

# The Truth About Antenna Tuners

A mathematical proof of how antenna tuners work

# Intro

This presentation is meant to provide a mathematical proof of what antenna tuners do and how they actually work. This presentation will help to dispel many of the urban myths and legends that continue to circulate on the information superhighway.

# Presentation Outline

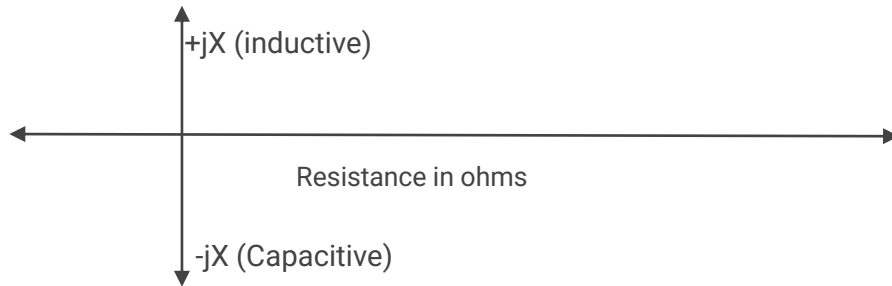
- Tuner Impedance Matching
  - Refresher on resistance, reactance, admittance, conductance and susceptance
  - Refresher on the Smith Chart
  - Impedances in parallel and/or series plotted within the Smith Chart
  - Network topologies for varying impedance values
- Tuners and Reflected Energy
  - Refresher on transmission line characteristic impedance
  - Refresher on transmission and reflection coefficients
  - Mathematical accounting for all energy in an antenna system
  - Examples
    - The quarter wave impedance transformer
    - The LC network
- Tuner Efficiency
  - How to turn your tuner into a space heater
- Tuner Myths and Legends
  - Can we put some of this stuff in the dust bin please?
- Acknowledgements and Important Resources

# Tuner Impedance Matching

# Refresher on Resistance, Reactance, Admittance, Conductance and Susceptance

In order to fully understand what an antenna tuner does, we must first fully understand the environment in which it is used. For RF systems things like resistance and reactance (also known as impedance) and its reciprocal form, admittance, are very important concepts.

Impedance is a combination of resistance and an imaginary number value referred to as reactance. Impedance allows us to represent both an ohmic resistance along with an inductive or capacitive reactance that is also expressed in terms of ohms. The representation of these values in chart form looks like an (X, Y) coordinate pair, where both the vertical axis and the horizontal axis are expressed in ohms.



## Refresher cont...

Mathematically, adding impedances together in parallel leads to very messy algebraic formulas. James Clerk Maxwell invented Admittance, and its subcomponents (conductance and susceptance) as reciprocals to impedances as a way to clean up the math. Admittances allow us to simply add together values that would otherwise require complicated and error prone mathematics.

Example: Resistance (DC) in parallel:

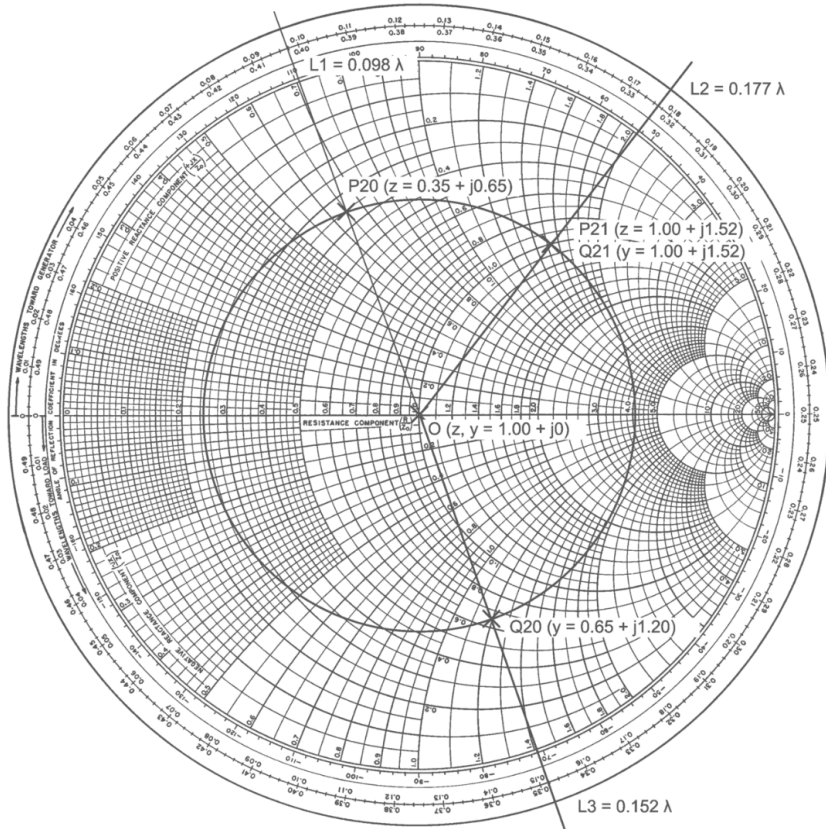
$$1/R_1 + 1/R_2 + 1/R_3 \text{ (resistances)} = G_1 + G_2 + G_3 \text{ (Conductance)}$$

Example: Capacitance in series:

$$1/C_1 + 1/C_2 + 1/C_3 \text{ (capacitance)} = B_1 + B_2 + B_3 \text{ (Susceptance)}$$

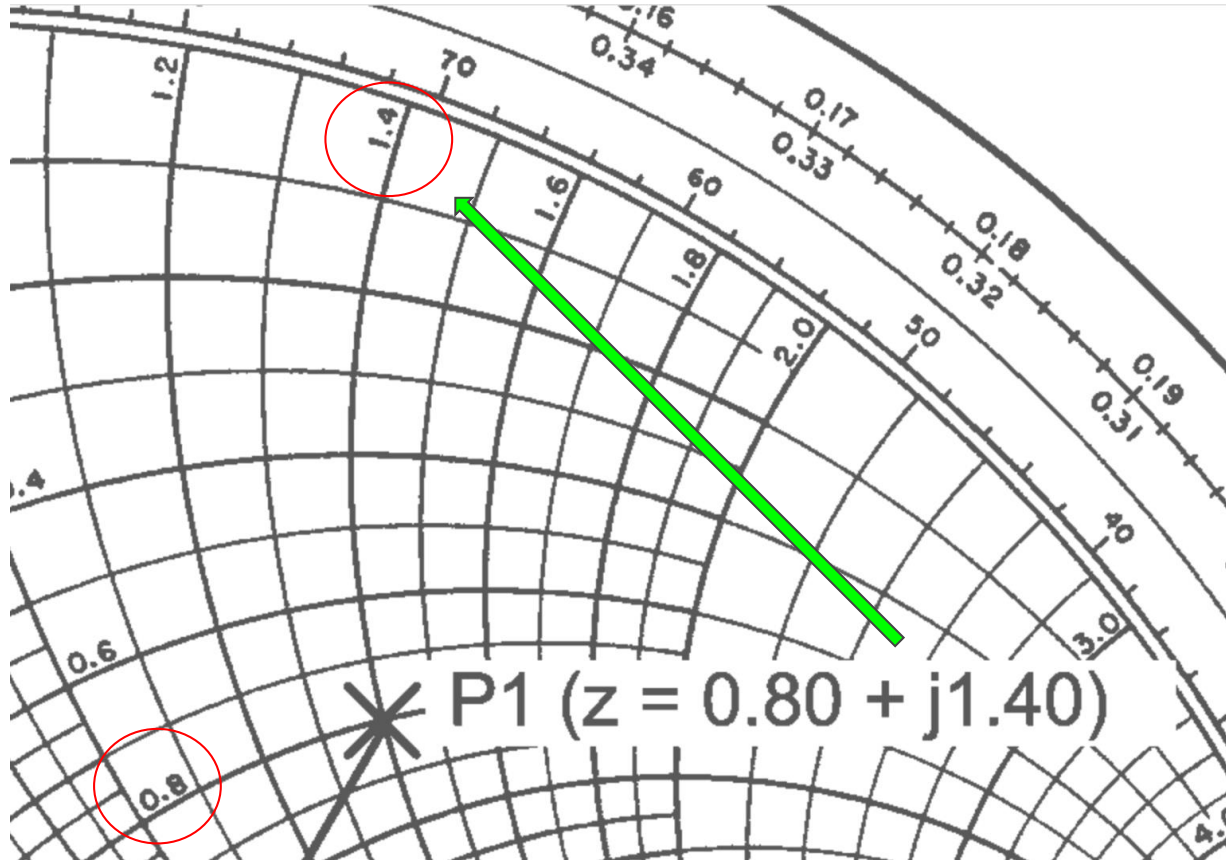
Why is this important for a presentation on Antenna Tuner? Because Impedance and Admittance are the fundamental underpinnings of the Smith Chart.

# Refresher: The Smith Chart (Impedance)



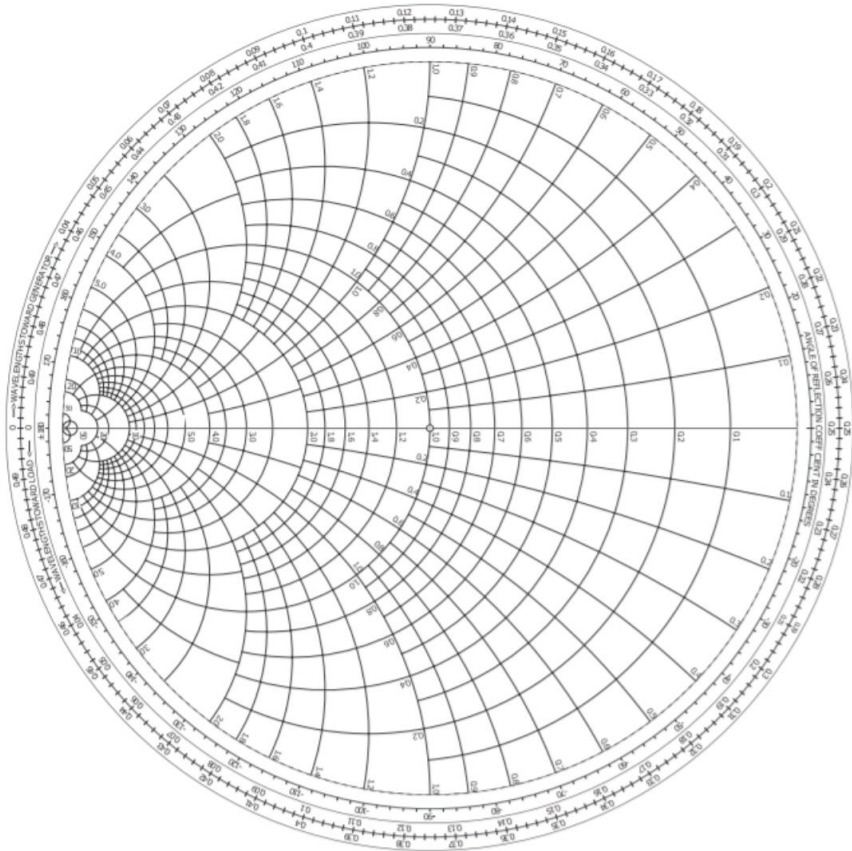
The Smith Chart outer rings represent values of wavelength and degrees. The circle in the center represents a reflection coefficient determined by the load impedance and the characteristic impedance of the feed line. The circles starting at the right are the constant resistance circles and the arcs starting at the right and going to the outside edge are called the constant reactance circles.

## Refresher: The Smith Chart (Impedance)



The value 1.4 is the reactance and the value .8 is the resistance. These values sit on circles of constant resistance and constant reactance.

# Refresher: Smith Chart (Admittance)



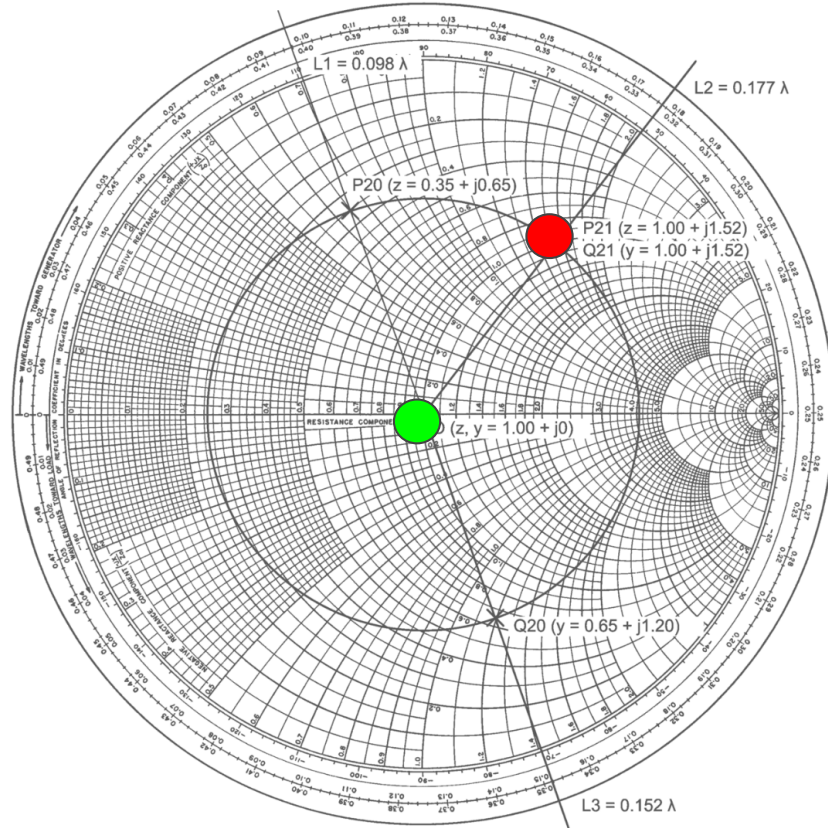
Recall that admittance is the reciprocal of impedance and thus the lines of conductance and susceptance are the reciprocals of resistance and reactance shown on the previous Smith Chart.

Often these two types of charts are combined together in the simulation tools that we use.

## Refresher cont...

So why is this important to us. Well, it turns out that the Smith Chart is the best tool we have for visually building out components and their values for Antenna Tuners. The resistance and reactance circles of the impedance Smith Chart allow us to plot changes in **series** component values and the admittance side of the Smith Chart allows us plot changes in **parallel** component values, thus helping us to visualize how the network layout and the value of the components can help us resolve a reactance and transform an impedance.

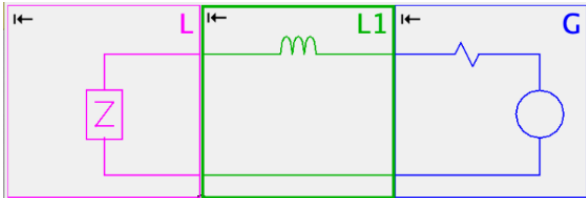
# Refresher cont...



The ultimate job of an antenna tuner is to transform impedances (resistive and reactive) values into something that we can use with a transceiver. In order to do that, we must combine reactive components in different configurations and with specific values that will allow us to eliminate reactance and transform resistance.

Note: As we change components values to move the red dot to the green dot, the diameter of the reflection coefficient circle becomes smaller. The reflection coefficient goes to zero (0) as we approach 50 ohms and zero reactance. 50 ohms being the normalized center of the Smith Chart that we are interested in.

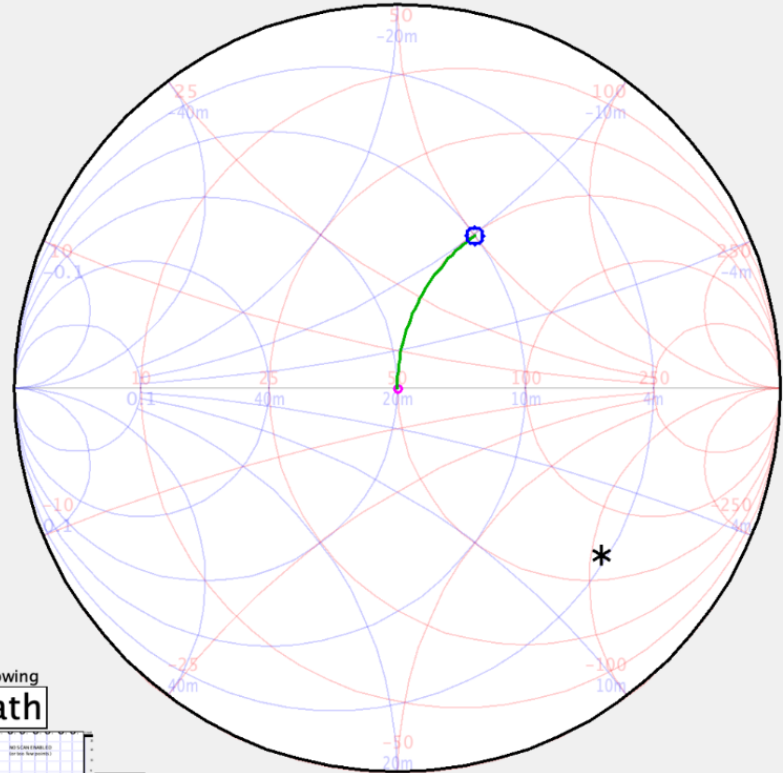
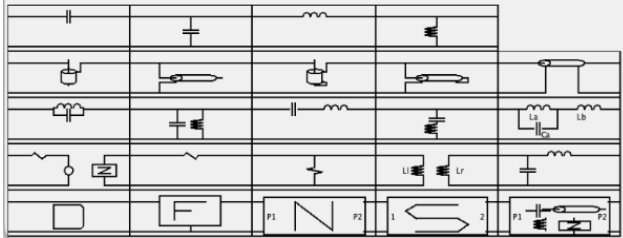
# Examples: Inductor in series (Plotted as an Impedance)



$R = 50$        $R = 50.25$        $SWR = 2.612$   
 $X = 0$          $X = 50$          $\Gamma = 0.446 \angle 63$   
 $\leftarrow W = 796.8$      $\leftarrow W = 800.8$   
 $\pm V, I = 199.6, 3.992$      $\leftrightarrow V, I = 199.6, 3.992$       runtime: 3m

50 ohms	795.8nH	10MHz
0 j ohms	200Q	50Zo
<none> file	0@MHz	useZo(1000)V_
		Plots Plt

type	numPnts	from	to	name	sweep
lin	100	1	30	G.MHz	n

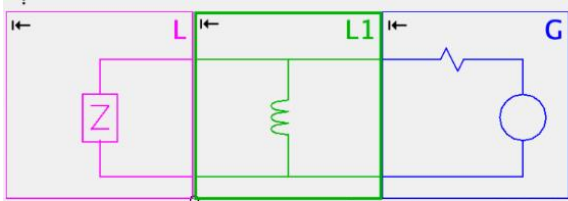


showing Path



0Q  
 0SWR  
 Mark

# Examples: Inductor in parallel (Plotted as an Admittance)

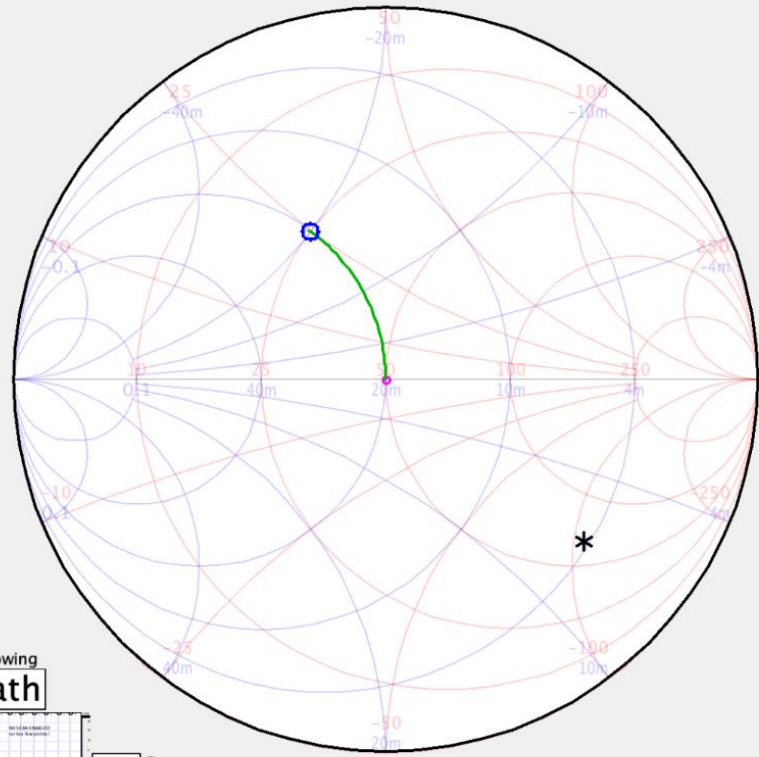
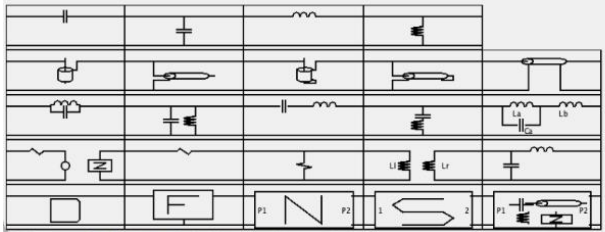


$R = 50$        $R = 25$        $SWR = 2.612$   
 $X = 0$        $X = 24.88$        $\Gamma = 0.446 \angle 117$   
 $\leftarrow W = 796.8$        $\leftarrow W = 800.8$

$\dagger V, i = 199.6, 3.992$        $\dagger V, i = 199.6, 3.992$       runtime: 15m

50 ohms	795.8nH	10MHz
0 j ohms	200Q	50Zo
<none> file	0@MHz	useZo(1000)V_
		Plots Plt

type	numPnts	from	to	name	sweep
lin	100	1	30	G.MHz	n

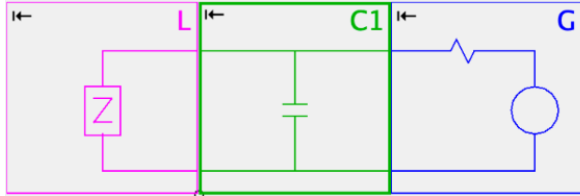


showing Path



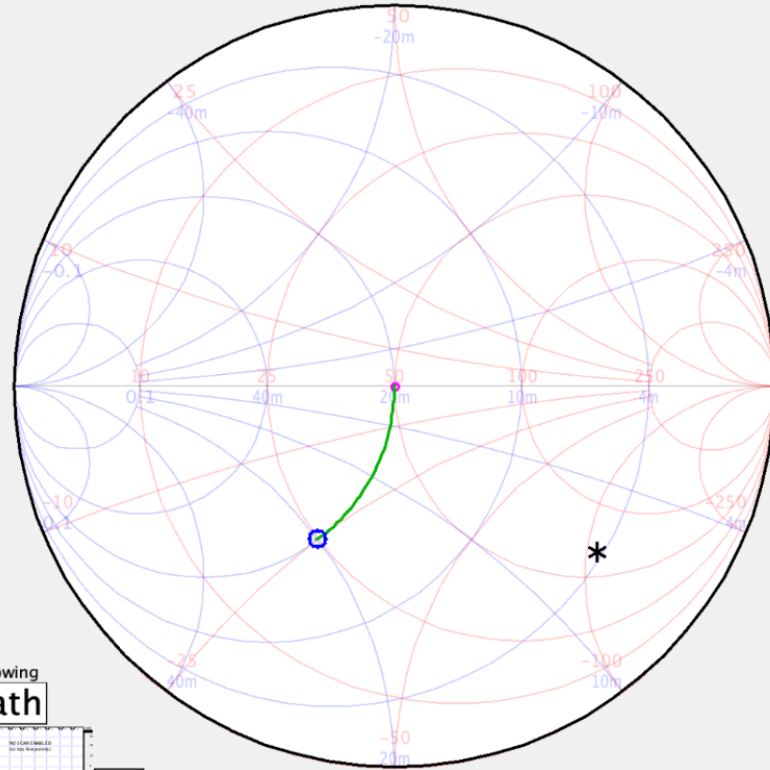
0 Q  
 0 SWR  
 Mark

# Examples: Capacitor in parallel (plotted as an admittance)

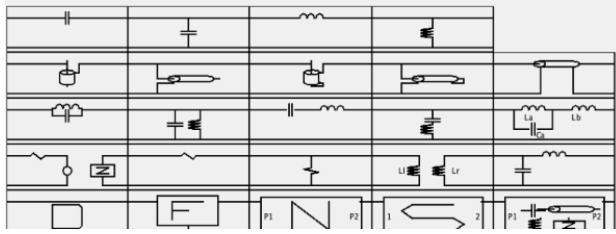


$R = 50$        $R = 25$        $SWR = 2.617$   
 $X = 0$        $X = -24.99$        $\Gamma = 0.447\angle -117$   
 $\leftarrow W = 799.7$        $\leftarrow W = 800.1$   
 $\uparrow V, i = 200, 3.999$        $\uparrow V, i = 200, 3.999$       runtime: 3m

50 ohms	318.3pF	10 MHz
0 johms	2KQ	50 Zo
<none> file	0 @MHz	useZo(1000) V_
		Plots Plt

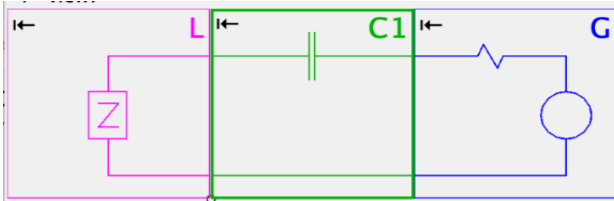


type	numPts	from	to	name	sweep
lin	100	1	30	G.MHz	n



showing  
**Path**  
 NO LINES DISPLAYED  
 (check Parameters)  
 0 Q  
 0 SWR  
 Mark |

# Examples: Capacitor in series (plotted as an impedance)

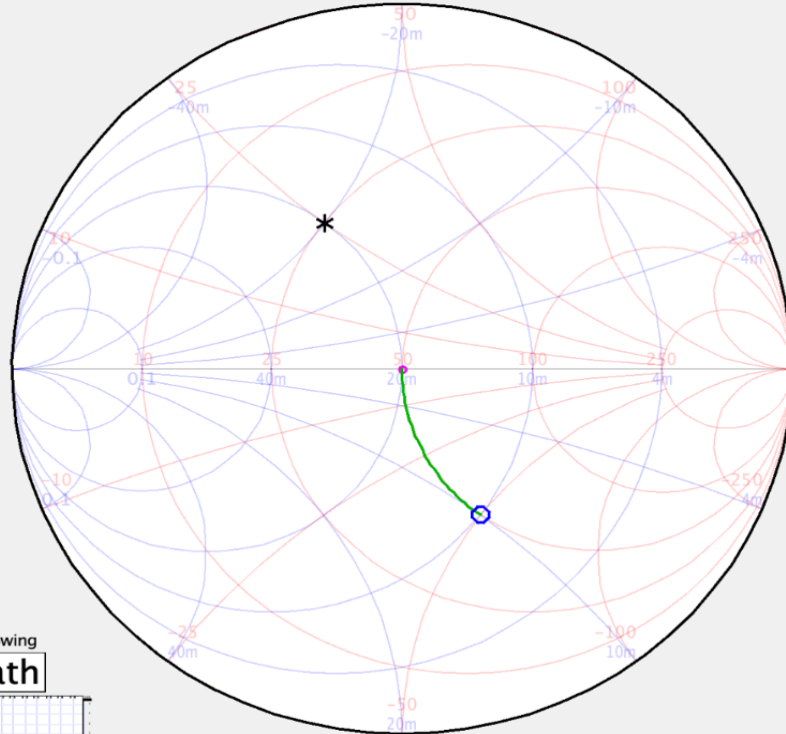
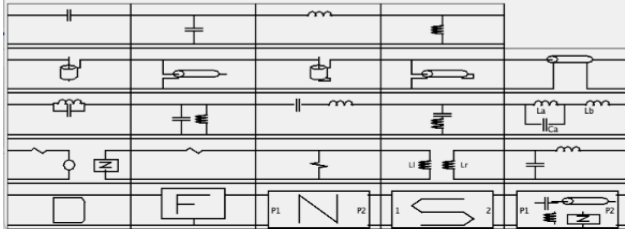


$R = 50$        $R = 50.03$        $SWR = 2.618$   
 $X = 0$          $X = -50$          $\Gamma = 0.447 \angle -63$   
 $\leftarrow W = 799.7$      $\leftarrow W = 800.1$

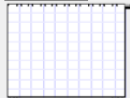
$\uparrow V, i = 200, 3.999$      $\leftrightarrow v, i = 200, 3.999$       runtime: 5m

50 ohms	318.3pF	10 MHz
0 ohms	2KQ	50 Zo
<none> file	0@MHz	useZo(1000); V_
		Plots Plt

type	numPts	from	to	name	sweep
lin	100	1	200	G.MHz	n

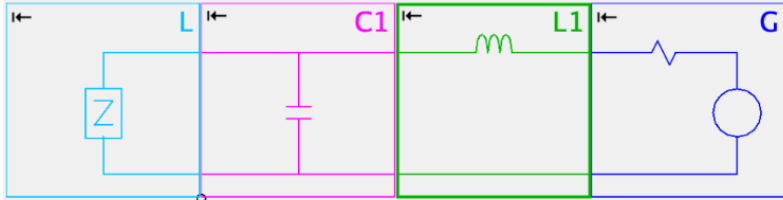


showing  
Path



$0 \angle Q$   
 $0 \angle SWR$   
 Mark

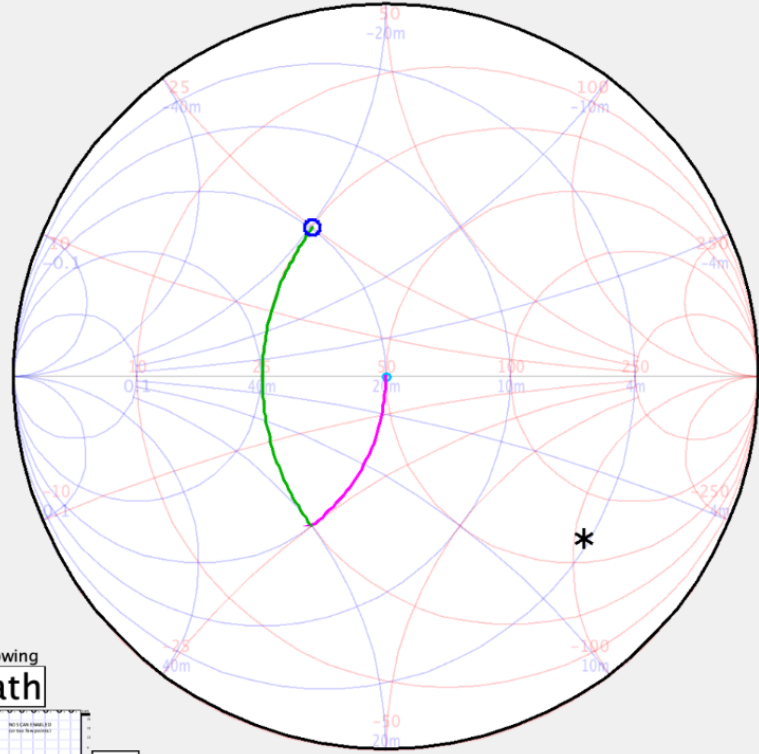
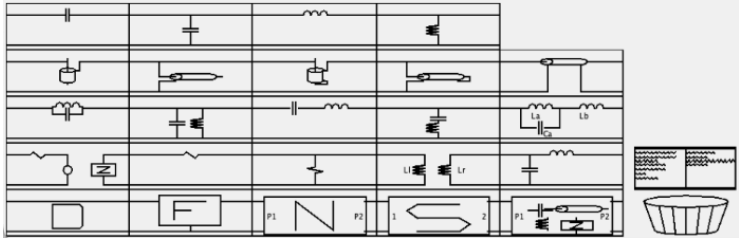
# Example: (Lumped circuit)



$R = 50$        $R = 25$        $R = 25.25$        $SWR = 2.595$   
 $X = 0$        $X = -24.99$        $X = 25.01$        $\Gamma = 0.444 \angle 116$   
 $\leftarrow W = 794.7$        $\leftarrow W = 795.1$        $\leftarrow W = 803.1$   
 $\uparrow V, i = 199.3, 3.987$        $\uparrow V, i = 199.3, 3.987$        $\leftrightarrow v, i = 282, 5.64$       runtime: 2m

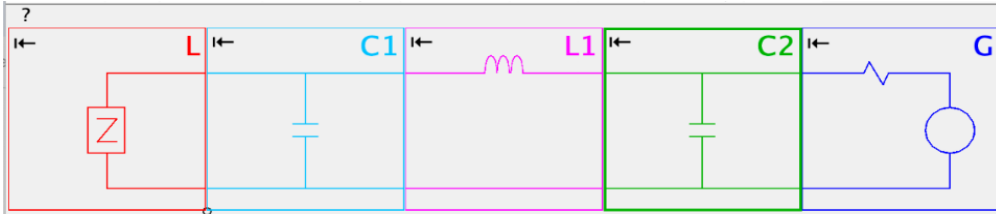
50 ohms	318.3pF	795.8nH	10 MHz
0 johms	2K Q	200 Q	50 Zo
<none> file	0 @MHz	0 @MHz	useZo(1000) V_
			Plots Pit

type	numPnts	from	to	name	sweep
lin	100	1	30	G, MHz	n



showing  
**Path**  
 0 Q  
 0 SWR  
 Mark

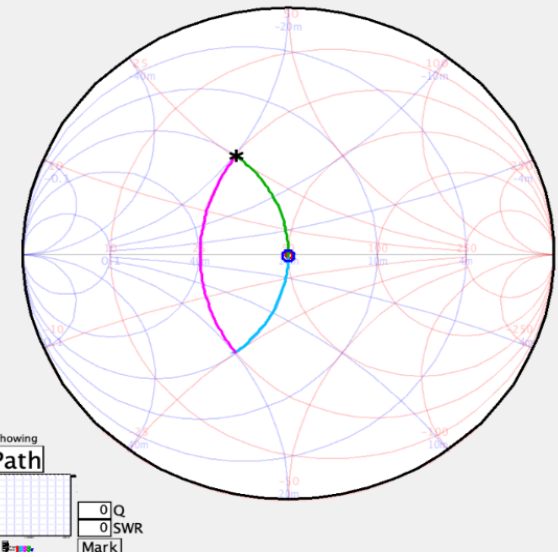
# Example: (Lumped circuit)



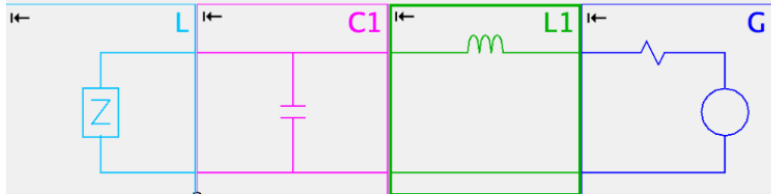
$R = 50$        $R = 25$        $R = 25.25$        $R = 50$        $SWR = 1.01$   
 $X = 0$        $X = -24.99$        $X = 25.01$        $X = -0.4973$        $\Gamma = 4.97m \angle -90$   
 $\leftarrow W = 989.1$        $\leftarrow W = 989.6$        $\leftarrow W = 999.5$        $\leftarrow W = 1K$   
 $\uparrow V, i = 222.4, 4.448$        $\uparrow V, i = 222.4, 4.448$        $\leftrightarrow V, I = 314.6, 6.291$        $\uparrow V, i = 223.6, 4.472$       **runtime: 1m**

50 ohms	318.3pF	795.8nH	318.3pF	10MHz
0 johms	2K Q	200 Q	2K Q	50 Zo
<none> file	0 @MHz	0 @MHz	0 @MHz	useZo(1000); V_
				Plots Plt

type	numPnts	from	to	name	sweep
lin	100	1	200	G.MHz	n



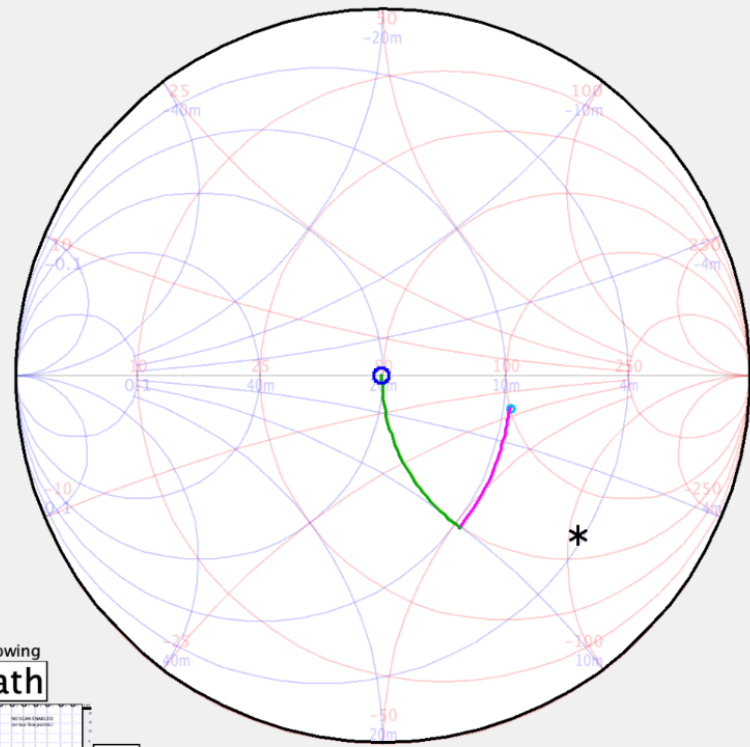
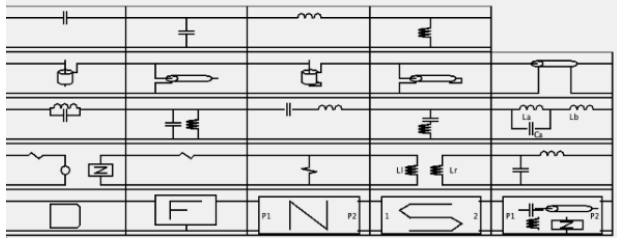
# And Finally, resolving an impedance of $100 - j20$ ohms to $50 + j0$ ohms



$R = 100$        $R = 49.49$        $R = 49.75$        $SWR = 1.005$   
 $X = -20$        $X = -51.92$        $X = 0.1133$        $\Gamma = 2.71m \angle 155$   
 $\leftarrow W = 994.3$        $\leftarrow W = 994.8$        $\leftarrow W = 1K$   
 $\uparrow V_i = 321.6, 3.153$        $\uparrow V_i = 321.6, 2.626$        $\leftrightarrow V_i = 233.3, 4.483$       runtime: 2m

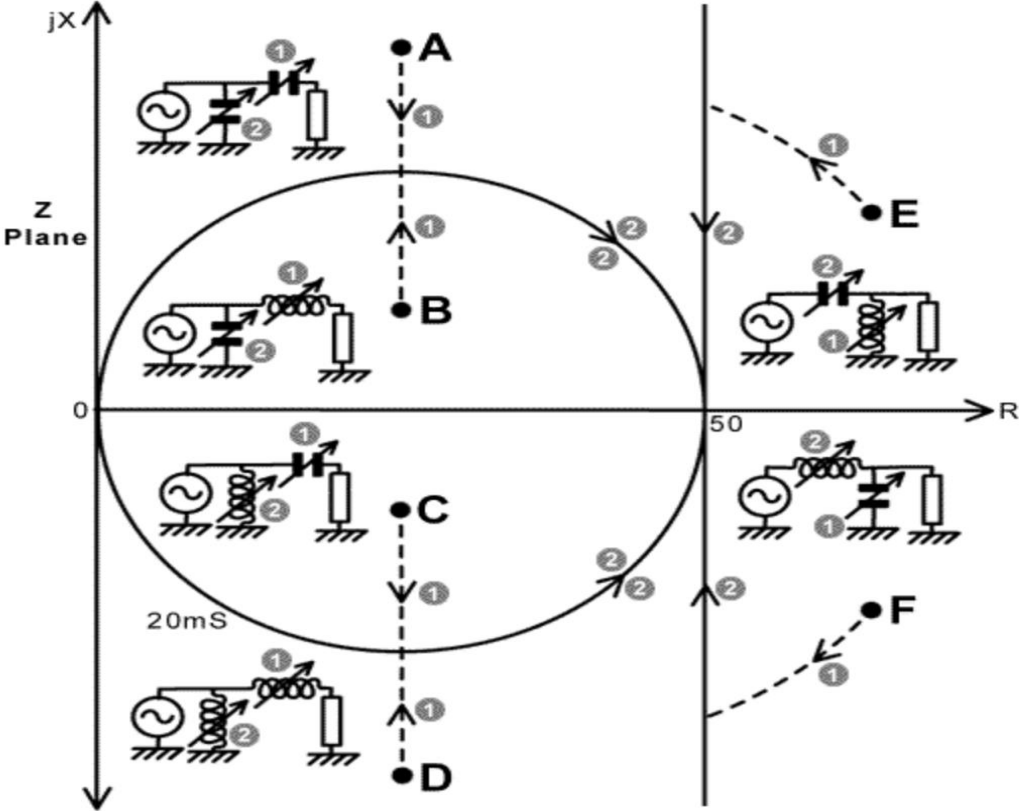
100 ohms	130pF	828.1nH	10 MHz
-20 johms	2K Q	200 Q	50 Zo
<none> file	0 @MHz	0 @MHz	useZo(1000) V_
			Plots Plt

type	numPnts	from	to	name	sweep
lin	100	1	30	G.MHz	n



showing  
**Path**  
 showing a small grid plot  
 0 Q  
 0 SWR  
 Mark

# Suitable Network Topologies for various impedance values



Source: David Knight (G3YNH)

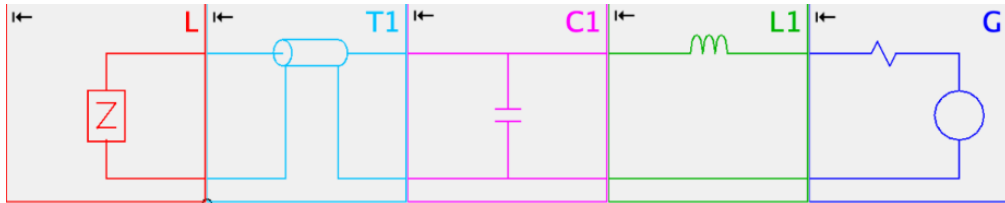
# Resolving Reactance and Transforming Resistance

So, as we have seen, we can use various components in parallel and series in order to eliminate reactance and transform resistance such that we can present a  $50 + j0$  ohm load to our transceiver. We've also seen how we can use the Smith Chart as a graphical tool to help us with this task.

All of the above was done with SimNEC, which can be downloaded for free from the internet. The tool is platform agnostic and will run on Windows, Mac and Linux with the same download.

See the Resources section at the end for more information on SimNEC.

# But, before we leave this section...

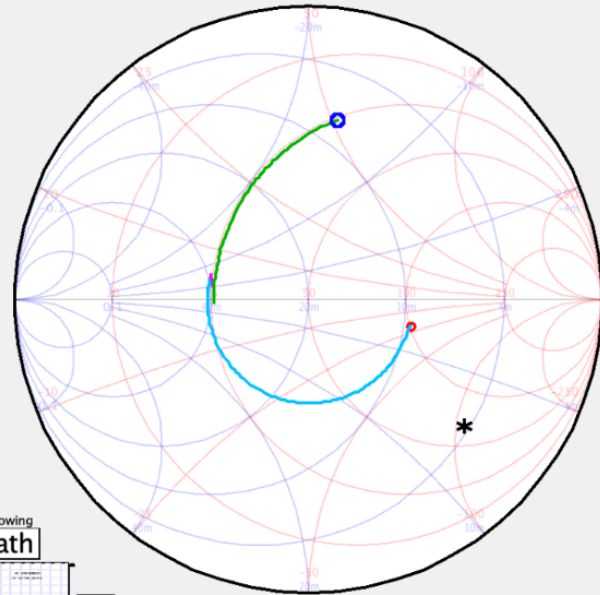
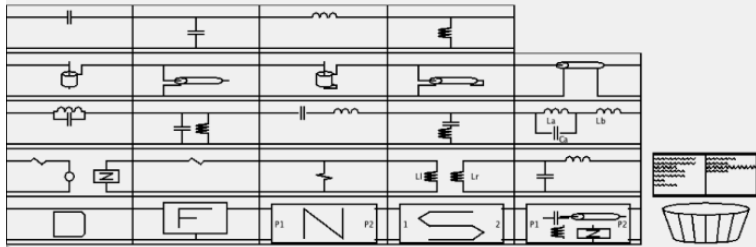


$R = 100$        $R = 24.77$        $R = 25.65$        $R = 25.91$        $SWR = 4.262$   
 $X = -20$        $X = 4.69$        $X = -0.5203$        $X = 51.51$        $\Gamma = 0.620_{\angle 81}$   
 $\leftarrow W = 593.5$        $\leftarrow W = 609.5$        $\leftarrow W = 609.5$        $\leftarrow W = 615.7$   
 $\uparrow V, i = 248.5, 2.436$        $V, i = 125.1, 4.96$        $\uparrow V, i = 125.1, 1.021$        $\leftrightarrow v, i = 253.7, 4.875$       runtime:2m

100 ohms	90.24 ~deg	130pF	828.1nH	10MHz
-20 ohms	10 @MHz	2KQ	200Q	50 Zo
<none> file	20.83 ft	0 @MHz	0 @MHz	useZo(1000) V_
	(LMR-400) Mdl			Plots Plt

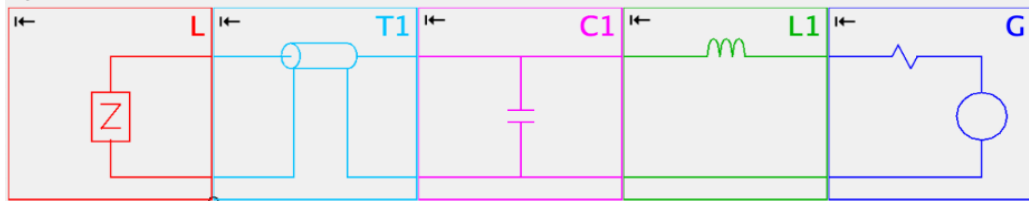
0.85 VFnom
50 Zo
26.41m k0
0.1248 k1
187u k2

type	numPts	from	to	name	sweep
lin	100	1	30	G.MHz	n



showing Path  
 0 Q  
 0 SWR  
 Mark

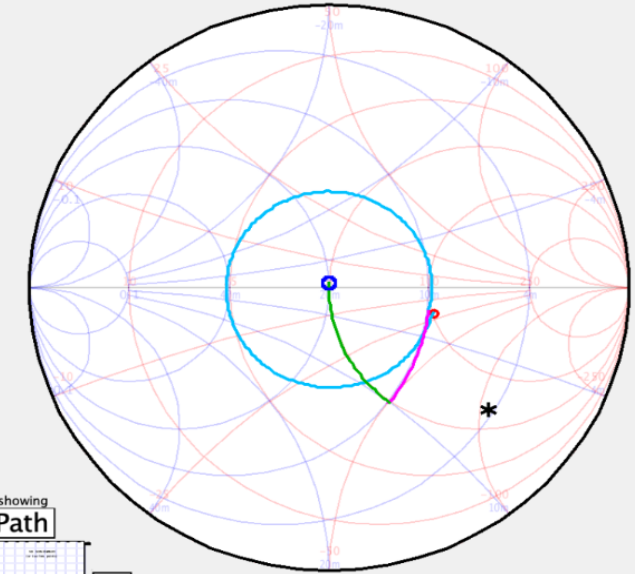
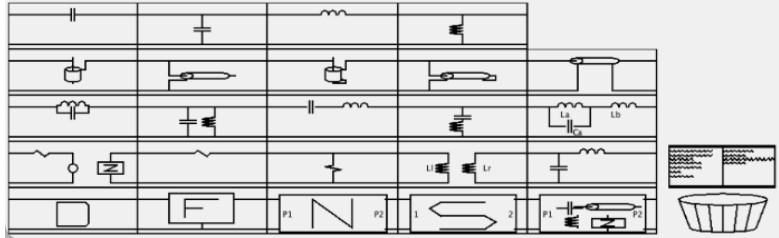
# And now at 180 degrees.



R = 100	R = 97.42	R = 49.71	R = 49.97	SWR = 1.032
X = -20	X = -18.6	X = -50.46	X = 1.571	$\Gamma = 15.7m\angle 90$
$\leftarrow W = 947.5$	$\leftarrow W = 994.1$	$\leftarrow W = 994.5$	$\leftarrow W = 0.9998K$	
$\pm V, i = 313.9, 3.078$	$V, i = 316.8, 3.194$	$\pm V, i = 316.8, 2.588$	$\leftrightarrow v, i = 232.7, 4.473$	runtime: 57m

100 ohms	180 ~deg	130 pF	828.1 nH	10 MHz
-20 johms	10 @MHz	2K Q	200 Q	50 Zo
<none> file	41.55 ft	0 @MHz	0 @MHz	useZo(1000) V_
	(LMR-400) Mdl			Plots Plt

type	numPnts	from	to	name	sweep
lin	100	1	30	G.MHz	n



showing Path

0 Q
0 SWR
Mark

# Tuners and Reflected Energy

# Tuners and reflected energy

Ok, we've seen how tuners resolve impedances (resistive and reactive), now we have to address the elephant in the room.

Resolving an impedance generally means that we've got an impedance mismatch somewhere in your system. This generally happens at the antenna and feed line interface, but it can also happen at any other impedance discontinuity in an antenna system.

An impedance mismatch between the feed line and the antenna will result in reflected energy coming back toward the source (transmitter). We must now explain how the antenna tuner handles this reflected energy such that it doesn't show up as SWR at your transmitter..

# But first, a refresher course on a few important items

## Transmission line characteristic impedance:

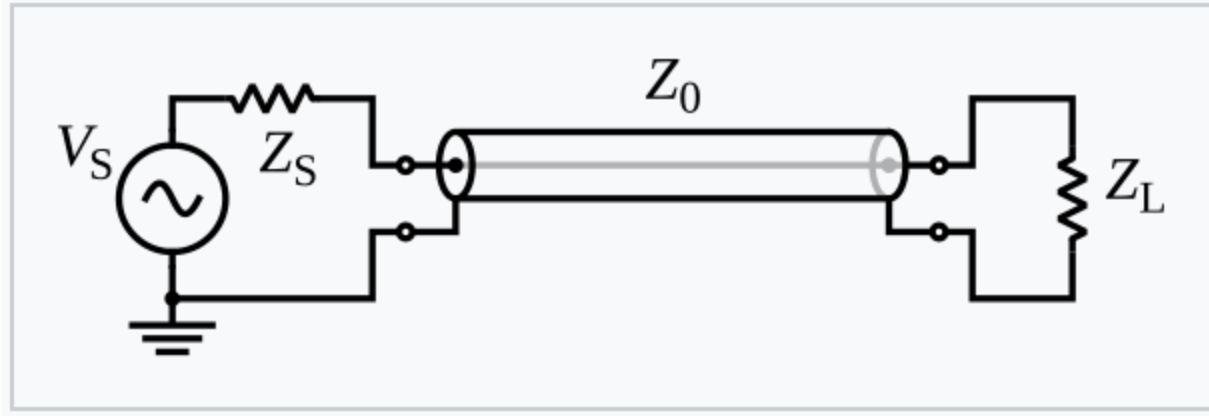
A transmission line has a characteristic impedance. We're all familiar with 50 ohm coax and 450 ohm window line, but why do these lines have a characteristic impedance in the first place? How can I measure it and why doesn't it change with line length?

Characteristic impedance of a feed is defined as the line's input resistance when the line is infinitely long. ***Specifically it is the ratio of the amplitudes of voltage and current along the length of the line.*** Recall that the amplitude of the voltage and current waves along a transmission line will remain the same **UNLESS** acted upon by a reflection from a discontinuity along the line (i.e., reflected power).

Maximum transfer of power (no reflections) happens when a feed line is terminated in its characteristic impedance. This means that power applied to the line is completely absorbed by the load attached to the far end of the line IF the load is the exact same impedance as the line itself. This is how the characteristic impedance of a transmission line is found.

# Transmission line characteristic impedance

Ok, so why is it important for us to know the characteristic impedance of a transmission line?



The formulas for the transmission and reflection coefficients at a discontinuity all depend on the characteristic impedance of the transmission line ( $Z_0$ ) and the impedance directly on the opposite side of the discontinuity.

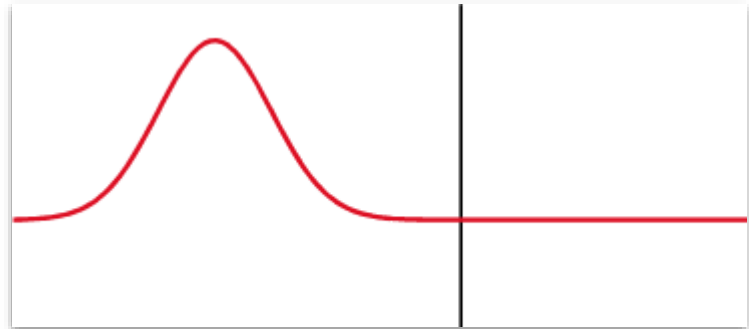
# Transmission Coefficient

What is a transmission coefficient? It's the ratio of amplitude of the transmitted wave vs the amplitude of the reflected wave.

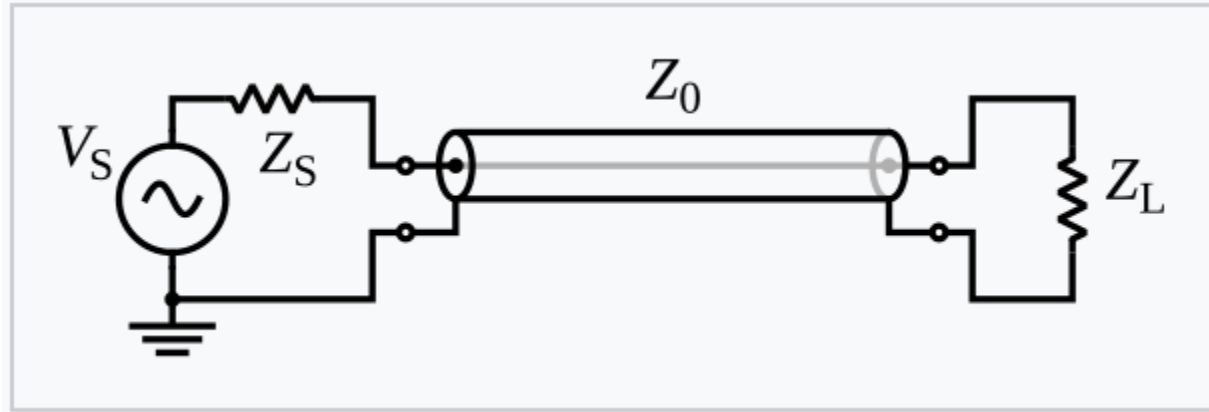
The formula for the transmission coefficient is

$$T_{coef} = 2(Z_1) / (Z_1 + Z_0)$$

Where  $Z_1$  is where the energy is going and  $Z_0$  is where the energy is coming from. Or, in our case, the impedance of the load ( $Z_1$ ) vs the characteristic impedance of the transmission line  $Z_0$ .



## Transmission coefficient example.



Let's say  $Z_0$  is 50 ohms and  $Z_L = 100$  ohms. Our transmission coefficient would be:

$$T_{\text{coef}} = 2(100) / (50 + 100) = 1.33$$

# Reflection coefficient and example

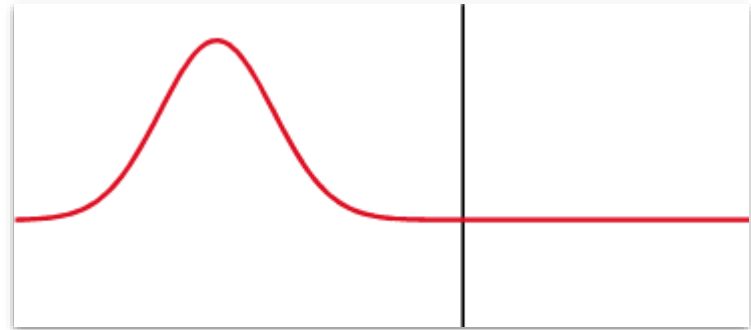
The reflection coefficient formula looks like this:

$$\mathbf{Rcoef = ZL - Zo / ZL + Z0}$$

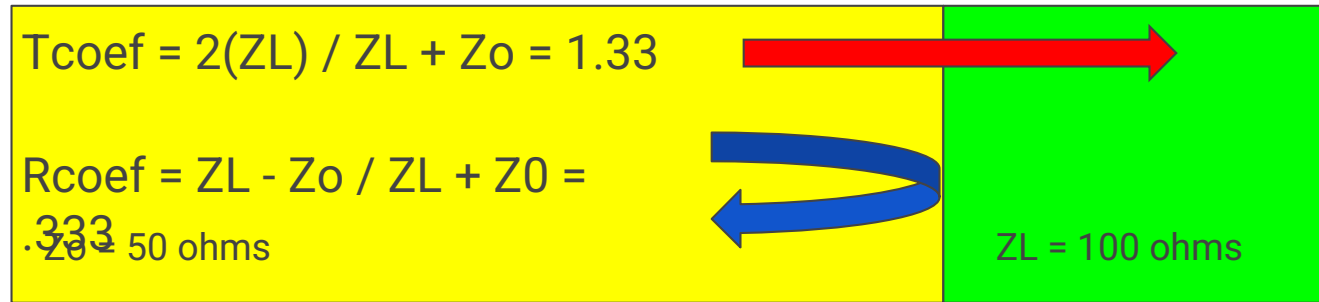
And in our example,  $ZL = 100$  and  $Zo = 50$ , so the reflection coefficient is

$$\mathbf{Rcoef = 100 - 50 / 100 + 50 = .333}$$

Note that transmission coefficient =  $1 + Rcoef$  and in our case the  $Tcoef = 1.333$



# Transmission and Reflection Coefficients



Note that:

$$1 + R_{coef} = T_{coef}$$

Indicating that we have conservation of energy at the discontinuity.

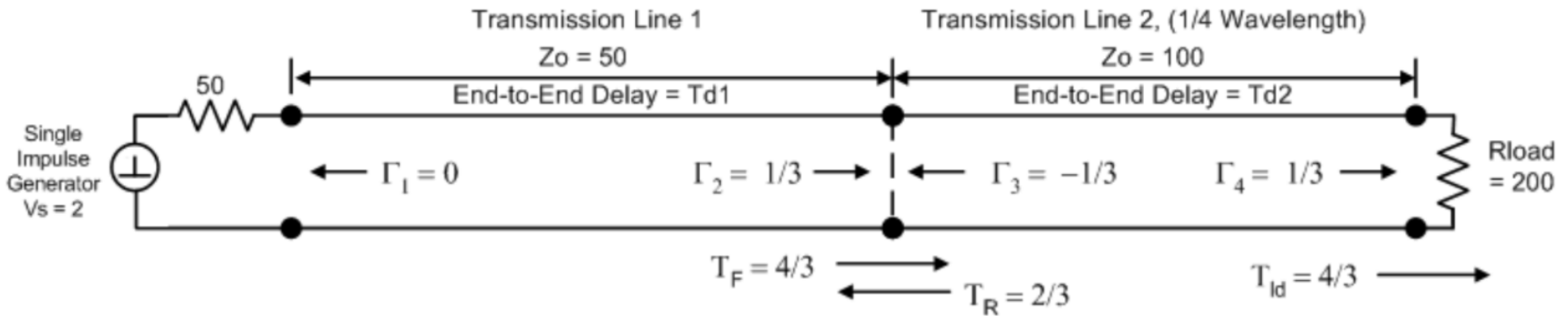
# Reflections: Why just look at impedances at the borders?

The question is, why do the Tcoef and the Rcoef only take into account the impedances directly on either side of the border? Why don't the formulas consider the total impedance of the rest of the system instead of just the differences at the boundaries?

**Answer:** Think of the power coming from the transmitter as a single impulse of power. This impulse of power can't see into the future, it has no idea what is on the other end of the transmission line (could be a short, could be an open, could be an infinitely long line, could be an antenna). Until something comes back from the other side (the round trip), the total impedance of the system from any single point forward cannot be predicted by a single impulse of power. Over time, there will be reflected signals and a steady state of forward and reflected power will stabilize on the line. This is the point when impedances are fully realized. Thus our formulas are only interested in the impedances that can be seen immediately on the opposite side of a boundary.

# The Quarter Wave Impedance Transformer

## Quarter-Wave Transformer, Reflection and Transmission Coefficients Calculated for an Impulse



Here are all of the calculated coefficients for all transmission and reflection points in this system.

**Source:** Jeff Anderson (K6JCA)



## Quarter wave impedance transformer

$$V_{R1} = V_i(0)\Gamma_2 + V_i(2T_{D2})T_F\Gamma_4T_R + V_i(4T_{D2})T_F\Gamma_4T_R(\Gamma_3\Gamma_4) + V_i(6T_{D2})T_F\Gamma_4T_R(\Gamma_3\Gamma_4)^2 \dots$$

Adding everything up, we end up with an infinite series of reflections that need to be added together.

Fear not, though, after a few cycles, the reflections have become smaller and smaller over time and a steady state state formula for both reflections as well as transmissions can be derived.

**Source:** Jeff Anderson (K6JCA)

# Quarter Wave Impedance Transformer

*In steady state, the infinite series converges to:*

$$V_{R1} = V_i \left( \Gamma_2 - \frac{T_F \Gamma_4 T_R}{1 - (-\Gamma_3 \Gamma_4)} \right)$$

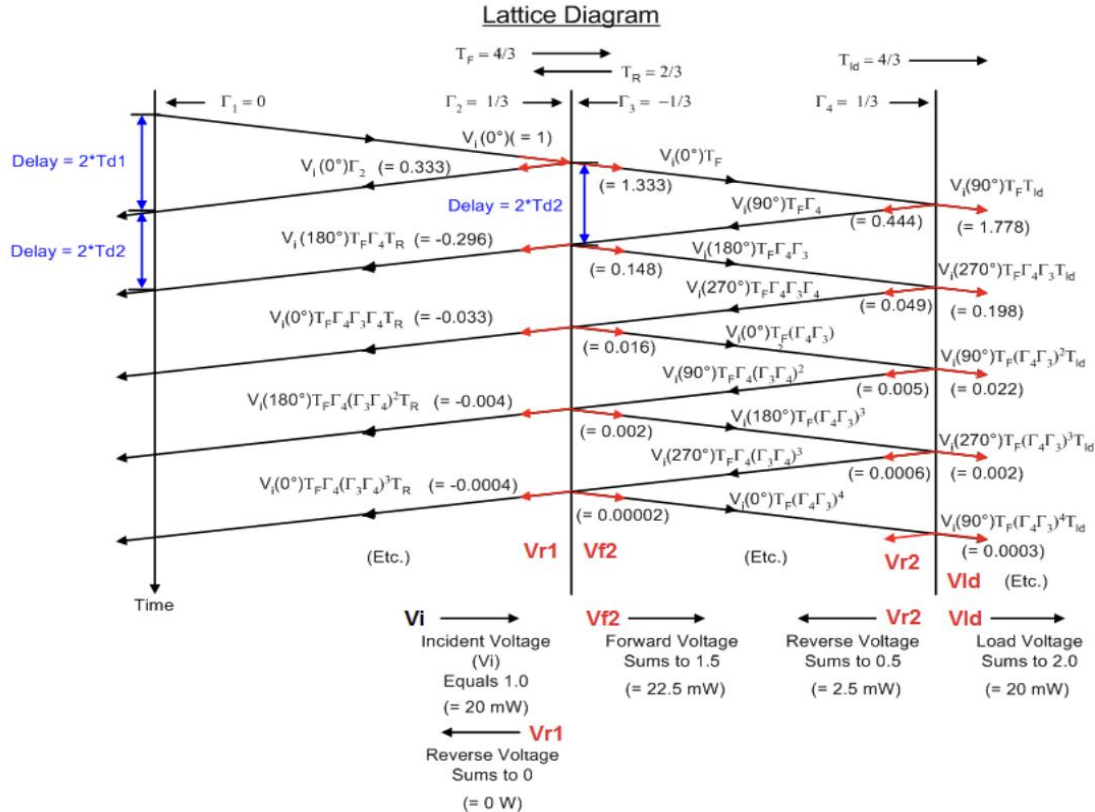
*And the "apparent  $\Gamma_2$ " (in steady state) is:*

$$\text{Apparent } \Gamma_2 = \frac{V_{R1}}{V_i} = \Gamma_2 - \frac{T_F \Gamma_4 T_R}{1 - (-\Gamma_3 \Gamma_4)}$$

*Note that in a matched system, "apparent  $\Gamma_2$ " equals 0 (there are no reflections back to the source).*

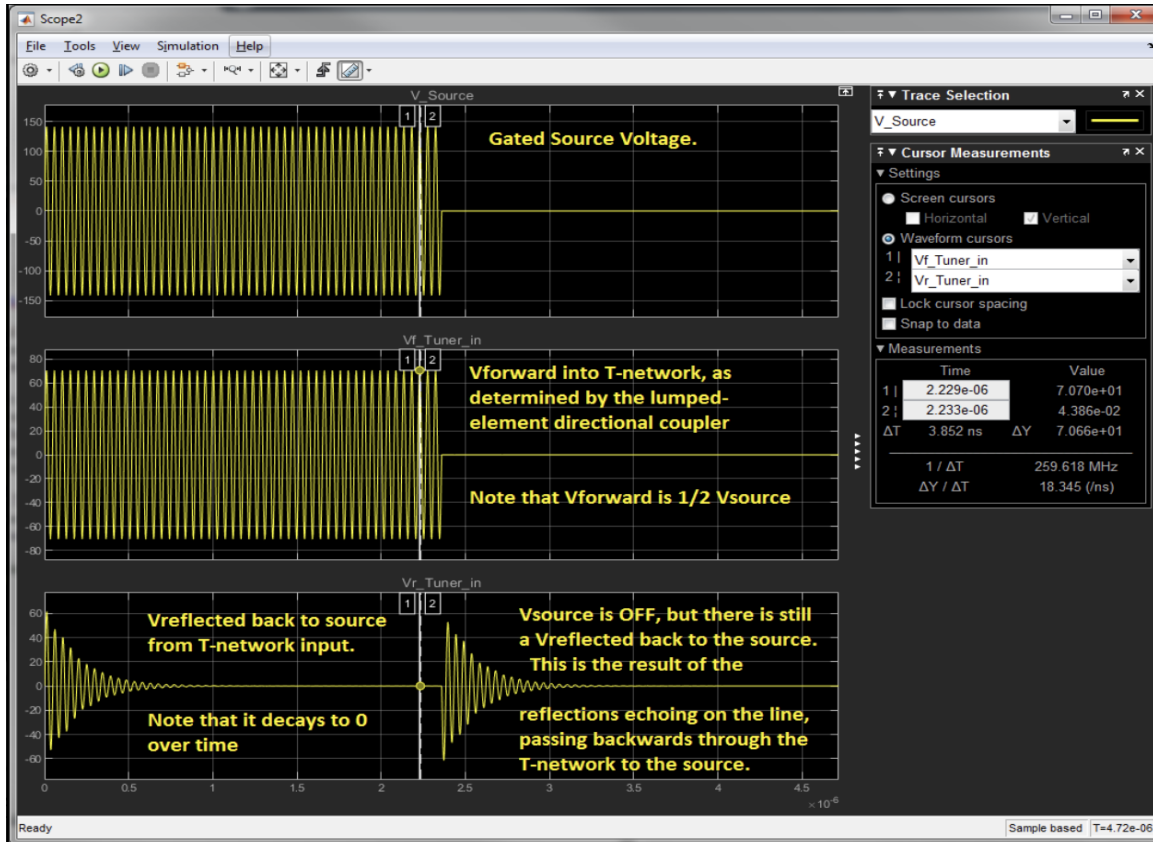
**Source:** Jeff Anderson  
(K6JCA)

# Quarter wave impedance transformer



Source: Jeff Anderson (K6JCA)

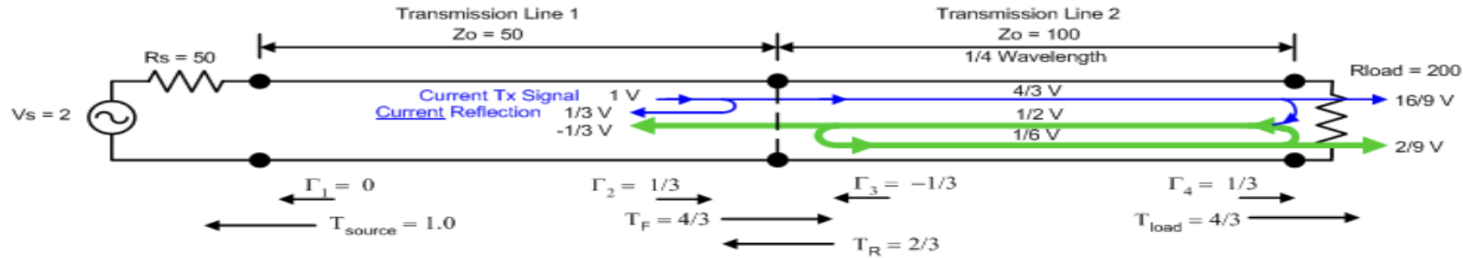
# Quarter Wave Impedance Transformer



Source: Jeff Anderson (K6JCA)

# Quarter Wave Impedance Transformer

Steady-state Result of Convolution of a Sine Wave Signal with the System's Impulse Response



## On Transmission Line 1

$$Vr1 = 1/3 \text{ V} - 1/3 \text{ V} \\ = 0 \text{ V}$$

## On Transmission Line 2

$$Vf2 = 4/3 \text{ V} + Vr2 \text{ (re-reflected)} \\ = 4/3 \text{ V} + 1/6 \text{ V} \\ = 1.5 \text{ V}$$

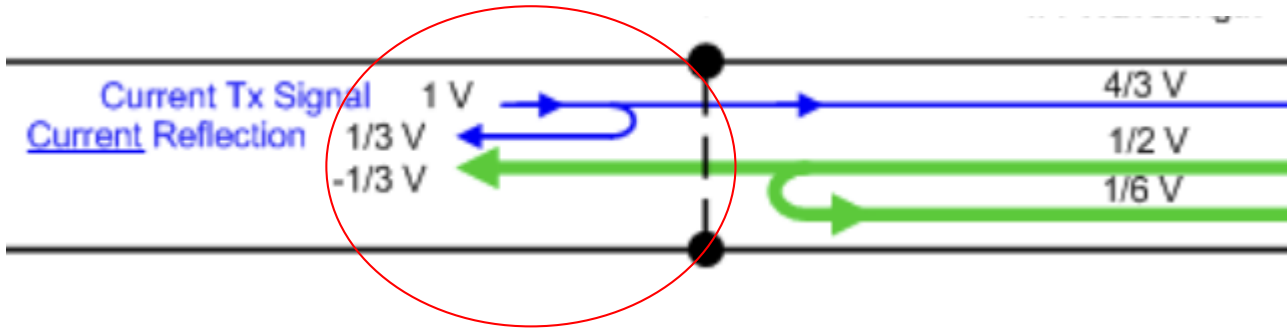
$$Vr2 = Vf2 * \Gamma_4 \\ = 1.5 \text{ V} * 1/3 \\ = 0.5 \text{ V}$$

$$Vr2 \text{ (re-reflected)} = Vr2(180^\circ) * \Gamma_3 \\ = -0.5 * (-1/3) \\ = 1/6 \text{ V}$$

## At Rload

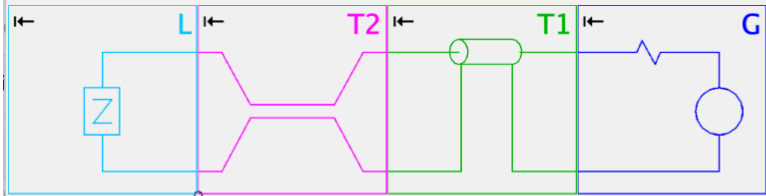
$$Vld = 16/9 \text{ V} + 2/9 \text{ V} \\ = 2.0 \text{ V}$$

# Quarter wave impedance transformer



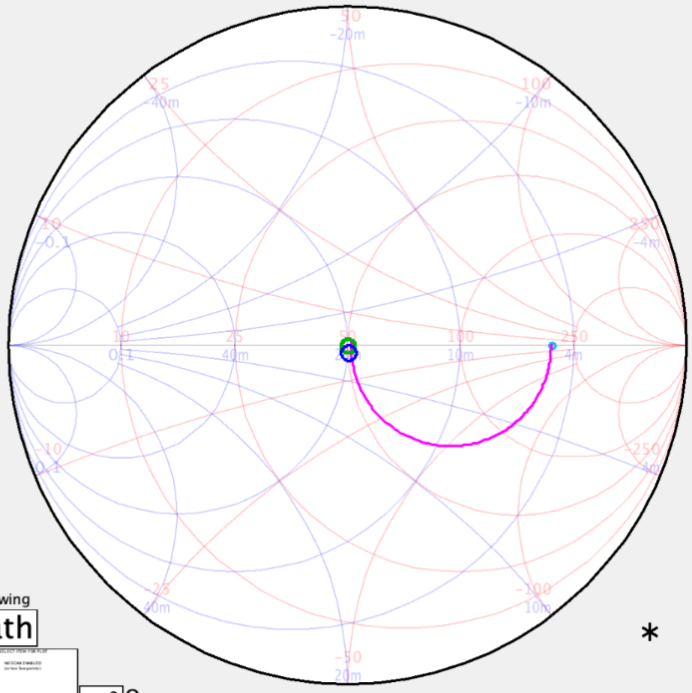
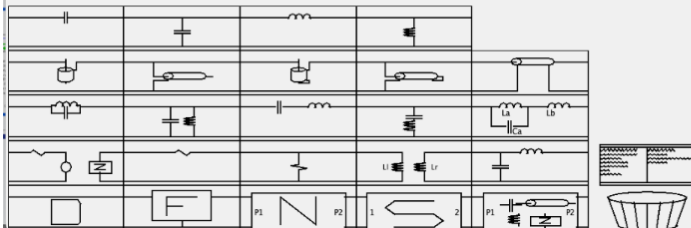
Now, focus your attention on this close up of what's happening at the first discontinuity. There is a reflected wave heading back to the generator due to a reflection at the beginning of the quarter wave transformer (discontinuity). This reflected wave is completely cancelled out by the reflected wave coming from the antenna interface. The reflected wave is  $\frac{1}{3}$  volt and the antenna reflected wave is  $-\frac{1}{3}$  volt. Why is the reflected wave from the antenna negative, because the incident wave traveled 90 degrees up to the antenna and 90 degrees back (180). The reflected wave from the antenna is 180 degrees out of phase with the reflected wave at the first discontinuity. Note that voltage waves don't shift their phase on reflection (for the most part) but current waves do.

# Quarter Wave Impedance Transformer.



$R = 200$	$R = 51.14$	$R = 50.42$	$SWR = 1.046$
$X = 0$	$X = 1.766$	$X = -2.207$	$\Gamma = 22.4m\angle -78$
$\leftarrow W = 879.3$	$\uparrow W = 17.78$	$\uparrow W = 102.5$	
$\uparrow V, i = 419.3, 2.097$	$V, i = 214.3, 4.188$	$V, i = 224.7, 4.452$	runtime: 44m
200 ohms	90 ~deg	432.8 ~deg	14.2 MHz
0 johms	14 @MHz	10 @MHz	50 Zo
<none> file	11.71 ft	100 ft	useZo(1000) V_
simplified Mdl	(LMR-400) Mdl	Plots	Pit
0.6667 VFnom	0.85 VFnom		
100 Zo	50 Zo		
0.5 /100f	26.41m k0		
10 @frq	0.1248 k1		
	187u k2		

type	numPnts	from	to	name	sweep
lin	500	14.2	14.21	G.MHz	n

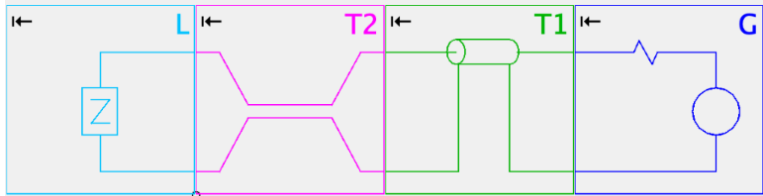


showing Path

0 Q  
0 SWR

Mark

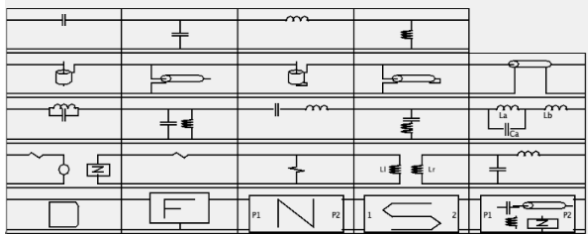
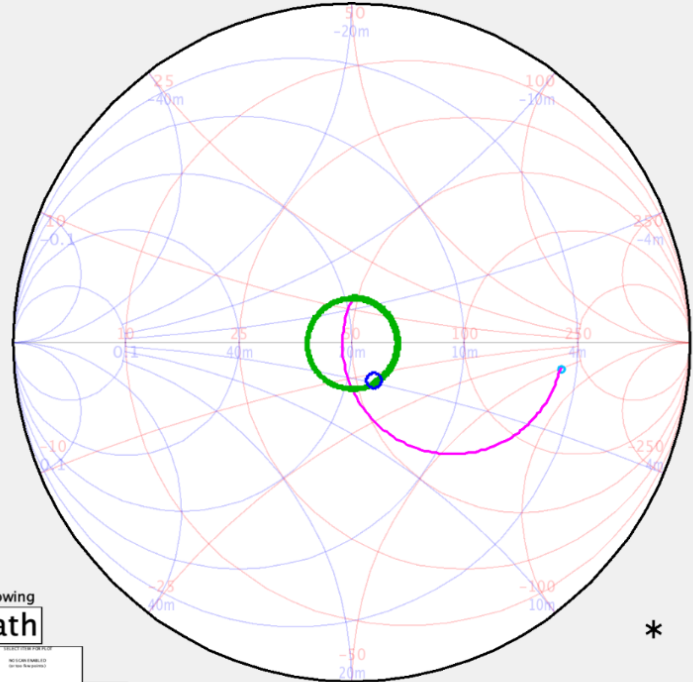
# Quarter Wave Impedance Transformer.



R = 200	R = 48.67	R = 55.43	SWR = 1.298
X = -50	X = 13.72	X = -12.67	$\Gamma = 0.130 \angle -60$
$\leftarrow W = 860.5$	$\uparrow W = 20.42$	$\uparrow W = 102.3$	
$\uparrow V, i = 427.6, 2.074$	$V, i = 215.1, 4.254$	$V, i = 239.5, 4.212$	runtime: 11m
200 ohms	90 ~deg	432.8 ~deg	14.2 MHz
-50 johms	14 @MHz	10 @MHz	50 Zo
<none> file	11.71 ft	100 ft	useZo(1000) V_
	simplified Mdl	(LMR-400) Mdl	Plots Plt
	0.6667 VFnom	0.85 VFnom	
	100 Zo	50 Zo	
	0.5 /100f	26.41m k0	
	10 @frq	0.1248 k1	
		187u k2	

type numPnts from to name sweep

lin 500 14.2 14.21 G.MHz n



showing Path

0 Q

0 SWR

Mark

# Quarter Wave Matching Transformer

What are the takeaways from this explanation of the quarter wave transformer as an antenna tuning tool.

- The  $\frac{1}{4}$  wave transformer works best when the system is purely resistive.
- The solution to the impedance mismatch that we have corrected with a  $\frac{1}{4}$  wave transformer works exactly the same way in more complicated antenna tuners. (We'll see this next).
- Reflected waves are a fact of life, even in perfectly matched system, because there is no such thing as a perfect match, or lossless transmission line, or environmental impacts.
- Antenna tuners do not present a reflection coefficient of 1 (total reflection) to energy reflected by the antenna. This is a long standing myth that simply is not true.
- Reflections happen at the INPUT side of an antenna tuner. This is true regardless of whether the match is through a  $\frac{1}{4}$  wave transformer or through a T, L or Pi network. They all present a 2nd discontinuity in the transmission line and they all resolve reflected energy from the antenna in exactly the same way.
- The  $\frac{1}{4}$  wave transformer presents a 50 ohm load to the transmission line BECAUSE of the reflections being canceled. The "apparent" reflection Coef at that boundary becomes 0 due to the cancellation of the forward and reverse waves.

# The “LC” Network Antenna Tuner.

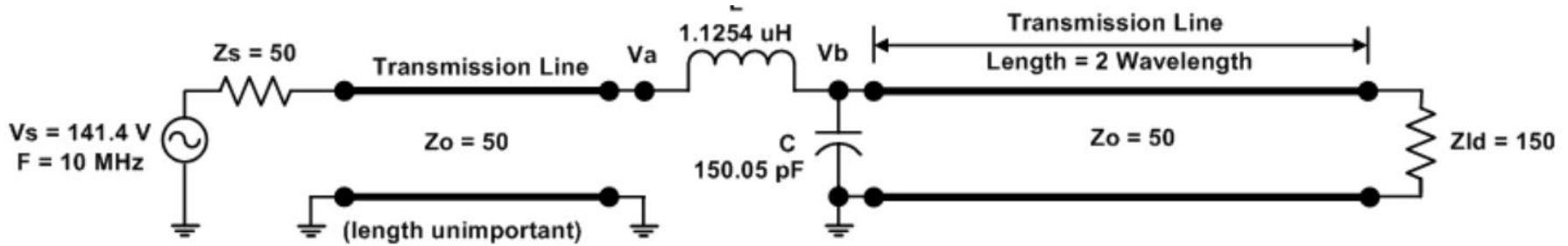
All of the following material comes from 3 separate sources.

- Dr. Steven R. Best (VE9SRB)
- M. Walter Maxwell (W2DU) (SK)
- Jeffrey C. Anderson (K6JCA)
- David W. Knight (G3YNH) (SK)

The original publication of Dr. Best’s explanation of how a T-network antenna tuner works was first published in 2001 (jan/Feb, July/Aug, Nov/Dec) in QEX Magazine, and are still available today in the QEX archives. Maxwell’s rebuttal to the published works of Dr. Best were published in 2004 (Jul/Aug) edition of QEX magazine. Walt’s work is also still available in the QEX archives.

Maxwell did not agree completely with Best’s analysis, which is why this subject was revisited by Jeffrey Anderson in October 2021. Anderson found that Maxwell had misunderstood Best’s analysis and proceeded to run the mathematics himself once again proving that Dr. Best had it right in the first place.

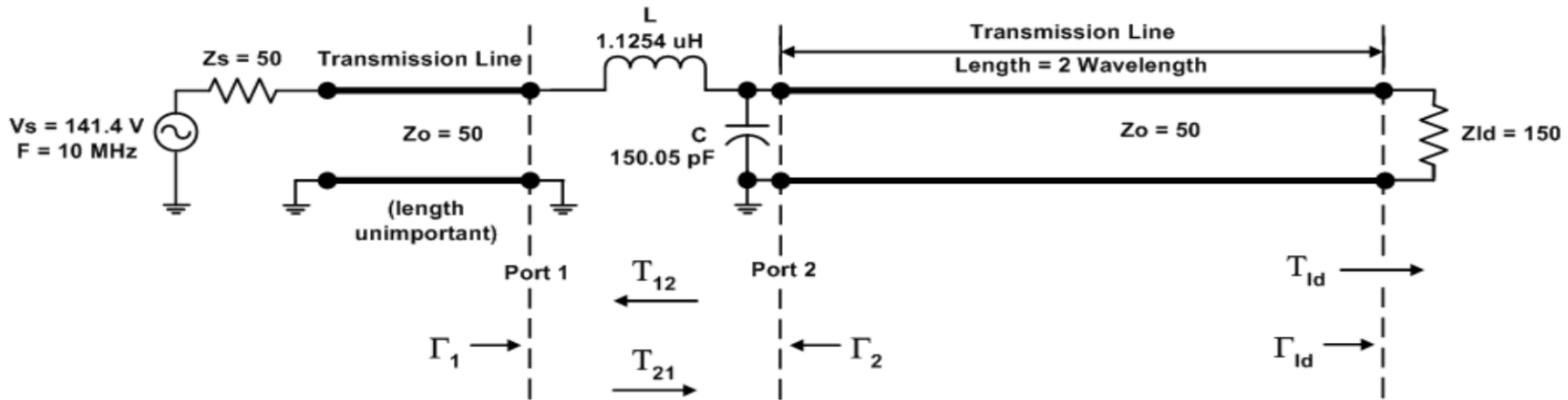
# The “LC” Network Antenna Tuner.



For the LC network antenna tuner, the only difference between it and the  $\frac{1}{4}$  wave impedance transformer from the last section, is in the calculation of the transmission and reflection coefficients as some of them now include impedances from the lumped components. Note that in a case like this where the components are lumped into a 2 terminal network, the component values can be taken into account immediately.

# The "LC" Network Antenna Tuner.

## System Reflection and Transmission Coefficients



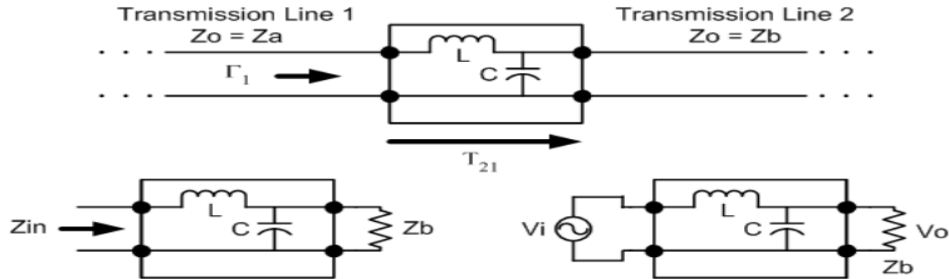
Lumped-element  
2-port  
Transmission and  
Reflection  
Coefficients

Load  
Transmission  
and Reflection  
Coefficients

Source: Jeff Anderson (K6JCA)

# The “LC” Network Antenna Tuner. (Input port looking in)

Given the LC Network, below,  
Calculate  $\Gamma_1$  and  $T_{21}$



1. Calculate Port 1  $Z_{in}$  with Port 2 terminated in  $Z_b$

$$Z_{in} = Z_l + (Z_c \parallel Z_b)$$

("||" means "in parallel with")

2. Calculate Reflection Coefficient at Port 1 using  $Z_{in}$

$$\begin{aligned} \Gamma_1 &= (Z_{in} - Z_a) / (Z_{in} + Z_a) \\ &= \frac{(Z_l + (Z_c \parallel Z_b)) - Z_a}{(Z_l + (Z_c \parallel Z_b)) + Z_a} \end{aligned}$$

3. Calculate Transmission Coefficient into Port 1 using  $Z_{in}$

$$\begin{aligned} T_1 &= 2 * Z_{in} / (Z_{in} + Z_a) \\ &= \frac{2 * (Z_l + (Z_c \parallel Z_b))}{(Z_l + (Z_c \parallel Z_b)) + Z_a} \end{aligned}$$

4. Calculate Gain from Port 1 to Port 2 with Port 2 terminated in  $Z_b$

$$A_{V21} = \frac{(Z_c \parallel Z_b)}{(Z_l + (Z_c \parallel Z_b))}$$

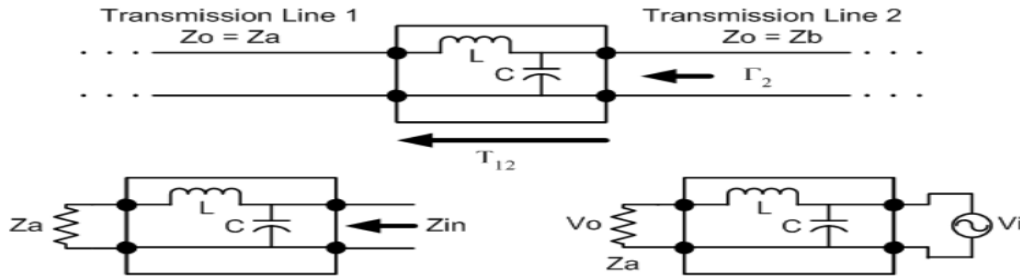
5. Calculate Transmission Coefficient *through* Network

$$\begin{aligned} T_{21} &= T_1 * A_{V21} \\ &= \frac{2 * (Z_l + (Z_c \parallel Z_b)) * (Z_c \parallel Z_b)}{(Z_l + (Z_c \parallel Z_b)) + Z_a * (Z_l + (Z_c \parallel Z_b))} \end{aligned}$$

Source: Jeff Anderson (K6JCA)

# The “LC” Network Antenna Tuner. (output port looking in)

Given the LC Network, below,  
Calculate  $\Gamma_2$  and  $T_{12}$



1. Calculate Port 2  $Z_{in}$  with Port 1 terminated in  $Z_a$

$$Z_{in} = Z_c \parallel (Z_l + Z_a)$$

("||" means "in parallel with")

2. Calculate Reflection Coefficient at Port 2 using  $Z_{in}$

$$\Gamma_2 = \frac{(Z_{in} - Z_b) / (Z_{in} + Z_b)}{((Z_c \parallel (Z_l + Z_a)) - Z_b) / ((Z_c \parallel (Z_l + Z_a)) + Z_b)}$$

3. Calculate Transmission Coefficient into Port 2 using  $Z_{in}$

$$T_2 = \frac{2 * Z_{in} / (Z_{in} + Z_b)}{(Z_c \parallel (Z_l + Z_a)) + Z_b}$$

4. Calculate Gain from Port 2 to Port 1 with Port 1 terminated in  $Z_a$

$$A_{V12} = \frac{Z_a}{Z_l + Z_a}$$

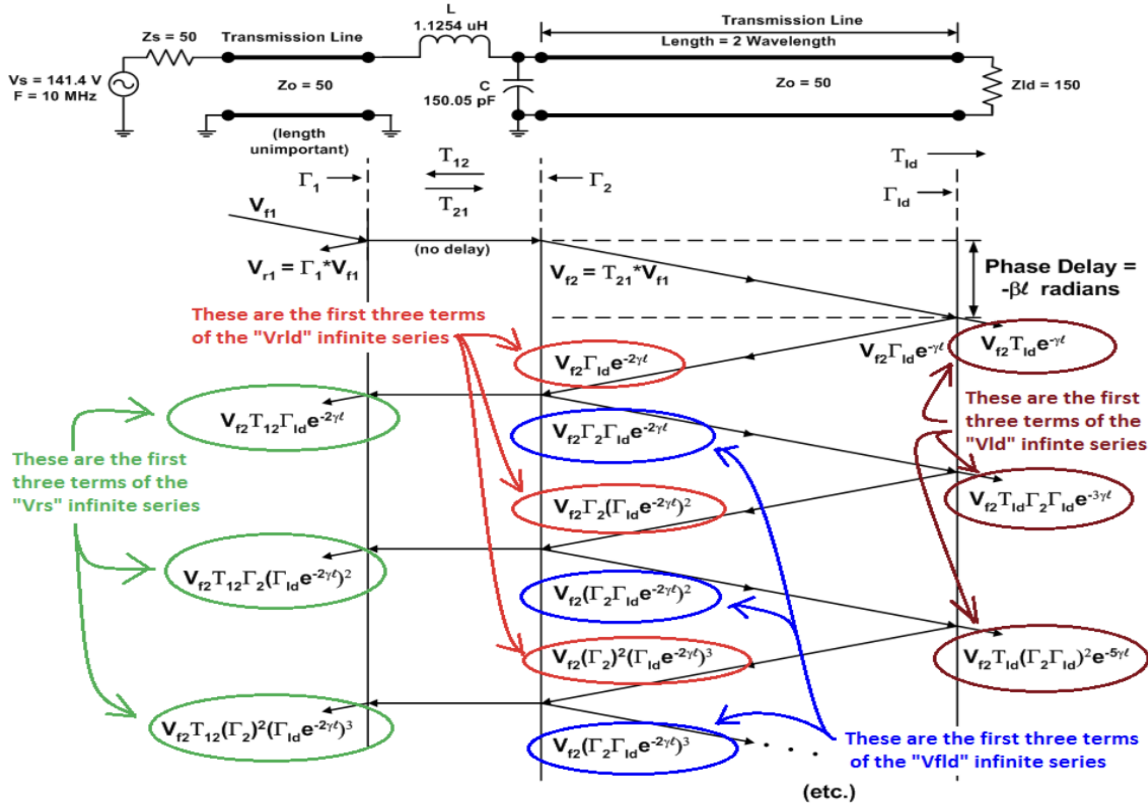
5. Calculate Transmission Coefficient *through* Network

$$T_{12} = T_2 * A_{V12} = \frac{2 * (Z_c \parallel (Z_l + Z_a)) * Z_a}{((Z_c \parallel (Z_l + Z_a)) + Z_b) * (Z_l + Z_a)}$$

Source: Jeff Anderson (K6JCA)

# The "LC" Network Antenna Tuner. (Reflections)

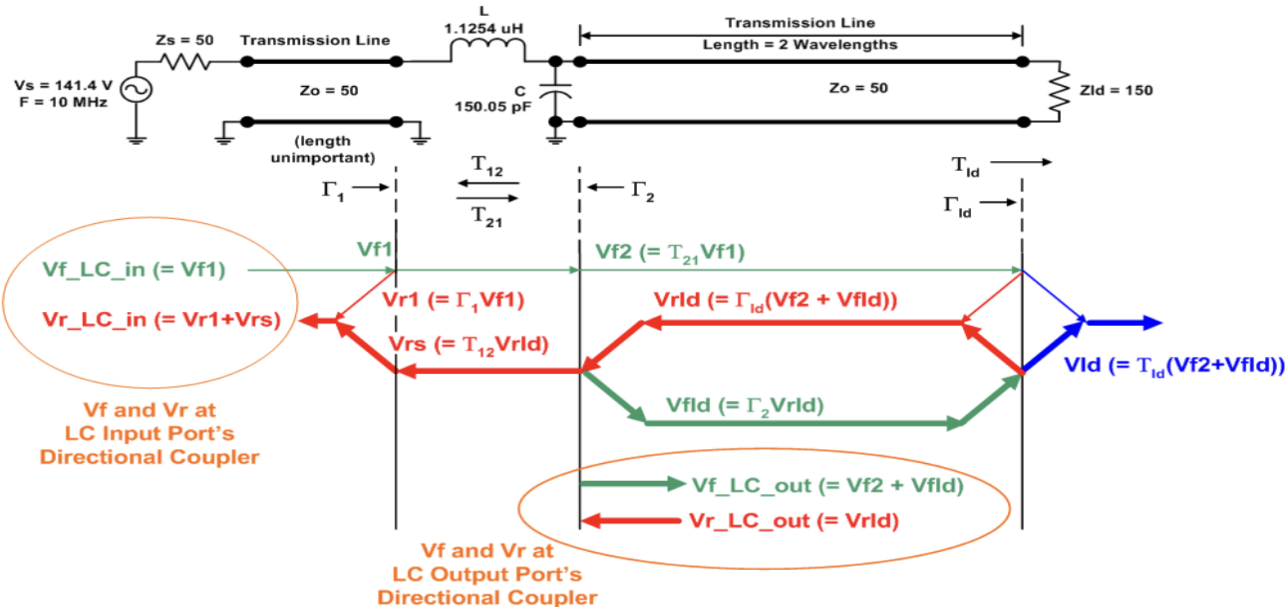
## The Four Infinite Series



Source: Jeff Anderson (K6JCA)

# The "LC" Network Antenna Tuner. (Steady State)

## Steady-State Traveling Voltage Summary

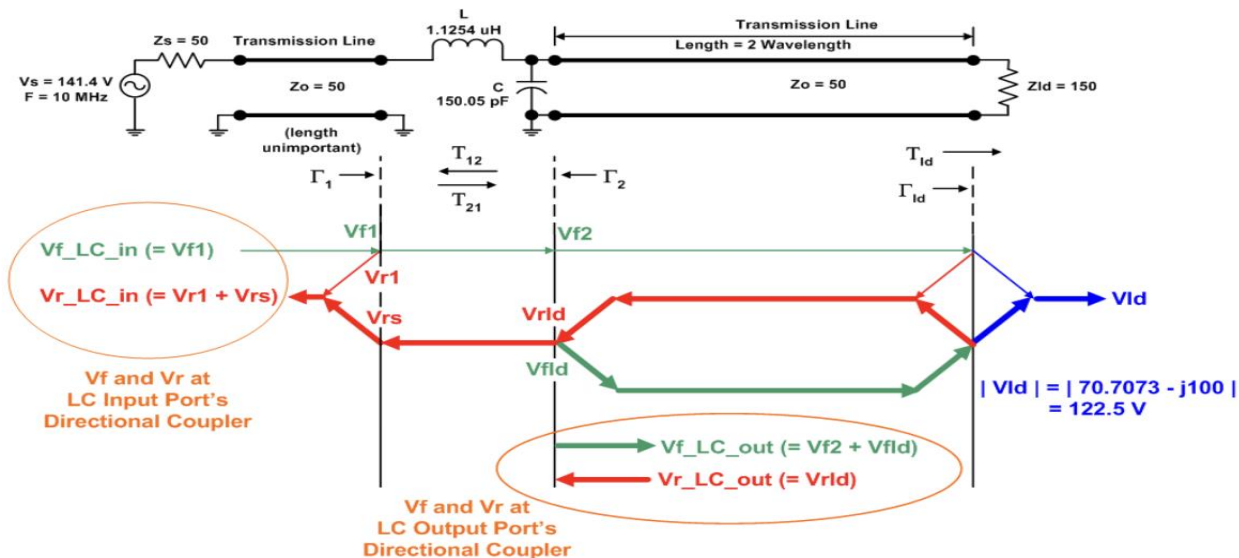


Note: Voltage sums are the vector sum of those voltages taken, simultaneously, at a common point along the transmission line

Source: Jeff Anderson (K6JCA)

# The "LC" Network Antenna Tuner. (Final values)

Directional Coupler and Load Voltages  
in Steady-state



$$|V_{f\_LC\_in}| = |V_{f1}| = 70.71 \text{ V}$$

$$|V_{r\_LC\_in}| = |V_{r1} + V_{rs}| = |(11.78 + j33.33) + (-11.78 - j33.33)| = 0 \text{ V}$$

$$|V_{f\_LC\_out}| = |V_{f2} + V_{fld}| = |(35.3537 - j50) + (11.7846 - j16.66)| = 81.65 \text{ V}$$

$$|V_{r\_LC\_out}| = |V_{rld}| = |23.5691 - j33.33| = 40.82 \text{ V}$$

Source: Jeff Anderson (K6JCA)

# Best's Conclusion

In order for Best's conclusion to be correct, the reflected voltages at the input of the tuner need to be equal in amplitude and opposite in phase.

In our example, the following is true:

$$|V_{r1}| = 35.35$$

$$\text{Angle}(V_{r1}) = 70.53 \text{ degrees}$$

$$|V_{rs}| = 35.35$$

$$\text{Angle}(V_{rs}) = -109.47 \text{ degrees}$$

$$\text{Delta angle} = \text{Angle}(V_{r1}) - \text{Angle}(V_{rs}) = 180 \text{ degrees}$$

# LC Network Summary

For brevity I have skipped over a lot of the intermediate mathematics necessary to form the steady state equations used in the previous slides. For an in depth review of this material, I highly recommend following these links to the original source materials from Dr. Steven Best and Jeff Anderson.

Jeff Anderson (K6JCA)

<https://k6jca.blogspot.com/2021/10/revisiting-maxwells-tutorial-concerning.html>

For Dr. Best's work, you'll need to use your ARRL membership and login to access the QEX archives.

QEX\_Jan\_2001\_Wave Mechanics of Transmission lines, Part1\_Equivalence of Wave reflection analysis and the transmission line equation

QEX\_Jul\_2001\_Wave Mechanics of Transmission lines, Part2 Where does reflected power go

QEX\_Nov\_2001\_Wave Mechanics of Transmission lines, Part3, Power Delivery and Impedance matching

# LC Network Summary

Walter Maxwell responded to Best in 2004 with an article in QEX. While Maxwell may have disagreed with some of what Best wrote, it is clear that the end result consisting of wave cancellations at the INPUT of the tuner, is the same. Walt, of course, concentrated on conjugate matching of the two waves while Best concentrated on amplitude and phase. Is there really a difference? Not as far as I'm concerned.

Walt's rebuttal to Best's work can be found here:

[QEX\\_Jul\\_2004\\_A Tutorial Dispelling Certain Misconceptions Concerning Wave interference in impedance matching](#)

# Tuner Efficiency (Turn your tuner into a space heater)

For the most part, antenna tuners are highly efficient parts of an antenna system. Keep in mind that there's not much difference between an antenna tuner and the PA "tank" circuit of your favorite boat anchor. Antenna tuner components are mostly reactive in nature and not resistive, but there are limits (of course)

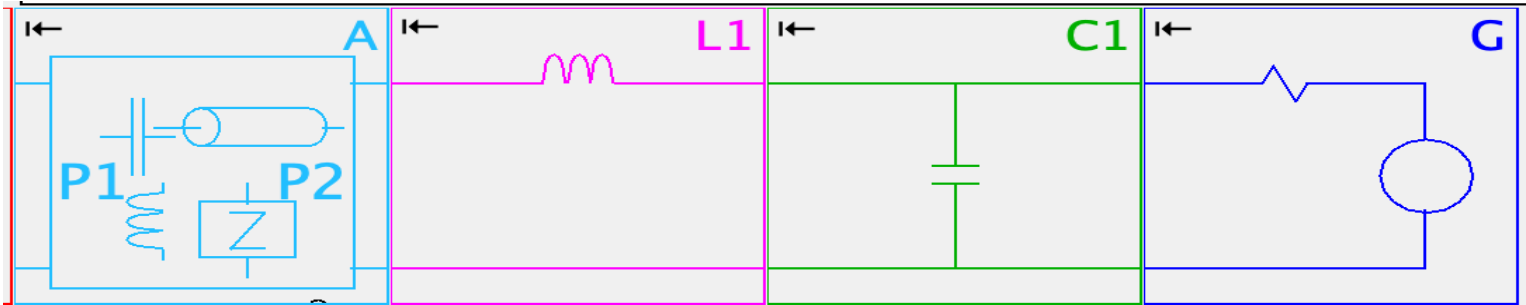
Inductors in an antenna tuner are the major culprits when it comes to losses when tuning vast excursions into the impedance plane. An inductor becomes resistive when the amount of reactance dialed into a roller inductor goes up and the "Q" of the component goes down. Good roller inductors will have a Q value around 400 in low impedance solutions, but that value can drop as more of the coil is used to offset a capacitive reactance.

The resistance of an inductor can be found using the following formula:

$$R = Xl/Q$$

Where Xl is the reactance of the inductor and Q is the quality value. As the inductance goes up and the Q goes down, the resistance in an inductor becomes more of an issue. Where this REALLY becomes a problem is with antenna systems that present very low resistive values and very high impedance values.

# Space Heater, Example #1



$R = 13.29$   
 $X = -1.178K$   
 $\leftarrow W = 687.8$

v,i not unique

name	equ
65	len
40	height
0.1	wireDiameter
Somerfield	env

$R = 19.3$   
 $X = 23.27$   
 $\uparrow W = 310.7$

$\leftrightarrow v, I = 8.64K, 7.193$

50.31u	H
200	Q
0	@MHz

$R = 47.29$   
 $X = 1.186$   
 $\uparrow W = 0.5893$

$\uparrow v, i = 217.4, 5.421$

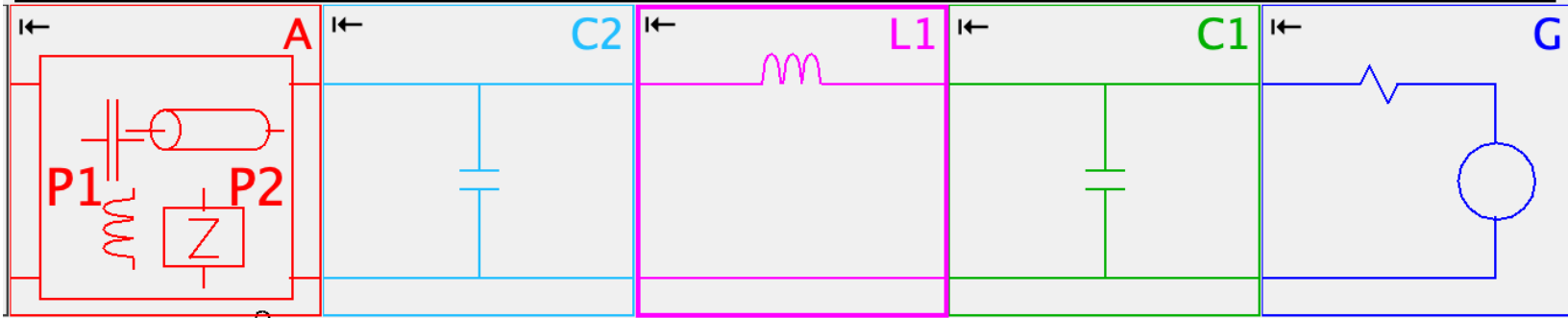
1.044n	F
2K	Q
0	@MHz

$SWR = 1.063$   
 $\Gamma = 30.4m \angle 156$

runtime: 76m

3.8	MHz
50	Zo
useZo(1000)	V_
Plots	Plt
0	C2
0	B
0	T1

# Space Heater, Example #2



$R = 13.29$   
 $X = -1.178K$   
 $\leftarrow W = 253.8$   
 $v, i$  not unique

name	equ
65	len
40	height
0.1	wireDiameter
Somerfield	env

$R = 0.4744$   
 $X = -201.9$   
 $\uparrow W = 54.34$   
 $\uparrow V, i = 5.147K, 21.12$

171.8p	F
2K	Q
0	@MHz

$R = 1.523$   
 $X = 7.841$   
 $\uparrow W = 681.2$   
 $\leftrightarrow v, i = 5.346K, 25.48$

8.787u	H
200	Q
0	@MHz

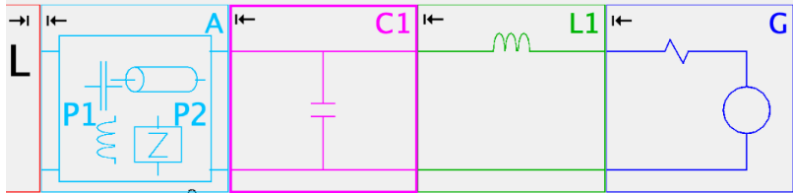
$R = 41.76$   
 $X = -0.7192$   
 $\uparrow W = 2.555$   
 $\uparrow V, i = 203.6, 25.1$

5.164n	F
2K	Q
0	@MHz

$SWR = 1.198$   
 $\Gamma = 90.1m \angle -175$   
 runtime: 89m

3.8	MHz
50	Zo
useZo(1000)	V_
Plots	Plt
0	B
0	T1

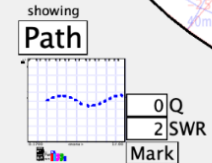
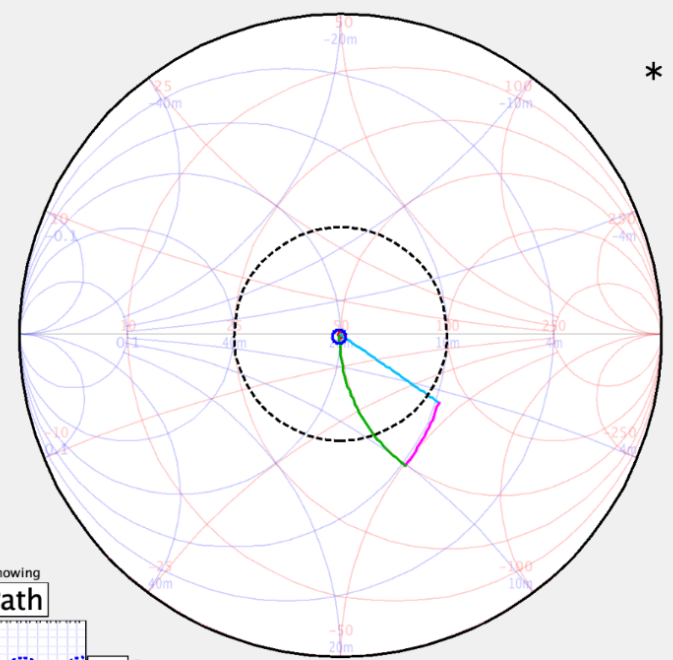
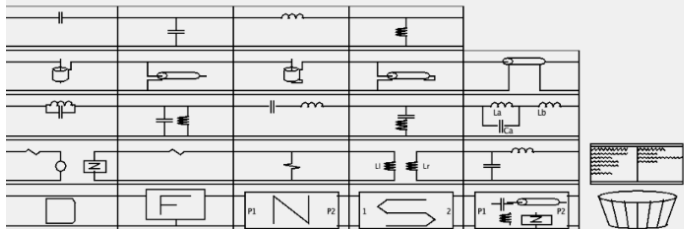
# Space Heater, Example #3



$R = 50$        $R = 81.88$        $R = 49.45$        $R = 49.7$        $SWR = 1.012$   
 $X = 0$          $X = -40.29$        $X = -50.82$        $X = -0.5172$        $\Gamma = 5.99m \angle -120$   
 $\uparrow W = 994.6$        $\uparrow W = 0.2665$        $\uparrow W = 5.06$   
 $v, i$  not unique       $\uparrow V, i = 318.1, 1.676$        $\leftrightarrow v, i = 225.6, 4.485$       runtime: 99m

name	equ	116.5pF	1.112uH	7.2MHz
65	len	2KQ	200Q	50Zo
40	height	0@MHz	0@MHz	useZo(1000) V_
0.1	WireDiameter			Plots
Sommerfield env				0B

type	numPnts	from	to	name	sweep
lin	1K	1	3	G.MHz	n



## Space Heaters, Cont...

So, YES, antenna tuners can be lossy under certain circumstances. But let's be realistic about what's going on. The antenna tuner represents  $\frac{1}{3}$  of your antenna system. The other parts are your transmission line and the antenna itself. If a ridiculously low impedance is being supplied to your antenna tuner, don't expect your tuner to be able to perform a miracle and don't blame the tuner when it goes up in smoke.

It's time to address the balance of your antenna system if the impedance presented to the antenna tuner is an unreasonable value.

# Myths and Urban legends.

“Antenna tuners just fool your radio into believing there’s a match”.

“Antenna tuners burn up reflected power and send it to ground”.

*(I was actually told this on an internet forum)*

“I don’t need an antenna tuner, my antennas are all resonant”

“Resonant antennas radiate better than non-resonant antennas”

*(While not a tuner myth specifically, it goes with the last myth)*

“A tuner will improve antenna performance”

*(False: A crappy antenna is still a crappy antenna)*

“My Johnson Viking KW Matchbox will tune the bedsprings on 160 meters”

*(True: But it also makes a great space heater)*

# Acknowledgements and Important Resources

A huge shout-out to Dr. Jeff Anderson (K6JCA) for his guidance during the creation of this presentation. Also, a big thanks to Rick Westerman (DJ0IP) for his help in reviewing this work. And a huge thanks to all my friends at WARC (Watauga Amateur Radio Club) in Boone, NC for their help and encouragement and to Ward Harriman for his use of SimNEC, which was used to provide most of the illustrations.

*This presentation was made possible by the work from the following influential authors:*

Jeff Anderson (K6JCA) <https://k6jca.blogspot.com/>

Walter Maxwell (W2DU SK) <https://www.qcwa.org/w2du-05938-sk.htm>

Dr. Steven Best (VE9SRB): <https://ieeexplore.ieee.org/author/37276723400>

David Knight (G3YNH SK) <https://www.g3ynh.info/index.html>

*Additional reading and resource*

Rick Westerman (DJ0IP): <https://www.dj0ip.com/>

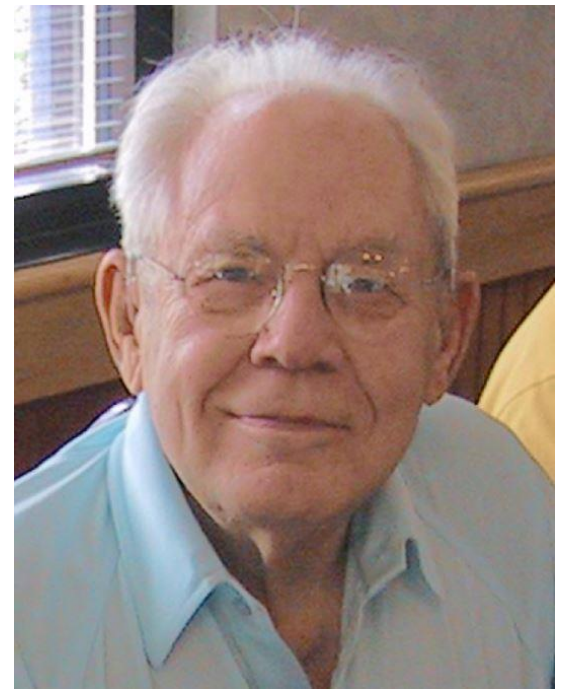
Ward Harriman (AE6TY) Author of SimNEC: [https://www.ae6ty.com/smith\\_charts/](https://www.ae6ty.com/smith_charts/)



Jeff Anderson



Steven Best



Walter Maxwell



David Knight

ur Radio (WBORXQ)

# Thanks!

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