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Exploratory Paper

Vector Network Analyzer Usage and Calibration Techniques

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Table of Contents

Table of Figures

Table of Tables

1. Introduction

In this paper I am speaking primarily to the engineer, technician or experimenter who has become interested in Vector Network Analyzer (VNA) measurements and techniques. Information on practical calibration and measurement techniques for me has been hard come by and difficult to sort out the information relevant to my needs.

The purpose of the paper is to bring out the salient information about the practice of employing VNAs to accurately measure unknown circuits. Where I am going is to develop the techniques to calibrate the user generated calibration kit to determine the calibration kit parameters the instrument needs and uses. I don't mind displaying my ignorance if in response to that relevant information comes forth. Also, I have not dug through the IEEE papers and such. I have depended on lower level searches. My objective is the ability to make accurate VNA measurements and to pass on that information along with the pitfalls. I have run up against the pitfalls in my work and want to be on top of them. I am particularly concerned about people like myself who have come into the VNA community by acquiring one and having to learn how to use them.

This paper is an exposition of my knowledge and experience regarding VNA usage and calibration. Much of this has come from the school of hard knocks. It is my intent that this paper will provide a forum for the evolution of the knowledge concerning vector network analyzer usage and calibration that will benefit me and others. It is expected that this will change, evolve and correct as the project proceeds and as knowledge and experience are gained. Of particular interest is the creation and calibration of calibration/verification kits for VNAs.

I have been intently interested and intrigued by vector network analysis and MathCAD capabilities for the past several years. My introduction to VNAs began about ten years ago when I was studying T3 and GigE transmission magnetics for a client. About five years ago, after much consternation, I acquired a competent VNA. For me this has been a love affair with the possibilities to measure and understand electromagnetic phenomena. I learned early on that proper calibration was essential and crucial to accurate measurements. As time has passed I have learned more and more just how true that is. Also, I have learned how difficult information on this subject is to come by.

Another aspect that has disturbed me was the lack of understanding of VNA calibration and the cavalier techniques I have observed many otherwise competent engineers employ in VNA calibration and measurement. A given with VNA measurements is ***they will always give you numbers***. Whether they tell you what you want to know about the circuit being measured is another question altogether. Proper calibration and connection to the circuit is the key.

This paper will be primarily concerned with S11 measurements that are the measurement of the reflection coefficient of the unit under test.

This paper is critical of the general practices I have observed in the use of VNAs to make important decisions in the design and verification of electronic circuits and systems.

The paper is far from being finished. And I am not attempting to answer the question as much as to ask it. If someone has a simple way to calibrate a VNA to get accurate verifiable measurements in the low GHz range with non-standard connectors I would like to hear it and I will adopt it and let it be.

The bottom line is that I want the capability to make accurate verifiable measurements with the VNA. Today I know a lot of barriers to that that are being either unconsciously ignored or swept under the rug. I know part of the way of getting there and am looking for more.

2. VNA Usage – S11

Generally, a VNA is employed to characterize a circuit of some kind at RF frequencies. It is necessary that the VNA be calibrated to obtain accurate results.

2.1. Calibration

Calibration establishes a measurement plane for which the measurement results are applicable. For most measurements the measurement plane will be the junction between the VNA or the VNA cable and the circuit to be measured. The operator needs to know that the measurement results apply to a circuit connected to that point. If the point of measurement is not at the measurement plane, then the path from the measurement plane must be translated. If the path between the measurement plane and the point of measure is a transmission line of known parameters, this can be accomplished on the Smith chart. If not it becomes very difficult to accomplish. The point is that the measurement plane should be established if at all possible at the point of measure.

Whether properly calibrated or not the VNA will always produce results. It is up to the operator to determine that those results are relevant to the desired measurement at hand. Calibration and verification provide the tools for accomplishing this.

There are a couple of predominant methods for doing this.

2.1.1. Calibrate at VNA Front Panel

The first is to calibrate at the VNA front panel using a calibration kit. Measurements are then taken using a coaxial cable connected to the unit under test (UUT). The measurements taken must then be translated via Smith chart techniques from the VNA calibration plane to the desired measurement plane. This requires accurate knowledge of the cable characteristics and the connection to the UUT. At the lower frequencies this is not too difficult; however at the higher frequencies this can be problematic and a great source for errors to creep in.

2.1.2. Calibrate at End of Measurement Cable

The second and my preferred method is to calibrate at the end of the measurement cable. This requires a cable at the characteristic impedance of the VNA and a calibration kit with the type of connector employed on the cable end. This works fine if the UUT is equipped with that type connector and a calibration kit for that connector is available. My experience has been that neither of these conditions is generally true. In addition calibration kits if available are expensive and in my opinion lacking in verification terminations. I will discuss this in more detail below.

2.1.3. VNA Calibration Kit Parameters

An essential part of the calibration kit is the set of kit parameters that are either manually or by file entered into the VNA. It is also essential to know that that there is generally a set of calibration parameters in the VNA whether the operator has entered them or not. The set of resident parameters may or may not describe the calibration kit in use at the time. It is the operator's responsibility to be certain that the proper parameters are in the instrument. A question? What set of parameters are applicable when an arbitrary set of terminations is employed to calibrate the instrument? Many operators I have observed have used an in-lab fabricated short, open and load to calibrate the instrument without determining the parameter set in use.

It is important to know that most VNAs have resident a selection of calibration kit parameters and that one of the sets is selected by default. On the Advantest R3765 it is the type N female set. Unfortunately, for almost all of the measurements I make this is the least desirable set for my calibrations. When a calibration is performed a set of calibration kit parameters will be employed by the instrument. It is up to the operator to select the proper set.

2.1.4. Calibration Verification

In my opinion an essential but rarely employed part of VNA calibration is verification of calibration. This requires a set of terminations with known impedances different from those of the calibration kit. Generally the calibration kit consists of a short, an open, a load and a thru connection. These cannot be used to verify calibration. The instrument calibrates to these values based on the calibration parameters it is aware of. Therefore a measurement of these terminations will simply yield what the instrument has been told is the appropriate value. With the exception of the load value, If the inappropriate parameters are in the instrument the resultant data will appear correct. The only way I know to verify calibration is to use a set of terminations removed in value from the load value. I have found it important to use both resistance and reactance terminations for this purpose.

In my opinion calibration without verification is “sloppy” laboratory technique, because the operator cannot ***know*** that the instrument is calibrated without it.

2.2. Termination Connectors

2.2.1. Standard Connectors

Calibration kits are available for a number of standard connectors. However, standard connectors in many cases are difficult to employ unless the UUT has been properly prepared with the desired connectors. When attempting to make measurements on existing boards for example, some sort of connector must be kludged onto the board. Generally standard connectors are difficult to properly kludge onto the board to measure the circuit of interest.

2.2.2. Non-Standard Connectors

If you are able to make a standard connector for which you have a calibration kit work that is great. In my work this has rarely been the case and as time has gone by the frequencies of interest have gone up and the dimensions of the circuits has shrunk. Therefore I have developed calibration kit terminations for my lab use around some non-standard connectors, at least in the sense of standard RF connectors for which calibration kits are available. This has worked well for me, particularly in that most of my past measurements; the frequencies involved were 100 MHz or less. Now I desire to make competent measurements at higher frequencies and my verification is showing that, even at the lower frequencies, I have to pay much more attention to the calibration kit parameters. Otherwise, the further I get from the calibration kit load impedance the greater the measurement errors are. And the errors grow with frequency. So, the next step comes down to accurately determining the calibration kit parameters for the kits I fabricate.

2.3. Measurements in Actual Circuits

3. Making Calibration Kits

Regarding calibration kits, few people have them and fewer yet who have them for more than one connector type (usually a type N}. Also, in today's smaller and denser circuits, standard connector types are not an option. So how do you get at valid information about those circuits behavior if you can't calibrate for an interface to that circuit.

3.1. Selecting Connectors

If a standard connector will effectively interface the circuit desired to be measured and a calibration kit is available for that connector, the problem is simpler. However, even in this case a barrier can be the cost of the calibration kit. For many of the circuits that I desire to measure a standard connector is not applicable. In these cases I have developed connection systems around 100 and 50 mil pin/socket strips cut to length. These can be soldered directly to the circuit in question, are small and have little delay and parasitic inductance and capacitance. An example is the measurement of an antenna on an automotive key fob to facilitate matching the antenna to its driver.

Worthy of mention is a new connector being used in cel phones and such is the UMCC connector. It is tiny and terminated cables can be purchased economically. It seems practical that in a number of circuits that need to be characterized in the development process that the footprint for this connector could laid out without interference to normal circuit operation and loaded only for test purposes. This would facilitate an intimate connection to the circuit in an unobtrusive manner to allow accurate measurements.

3.2. Calibrating the Calibration Kit

I have been able to find very little information on calibration kit calibration. I have developed methods of cut and try to determine the values of the calibration kit parameters for the VNA. This is a grueling and arduous task. Also, I am lacking in a definition on the parameters and a procedure for determining them. Some are straight forward and some are not. I feel that some have a historic basis that is really not applicable anymore, yet has become embedded. I would like to find a systematic method to determine the parameters from a straight forward measurement. Cut and try sucks.

There are four capacitance values and a length value for the open and a length value for the open and the short. The determination of these values is critical. It appears to me that the capacitance values are the coefficients for a polynomial expansion of the termination capacitance with frequency, however I don’t know that.

The fact is I have found NO information on this and that is the question I am putting out that is at the basis of this. What I have been discovering in asking that question is that I had to explain the background in much more detail in order to ask the question and not get trite answers that I had already gone past.

I have read the section in the Agilent 8753 User Manual on calibration. There is a lot of good information there, even a discussion changing the calibration kit parameters in the instrument, however no in-depth description or definition of them or how they are obtained. There is bound to be a better way than trial and error.

Table 3-1 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

4. Some Examples

Some examples will be helpful in demonstrating the problem. Just to look at the problem requires looking at a lot of data and getting it in the right form is very helpful. For me this is where MathCAD comes in quite handy. The first example I will give is for calibrating my Advantest R3765CG VNA from 300 KHz to 3.8 GHz using the built calibration kit parameters for the type N female calibration kit (instrument default). Then after completing measurement of the calibration and verification terminations, calibrating wit the instrument Don't Care parameter set (no corrections) the verification measurements are repeated. Coming from the VNA is a 50 ohm coax terminated in my 50 mil connector. I have built a twelve element calibration and verification kit with the values shown in Table 4-1. The open, short and 50 ohm terminations form the calibration kit and the remainder from the verification kit. I chose the 50 mil connector because at the time it was the tiniest connector I could easily find and build terminations with very small parasitic inductances and capacitances and would be a miniscule part of a wavelength. (I have found what I think is a superior connector for the purpose and that is the UMCC connector. I intend to build a measurement system around that next.)

The process is to calibrate the VNA with the calibration kit and a given set of calibration kit parameters. Then measure the verification kit and compare the results to values that would be expected for those terminations. As discussed below, unfortunately those will not be nice straight lines because even the tiny terminations are not free from parasitic inductance and capacitance. However, if the correct calibration kit parameters are not used large errors are introduced and this cannot be seen without verification terminations. With just the standard calibration, even of the highest quality, you cannot verify the calibration of the instrument without some known terminations with values other than those of the calibration kit; you just have to take it on faith in the calibration kit. Needless to say, I have burnt by this on a number of occasions to the point that I am much more wary now.

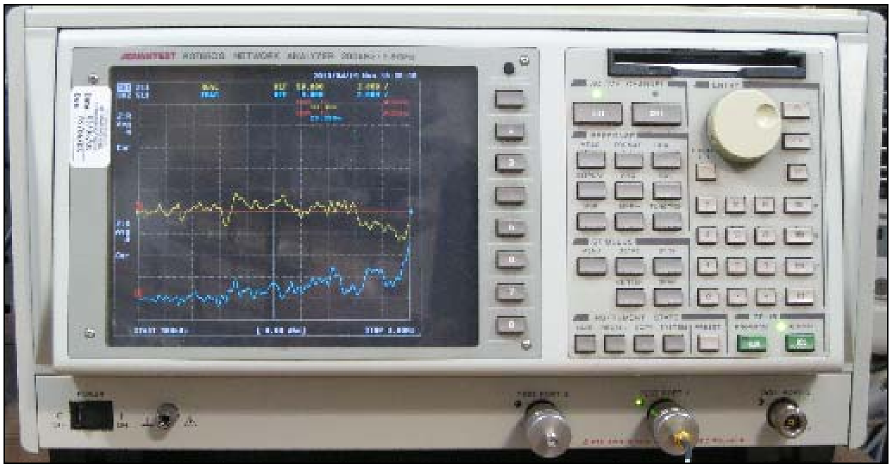

Figure 4-1 Advantest R3765CG Vector Network Analyzer

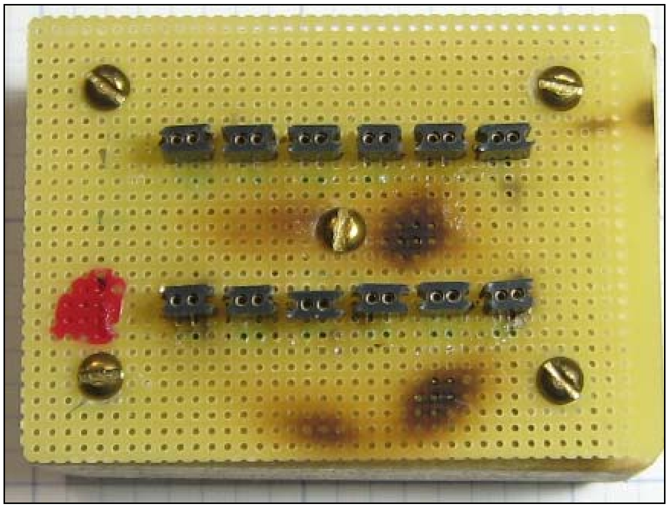

Figure 4-2 12 50 mil 12 Termination Calibration Kit – Top View

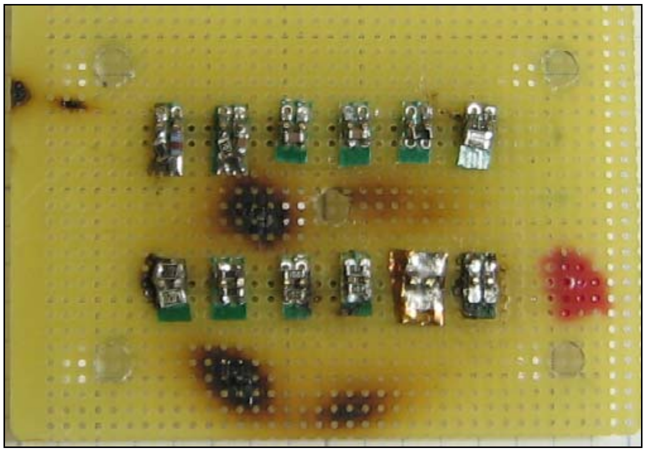

Figure 4-3 50 mil 12 Termination Calibration Kit – Bottom View

Table 4-1 TELI 50 mil Calibration 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.

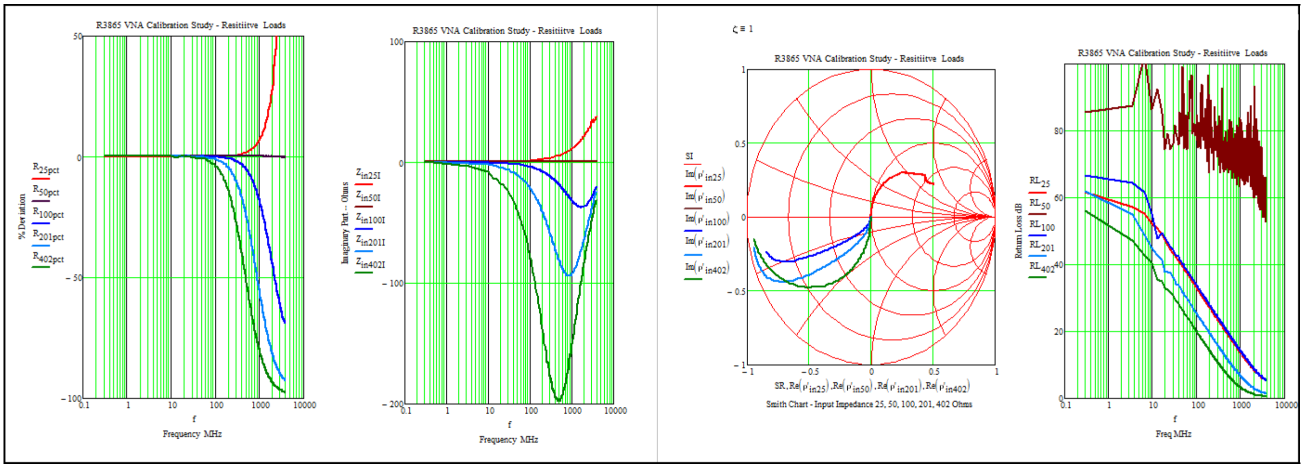

Figure 4-4 Parameter Set Type N Female – Resistive Terminations

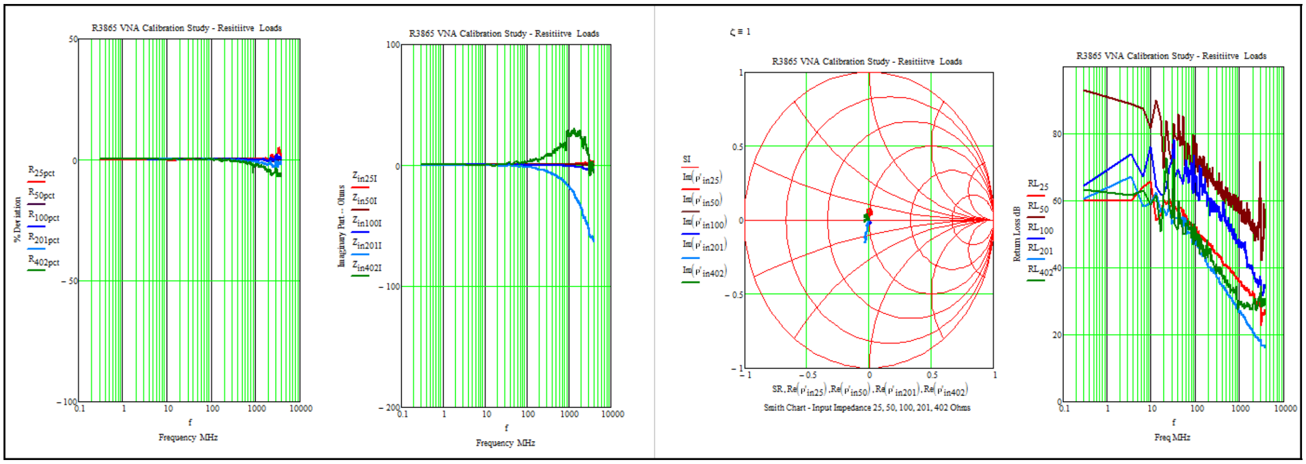

Figure 4-5 Parameter Set Don't Care– Resistive Terminations

Table 4-2 Color on Chart vs. Resistor Value

Resistor	Color on Chart
25	Red
50	Black
100	Blue
200	Light Blue
402	Green

The left hand plots show the percent deviation from the resistor value vs. frequency. Of course the 50 ohm resistor shows no deviation since that was the calibration reference. However the other values vary significantly as frequency increases. Ideally the plot would show a straight line at zero for all values and the Smith chart would be a dot at the center, however the resistances are not pure. The termination is a combination of R, parasitic L and parasitic C. In **Error! Reference source not found.** is a calculation of what the behavior of the resistive terminations look like with estimates of parasitic L and C.

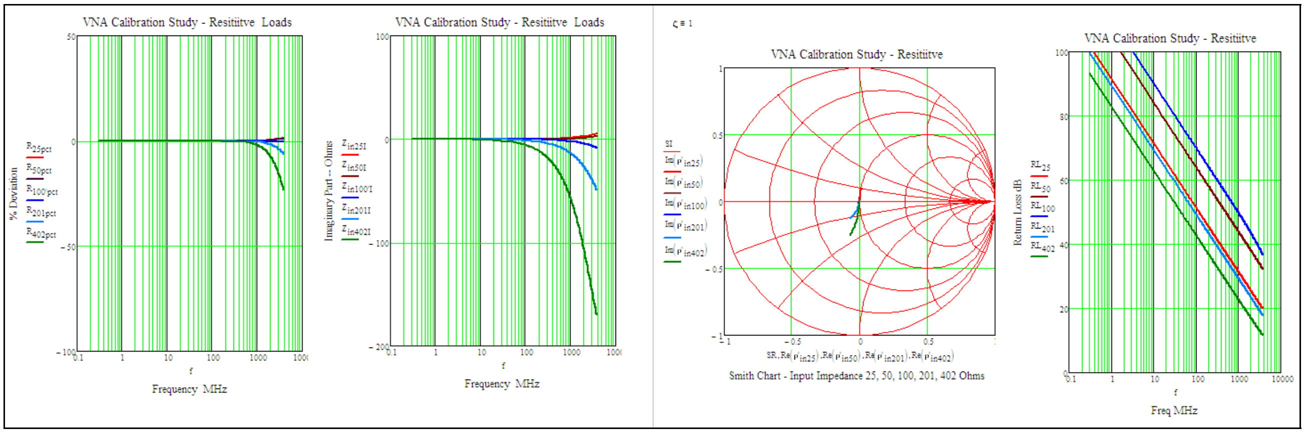

Figure 4-6 Calculation of Restive Terminations with Estimated Parasitics

It can be seen that for the higher resistance values the capacitance dominates the imaginary part. Interestingly the real part falls off significantly due to the parasitics at the higher frequencies. This is the true impedance of that termination and not a VNA error.

It can be seen that the type N parameter set is not appropriate for this calibration kit and introduces significant error to the VNA measurement, particularly as frequency increases.

Shown below for completeness are comparisons of the other verification terminations vs. parameter set.

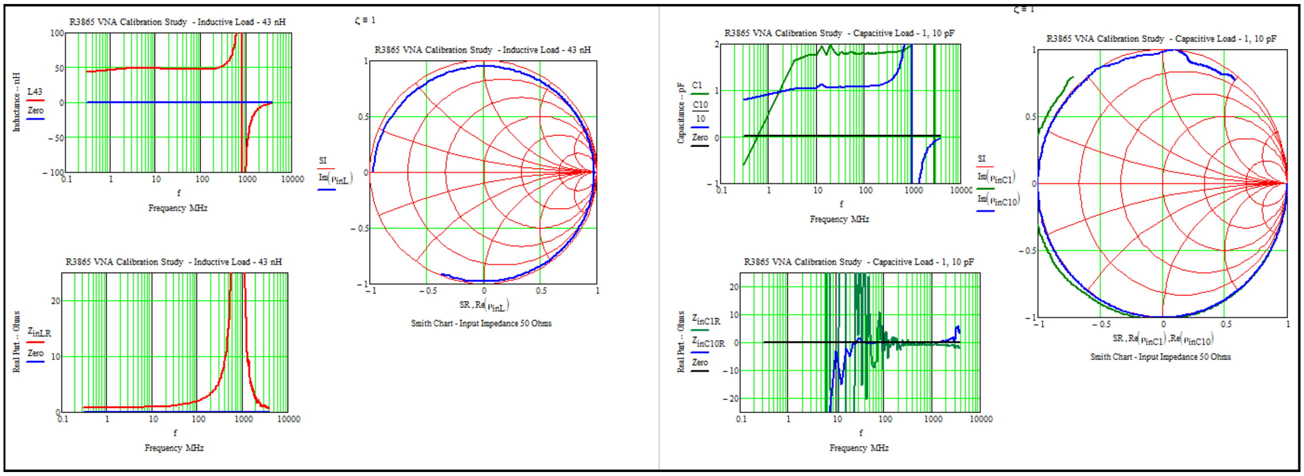

Figure 4-7 Set Type N Female – Inductance and Capacitance Measurements

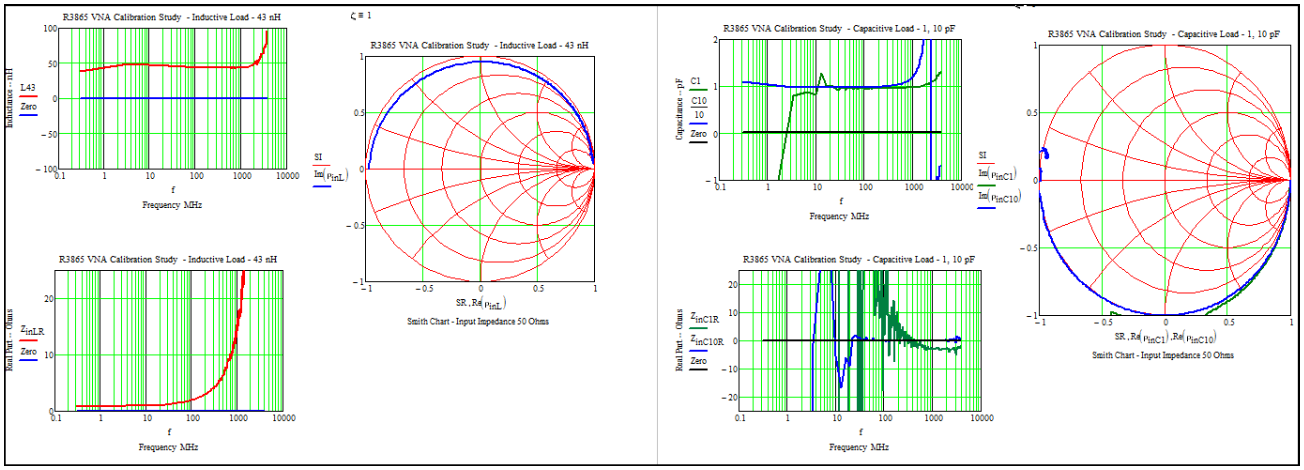

Figure 4-8 Set Don’t Care – Inductance and Capacitance Measurements

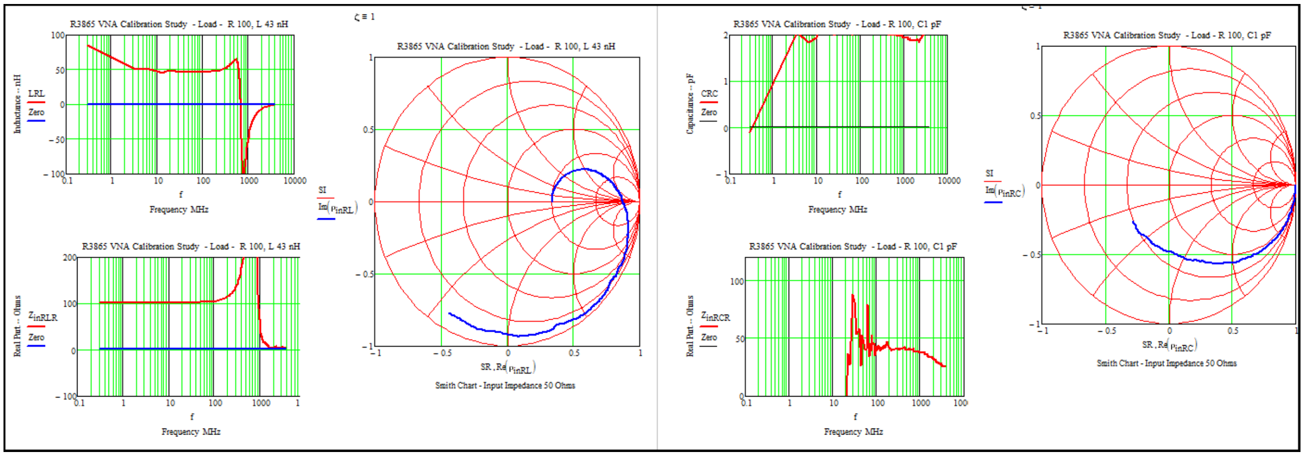

Figure 4-9 Set Type N Female – Mixed Inductive Measurement

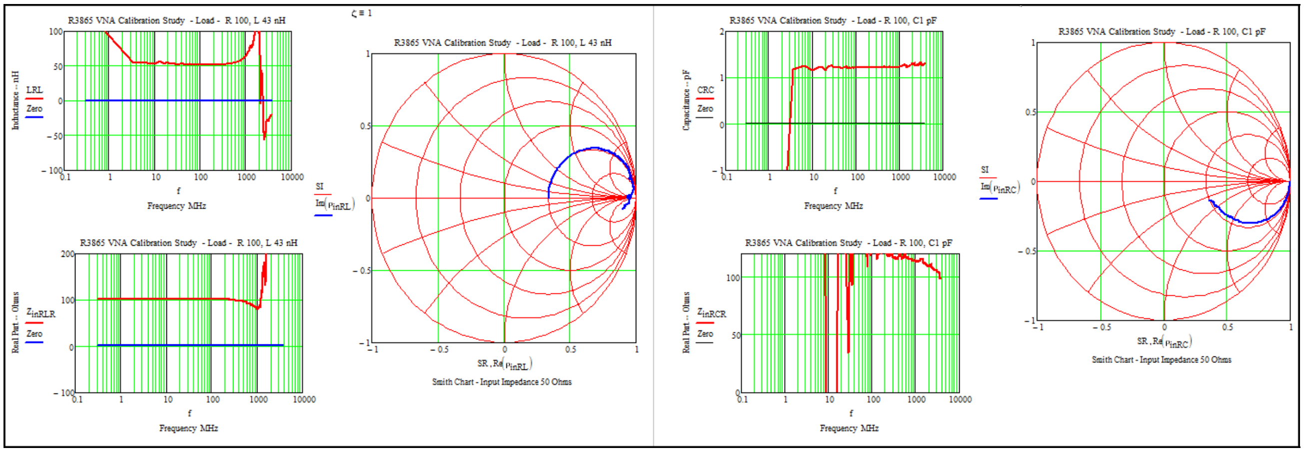

Figure 4-10 Set Don't Care – Mixed Capacitive Measurement

5. VSWR, Frequency, Smith Chart and Sensitivity

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 5-1 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.

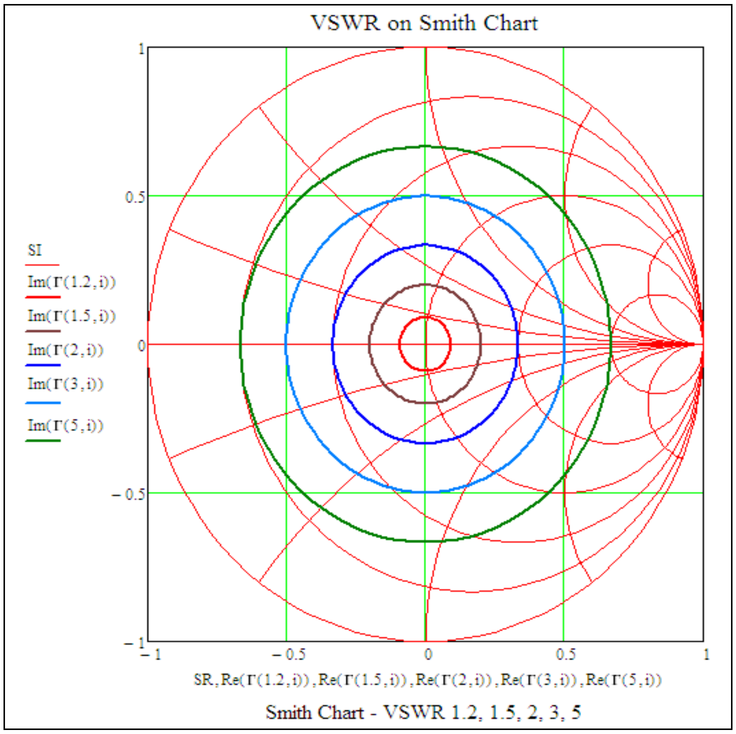

Figure 5-1 VSWR on Smith Chart

6. The Question

The point of all this exposition is to ask the question; how do I go about competently estimating the calibration kit parameters? It would appear that for the 50 mil connectors the Don’t Care or zero corrections is pretty close to correct. This may not be the case for larger connectors.

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