Teltest Electronics Laboratories, Inc.
Austin, Texas

Exploratory Paper

Vector Network Analyzer Calibration Pitfalls

Rev 0.03
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A Work in Progress

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1. Introduction

There is more to Vector Network Analyzer (VNA) calibration than meets the eye, particularly as frequency increases. There are a number of pitfalls on the way to competent VNA measurements. I want to share some of the things I have learned from the school of hard knocks. I have also observed and discussed VNA calibration with a number of what I consider competent and highly skilled engineers and technicians. From my observations, there is a general blind spot regarding VNA calibration. Many really believe their procedure for VNA calibration yields the desired results, when it is obvious to me that they do not. At last I have come up with a set of calibrations and measurements that clearly demonstrates what can go wrong and how to correct it.

In this paper I am most concerned with the reflection coefficient or S11/S22 measurement. I haven't been bitten by through measurements to the degree I have with S11. Therefore the discussions that follow concern only the reflection coefficient measurement.

One object of this paper is to provide information for an engineer or technician to determine the quality of the VNA calibrations in their own laboratory with readily available materials.

At the lower frequencies, the potential errors resulting from a less than ideal calibration can be minor, at the higher frequencies potential errors can be quite large. A factor comes into play relating to habits spawned in the low frequency arena carry over to high frequency measurements.

This paper will attempt to show where and when particular attention should be paid to the VNA calibration procedure and how to go about it.

The frequency range discussed here is from 300 KHz to 3.8 GHz that happens to be the limits of the instrument that I have at my disposal.

2. Calibration Kits

In many facilities, along with the VNA there is a calibration kit. The kit consists of open, short and load terminations. For each kit there is a set of parameters that describe the kit to the VNA. These parameters are essential to a valid calibration. My VNA (Advantest R3765CG) contains built in calibration kit parameter tables for several popular calibration kits. Its default is for type N connectors. I am not sure how other VNAs treat this; however I am pretty sure it is similar. This is a source of potential calibration problems as I will discuss later. The point is that you can pretty well assume that even though you haven't asked for one, a set of calibration kit parameters has been provided for you and more than likely it is the worst possible choice.

One of my pet peeves with calibration kits is that in general they do not provide verification terminations. Why is this a problem, you say? The point is that with just a calibration kit, you can in no way verify the performance of the VNA without at least one known termination other than the open, short or load. If you measure the load, it will repeatedly give you a nice straight line at the value you told it the load was even if it is not that value. Not much information here. To get meaningful information you must measure a termination of known value different from the calibration kit values.

3. No Calibration Kit

Many installations I have visited do not have a calibration kit or if they do have one it is a type N set which is quite close to not having one. What do you do now when you want to make valid VNA measurements? I'll answer this with what I have seen in many cases and is the case I have evolved from. You use a simple open, short and load constructed with what ever type of connection technique you are using to access your circuit of concern. This seems valid. But wait. What parameter set are you using? You can bet that that the VNA is using one and it probably doesn't represent the "calibration kit" you are using. I can tell you that your results will less than optimal.

The reason I said that the type N calibration kit is close to not having one is that type N is applicable to very few actual measurements I have made. I have to qualify that in that generally I am measuring small circuits and components. Getting connection to the circuit or component is usually a challenge in itself. As a result I have developed small connector sets for this purpose.

4. Verification Kits

I have become a strong proponent of calibration kits containing a number of verification terminations. In this way verification can performed routinely and one can have much more confidence in the measurements taken. A VNA will always give you numbers, whether those numbers are meaningful to your objectives is another matter.

5. Some Calibration Examples

Some example calibrations and the results obtained via verification are useful at this point. What I will do here is calibrate my VNA with the sets of calibration kit parameters resident in the instrument sequentially and for each set measure the verification terminations and display the results. You can then see for yourself the errors that result. My VNA has six parameter sets built in. They are shown below.

Table 5-1 Advantest R3765CG Cal Kit S11 Parameters

Cal Kit	C0	C1	C2	C3	Open Offset Delay	Short Offset Delay
N Female	99.14	353.6	62.23	0.0	37.042	42.125
N Male	103.0	0.0	-110.0	10.2	19.42	24.503
3.5mm Female	60.75	-1288	107.5	-2.146	14.485	16.678
3.5mm Male	63.17	-1178	109.6	-1.91	14.485	16.678
7mm	92.85	0.0	7.2	4.3	0.0	0.0
Don't Care	0.0	0.0	0.0	0.0	0.0	0.0
Units	$x10^{-15}$ F	$x10^{-27}$ F/Hz	$x10^{-36}$ F/Hz^2	$x10^{-45}$ F/Hz^3	pSec	pSec

5.1. TELI Calibration/Verification Kit

The calibration/verification kit used is one created in the TELI laboratory. It consists of twelve terminations built around 50 mil pin socket connectors. This kit is shown in Figure 5-1 and Figure 5-2. The kit has evolved through a series of connectors in an effort to obtain a means to connect into tiny circuits on PCBs, while also introducing the least delay and parasitic inductance and capacitance. In other words, to obtain as near an ideal termination as possible in my laboratory.

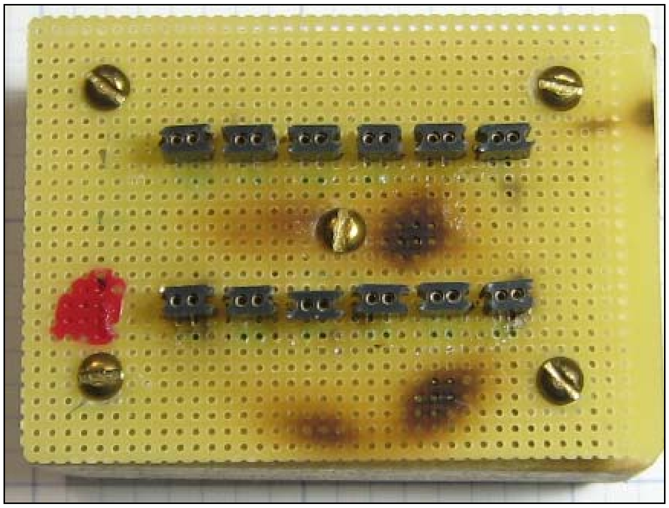

Figure 5-1 50 mil 12 Termination Calibration/Verification Kit – Top View

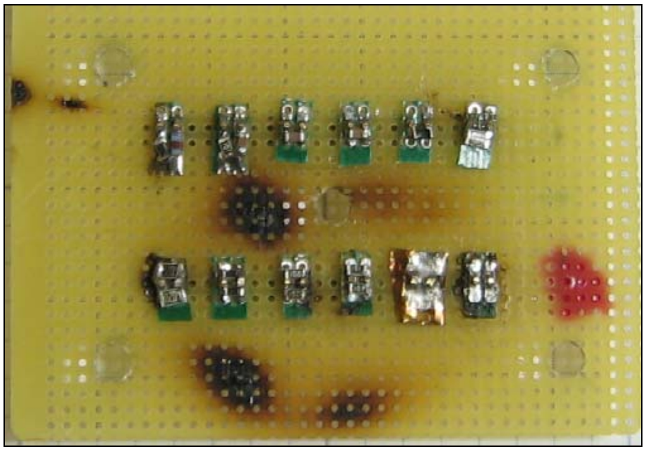

Figure 5-2 50 mil 12 Termination Calibration/Verification Kit – Bottom View

The values of the terminations are shown in Table 5-2.

Table 5-2 TELI 50 mil Calibration/Verification Kit Values

Termination	Value
1	Open
2	Short
3	50 Ohms
4	100 Ohms
5	25 Ohms
6	201 Ohms
7	402 Ohms
8	43 nH Inductor
9	1 pF Capacitor
10	10 pF Capacitor
11	100 Ohms + 1 pF
12	100 Ohms + 52 nH

The calibration is accomplished using the open, short and 50 ohm load. Then each of the elements is measured and recorded. The files are then brought into MathCAD for analysis and are shown and discussed below.

There is a large amount of data to peruse and compare, therefore I will show each type of plot and discuss it large scale so that the reader can be familiar with the presentation. Then I will show comparative combined plots on a smaller scale.

5.2. Resistive Terminations

The first plot, shown in Figure 5-3, is the deviation from the expected value for each resistive termination and presented in percent deviation vs. frequency. The frequency range is 300 KHz to 3.8 GHz. The expected deviation does not take into account parasitic inductance and capacitance for each termination. This will be discussed below.

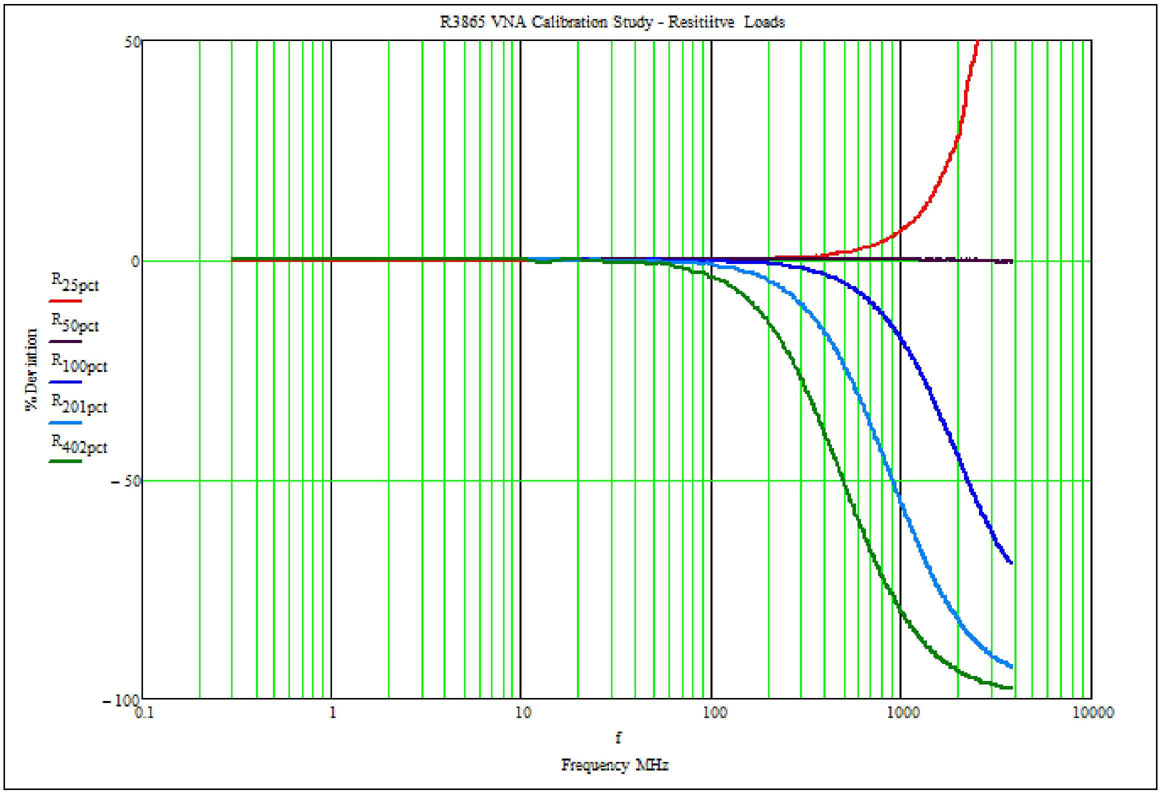

Figure 5-3 Parameter Set Type N - % Deviation of Resistive Terminations

The next plot, shown in Figure 5-4, is the measured imaginary part or reactance for the terminations in ohms. It can be seen that there is a large reactance observed at the higher frequencies. What should the reactance of the resistive termination be? If the termination were ideal, there would be no reactance. However, the terminations are not ideal, although they are close, and there will be some reactance. The question is how much reactance and how much of that is due to the termination and how much is an artifact of the calibration. This discussion will evolve in the presentation that follows.

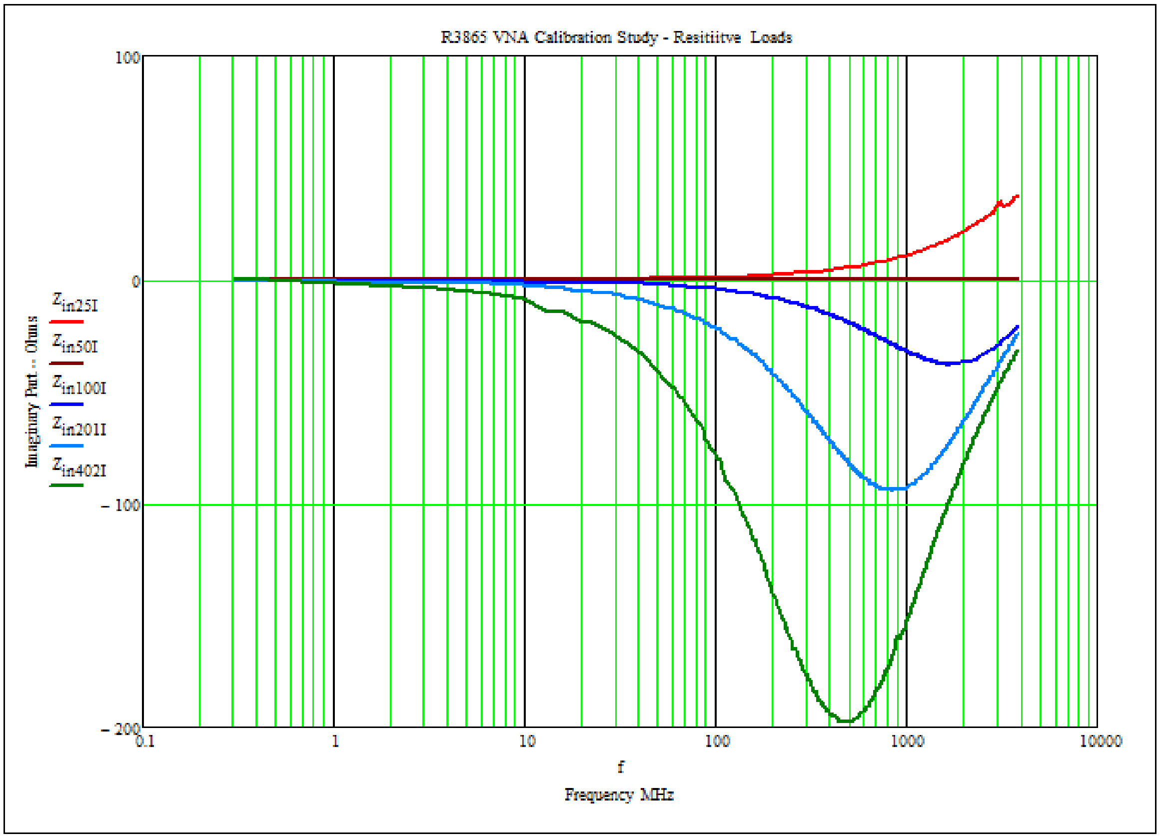

Figure 5-4 Parameter Set Type N – Measured Reactance of Resistive Terminations

Shown in Figure 5-5, are the Smith chart and return loss plots for the resistive terminations. These are helpful to me to visualize the quality of the calibration as I think the reader will appreciate as the presentation continues.

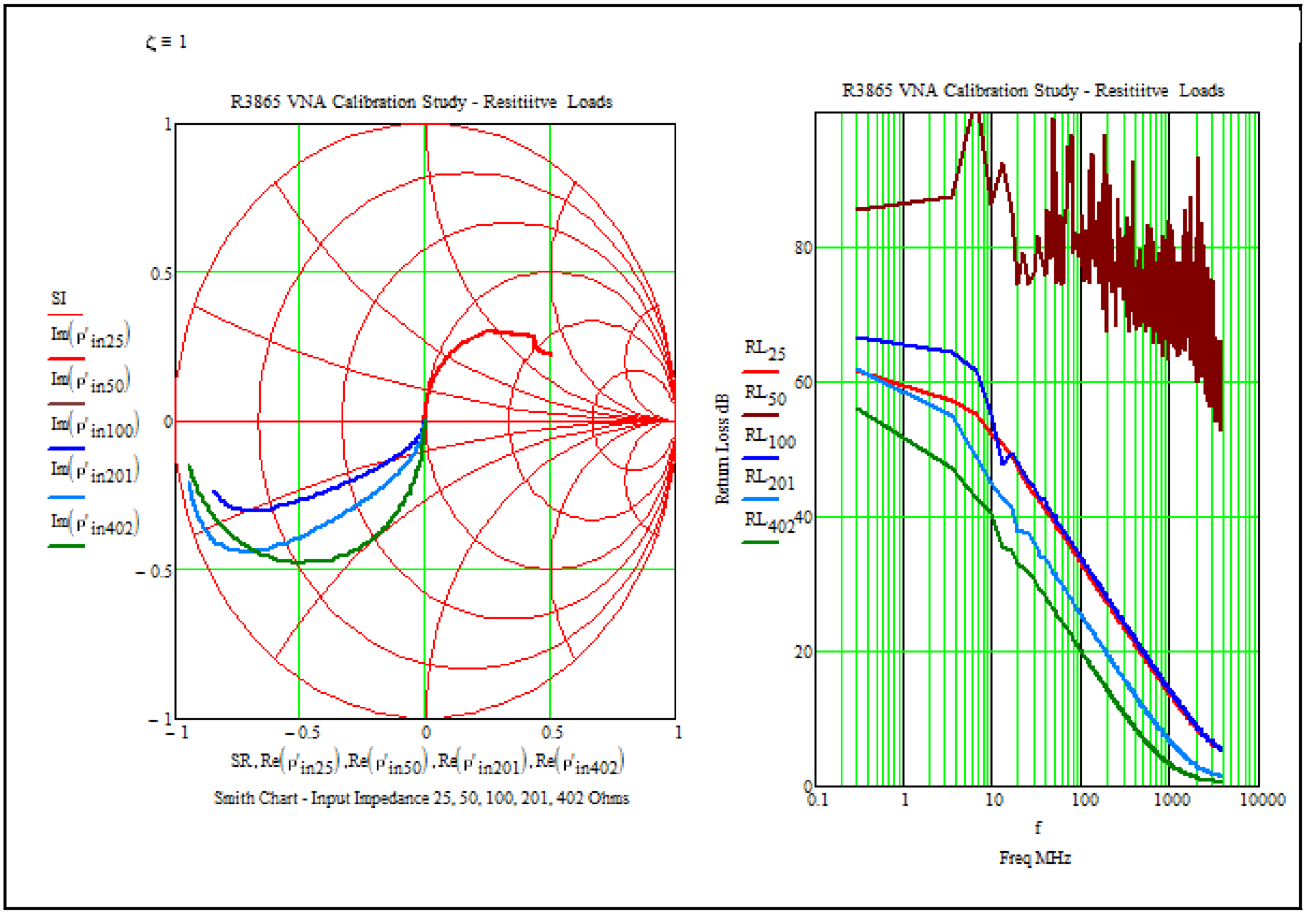

Figure 5-5 Parameter Set Type N – Smith Chart and Return Loss of Resistive Terminations

At this point I will present The combination of the above plots for all of the parameter sets.

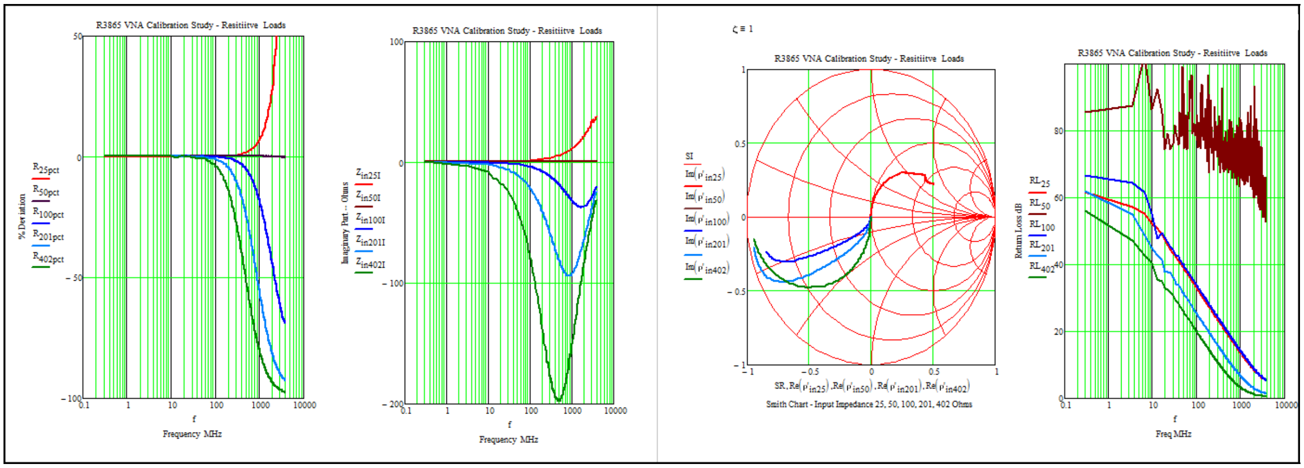

Figure 5-6 Parameter Set Type N Female – Resistive Terminations

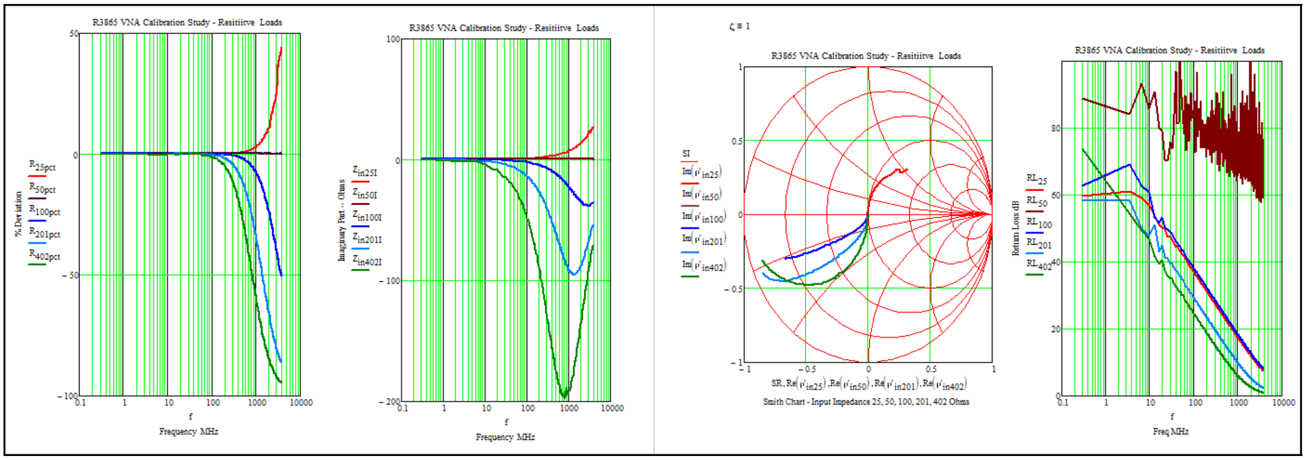

Figure 5-7 Parameter Set Type N Male – Resistive Terminations

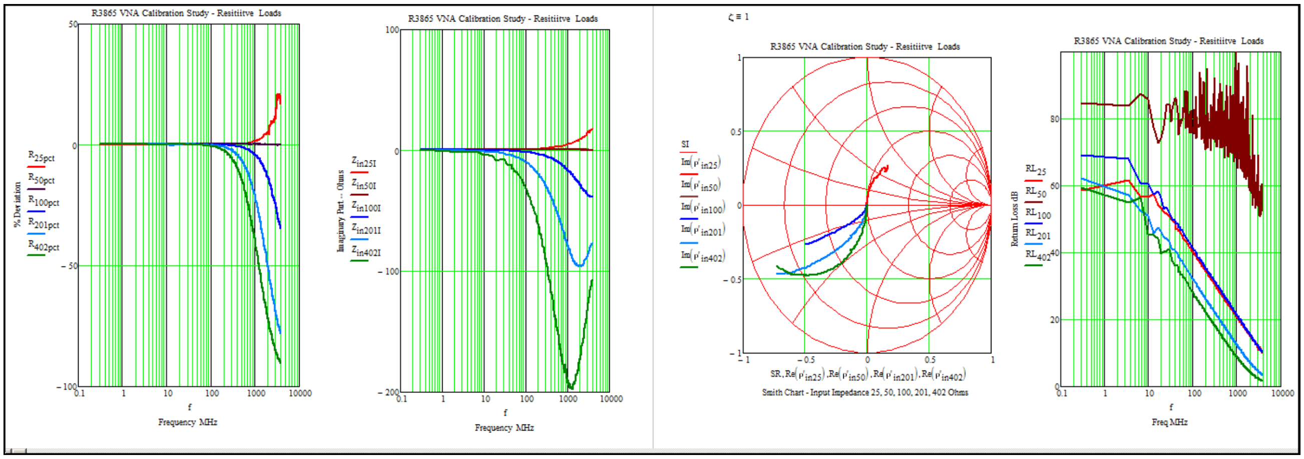

Figure 5-8 Parameter Set Type 3.5mm Female – Resistive Terminations

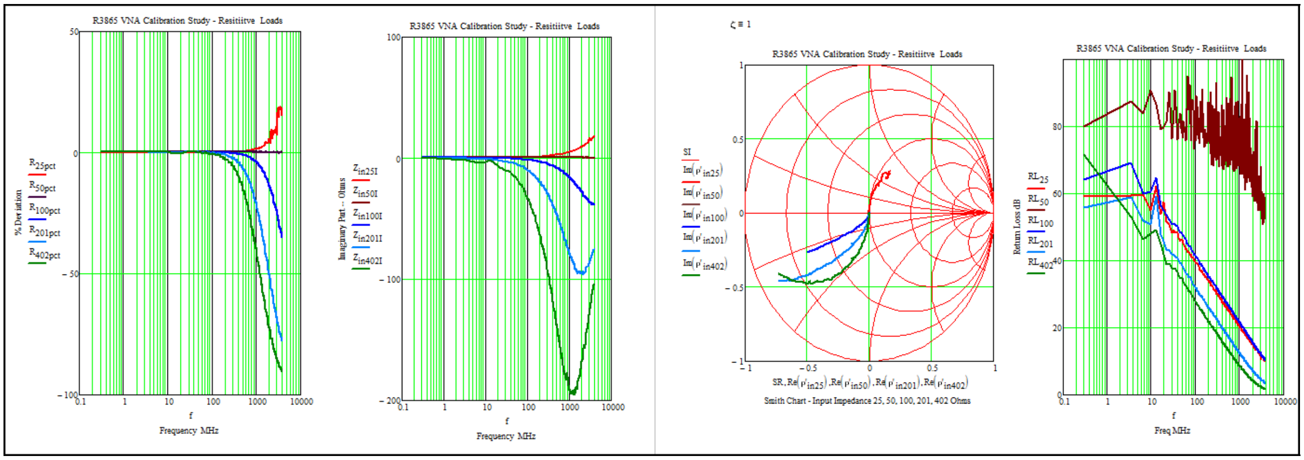

Figure 5-9 Parameter Set Type 3.5mm Male – Resistive Terminations

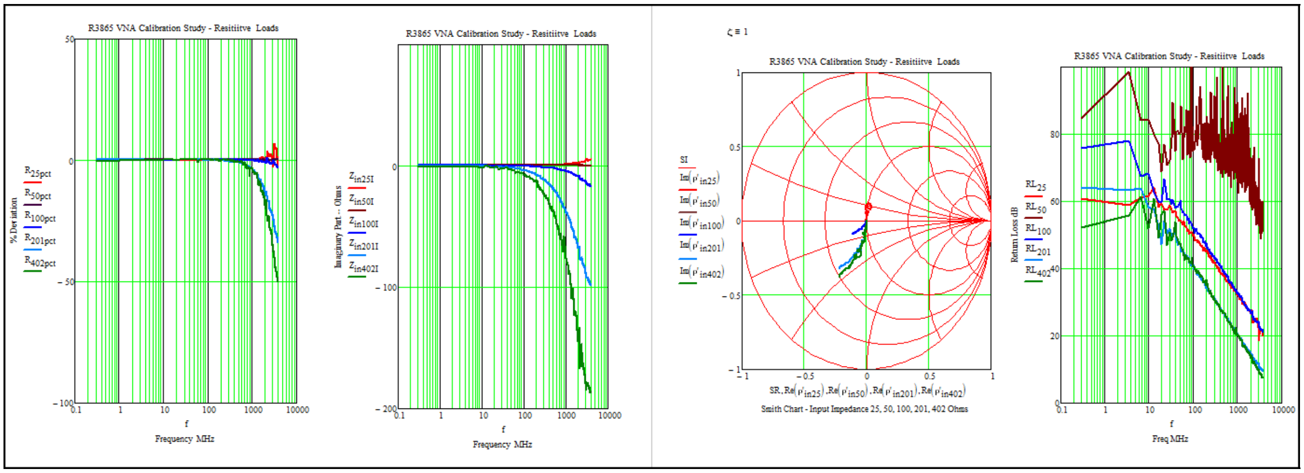

Figure 5-10 Parameter Set Type 7 mm– Resistive Terminations

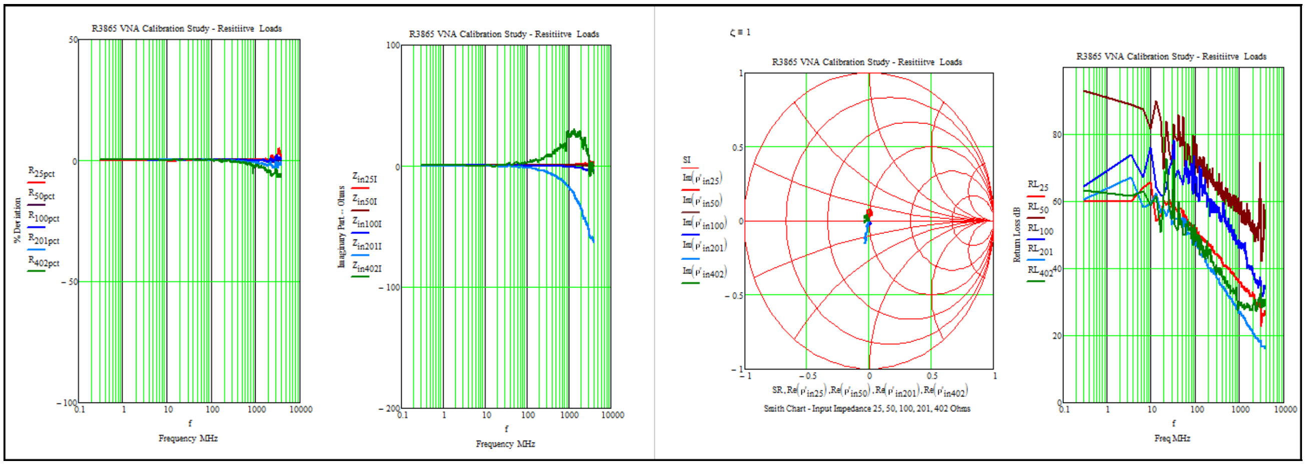

Figure 5-11 Parameter Set Type Don’t Care– Resistive Terminations

It is obvious that parameter set chosen makes a big difference in the quality of the calibration. There are a number of questions that remain. The terminations do have parasitic inductance and capacitance and the question is how much? This gets to be complex to determine and involves a bit of the “chicken and the egg” conundrum. I have to have the VNA calibrated accurately to determine the parasitic elements and I have to have the parasitic elements determined to calibrate the VNA. I have made some reasonable estimates and calculations on this to the point that I believe the parameter set Don’t Care is the closest to an accurate calibration for the VNA. I will continue working on this and it will be the subject of a future paper.

Figure 5-12 shows plots of these calculations on the same scales as the previous plots.

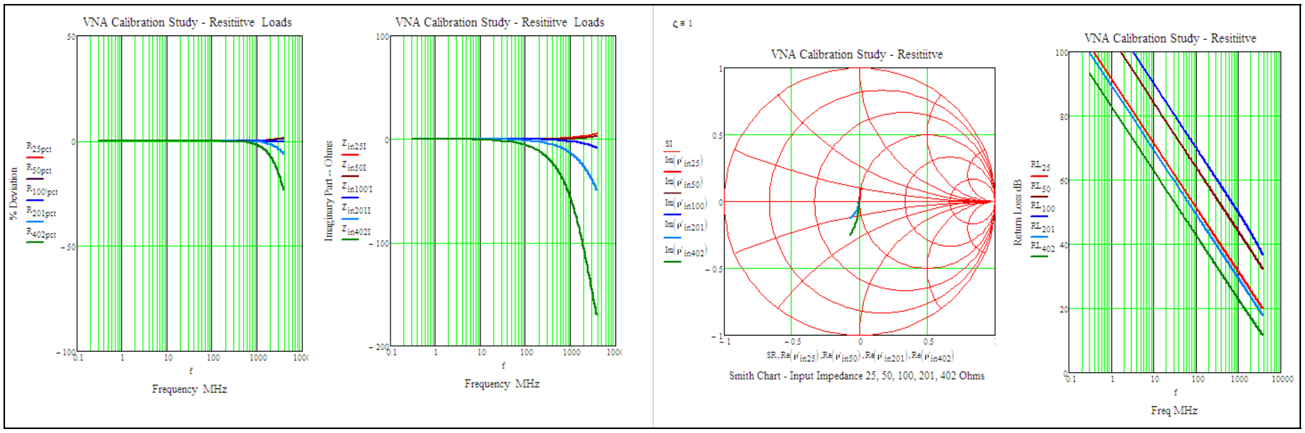

Figure 5-12 Calculation of Restive Terminations with Estimated Parasitics

I will assume for the moment that the Don’t Care calibration (no corrections) is correct for this calibration kit and that the plots represent the actual values of the terminations. I can then use those values to see when and where for example the Type N Female parameter set introduces errors in the measurements. To see the errors more clearly, I have expanded the plots. Figure 5-13 shows the results from the Don’t Cars set calibration and Figure 5-14 shows the results from the Type N Female set calibration.

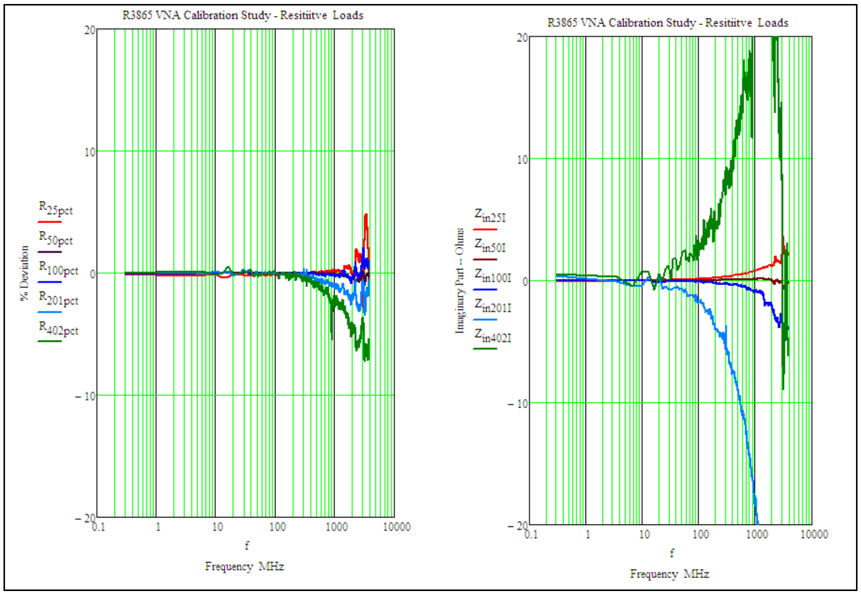

Figure 5-13 Parameter Set Type Don’t Care– Resistive Terminations Expanded

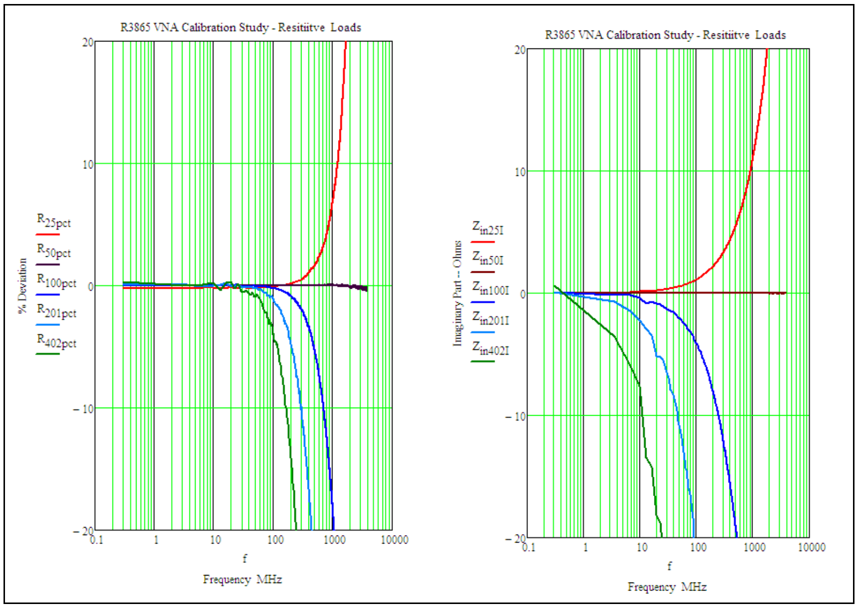

Figure 5-14 Parameter Set Type N Female – Resistive Terminations Expanded

One interesting point is that if it the measurements of interest involve an area quite close to the calibration load value, in this case 50 Ohms, little errors are observed with any of the calibrations. An example of this would be tuning a load, say an antenna, to match the calibration load value. The measurement would be precise when tuned.

Otherwise, one must consider the frequency and how far the measurement is from the load calibration value. One way of looking at this is with the Smith chart. One full rotation on the Smith chart is ½ wavelength. Thus as frequency increases, wavelength decreases and for a given length the rotation increases as frequency increases. Couple that with the fact that the further from the center the value is the more it changes with rotation. For example at the center, the value does not change with rotation, however at the edge it changes drastically. Therefore, as frequency and distance from the center increase much more care must be taken with calibration to measure an unknown accurately. Figure 5-15 is a plot of several VSWR values on a Smith chart. For high frequency and VSWR values more attention must be paid to calibration to obtain accurate results.

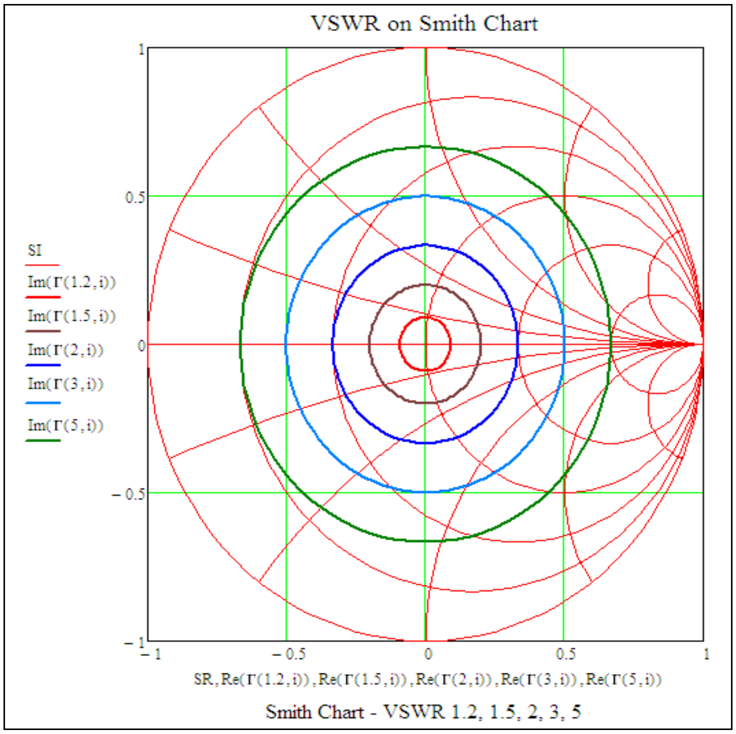

Figure 5-15 VSWR on Smith Chart

5.3. Inductive and Capacitive Terminations

There are more terminations in the calibration/verification kit and I will present these in a similar manner. The first will be pure inductance and capacitance. Figure 5-16 shows the measurement of a 43 nH inductor on a larger scale for the Type N Female set to examine the plots.

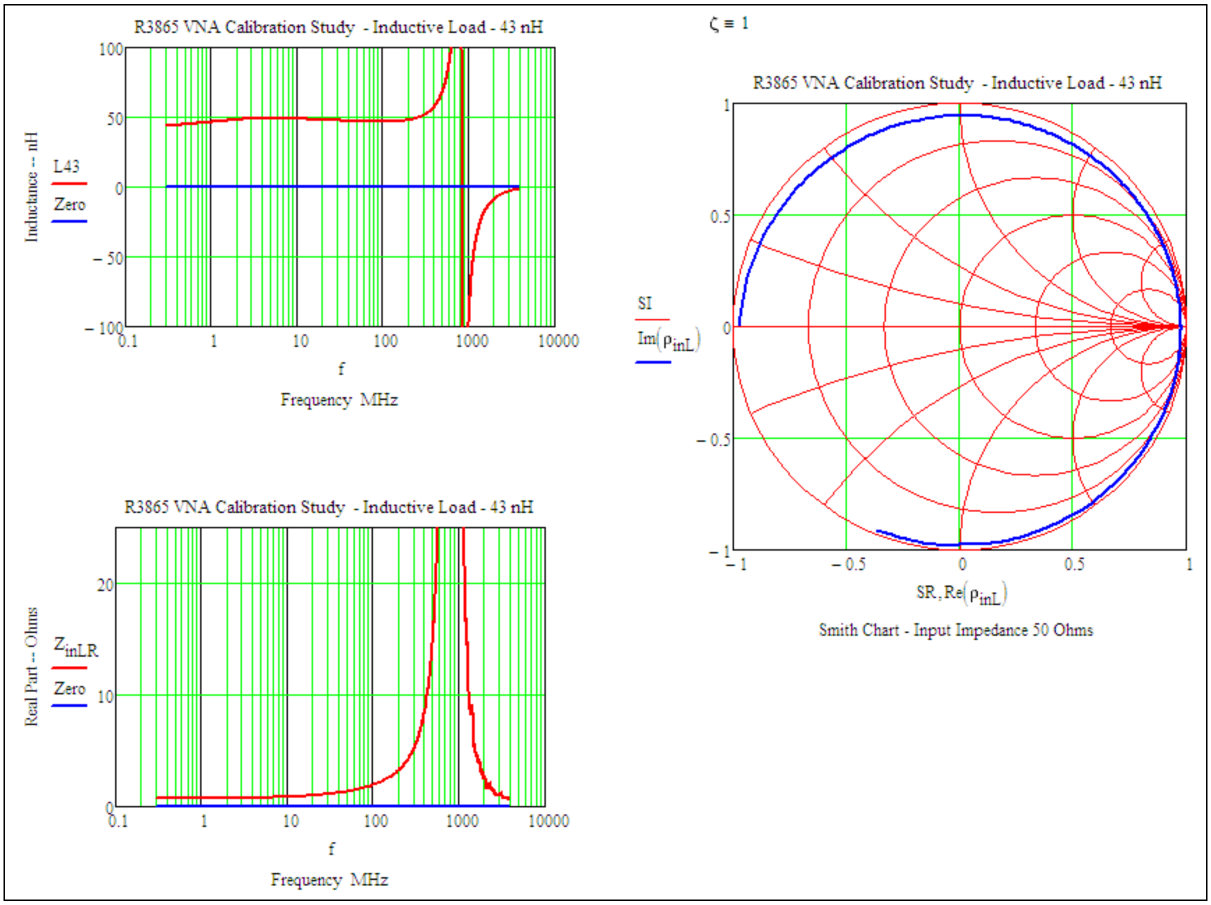

Figure 5-16 Parameter Set Type N Female - Expanded Pure Inductance Measurement

The upper left plot shows the plot of inductance value. It can be seen that the value is quite constant up to the self resonant point of the inductor. The exception is at 300 KHz. Here the inductive reactance is so much less than the resistance (approximately 0.9 Ohms) that the phase angle is very small and therefore the instrument has trouble resolving the reactive part accurately. The next data point is at 3.466 MHz, so it appears the deviation goes lower in frequency than it actually does. This effect can be seen on other plots that follow.

The lower left plot shows the real or resistive part of the termination impedance. The value starts near its actual value at low frequencies and increases steadily as the frequency approaches resonance.

On the right is the Smith chart presentation. It starts on the left at the value of 0.9 Ohms real and rotates with frequency around the edge of the chart.

Figure 5-17 shows the measurement of two capacitors, a 1.0 pF and a 10.0 pF.

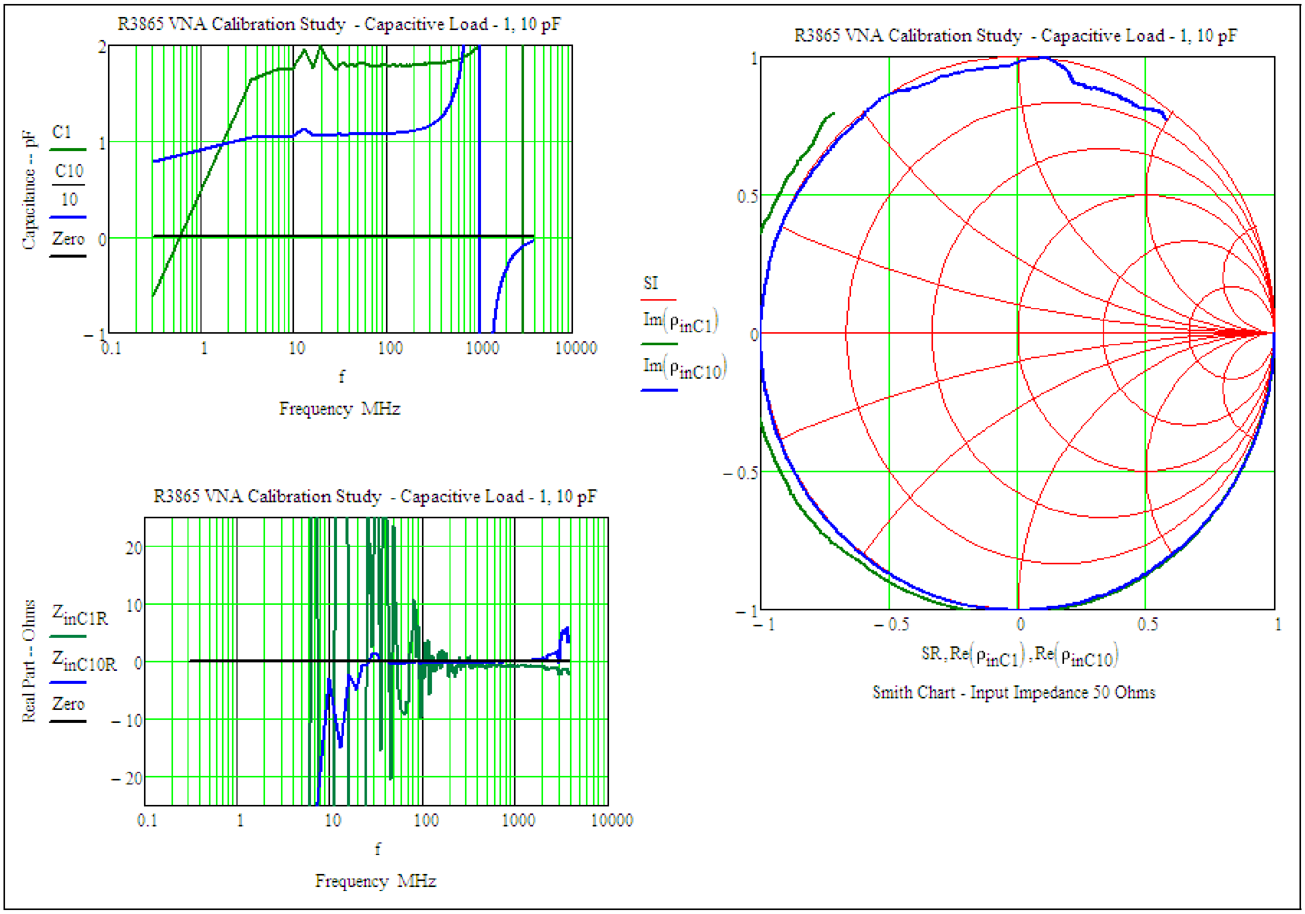

Figure 5-17 Parameter Set Type N Female – Expanded Pure Capacitance Measurement

The measured capacitance values are shown on the upper left plot. Note that the 10 pF value has been divided by two so that it can be presented with the 1 pF value on the same scale. Also note that the value is approximately 1.8 pF, a substantial error. That is consistent up to resonance. As mentioned above the value at 300 KHz is off, however it is on track at 3,466 MHz. The capacitive reactance for the 1 pF termination is 530 kOhms at 300 KHz. Both capacitive terminations show resonance with parasitic inductance at the upper end.

The resistive or real part is shown in the lower left plot. The value of the reactance is large and the phase angle is near 90 degrees at the lower frequencies and therefore the real part id difficult to accurately determine, however it begins to settle out as frequency increases. Note that the real part for the 10 pF termination begins to settle about an order of magnitude lower in frequency as might be expected.

On the right is the Smith chart presentation. It starts on the right real and rotates with frequency around the edge of the chart.

Figure 5-18 and Figure 5-19 compare the results of the calibrations with the Type N Female and Don’t Care parameter sets.

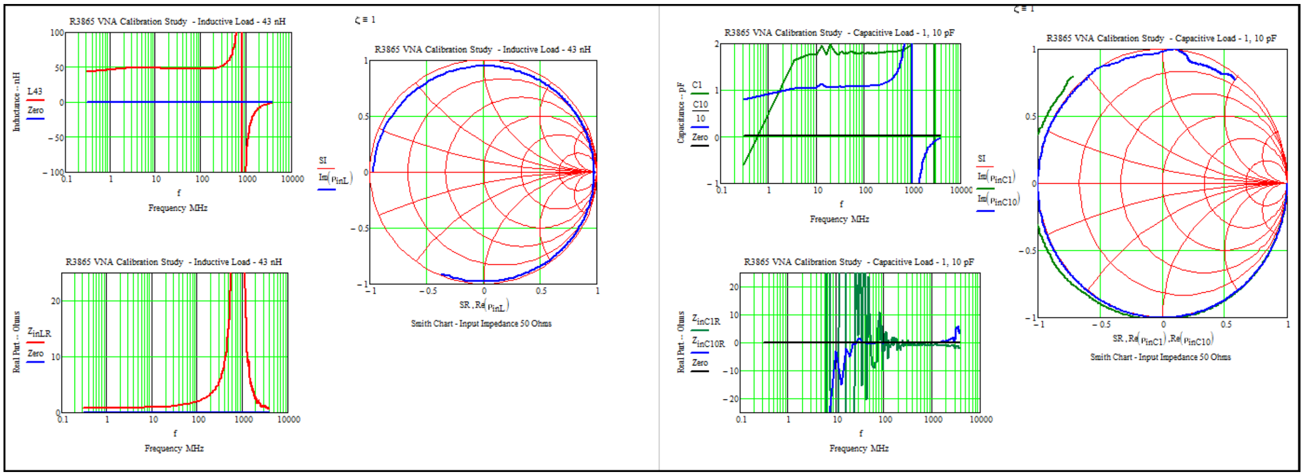

Figure 5-18 Set Type N Female – Inductance and Capacitance Measurements

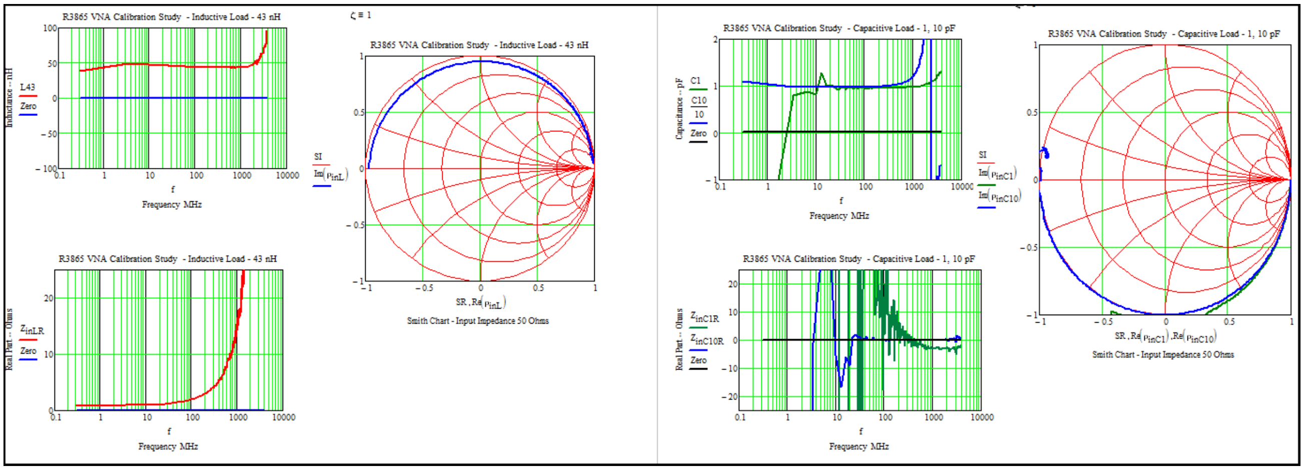

Figure 5-19 Set Don’t Care – Inductance and Capacitance Measurements

For the inductance termination it can be seen that the resonant frequency is higher and also that the 1 pF is accurately measured with the Don’t Care set.

5.4. Mixed Terminations

Two types of mixed terminations are employed, a 52 nH inductor and a 100 Ohm resistor in series, and a 1.0 pF capacitor and a 100 Ohm resistor in series. The expanded mixed inductive termination measurement is shown in Figure 5-20.

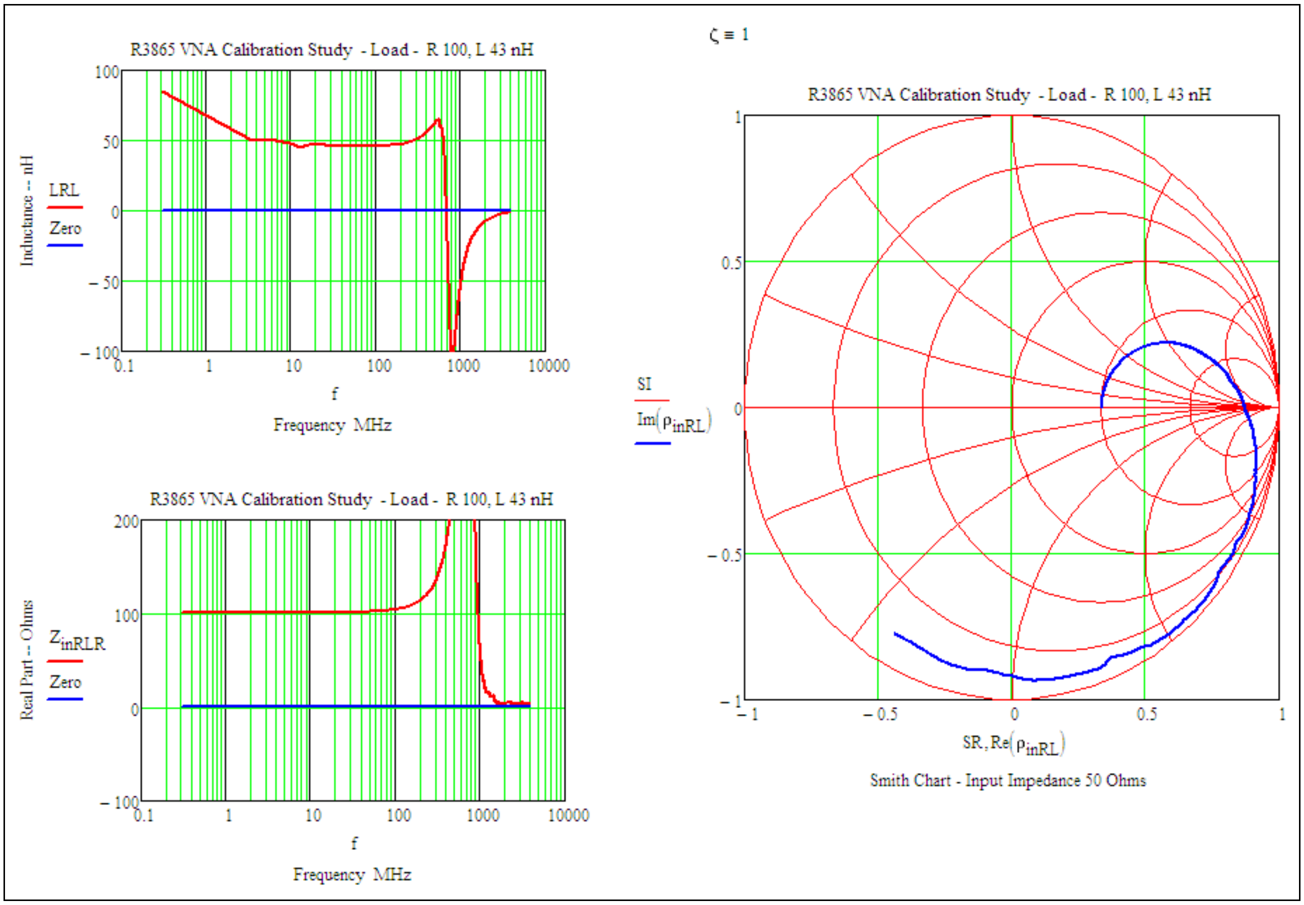

Figure 5-20 Parameter Set Type N Female – Expanded Mixed Inductive Measurement

The upper left hand plot shows the measured inductance. Except at the beginning and as resonance is approached the value of the inductance is approximately 48 nH.

The lower left hand plot shows the resistive or real part of the measurement and can be seen to be approximately 100 Ohms until resonance is approached.

The right hand plot shows the Smith chart for the measurement.

The expanded mixed capacitive termination measurement is shown in Figure 5-21.

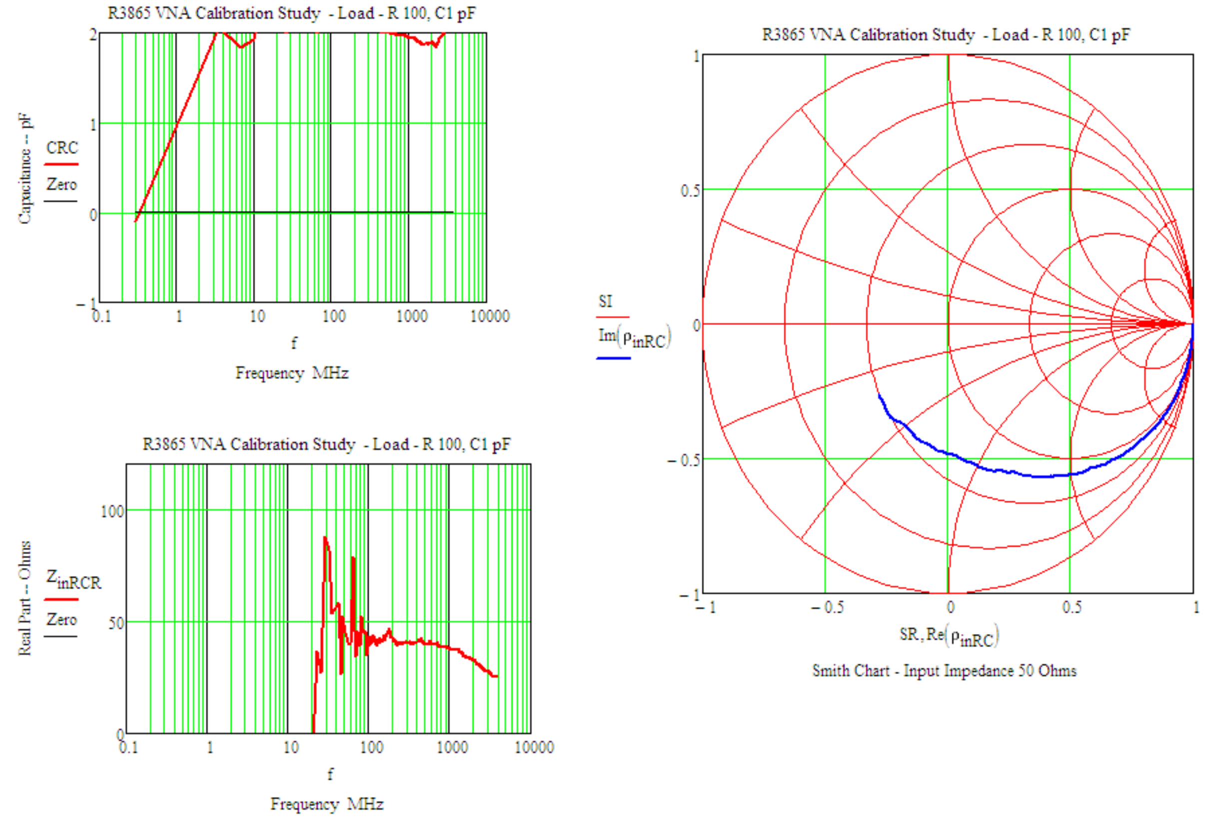

Figure 5-21 Parameter Set Type N Female – Expanded Mixed Capacitive Measurement

The upper left hand plot shows the measured capacitance. Except at the beginning and as resonance is approached the value of the capacitance is approximately 2 pF.

The lower left hand plot shows the resistive or real part of the measurement and can be seen to wander about til about 100 MHz and then seems to settle for a value less than 50 Ohms.

The right hand plot shows the Smith chart for the measurement.

Figure 5-22 and Figure 5-23 show the comparison between the Type N Female and Don't Care parameter set calibrations for these measurements.

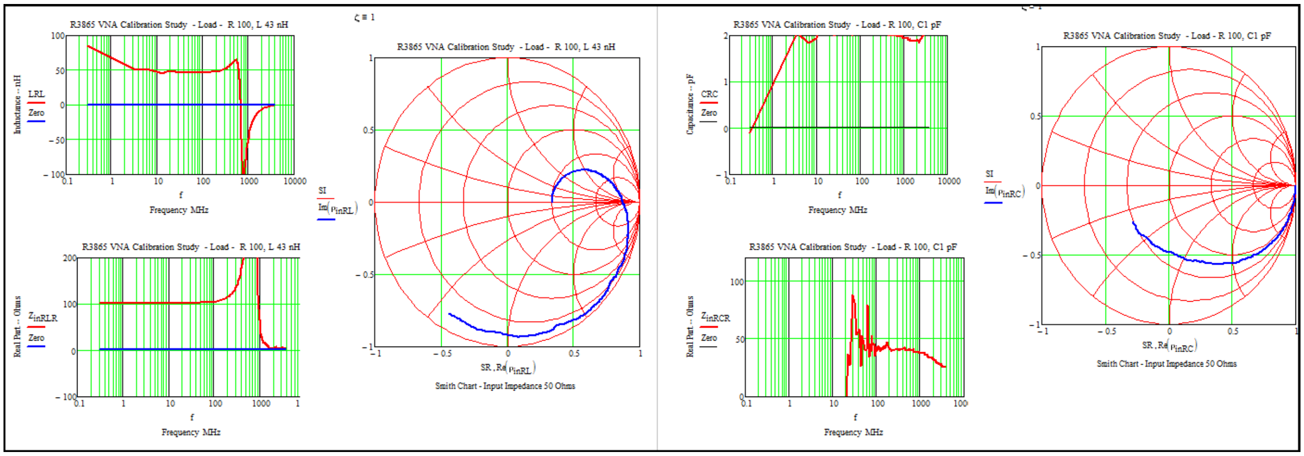

Figure 5-22 Set Type N Female – Mixed Inductive Measurement

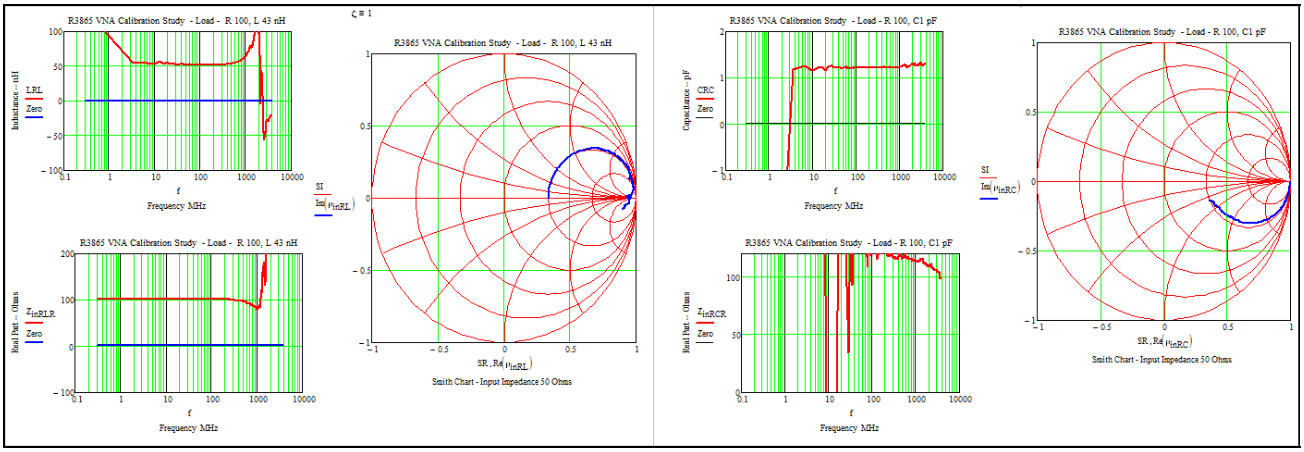

Figure 5-23 Set Don't Care – Mixed Capacitive Measurement

Note that the measurement accuracy is better for both the capacitance and the inductance measurements along with the resistive for the mixed capacitive measurement with the Don't Care parameter set.

5.5. Open and Short Terminations

I don’t have any commentary for the open and short measurements, however they included fro completeness.

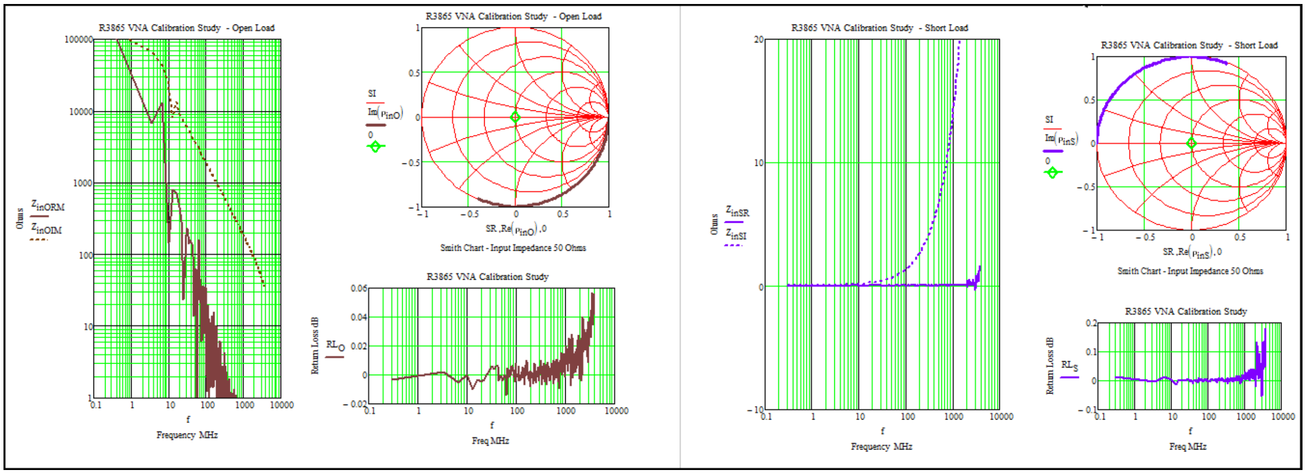

Figure 5-24 Set Type N Female – Open and Short Measurements

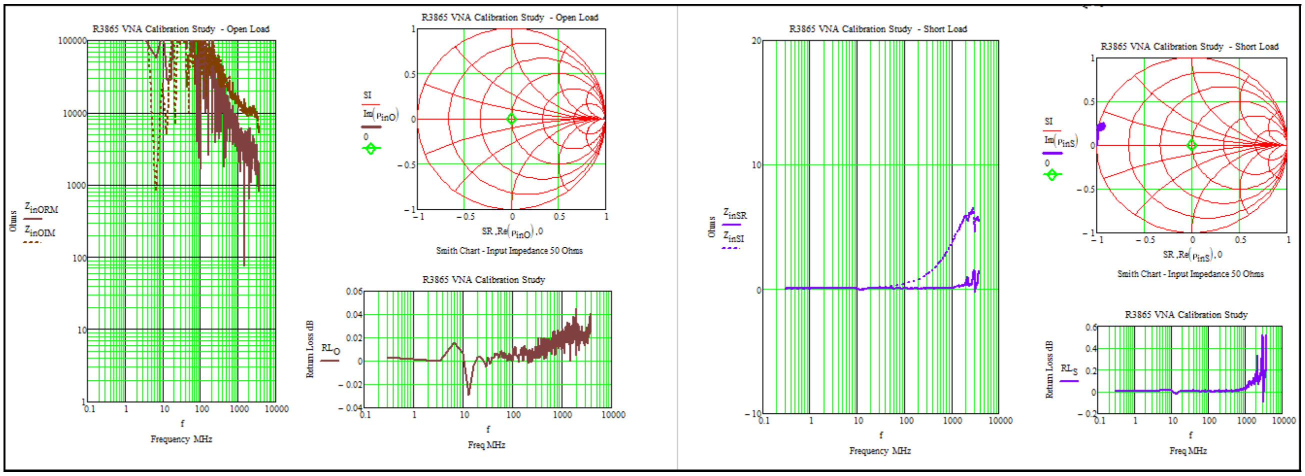

Figure 5-25 Set Don’t Care – Open and Short Measurements

6. Conclusions

It does make a difference how a VNA is calibrated regarding the accuracy of the measurement result in most all cases. Granted below 20 MHz most of the resulting errors are rather benign, some can be important particularly if the unknown is a high vswr. Even at low frequency, there were significant errors for the mixed terminations when the type N parameter set was used for calibration.

As the frequency increases and as the vswr increases the effects calibration parameter set choices on the measurement accuracy increase significantly.

It is important to be aware of the parameter set in use by the instrument when the instrument is calibrated. This is especially true when the frequency or vswr of interest increases.

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