a basic tutorial on the Calibration and Operation of the Vector Network Analyzer or VNA. An excellent discussion of these topics can be found on the Internet at the Wikipedia website using the search key "Network analyzer (electrical)" [1]. The use of the qualifier "electrical" separates this topic from computer LAN and WAN network analyzers. They are two completely different types of hardware. Various manufacturers of high-performance professional VNA's offer well written and illustrated manuals designed to inform and educate the newcomer to the field of VNA's. Such manuals are available from Anritsu [2], Rhode & Schwartz [3], Agilent/Keysight [4] and National Instruments [5]. Links to these files can be found in the References section (page 10) at the end of this document. The purpose of this document is to acquaint the new user with a few of the basic concepts behind the VNA and how to properly calibrate the NanoVNA device. The new owner of a NanoVNA is also directed to the YouTube website which contains some excellent videos on the subject.

This document is in three parts. It is meant to be a preliminary discussion of the various types of Calibration Procedures for a general Vector Network Analyzer, then a sequential series of steps to perform these Calibrations procedures on a NanoVNA unit and finally, a collection of notes that explain and define why these steps and their order are especially important in the case of the NanoVNA. Since the very low cost of the NanoVNA brings the capabilities of a Vector Network Analyzer into the hands of a whole new range of end users, including those who may have never had an opportunity to use such a device, it is important that we start with some definitions and explanations as to why proper calibration is so very important when using a VNA and interpreting the results.

Scattering Parameters and the "DUT"

Any operational knowledge of how to use a VNA must begin with at least a rudimentary understanding of S-parameters, otherwise known as Scattering Parameters. The study of S-parameters comes out of the study of Optics. It is in the study of Optics that we can observe first-hand the relationship between light and the medium through which it travels. When light rays from an image encounter a photographic lens, most of the light rays – BUT NOT ALL – pass through the lens. Some of the light rays are 'scattered" back toward the source. In Optics this is referred to as the S11 scattering parameter. The light that does pass through the lens can be examined on the output side of the lens and studied as the S21 scattering parameter [6].

This same study of "incidence", "reflection" and "transmission" can be applied to the RF energy that exits an oscillator or transmitter circuit, travels through a piece of coaxial cable as its transmission medium and terminates at an antenna or some other type of load. Similarly, RF amplifiers and filters can be examined in this same way. By measuring the transmitted and received signals accurately it is possible to calculate and graphically display a whole host of electrical parameters including gain (or loss), return loss, voltage standing wave ratio (VSWR), reflection coefficient, amplifier stability, frequency response and many others.

What makes the Vector Network Analyzer a unique instrument is that not only can it measure and compare the amplitude of any of these signals, it can also compare the Phase Relationship of these signals to each other and to a precisely generated Reference Signal. This is what separates the VNA from the Scalar Network Analyzer (SNA, no Phase measurements available) and the Spectrum Analyzer [7].

It is the function of the VNA to accurately generate these RF signals, apply them to the "Device Under Test" (DUT) and then capture, measure and display the incident, reflected and transmitted signals in both amplitude and phase. Although a VNA will most like come fully calibrated from the factory, the connection of the VNA to the DUT can cause its own set of problems that must be dealt with by the end user. Hence the need for secondary calibration tools and a known and repeatable calibration procedure. That procedure is what this document hopes to provide.

Types of Secondary Calibrations

There are several types of secondary calibrations, defined by what ports are involved and what level of correction is accomplished. These calibration types include [8]:

- **Full 2-Port** - This is the most commonly used and most complete calibration involving two ports. All four S-parameters (S11, S12, S21, and S22) are fully corrected.
- **Full 1-Port** - In this case, a single reflection parameter is fully corrected (either S11 or S22). Both ports can be covered but only reflection measurements will be corrected. This calibration type is useful for reflection-only measurements, including the possibility of doing two reflection-only measurements at the same time.
- **1-Path 2-Port (forward or reverse)** - In this case, reflection measurements on one port are corrected and one transmission path is partially corrected, but load match is not. Here forward means that S11 and S21 are covered, while reverse means that S12 and S22 are covered.
- **Frequency Response (reflection response and transmission-frequency response)**
- **And there are others.** (See Reference Item 8 at the end of this document for more information.)
- **For purposes of reference to the NanoVNA, port 1 is associated with CH0 and port 2 is associated with CH1.**

Due to circuitry and cost restrictions, the NanoVNA is only capable of measuring the S11 and S21 parameters and it can be reasonably calibrated for these measurements using the supplied calibration tools for a SOLT type calibration (Short, Open, Load and Thru). By reversing the DUT, the S22 and S12 parameters can be measured as well and with an equivalent degree of measurement accuracy. The act of reversing the DUT does however introduce a degree of uncertainty in the measurement results, but it does yield a full set of S parameters that most amateurs will find quite adequate for nearly all applications they are likely to encounter in the HF spectrum, and for many applications well into the VHF/UHF spectrum as well.

The quality and accuracy of the calibration is only as good as the tools provided. The quality of the NanoVNA hardware is sufficient to produce stable and repeatable measurements with good accuracy using the included calibration kit, or a kit of similar quality purchased separately. Even a carefully constructed set of DIY calibration standards will satisfy the requirements of many users.

The accuracy of the NanoVNA is established by the process of calibration. This process includes taking measurements of a precisely defined set of calibration standards, characterizing the measurement environment and normalizing the measurements to a 50 + j0 ohm Complex termination impedance. The Complex number contains information on both the amplitude and the phase relationship of the measured signal. An excellent discussion of the theory behind Complex Numbers can be found on the Internet. [9]

It should be obvious that errors in the standards being used should be known and accounted for in the calibration process. Doing so will achieve optimal accuracy and precision in any VNA measurements. There are no known provisions for doing so in the NanoVNA, and as such, accuracy is bounded by the absolute accuracy of the standards being used. In spite of this limitation, the accuracy is impressive, and generally adequate throughout its useable operating range.

Together; hardware stability, repeatability, calibration kit uncertainties and the correction algorithms used, all contribute to the NanoVNA's measurement uncertainty. Even so, the accuracy obtained is reasonable but it is not as precise as a high-end laboratory grade VNA. Still, for most amateur radio applications, the supplied level of accuracy is sufficient for most beginning test requirements and will more than satisfy most users.

Calibration of a 4-trace NanoVNA

This is the beginning of the procedure to calibrate a NanoVNA. As delivered, the NanoVNA came with a set of calibration data stored in Memory Location 0 (zero) and by default that data is used during the turn-on process. This is indicated by the display of “C0” in the “Cal Status” area of the display. It is possible for that calibration data to become corrupted or lost. The following procedural steps will enable the end-user to recreate that data. Also, if the Firmware in the nanoVNA is ever updated, all initial calibration data (in Memory0) will be lost and the unit will require re-calibration using this method.

Note 1:

Before starting this procedure it is recommended that you review the “NanoVNA Menu Structure” document. It can be found at https://groups.io/g/NanoVNA-users/attachment/560/0/NanoVNA%20Menu%20Structure%20v1.1.pdf

Note 2:

The following Calibration Procedure is for a NanoVNA that has Firmware that supports 4-trace operation (yellow, blue, green and magenta). A two trace display is recommended but not required during the calibration to minimize distractions and confusion on the display.

Note 3:

Used in this procedure are two approximately equal length coaxial cables, SMA-Male Short, Open and 50 ohm termination connectors and a female-to-female SMA adapter. These components should have been included with your NanoVNA. If they are not present, then you *will need to purchase or acquire them separately. A second SMA-Male 50 ohm termination and female-to-female adapter will further simplify the procedure. Such components can be obtained for less than $10 USD from Amazon, eBay or other vendors.*

Note 4:

Turn ON the NanoVNA and note the vertical column of characters along the left edge of the display. These characters identify the CAL Status of the displayed data and the first (top) characters show the memory location of the current Calibration Parameters being used. The default calibration data is always displayed at Power-up and is stored in location "SAVE0". ***C0*** *indicates the default calibration data is enabled. No vertical data column to the left of the display indicates that no calibration data is stored in the memory location (**C0** at Power-up), and the data shown on the display is uncorrected.*

*If some characters are displayed, but the memory location (**C0**) is not, a calibration file has been saved in "SAVE0", but "CORRECTION" has been disabled. If you wish to have this enabled (not required for calibration), navigate to CAL > CORRECTION, and toggle CORRECTION until **C0** appears at the top of the column on the left of the display.*

*If a calibration has been performed and is available, the CAL Status will be displayed as **Cx**.* ***C**** *indicates a calibration has been performed and is currently active; but it has not been saved. Measurements made in this mode will be valid and corrected, but the calibration will be discarded when the NanoVNA is turned off or discarded and replaced if a saved location is recalled.* ***C0*** *to* ***C4*** *are the 5 calibration files that can be Saved and Recalled.*

*There are several ways that users may find it convenient to save frequently used calibration data. Some users may prefer to keep the factory default calibration data in **C0** and then select locations **C1** through **C4** for other ranges of interest. Other users may wish to keep the calibration data for their current experiments in **C0** so that it is immediately available at power-up. The default data set could then be stored elsewhere (**C1** through **C4**) or discarded and recreated if needed. The choices are as varied as the applications for the NanoVNA.*

*The letters below **C** indicate that the following error terms have been applied.* ***D:*** *Directivity,* ***R:*** *Reflection Tracking,* ***S:*** *Source Match,* ***T:*** *Transmission Tracking and* ***X:*** *Isolation.*

Note 5:

Saved or unsaved calibration parameters can be enabled and disabled by toggling the CORRECTION button under the CAL menu. The top CAL Status character on the display will toggle to reflect the current state of the displayed data. This serves as a useful diagnostic tool following a calibration procedure to verify the success and quality of the calibration just completed prior to making measurements on an unknown DUT or saving the result to a memory location for use in the future.

Note 6:

Connect the two equal length Male-to-Male coaxial cables to CH0 and CH1 of the NanoVNA with the Female-Female SMA connected to the free end of the cable connected to CH1. Dress these cables away from the NanoVNA in a parallel line and do not let them cross.

Note 7:

Each of the following numbered items represent a press of a softkey on the screen of the Nano-VNA. Tap the touchscreen or depress the jog wheel to bring up the Home Menu. If using a stylus, touch and hold on menu options until the selected option turns flash green to confirm its selection.

Select and actuate menu items as follows:

1. DISPLAY
2. TRACE
3. TRACE 0
4. SINGLE

Tap the screen again and continue (if necessary).

5. BACK
6. FORMAT
7. LOGMAG

Tap the screen again and continue (if necessary).

8. BACK
9. TRACE
10. TRACE 1

Tap the screen again and continue (if necessary).

11. FORMAT
12. LOGMAG

Note 8:

At this point there should only be two traces on the screen: Trace0 in yellow and Trace1 in blue. Trace0 should indicate "CH0 LOGMAG" and TRACE1 should indicate "CH1 LOGMAG". We are now displaying S11 and S21 as CH0 and CH1 respectively.

Note 9:

We are now about to set the Frequency parameters for this particular calibration. They can be set with either START and STOP commands or CENTER and SPAN commands. It should be *noted here that the NanoVNA was designed with a fixed number of steps between the START and the STOP frequencies. That number of steps is 101 (one hundred and one). It must be pointed out that with an extremely wide frequency range (say, the default 50 kHz. to 900 MHz.) and only 101 steps that the calibration data will be extremely course and provide a very "grainy" calibration.*

*The default calibration **C0** (50k to 900M) is meant to be that way - grainy. It is meant to be a starting place to begin the examination of a "black box" device. Once interesting artifacts are observed on the display, then the VNA can be recalibrated and "zoomed in" on particular frequency ranges of interest.*

*Another way to use the VNA is to create and save different calibration data for different portions of the radio spectrum. In this case **C0** would be the broadband and default calibration and **C1** could be for the HF bands and **C2** for the VHF band and **C3** for the UHF band and so forth. This would still leave one other calibration memory for an even closer look at a particular band (say 6 MHz to 8 MHz for 40 meters or 144 MHz. to 148 MHz. for 2 meters). As the operator of the VNA it is your responsibility to properly set up and calibrate the instrument to ensure that the measurements you obtain are of the highest precision that you can accomplish with the tools at hand.*

Tap the screen again and continue.

13. STIMULUS
14. START 50 kHz.
15. STOP 900 MHz.
16. BACK
17. CAL
18. RESET

Note 10:

Invoking the RESET command at this point is <u>key</u> to a proper calibration sequence. The RESET button will highlight and stay highlighted. Invoking the RESET function will destroy all the previously saved calibration data. It is now imperative that this procedure run to completion to generate new data. Now continue.

19. CALIBRATE

Note 11:

At this point <u>none</u> of the seven softkeys on the right side of the display are highlighted. Place an OPEN SMA-Male connector on the CH0 cable end. This will require using the F-F SMA adapter. The OPEN connector does not have a center pin. Leave the CH1 cable alone.

Some end users suggest that the OPEN SMA connector is not as good as simply connecting NOTHING to the end of the CH0 cable. The choice is yours. Try experimenting to see if you can detect any difference.

20. OPEN

Note 12:

Replace the OPEN SMA connector with a SHORTed SMA connector. Again, leave the CH1 cable alone.

21. SHORT

Note 13:

Place 50 ohm SMA-Male terminators on the ends of BOTH CH0 and CH1 cables. This will require a second 50 ohm terminator and a second F-F adapter.

22. LOAD

Note 14:

If you have two 50 ohm SMA terminations; leave them connected as discussed in Note 13.

If only one termination is used; place it on the end of the CH1 cable using the Female-Female adapter.

23. ISOLATION

Note 15:

Remove the two 50 ohm terminators and connect the two cables together. This will require the use of only one F-F SMA adapter.

24. THRU
25. DONE

Note 16:

*It is now time to SAVE the calibration data. You may save the data in any one of the five available storage registers (SAVE0 through SAVE4). Since this was a broadband (end-to-end) calibration that you may wish to return to regularly, it is recommended that this data be saved in **C0** and perhaps one of the other long term memories (**C1 – C4**). The choice is yours.*

26. SAVE 0

Note 17:

The calibration data has now been saved. Cycle POWER on the NanoVNA and confirm that the CAL Status display on the left side of the screen contains the full vertical string of character. You may also wish to verify that the data was saved in the desired long term memory.

27. RECALL/SAVE
28. RECALL
29. RECALL n (wherever you previously saved the data)

Note 18:

We will now verify calibration success by using a Smith Chart display and feeding it with a SHORT, OPEN and 50-ohm LOAD. We will begin by recreating the Smith Chart trace.

Tap the screen to bring up the Home Menu

30: DISPLAY

31: TRACE

32: TRACE2

Note 19:

There should now be three traces visible on the NanoVNA screen: yellow which is TRACE0 and labelled as CH0 LOGMAG, blue which is TRACE1 and labeled as CH1 LOGMAG and green which is TRACE2 and labeled as CH0 SMITH. If the displays are not presented as described then navigate to each Trace found in error and edit them to reflect the correct CHANNEL and FORMAT indicated above.

Note 20:

Connect a 50 ohm SMA terminator to the cable connected to CH0. The Smith Chart display should show data (dots) in the center of the chart. Then replace the 50 ohm terminator with an SMA SHORT connector. This represents 0 ohms and the Smith Chart display should show data (dots) at the extreme left side of the screen. Finally, remove the SHORT and leave the cable OPEN (unterminated). You should see data (dots) on the extreme right side of the screen.

If this is not what you observe, then the Calibration Procedure has ***FAILED!*** *Return to Note 7 above and repeat the entire Calibration Procedure.*

Note 21:

The final test is to connect together the cables from CH0 and CH1. This will require the use of an SMA F-F adapter. When connected observe TRACE1 (the blue trace) showing the LOGMAG data from CH1. You should see a straight line all across the screen. It should be one division down from the top of the screen and the digital readout should indicate essentially 0.00 dB.

At this point the "Reference Plane" (point of calibration) is at the open end of the two coaxial cables with the SMA Female-Female adapter installed at the end of the CH0 cable. This is the interface in which the DUT is installed and measured. If you should remove the cables and replace them with longer (or shorter) cables, use adapters only instead of the cables or attach the DUT at any location other than the Reference Plane then the Calibration becomes invalid and measurement errors will result.[10] *To ensure the greatest accuracy, it is imperative that the location and connection to the DUT be established prior to calibration and the NanoVNA subsequently calibrated with respect to the DUT interface(s) which are thereby established as the reference plane for the measurements of the DUT that follow. Failure to observe the Reference Plane criteria described above may be tolerable at lower (HF and below) frequencies but it will introduce considerable error at frequencies near the upper limit of the NanoVNA.*

Note 22:

A subset of this procedure can be used if only single port reflection measurements are desired. Simply establish whether you wish to connect the DUT directly to the NanoVNA (Only the CH0 port is used) or if you wish to connect the DUT to CH0 through a cable. This defines the physical location of the Reference Plane where the calibration kit standards will be connected during calibration. Proceed by performing the calibration procedure as outlined above, ignoring the steps for isolation and thru.

Congratulations! You have successfully completed a full bandwidth Calibration Procedure for the NanoVNA. It is suggested that you now return to Note 9 above and create other calibration files for different portions of the radio spectrum.

(see References on Page 10)

REFERENCES

[1] “Network Analyzer (electrical)” https://en.wikipedia.org/wiki/Network_analyzer_(electrical)
See also “External Links” at end of article for more information.

[2] “Primer on Vector Network Analysis” an Anritsu Application Note
https://web.archive.org/web/20070710174350/http://www.us.anritsu.com/downloads/files/11410-00387.pdf

[3] “Rohde & Schwarz presents basics on vector network analysis in five independent and comprehensive videos.” https://www.youtube.com/playlist?list=PLF5DA69583F0DDAC2

[4] “Network Analyzer Basics” Agilent/Keysight
https://www.keysight.com/upload/cmc_upload/All/BTB_Network_2005-1.pdf See also:
“Understanding the Fundamental Principles of Vector Network Analysis”
https://literature.cdn.keysight.com/litweb/pdf/5965-7707E.pdf

And see also: “Brushing up on Network Analyzer Fundamentals” *Microwaves and RF* Magazine https://www.mwrf.com/print/18192

[5] “Introduction to Network Analyzer Measurements: Fundamentals and Background”
http://download.ni.com/evaluation/rf/Introduction_to_Network_Analyzer_Measurements.pdf

[6] “Scattering Parameters” https://en.wikipedia.org/wiki/Scattering_parameters

[7] “Scalar Network Analyzer vs Vector Network analyzer basics” RF Wireless World
https://www.rfwireless-world.com/Terminology/SNA-Scalar-Network-Analyzer-vs-VNA-Vector-Network-Analyzer.html

[8] “Understanding VNA Calibration” PDF, Page 6 of 36,
http://anlage.umd.edu/Anritsu_understanding-vna-calibration.pdf

[9] “Complex Number” https://en.wikipedia.org/wiki/Complex_number

[10] “Understanding VNA Calibration” http://anlage.umd.edu/Anritsu_understanding-vna-calibration.pdf
See also “VNA Calibration: the Basics” a Rhode and Schwartz White Paper
https://pdfs.semanticscholar.org/2497/8e60b68a24a4169eecbd0763d4a9287037e4.pdf

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