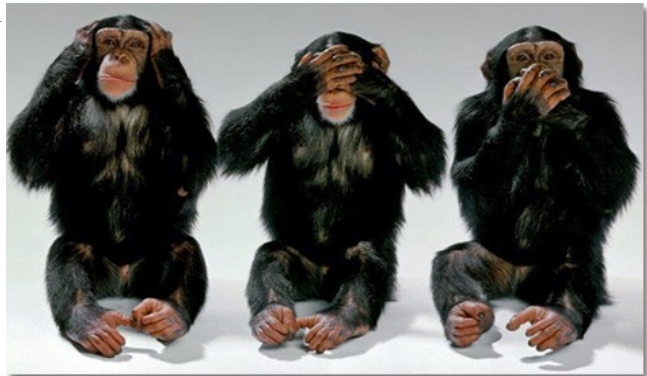


## Calibration

### Introduction

One thing to keep in mind, a vna, also our vnwa, is dumb, deaf and blind, it does know nothing from the world we live in. It is like a child that has to be learned how that world looks like and its rules and values. We are the ones who have to do that. I will not tell you how to operate the vnwa while calibrating. The help file is clear enough with lots of pictures. I will try to explain the importance of calibration, why you have to calibrate and how it looks like. Also some background information to give you more understanding about calibration.

For this tutorial I assume you have a commercial calibration kit with known parameters. If you have an unknown kit or homemade you must extract the parameters. This is for the more advanced user. I will describe this in short at the end of the tutorial because you have to know more to understand this. But Kurt OZ7OU has written some very good papers about how to do this using “enable real time calibration” in the calkit menu (setting, calibration kit, from now on I will address this as the calkit menu)



Also I assume you read the other tutorials so you are familiar with how the vnwa works and what all traces mean. The problem is you must be able to understand calibration before you can make good measurements but you can not understand calibration if you do not know how to measure. A bit like the chicken and the egg problem, who was there first.

In the case of the vnwa, my opinion is: better learn first to measure with non-perfect results due to faults in calibration as to use an invalidate calibration. Just use the option, ideal calibration kit, and after that learn to calibrate perfect. Because then you recognise faults and know what the traces mean and what you are doing.

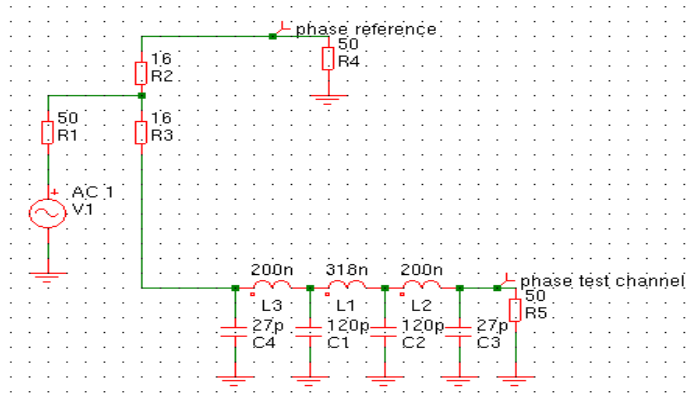
### Why calibration

When we measure something, let's say, 100 ohm, the vnwa measures the voltage- and phase-difference between its reference receiver and test-receiver. So he knows two ratios. How does he know that ratio is to be translated in 100 ohm? He must learn zero Ohm, infinitive and 50 Ohm. Simple, we tell him. For this we need a calibration kit. These are very important parts of our vnwa setup. I use the amphenol female kit in this tutorial. But the “real” stuff is some other story. The picture here is from an Agilent budget calibration kit and that is why it only cost 6400 dollar .....

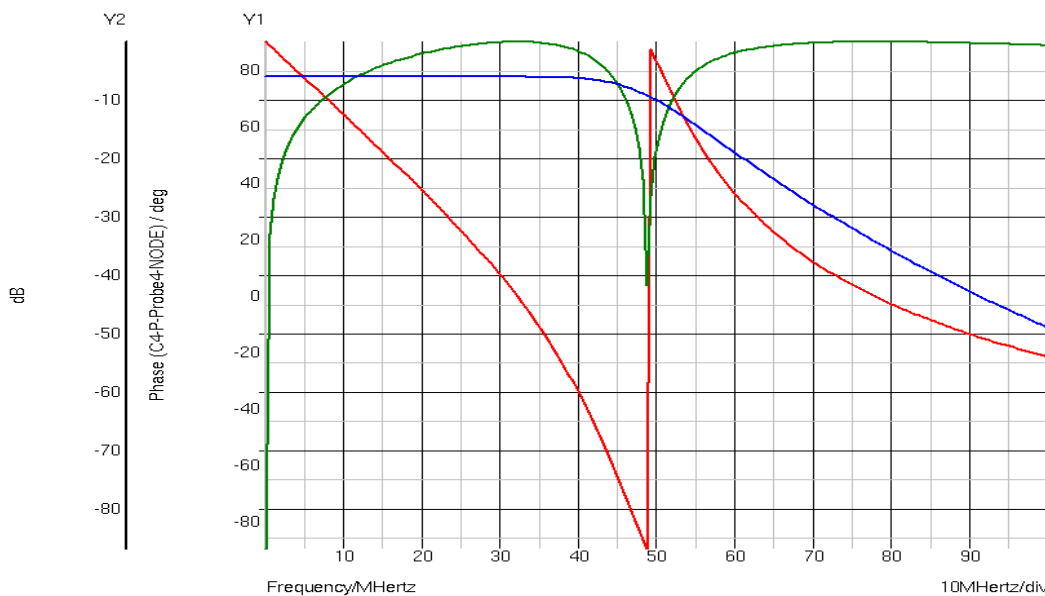
### SOL calibration

That is Short, Open, Load. It does not matter what you do first, as long if you do them all. We connect a 50 ohm resistor to the TX port and do a S11 sweep. And by using the calibration function we tell him; “listen, if you get these ratios, you are measuring a 50 ohm resistor.” An ideal resistor does not give a phase change so we have to tell him too what a phaseshift is. We are talking here about Phase related to time, not the Phase difference between current and voltage. Our phase has to do with the delay between the signal received by the reference receiver and the signal received by the measurement receiver. This causes a phaseshift.





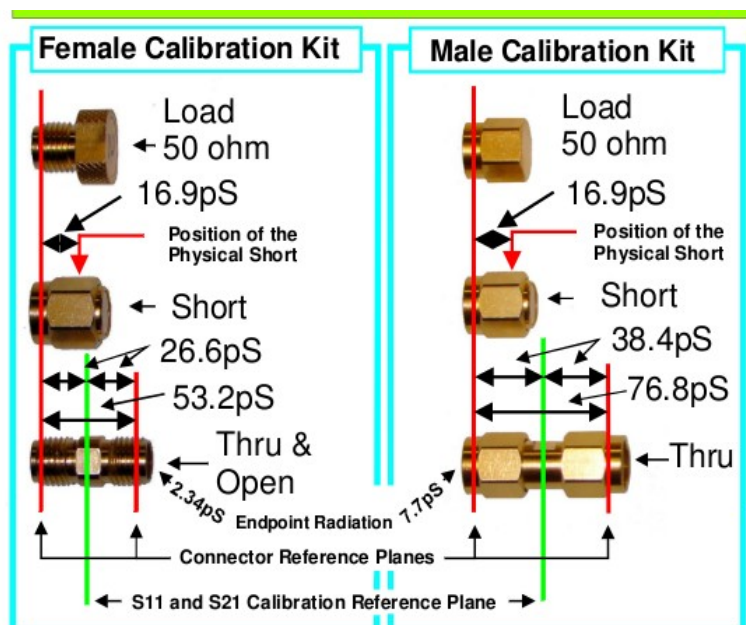
Here you see the powersplitter and two receivers. This would be a vna setup, but without the reflection bridge so this is a S21 setup. The vna measures the phase and magnitude difference between both receivers (R4 and R5) Our vnwa has an internal bridge and internal reference receiver.



The result is the difference in Phase between the two receivers (red) the difference in amplitude (green) and the resulting filter S21 amplitude response (blue)

We are going to do that with an **open** and a **short**. An open is just the open end of the port or cable you are using. If the cable is open all the power is reflected back to the TX port. Voltage at the end is max but current is minimal, so the voltage reflects the same way as it came

What really happens is complicated and has to do with time. Although radiowaves are fast, they need to travel from the tx port to the end of the cable when you start a sweep. So at the start the voltage is twice as high a when terminated in 50 ohm. The



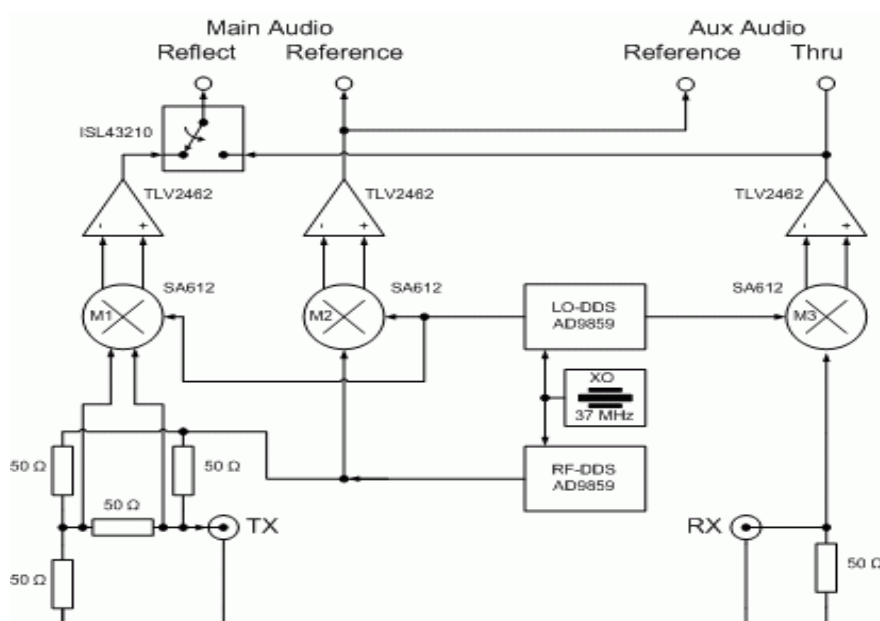
current is at start zero. Then the wave travels to the end of the cable, there it expects to see a 50 ohm load. The internal resistance of the vna is also 50 ohm so the voltage we would measure drops after the reflection to half the start voltage. We have just formed a voltage divider. There is a rule that we have maximum power transfer as the impedance of TX and RX are the same.

In this case all power will be dissipated in the 50 ohm terminator. Then there happens a series of magical things that are described as the transmission line equations. The result is the TX voltage settles to the half value of the amplitude at first signal start. Because all power is burned and Ohms law is a law and not an advise the TX voltage value must be half the initial voltage while current is not zero any more. Just simple Ohms law. This is a very short and incomplete version to give you an idea about what happens.

Because we are talking about waves we can say, the wave reaches the load and current begins to flow. So there is a wave on its way, a joined force of voltage and current that likes to keep the relation as it is. When that reaches the load we have a current that is perfect for 50 ohms, the vna can not deliver more because of its 50 ohm series resistance, so the voltage is too high to make Ohms law true, to keep power constant a part of the wave travels around and goes back. This voltage does its magic with amplitude and phase with a result that the TX and reflected amplitude subtract with half the amplitude as a result. Once this state is reached it stays like it is. The phase relation does not change.

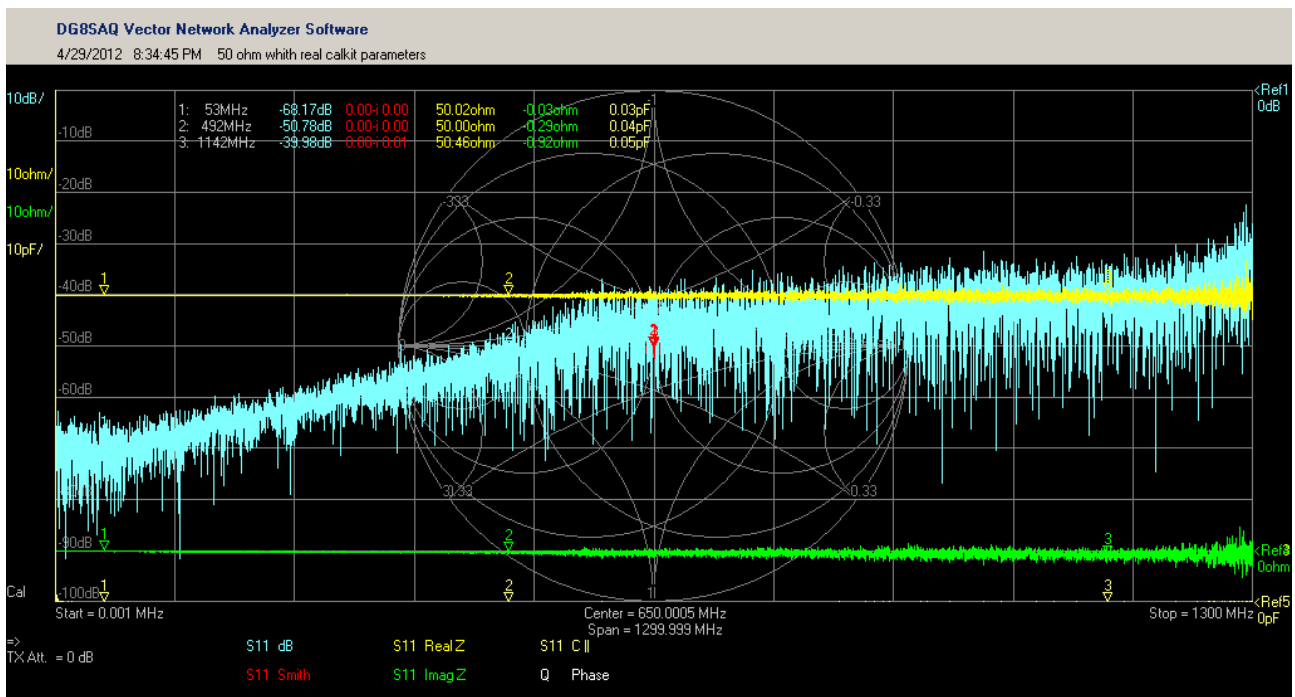
But remember, it is about ratios. The transmitted signal is internally (or with a classical vna external) split in two. One half goes to the TX port and DUT, the other half goes to the reference receiver with its own internal 50 ohm load. If we terminated the TX port with 50 ohm the voltage and phase measured on both receivers is the same. So the result is no difference in phase and no difference in amplitude. That is what we do using a 50 Ohm load calibration. Tell him the starting point.

The error signal is zero. And zero signal is a lot of dB less as the transmitted signal. In network analysis we say there is a huge return loss. Sound strange? No, see it like this, the maximum power that can be returned is degraded to zero, so all that potential power is lost in the load. The ideal return loss is infinite. But we do not live in a perfect world and the directivity of our internal bridge circuit is not perfect so some power will leak through, some gets lost in the cable, tracks ect. But if we have (build) a very good vna and bridge we can get 40 to 50 db return loss. This is what you see when you do S11 in dB. This is a picture of the internal layout of the vna.



Left under you see the bridge.

This is a screen shot of a 50 ohm termination after calibration and using the right calkit parameters that are delivered by SDR-kits for the Amphenol sma calkit. My other tutorials are made using a VNWA 2.6 with bnc's and a testset, this tutorial is made with my VNWA 3, that has the breakout board and RF-IV head. This I use for precise component research and this whole setup is sma.



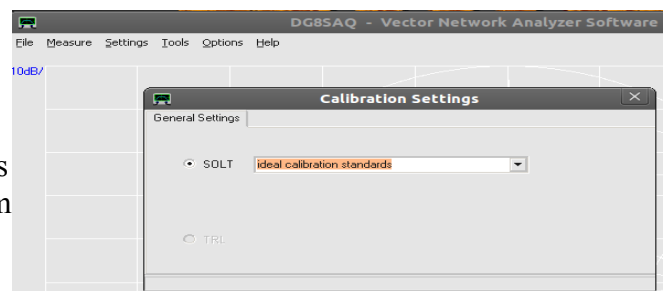
But if we have not told the vna against what reference it is measuring we are in trouble, remember, the vna is dumb, it only knows that it has to compare everything to a perfect 50 ohm and because a vna is the emperor of analysers he thinks he is perfect too... So be aware, a vna is powerful but results can never be better as the calibration.

Like many VNA's (affordable for mortal human beings) our vna and calibration kit are good but not perfect. The termination has parasitic effects (capacitance or inductance and also not exact 50 ohm) So because these effects it is not exact 50 ohms real over the whole sweep, besides that our bridge leaks some power and there are several other factors like non linear amplification of the transmitted and received signal ect.. But that is no problem, as long as we are honest to our vna there is no problem. If I tell you a piece of wood measuring 120 cm is exact 1 meter and you use that to hacksaw an other piece of wood , then you think you have two pieces that are exact 1 meter. To bad I lied to you. You did your best but I was not honest so you made a mistake.

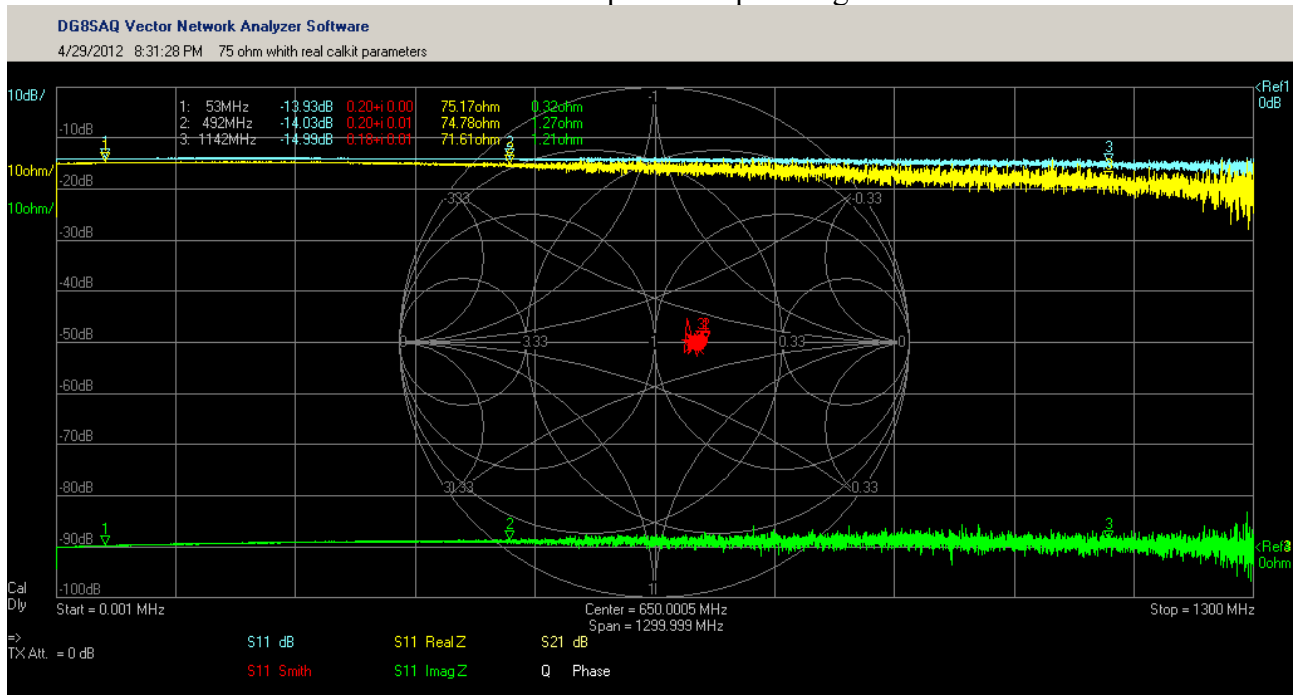
So what we do is, we take an, as perfect as possible, 50 ohm terminator, we call load, and we tell the vna in a menu called calibration kit, what its parameters are. In this case this is 50.01 Ohm and 30fF. So if we sweep the load doing the calibration, the software makes a table for correction. So all reflected waves and phaseshifts due to the imperfection of the system are know and can be used for correction in measurements. If you had known the piece of wood was 120 cm you would have known you had the cut the other piece of wood 20cm shorter. So the parameters of the calibration kit are not a problem as long as they are known. BUT, the amount of correction the software can do is not endless so try to get a good kit.

Now the picture above showed a perfect load, good return loss over the whole sweep and nice in the centre of the smith chard. The R+jx traces shows it is, like we have described it. 50.01 ohm and 30fF.

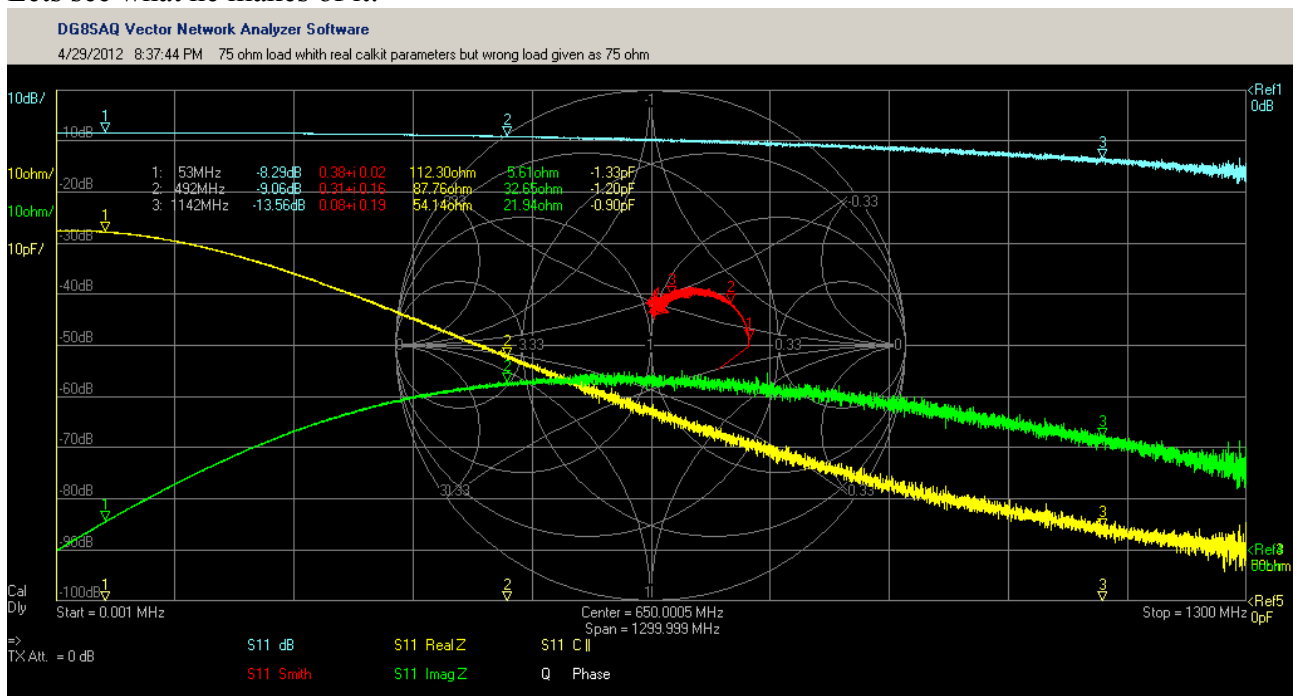
I wanted to show you also the difference



between real calkit parameters and the ideal cal kit option but this kit is almost ideal so that made no sense. So I did it the other way around. First as reference, I measured a 75 ohm terminator. You see in the picture below, left from the gratitude, Dly . This is because I used port-extensions to shift the reference level for the extra sma to bnc adapter. This picture gives a useful and realistic result.



But what if we had done a sloppy calibration ? I simulated that through the use of the calkit parameters. I sneaky told the vnwa my perfect 50 ohm load is 75 ohm instead of the used 50.01 Ohm. After that, I measured the 75 ohm terminator again. The vnwa measures the ratios and now thinks this ratios are based on 75 ohm, he thinks I used a 75 terminator to calibrate. But I did not. Lets see what he makes of it:

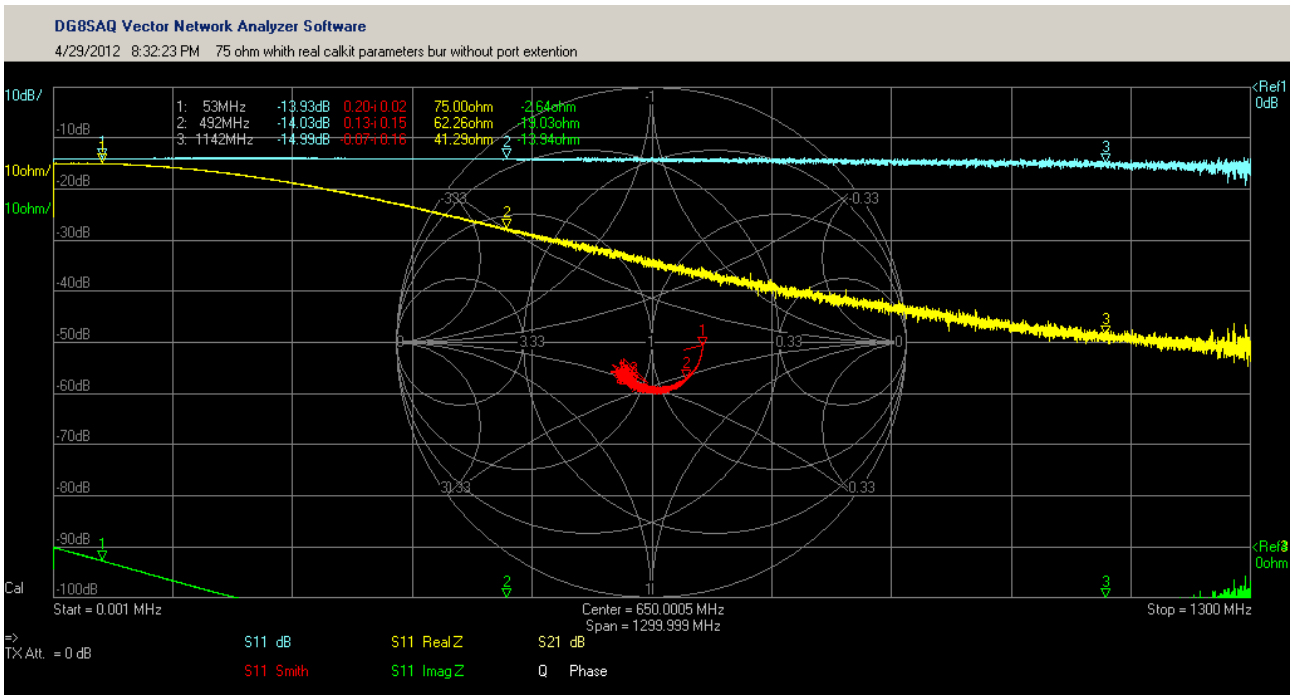


This is a little bit over the top but a clear example and this is important, if we lie to the vnwa the vnwa takes revenge and lies back to us.

I can not tell you enough the importance of calibration. So an other example to show you it does not have to be an over the top mistake to get bad results. This is same sweep as the one that showed the



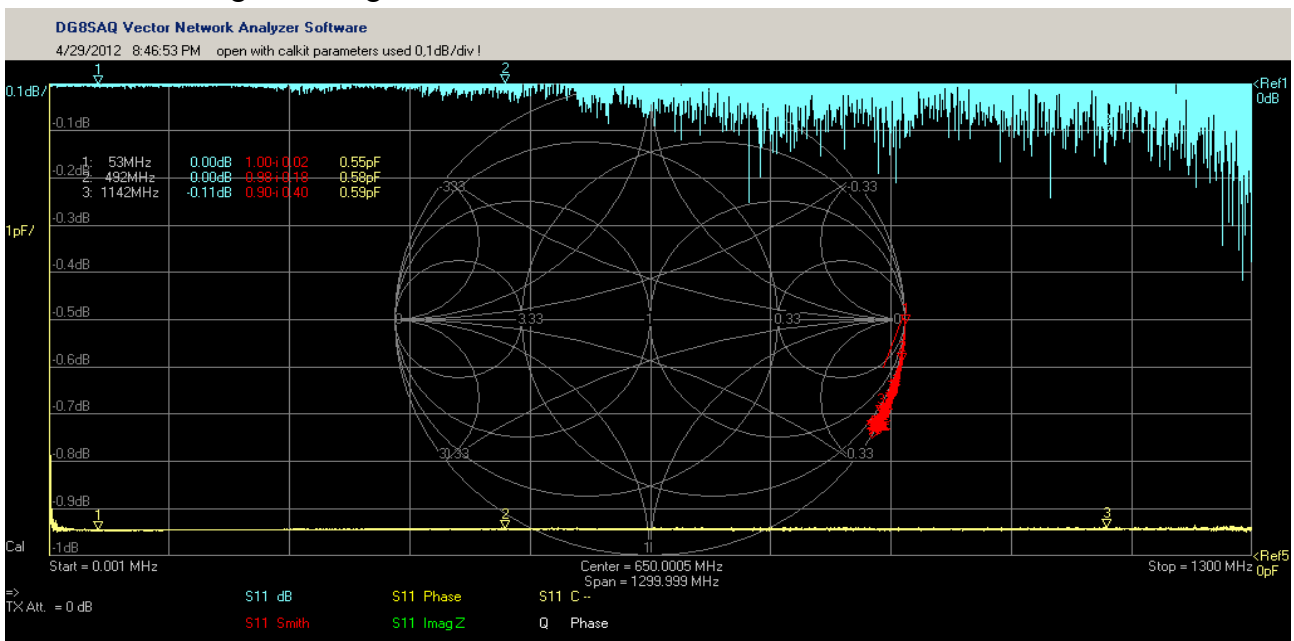
decent 75 ohm terminator, the only thing I did was turning off the port extensions. You see the result. It looks like the terminator is only usable for low frequencies. Just a 240 ps difference in reference level gives this significant difference in result.



But the vna needs to know about the extremes too. The first extreme is maximum current and zero voltage. The other is maximum voltage and zero current. We use open en short for this.

## Open

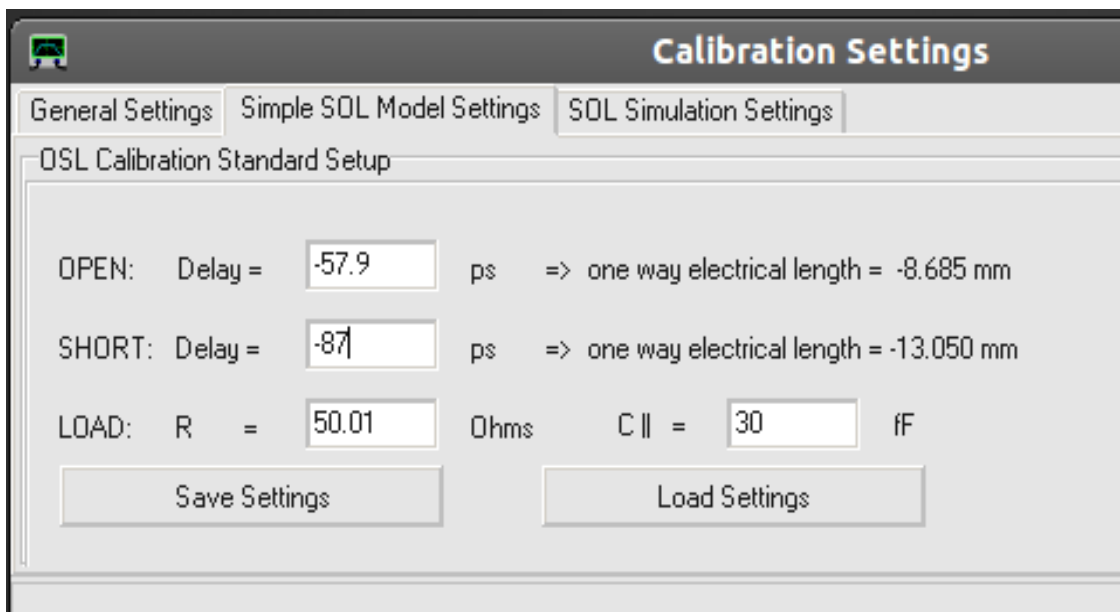
Lets start with open. This is like we described before. The wave amplitude starts at max voltage, travels to the end to find there is nothing there, so no load to dissipate and zero current. The wave returns back to the TX port, all reflects. There is no power dissipated in a load, there is no returning power lost and so S11 gives a returnloss of zero dB. A perfect open is an infinitive resistance We see a dot on the right real edge of the smith-chart.



So while calibrating we have to tell the vna, this is an open. How weird it may sound, an open is most times not perfect. It has some capacitance between the open end and the shield, it picks up some external signals and the open end of the cable is not always our reference plane (you see that in the smith chard, the trace travels down. I will explain that later)

So we put the delay specs of our open in the calkit field and we do the calibration. (it is no problem to do the calibration first and later tell the specs) As long as the software has the measurement data and the calkit parameters it is OK. So do a sweep and play with those parameters and see what they do. See the helpfile on how to do that. There is a check box in the calkit menu you can use to see the changes in your traces while altering them. But be careful, if you look at my load you see the 30fF, you see the return loss ect. I can alter the parameters in such a way my calkit looks stunning. To be honest, I have done that for measurements in some of the first tutorials to make it look more understandable and clear. It is hard to understand a good calibration shows the faults in your calkit but that is the harsh reality. We want real results, not fairytales.

In case of the open I use the female calibration kit. The load is female but a short is male so we mount a tru and use that as an open. Why ? A female sma is just a better open as a male. The problem that we now shift our reference level a bit more away from the vna is no problem, we just tell it we did. In this case by typing -57.9 ps in the field for open. The signal travels a bit longer as needed, so we subtract (twice) that time. We want one strict defined place to use as a reference. This has to do with impedance transformation. You already have seen an example using the port extensions. Twice because doing reflection measurements the signal goes to twice that distance.



The Amphenol settings for the female kit with tru centre as referenceplane.

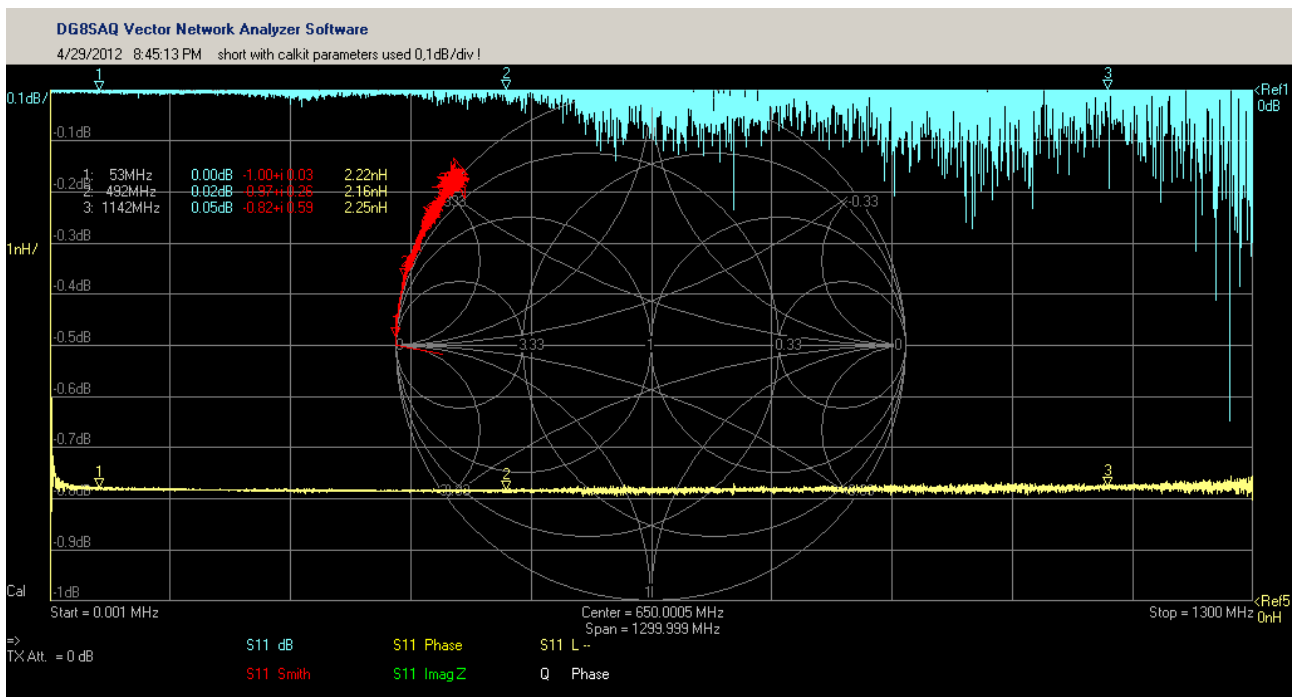
The picture of the traces above is not as horrible as it looks. It is just the scale. The S11 dB trace is 0,1dB/div and you see on the smith-chart the extra delay just like there is in reality. But it must stay on the outer edge of the chard. If it goes outside the chart there is a fault in your calibration or parameters.

Here you can make the same mistake as the 75 ohm example. You can give such a delay you get a nice dot at the etch of the smith-chart. This looks nice but is not good, Weird ? The wrong one looking perfect. Yes, but it is not perfect, I only told the vna it is, so if you measure something else he compares that to a perfect open and makes the wrong corrections. If we then should measure a real perfect open, he would show the inverse deviation of the imperfectness of our calibrated open.

## Short

Now you probably think, Fred keeping it short, nahh , not possible ! But this is an other short. The last calibration standard regarding reflection is the Short. There are more calibration schemes but that is more advanced stuff and for that I would advise to look in the tutorials from Kurt.

A short is, you already guessed, also not perfect. It has some inductance and also here the reference plane shifts. In this case the wave starts at a max amplitude and reaches the short, now maximum current will flow. This will be twice the current as when using a load because now it flows through 50 ohm instead of 100 (TX resistance in series with the 50 Ohm load) the voltage is zero. So the wave reflects, there is no power lost in the zero ohm short, so again Return loss is 0dB. We tell the vna the specs of our short and calibrate. If we cheat we get the same problem as we did cheating while calibration the open. You see the trace is now on the other side of the smith-chart. It is 180 degrees shifted over the outside of the chart. You also see the self inductance.



## Trough

The last step in calibration is the trough calibration (called tru) . This is not something special. Just connect the cable of port one (always use the same cable you used to calibrate, the cable is part of the calibration because its Vf and its length) with the cable of port 2 and use the tru to connect them. The tru calibration has as function to find and later correct amplitude and phase errors while doing a S21 measurements. Tru match is there to match the RX port to 50 ohms. If you need to do very precise S21 measurements and the normal calibration is not good enough you can use an external 50 ohm in-line terminator at the RX port to get a better 50 ohm response. I use this sometimes on my bnc equipped vna. (I have no sma inline terminator) The RX port is not a perfect 50 ohm above 500MHz.

## Reference plane.

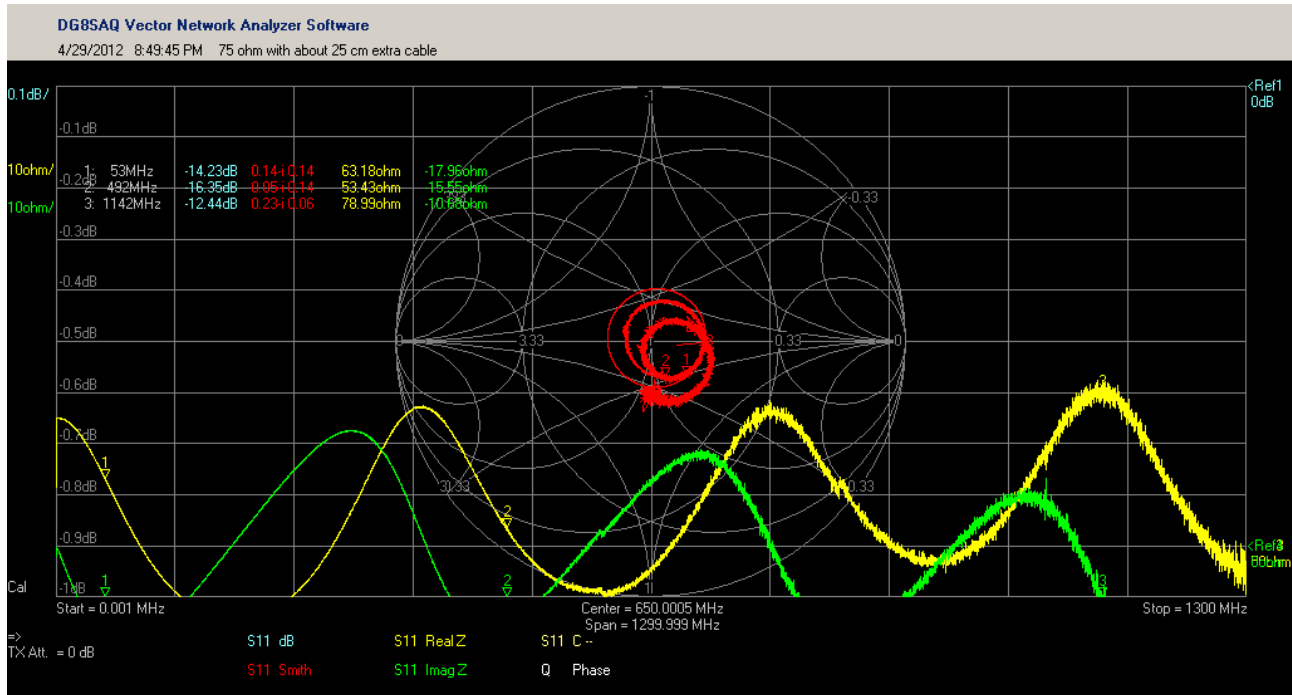
I used this term before.

For many people a hard to understand topic but if you know why and what you will see it is not so hard. It has all to do with a special feature of transmission lines. And this feature is something that is very important for other network measurements too. We have already talked about it brief in other

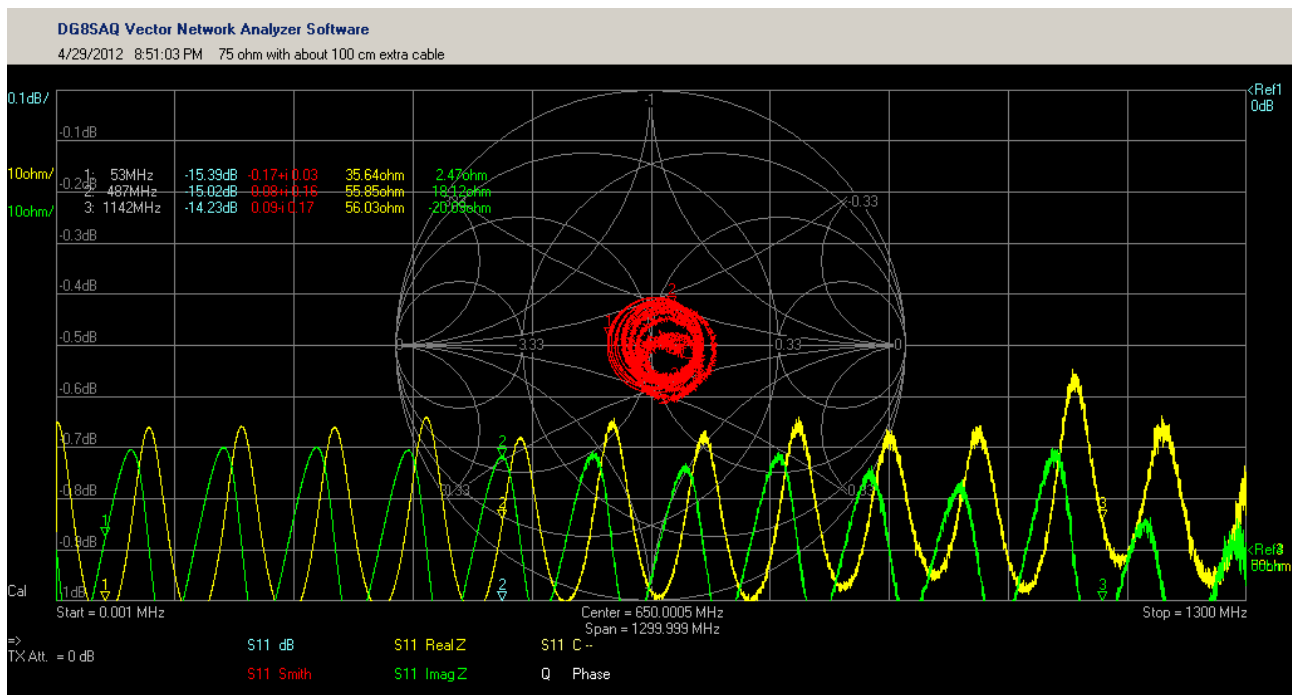


parts of this series. This feature is impedance transformation.

First I will show you what the effect is of transformation. But to be more precise, this transformation happens only if the line is not terminated in its own characteristic impedance. And very important, it can never transform to its characteristic impedance if it is not terminated by that.



Here is our friend the 75 ohm terminator again. This time I added 25 cm of extra coax and the sma-bnc adapter without using port extentions. This is what you get if you calibrate the right way, then take a piece of extra coax and couple it to an antenna. You see the impedance going around the smith-chart in circles. And also “waving” in the green and yellow trace. You also see it never becomes 50 ohm. There are several resonance points but never at 50 ohm. Look around to fellow Hams using an antenna analyser or mini-vna or whatever and most of them make this mistake. And this is only 25 cm, I have seen people using several meters.

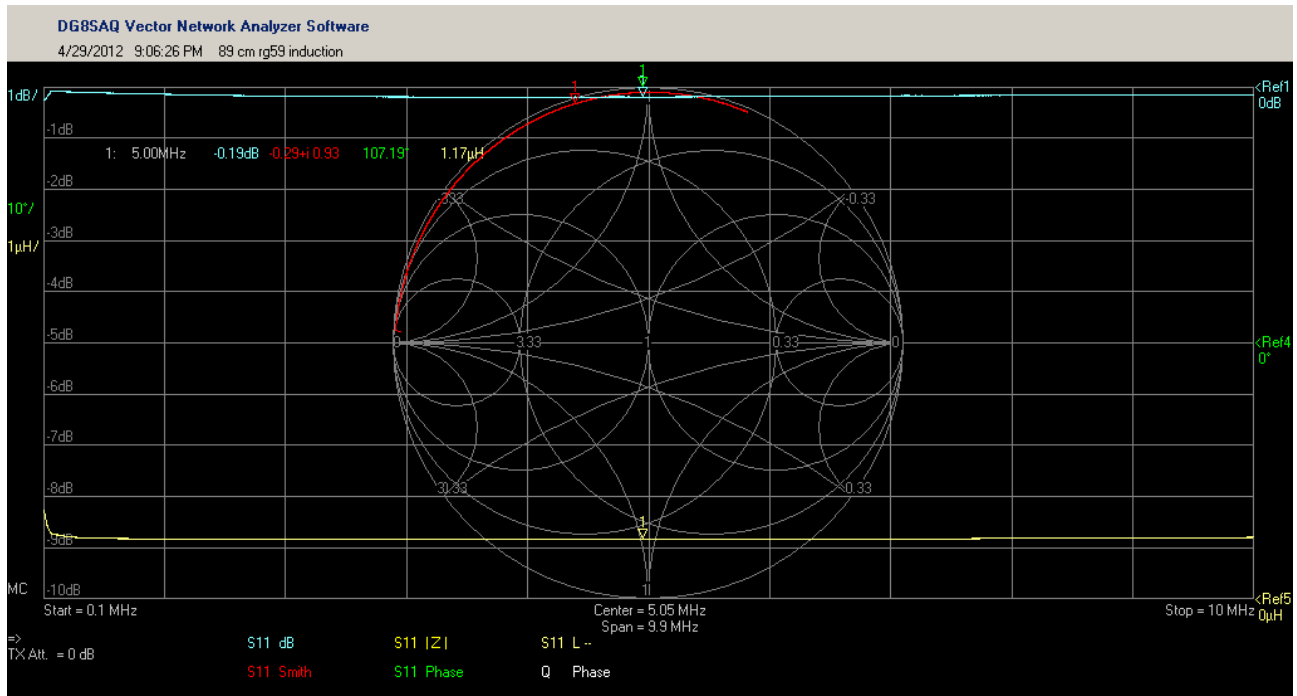


This happens if I replace the 25 cm coax for a longer piece (almost a meter) So you see why we need a reference plane. In the picture above you can not tell we are measuring a 75 ohm terminator.

### Transmission line

Have you thought about what a transmission line really is ? It is what we call a distributed LC network. The inner conductor is a coil. OK, it does not look like a coil but every wire has self inductance. If you make a spiral from it, you get more self inductance and if you wind it on something like ferrite, this effect even becomes stronger.

But for the non believers we do an experiment: take your favourite dutholder and a piece of coax. Does not matter how long. Strip the ends free, and connect the begin and end of the core to the dutholder. We will do a S11 measurement, so connect it between port 1 centre and port 1 gnd. Now choose S11 smith and L--.

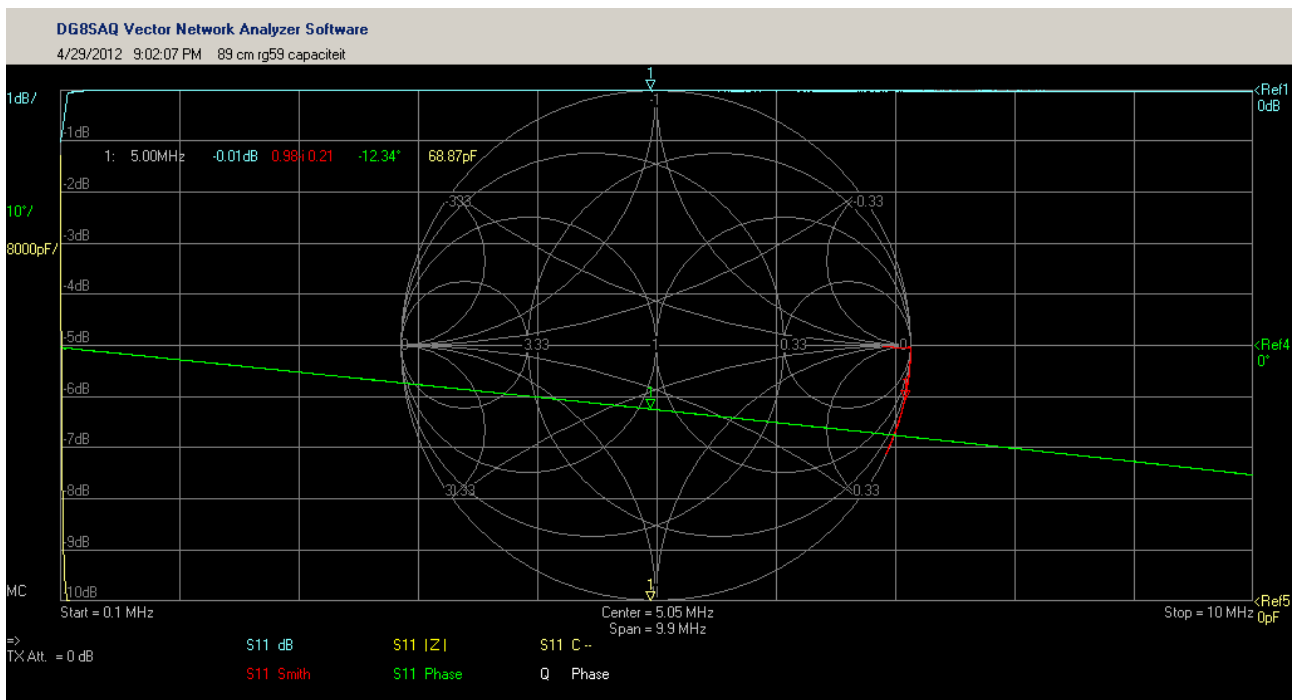


This is 89 cm of RG59 coax. That is 75 ohm cable, open at the end.

You see the trace circle counter clockwise along the edge of the Smith-chart like an inductance should do. You learned that in the tutorial about inductors. If you would take a real long piece of cable you will see it circle more to the centre instead of the outside. This is the resistive element from the copper, and at higher frequency the skin effect makes it circle in a spiral form toward the centre. Skin effect increases in resistance with increasing frequency. In this case you see 1.17uH. This is not correct. I use two crokclips to hold the cable and those have inductance an capacitance. The residue measured by shorting the crocs, was 80nH. So the inductance is 1,09 uH at 5MHz. The resistance measured with a bridge was 770mOhm and you see the trace is just a bit inside the outer border because of this resistance.

But a coil alone does not made a transmission line so we need capacitance too. So disconnect the centre of the coax from the ground side of the dutholder and connect the shield instead. But if you have a LCR meter you can use that too, nothing magical, try it and you see it is just plain capacitance.

I measured 61.61pF (corrected for the residue from the crocs)

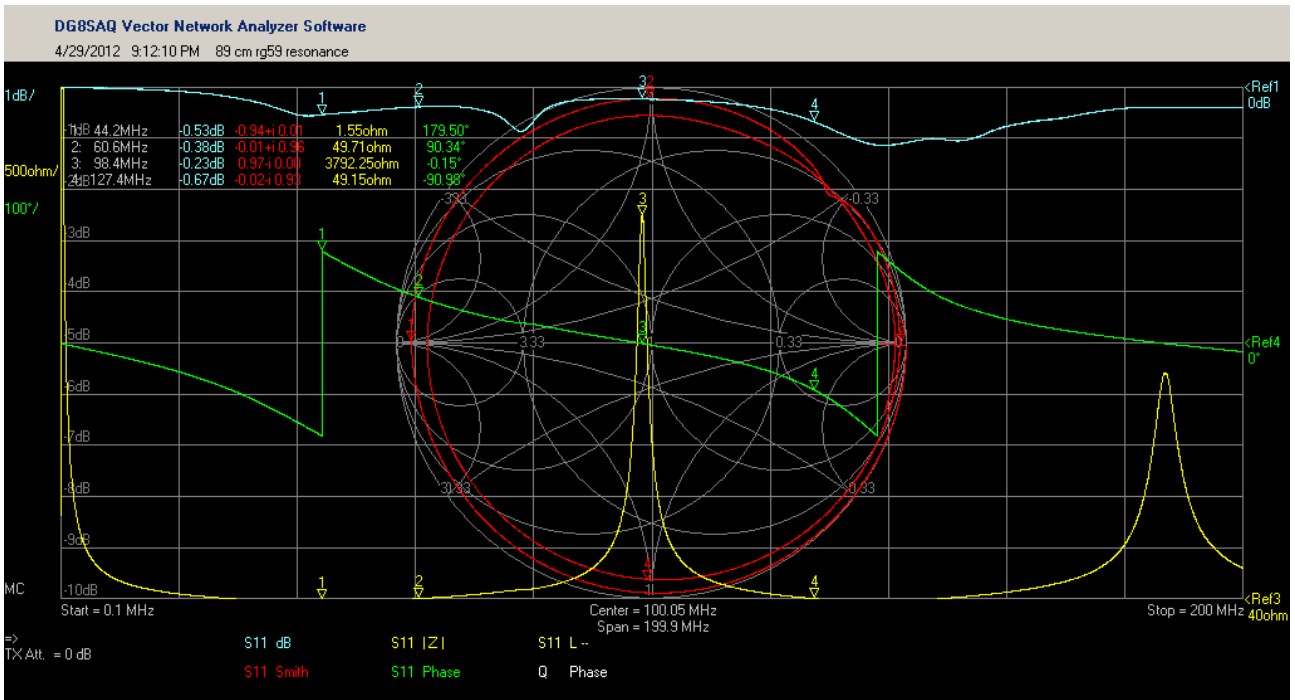


Now I will tell you the trick, because a transmission line always is made by paralleled conductors, be it open wire antenna feeders or coax, they are always parallel to each other. So we have two big inductors and between those inductors we have capacitance. Because the capacitance if everywhere along the line the same amount you could make a thought experiment and split the line in two pieces. Now we split the inductance in two but also the capacitance. If we join them together we put the inductors in serie and the capacitance parallel. So they both add up. Now split it in 4, then in 100, then in a zillion parts. You see the picture ? Every piece is a one zillionth of the inductance and one zillionth of the capacitance. The ratio between the two stays the same and if you use the right math and take both reactances you get the characteristic impedance of the line.

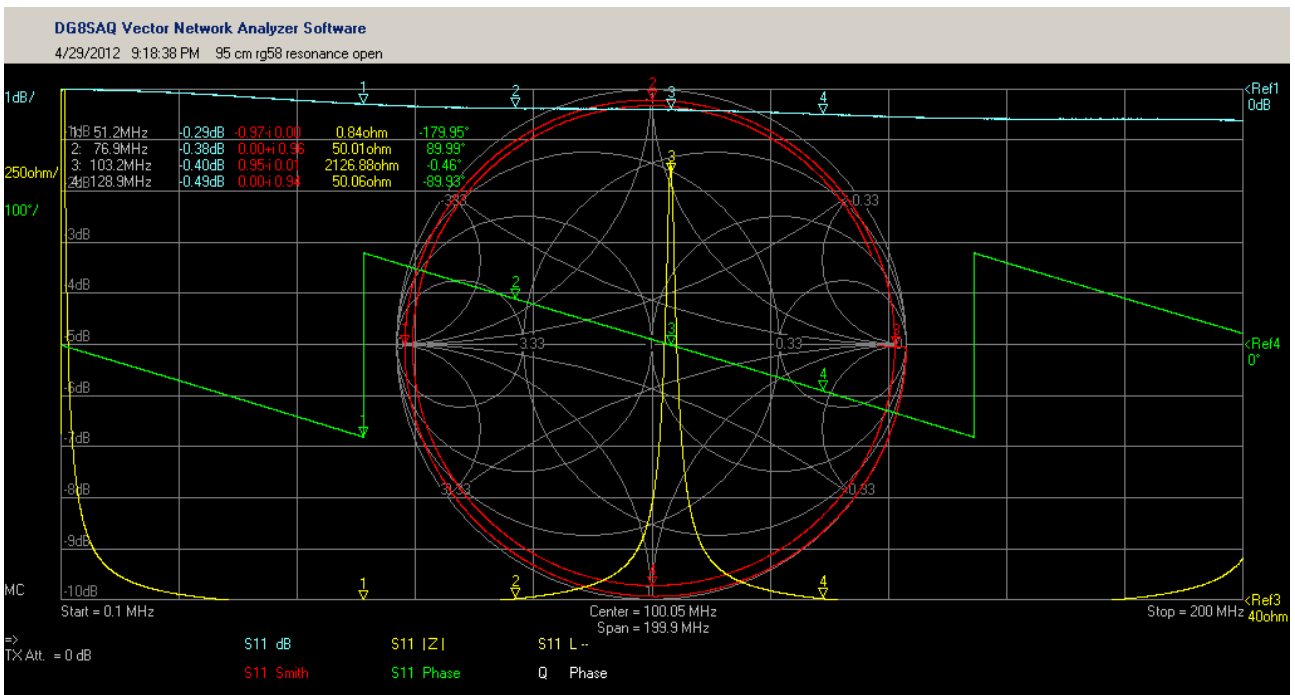
So we have a distributed LC network. And if you remember from the tuner tutorial a LC network can be used to transform impedance. But this is frequency dependent. So 1 meter extra coax has a total different transformation effect at 10KHz as it has at 1 GHz That is why we choose a fixed point as a reference. If we add some cable, a connector or a DUT holder we tell the vnwa we did so using port extensions or a fresh calibration.

Some homework, cut your cable in two and measure, cut one piece again in two and measure again. Isn't that cool ! A nice experiment is to connect a potentiometer to the end. Sweep and look if you can find the value the 50 ohm of the vnwa is transformed too. Hint: use the vswr trace. Then measure the potentiometer and you know the transformation. You can make matches or filters like this.

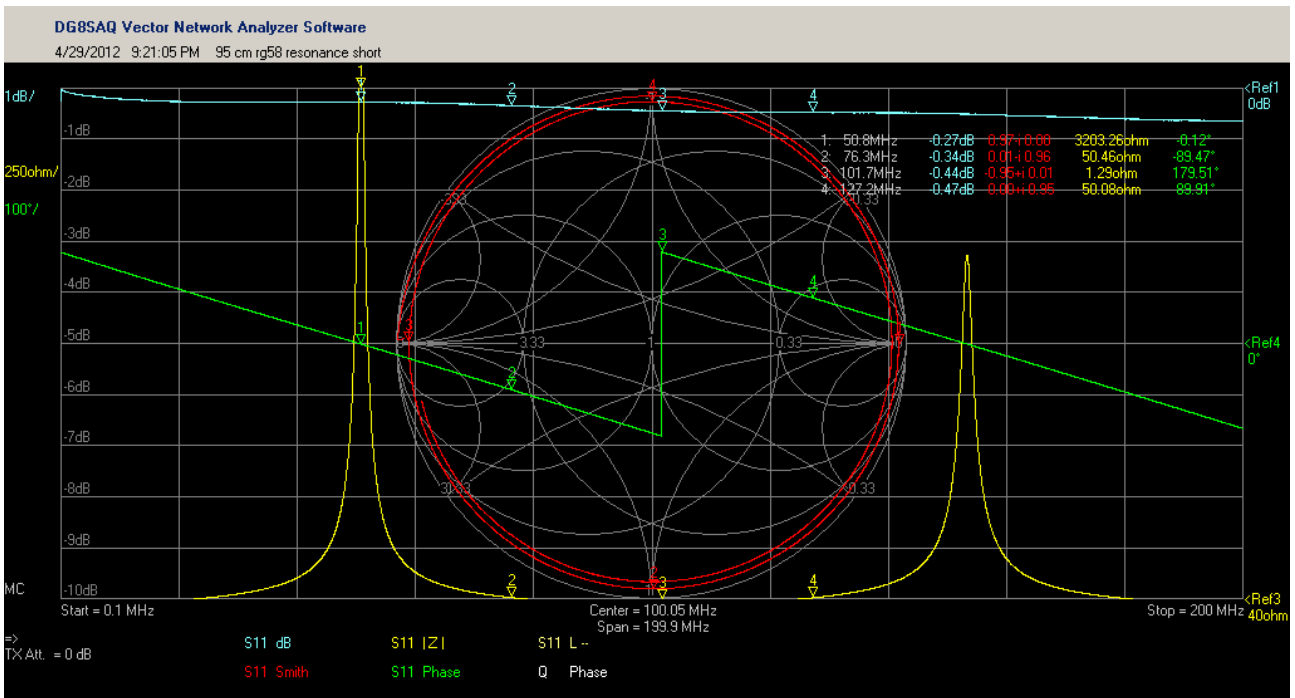
The next page you see a transmission-line sweep. I connected the open RG59 to the crocs and swept. Look at the 4 markers. They are 90 degrees apart. 90 degrees is a quarter wave. You see an impedance minimum, an impedance maximum and two places the impedance is near 50 ohm again. Each a quarter wave separated.



But here the crocs are a cause of faults so I took a piece of RG58 with connectors. Here you see something similar as with the 75 ohm cable but now the impedance transforms almost exact to 50 ohm. You see the green phase trace. The markers split it in 4 equal pieces between phase jumps. At a quarter wave and  $\frac{3}{4}$  wave you see it is 50 ohm, at a half wave it is a few thousand Ohms and resonant. Also in smith you see they are nice spread.



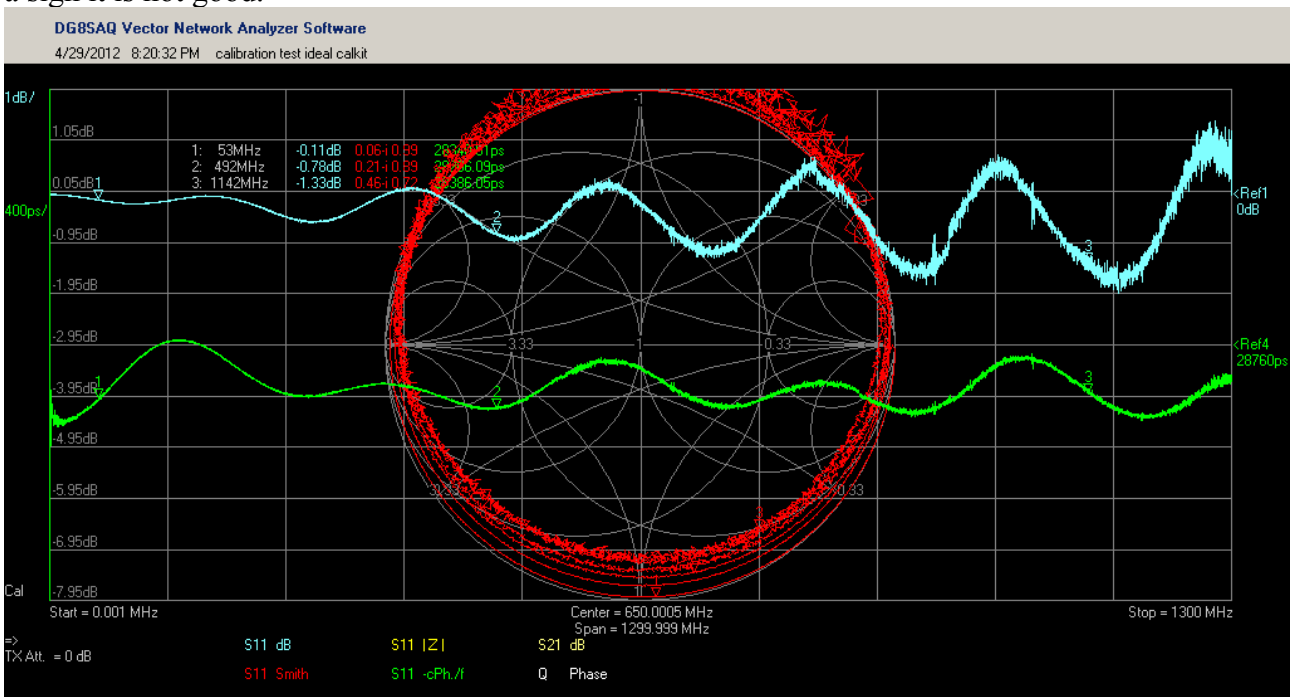
But now we are on this subject. You can also short the end of the coax and do the same trick. You see again the highest impedance at the middle of the phase trace but look at the frequency. 50 ohm is still unchanged but the highest impedance is now switched places with the lowest.



## Validation of calibration

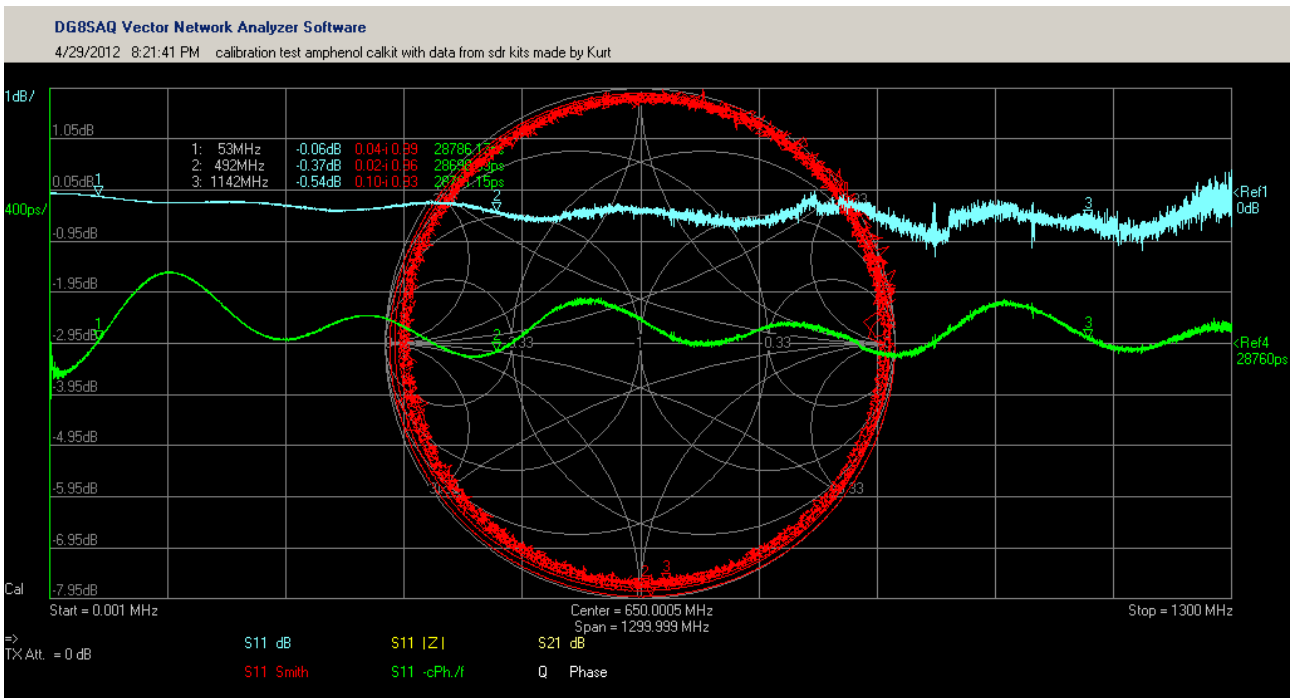
There is a simple way to validate your calibration or to extract the parameters. Connect about 30-40 cm of coax to your reference level. Use a S11 with dB, smith and cont.phase/f.

The first picture is using the ideal parameters calkit. You see the trace go out the smith-chart. That is a sign it is not good.



But using the right parameters you get this:





You see a reduced ripple in the return loss and the trace stays within the smith chart. Tom has explained in the helpfile how you can extract you own calkit parameters. The result should be as above.

Hope this information was a bit useful.

April 2012 Fred PA4TIM