Basic Electronics Series

Understanding Smith Charts

What is a Smith Chart?

- The Smith Chart is a graphical means of visualizing the effects of impedance, admittance, voltage, and current on transmission lines and antennas, or on waveguide systems.
- The concept was the brainchild of Phillip H Smith *et al*, and was developed in the 1930's.
- It has become the *de facto* world-wide standard for such visualizations.
- We will explore the most commonly used aspects of the Smith Chart as applied to amateur radio.

Some History…

- The underlying design of the Smith Chart was proposed contemporaneously but independently by Tōsaku Mizuhashi in Japan, Amiel R. Volpert in Russia, and Phillip H. Smith in the United States.
- Smith finalized his version in 1937 with the collaboration of Enoch B. Ferrell and James W. McRae, while working at Bell telephone Laboratories, but did not publish it until 1939.
- Various forms of the chart have been known as the *Mizuhashi-Smith-Volpert Chart* as well as by different assemblages of those surnames.

Preliminary Terminology

- *Resistance (R)* – the opposition to current flow
- *Conductance (G)* – the opposite of resistance, and the potential for a material to allow current flow
- *Reactance (X)* – the opposition to AC current flow as a result of capacitance and/or inductance
- *Impedance (Z)* – a combination of resistance and reactance, the overall opposition to AC current flow
- *Admittance (Y)* – the opposite of impedance, and how easily a circuit allows a current to flow
- *Susceptance (B)* – the imaginary part of admittance, and the opposite of reactance

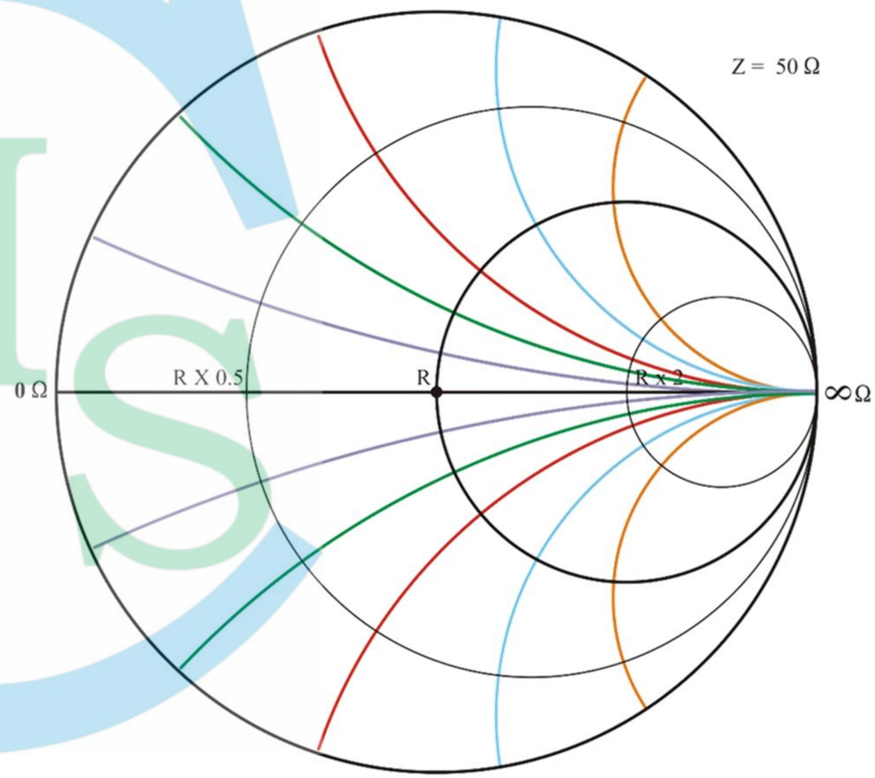
Term Relationships

- $R = \frac{1}{G}$
- $X = \frac{1}{B}$
- $Z = \frac{1}{Y}$
- $G = \frac{1}{R}$
- $B = \frac{1}{X}$
- $Y = \frac{1}{Z}$

Admittance and impedance are *complex values,* meaning that they have imaginary components as a part of their developed or expressed values.

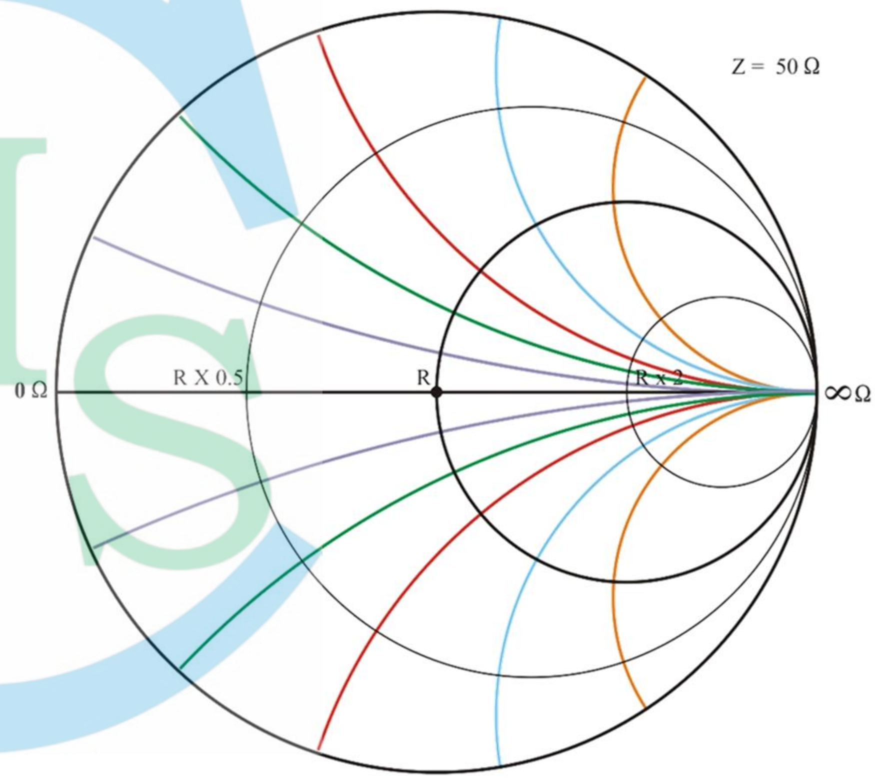
Smith Chart Basic Structure

- Center is the *"Prime Center"* and it represents the chart's characteristic impedance
- Black circles are *"constant resistance circles"*
  - Any number of circles representing different resistances can be drawn or inferred.



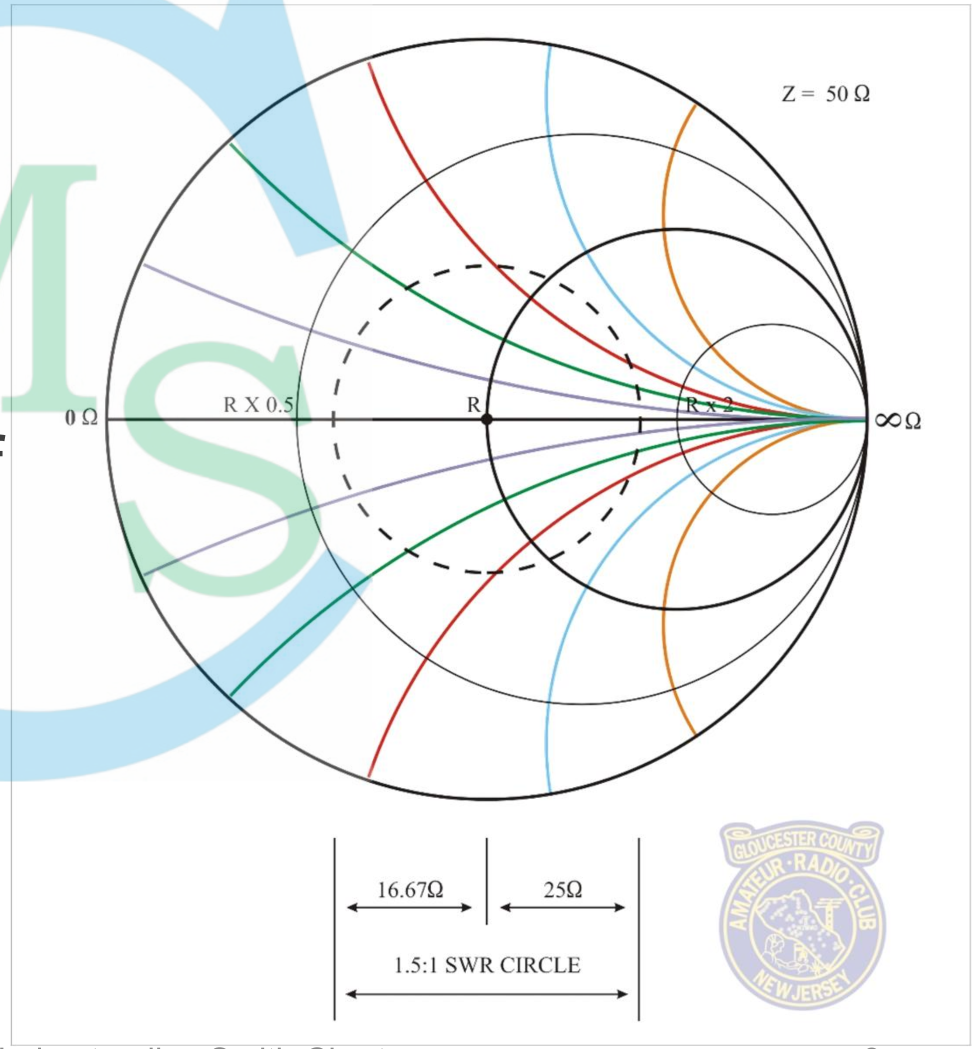
Smith Chart Basic Structure

- Colored arcs are *"constant reactance arcs".*
  - Any number of arcs representing different reactances can be drawn or inferred.
- Equator is pure resistance line or *"real axis"*
  - Zero ohms at left, infinite resistance at right
  - "Short circuit" at left side
  - "Open circuit" at right side



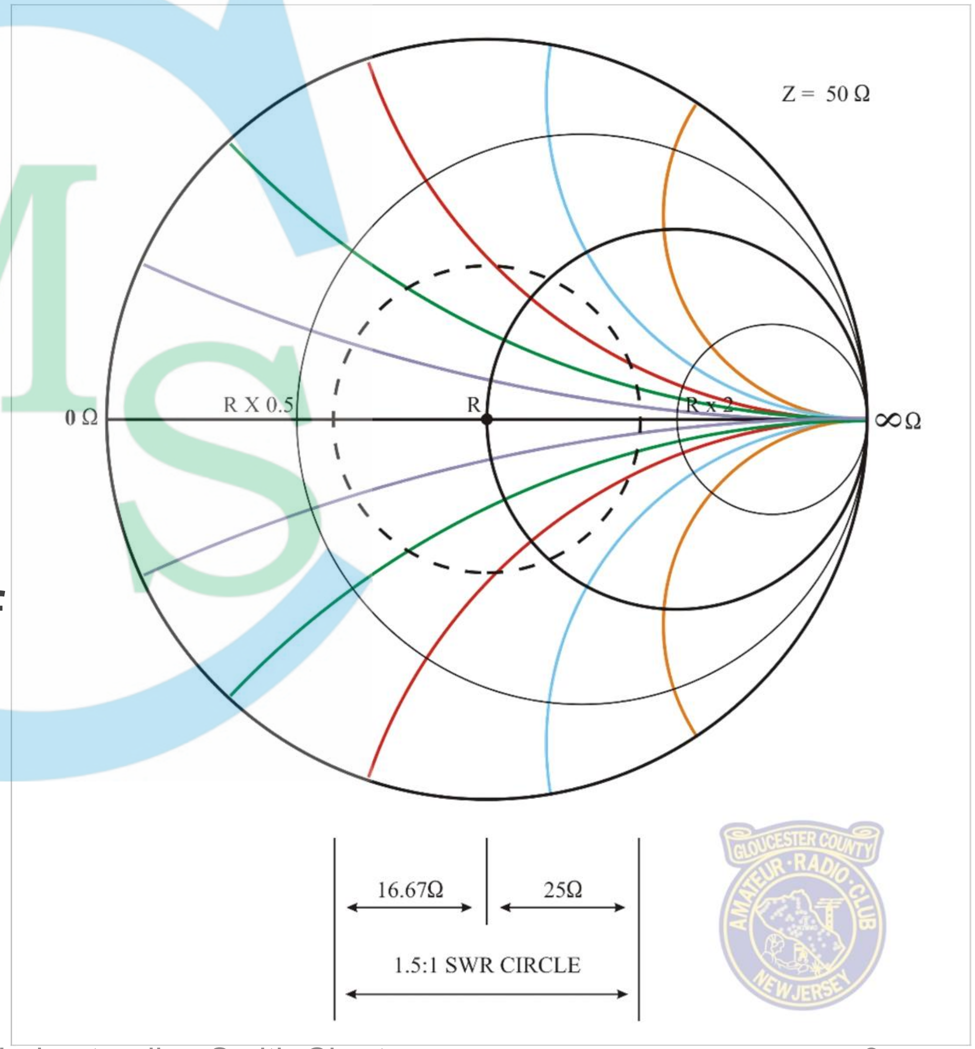
Smith Chart Basic Structure

- A dashed circle representing a 1.5:1 SWR has been added
  - Any point on that circle will represent an SWR of 1.5:1
- Pure resistance line, also called the *real axis,* is logarithmic in nature



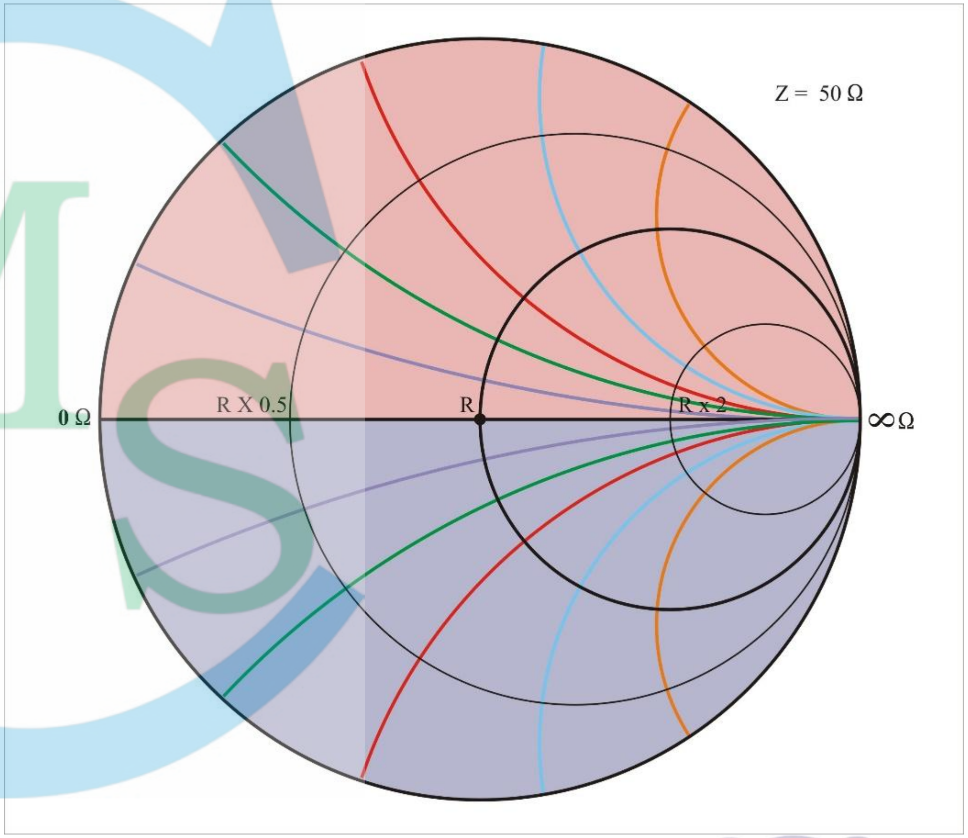
Smith Chart Basic Structure

- Note that the circle representing 1.5:1 SWR extends from 33.33Ω at left to 75Ω at right, and that the scale extends from zero ohms at left to infinite resistance at right, with the characteristic impedance at the center of this 50Ω chart.
- Thus, the left half equates to 50Ω while the right half equates to any and all resistances above 50Ω.



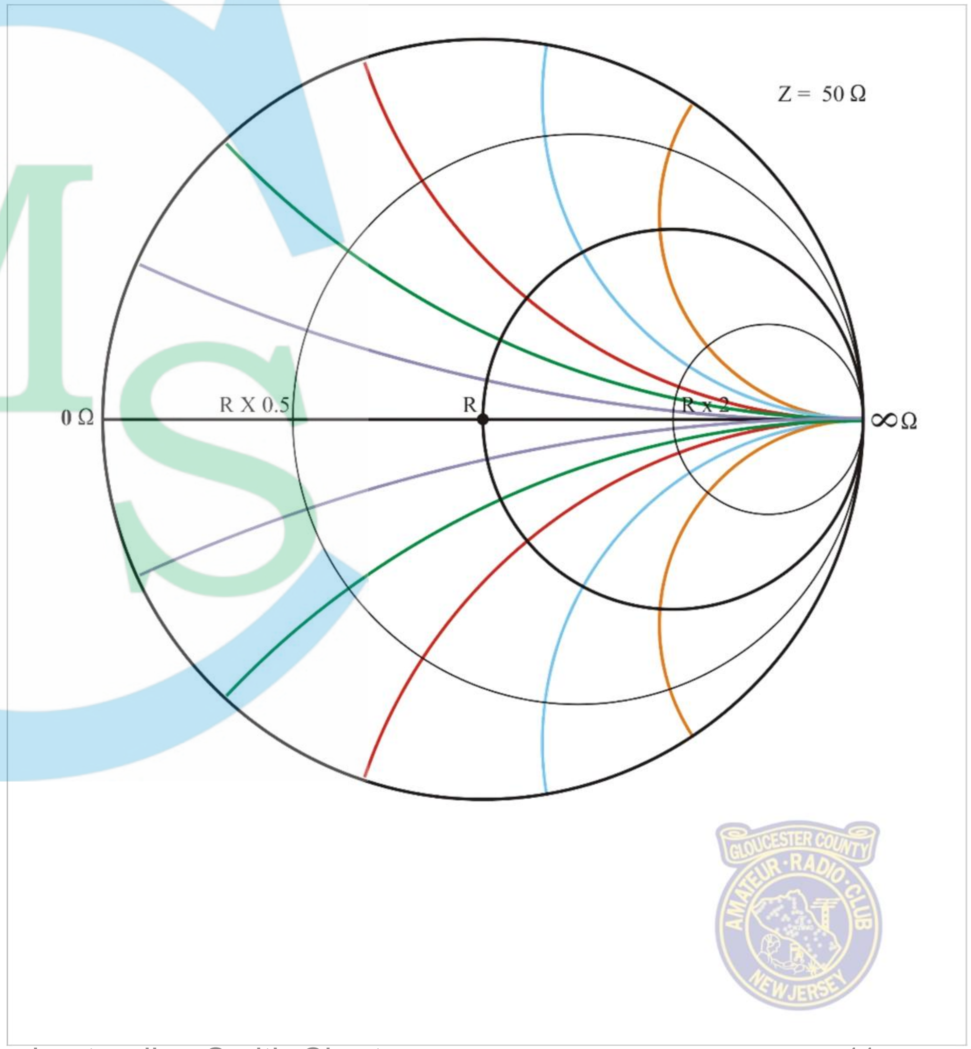
Smith Chart Basic Structure

- Any point in the upper (pink) hemisphere represents an inductive reactance
  - $R + jX$
- Any point in the lower (pale blue) hemisphere represents a capacitive reactance
  - $R - jX$



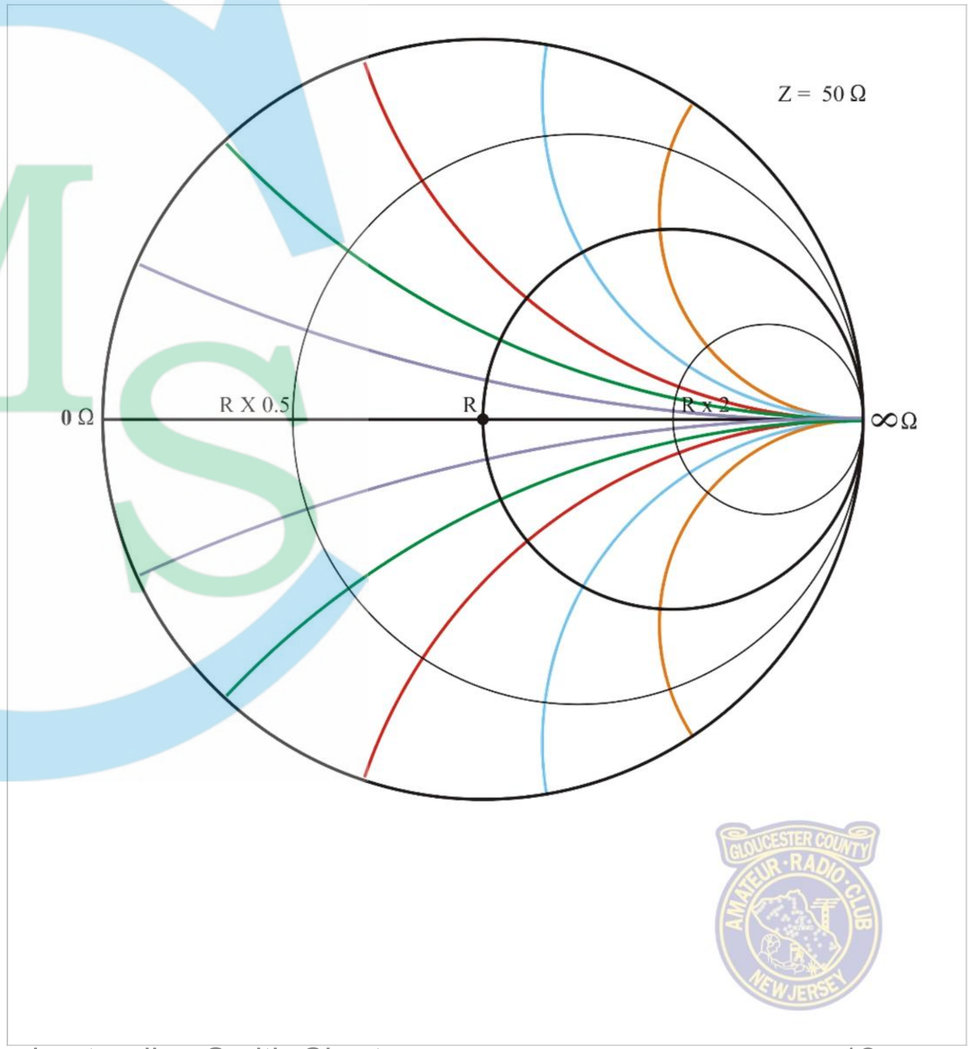
Smith Chart Basic Structure

- Complex impedances, written in the form $R \pm jX$ are represented on the Smith Chart:
  - The "real" part (R) is plotted on one of the many concentric circles
  - The "imaginary" part $(\pm jX)$ is then plotted on a reactance arc.



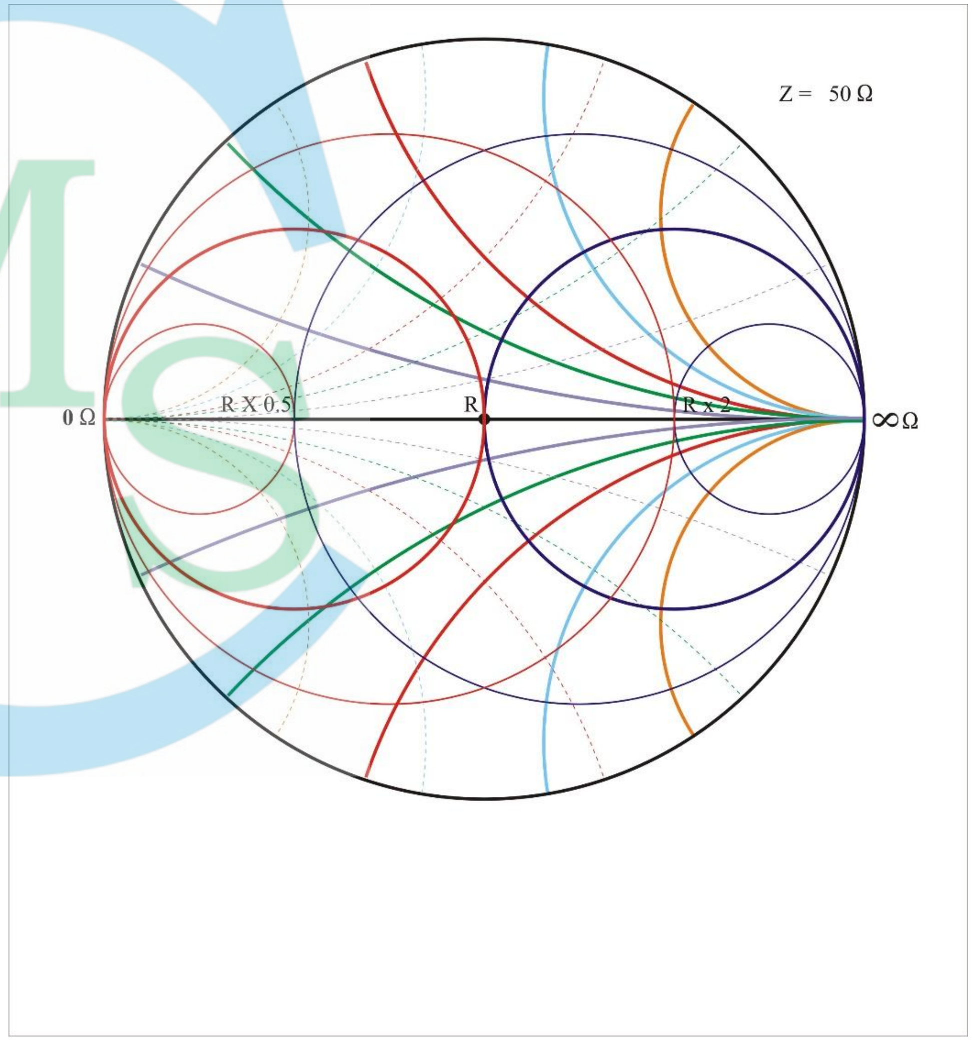
Smith Chart Basics

- Complex impedances that fall on *reactance arcs* are corrected by installing series cancelling devices.
  - An inductive reactance on a reactance arc requires a series capacitance for cancellation.
  - A capacitive reactance on a reactance arc requires a series inductance for cancellation.



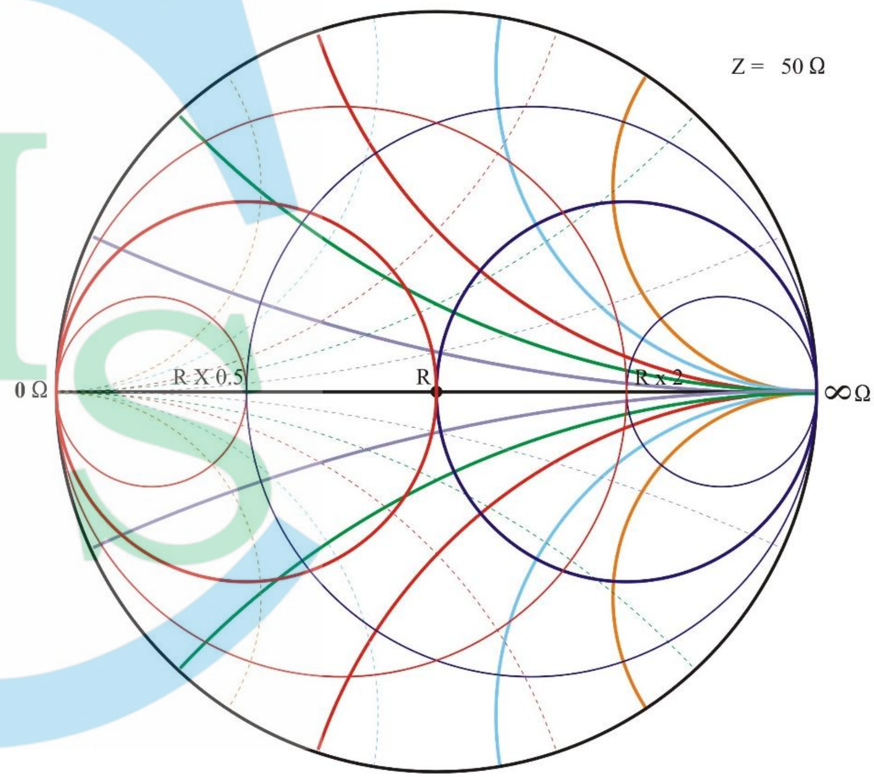
Smith Chart Basics

- On this Smith Chart, additional features have been added:
  - *"Admittance arcs"*, shown as colored dashed lines, and
  - *"Constant conductance"* circles, shown in red.
  - An inductive reactance on an admittance arc requires a shunt capacitance for cancellation.
  - A capacitive reactance on an admittance arc requires a shunt inductance for cancellation.



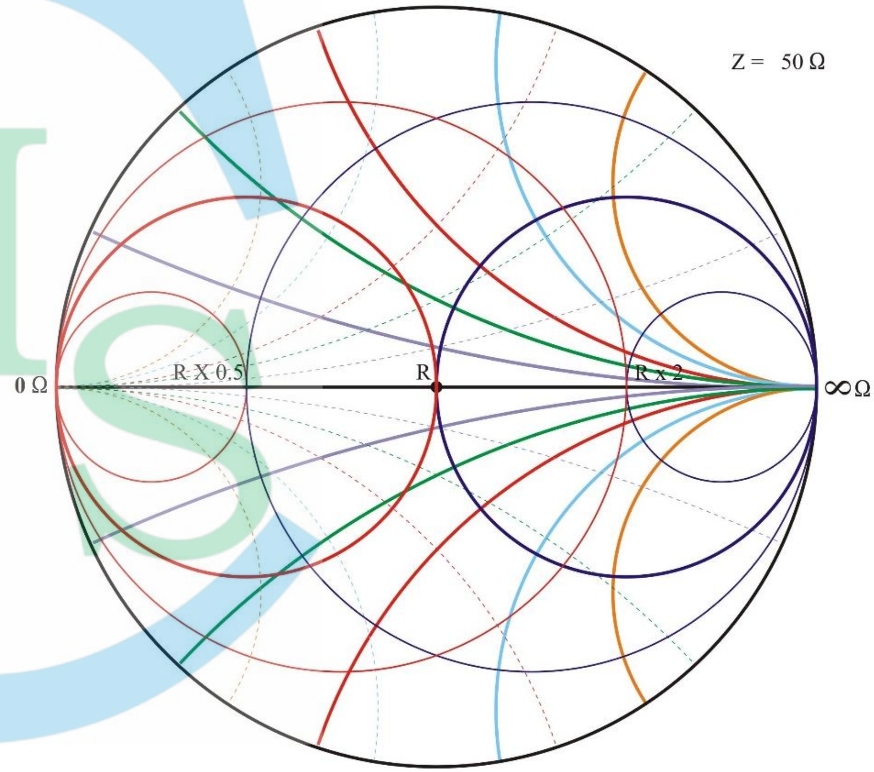
Smith Chart Basics

- Once the reactance has been cancelled, only the resistance remains.
- That resistance is then adjusted to bring it to the characteristic or system impedance.
  - If the pure resistance remaining is greater than the system impedance, a parallel resistance is needed to bring the value down to the system impedance value.



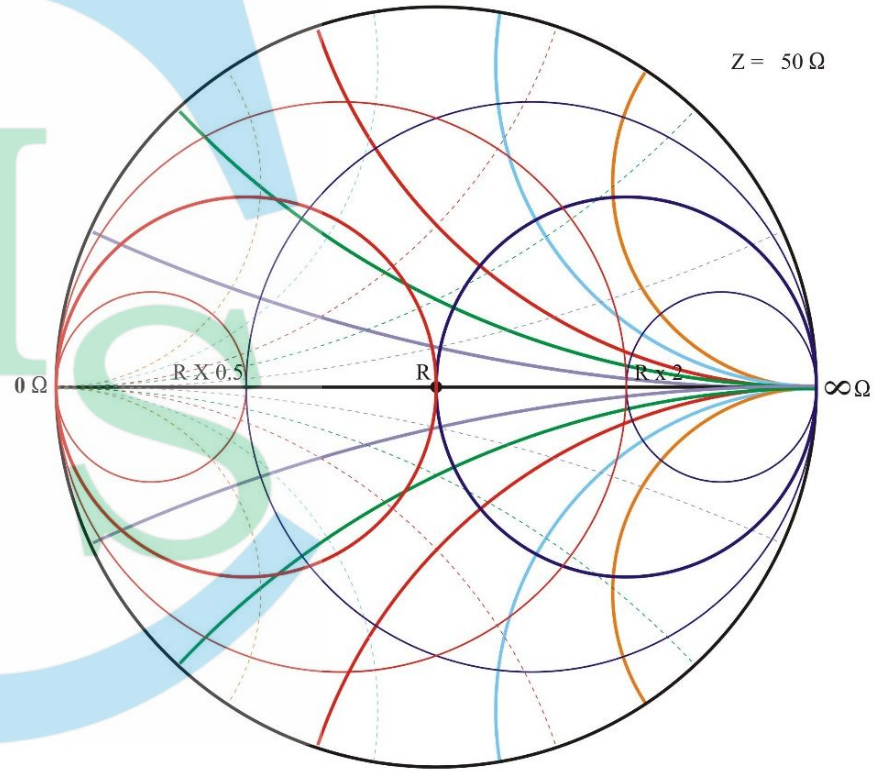
Smith Chart Basics

- If the pure resistance remaining is less than the system impedance, a series resistance is needed to bring the value up to the system impedance value.
- However, as we will see later, most often we can correct mismatches *without the* need to use any resistance, but with only the selective addition of inductance and capacitance.



Smith Chart Basics

- The black circle that extends from the right side to the center is called the "*unity resistance circle*".
- The red circle that extends from the left side to the center is called the *"unity conductance circle.*



Smith Chart Basics

- It is VERY IMPORTANT to understand that the values derived directly from the Smith Chart are ***NOT*** the actual system values.
- This is because the Smith Chart is based on a standard value where the Prime Center is equal to one ohm.
- This allows the Smith Chart to be used for systems having any value of characteristic impedance.

Normalization

- Values read on the Smith Chart must be *"normalized"* to have real-world meaning.
  - *"Normalizing"* means multiplying the chart-derived values by the characteristic impedance in use by the system under study.
- If a Smith Chart value of $1+j0.2\Omega$ is indicated, and the characteristic impedance is 50Ω, then the actual value is $50+j10\Omega$, a slightly inductive complex impedance.
  - This is reached by multiplying the Smith Chart values by 50, which is the system impedance in use by the system at hand.

Practical Example of Smith Chart Use

- Suppose we have a system in which we have a 33Ω real resistance and a 220pF real capacitance, at 14.2MHz…
  - Converting these values to a complex impedance, we arrive at *33-j51Ω*
    - The 33Ω is real, so we carry that through
    - The 220pF is converted as follows (why the negative??):
      - $X_C = -\frac{1}{2\pi f C} = -\frac{1}{6.28 \times 14200000 \times 0.000000000220} = -\frac{1}{0.01961872} = -50.97\Omega$
  - Thus, rounding the reactance, we get *33-j51Ω*

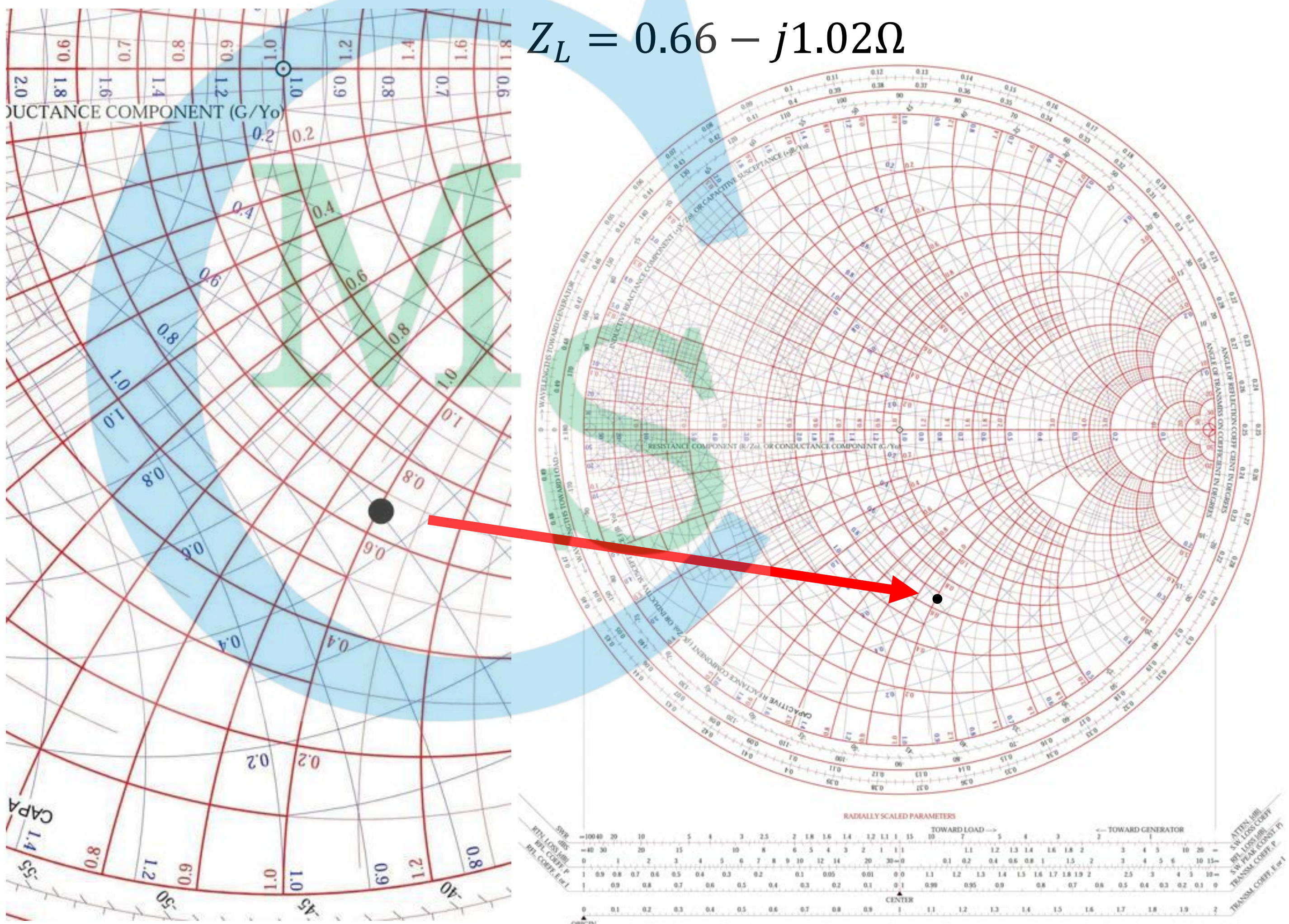
Practical Example of Smith Chart Use

- In order to plot this on the Smith Chart, we have to *de-normalize* the values…
  - Because we are working from the 50Ω system values, we have to *divide* the values by 50…
  - We get $\frac{33}{50} = 0.66\ and\ -\frac{51}{50} = 1.02$…
  - So we end up with *0.66-j1.02Ω* that we can plot on the Smith Chart.
  - That might look something like what is shown next.

Plotting A Point

Start by finding 0.66Ω on the equator, and then follow that circle around until the point where it meets the 1.02Ω capacitive reactance arc… plot the value at that location.

$Z_L = 0.66 - j1.02\Omega$



So Now What?

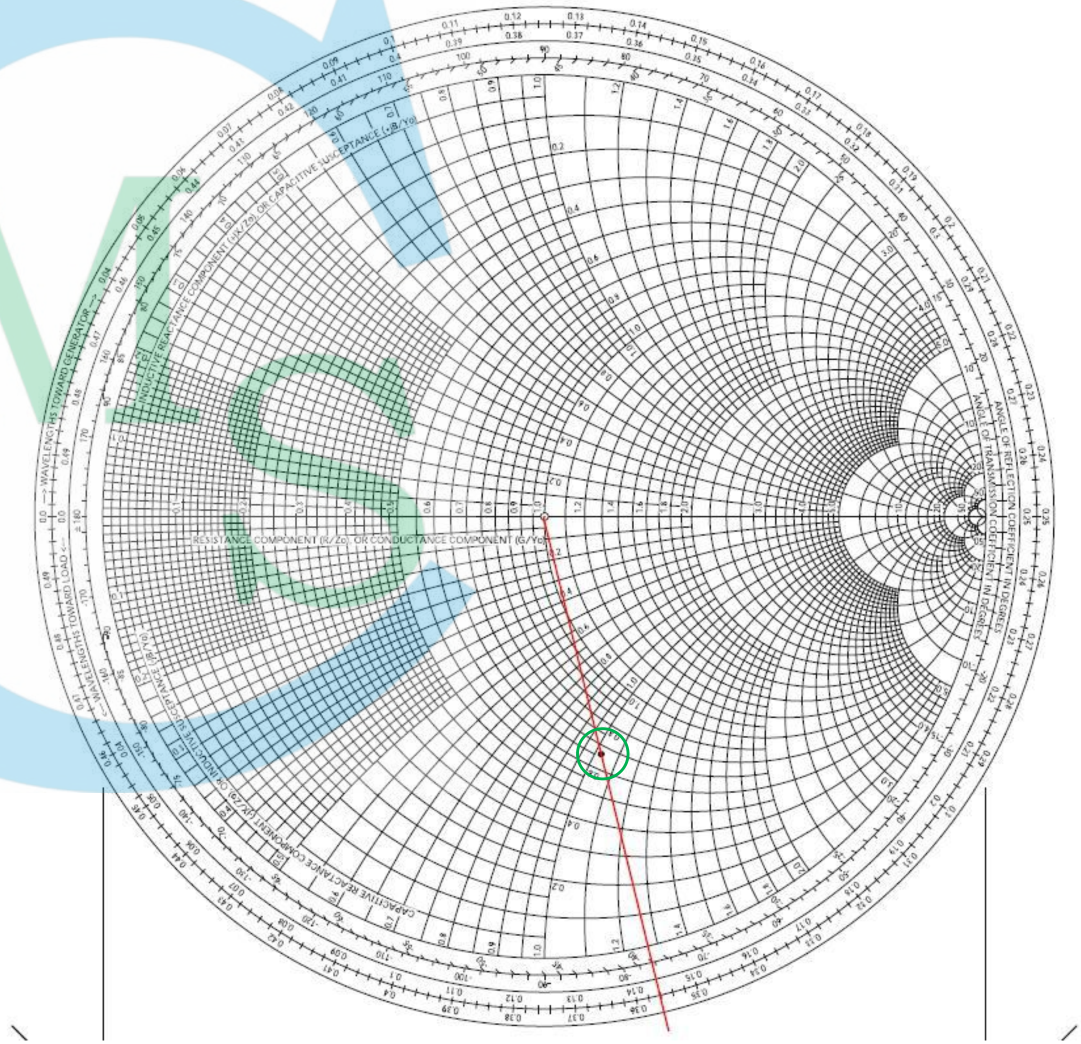
- There are several values that we might want to find, such as…
  - the complex reflection coefficient (gamma)…
    - $\Gamma = \frac{Z_L - Z_\emptyset}{Z_L + Z_\emptyset}$
  - the reflection coefficient (rho)…
    - $\rho = |\Gamma|$
  - the voltage standing wave ratio…
    - $VSWR = \frac{I + \rho}{I - \rho}$
  - the power reflection coefficient…
    - $\Gamma_{PWR} = |\Gamma|^2$
  - the return loss…
    - $Return\ Loss = 20_{LOG10}\left(\frac{VSWR+1}{VSWR-1}\right)$ or
    - $Return\ Loss = 10_{LOG10}\left(\Gamma_{PWR}\right)$
- We *could* calculate these often complex values, or… we can read them directly from the Smith Chart.

Reading Complex Values

- Start by drawing a straight line, using a ruler, from the Prime Center *through the plotted mark,* and out through the ring at the periphery of the circular part of the Smith Chart.
- Using a ruler or a divider, measure the distance from the Prime Center to the plot mark.
- Transfer that distance to the scales beneath the circular graph.
  - Start your line at the CENTER mark and extend it to the left. (WHY??)
- Draw a vertical line through the scales at the point where your measured line ends, and read the scales at that vertical marking…

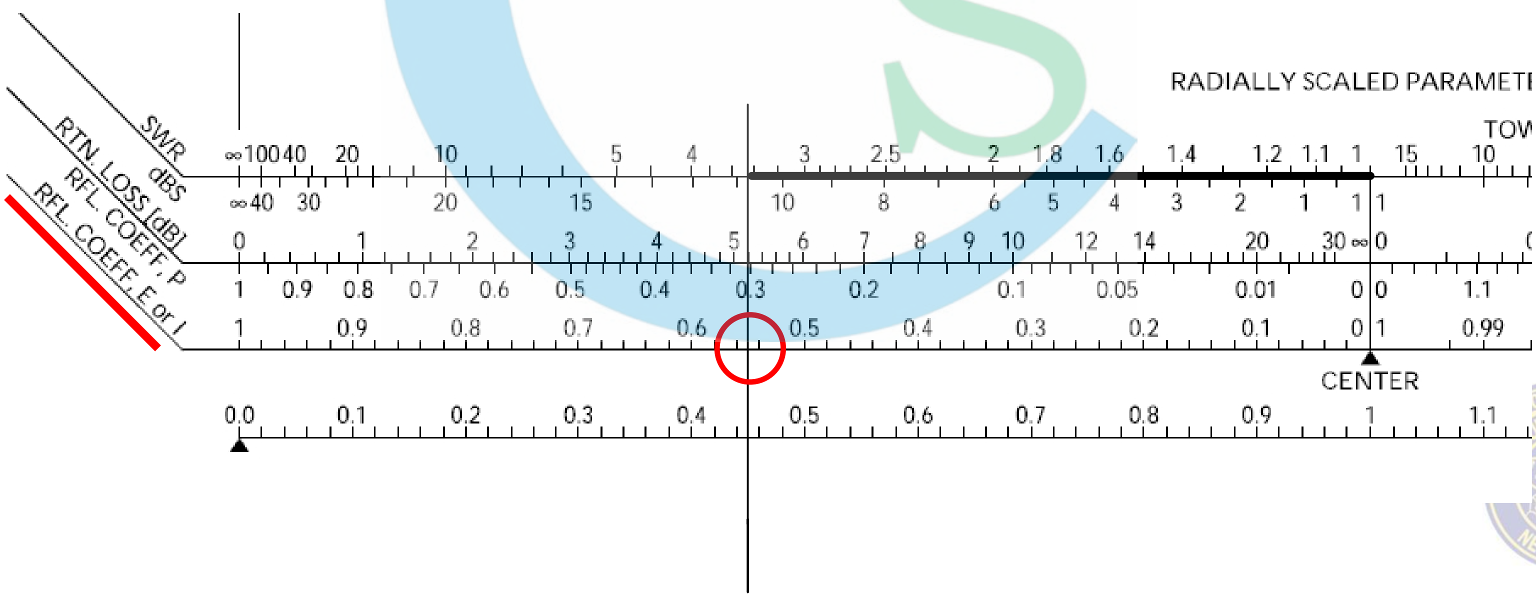
Reading Complex Values

- The graphic at right shows the line drawn through the plotted point (circled) and the edge of the chart.



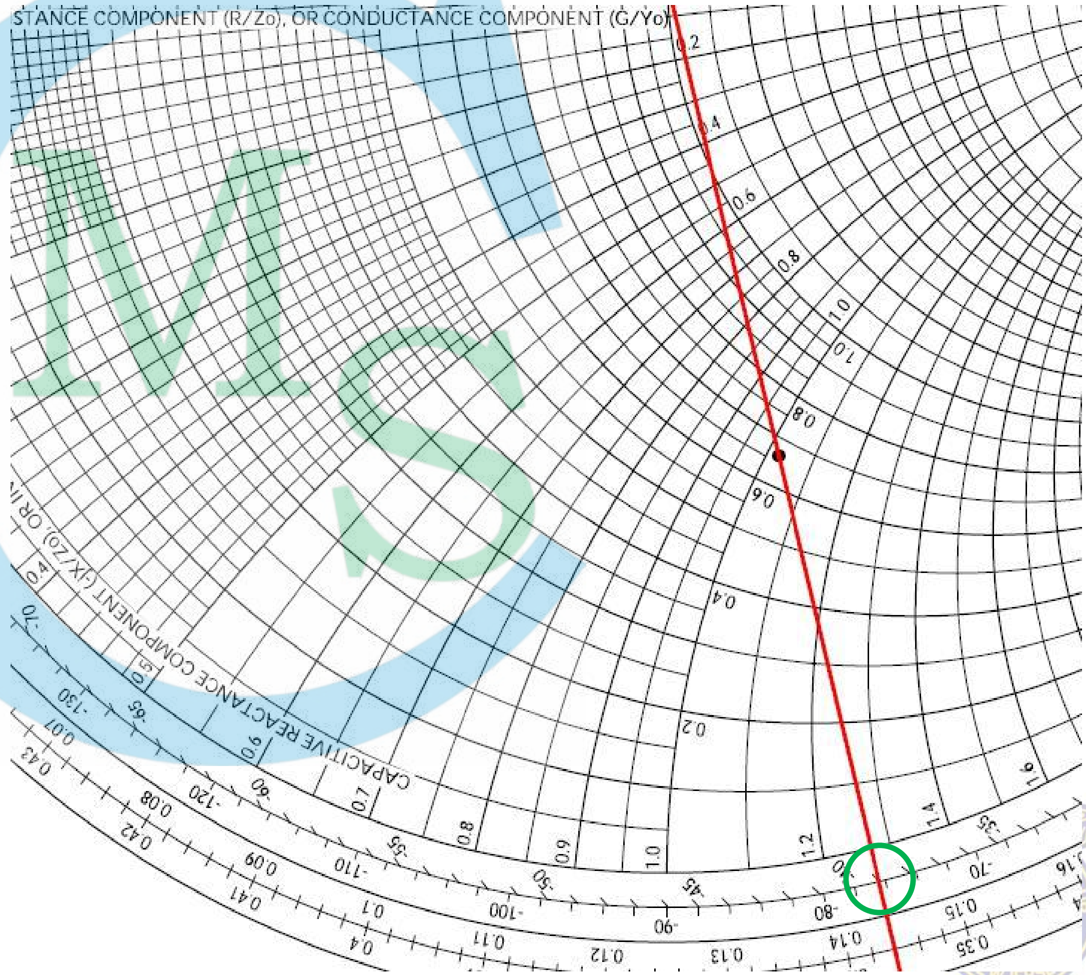
Reading Complex Values

- To read the complex reflection coefficient, we must make two readings, as that value is expressed in polar form as a magnitude and an angle.
  - The magnitude we can read directly from the proper scale beneath the circular portion of the Smith Chart as 0.545… but now we need to find the angle.



Reading Complex Values

- To find the angle, we look at the extended line that we drew through the plotted point and the edge of the circular part of the Smith Chart.
- In this case, we find that the angle identified is -76.2°.



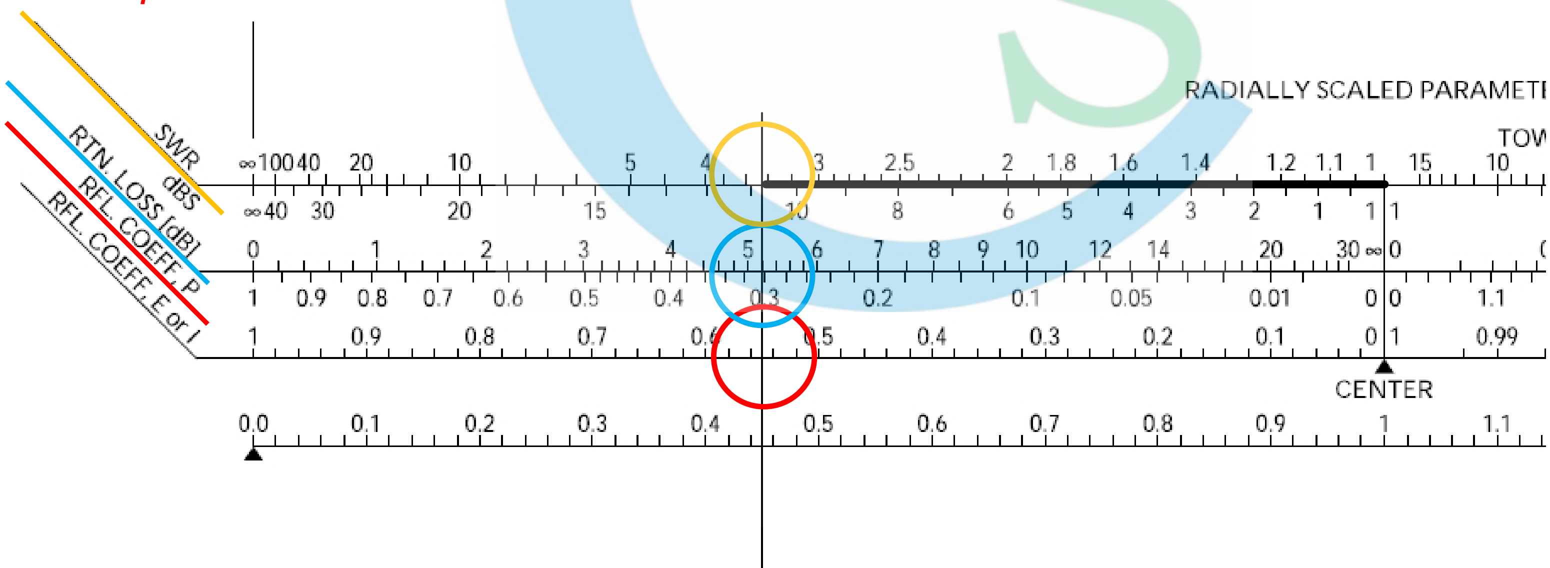
Reading Complex Values

- From the previous slides, we determined that the complex reflection coefficient, characterized in an equation as $\Gamma = \frac{Z_L - Z_\emptyset}{Z_L + Z_\emptyset}$ actually turns out to be quite simple to read from the Smith Chart.
- In this manner, we derive a solution as:

$$\Gamma = 0.545 \angle -76.2°$$

Reading Complex Values

- See the graphic below as we read the following values…
  - the standing wave ratio (SWR)…
    - SWR = 3.425:1 or ≈10.08dB
  - The return loss in dB…
    - Return loss = ≈5.2dB
  - the reflection coefficient (rho)…
    - $\rho = 0.31$



What Else Can We Do?

- These are nice magic tricks, but what else can we do with a Smith Chart?
  - We can predict the impedance value resulting from a change in feedline length…
  - We can then visualize the effect of the feedline on system impedance…
  - We can design a matching network for cancellation of the reactance measured in our system…

Predicting Impedance

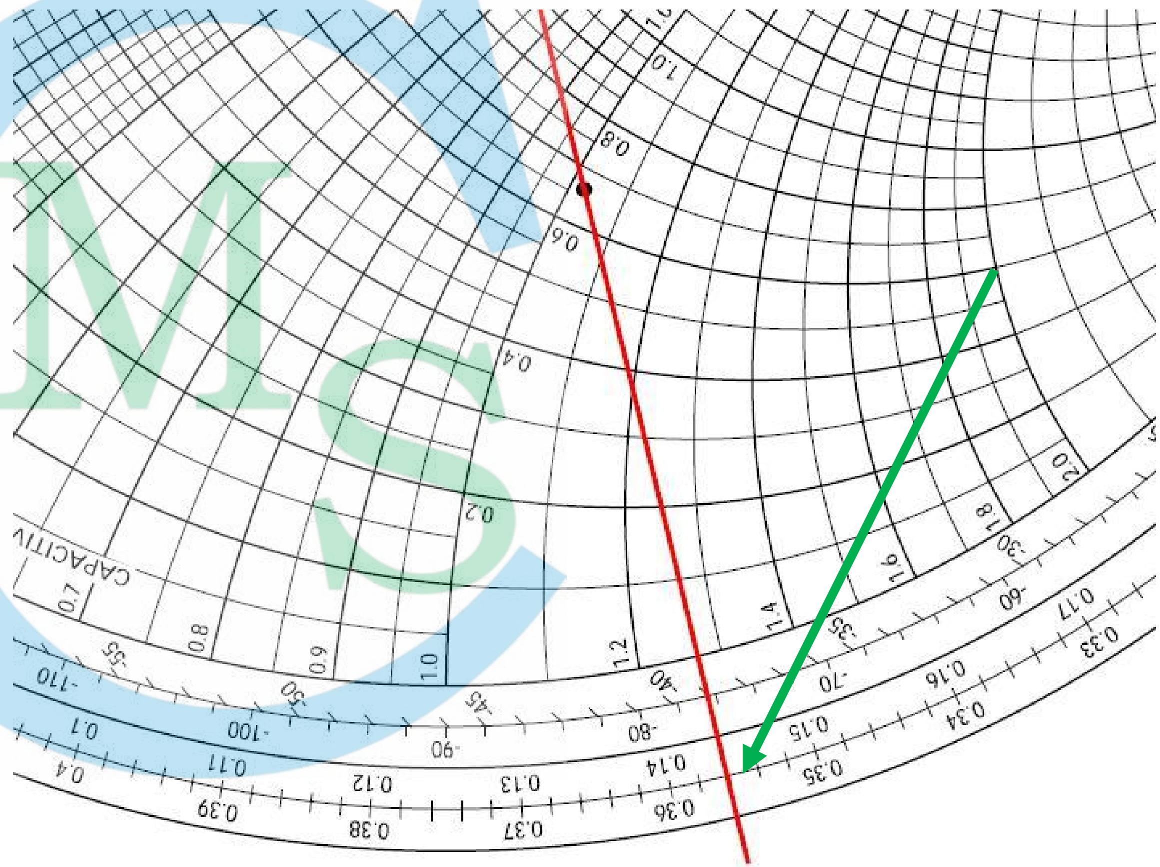
- Working with the same load as before, represented as *33-j51Ω* which normalized to a 50Ω system plotted as *0.66-j1.02Ω…* and staying with the same frequency of 14.2MHz…
- What would happen if we were to add a three-foot feedline into the system?
- We start by doing some math…

Predicting Impedance

- 3 feet = 0.916 meters $\left(\frac{36}{39.3}\right)$
  - How many wavelengths would that be?
    - $\lambda = \frac{300}{f_{MHz}} = \frac{300}{14.2} = 21.13m$
    - $\frac{0.916}{21.13} = 0.043\ wavelengths$
- We would then need to take that to the Smith Chart to see how it changes things…

Predicting Impedance

- The original plot falls at 0.356λ as can be seen in the graphic at right – the wavelength is shown by the outermost ring of the Smith Chart.

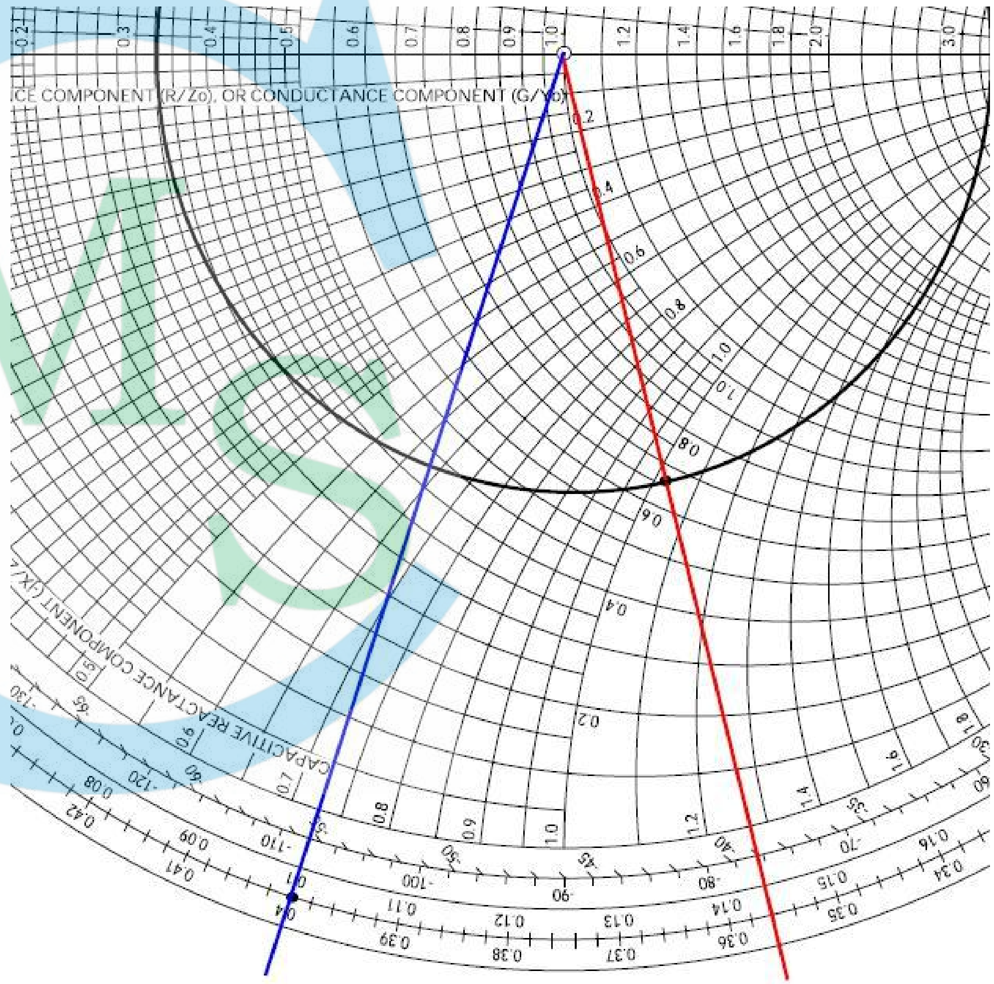


Predicting Impedance

- To predict the new impedance through the three-foot feedline section, we would need to add that wavelength fraction to the value read on the Smith Chart:
  - $0.356 + 0.043 = 0.399\lambda$
- Then we locate that value on the outer ring of the Smith Chart moving *clockwise* because we are moving from the load towards the generator (as labeled on λ ring)…

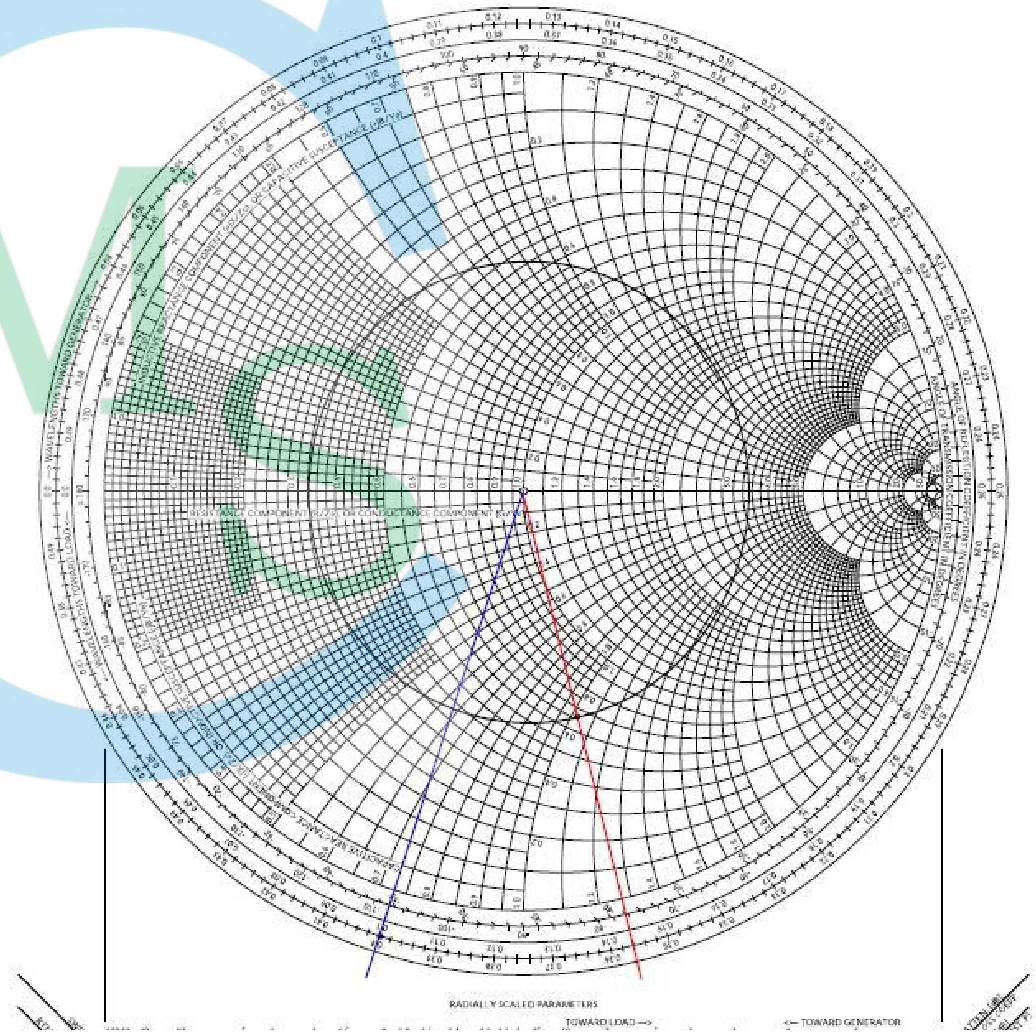
Predicting Impedance

- We then draw a line from that point on the outer ring to the center of the Smith Chart… but note that a circle has also been added.



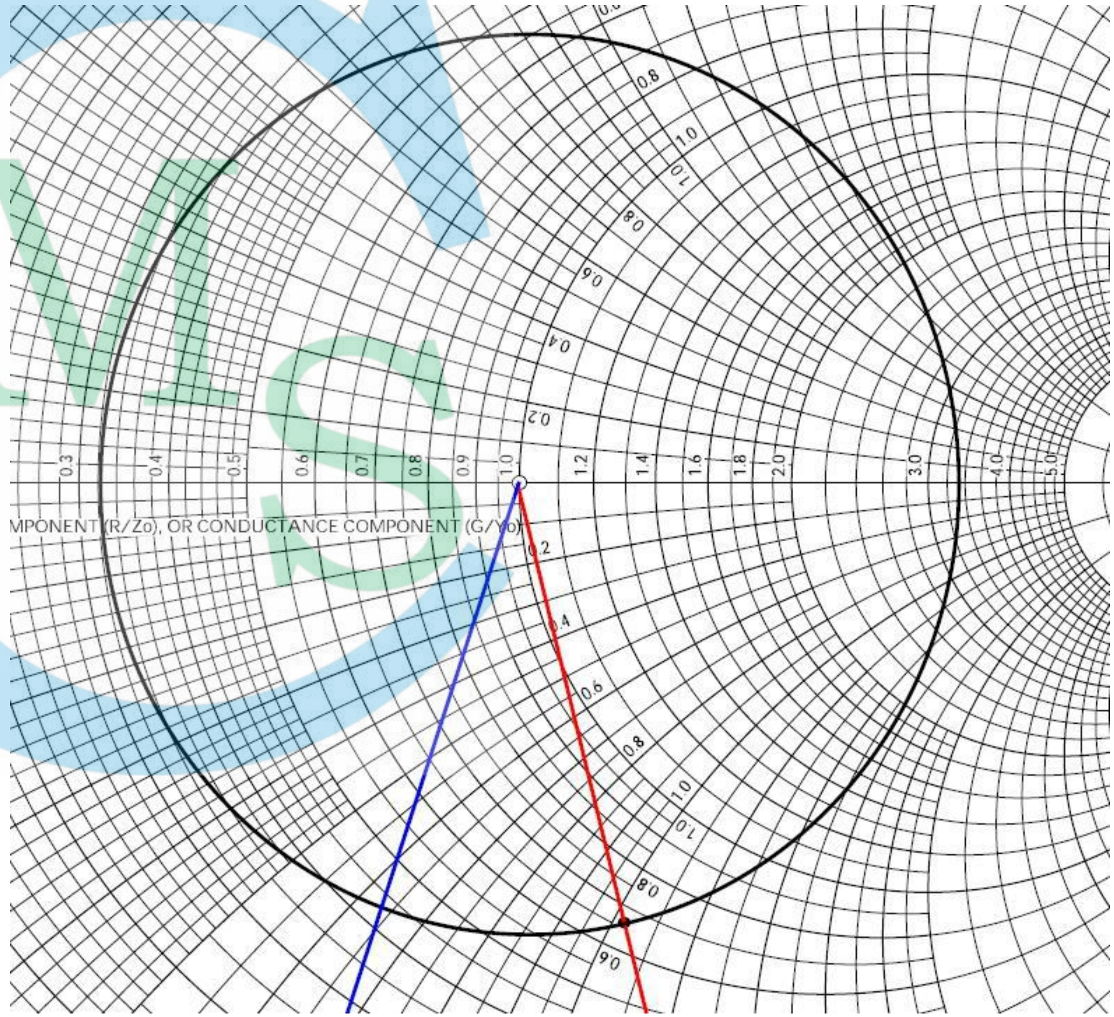
Predicting Impedance

- That circle is known as a *constant SWR circle* and it is centered at the Prime Center and passes through the original impedance plot point…



Predicting Impedance

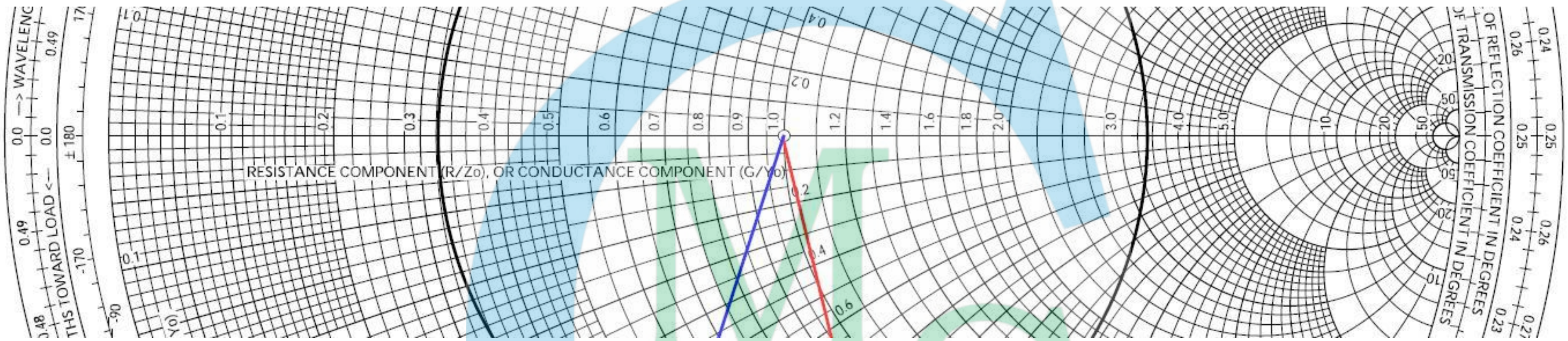
- All points that fall directly on that circle will represent points that have the same SWR, but will each have a different value of impedance until we come full circle.



Predicting Impedance

- Those different impedance values can be seen as – and are – the different impedance values that result from changes in feedline length.
- Looking carefully at the λ scale on the Smith Chart on the next slide, we can see that at the left side, there is a marking of 0.0λ, and at the right side, we have a marking of 0.25λ.
- Thus, it can be seen that a half circle on the chart equates to a quarter-wavelength, which means that a full circle represents a half wavelength.

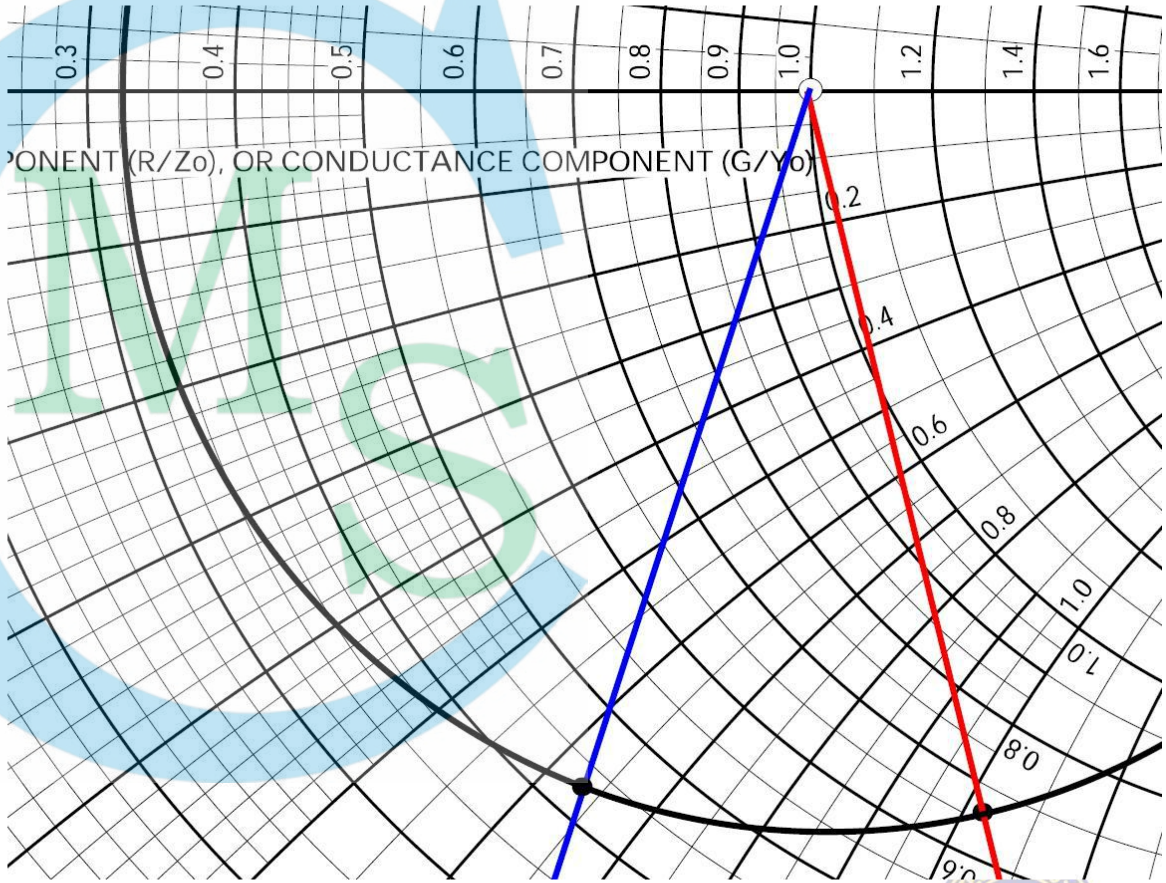
Predicting Impedance



- As we know from our study of basic radio theory, the feedline impedance repeats at each and every half-wavelength point along a feedline.
  - This concept is validated on the Smith Chart, as we have just seen.

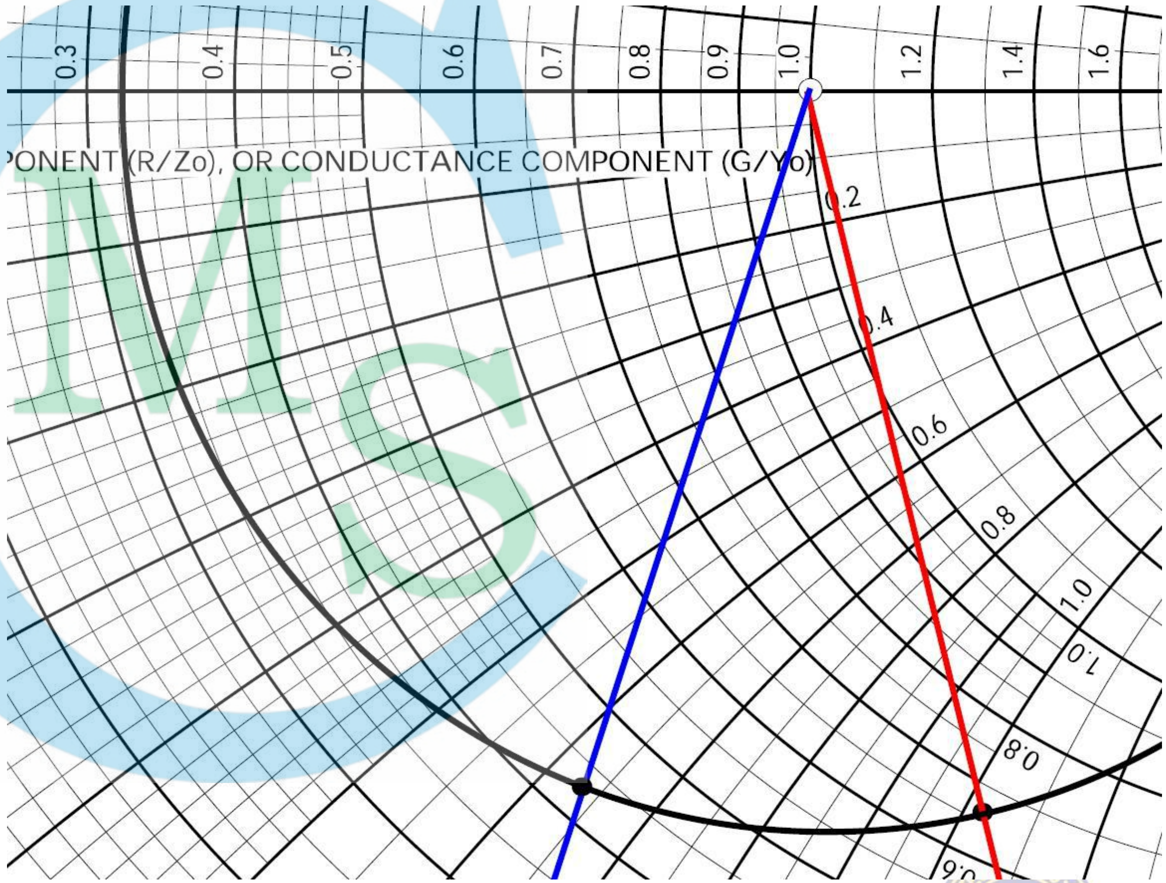
Predicting Impedance

- Our next step is to plot a point where the new (blue) line crosses the constant SWR circle, and then to read the impedance of that point.



Predicting Impedance

- The point appears to fall at about 0.43 on the resistance circle and about -0.63 on the capacitive reactance arc, so its value would be *0.43-j0.63Ω*



Predicting Impedance

- We would then have to normalize that plotted impedance back to its 50Ω value…
  - $(0.43 - j0.63) \times 50$ ...
  - $0.43 \times 50 = 21.5,\ and\ -0.63 \times 50 = -31.5$ ...
  - The resulting 50Ω impedance is *21.5-j31.5Ω*
- We can now see that adding a three-foot feedline changed the impedance from a value of *33-j51Ω* to a new value of *21.5-j31.5Ω,* but that the SWR did not change.

Common Application

- A common application of this concept might be as follows:
  - We know what the antenna system impedance as seen by the transmitter is, as we have measured that with an analyzer looking into the feedline at the transmitter end…
  - We know how long the feedline is…
  - We want to know what we would need in terms of a matching network that we can install at the antenna to reduce the antenna mismatch loss.

Common Application

- Start by reducing the feedline length to a fractional portion as follows:
  - Verify overall feedline length.
  - Calculate λ for the frequency of interest.
  - Divide the feedline length by the calculated λ.
  - Take the remaining partial wavelength and subtract any full *quarter-wavelengths* of that remainder.
  - Apply the final remainder to the Smith Chart.

Common Application

- For example, if the feedline is 377 feet long and the frequency of interest is 14.2MHz…
  - $\lambda = \frac{300}{14.2} = 21.13\, meters$ (14.2MHz wavelength)
  - $377\, feet = 114.91\, meters\, (377 \times 0.3048)$ (conversion)
  - $\frac{114.91}{21.13} = 5.438\lambda$ (feedline length in 14.2MHz wavelengths)
  - $0.438 \times 21.13m = 9.26m$ (length of remainder)
  - $\frac{21.13}{4} = 5.2825m$ (length of a 14.2MHz quarter-wavelength)
  - $9.26m - 5.2825m = 3.9775m$ (length of leftover portion)
  - $\frac{3.9775}{21.13} = 0.188\lambda$ (leftover length expressed in wavelengths)

Common Application

- Plot the original (measured) system impedance on the Smith Chart…
  - Remember to de-normalize the measured value.
- Using a compass, draw a constant SWR circle through the plot point with its center located at the Prime Center.
- Draw a line from the Prime Center through the plot point and continue through the λ ring.
- Note the value where that line crosses the λ ring.

Common Application

- *Subtract* the calculated change (0.188λ) from the noted value on the λ ring.
- Mark the result in the λ ring moving in a *counter-clockwise* direction because we are moving from the generator towards the load.
- Draw a line from that new mark to the Prime Center.
- Plot a point where that line crosses the constant SWR circle drawn earlier.
- Read the value of the impedance from the plot point location.

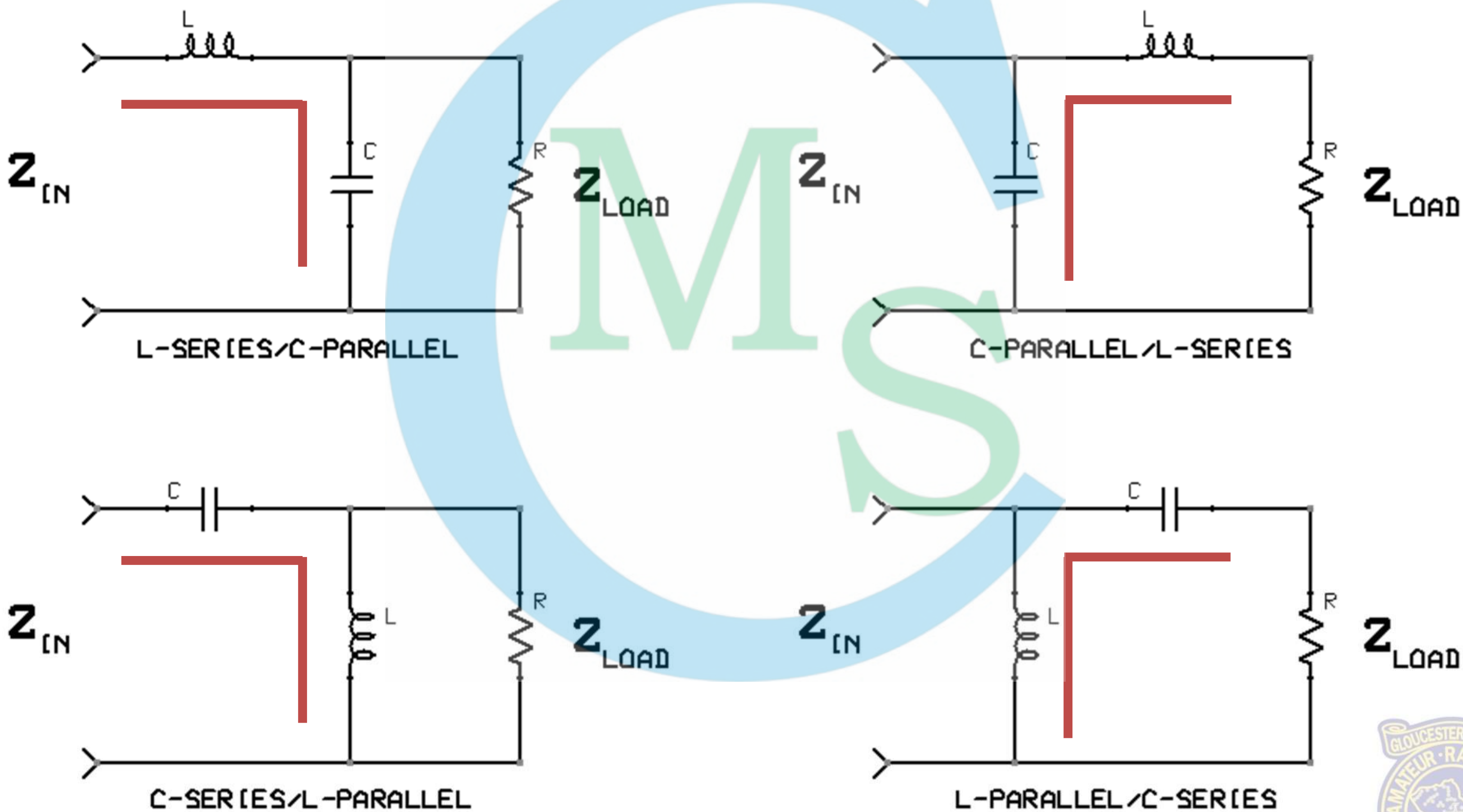
Common Application

- The value read from that plotted point will be the *load impedance* (at the antenna) as compared to the original measured impedance which was the total system impedance as seen by the transmitter.
- The antenna (load) impedance can be used to design and construct a matching network.
- The matching network will keep the SWR on the feedline near 1:1, minimizing SWR loss.

Matching Networks

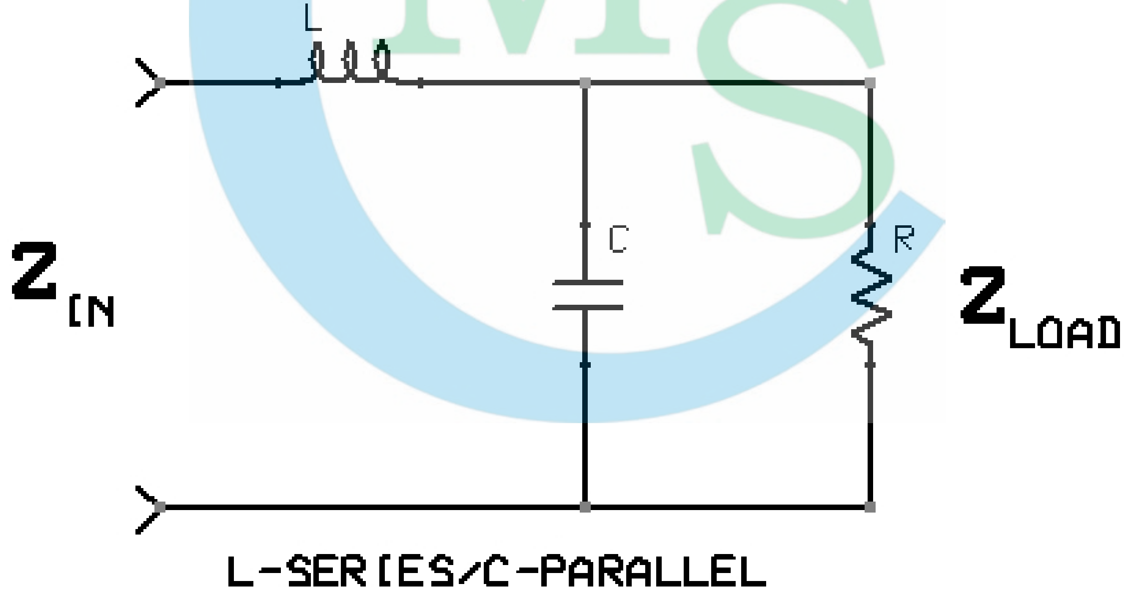
- The most frequently used impedance matching networks are those comprised of inductances and capacitances in various different physical arrangements.
- These arrangements are known by circuit descriptive names that indicate what the relative positions the elements have to each other and to the input and the load.
- Most common are the “L” matches, so called because of their physical circuit layouts.

Most Common "L" Matches



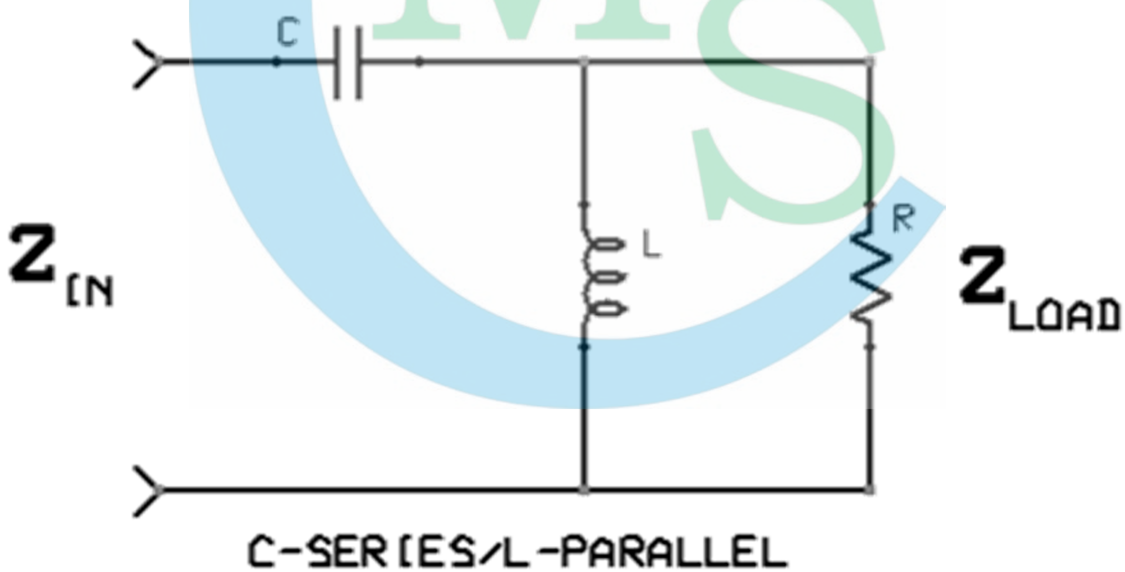
L_S-C_P Match

In the L-series/C-parallel match, the input is through a series inductance, with a shunt capacitance across the load.



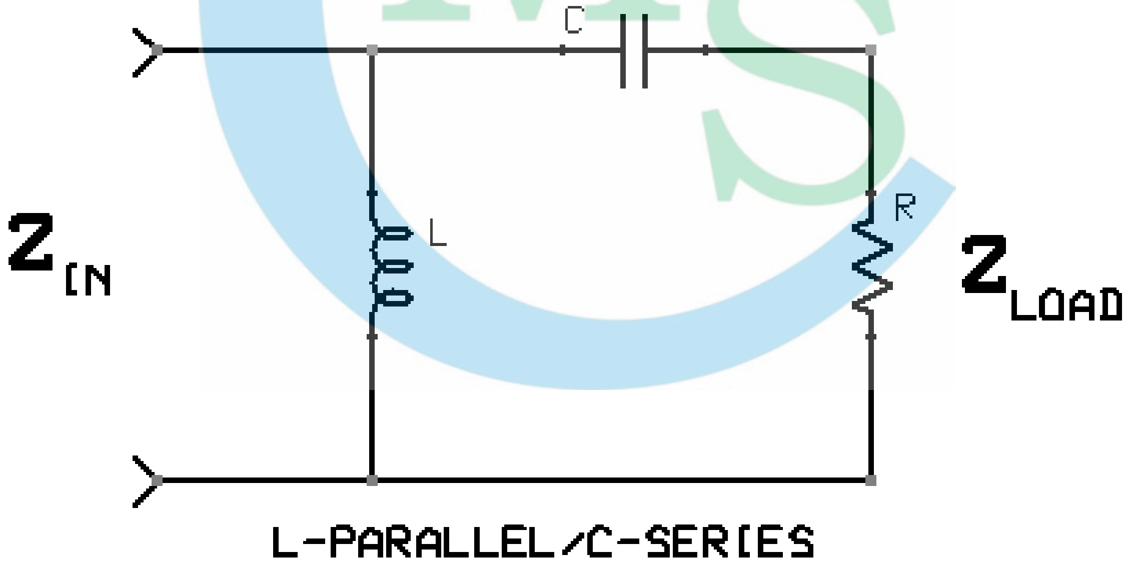
C_S-L_P Match

In the C-series/L-parallel match, the input is through a series capacitance, with a shunt inductance across the load.



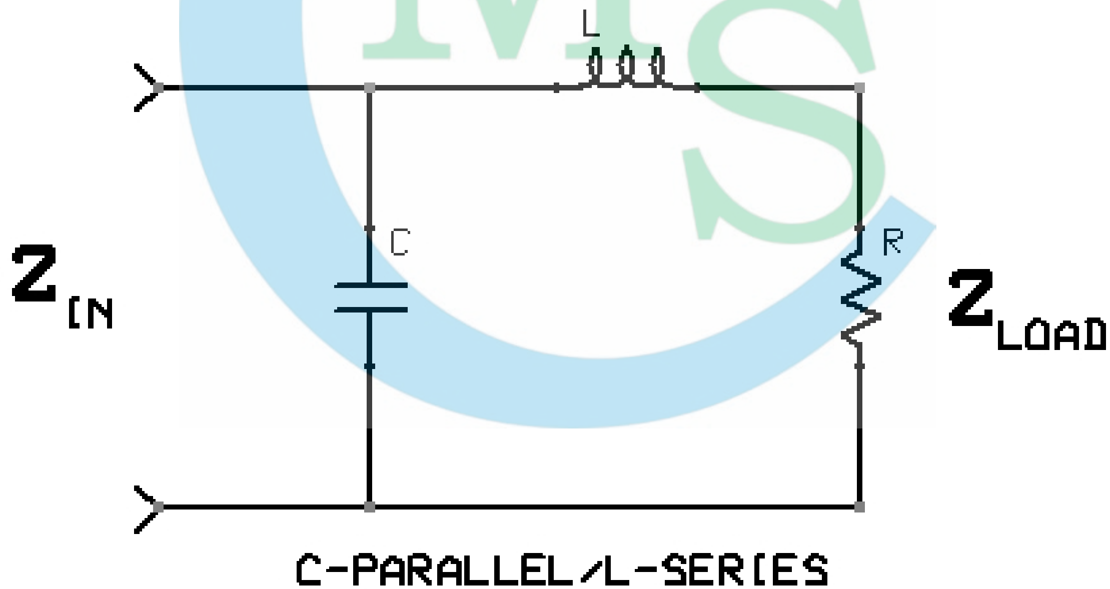
L_P-C_S Match

In the L-parallel/C-series match, the input is across a shunt inductance, followed by a series capacitance into the load.

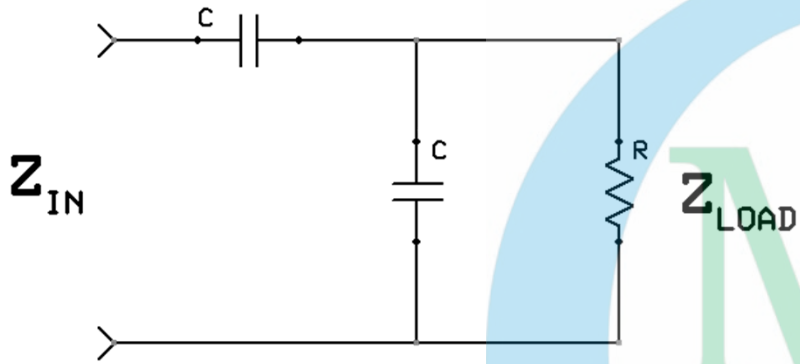


C_P-L_S Match

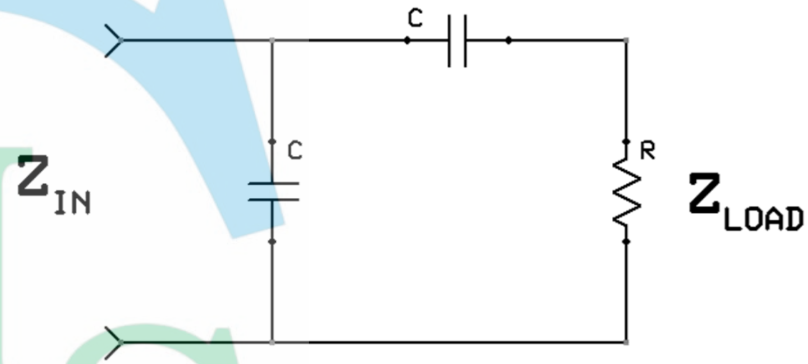
In the C-parallel/L-series match, the input is across a shunt capacitance, followed by a series inductance into the load.



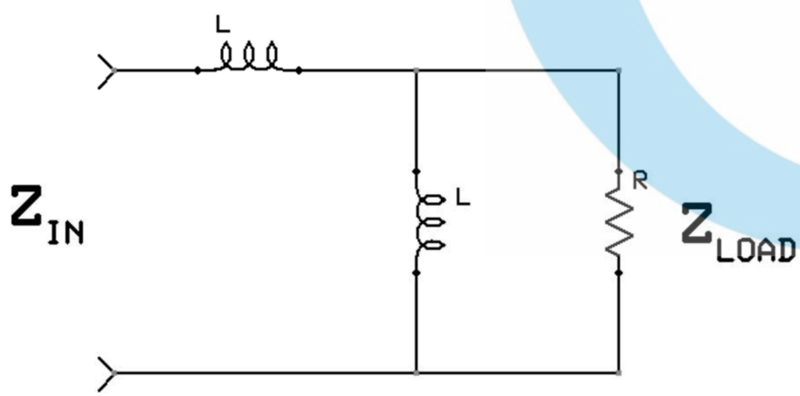
Less Common “L” Matches



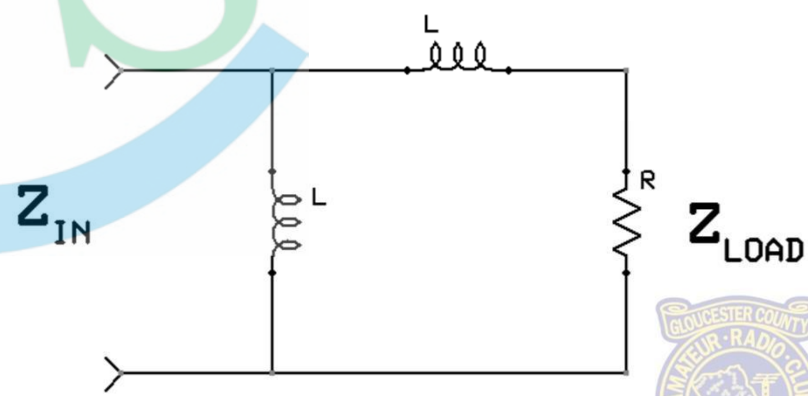
C-SERIES/C-PARALLEL



C-PARALLEL/C-SERIES



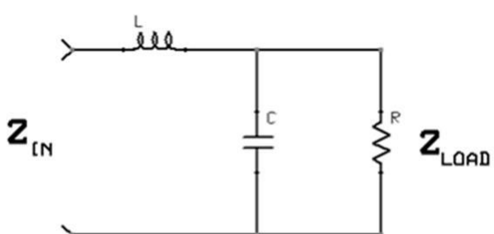
L-SERIES/L-PARALLEL



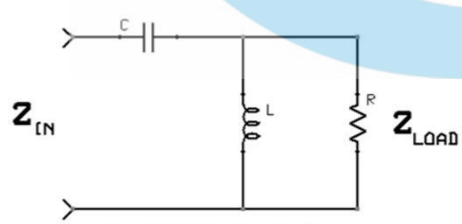
L-PARALLEL/L-SERIES

About the Circuits…

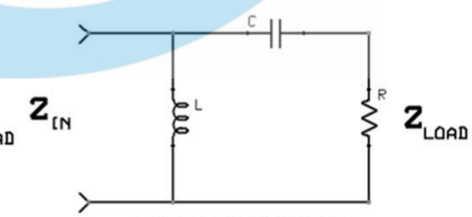
- Note that all of the matching circuits discussed here are inherently filter circuits.
- Knowing that, which of these matches are high-pass filters and which are low-pass filters, and why do you think so?



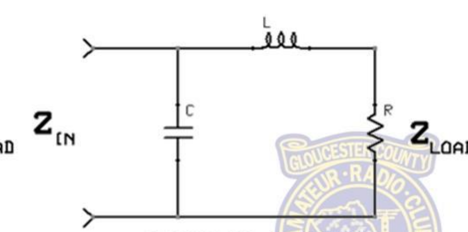
L-SERIES/C-PARALLEL



C-SERIES/L-PARALLEL



L-PARALLEL/C-SERIES



C-PARALLEL/L-SERIES

Series vs Shunt

- When we say that a circuit element is in "series", we mean that *the source current must flow through that element and then into the load*.
- When we say that a circuit element is in "shunt", we mean that *this element forms an alternate current path to ground (or the signal return point) that is parallel to the load*.

Back to the Smith Chart…

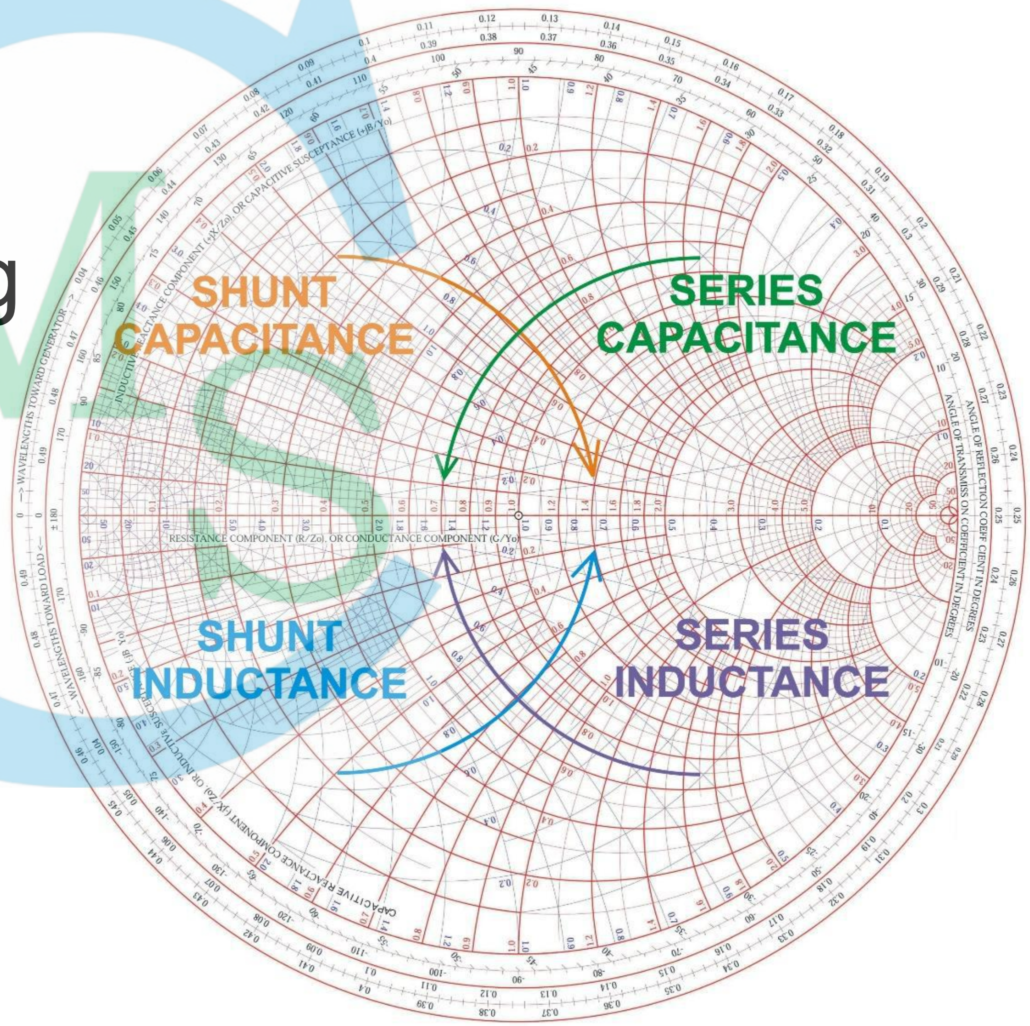
- When adding matching networks to a load, the effect of adding that element is different depending upon whether that element is added in series or in shunt to the load.
  - Adding a series element will shift the impedance along a reactance arc.
  - Adding a shunt element will shift the impedance along a admittance arc.
  - The direction depends on the element type.

Matching Element Effects

- A **series inductance** will shift the impedance *clockwise* along a *reactance* arc.
- A **shunt inductance** will shift the impedance *counter-clockwise* along an *admittance* arc.
- A **series capacitance** will shift the impedance *counter-clockwise* along a *reactance* arc.
- A **shunt capacitance** will shift the impedance *clockwise* along an *admittance* arc.

Matching Element Effects

- This graphic illustrates the effect of adding a correcting element in either series or shunt to the system load…
  - Shunt on admittance arcs
  - Series on reactance arcs



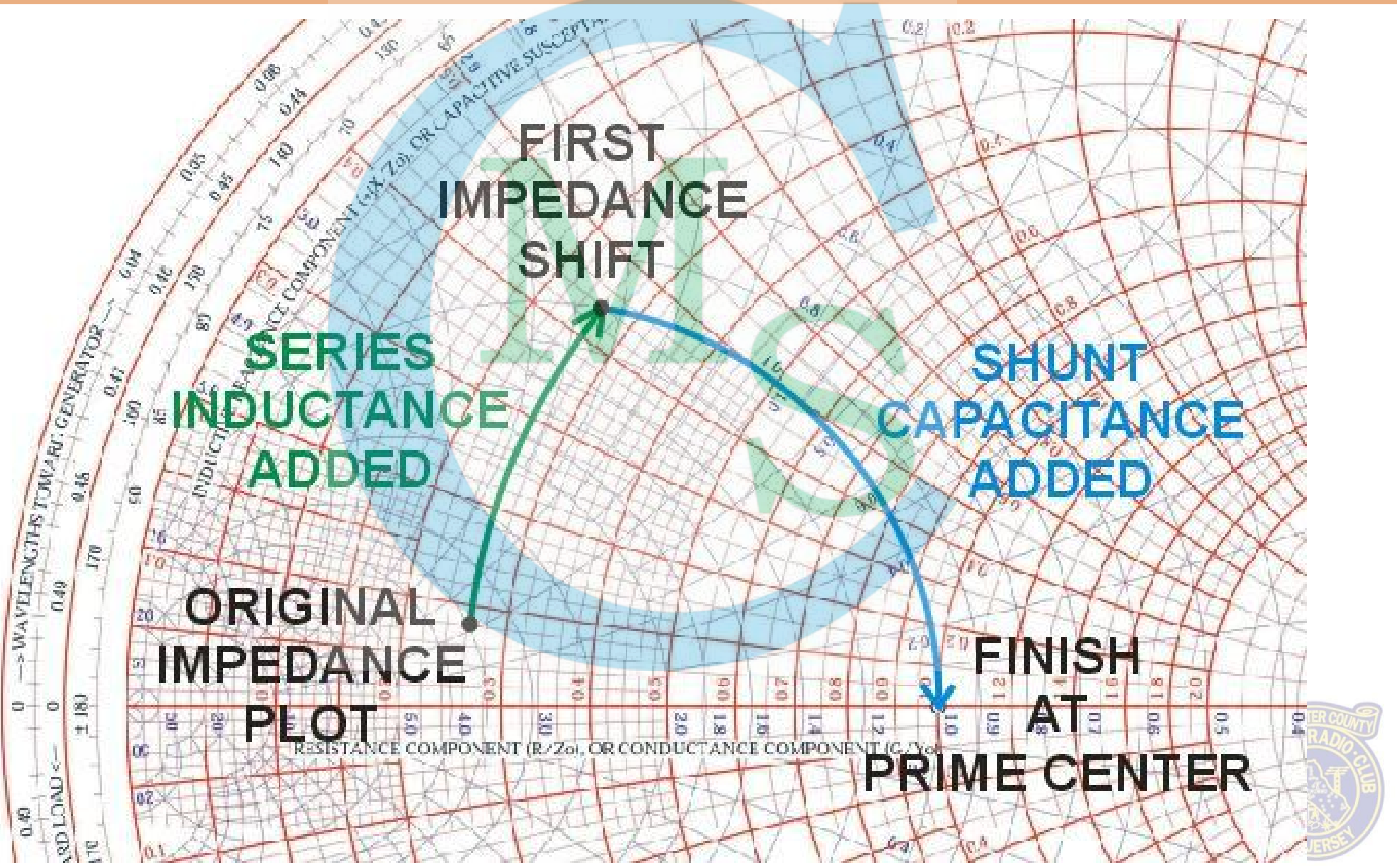
Matching Element Effects

- As a result, adding an inductive element will always shift the impedance "upward" towards and through or above the equator – "e**L**evate up" as a memory aid.
- Similarly, adding a capacitive element will always shift the impedance "downward" towards and through or below the equator – "**C**rash down" as a memory aid.

Matching Element Effects

- The object is to rotate the impedance on an arc to bring it to the equator, which is to say to the pure resistance line.
- Often, both inductive and capacitive elements will be added.
  - Each element will shift the impedance…
  - For example, we could use a series inductance to rotate an impedance that is plotted low above the equator on the left side up onto an admittance arc, and then use a shunt capacitance to rotate the impedance down along that admittance arc to the Prime Center.

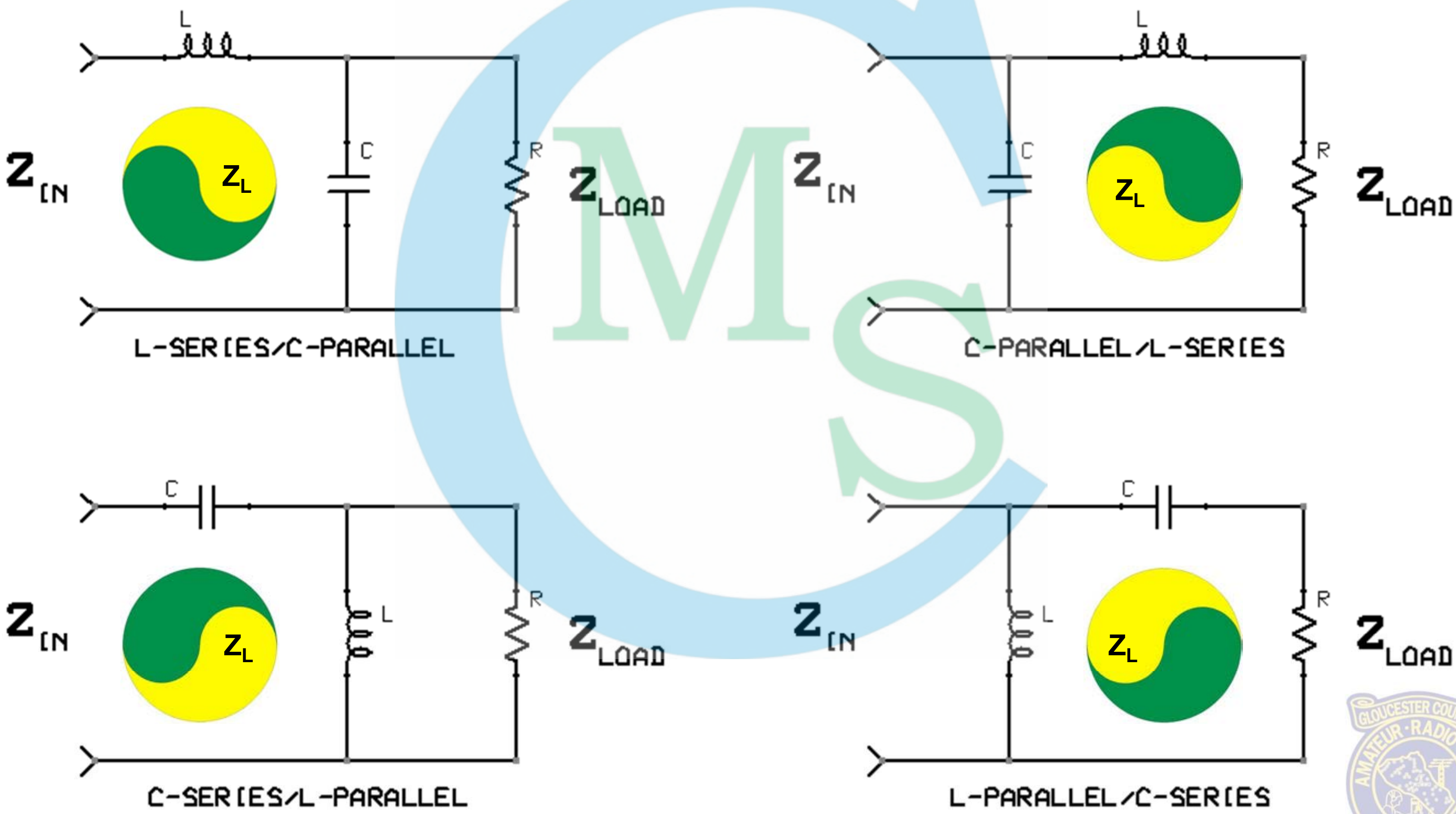
Example…


FIRST
IMPEDANCE
SHIFT
SERIES
INDUCTANCE
ADDED
SHUNT
CAPACITANCE
ADDED
ORIGINAL
IMPEDANCE
PLOT
FINISH
AT
PRIME CENTER
RESISTANCE COMPONENT (R/Zo), OR CONDUCTANCE COMPONENT (G/Yo)

Final Impedance

- Once the impedance is brought to the equator, the resistance can be corrected (if need be) to the system characteristic impedance value through addition of either a series (increasing) or parallel (decreasing) resistive element.
- Often, complete correction can be made with an optimal and carefully selected combination of "L" match network components.

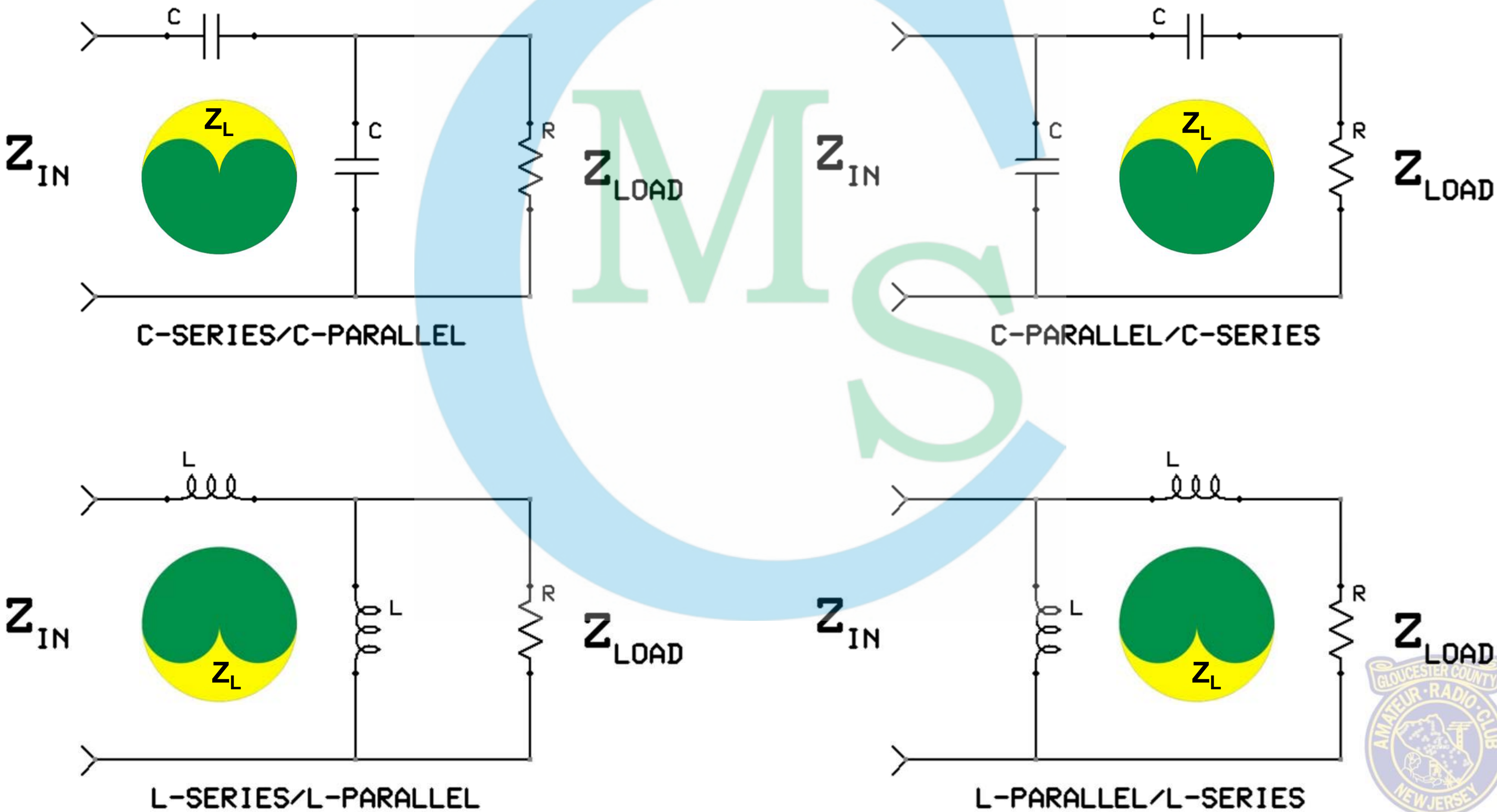
"L" Match Effectiveness



“L” Match Effectiveness

- Each “L” match arrangement can correct for load impedances only in certain specific regions of the Smith Chart.
- In the previous slide, the yellow regions depict those specific areas for each of the four common circuit arrangements.
- As any impedance in a yellow area can be corrected with an associated circuit, it is possible that different circuits will work for the same impedance condition.

"L" Match Effectiveness



"L" Match Effectiveness

- The same condition exists for the four capacitive/capacitive or inductive/inductive "L" match arrangements.
- Again, the yellow areas are those regions for which those individual circuits will be effective in correcting impedance mismatch.
- Note that these regions are considerably smaller than in the more common circuits.

Before We Design…

- The Greek letter *delta* (Δ) is used to signify or indicate a change in a value.
  - If we use the symbol Δ_X, we are referring to an amount of change to the value signified by X, or reactance.
  - If we use the symbol Δ_B, we are referring to an amount of change to the value signified by B, or susceptance.
  - These symbols will be used in the next slide(s).

Design the Match…

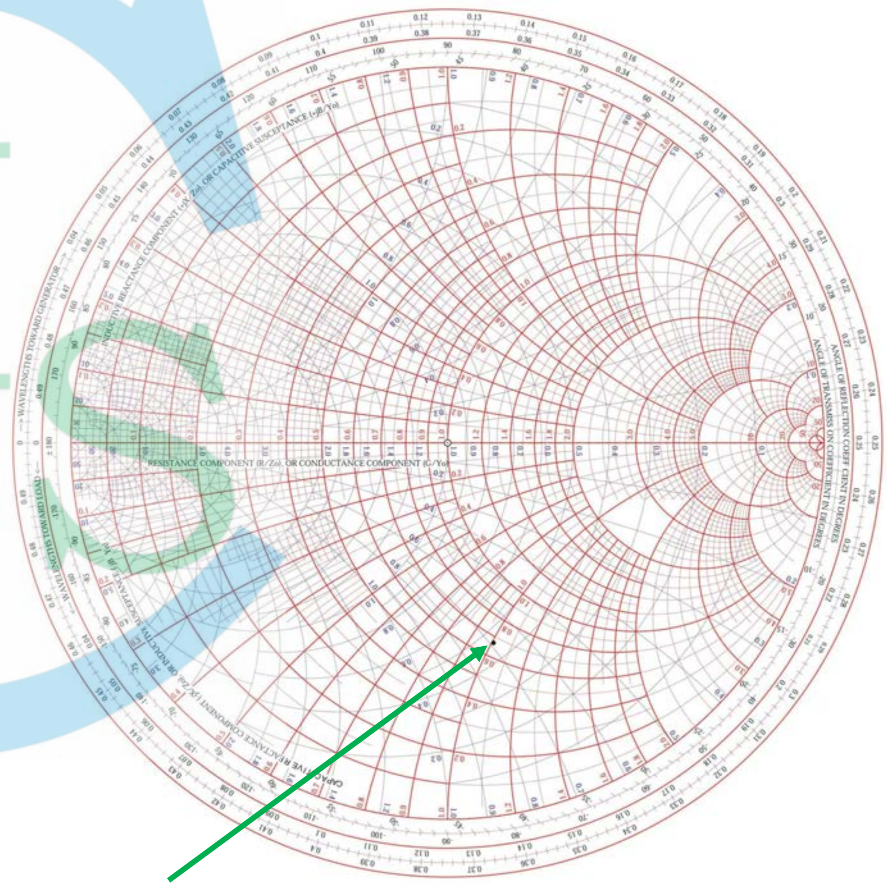
- Start by plotting the load impedance (Z_L).
- Add either a series or shunt inductance or capacitance to rotate that plot to either the unity resistance ($R = 1$) circle or the unity conductance ($G = 1$) circle.
- Record the change as either Δ_X or Δ_B.
- Add either a series or shunt inductance or capacitance to rotate the (moved) plot along the unity resistance or unity conductance circle until the Prime Center is reached.
- Record that change as an additional Δ_X or Δ_B.

Design the Match…

- Compute the inductance and capacitance values needed.
- Equations needed:
  - $X_C = \Delta_X \times 50 \quad or \quad X_C = \frac{1}{\Delta_B} \times 50$
  - $X_L = \Delta_X \times 50 \quad or \quad X_L = \frac{1}{\Delta_B} \times 50$
  - $C = \frac{1}{2\pi f X_C}$
  - $L = \frac{X_L}{2\pi f}$

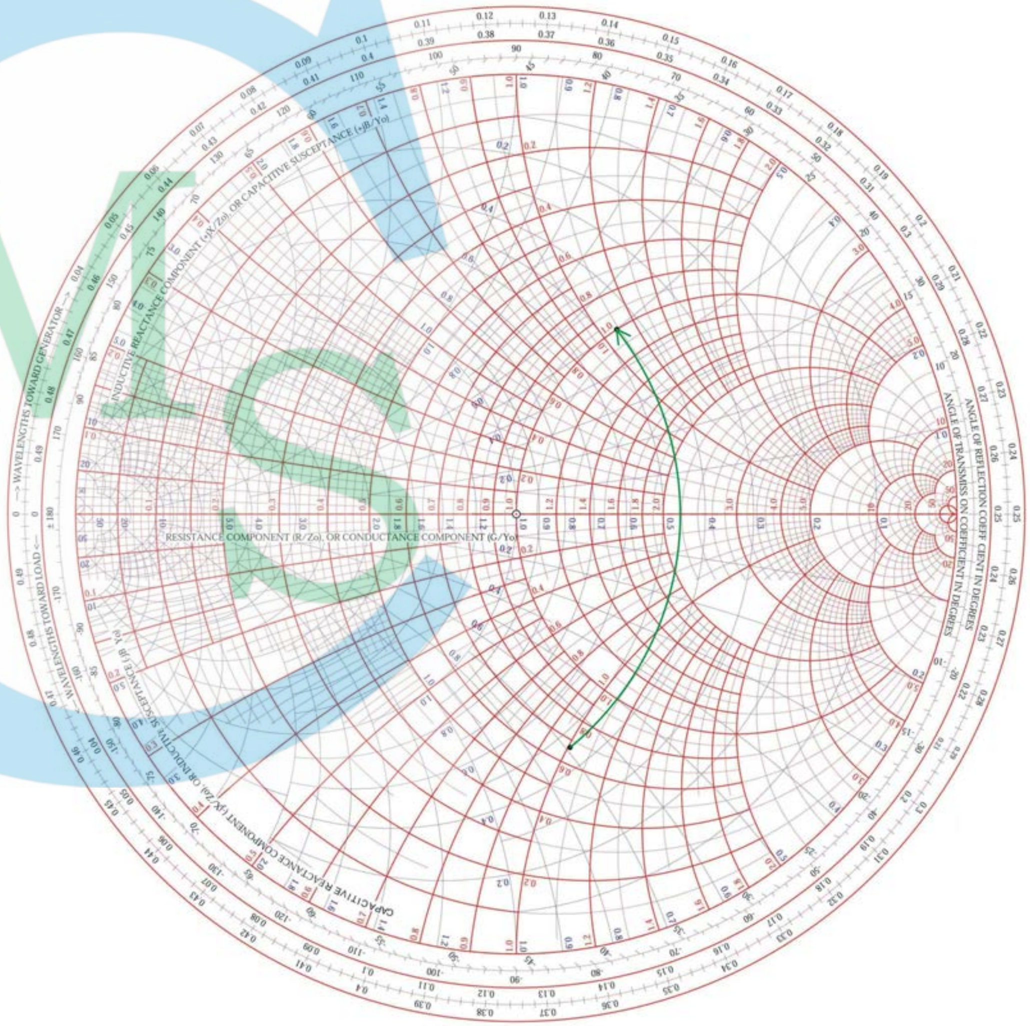
Example

- We are going to use the same impedance as we used earlier, $33\text{-}j51\Omega$, which we de-normalize to $0.66\text{-}j1.02\Omega$.
- Because of where this impedance falls, the best "L" match to use will be the C_S-L_P match.
    - This match will rotate the plot CCW first, then CW to the Prime Center.



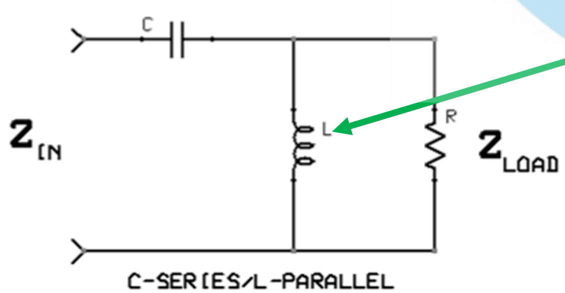
Example

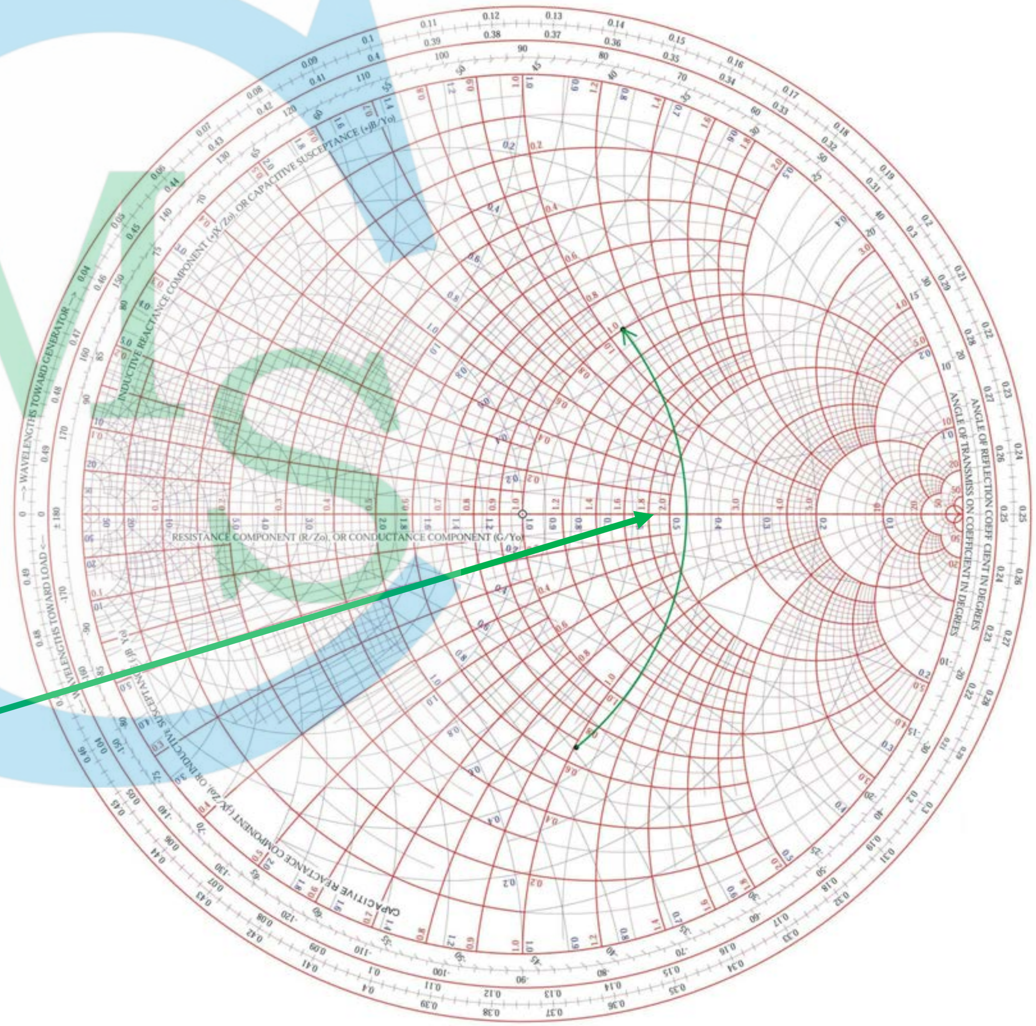
- We rotate the plot along the admittance arc on which it falls until we reach the unity resistance circle above the real axis.
- Then we note the ΔB (susceptance change) value that resulted.



Example

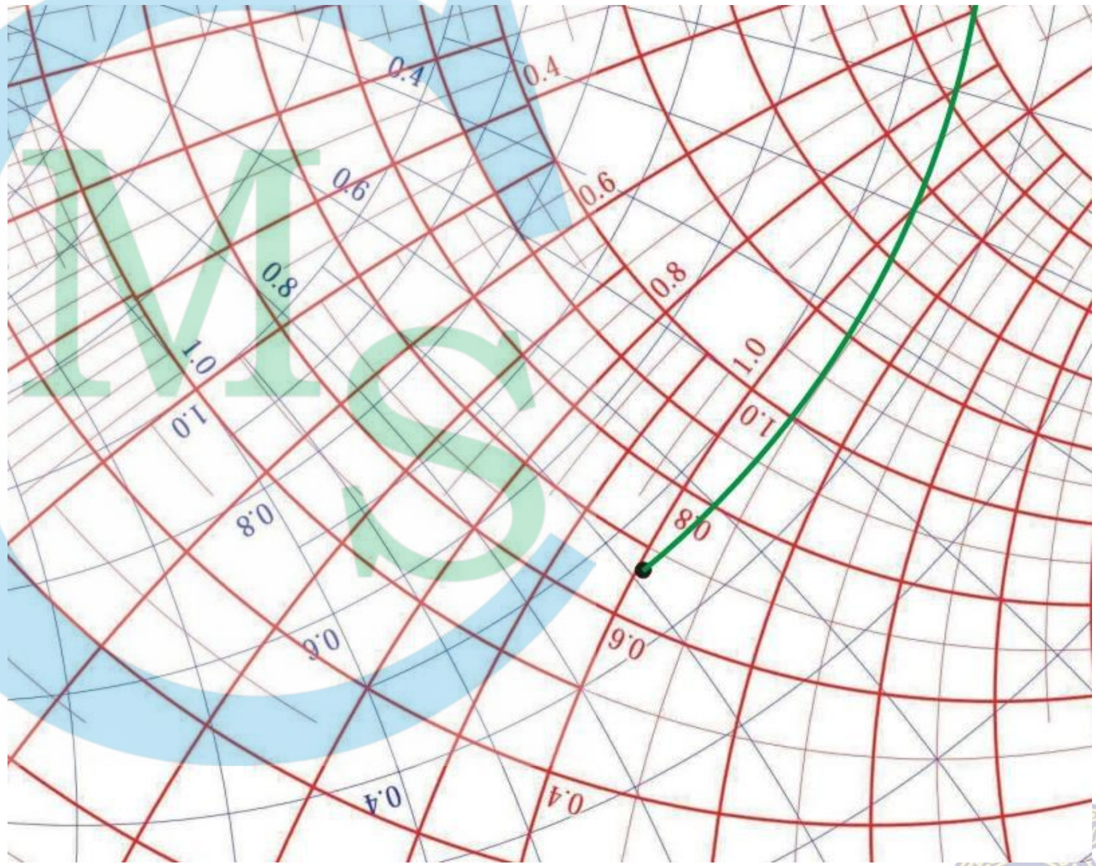
- The "L" match in use is the C_S-L_P match, and we are starting from the load, so the first component seen is the inductance…





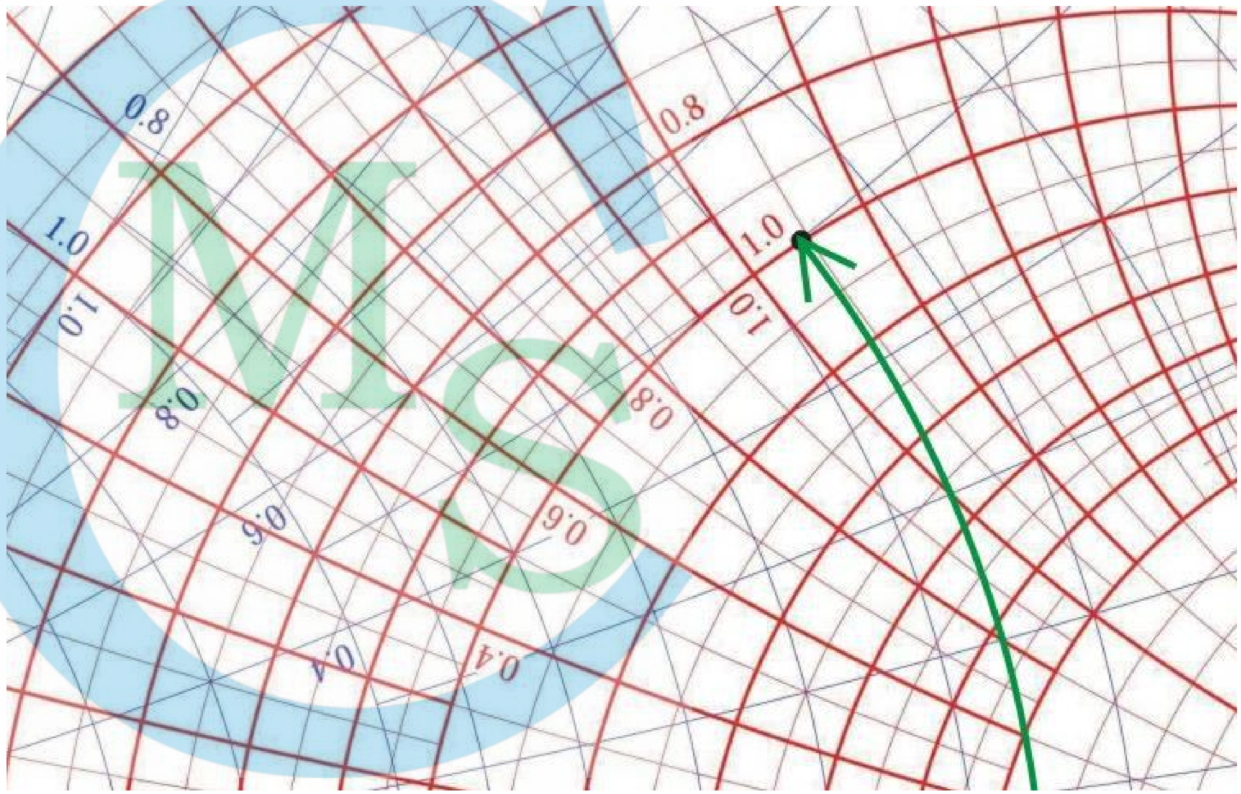
Example

- The original plot point is located on the -0.465 admittance arc – between the -0.4 and -0.5 arc lines on the chart… so we'll figure it to be -0.465 partial.



Example

- The "moved" plot point is directly on the 0.5 admittance arc… so it will count as an 0.5 partial value.

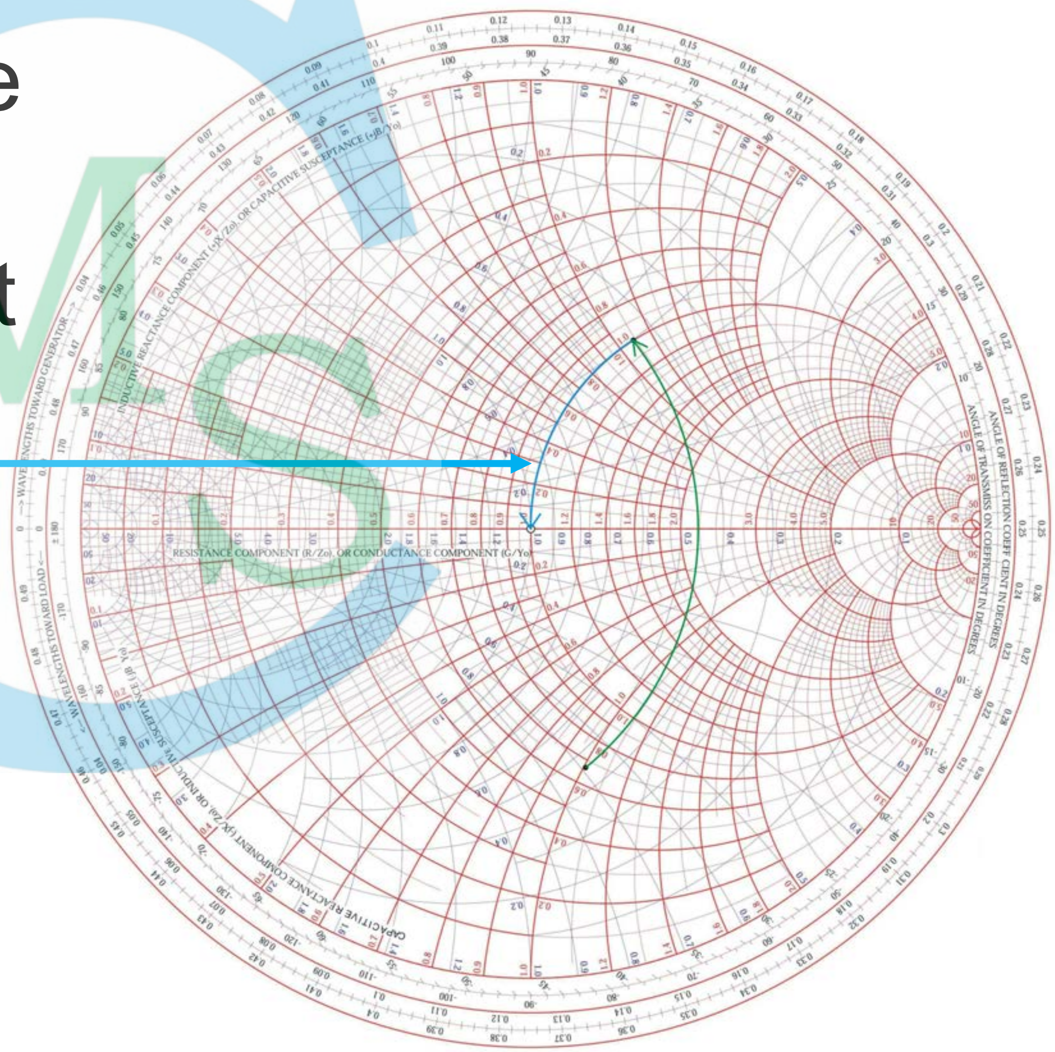


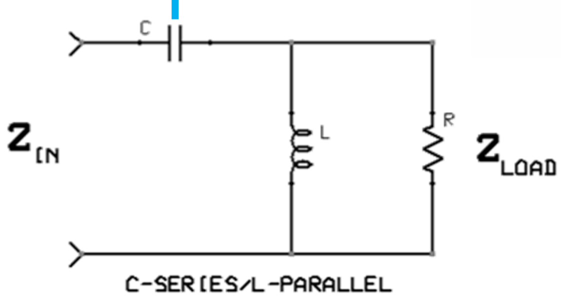
Example

- These two partial values, added together, produce a total Δ_B value of 0.965.
- Using the same frequency (14.2MHz) as earlier, we can now compute the needed shunt inductor for the matching circuit as follows:
  - $X_L = \frac{1}{\Delta_B} \times 50 = \frac{1}{0.965} \times 50 = 1.04 \times 50 = 52\Omega$
  - $L = \frac{X_L}{2\pi f} = \frac{52}{6.28 \times 14{,}200{,}000} = \frac{52}{89{,}176{,}000} = 583nH$
  - Thus, the parallel or shunt inductance for our "L" match will be 583nH.

Example

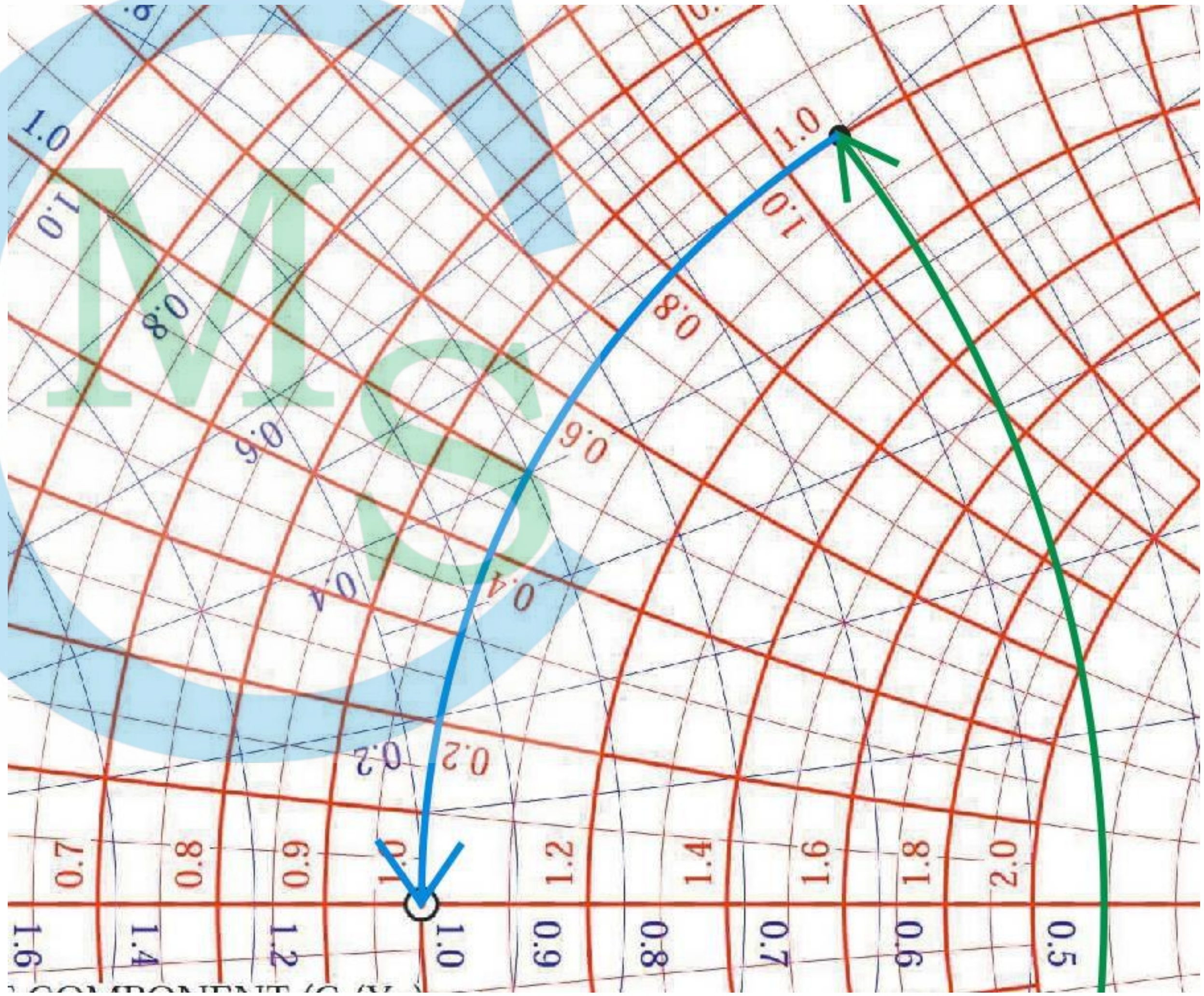
- The capacitance is the next component seen in the “L” match, and it brings us to the Prime Center of the chart…





Example

- In this case, the rotation spans a Δ_X of 1.09, as the point is just short of the reactance arc at 1.1, and it then spans the distance to the Prime Center at zero reactance.

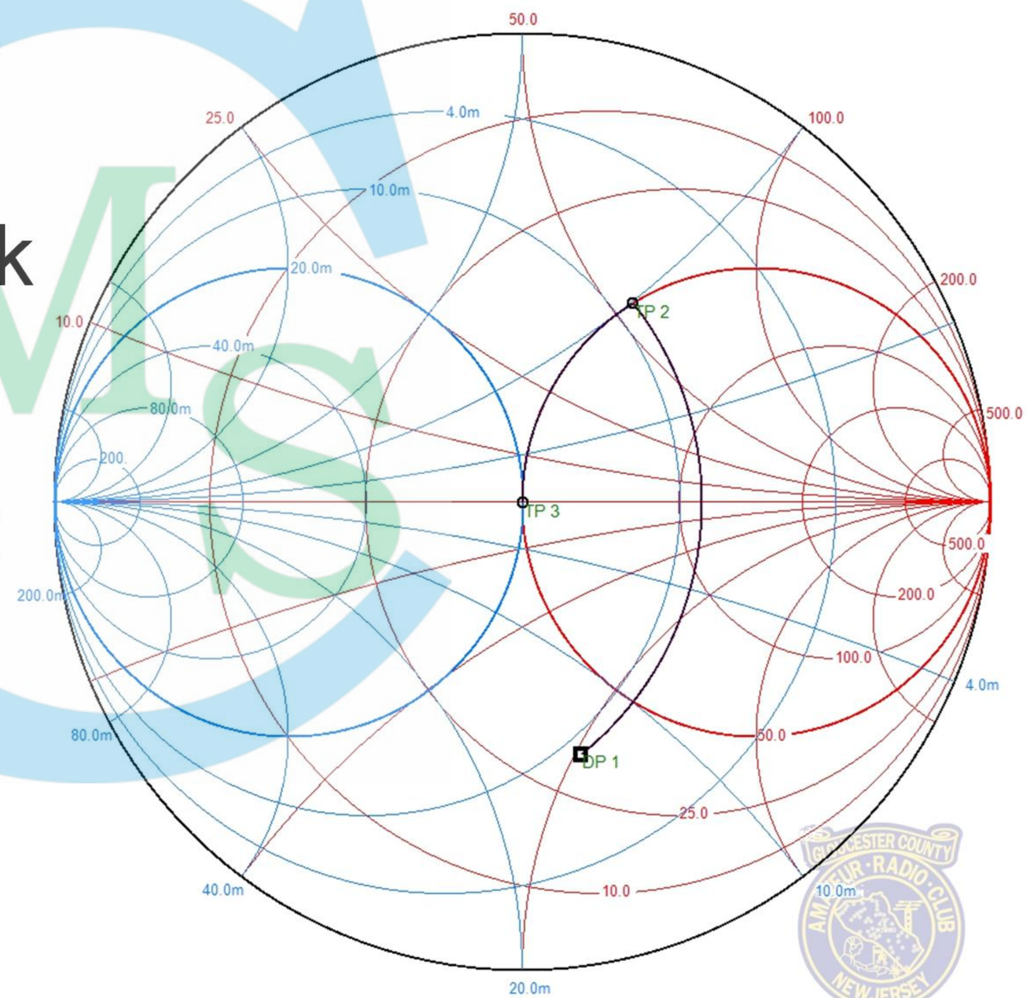


Example

- With a Δ_X of 1.09, we can now calculate the required capacitance for the "L" match…
  - $X_C = \Delta_X \times 50 = 1.09 \times 50 = 54.5\Omega$
  - $C = \frac{1}{2\pi f X_C} = \frac{1}{6.28 \times 14{,}200{,}000 \times 54.5} = 2.057^{-10}$
  - $2.057^{-10} = 0.0000000002057 = 205.7pF = 206pF$
  - Thus, the series capacitance required for our "L" match is 206pF.

Seen Another Way…

- This is the solution of the original complex impedance would look like when resolved using the *Smith v4.1* software (more about this later).
- Note the two arcs of correction created by adding reactances.



An Additional Resource

- There is a freeware utility called *QuickSmith v4.5* for Microsoft Windows that is available online.
  - ***Unfortunately***, *this application will not run on the 64-bit versions of Windows, nor on 64-bit machines.*
- While not a complete Smith Chart application, it nonetheless does an adequate job when it comes to helping with matching network design and associated calculations.
- It is ***not*** available for Mac or Linux machines.
- Download at:

https://quicksmith.software.informer.com/download/

The 64-Bit Alternative

- For those who are interested in a workable solution for the 64-bit environments, there is a different software application available:
  - A gentleman named Fritz Dellsperger has made his product *Smith v4.1* available to the community.
    - This is ***<u>not</u>*** freeware – license cost is $80 for hams and students, but it costs $120 for businesses and schools.
    - I have used this software – it is what you saw earlier when I simulated the matching filter design.
    - ***It is well worth the minimal cost for what it can do!***

Smith v4.1

- Download the software at:
  - http://www.fritz.dellsperger.net/downloads%20Smith/Setup%20Smith%20V4.1.0.0.zip
  - Install to your system to try the software
    - Demo version has limits and cannot do any file saves
  - License a copy if you are interested enough that you want a fully working installation.

In Conclusion…

- While it may seem as if we have really gone in depth here, we have in reality barely scratched the Smith Chart surface.
- If interested in further exploration, an excellent resource is a book authored by Phillip H. Smith, the Smith Chart inventor:
  - *Electronic Applications of the Smith Chart (In Waveguide, Circuit, and Component Analysis)*
    - Original copyright 1969 by McGraw-Hill Publishing
    - Noble Publishing edition © 1995

Questions?

Please address any questions to chris@ad2cs.com