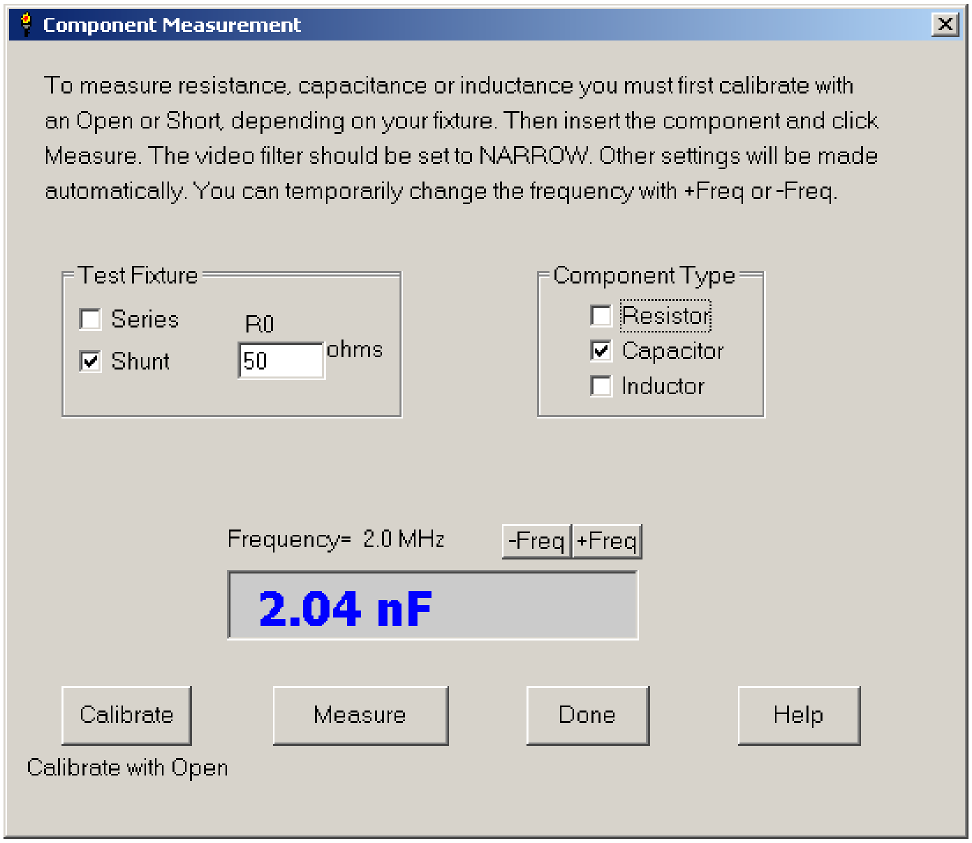
Analysis of Components with the MSA

Sam Wetterlin
11/6/09

There are many ways to use Scotty's Modular Spectrum Analyzer (MSA) to analyze electronic components, including resistors, capacitors, inductors, crystals and transmission lines. This document illustrates some of those methods.

Measure Components

The simplest method to measure resistance (R), capacitance (C) and inductance (L) values is to use menu Analysis→Measure Components. The feature is available in the MSA with the TG, and in the TG with full VNA. It does not require phase information, but will use it if it is available. The following dialog will open:



Component Measurement

To measure resistance, capacitance or inductance you must first calibrate with an Open or Short, depending on your fixture. Then insert the component and click Measure. The video filter should be set to NARROW. Other settings will be made automatically. You can temporarily change the frequency with +Freq or -Freq.

Test Fixture
☐ Series
☑ Shunt
R0 50 ohms

Component Type
☐ Resistor
☑ Capacitor
☐ Inductor

Frequency= 2.0 MHz

2.04 nF

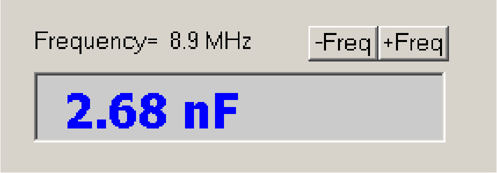
Calibrate with Open

Figure 1—Measure Components Dialog
(The numeric value in blue does not appear until you click Measure)

The Measure Components dialog handles all necessary calibration. You need to tell it whether the component is mounted in a series fixture (meaning the component is in series between the TG signal and the MSA input) or in a shunt fixture (meaning the component is shunted to ground from the line connecting the TG signal to the MSA input). To calibrate, you attach a Short (if a series fixture), or nothing (if a shunt fixture), and click the Calibrate button.

You may also specify the "reference resistance" (R_0) of the fixture, but for Measure Components it will generally be 50 ohms. Finally, you select the component type and click Measure. Continuous measurements will be made and displayed until you click "Stop". (The Measure button is relabeled Stop while measuring is in process.) The measurement shown in Figure 1 was made with a 2 nF, 1% capacitor.

When you have stopped measuring, the component value and the frequency at which it was measured are displayed. The MSA measures at 9 frequencies and then attempts to choose the frequency with the most accurate measurements. You can view the results at other frequencies by clicking the –Freq or +Freq buttons after stopping the measurement. Figure 2 shows the measurement at 8.9 MHz.


Frequency= 8.9 MHz

2.68 nF

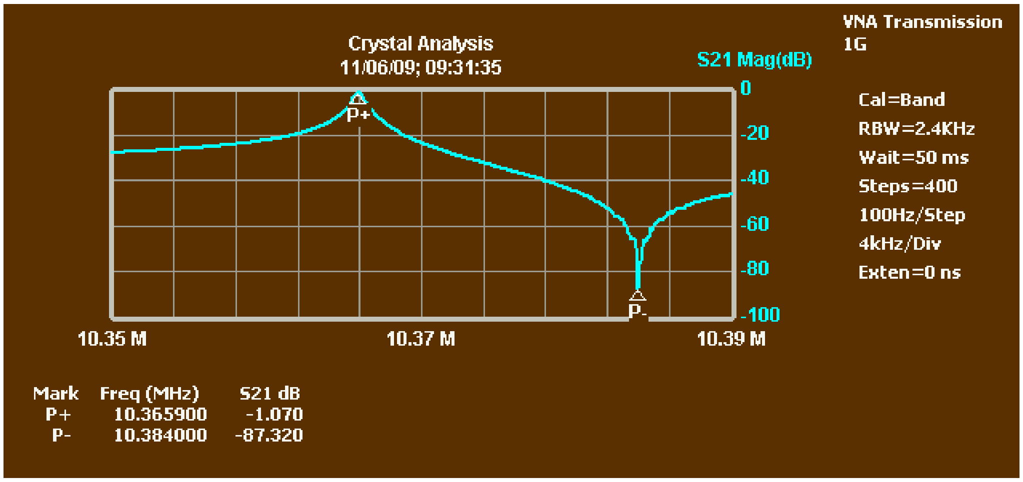
Figure 2—Results at 8.9 MHz
Influence of self-resonance can be seen

In Figure 2, the measurement increased to 2.68 nF. This capacitor was purposely left with long leads, which put its self-resonant frequency (SRF) at about 20 MHz. As a capacitor approaches its SRF, the impedance goes down, which means the effective capacitance goes up. (See the discussion of Figure 8 below.) Part of the goal of the more sophisticated techniques shown below is to remove the effect of self resonance, so the capacitor value can be measured without being influenced by the inductance of its leads.

Measure Components is a simple way to get the same sort of measurements that would be obtained with an RCL meter. The continuous measurement features allows you to measure many components in sequence without having to do any fiddling with the software.

Crystal Analysis
Using menu Analysis→Crystals in Transmission mode, we can measure the parameters of crystals. This feature is available in the MSA with TG or full VNA; phase measurement is not required.

The parameters of crystals need to be determined in order to use them in crystal filters. A crystal can be modeled as having several "motional" components—a resistor (Rm), capacitor (Cm) and inductor (Lm)—all in series, with a capacitor representing the package capacitance (Cp) in parallel with that entire combination. The series Rm, Cm and Lm will cause a series resonance (where the impedance drops to Rm) at the series resonant frequency (Fs). Slightly above that frequency, those series components will have a net inductance, which will resonate with Cp to create a very high impedance at the parallel resonant frequency (Fp). The profile of a typical crystal scan is shown in Figure 3.



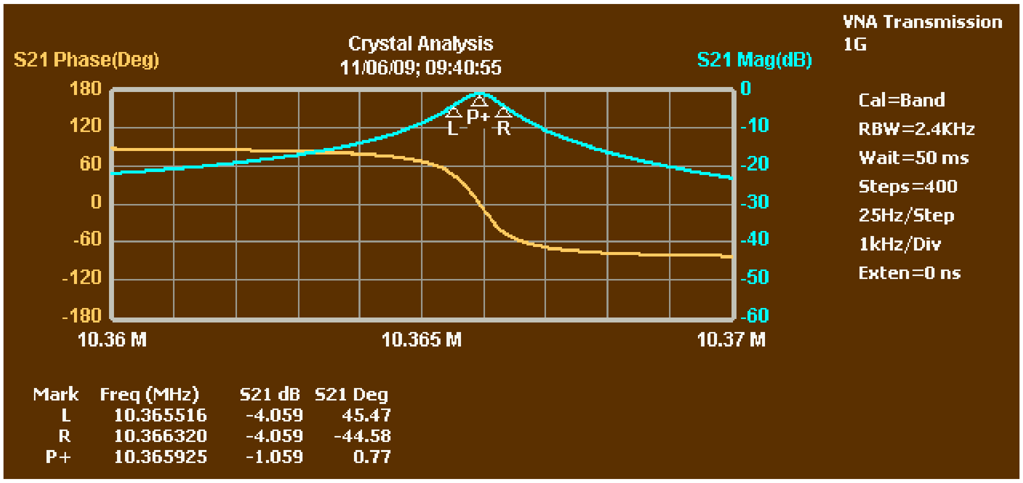
```
Cal=Band
RBW=2.4KHz
Wait=50 ms
Steps=400
100Hz/Step
4kHz/Div
Exten=0 ns

Mark   Freq (MHz)     S21 dB
 P+     10.365900     -1.070
 P-     10.384000    -87.320
```

Figure 3—Transmission of crystal

Series resonance is peak at P+; Parallel resonance is dip at P-

Crystal Analysis can determine all the parameters of the crystal from the scan shown in Figure 3. However, it is necessary to determine Fs with high accuracy—you may want accuracy in the range 5-50 Hz—which requires a very high resolution (and slow) scan. It is not necessary to determine Fp with such high accuracy, so it is generally a better approach to use a modest resolution scan such as that of Figure 3, record Fp, and then zoom in on the area around Fs, so you can graph Fs and the -3 dB points around it with high resolution. That may only require a sweep width of 5 or 10 kHz. Such a scan is shown in Figure 4.



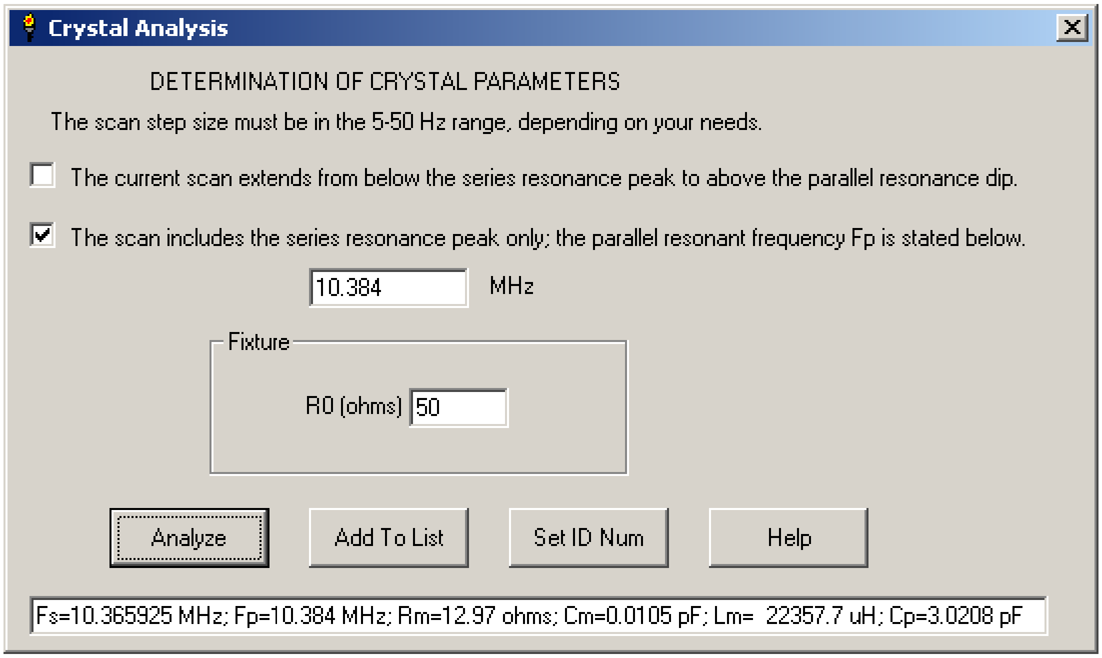
```
Cal=Band
RBW=2.4KHz
Wait=50 ms
Steps=400
25Hz/Step
1kHz/Div
Exten=0 ns

Mark   Freq (MHz)     S21 dB  S21 Deg
  L     10.365516     -4.059    45.47
  R     10.366320     -4.059   -44.58
 P+     10.365925     -1.059     0.77
```

Figure 4—Narrow scan around crystal Fs

Markers were automatically placed during Crystal Analysis

With the scan of Figure 4 in place (except that we don't need to place the markers), we open Analysis→Crystal and get the dialog of Figure 5.


Crystal Analysis

DETERMINATION OF CRYSTAL PARAMETERS

The scan step size must be in the 5-50 Hz range, depending on your needs.

☐ The current scan extends from below the series resonance peak to above the parallel resonance dip.

☑ The scan includes the series resonance peak only; the parallel resonant frequency Fp is stated below.

10.384 MHz

Fixture

R0 (ohms) 50

Fs=10.365925 MHz; Fp=10.384 MHz; Rm=12.97 ohms; Cm=0.0105 pF; Lm= 22357.7 uH; Cp=3.0208 pF

Figure 5—Crystal Analysis Dialog
The numeric values appear when you click “Analyze”

Crystal Analysis is always performed in a series fixture. The dialog allows us to specify the fixture. The “gold standard” for crystal analysis is a series fixture with R_0=12.5 ohms, although a standard 50-ohm series fixture seems to produce good results. Perhaps at frequencies well above 10 MHz the 12.5-ohm fixture has some advantage.

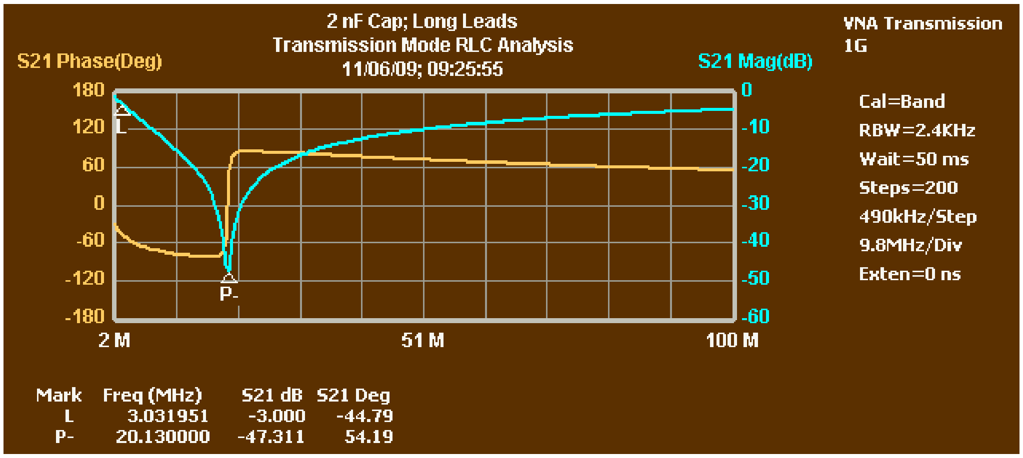
In Figure 5, we indicated that the scan did not include Fp, and manually entered it ourselves. We could instead have used the scan of Figure 3, and let the MSA find Fp, but in that case we would have had to perform that scan at a higher resolution, in order to get better accuracy for the more critical Fs.

RLC Analysis in Transmission Mode

Using menu Analysis→RLC in Transmission mode, we can measure RLC circuits at resonance. This feature is available in the MSA with TG or full VNA; phase measurement is not required. However, if the MSA has the full VNA, phase information will be utilized.

The R, L and C may be intentional components, or they may be parasitics. For example, our 2 nF capacitor includes significant parasitic inductance in its leads, and a small amount of parasitic resistance. While we may think of it as a “C”, it is actually a series RLC circuit.

Before opening the analysis dialog, you must perform a transmission scan that includes the resonant frequency and at least one -3 dB point, such as is shown in Figure 6.



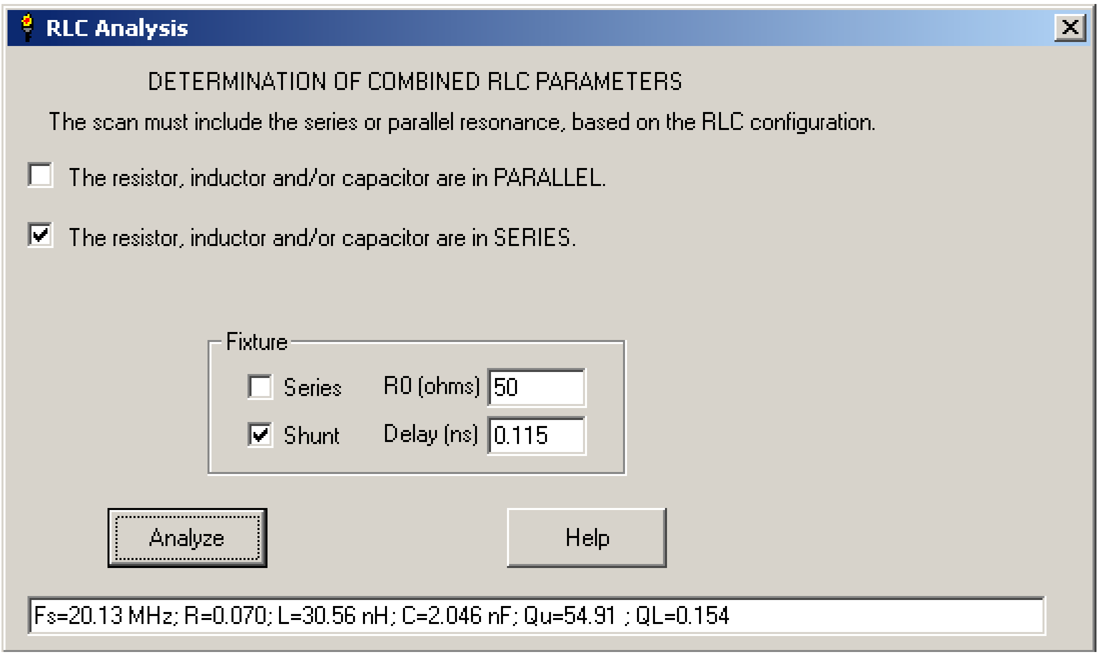
Cal=Band
RBW=2.4KHz
Wait=50 ms
Steps=200
490kHz/Step
9.8MHz/Div
Exten=0 ns

Mark	Freq (MHz)	S21 dB	S21 Deg
L	3.031951	-3.000	-44.79
P-	20.130000	-47.311	54.19

Figure 6—Scan of capacitor to be used for RLC analysis
The markers were placed automatically by RLC analysis

The analysis is performed by examining the resonant frequency and the -3 dB points, but only one of the -3 dB points is actually needed. In Figure 6, the upper -3 dB point is at a relatively high frequency off the high end of the graph, so we chose to omit it. It will generally be true for small capacitors that the upper -3 dB point is at a high enough frequency that measurement accuracy is questionable—remember that we are indirectly measuring impedance here, without the benefits of the OSL calibration that can be used in reflection mode. It is best to omit the upper -3 dB point in such cases. For large capacitors, the lower -3 dB point may be below 100 kHz, which is about the lower limit for good measurements in transmission mode. So for such capacitors we would omit the lower -3 dB point.

Note that for resonant circuits that produce a dip at resonance (parallel RLC in series fixture, or series RLC in shunt fixture), the -3 dB points are the points where the graph is at exactly -3 dB, not a value that is relative to the value at the peak of the dip. For circuits that produce a positive peak at resonance, the -3 dB points are 3 dB below the peak. We don’t have to worry about placing the markers ourselves, though.



DETERMINATION OF COMBINED RLC PARAMETERS

The scan must include the series or parallel resonance, based on the RLC configuration.

☐ The resistor, inductor and/or capacitor are in PARALLEL.

☑ The resistor, inductor and/or capacitor are in SERIES.

☐ Series R0 (ohms) 50

☑ Shunt Delay (ns) 0.115

Fs=20.13 MHz; R=0.070; L=30.56 nH; C=2.046 nF; Qu=54.91 ; QL=0.154

Figure 7—RLC Dialog in Transmission Mode

The numeric values at the bottom appear when we click “Analyze”
The DUT is a 2 nF capacitor with long leads.

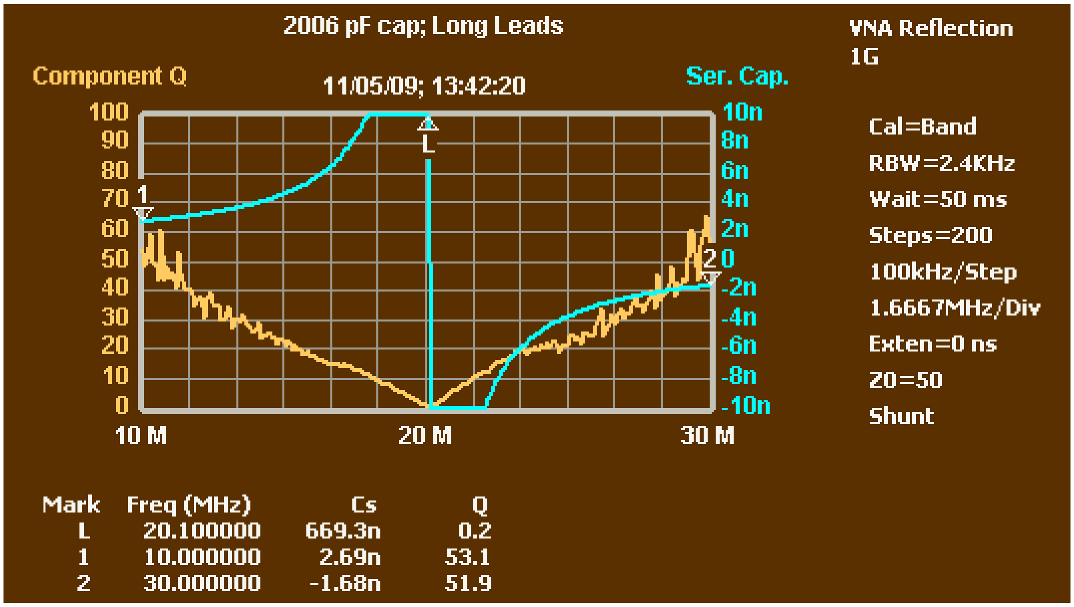
The dialog allows us to choose whether the fixture is series or shunt, and its R_0 (almost always 50 ohms). If the MSA has the capability to measure phase, we can also specify the time delay of the connector between the DUT and the “through” line of the shunt fixture. Specifying that delay improves accuracy at higher frequencies. A typical delay is 0.125 ns per inch. For this particular analysis, with Fs of 20 MHz, the delay specification has little effect.

When we click Analyze, the values at the bottom of Figure 7 appear. They include the resonant frequency, the R, L and C values, and Q (unloaded and loaded). Here, our 2 nF capacitor with long leads shows a capacitance of 2.05 nF, inductance of 31 nH and a small resistance of 0.07 ohms. Note that this analysis shows the actual values of the capacitor and its parasitic inductance, unlike Measure Components, which shows a capacitance value that reflects the effects of the parasitic inductance.

RLC analysis in Transmission mode is always performed at the resonant frequency. For capacitors, the value typically does not change much over frequency, so any frequency is generally fine. For inductors, we may be more picky about the measurement frequency. To change the measurement frequency for an inductor, we would put a capacitor in parallel with it. Note that we don’t even need to know the value of the capacitor, so we can use a variable capacitor and tune to exactly the frequency we want.

RC and RL Models In Reflection Mode

The simple way to analyze a capacitor in Reflection Mode is to scan its S11 and display the equivalent series capacitance (and series resistance if you want). You can also display Component Q, which is just the absolute value of reactance over resistance. Here's what we got doing that with a 2 nF silvered mica capacitor with long leads:



```
VNA Reflection
1G

Cal=Band
RBW=2.4KHz
Wait=50 ms
Steps=200
100kHz/Step
1.6667MHz/Div
Exten=0 ns
Z0=50
Shunt
```

```
Mark  Freq (MHz)       Cs       Q
  L   20.100000    669.3n     0.2
  1   10.000000     2.69n    53.1
  2   30.000000    -1.68n    51.9
```

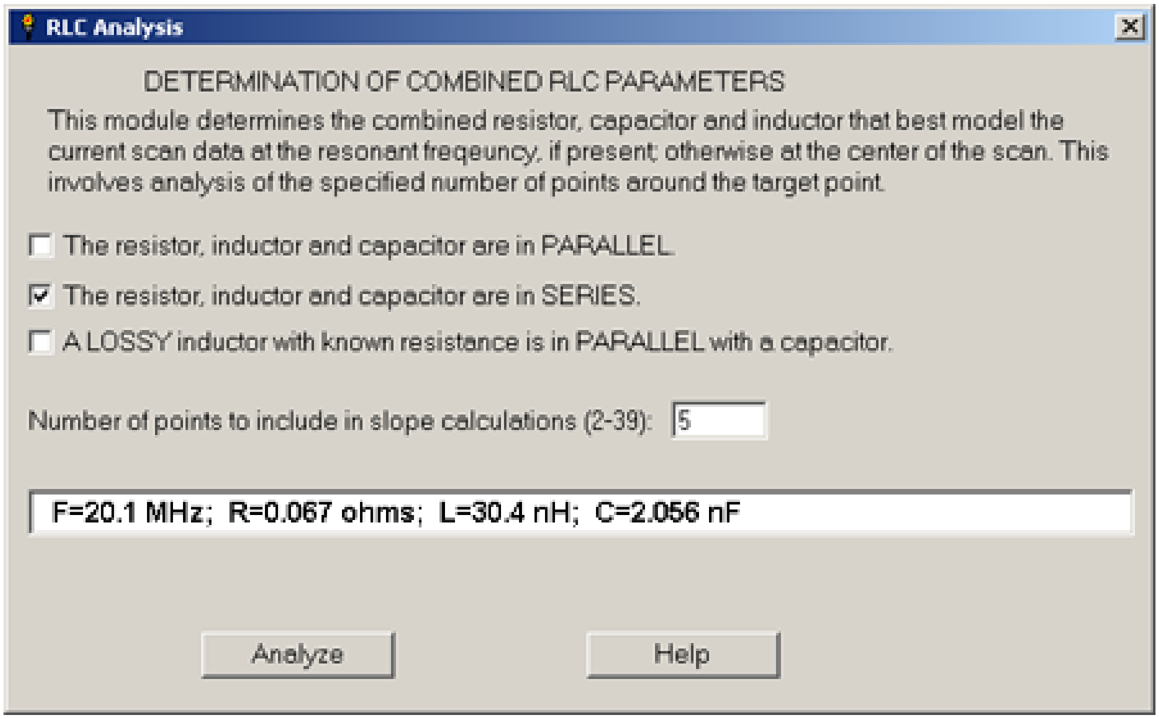
Figure 8–Simple model of capacitor

The self-resonant frequency (SRF) is 20.1 MHz. As the frequency approaches the SRF, a capacitor modeled as a simple RC circuit experiences an increase in capacitance. Even as low as marker 1 the capacitance is a bit high, and at L it is extremely high. Above SRF it goes negative, as the device becomes a net inductor. This is useful information, but it doesn't tell you the most basic thing about the device: what is its actual capacitance, free and clear of parasitics? The graph also shows Component Q, which would typically be used as a guide for how well the component would perform in a resonant circuit. That Q value goes to zero at the SRF, because at the SRF reactance is zero. At the SRF, the capacitor and its parasitic inductance form a resonant circuit with a particular bandwidth, but Component Q is useless in telling you what that bandwidth will be. If you were to add some series inductance to cause resonance at 18 MHz, this Q value also tells you absolutely nothing about what the bandwidth would be at that frequency. The problem is we are looking at the device as a capacitor, and near SRF that is a poor model of what the device is. In fact, it is sometimes a poor model at frequencies as low as 1/5 of the SRF.

This simple analysis therefore has exactly the problem faced by Measure Components: we have to be sure the measurement of C is done at a low enough frequency. The advantage we have here is that we can see the measurement over a broad frequency range, so we can see where the problem area is.

RLC Analysis In Reflection Mode

It is much better to view the capacitor as an RLC combination, with the R and L arising from parasitics. That is, rather than modeling it as just an RC circuit, with a C value that changes over frequency, we model it as having both an L and C. If the model is successful, the L and C values should be stable over at least modest frequency ranges. That is what the MSA's RLC Analysis does. To use it, you perform a scan in reflection mode. It is often most useful to include the resonant frequency, but you don't have to. Then you use the Analysis-->RLC menu to open the analysis dialog, which looks like this:



DETERMINATION OF COMBINED RLC PARAMETERS

This module determines the combined resistor, capacitor and inductor that best model the current scan data at the resonant freqeuncy, if present; otherwise at the center of the scan. This involves analysis of the specified number of points around the target point.

☐ The resistor, inductor and capacitor are in PARALLEL.

☑ The resistor, inductor and capacitor are in SERIES.

☐ A LOSSY inductor with known resistance is in PARALLEL with a capacitor.

Number of points to include in slope calculations (2-39): 5

F=20.1 MHz; R=0.067 ohms; L=30.4 nH; C=2.056 nF

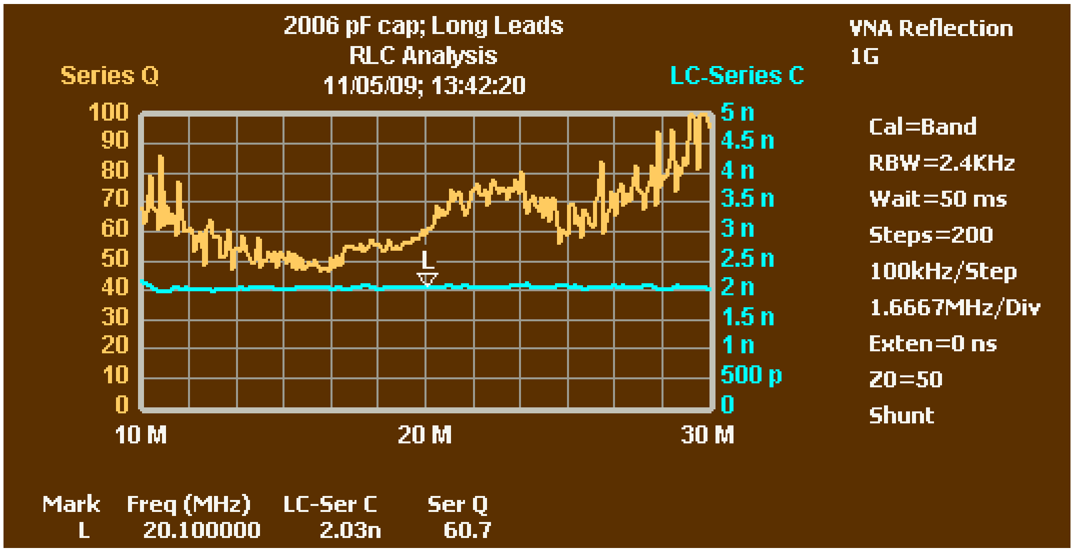
Figure 9–RLC Analysis dialog in Reflection mode

The F, R, L and C values are not shown initially. We indicate whether we want to use a series or parallel model. There is a special model for lossy inductors that we won't discuss here. Here, the series model is selected because that best represents a capacitor and its parasitics. The analysis requires computing the slope of reactance or susceptance, which is done in intervals of a certain number of points, which the user can specify. A large number of points in the interval smooths out noise, but for a broad scan, where the slope may vary significantly in a short distance, a smaller number of points is more appropriate.

When you press Analyze, the analysis is performed and results are displayed for the resonant frequency, if it is present, and otherwise for the center frequency. In addition, graph data is calculated for all frequencies and the graph changes to show the L and C values. Within this dialog, you can change the frequency with the +Freq and -Freq buttons. That can be useful to see how stable the results are to let you adjust the number of points included in slope calculations.

When we quit the dialog, graphs of L and C are shown. We can also graph resistance by selecting the normal series or parallel resistance graphs. We may also choose to graph Series Q (if you selected the series model) or Parallel Q (if you selected the parallel model). The graphs for L, C and Q are in addition to the regular graphs, and show up at the bottom of the graph list in the Y-axis parameter window. They remain available until Restart is performed.

The following graphs were obtained by changing the "LC-Series L" graph to Series Q:



VNA Reflection
1G

Cal=Band
RBW=2.4KHz
Wait=50 ms
Steps=200
100kHz/Step
1.6667MHz/Div
Exten=0 ns
Z0=50
Shunt

Mark	Freq (MHz)	LC-Ser C	Ser Q
L	20.100000	2.03n	60.7

Figure 10–Series C and Q values from RLC Analysis

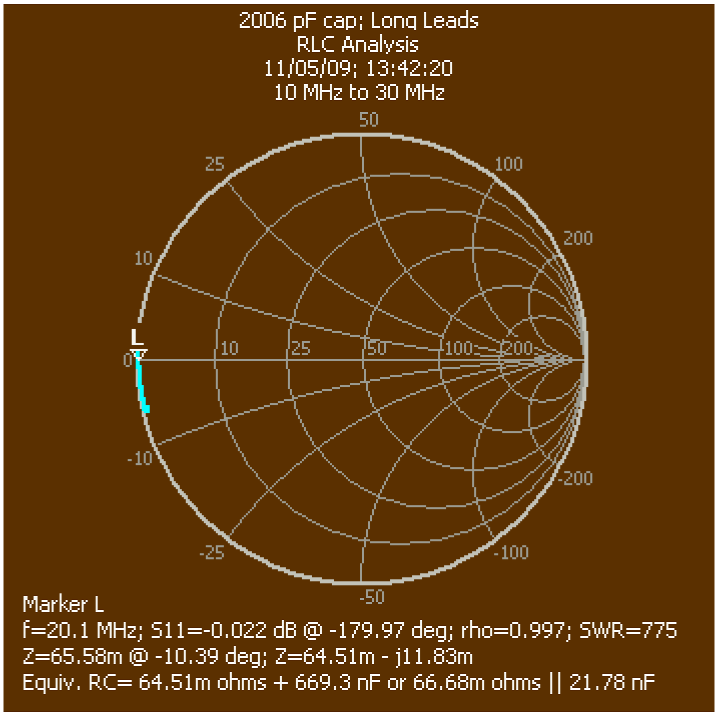
The L marker is at the series resonant frequency.

Note that the graph of LC-Series C shows a very stable value near 2 nF, even at the resonant frequency, unlike the first graph shown above. With this technique, the capacitor value can be measured accurately at any value on the graph. (The very low end always has some inaccuracy due to the slopes being calculated over an interval.) If we instead chose to graph the "LC-Series L", we would get a very stable graph of inductance at about 30 nH. Smoother graphs would be produced with a narrower frequency range, or more scan points.

Note also that the value of Series Q does not fall to zero at the resonant frequency, in contrast to the Component Q value shown in Figure 8. In fact, Series Q represents the actual unloaded Q value of the C and its parasitic L as a resonant circuit, and is therefore a useful value. The Q values to the left of marker L represent the resonant Q values we would obtain if we added some series inductance to lower the resonant frequency (assuming the added inductance is loss free). In the example given above, if we wanted to lower the resonant frequency to 18 MHz, we can see that the Q value would be lowered to about 55. Thus, this Series Q value is actually an indication of the quality of resonant circuit that can be constructed with this capacitor, which is the whole point of a Q value. The Component Q value in Figure 8 is virtually worthless anywhere close to the resonant frequency.

The Q values to the right of the L marker indicate the performance of resonant circuits where the frequency is increased by adding an ideal series capacitance. As a practical matter, our capacitor is not likely to be used this way. However, this same Q concept applies to transmission line stubs, and those higher frequency Q values are useful in that context.

Note that while the L marker in the last graph is at resonance, there is nothing in the graph to indicate that fact. We got the resonant frequency from the original measurement in the RLC dialog. In addition, the Smith Chart verifies that the marker is at resonance, because it lies on the horizontal axis (reactance=0).



```
2006 pF cap; Long Leads
RLC Analysis
11/05/09; 13:42:20
10 MHz to 30 MHz
```

```
Marker L
f=20.1 MHz; S11=-0.022 dB @ -179.97 deg; rho=0.997; SWR=775
Z=65.58m @ -10.39 deg; Z=64.51m - j11.83m
Equiv. RC= 64.51m ohms + 669.3 nF or 66.68m ohms || 21.78 nF
```

Figure 11–Smith chart verifying resonance

Conclusion

We have shown several different ways to use the MSA to measure component values. Measure Components provides the simplest and fastest method, and is suitable for low frequency measurements. Crystal analysis provides an excellent way to measure crystal parameters. RLC analysis models components as series or parallel combinations of resistors, inductors and capacitors, and has the ability to separate the underlying component value from the effect of component parasitics. RLC analysis can be performed in Transmission mode at the resonant frequency, or over a broader frequency range in Reflection Mode.

We have primarily illustrated these techniques with a capacitor. The same techniques apply to resistors and inductors, and to series or parallel RLC combinations where each of the R, L and C are “intentional”—i.e. not just parasitic. These techniques may also be used to analyze transmission line stubs, a topic that is covered elsewhere.