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Nano vs. Commercial

Comparing an Open-Source NanoVNA with a Keysight ENA

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1 Introduction

The NanoVNA, first introduced by that name in 2019, is a handheld, battery-powered, microwave Vector-corrected Network Analyzer (commonly just a "VNA") whose hardware and software are open-source. [1] A version 1.0 is surprisingly cheap, with a price tag of as little as USD \$50 as of 2021, and yet it can reach up to 1.5 GHz in frequency. Pre-assembled units are available from at least one supplier in each of a number of places in Asia, Europe, and the USA. [1] These machines are already used for educational [2, 3], amatuer/ham radio [4], and applied engineering [5, 6, 7, 8] purposes.

This article will compare a NanoVNA, or just the "Nano", to a professional instrument. The professional instrument used in the manuscript is a refined and respected Keysight ENA, model E5061A. We address the question "how much can be done with a Nano, and what can't you get without a full-cost VNA?"

2 Design Differences

The most fundamental difference between the Nano and a "full 2-port" commercial VNA is that the Nano is really a "1-port" VNA with an extra receiver. Behind port 1 of both instruments is a directional component capable of separately sensing both forward and reverse travelling waves. In the case of most commercial VNAs, there is a directional coupler or bridge, and the option of sourcing signal, at *all* ports. In the case of the Nano, the second port simply has a receiver, which is to say that it can sense magnitude and phase of a signal on that port, but can neither source signal nor sense any energy that might be reflected from the port owing to imperfect match.

The Nano is thus only doing a full calibration on 1 port, and a simple calibration on the receiver-only port assuming it represents a perfect match. This is good for measuring S_{11} and something close to true S_{21}. This will be noted in the measurements section where S_{11} measurements tend to be more accurate than S_{21}. If you want to measure S_{22} and S_{12}, you have to put the device under test (DUT) in backwards. In general, uni-directional VNAs cover the majority of real-world, everyday usage. Nevertheless, as we will see later, uni-directional VNAs preclude the use of some of the rather more convenient calibration techniques such as "unknown thru" [9, 10] and "adapter removal" [11].

The commercial VNA we have chosen reaches 3 GHz. Most "serious" VNAs start at this frequency, mostly because it is a relatively easy frequency to reach. The frequency range covers the original 2.5 GHz wifi band, and it is cost effective to do so. The Nano V2 that we will use here reaches 1.5 GHz, and that with reduced dynamic range owing to the use of harmonics of the source. There are versions of the Nano that span up to at least 6 GHz; the interested reader can find links in [1]. Unless otherwise stated, the Nano has been calibrated with the supplied standards and using its inbuilt firmware calibration. The Nano firmware allows the user to alter the value of the resistance of the load standard in its "cal kit". This will be used in the next section.

Vector calibrations rely upon repeatability of connectors. Commercial VNAs typically use N-type or 3.5 mm connectors. The Nano uses SMA connectors, compatible with 3.5 mm but lacking the precision, and potentially not rated for multiple reconnections. This may be satisfactory, but it will represent a source of error that will increase with continuous usage. The user should be aware of this. We are not going to address the problem of wear and reliability here.

It should also be noted that the '5061 was calibrated using an Arance Electronics, 6650F27-F cal kit and the Nano only with its included cal kit. A problem due to availability is that the 6650F27-F has only female SMA calibration standards and the Nano only male SMA calibration standards. This leads to a slight difference in where the calibration plane lies with respect to the DUT, since an adapter was required on one or other machine so that the DUT could be properly connected. A quality adapter was used, so this causes very small errors as may be seen in measurements below. The extra adapter caused some conspicuous effects, for example shifting frequency of resonance peaks of the DUT slightly due to the extra electrical length. The adapter was mostly used with the E5061B, so that its results will contain these errors.

3 Measurements

In this section we will present measurements of various common objects made with the two VNAs. All measurements using both VNA's were set up similarly. The IF bandwidth is 1 KHz, averaging of 16 samples per frequency point and 201 frequency points across the frequency range. Before carrying out these comparative measurements, however, we start by measuring the calibration standards supplied with the Nano using the E5061. This provides an insight at the baseline accuracy of the Nano. Figure 1 & figure 2 present the results.

Of interest is the residual reflection of the load in figure 2. S_{11} starts at about -48dB rising to about -35dB at 1 GHz. The phase of the load's reflection allows the resistance of the load to be calculated. The load is $\approx$ 50.4Ω at low frequency, 1 MHz. Most Nano VNA users will only have a Digital MultiMeter (DMM) to measure the load's resistance. The dc value is also 50.4Ω, meaning that a dc measurement is quite satisfactory. This value can be entered into the Nano calibration to improve accuracy.

The change with frequency visible in the magnitude in figure 2 is likely to be a small series inductance. The phase is made up of a contribution from the inductance, and the length of the load from calibration plane to resistive element, which could be unwound if the user was interested.

3.1 Cable

A 50 Ω Rigid Coaxial Cable (Jinayi, RG402) was used as the initial DUT for measurement comparisons. A coaxial cable was measured because checking cables is a common application, its characteristic impedance is known, and the result of the measurement is easy to anticipate. It also illustrates the phase shift in the signal due to line length. The cable was coiled to minimise

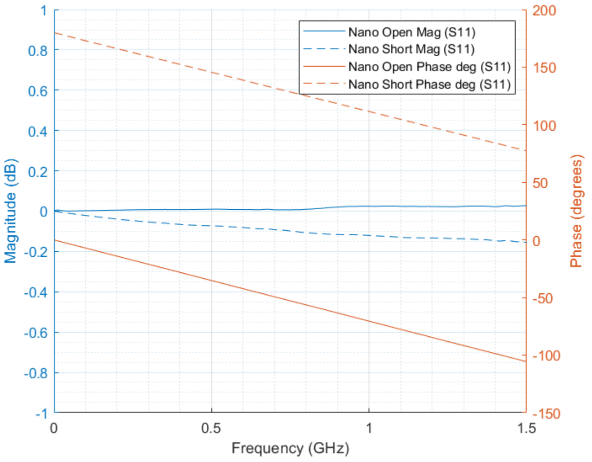

Figure 1: S_{11} of the calibration standards, short and open supplied with the Nano. Measured using the E5061A calibrated with the 6650F27-F cal kit.

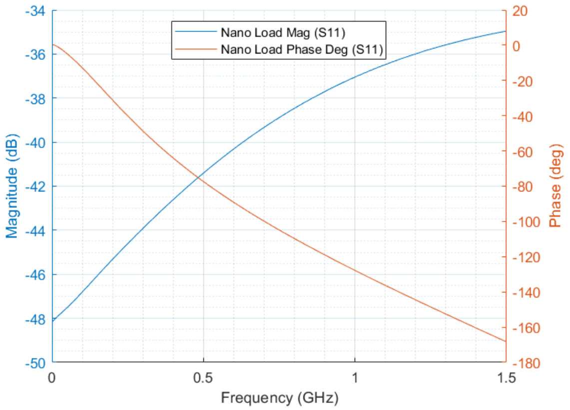

Figure 2: S_{11} Magnitude & Phase of the Nano load calibration standard. Measured using the E5061A calibrated with the 6650F27-F cal kit.

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excessive bending in between measurements. Either end of the cable was soldered with male SMA connectors.

Consider the input reflection coefficient of the cable with the far end left open. One would expect to see near complete reflection at low frequency, with loss rising, accompanied by ripples from (connector?) mismatch. Figure 3 shows the two machines' measurements. They are similar up to 1 GHz. Above there, the Nano shows wilder ripples than the better VNA. The regular ripples offered by the E5061A are more convincing; we attribute the Nano result to lower-quality connectors and worse source match.

The length of cable was physically measured, showing a length of about 1050 mm. The Nano is provided with a time-domain reflectometry (TDR) function that uses a Fourier transform. Figure 4 shows the Nano VNA's estimated cable length using its TDR function. As can be seen from the peak of the reflected signal, the Nano shows a length of 1020 mm; we attribute the discrepancy to the value of the relative velocity factor.

For completeness figure 5 shows the S_{11} of the coaxial cable obtained when connecting both ends to the two ports of the VNAs. This means the cable has been terminated to 50 Ω at port 2 and so we expect very little reflections (S_{11}) and most of the power is delivered to port 2 (large S_{21}). The S_{11} of the Nano is mostly 10 dB above the '5061 values and has a slightly different ripple structure. We attribute this to imperfect match on the second port of the Nano, and the lack of a full two-port cal that might correct for this. This is a decent exposé of a circumstance where a full 2-port calibration might be useful.

3.2 Frequency Accuracy and Resolution

Frequency accuracy and resolution are important with any VNA. They are important because of the occasional need to measure narrow bandwidth DUT's such as a quartz crystal or a high Q-factor resonant circuit.

Figure 6 shows the measurement of the source frequency of each VNA compared with values from a Digital Frequency Meter (DFM) referenc-

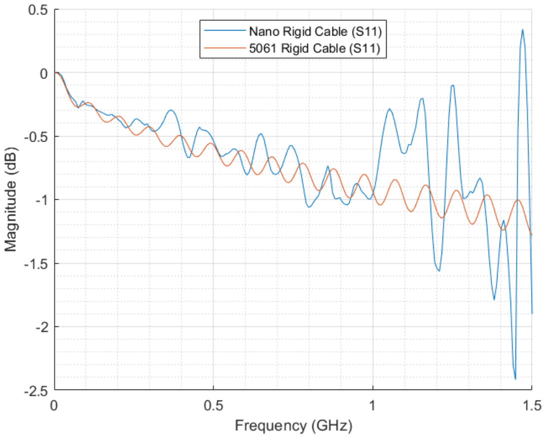

Figure 3: Comparison of S_{11} of a 1050 mm length of rigid coaxial cable fitted with male SMA connectors. The far end of the cable has been left unconnected. The E5061 was SOL calibrated with a 6650F27-F cal kit, and the Nano was calibrated with the supplied SOL standards of the default calibration kit.

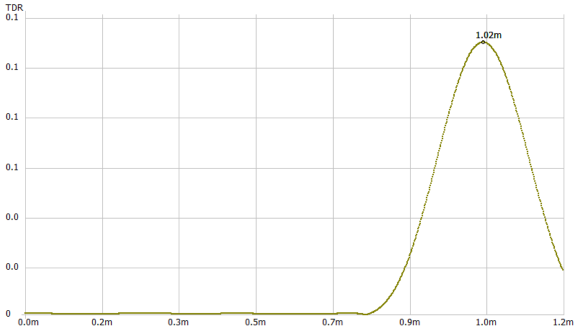

Figure 4: TDR measurement using the NanoVNA of a 1050 mm length of rigid coaxial cable fitted with male SMA connectors. The far end of the cable has been left unconnected (open). The Nano provides only a screen dump, not data, for this mode, explaining why axis fonts are painfully small.

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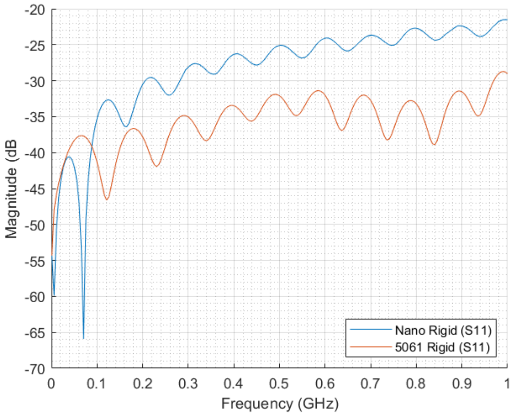

Figure 5: Comparison of S_{11} of the rigid coaxial cable. The far end is connected to port 2 of the VNA. The E5061 was SOL calibrated with a 6650F27-F cal kit, and the Nano was calibrated with the supplied SOL standards of the default calibration kit.

ing a rubidium standard. The results using the Nano are excellent; using 1 Hz steps the Nano is able to resolve to within 1 Hz around 9 MHz. The Nano is only −13 Hz different from what is actually requested, an error of about 1 ppm. This is quite adequate, and especially reasonable considering the ’5061 is −9 Hz away from its set value.

The spectral features of quartz crystals can be as narrow as a few Hz wide and provide a good example of where resolution and accuracy are important. In practice, an amplifier or filter might be designed around a crystal, but for brevity we have simply connected the crystal to a coaxial cable. This reduces the Q-factor, but provides a decent test for comparing the VNAs. Refer to figures figure 7 & figure 8. Both figures show excellent agreement. The x-axis of the first figure spans 12 kHz, and shows both series and parallel resonances of the crystal. Both machines would allow resonance Q to be found accurately.

In figure 8, the crystal is connected directly to ground. The x-axis now spans only 200 Hz. The Q factor is higher, and the agreement remains excellent. Around the resonance point, with 201 points in a sweep, points are 1 Hz apart. The Nano is every bit as useful as the commercial machine in this application.

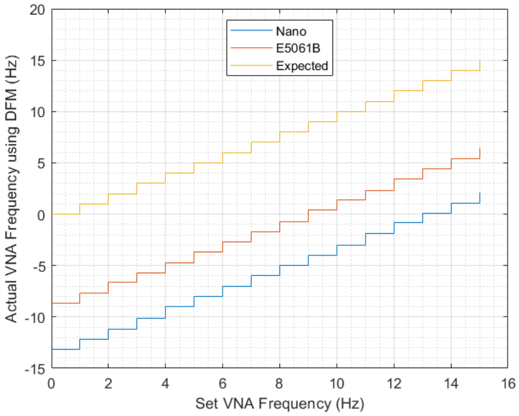

Figure 6: The Nano VNA and the E5061 were set to transmit a single frequency tone and the frequency is measured using the DMM. Results show the frequency resolution and accuracy of the two VNAs. CW frequencies were requested in 1 Hz steps around 9.00 MHz precisely. The reference DFM has better than 1 ppm accuracy calibrated against a rubidium standard. Axes are scaled by subtracting the carrier frequency.

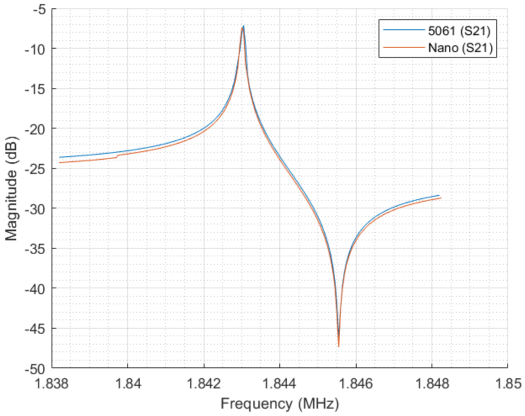

Figure 7: Comparison of S_{21} through a 1.8432 MHz quartz crystal. The crystal is connected between the active conductors of the two ports in order to measure S_{21}.

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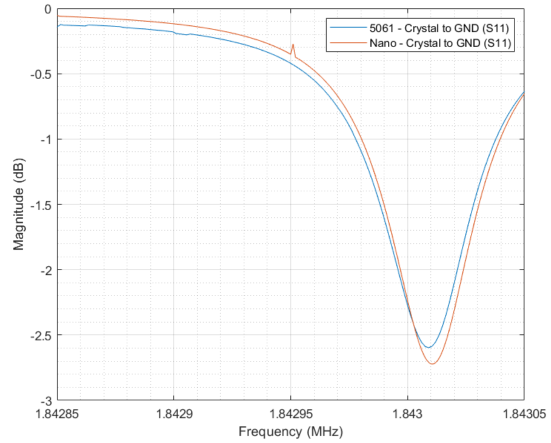

Figure 8: Comparison of S_{11} looking into the 1.8432 MHz Crystal. The crystal is connected to the ground.

3.3 Attenuator

In order to test the dynamic range of the instruments, and to run through an exercise that might well be carried out in a lab with the help of a VNA, a "home made" attenuator was designed and built. It is constructed in coplanar waveguide (CPW) [12], on cheap fibreglass PCB, by scratching grooves into single-sided copper board. Since Wen's original equations do not anticipate the use of thin, low dielectric-constant PCB, the dimensions of the CPW board (groove width, trace width, etc) were found using an online calculator [13].

Provision is made to create several stages along the board, each bearing SMD resistors arranged in the π-configuration, values selected to produce 20 dB of attenuation per stage. Some SMA connectors are crudely attached, and the S-parameters measured at various stages. The photograph in figure 9 gives the idea.

Figure 10 exemplifies the progress. Initially we measured the PCB with no resistors, to see how good the CPW is as a "thru" device. This "thru", and each progressive stage, is measured with both VNAs. The Nano result implies that the basic board with connectors is not as good as the '5061 says it is. Again we attribute this to the imperfect load provided by port 2 of the Nano,

Figure 9: Photo of a hand-built 1 stage attenuator in Coplanar Waveguide (CPW). One π network is soldered to the CPW with two SMD chip resistors in parallel as the series element, and on either side of the series resistance two shunt resistors. Resistor values are chosen to give 20 dB of attenuation.

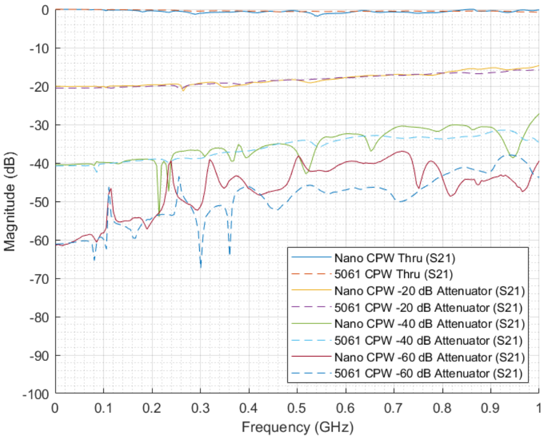

Figure 10: Comparison of S_{21} of a hand-built attenuator in Coplanar Waveguide (CPW). Traces progressively show the PCB with no attenuator stages, and with 1, 2, and then 3 separate 20 dB π networks in series.

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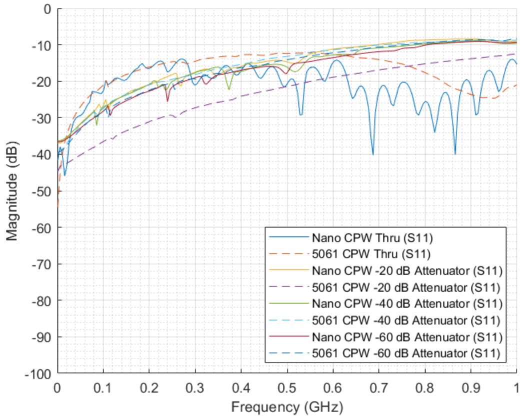

Figure 11: Comparison of S_{11} of the CPW attenuator. Traces progressively show the input match with no attenuator stages, and with 1, 2, and then 3 separate 20 dB π networks.

and the lack of full 2-port calibration. Given the quick construction, the poorer result would be credible. If we sought to improve the base PCB, the Nano would not be helpful.

Now a cut is made in the center conductor, and some resistors added, to create a 20dB π attenuator. Some algebra suggests that pairs of resistors of 120Ω in parallel on either side of a series resistance composed of 470Ω and 560Ω resistors in parallel will produce 20.3 dB of attenuation and a termination impedance of 49.5Ω for a reflection coefficient of better than -45 dB. Carrying this out leads to the "-20 dB" traces. Both VNAs give credible, similar results. The Nano is fine here. The trace slides upwards, showing decreasing attenuation with frequency, easily attributed to stray capacitance and radiative transmission across the cut in the main conductor on the board.

Nevertheless, we want more attenuation. Another stage is added. This leads to the "-40 dB" traces. Once again, the Nano tells us that we are doing a worse job than the '5061 perceives. This might be a problem if we seek to improve our attenuator... the Nano will be all but useless in reporting whether a small change improves things, as it is contributing most of the ripple and nastiness. The trend is good, the detail is obscured.

Pressing on to the next stage and the "-60 dB" traces, it is clear that we did our design well, as the very lowest frequency data sits at about the right level. Sadly we are not very good attenuator-makers, and both VNAs agree on this. Disappointingly, the two disagree by up to 25 dB about exactly where we went wrong, so again the Nano would be of little use in pursuit of improvement.

Meanwhile, figure 11 depicts the same progression, but looking at the input return loss or S_{11}. It is probably a good thing we are easily satisfied with 10 or more dB of return loss, because the Nano is often in serious disagreement with the '5061 on how we are doing.

3.4 Directional Coupler

Directional couplers are intriguing components symbolic of the magic possible in the microwave & RF world of travelling waves [14]. They are common devices, as already mentioned directional couplers are internally built into nearly every VNA to separate out the forward and backward waves. A directional coupler is a 4-port device, but a 4-port VNA is something of a luxury, meaning to measure an external coupler without changing physical connections a 4 port VNA is needed. In this section we use our two 2-port VNAs to characterise an external 20dB, 30–800 MHz coupler. To achieve this, the two unused ports of the directional coupler must be terminated in 50Ω to avoid the reflections off those ports affecting the wanted measurements. Figure 12 shows each of the "important" S-parameters of the coupler, the through, sampled, and isolated cases. The results with the Nano are very close to those of the '5061, although they show more ripple in every case. S_{21} and S_{31} easily confirm that the coupler is within specification, and substantially agree with the '5061. S_{41} is much lower and it is more susceptible to the shortcomings of a simple 2-port cal. Here the Nano trace shows several dB of ripple that is absent in the '5061. Figure 13 blows up the S_{21} trace from figure 12. The Nano is struggling to accurately measure S_{21} as observed earlier, and a user who sought to fix a problem in a coupler that was causing even one-tenth of a dB of ripple would be unable to discriminate between that in the coupler and that caused by shortcomings in the measurement.

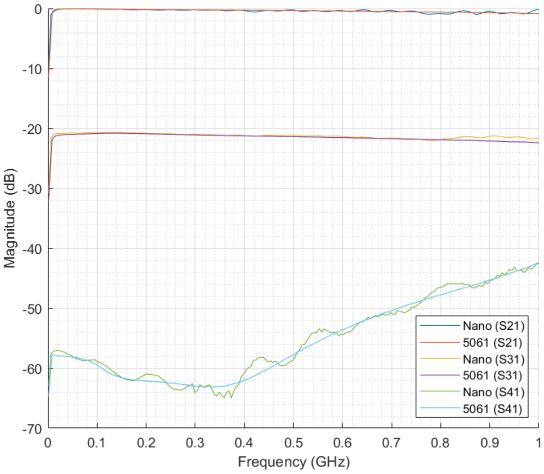

Figure 12: Comparison of S_{21}, S_{31} & S_{41} of a directional coupler with -20dB coupling factor, rated for 30 MHz–800 MHz. Port 1 of the directional coupler is connected to port 1 of the VNA, and each of the other ports are connected to port-2 of the VNA, one at a time, with unused ports terminated in loads.

4 Discussion

The Nano VNA performs well against the E5061 Keysight ENA. The word "fantastic" comes to mind given the price. The Nano was able to achieve decent results on every measurement we threw at it, and mostly with adequate accuracy. A surprising result was finding the Nano can resolve to within 1 Hz. This frequency resolution will enable fine bandwidth measurements.

In several instances the simple "1-port plus response" calibration of the Nano resulted in spu-

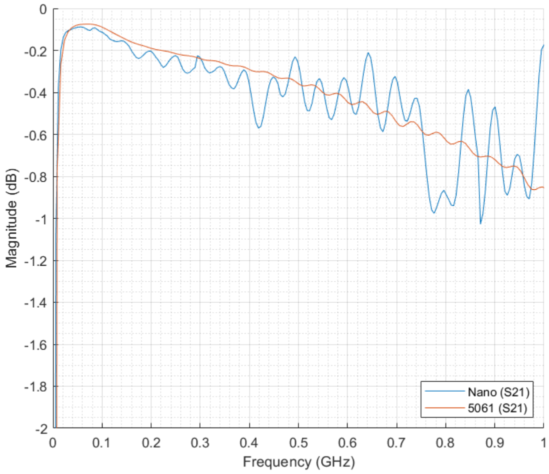

Figure 13: Comparison of S_{21} of the coupler, blown up from figure 12.

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rious ripples in the measured trace. If a smaller error margin is desired in any of these cases, then one has to buy the professional VNA. In particular, construction of a "clean" device, free from undesirable internal reflections, would be impossible without the superior performance of a professional instrument, because the Nano introduces too much of its own shortcomings.

Dynamic range of the Nano was fine up to 1 GHz, considering that harmonics are used above 300 MHz. We failed to reach the Nano's dynamic range limit. This was essentially because the calibration limitations kicked in first. The range is clearly better than -60dB, which seems more than adequate.

It is a shame about the inability to implement a full 2-port calibration with the Nano. Not only would this give S_{12} & S_{22} but it would correct for poor port-2 match, at least one (the major?) cause for extraneous ripples in many measurements.

A second directional structure, the ability to source signal from port 2, and an extra receiver channel would enable unknown-thru and adapter-removal calibrations. An unknown thru is useful in the case where a well-known thru is not available.[10] This turns out to be a common circumstance. This cal enables any device to be used as a thru, provided the device is reciprocal and the phase shift to within one-quarter of a wavelength is known. That through can connect otherwise-incompatible connectors or bridge a mechanical gap that cannot be reduced to zero or prevent stretching and bending of near-rigid cables. It will allow calibration to measure an "insertable device", given only one gender of calibration standards. (An insertable device is one that has one male and one female connector, so that it can be connected in series with other devices without an additional adapter. Most attenuators, unlike ours, are insertable, for example.)

Adapter removal is equally marvellous. Consider the difficulty of measuring a device that as an SMA connector on one end and an N-type on the other. If an adapter's behaviour can be calibrated out, a more accurate measurement of the DUT can be found.

The authors' expectation is that once the appeal of better calibration, and the simplicity of extra hardware are understood, the Nano VNA will acquire the ability to carry out these full 2-port calibrations. It will be worth the few extra dollars of hardware.

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