Smith Charts & Impedance Matching

RVARC Club Meeting – April 1, 2010

Tom McDermott, N5EG

Outline

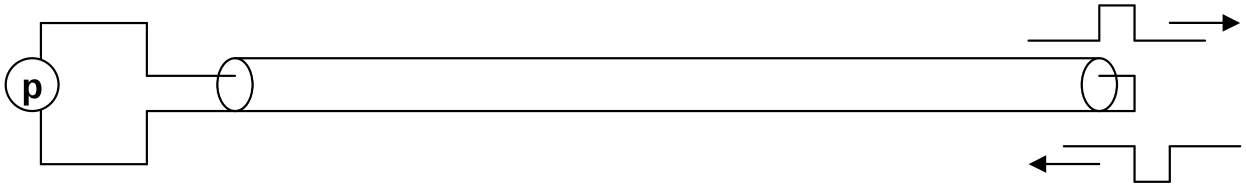
- Transmission Lines & Reflections
- Ways to visualize impedance
- Graphical Impedance Matching
- Example

Transmission Line

- Has ‘characteristic impedance’ (sometimes called ‘surge impedance’).
  - Typical ham line is near 50 ohms.
    - Actual line varies. One measured recently was 51.5 – j0.6 ohms.
    - Below about 1 MHz, the impedance changes dramatically.
  - 75 ohm line is also commonly available.
- Loss is frequency-dependent.
  - Roughly $Loss = k_1 f + k_2 \sqrt{f}$

Pulse – shorted load

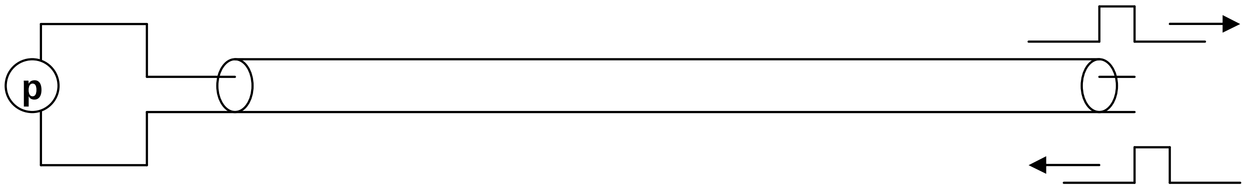
- Line reflection is easily seen using pulses.
  - Boundary condition at the load determines behavior.



  - The voltage at a short must be zero. The current travels through the short and reverses direction.
  - Equivalent to launching an inverted pulse from the opposite direction.
  - Called a “reflection”

Pulse – open load

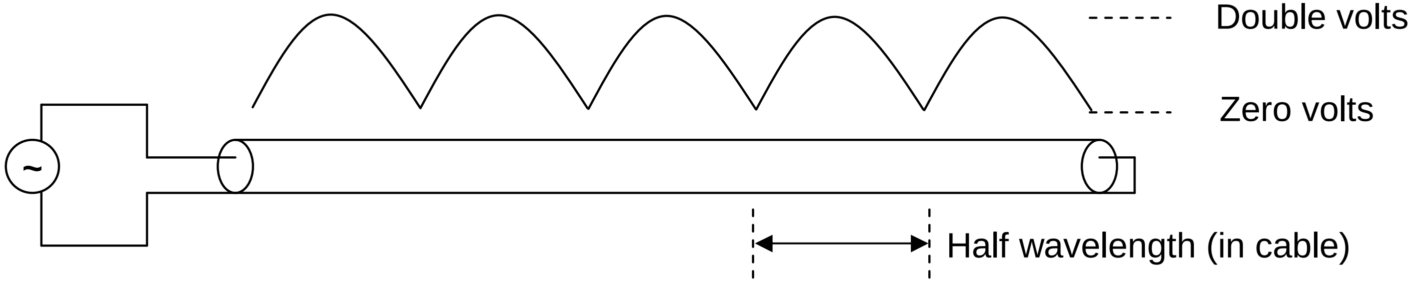
- Line reflection is easily seen using pulses.
  - Boundary condition at the load determines behavior.



  - The current through an open must be zero. Equivalent to launching a reverse canceling current. The voltage at the open thus doubles.
  - Equivalent to launching a same-polarity pulse from the opposite direction.
  - Called a “reflection”

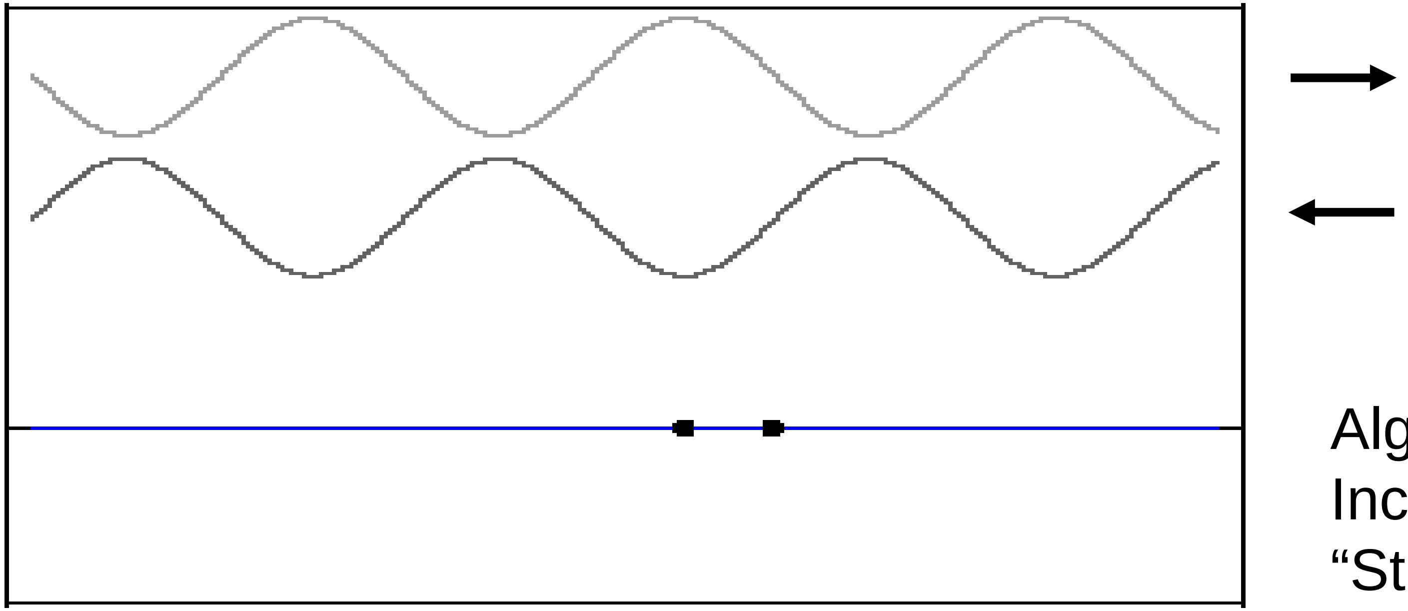
Reflections – sine waves

- When transmission line is terminated in something other than it's characteristic impedance, a reflection is generated at the discontinuity.
- The sum of the forward-wave and the reflected-wave add up in phase and out of phase at various points on the line.
  - At maximum reflection, the forward and reflected waves are the same amplitude.
  - The sum of the two in-phase is ±2. The sum of the two at quadrature phase is zero.
  - The ratio: maximum value / minimum value is called the Standing-Wave-Ratio – or SWR or S.
  - At maximum reflection, S = infinite (2 divided by zero).



Standing Wave from reflection

100% reflection, shorted load



Incident Wave

Reflected Wave

Algebraic Sum of
Incident + Reflected
“Standing Wave”
(Animated).

Lots of different ways to view the same sine wave reflection

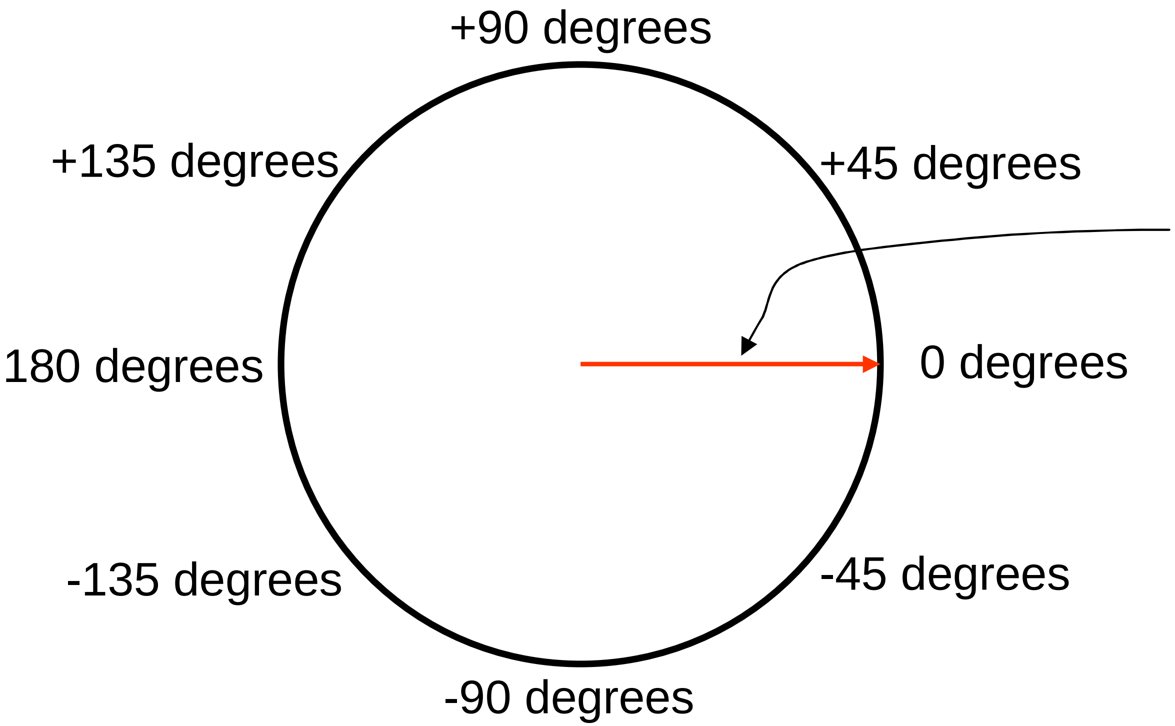
- The magnitude of the reflection, and the phase of the reflection compared to the magnitude and phase of the incident wave (rho, S11).
- The resulting maximum divided by minimum (SWR).
- The loss of the reflected wave compared to the incident wave (return loss).
- The equivalent load impedance that would have produced the same reflection (Zin).

Resonance

- A load is *resonant* when the phase of the reflected voltage at the load is exactly in-phase or exactly-out of phase with the incident voltage.
  - The reflection takes time to travel back up the cable, the reflection phase angle changes compared to the source at the generator.
  - A resonant load thus produces a reflection at the generator that may or may not be in-phase with the generated signal.
  - Thus, the generator may or may not see resonance even from a resonant load.
- If there is no reflection (cable is terminated in it’s characteristic impedance) then the cable is *matched* to the load.
  - The generator always sees a matched condition because there’s no reflection.

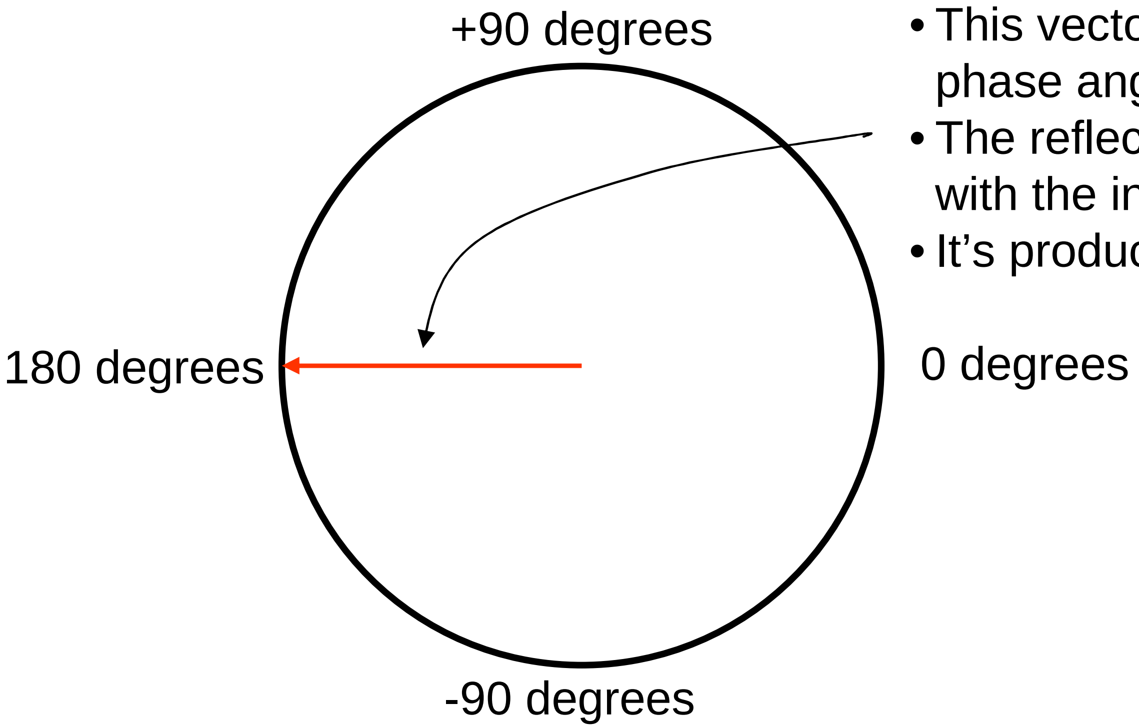
Reflection – polar view

- We can describe the reflection as a *polar vector*. The *length* of the vector is the magnitude of the reflection, the *direction* of the vector is the phase angle of the reflected voltage – both compared to the incident voltage.



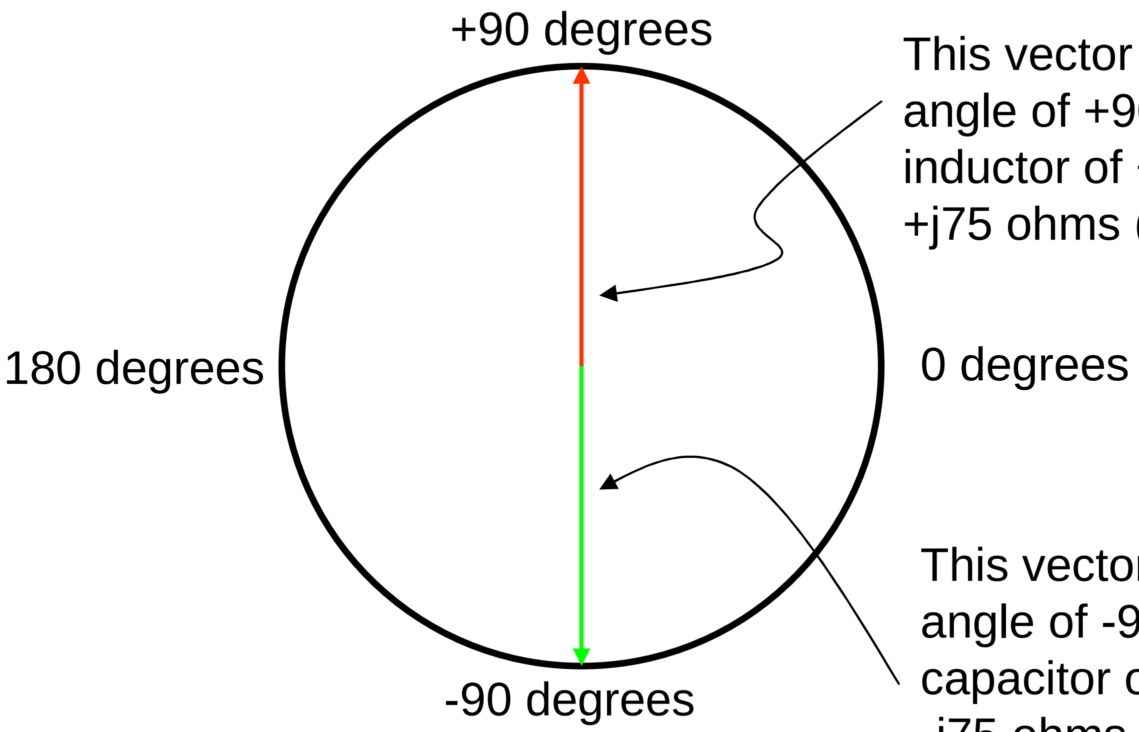
- This vector has a length of one, and a phase angle of zero degrees.
- The reflection is in-phase with the incident wave.
- It’s produced by an open circuit load.

Polar vector – examples



- This vector has a length of one, and a phase angle of 180 degrees.
- The reflection is exactly out-of-phase with the incident wave.
- It’s produced by a short circuit load.

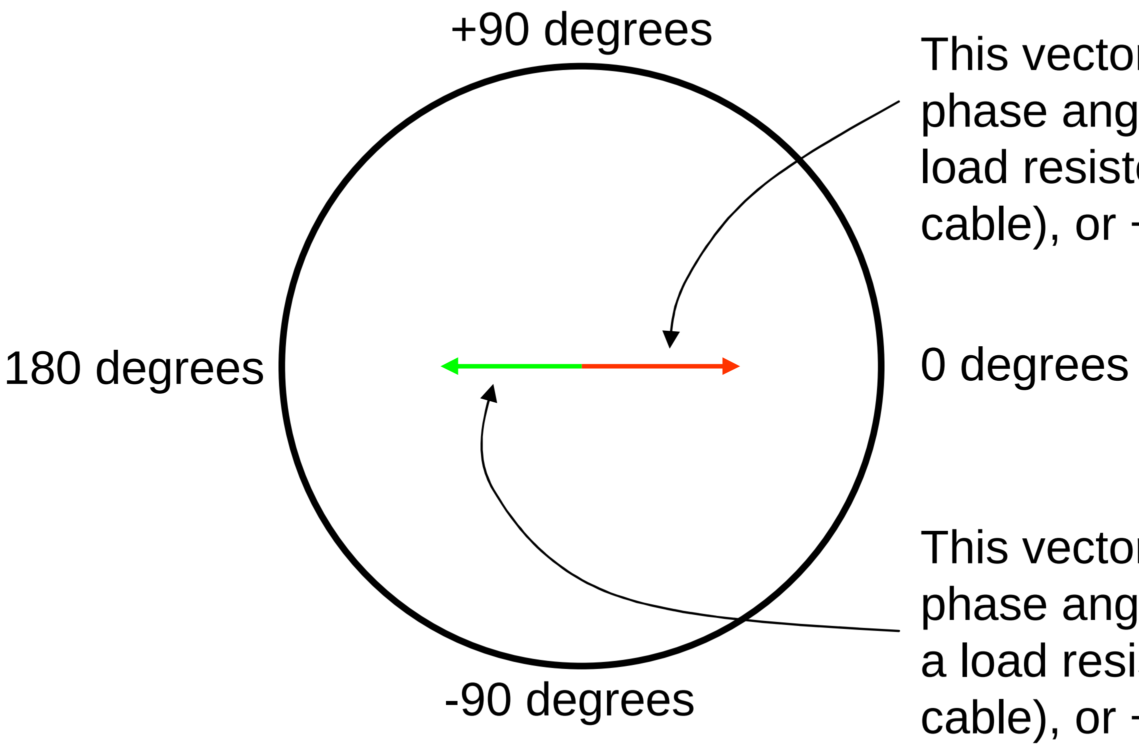
Polar vector – examples



This vector has a length of one, and a phase angle of +90 degrees. It’s produced by a load inductor of +j50 ohms (for 50 ohm cable), or +j75 ohms (for 75 ohm cable).

This vector has a length of one, and a phase angle of -90 degrees. It’s produced by a load capacitor of -j50 ohms (for 50 ohm cable), or -j75 ohms (for 75 ohm cable).

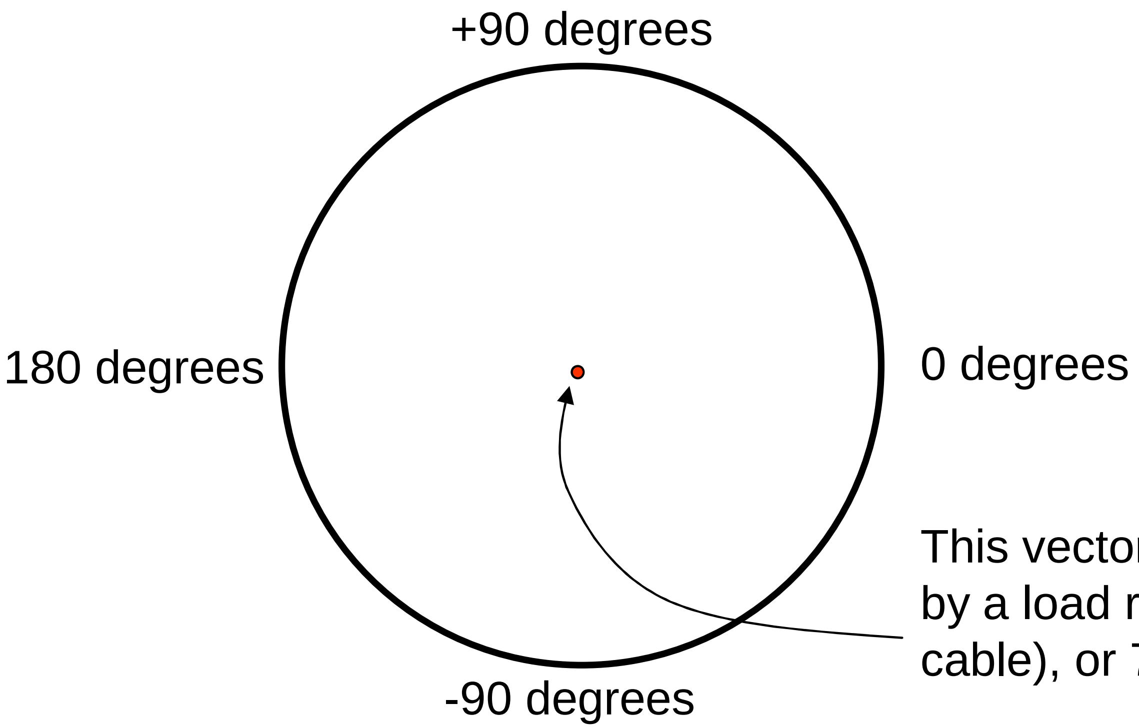
Polar vector – examples



This vector has a length of one-half, and a phase angle of 0 degrees. It’s produced by a load resistor of +150 ohms (for 50 ohm cable), or +225 ohms (for 75 ohm cable).

This vector has a length of one-half, and a phase angle of 180 degrees. It’s produced by a load resistor of +16.7 ohms (for 50 ohm cable), or +25 ohms (for 75 ohm cable).

Polar vector – examples



+90 degrees

180 degrees

0 degrees

-90 degrees

This vector has a length of zero. It’s produced by a load resistor of 50 ohms (for 50 ohm cable), or 75 ohms (for 75 ohm cable).

An **SWR bridge** measures the length of the reflection vector, but not it’s angle. It gives only a rough general idea about the reflection.

Length = 0 → SWR = 1:1
Length = 1 → SWR = infinite
Impedance = “cannot determine”

Reflection compared to Source

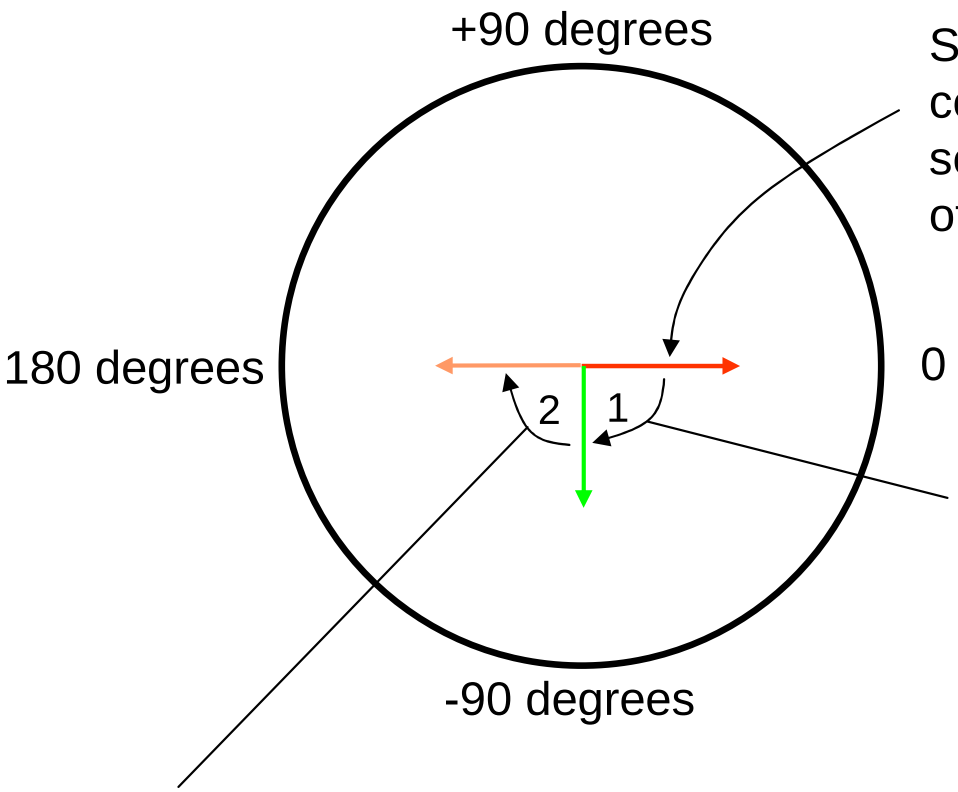
- If we add one meter of cable, the signal from the generator has to travel one meter further to the load. The reflection also has to travel one meter further back to the source.
- Thus compared to the source, the phase of the reflection appears delayed by the equivalent of 2 meters of cable.

→ One-half wavelength of additional cable delays the reflection by exactly one complete revolution around the polar chart.

→ One-quarter wavelength of additional cable delays the reflection by exactly one-half revolution around the polar chart.

- The length (magnitude) of the reflection vector does not change (assuming that the cable has no loss).

Adding Cable ~ 200 MHz example. (Wavelength is 1 meter in cable, V_f = 0.66) 150+j0 ohm load.



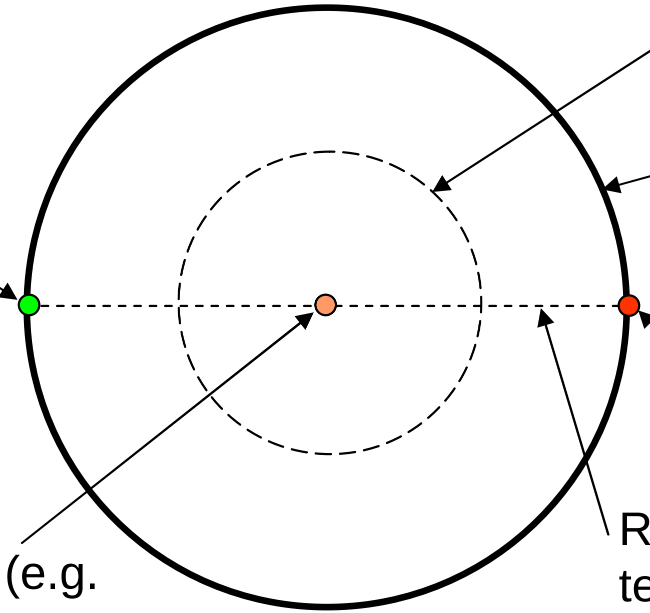
Start with generator and load directly connected (zero length cable). Generator sees 150+j0 ohms load. (Resonant). Length of vector = one-half.

1. Add one-eighth meter of cable (1/8 wavelength).
Generator sees 30-j40 ohms load.
(NOT Resonant).

2. Add another one-eighth meter of cable (total now one-quarter meter, or ¼ wavelength). Generator sees 16.7+j0 ohms load. (Resonant).

SWR in this example is 3:1

Some useful points on the chart



Constant SWR. Any vector terminating on the 0.5 diameter circle has an SWR of 3:1

Short circuit.

Constant SWR. Any vector terminating on the 1.0 diameter circle has an SWR of infinite.

Open circuit.

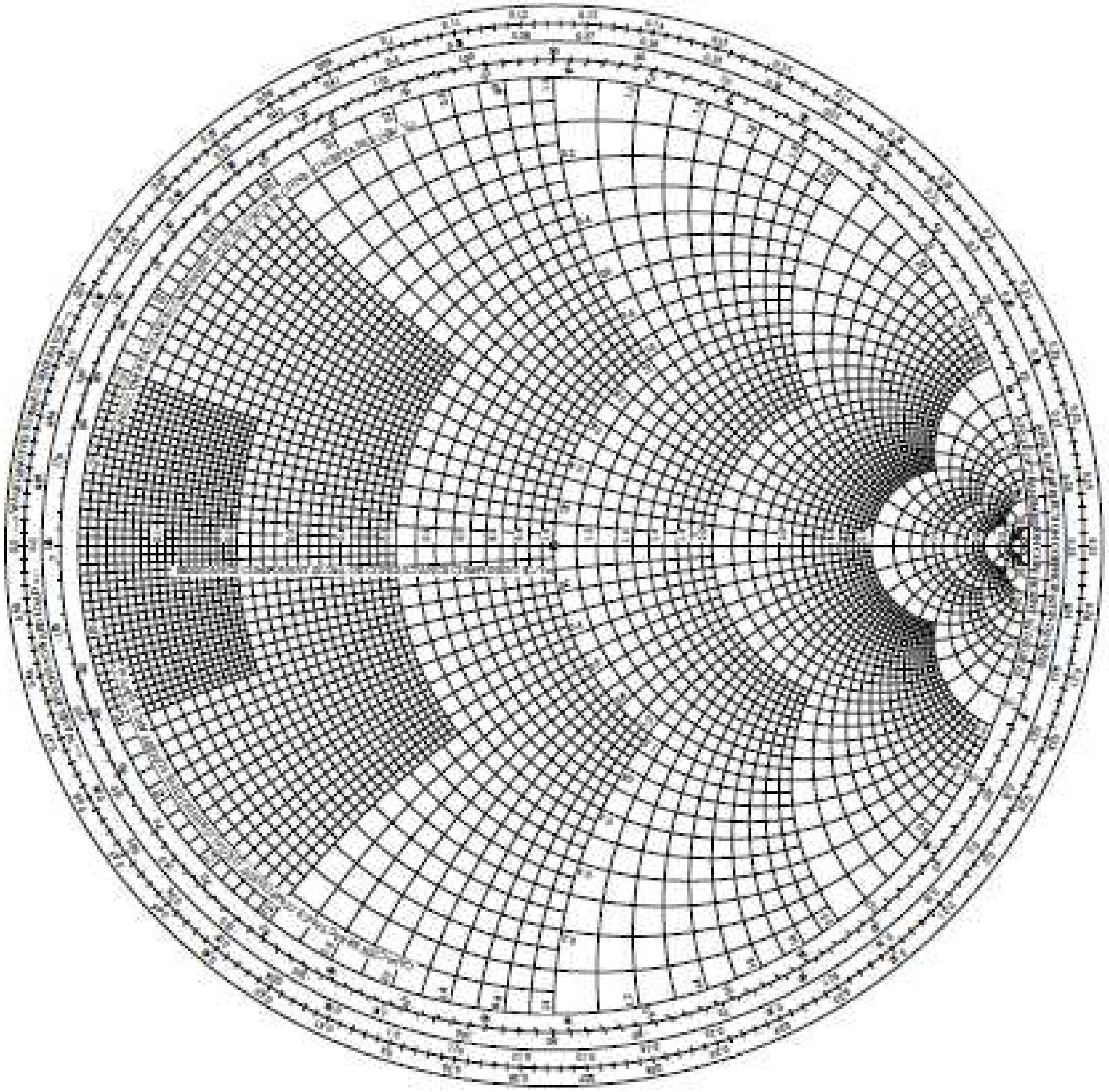
Resonant. Any vector terminating on this line is purely resistive. R+j0.

Matched load (e.g. 50 ohms, or 75 ohms). SWR is 1:1.

- Short-hand notation: just plot the tip of the vector as a dot, rather than drawing the complete vector from the center of the chart to the tip.

Smith Chart

- The Smith Chart is this same polar vector diagram with added grid for impedance, radial scale for distance in wavelengths, etc.
- It’s normalized to 1 ohm and 1 wavelength.



Adding lumped components

- Adding lumped component changes the impedance.
  - Example: load is 50 ohms. Adding a +j50 inductor in series gives a load impedance of 50+j50.
  - Adding a –j50 ohm capacitor in series with a 50 ohm load gives 50-j50 ohms.
  - Adding a +j50 ohm inductor in series with a 50-j50 ohm load yields 50+j0 ohms (resonates the load).
  - Adding a +j50 ohm inductor in parallel with a 50 ohm load gives 1/(1/50 + 1/j50) or 25+j25 ohms.

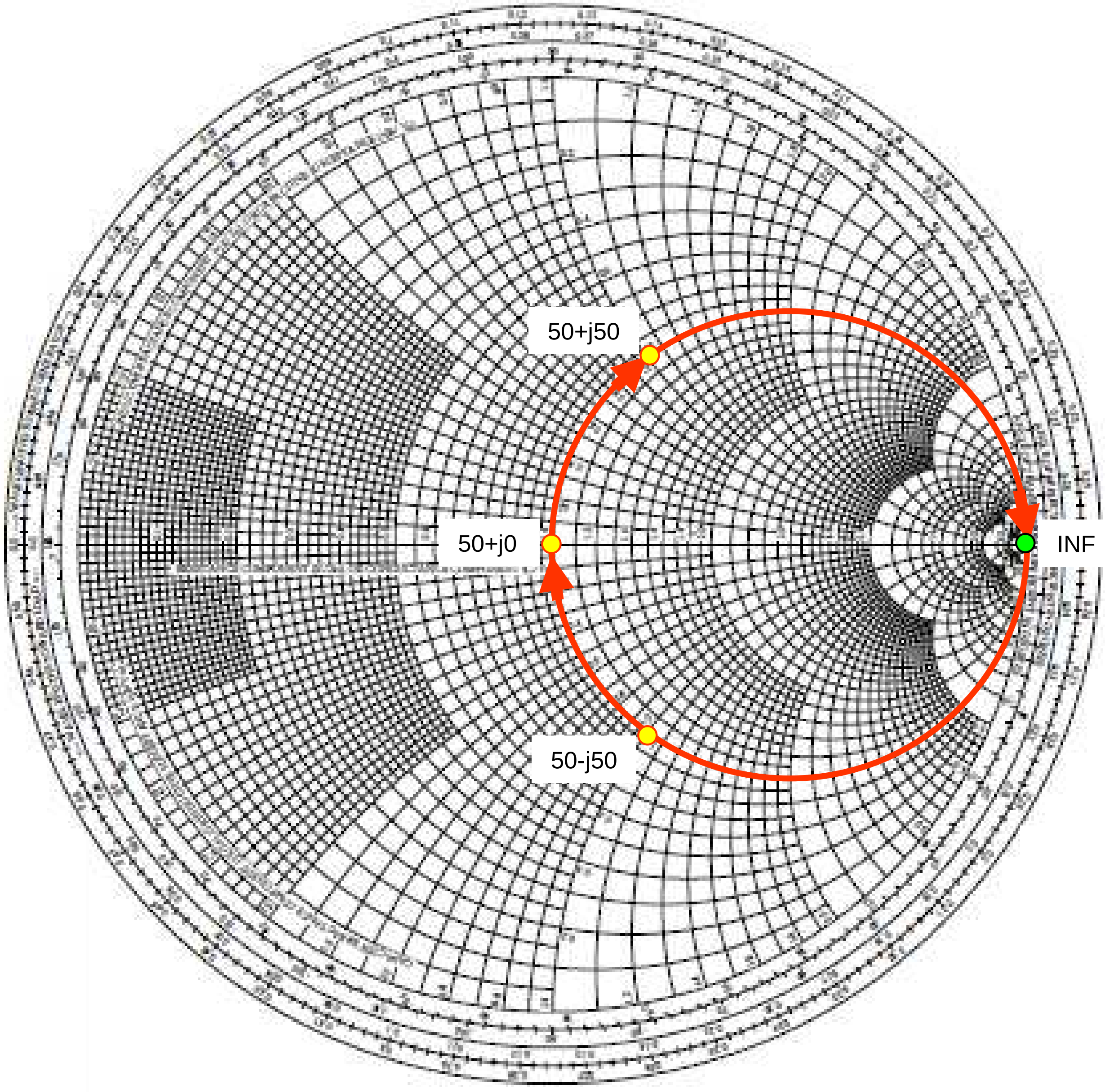
(Remember: 1/j = -j)

Adding lumped components on the Smith Chart

- Adding series component.
  - As the series component reactance gets larger, we move towards an open circuit (infinite Z, right-hand side).
- Adding shunt component.
  - As the shunt component reactance gets smaller, we move towards a short circuit (zero Z, left-hand side).
- Impedance matching.
  - Is the process of adding components to move from some point on the chart to the center (50+j0) or (75+j0).
- Normalized: the center is shown as 1+j0.
  - Multiply all numbers on the chart
    - By 50 when using 50 ohm cable
    - By 75 when using 75 ohm cable
    - By 400 when using 400 ohm cable, etc.

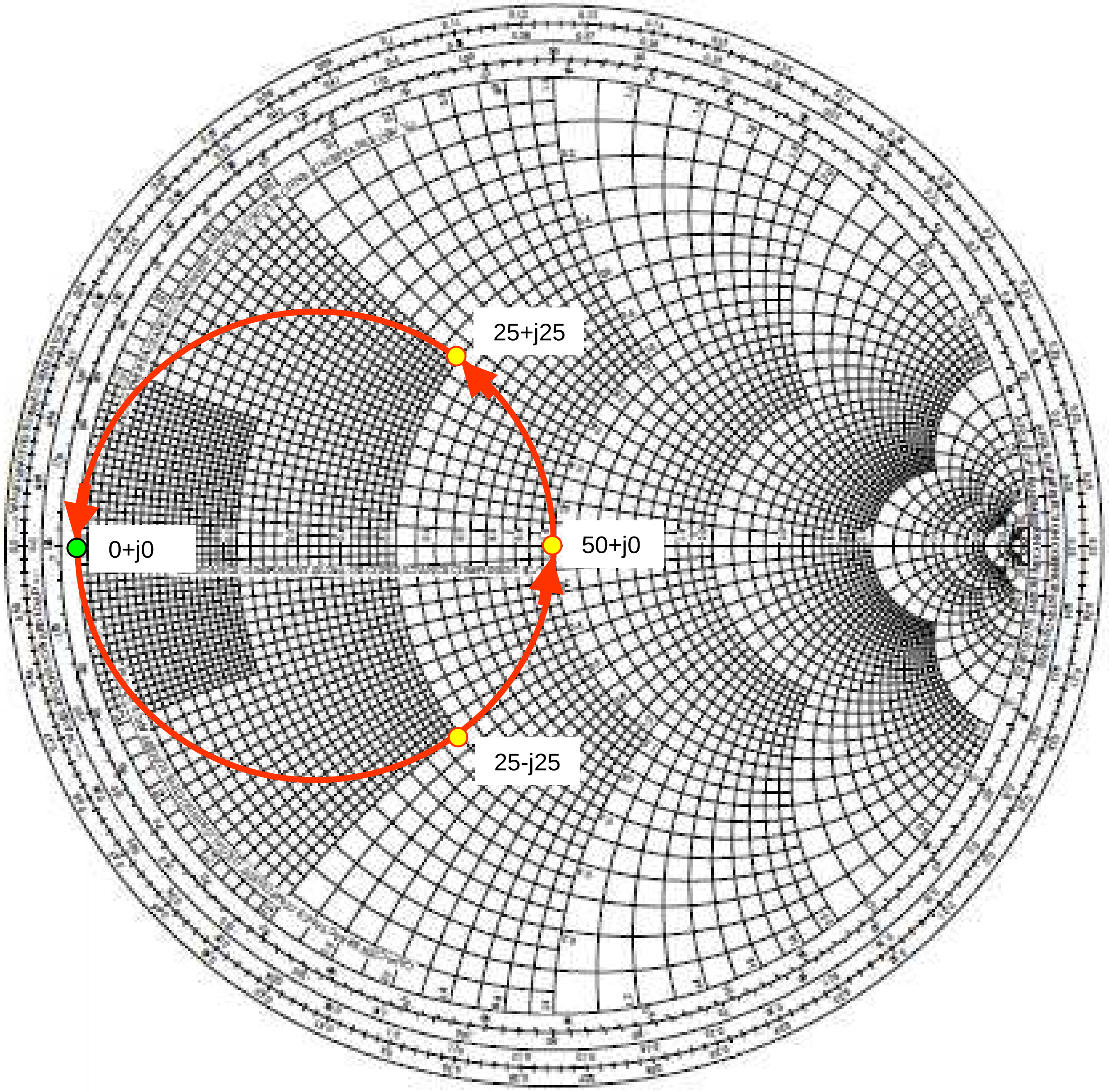
Series Component

- Example: adding +j50 **<u>inductor</u>** <u>in</u> **<u>series</u>** with a 50 ohm resistor moves **<u>clockwise</u>** from the center of the chart (50+j0) along the circle to 50+j50 point.
- Adding +j INF to 50 moves to the right-hand center of the chart (open circuit).
- Adding +j50 to 50-j50 yields 50+j0.
- Can’t go past the infinite point now matter how much inductance is added.
- **<u>Series capacitance</u>** goes in **<u>counterclockwise</u>** direction (but not past infinite point).



Shunt Component

- Example: adding +j50 **inductor** in **parallel** with a 50 ohm resistor moves **counterclockwise** from the center of the chart (50+j0) along the circle to 25+j25 point.
- Adding +j0 in parallel with 50 moves to the left center of the chart (short circuit).
- Adding +j50 to 25-j25 yields 50+j0.
- Can't go past the zero point now matter how small an inductance is bridging.
- Series **shunt capacitance** goes in **clockwise** direction (but not past zero point).



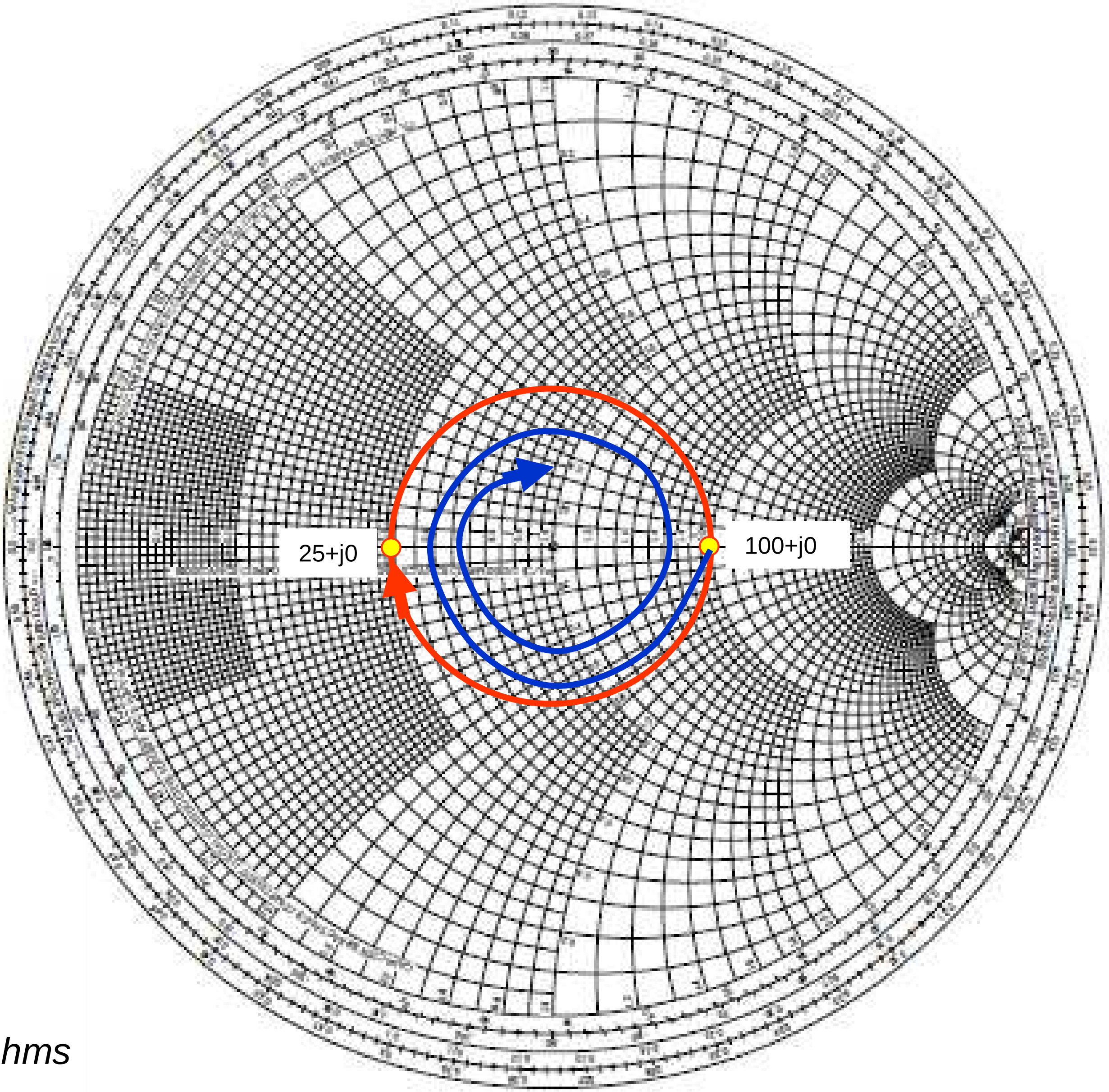
Transmission Line

- Example: adding ¼ wave line 'inverts' the impedance. Normalized Z → 1/Z.
- Example: 100+j0

  Normalized is (100+j0)/50 = 2+j0

  1/(2+j0) = 0.5+j0

  Denormalized is 50*(0.5+j0) = 25+j0.
- Adding transmission line **rotates clockwise** around the center point.
- Lossy transmission line **spirals clockwise** around and into the centerpoint of the chart.
  - Add enough line and the load is matched! But it doesn't receive any power.



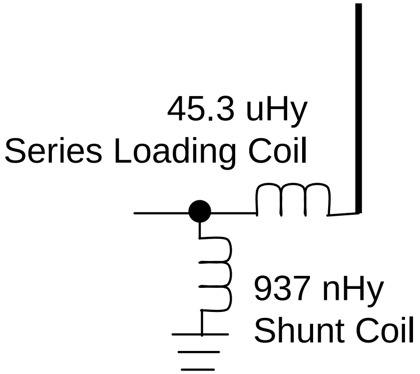
Examples assume that line Z = chart Z
i.e. 50-ohm line, and chart center is 50 ohms

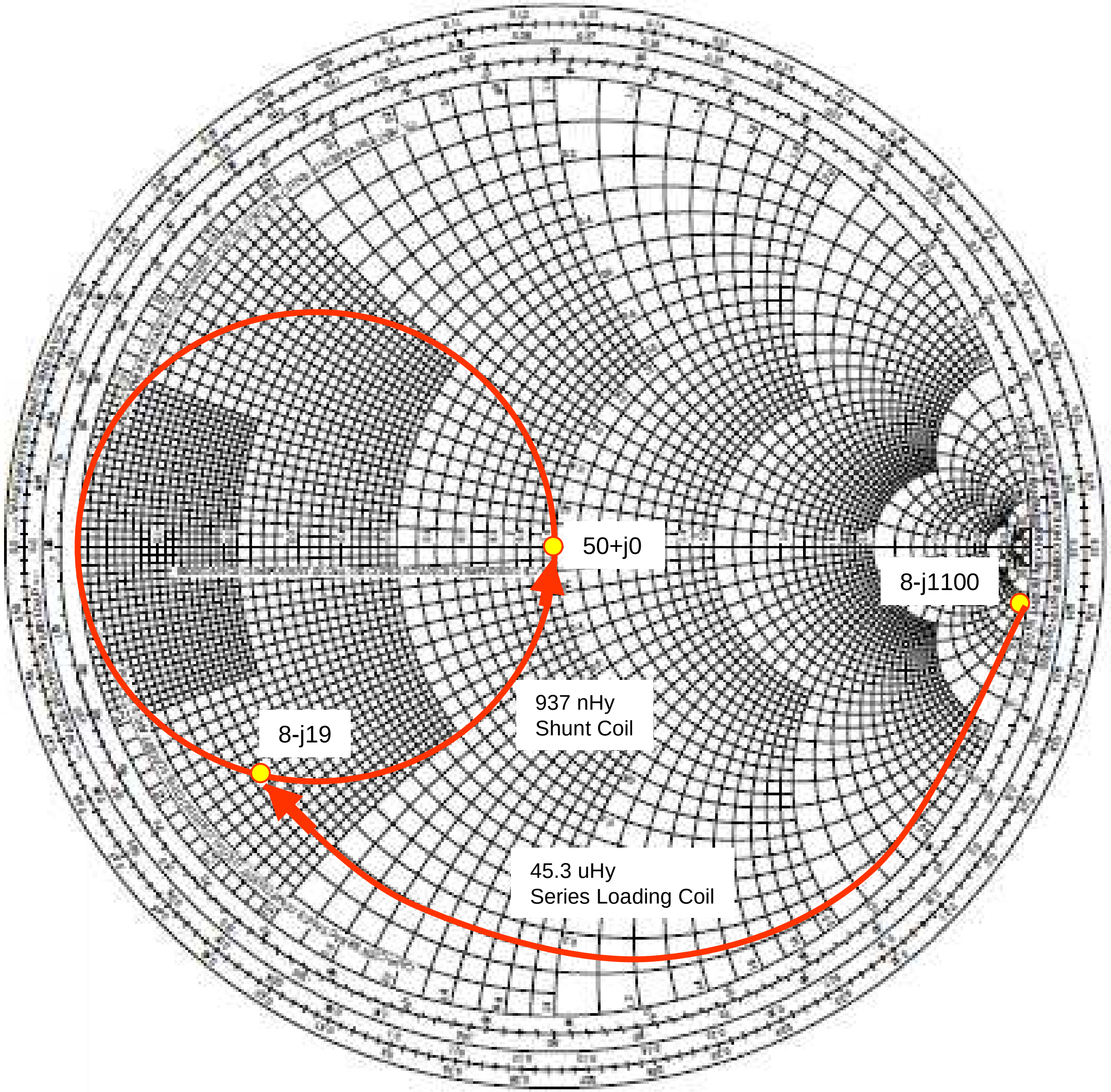
Example: HF Mobile Antenna

Solution #1

- 3.8 MHz: Z = 8 - j1100 ohms antenna (excellent mobile ground!).

1. Add series inductance (base loading coil).
2. Intentionally make the coil too short – 45.3 uHy. Z is now 8-j19 – NOT RESONANT.
3. Add shunt inductor 937 nHy. Z is now 50+j0.



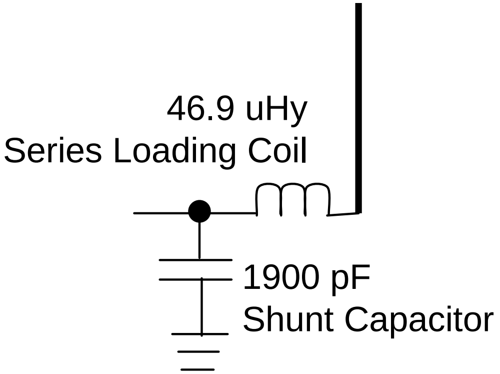


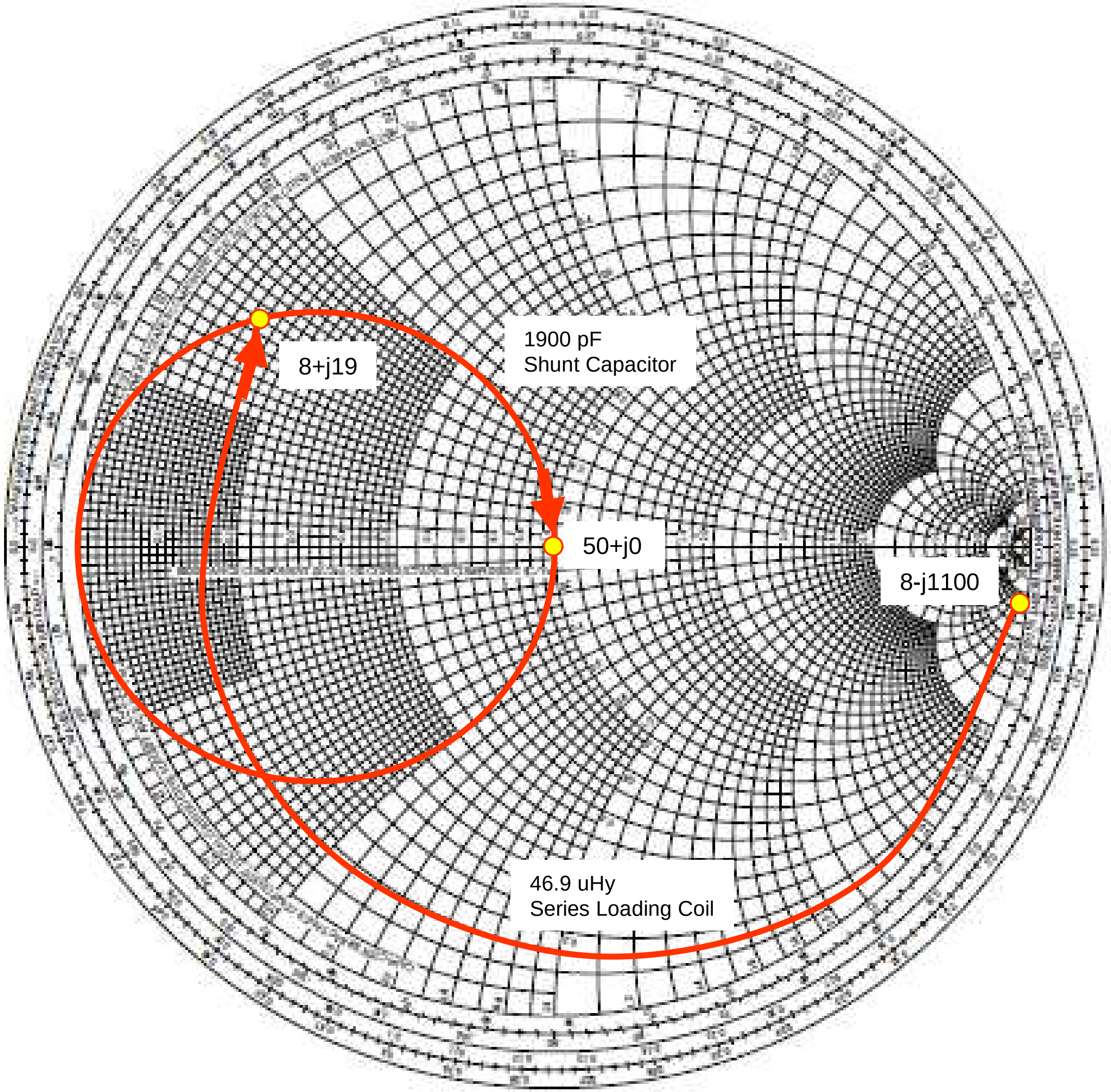
Example: HF Mobile Antenna

Solution #2

- 3.8 MHz: 8-j1100

1. Add series inductance (base loading coil).
2. Intentionally make the coil too long – 46.9 uHy. Z is now 8+j19. NOT RESONANT.
3. Add shunt capacitor 1900 pF. Z is now 50+j0.



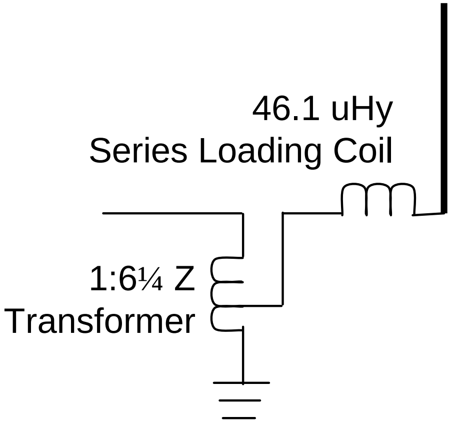


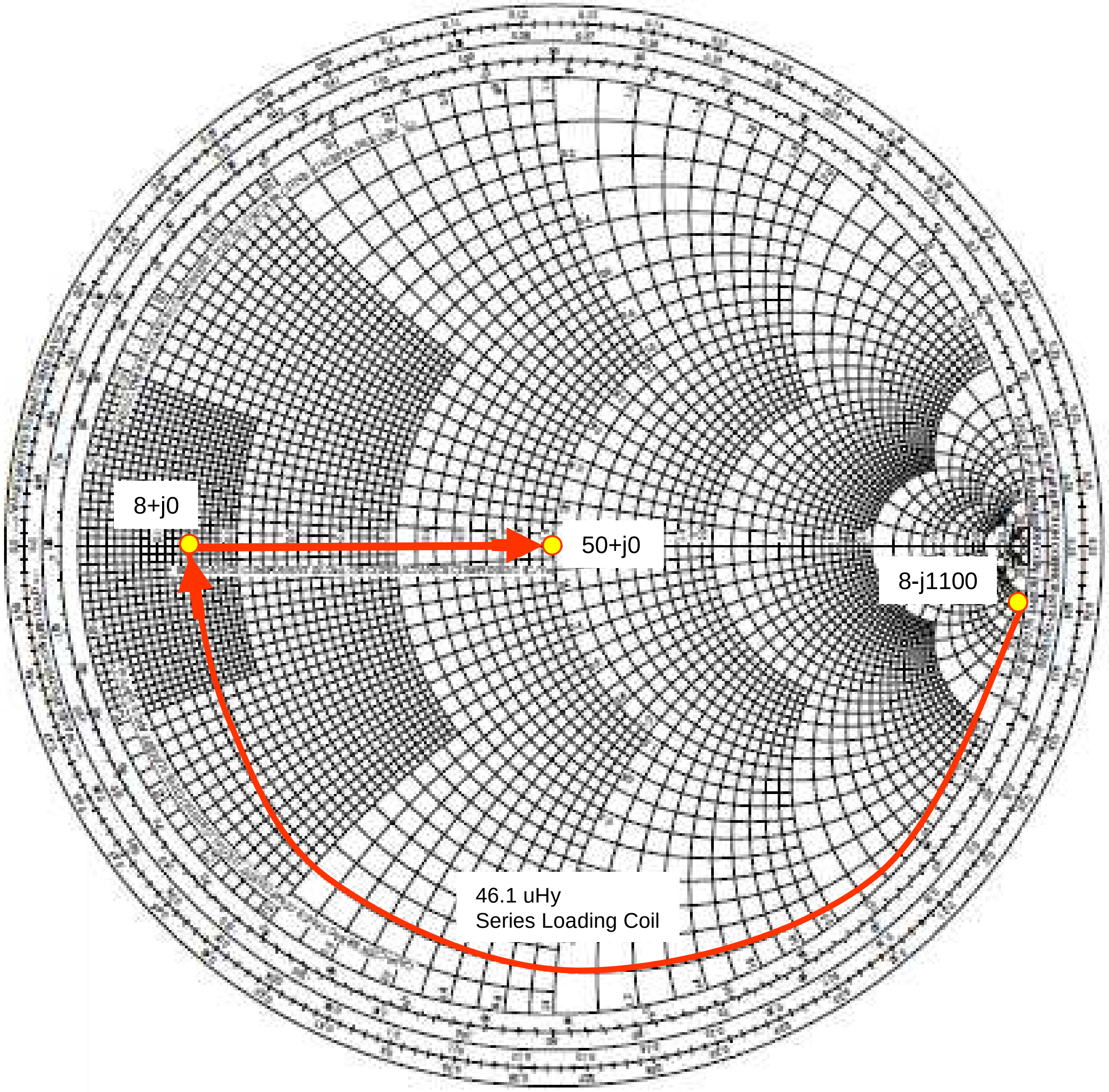
Example: HF Mobile Antenna

Solution #3

- 3.8 MHz: 8-j1100

1. Add series inductance (base or center loading coil).
2. Make the coil resonant– 46.1 uHy. Z is now 8+j0. RESONANT.
3. Need 1:6¼ Z ratio transformer to match to 50 ohms. [1:2.5 turns ratio]. Tough to make good low-Z transformer.





Resources

- Smith V3.01 – free Smith Chart tool (demo mode).
  - Allows entering load point, trying out multiple solutions on the Smith Chart. Free tool limited to 5 compensating elements.
    - http://www.fritz.dellsperger.net/
  - Print Free Graph Paper – has an option to print Smith Charts on ‘Letter’ or ‘A4’ paper (PDF).
    - http://www.printfreegraphpaper.com/