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## AT16802: Antenna Tune Up

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### APPLICATION NOTE

### Introduction

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Antenna tuning is an illusive process, which combines complex mathematical theory and heuristic methods. This paper endeavors to inform Engineers how to tune, or match, antennas for s-band radios. This example matches a 2.4GHz chip antenna that could be used for ZigBee®, Wi-Fi®, or Bluetooth® Radios. A Vector Network Analyzer and Smith Chart are used. The author assumes a basic knowledge of these tools.

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## 1. Background

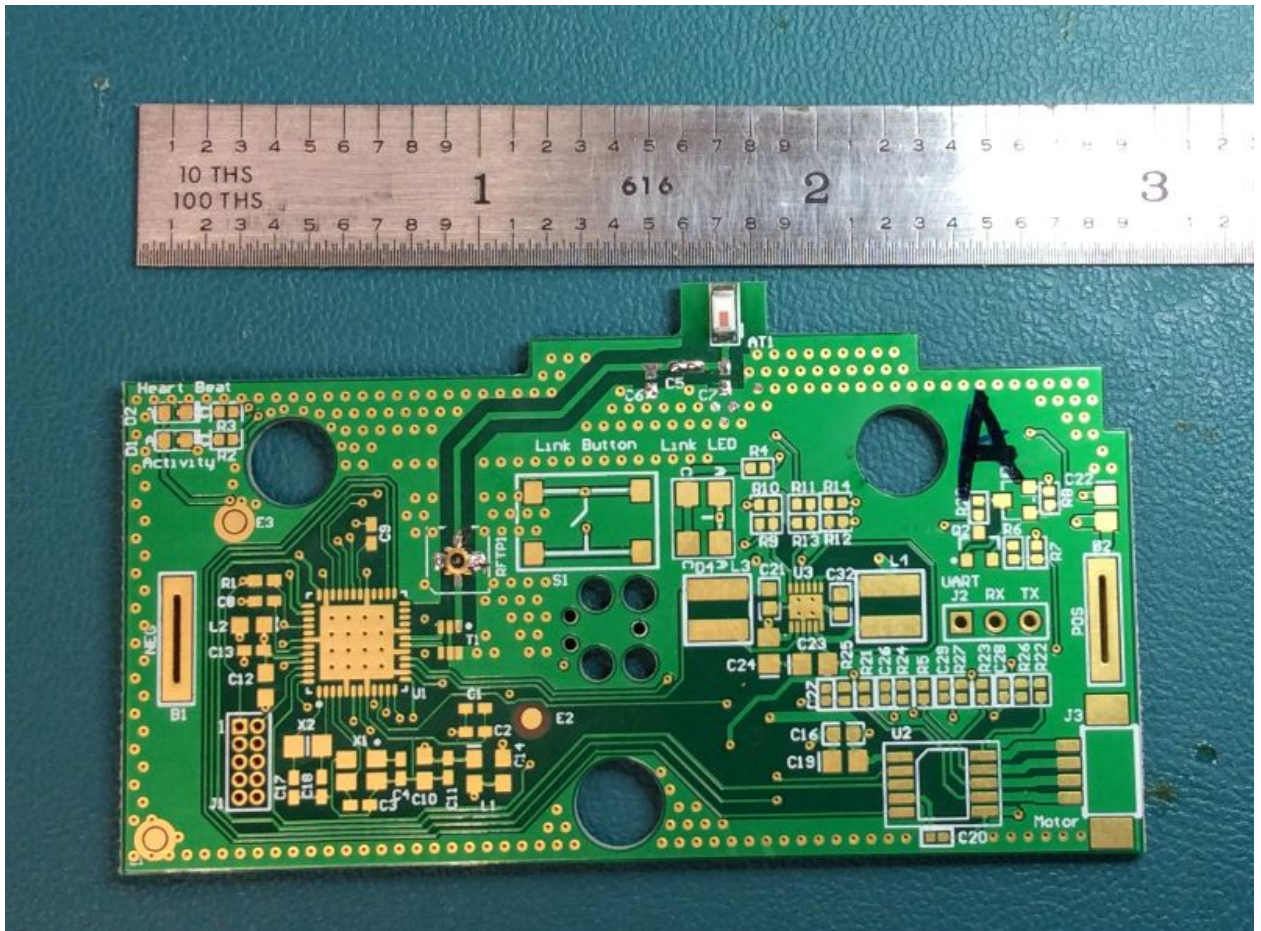
RF Designers need to properly match the antenna and transmission line to achieve optimal radiated performance from their wireless products. Antenna matching is the last step in a technically challenging design process and is usually done late in the development process. At microwave frequencies the Printed Circuit Boards and Enclosures are influential circuit elements. Layout Engineers try to minimize the effects of parasitic reactances, but they still have significant influence on antenna behavior. Sophisticated modeling tools can provide detailed analysis and match values. However, they are very expensive and require detailed calibration of component parameters and construction materials. Using a Vector Network Analyzer (VNA) and Smith Chart can provide useful in situ analysis and a practical alternative for a basic antenna matching.

## 2. Overview

The key concept of antenna matching is making the antenna resonate efficiently at the carrier frequency. This is manifest by Return Loss (RL) and in-band Radiated Power (ERP.) To do this the antenna electrical length must be trimmed or 'matched' to allow a standing wave to build in the space surrounding the resonant structure. For PCB antennas and wire-whips this can be done heuristically by snipping off small increments of metal until a resonance length is found, basically the same process as tuning a slide-whistle. Chip antennas pose a harder problem because they cannot be modified. RF designers using Chip antennas need to provide locations for matching components.

The primary tool used for the tune-up is a Vector Network Analyzer (VNA). This instrument measures the complex impedance of a physical circuit and displays it graphically as a Smith Chart or Log-Linear plot. The connection and calibration of the VNA is critical for reliable measurements. Additional tools included an RF spectrum analyzer and shielded cage to make radiated power measurements but these can be replaced with PER range tests. And finally the test engineer will have to obtain a sample kit of passive components for RF work, usually in the range of 0.5 to 20pF and 0.5 to 20nH.

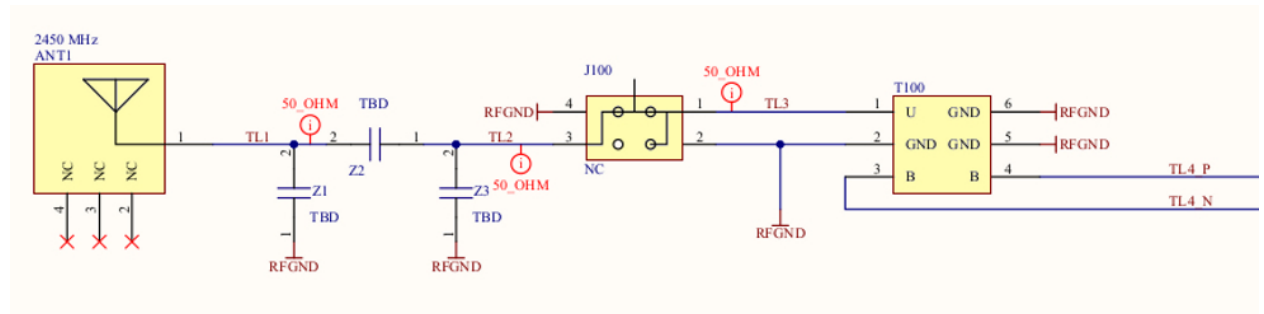
Figure 2-1. DUT



Design features used in this example can help test engineers to quickly probe the workpiece and get consistent results. In this example we show a DUT with a chip antenna, Pi matching-network, microstrip transmission line, and coaxial RF probe connector. The chip antenna is trimmed with a the Pi matching-network. The component values of the Pi circuit are unknown before the tune-up so the reference designators are generic; the shunt element nearest the antenna is “Z1”, the series element is “Z2” and the shunt element abutted to the transmission line is “Z3”. The matching-network is physically placed close to

the antenna terminal, or "launch". The microstrip transmission line is about one inch long. See the [Atmel® AT02865: RF Layout with Microstrip](#) application note for details on microstrip transmission line construction. The coaxial RF connector is placed at the other end of the transmission line near the balun. Normally the connector would be used to make conducted measurements of RF signals. However, for the antenna tune-up we can physically rotate the connector by 180° and probe the antenna. Also note the PCB does not need to be fully populated, initial testing can start as soon as engineering samples of the PCB are released.

**Figure 2-2. RF Front End**



### 3. Radiated Power Baseline

To verify benefits the Radiated Power was measured before adding any matching components. To test the initial Radiated Power short the location Z2 and open Z1 and Z3. An Atmel ATSAMR21-XPRO board running the Atmel Performance Analyzer application is connected to the coax RF connector and will be our signal generator.

Figure 3-1. Radiated Power Test

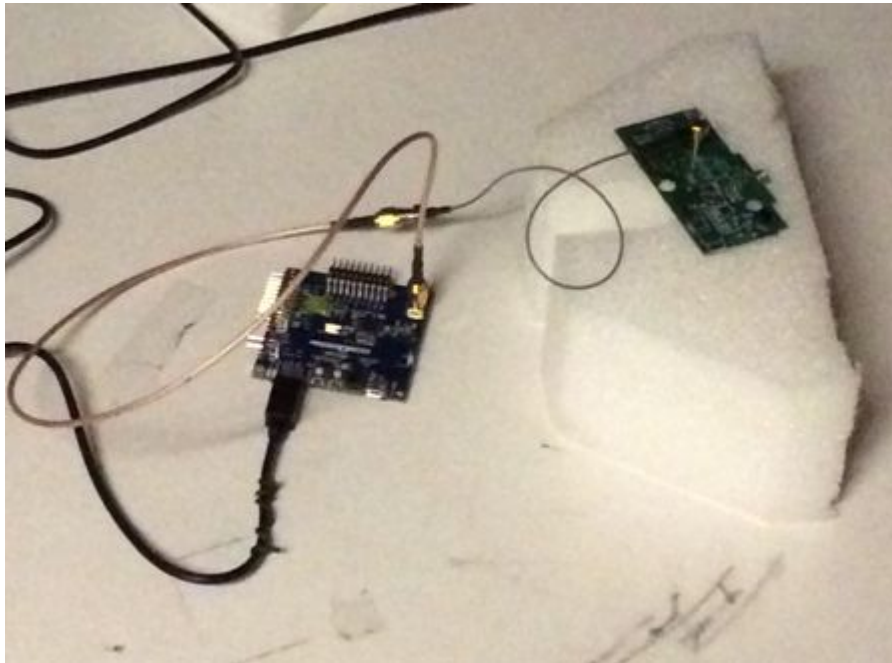
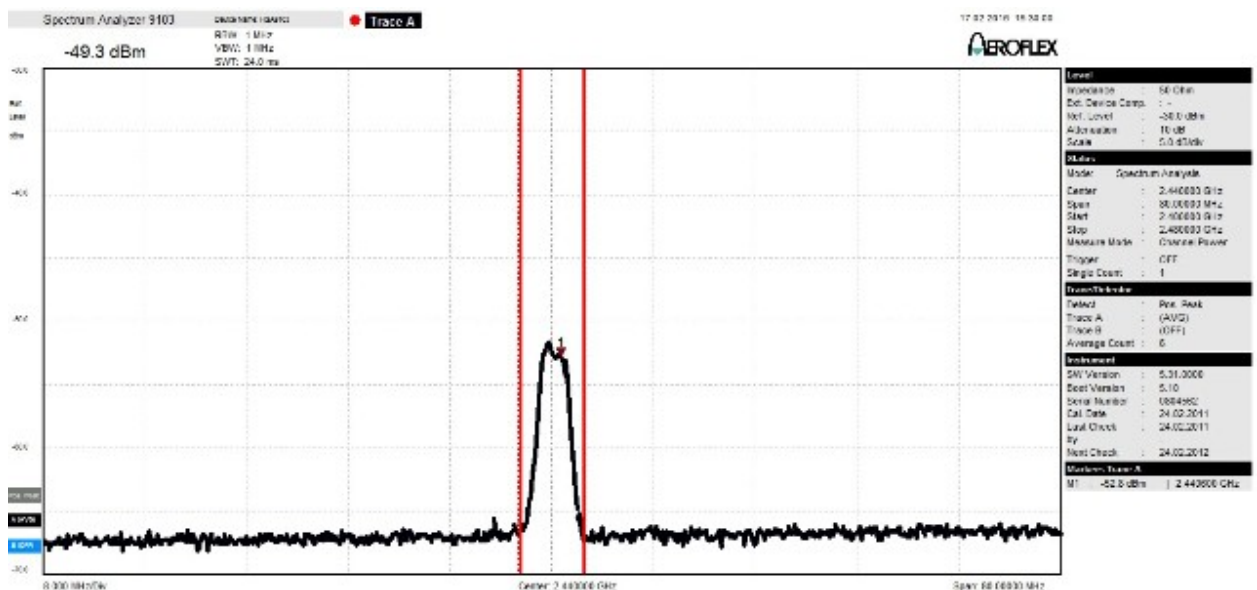


Figure 3-2. Radiated Power "Before"



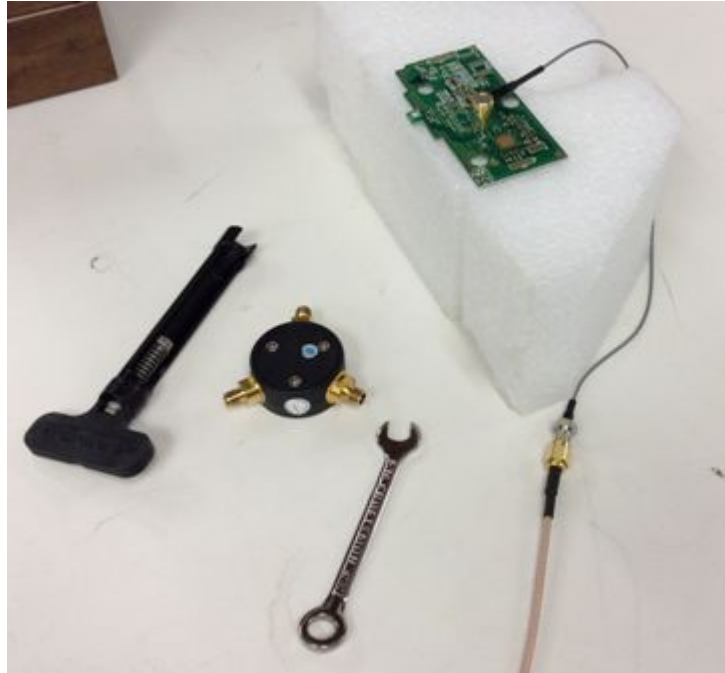
This "Before" measurement value is -49dBm. The units are erroneous because the test range was shorter than the conventional 3 meters. However, for our purposes absolute measurements are not necessary. Relative measurements are good enough to verify the benefits of tuning. We just need to make a "Before" and "After" measurement using the same set-up.



## 4. VNA Setup

Configure the VNA to make  $S_{11}$  measurements. The DUT will be connected to the VNA using an SMA cable plus an adapter cable that mates to the coax RF connector on the PCB. The entire system is 50 $\Omega$ . We need to calibrate the setup using an appropriate calibration kit. The electrical length of the SMA cable is subtracted from the measurement using the cal-kit and calibration routines built into the VNA. After calibration, the instrument is corrected to the end of the SMA cable.

**Figure 4-1. VNA Tools**

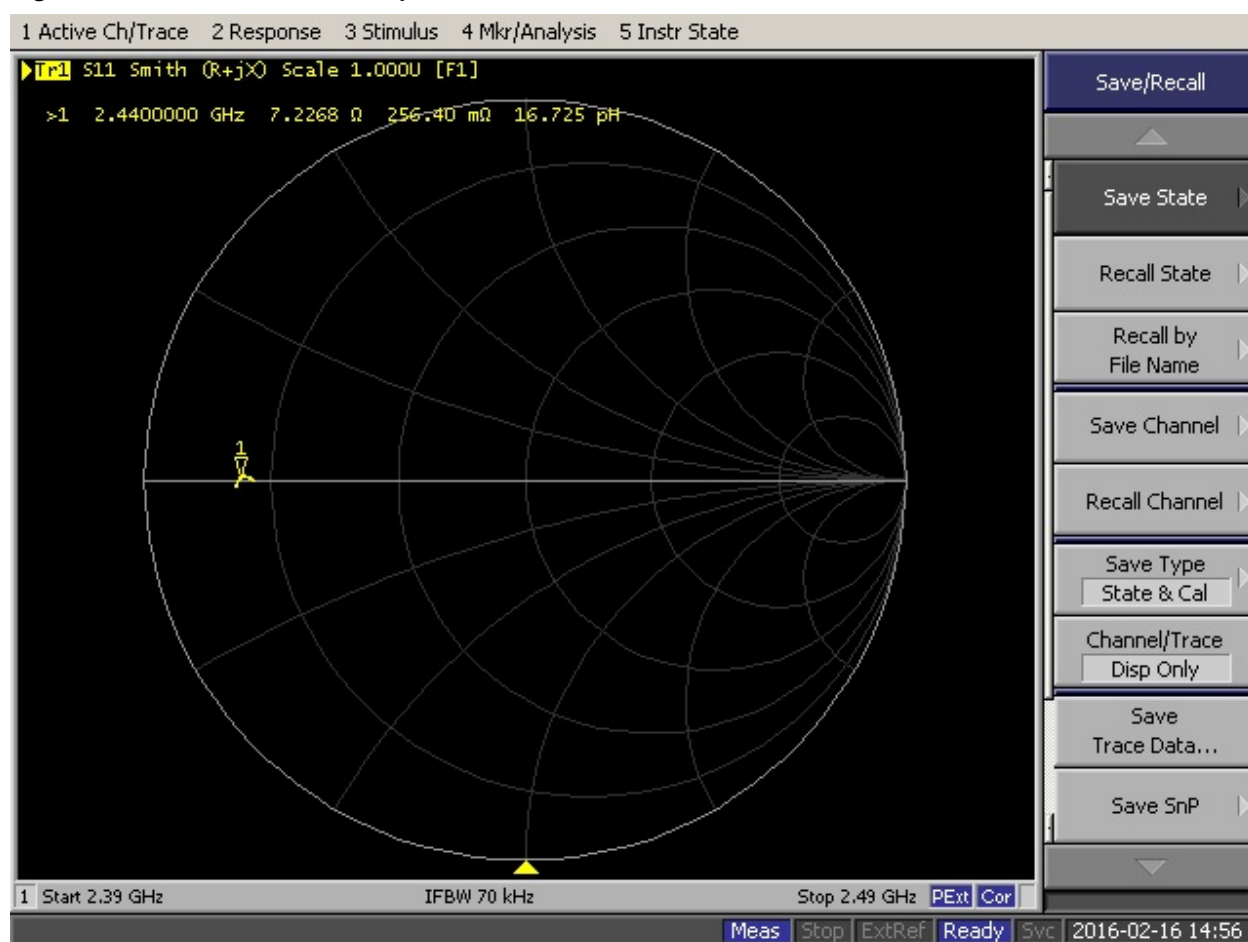


Note the use of a proper torque wrench and open-end wrenches to reduce wear on the SMA connectors and ensure consistent measurements. Additionally the use of a non-conductive polystyrene pedestal provides separation between the DUT and conductive materials within the test bench.

After the length of the SMA cable has been calibrated out, or de-embedded, the next step is to use the Port Extensions feature and correct for the remainder of the RF signal path to the Lumped Elements. The “Lump” of elements includes the antenna and the Pi circuit. Because they are tightly clustered together the impedance can be plotted directly on the Smith Chart as a single point. In contrast Distributed Elements are separated by non-trivial distances and require rotation on the Smith Chart to account for transmission line delays.

The transmission line and adapter cable have significant delays and have to be calibrated out of the measurement. To do this location Z3 is shorted. Z3 is the boundary between the transmission line and the Lump. The VNA used in this experiment has an Auto-Port Extensions feature. With Z3 shorted, select the 'SHORT' termination and the instrument does the rest. For manual Port Extensions the test engineer will have to measure the length of the adapter cable plus the transmission line. Then calculate the electrical length between the SMA cable and Z3 using the speed of light and the velocity factors of the cable and transmission line. This will give an approximate extension length, or delay period. Then using a Smith Chart display and then fine adjust (AKA the suicide knob) dial-in the Port Extension value until the trace crosses the resistive axis on the short side of the chart. The figure below shows the calibrated measurement of a Short at location Z3.

Figure 4-2. Calibration to the Lump with Port Extensions



In the calibrated chart, the marker is placed mid-band at 2440MHz. The impedance is about  $7\Omega$ , which agrees with the DC measurements of the cable. Note the adapter cable plus transmission line is a Distributed Element and the VNA, in  $S_{11}$  mode, sees twice the real resistance observed by a DVM in  $S_{21}$  mode. Record the calibration settings in the instruments memory and now we're ready to get on with it.



## 5. Raw Impedance

Now that the VNA is calibrated “to the Lump” we can measure the raw impedance of the antenna and the surrounding PCB. To do this remove the short at location Z3 and insert a short in the series location Z2. The signal path is now direct from the VNA to the antenna. The figures below show the raw impedance and return loss with Z2 shorted.

**Figure 5-1. Raw Impedance Z2 Shorted**

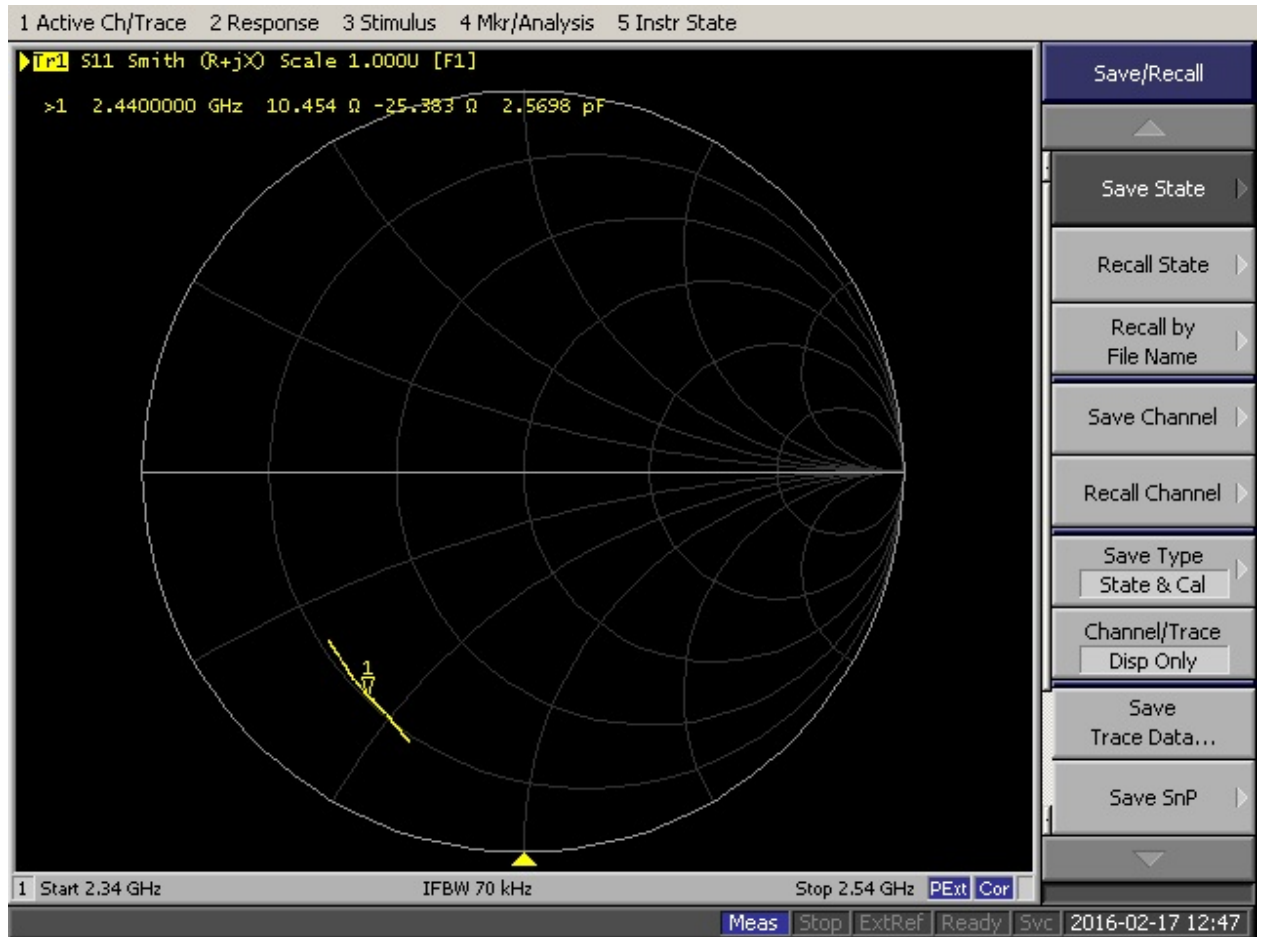
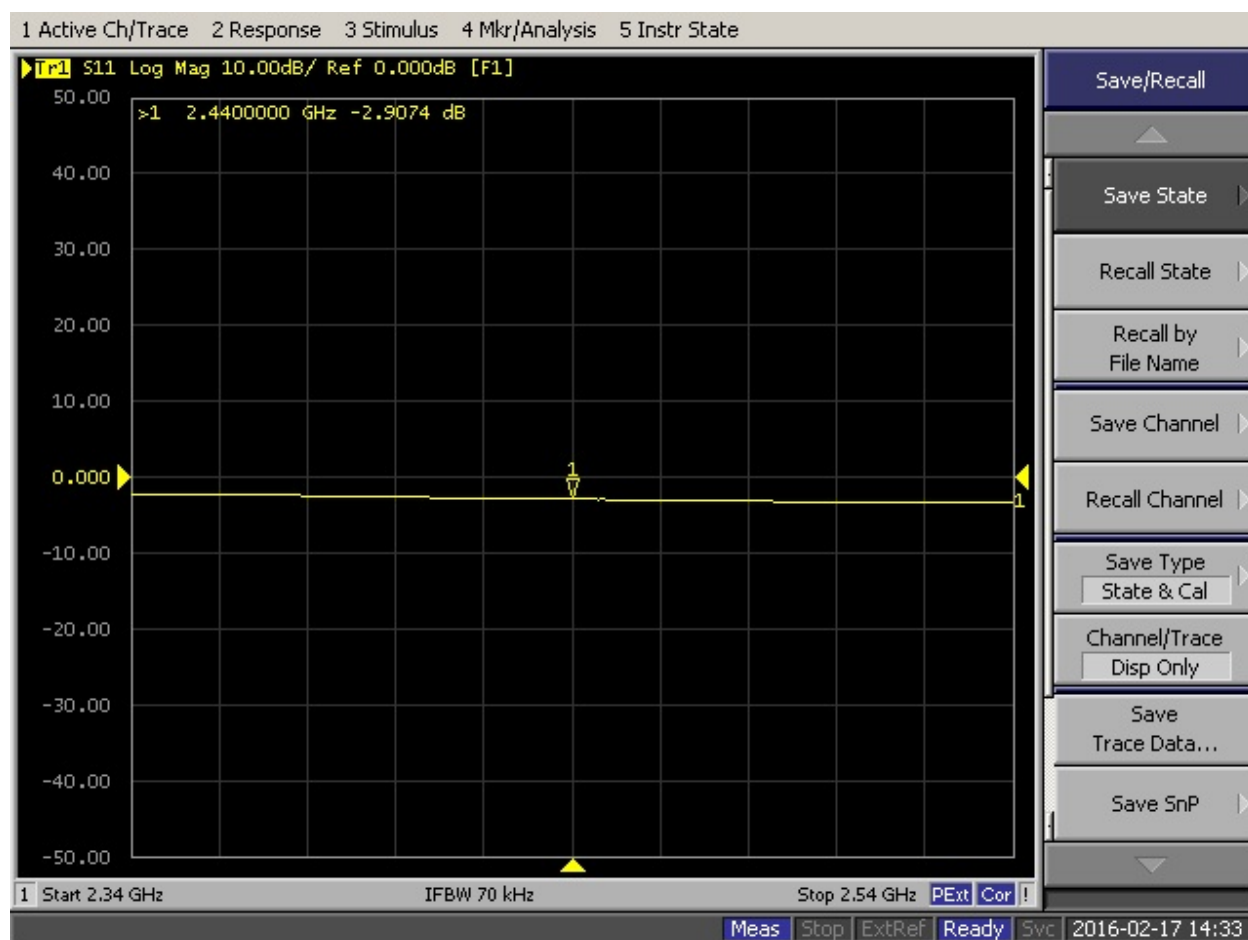


Figure 5-2. Raw Return Loss Z2 Shorted

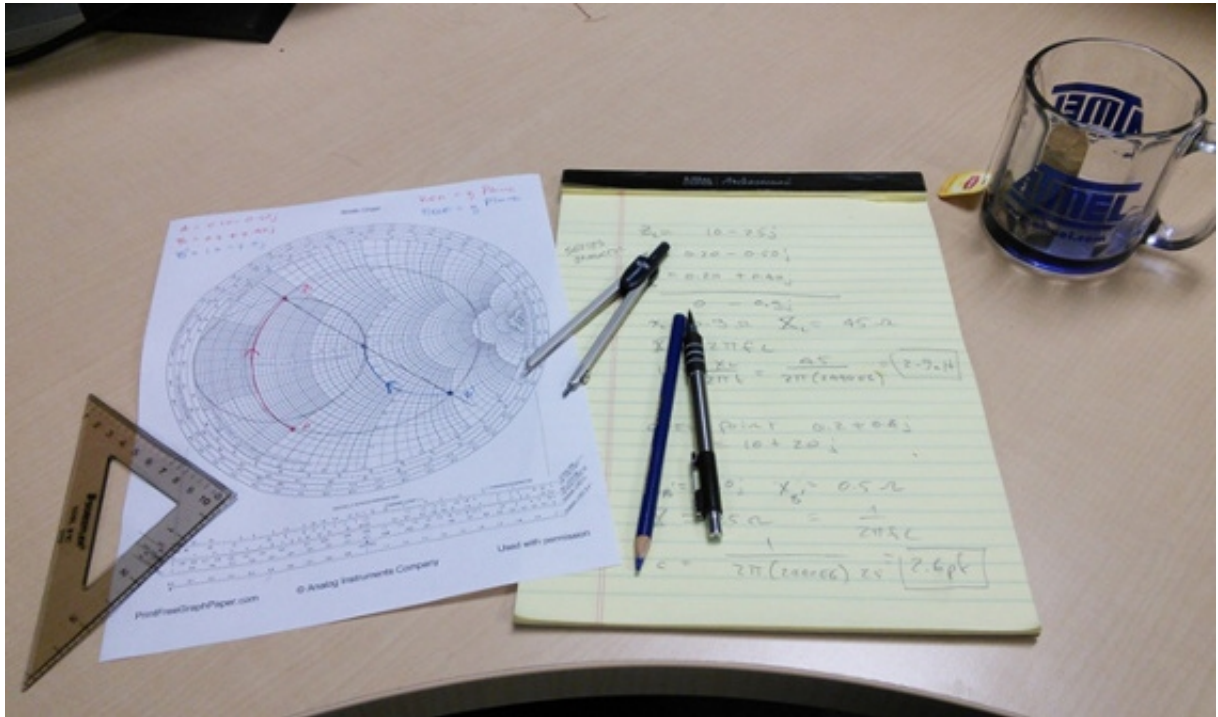


The VNA Smith Chart shows an impedance of  $(10 - 25j)$  capacitive and the Return Loss is an unimpressive -3dB. This means the Lump is not resonating at 2440 MHz and 53% of the RF energy is being returned to the VNA. The next phase of the tune up is to plot a match-network solution using a Smith Chart.

## 6. Plotting the Match-network

The Smith Chart is a classic engineering tool from the 20<sup>th</sup> century. The chart reduces complicated complex mathematics to simple geometric diagrams drawn with a straight edge and compass. The Smith Chart's elegance and utility has withstood the test of time. There is plenty of information about Smith Charts on the internet if the reader is interested (see 1 and 2 in the [Bibliography](#) chapter). A summary of Smith Chart tips is included in the [Appendix](#).

**Figure 6-1. Engineering with the Smith Chart**



To start the plotting we normalize the Raw Impedance to  $50\Omega$ . To do this divide  $(10-25j)$  by  $50\Omega$  and place it on the chart at point A ( $0.20-0.5j$ ). On this chart both the impedance and admittance planes are shown. Operations on the impedance plane are shown in red and operations on the admittance plane are shown in blue. To convert a point from impedance to admittance, or vice versa, the point is rotated  $180^\circ$  round the chart using a compass and straight edge. To match the antenna we need to find a path from point A to the center of the chart.

Figure 6-2. Ideal Match with the Smith Chart

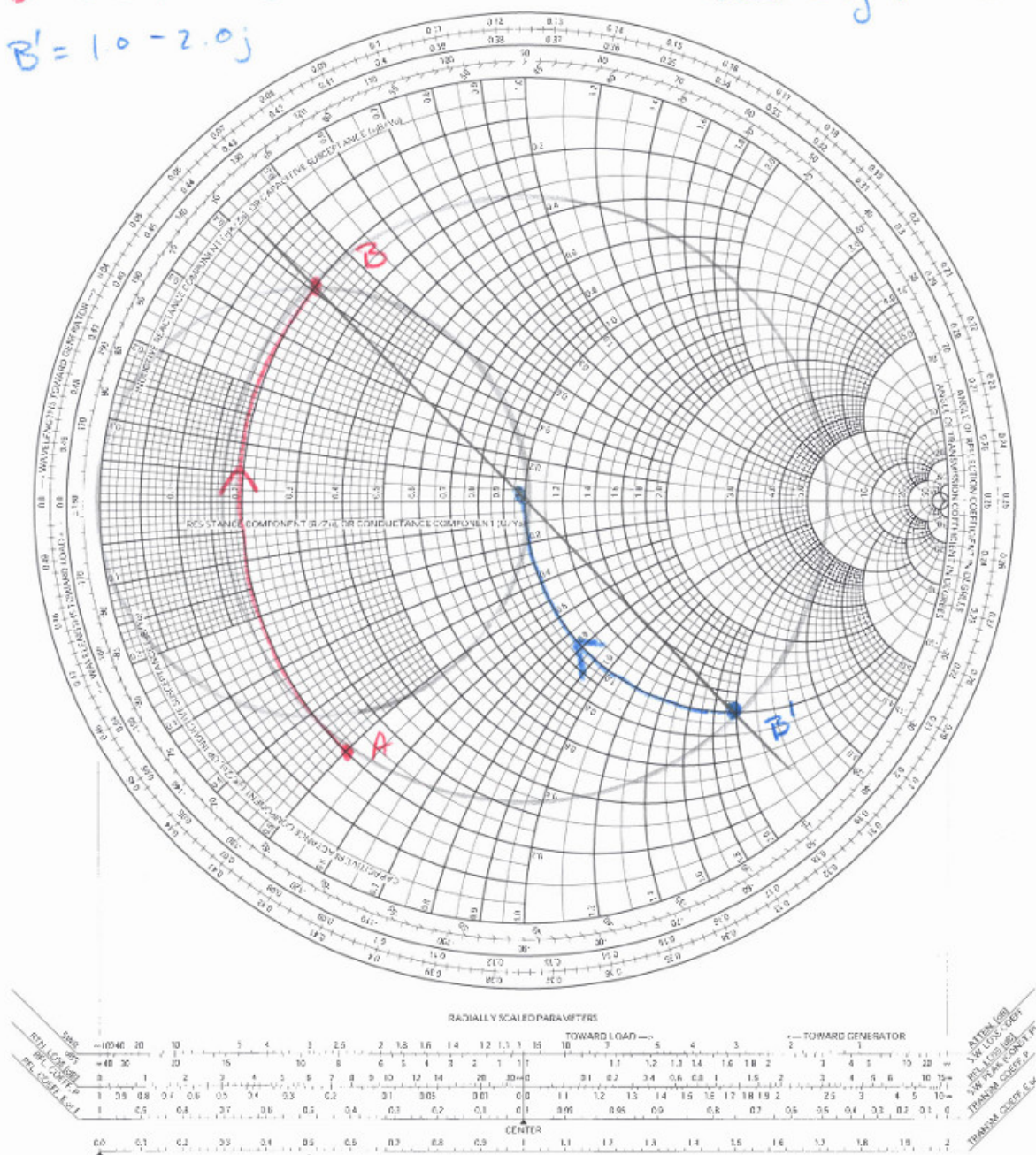
$$A = 0.20 - 0.50j$$

$$B = 0.2 + 0.40j$$

$$B' = 1.0 - 2.0j$$

Smith Chart

RED =  $z$  Plane  
BLUE =  $y$  Plane



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Mathematically there are an infinite number of solutions that will do the job, but there are some practical constraints that need to be considered. Series inductors and shunt capacitors are preferable because increasing the component value moves the point on the chart farther along the locus. In other words we

can easily increase a shunt capacitor from 0.5 to 2pF but decreasing a series capacitor from 0.5 to 0.05pF is not practical with real-world surface mount components. For this example we used a series inductor at location Z2 and a shunt capacitor at location Z3. Z1 will not be populated. However, the location would have been necessary if the initial impedance was inductive. Another issue is the resolution of the chart. Many computer generated Smith Charts and simulations show several digits of resolution, which can be misleading. In reality the uncertainty of pencil marks and real-world component values are accurate to two decimal places. Additionally component values are coarsely quantized. Ideal linear mathematics is nice, but tuning s-band circuits with 0402 components is a little like cabinet making with a hatchet.

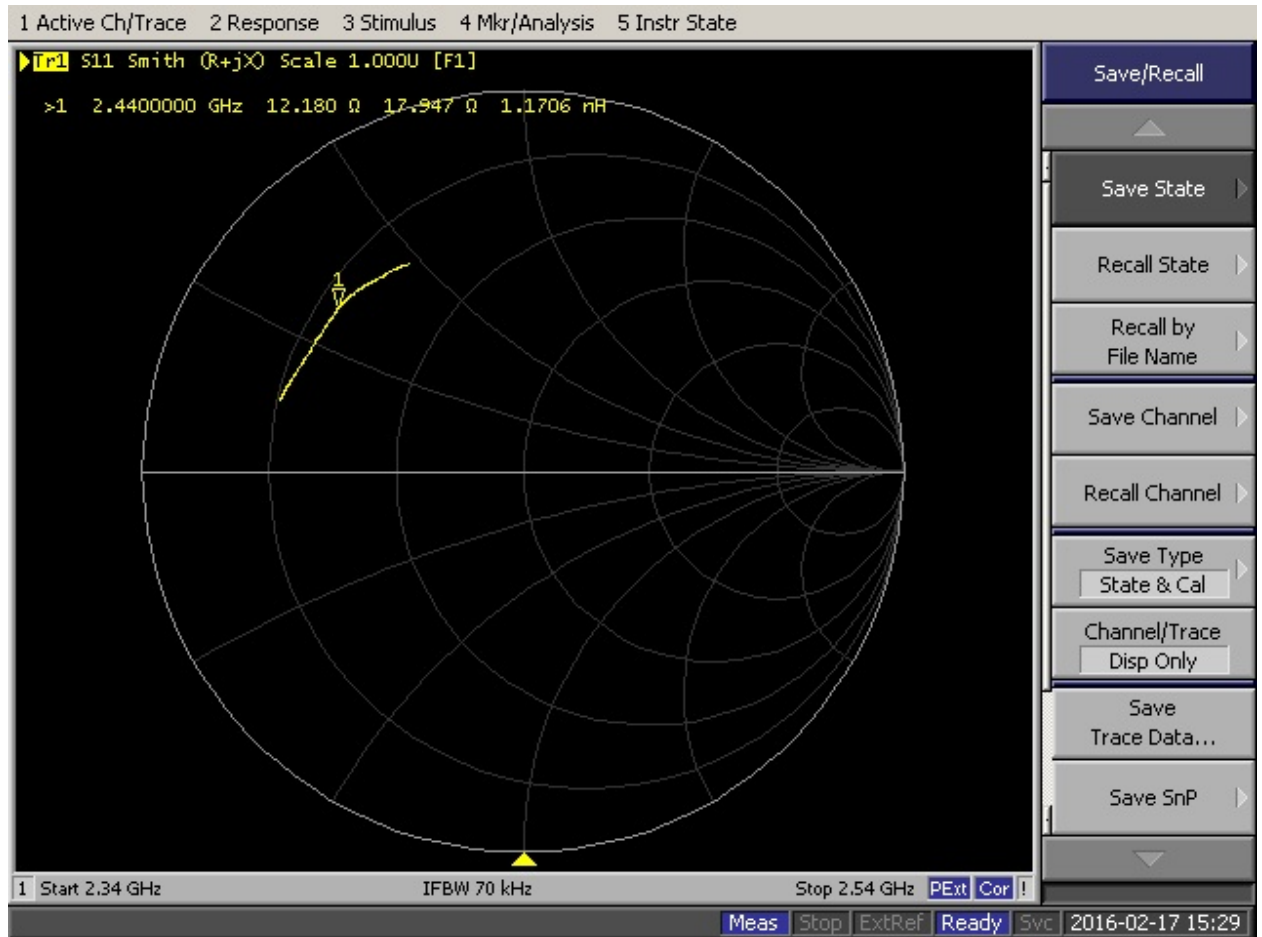
The first move in a two element match is to intersect with either the  $|z| = 1$  circle, or the  $|y| = 1$  circle. The chart shows a red arc from A (0.2-0.5j) to B (0.2+0.4j) along the  $r = 0.2$  circle. The change in impedance is  $x = +0.9j$ . This scales up to  $X_L = 45\Omega$ . At 2440MHz this is equivalent to a 3.0nH inductor. Point B is on the  $|y| = 1$  circle. If this is point scaled to  $50\Omega$ , the impedance will be  $(10+20j)\Omega$ . We can observe this check-point on the VNA.



## 7. Verification and Analysis

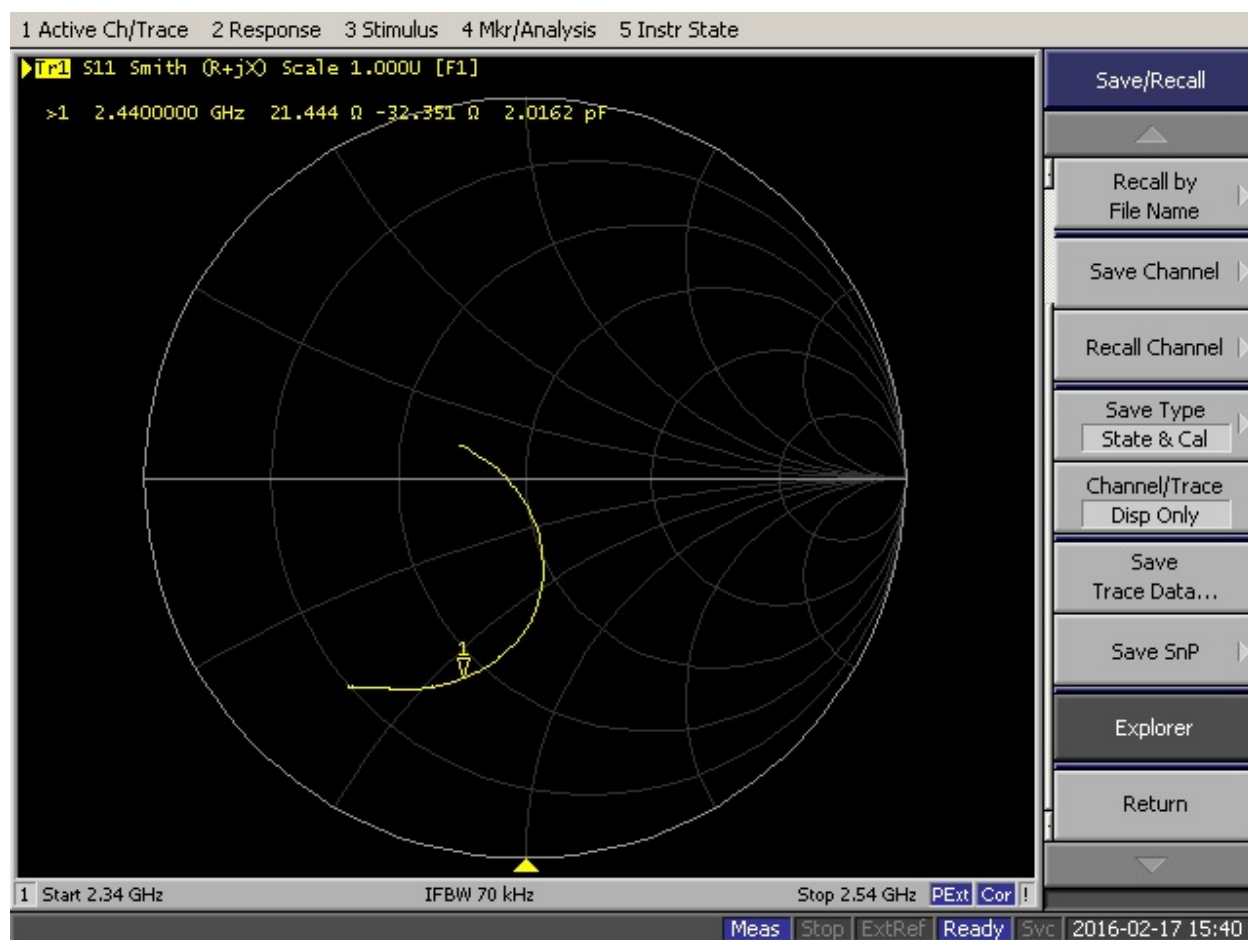
This is a good point to take a sanity-check measurement with the VNA just to make sure your circuit is in agreement with the twisted world Smith Chart plots. An impedance measurement with only the 3.0nH inductor in location Z2 is shown below. The addition of the Z2 caused a movement on the VNA display along the  $r = 0.2$  circle of the Smith Chart, this agrees with the ideal plot. So far so good.

Figure 7-1. Z2 = 3.0nH



Next, calculate the shunt capacitance for location Z3. To work with shunts convert point B from impedance to admittance. To do this, use a compass and draw a circle with the radius of B. Next, draw a line through B and the Origin intersecting with the other side of the circle. This intersection is shown as point B' or (1.0-2.0j) on the blue admittance plane. To calculate the required capacitance we draw an arc from B' to the origin along the  $|y| = 1$  circle. This has a length of  $b = 2.0$  on the chart, but remember this is an admittance value. To calculate a component value take the inverse of  $b = 2.0$  on the admittance chart to get  $x = 0.5$  normalized impedance. This scales up to  $X_C = 25\Omega$  or 2.6pF at 2440MHz. The closest standard value is 2.7pF. The resulting plot is shown below. The impedance is closer to the center but it overshot the mark.

Figure 7-2.  $Z_3 = 2.7\text{pF}$



Now for the heuristic iteration; try incremental adjustments to the Smith Chart prediction and see what works the best. VNA measurements for  $Z_3 = 2.4$  and  $2.0\text{pF}$  are shown below.  $2.0\text{pF}$  gave the best results. The locus crosses the resistive axis near the middle of the 2400 to 2480MHz band and circles around the origin in a constant VSWR circle of about 1.7:1. Crossing the resistive axis in-band is good, this indicates a local minimum in the Return Loss graph. The Return Loss has improved from -3 to -13dB, The energy being returned to the VNA has dropped from 50% to 5%. The Lump is now resonating throughout the desired frequency band and emitting 45% more RF energy into space.



Figure 7-3. Z3 = 2.4pF

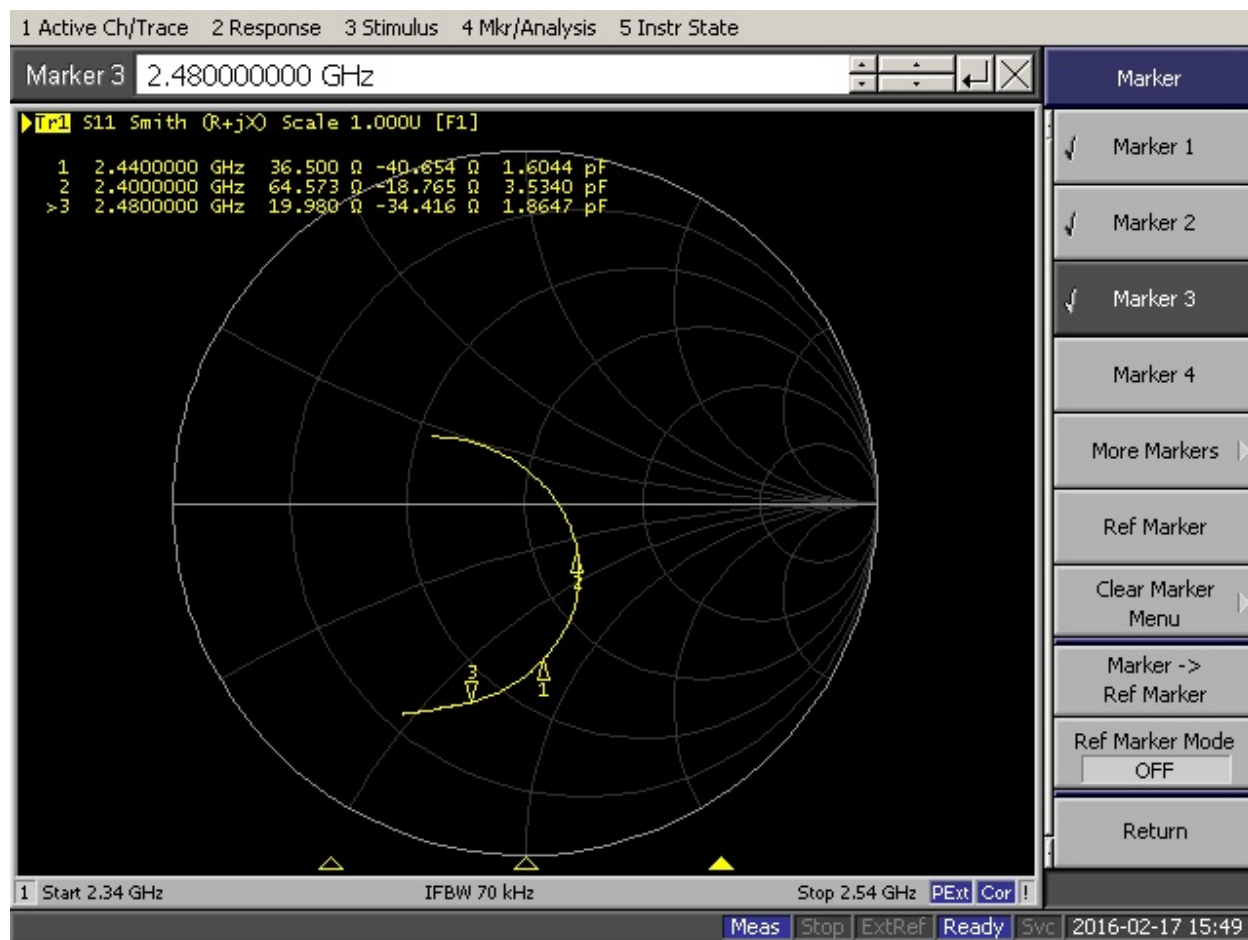


Figure 7-4.  $Z_3 = 2.0\text{pF}$

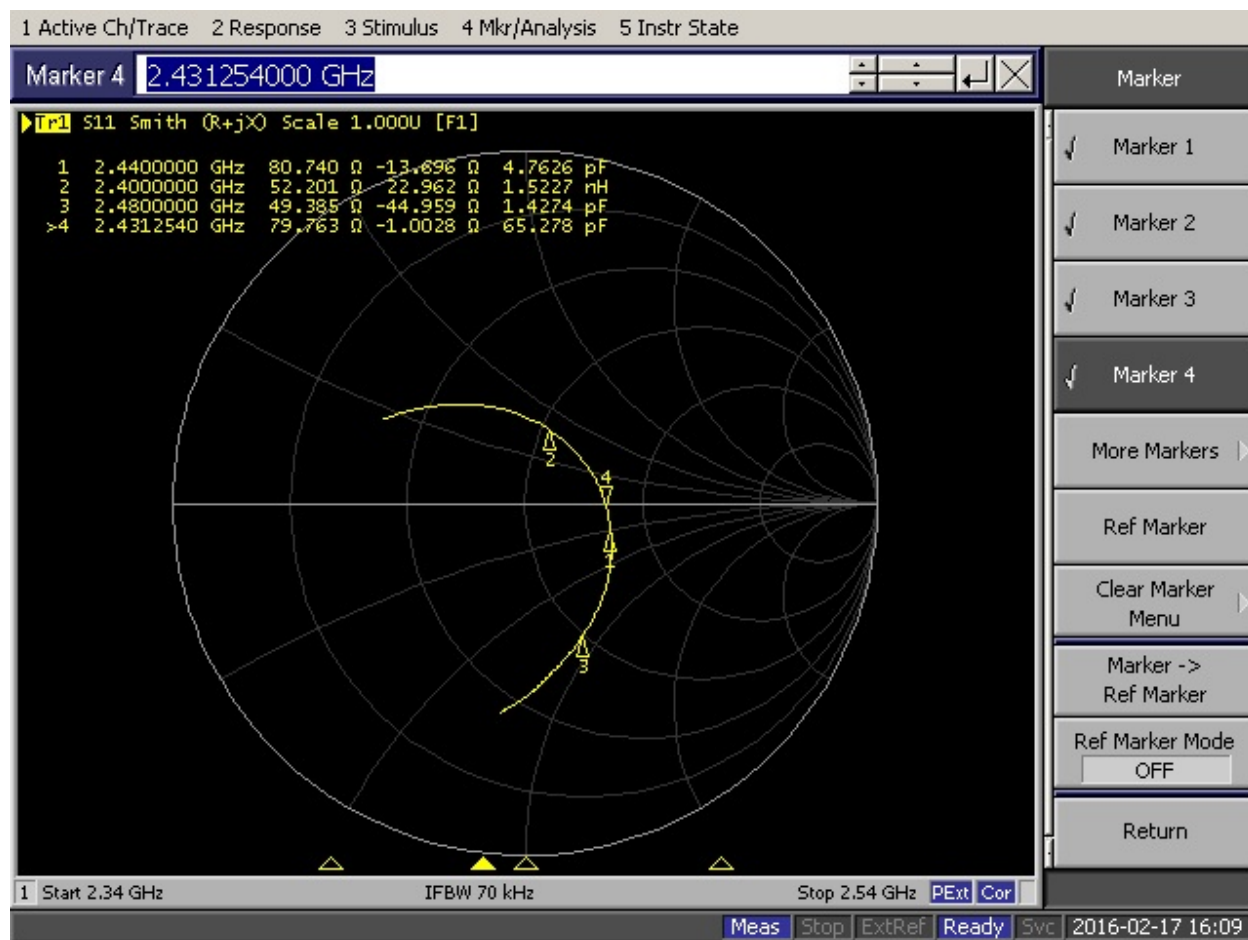
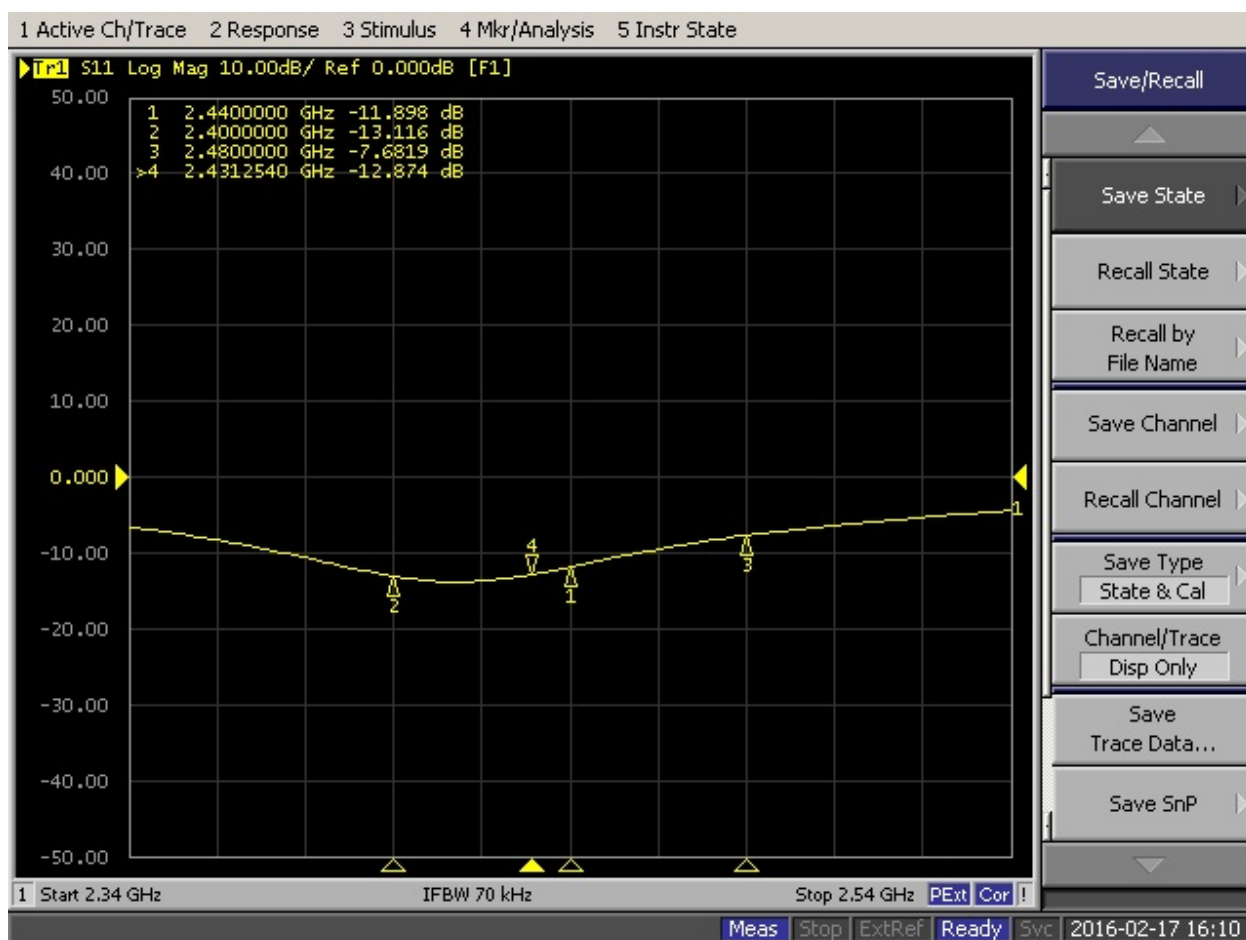


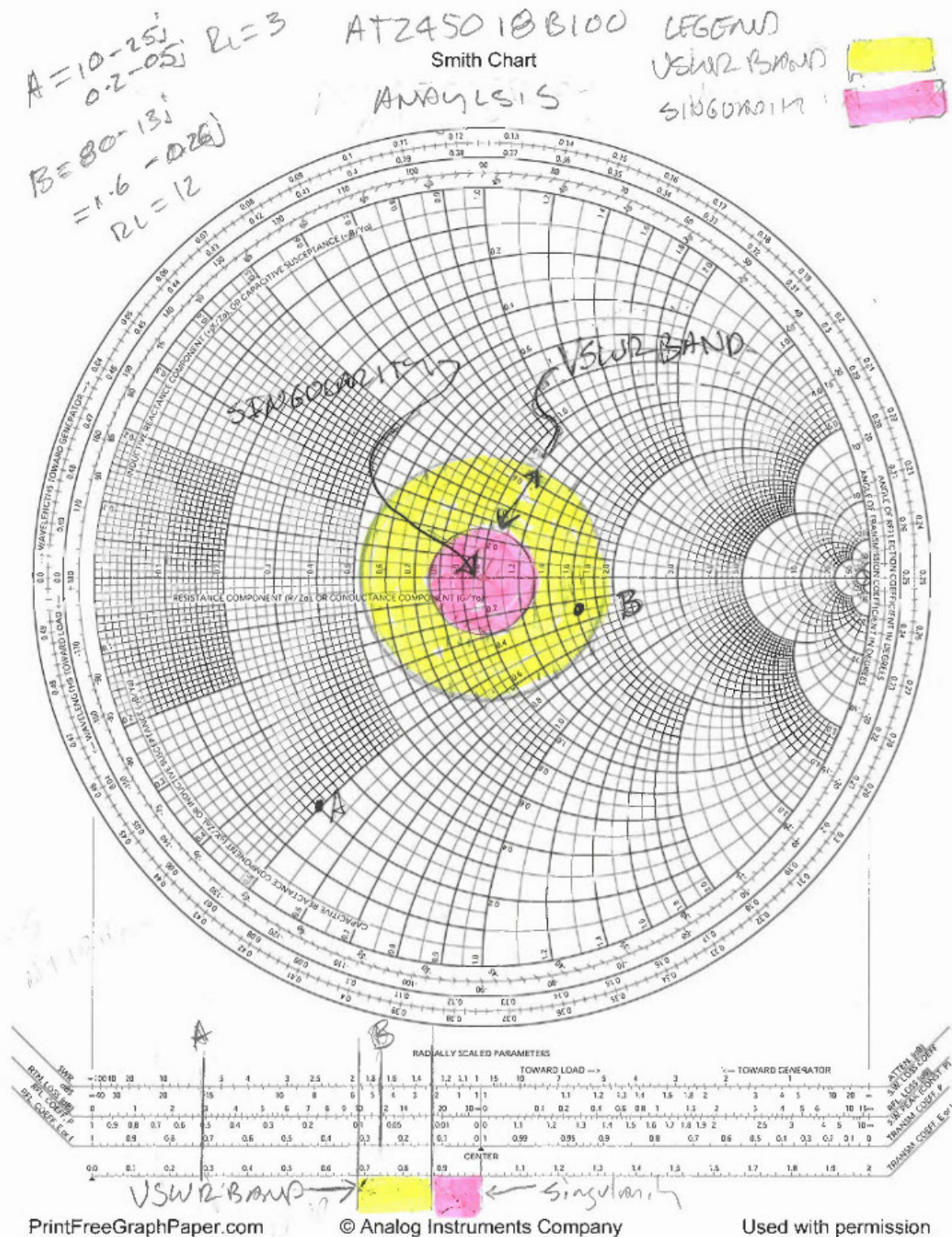
Figure 7-5. Z3 = 2.0pF Return Loss



The mathematically ideal plot put the locus right in the center of the chart but the resulting physical measurement was (21-32j). What happened?

To understand the disagreement between the ideal and measured data take a look at the antenna datasheet (see 4 in Chapter Bibliography). The Return Loss graph in the antenna datasheet shows losses below -10dB in the 2360 to 2590MHz band with a minimum of -18dB. Using the RL-to-SWR conversion scale at the bottom of the Smith Chart, this information can be used to draw a circular band round the center of the Smith Chart from 1.3 to 1.9 SWR. For the real-world antenna there is a singularity at the center of the chart because the antenna cannot be 100% efficient. As we adjust the match-network on the bench the impedance locus will skirt the singularity. The best a real-world match can be is somewhere in this SWR band. Using a value of Z2 = 2.0pF resulted in a measured impedance of (80-13j) at 2440MHz. This is shown on the Smith chart below at point B. For comparison the initial Raw Impedance of (10-25j) is shown at point A.

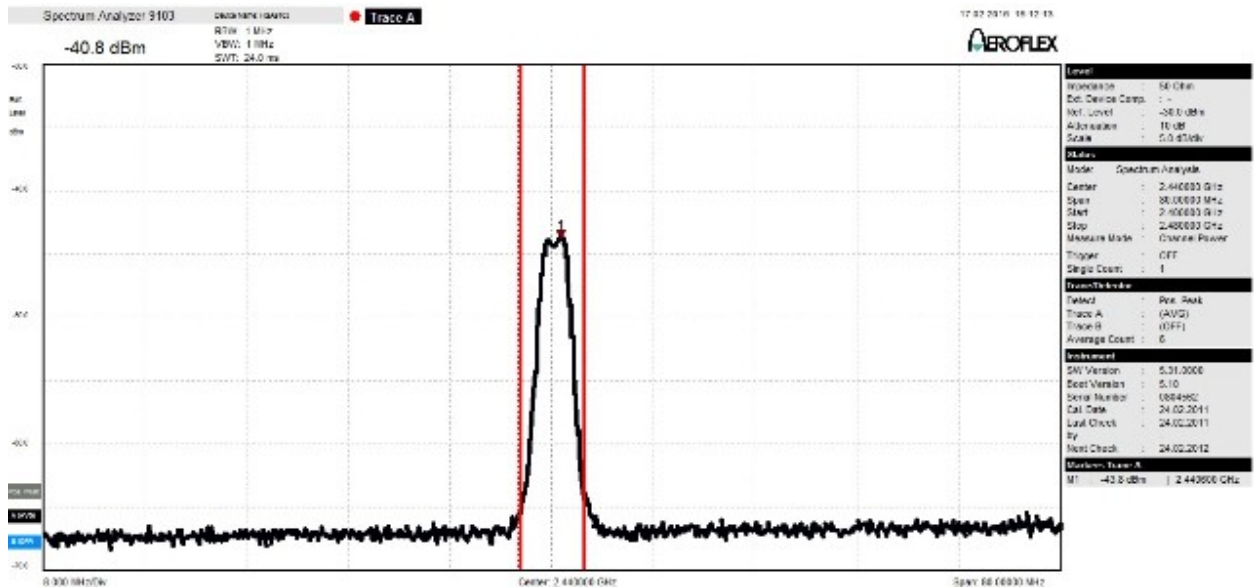
Figure 7-6. Measured Match and Analysis



## 8. Conclusion

The final values chosen were Z1 = Open, Z2 = 3.0nH, and Z3 = 2.0pF. The Return Loss improved from -3dB to -13dB, or from 6.0 to 1.6 VSWR. To verify our results a final radiated power measurement is shown using the same setup as before. The results are shown in the figure below. The Radiated power increased by +9dB, from -49 to -40dB. This is significant. Radio range doubles for every 6dB. Our efforts have resulted in a 3x range extension of the radio link. This result was well worth the effort.

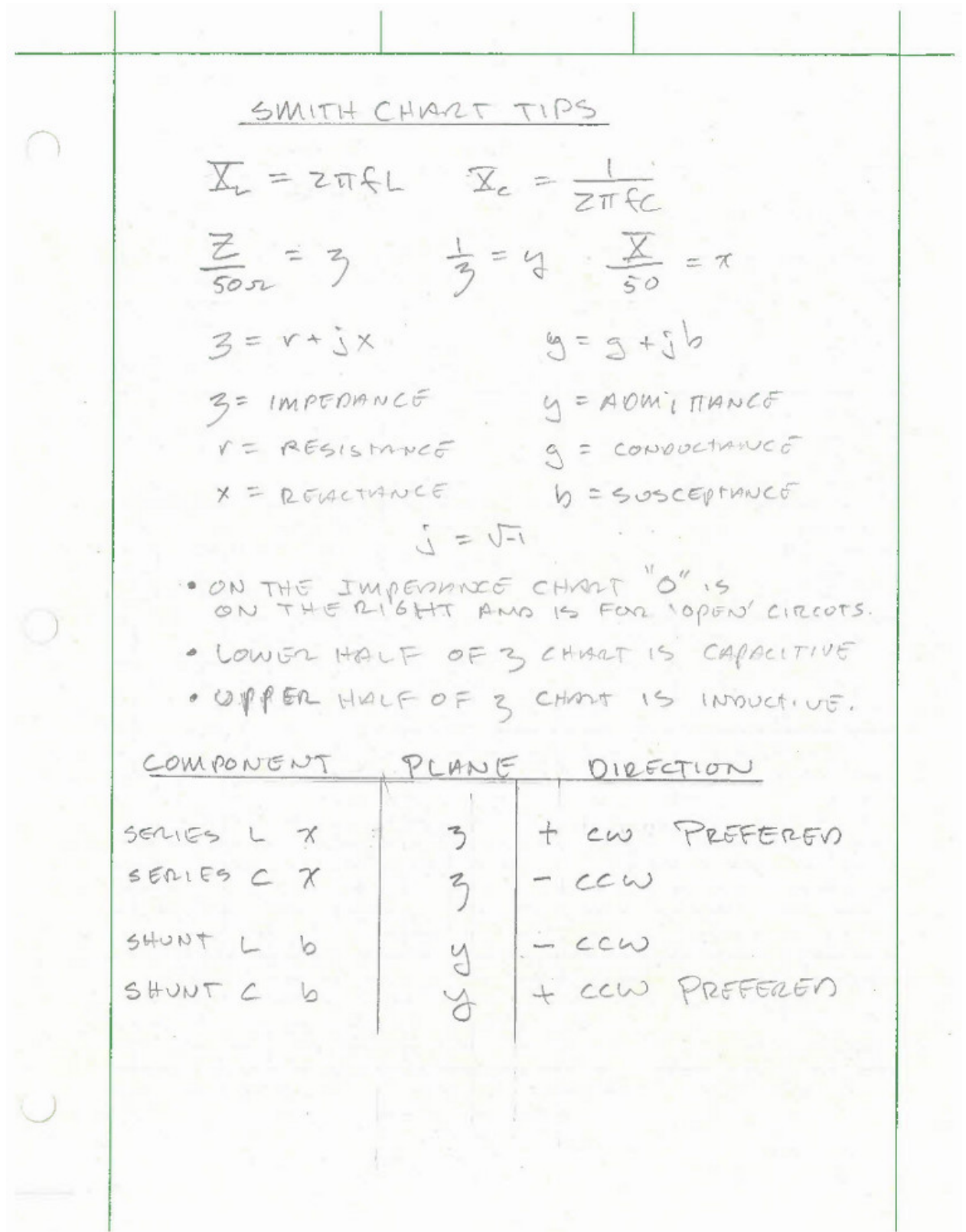
Figure 8-1. Radiated Power "After"





## 9. Appendix

Figure 9-1. Smith Chart Tips



## 10. Bibliography

1. Impedance Matching and the Smith Chart, MAXIM APP 742.
2. [https://en.wikipedia.org/wiki/Smith\\_chart](https://en.wikipedia.org/wiki/Smith_chart)
3. [Atmel AT02865: RF Layout with Microstrip](#) application note.
4. Johanson Technology 2450AT18B100 datasheet.



## 11. Revision History

Doc. Rev.	Date	Comments
42732A	05/2016	Initial document release

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