Smith Chart in the nanoVNA

Applications for the radioamateur
Sheets for a presentation or a hamradio lecture

By:
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PA3A

- The thing radio amateurs measure most: VSWR curve
- VSWR and the Reflections (what is the relation?)
- Smith Chart in the (nano)VNA; what does it show
  - Where are the reflections and the VSWR in the Smith Chart
  - Smith Chart: what is there more to see?
  - Why is the Smith Chart as it is
  - Demo with L, C, R
- **Pause**
- Application in direct tuning of antennas or networks in general
  - Effects of L and C on impedances visible on the Smith Chart
  - L – tuner + Demo – tuning SWR=3 to SWR=1
  - Pi – tuner
  - T- tuner
- Online - tools

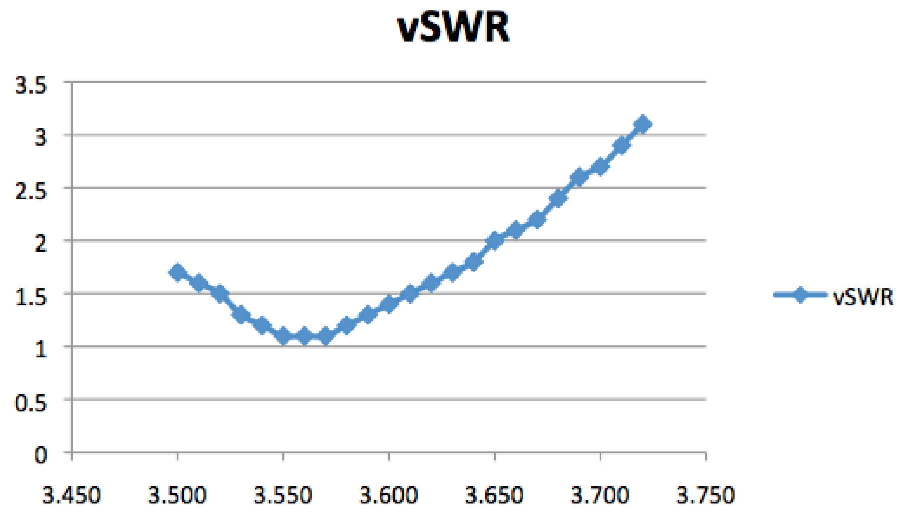
More info about measurements with the VNA:
https://pa3a.nl/nanovna-metingen-and-smith-chart-articles/

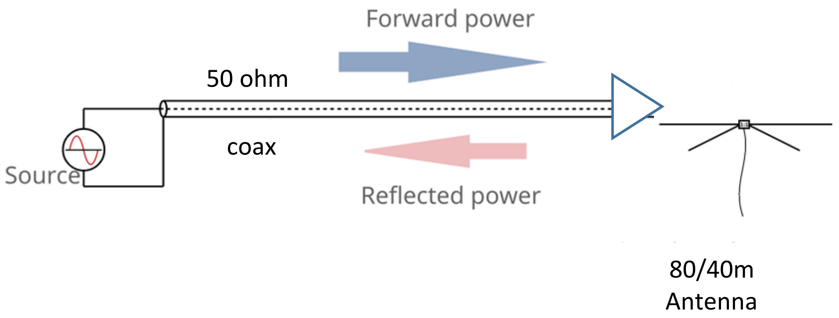
VSWR | Reflection | Smith&Z_L | Coax | PAUSE | Admittantance | Tuners | Demo | software

Antenna measurement

- Radioamateurs nearly always measure the SWR
  Why? What does it show?

- A curve:

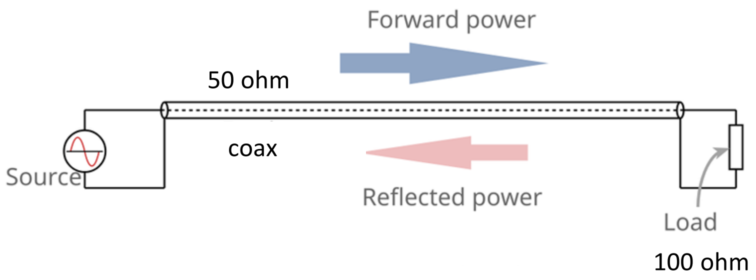




- Standing Wave Ratio (SWR)
- A measure for the amount of reflected voltage by the load
  (and for reflected power)

VSWR

SWR and Reflection are connected



- Well known formula:

$$\text{SWR} = \frac{Z_{load}}{Z_{kable}} \text{ or } \frac{Z_{kable}}{Z_{load}}$$

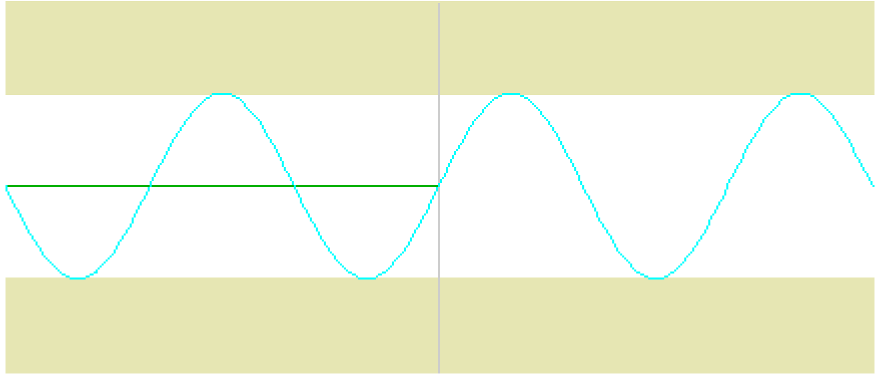
e.g. Z_{load} = 100 ohm , then SWR = 100 / 50 = 2

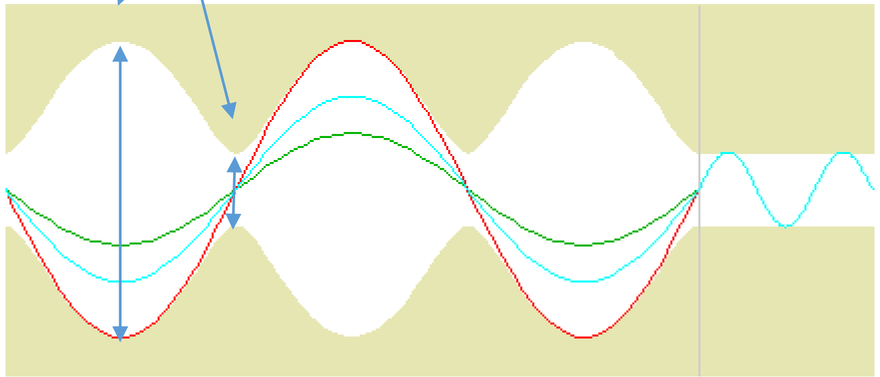
Which other Z_{load} (apart from 100 ohm) also produces an SWR = 2 ? Z_{load} = ??

- SWR = 1 : 1 >> % reflection = ??
- SWR = 1 : infinity >> % reflection = ??
- SWR = 1 : 3 >> % reflection = ?? (we'll come back on that)
- Are there more Z_{load}'s who produce SWR = 2 ? (more on this later…)
- Good to know: we are talking about reflected **voltage (VSWR)**

VSWR

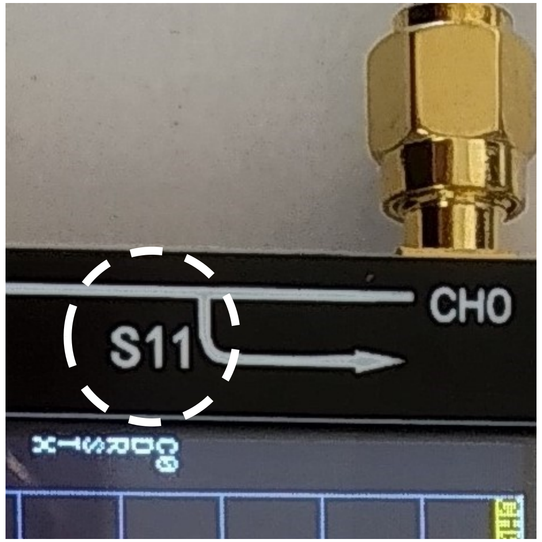
Reflections





SWR is about reflections so

- There is the so coalled **Reflection Coefficient** **RC**
  (also known as '**S_{11}**')
  This is the **percentage of reflected voltage** as caused by the mismatch and follows from the (relatively unkown) formula:



$$\mathbf{RC} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Z_L = Load impedance
Z_0 = Characteristic impedance of the transmissionline (often 50 ohm)

reflection

$$RC = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Let’s calculate (example) with a coax of 50 ohm

- Coax with shorted end ($Z_L = 0$), then the calculation: RC = -50 / 50 = – 1
  This is RC = **100% reflection in opposite phase** (the minus-sign)

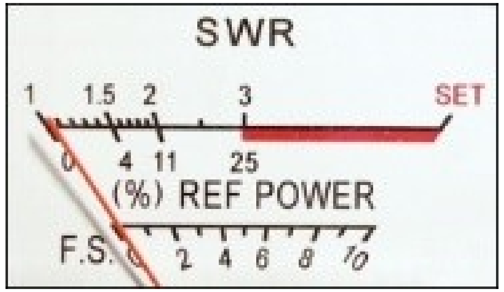
  Open coax (Z_L = 100.000, or nearly infinity): RC = 99.950 / 100.050 ≈ 1
  So the RC = **100% reflection in phase**

- Suppose Z_L = 150 and Z_0 = 50 (SWR = 1 : 3)
  RC = 150 - 50 / 150 + 50 = 100 / 200 = 0,5 = **50% reflection**

  This is **Voltage reflection** so the **Reflected Power** = 25%
  (P = U^2 / R)

and now the Smith Chart….

Old 27Mc CB SWR meter

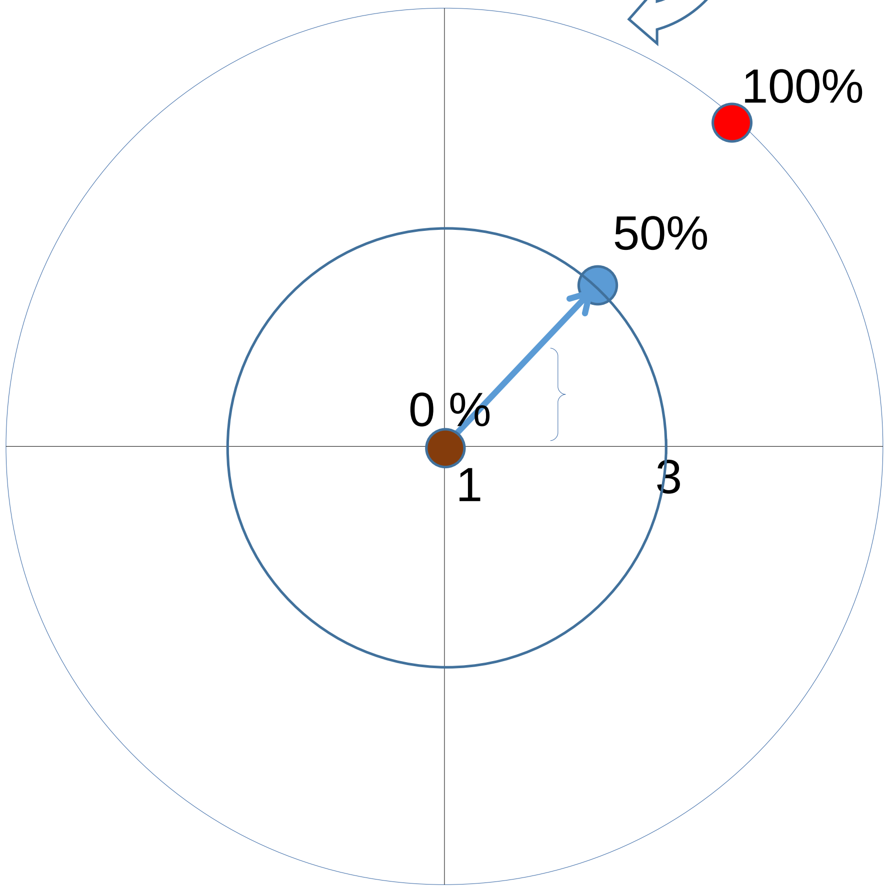


reflection

Smith Chart: that is about *reflections*

- In the Smith Chart (a set of circles) you see:
  - percentage reflection
  - phase shift
  - Dot in centre: 0% reflection
  - Dot on outer circle: 100% reflection
  - Dot on middle circle: Length arrow = 50% reflection
    In this example, there is a phase shift of 45 dgs

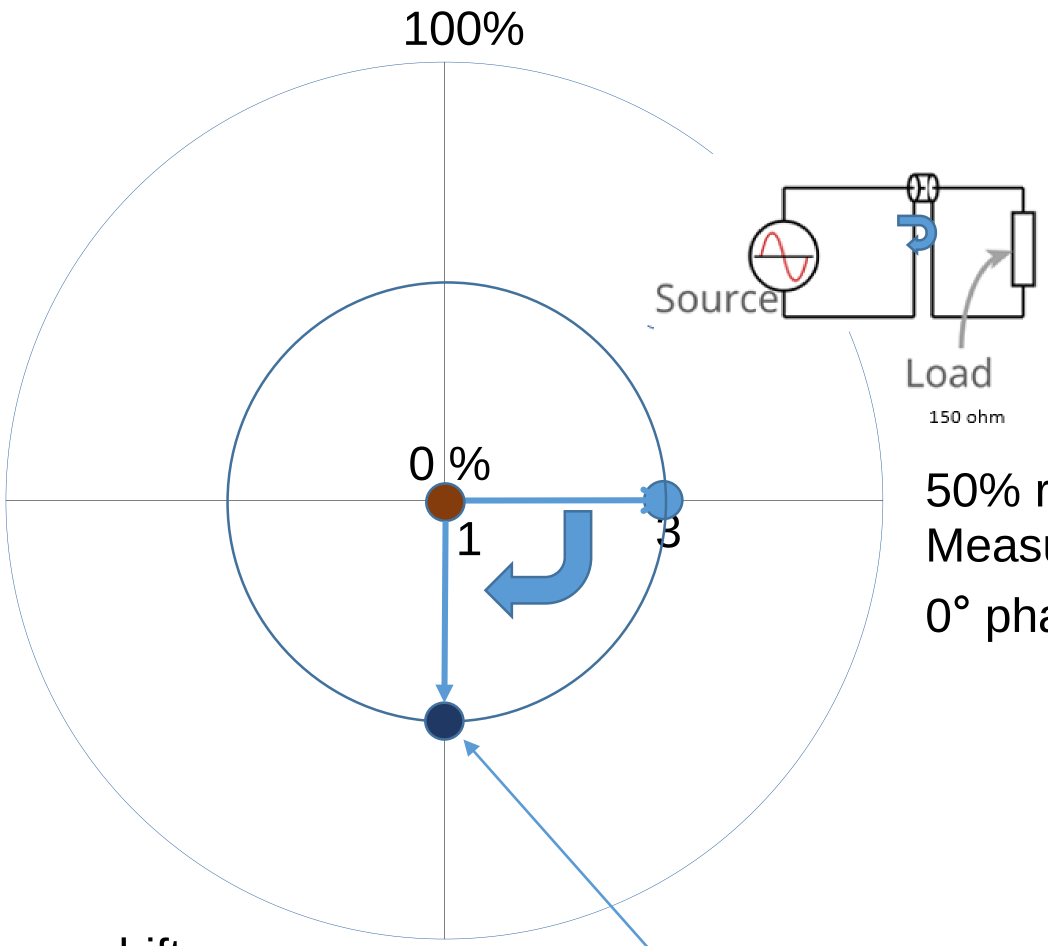
- Reflection Coëfficiënt RC = 50% (the blue dot)
  - Turn the blue arrow clockwise to the horizontal axis, at the end of arrow, you find the SWR.
  - and…. All reflections of 50%, no matter under which phase angle, have the same SWR!!
    (Thank you very much Mr. Smith)



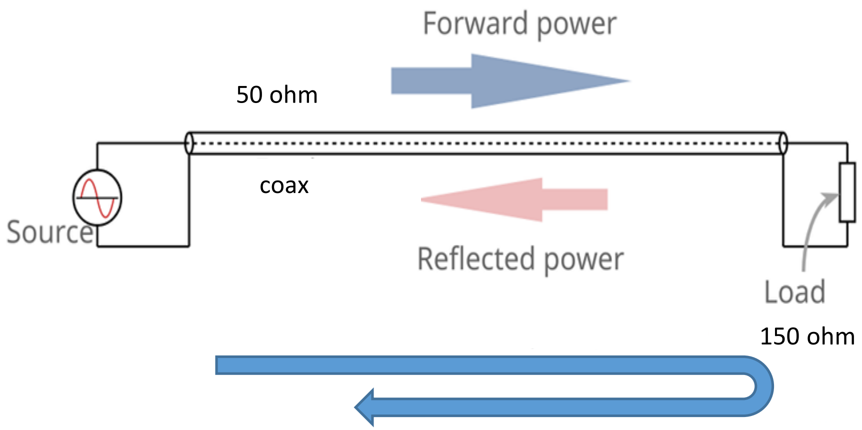
An important question:
What Z_{load} was connected that caused that blue dot at 50% with 45 dgs phase shift in the first place?

reflection

Smith Chart: is about *reflections* ***and transmission lines***



50% reflection (SWR = 3) by a 150 ohm resistor
Measurement at the load, reflection is in phase,
0° phase shift.



Phase shift:
45° to the load and 45° back, so the reflection is shifted 90° compared to the original.

The SWR is still 3

reflection

50% reflection (SWR = 3) by 150 ohm resistor with e.g. 1/8 wavelength (= 45°) loss-free coax between source and load

What did Mr. Smith do?

- All possible Z_{Load}'s calculated (real and complex) to a reflectionpercentage plus phase shift using the already mentioned formula

$$\mathbf{RC} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Z_0 is a given thing = impedance of the transmissionline
Z_L can be any value,
ohmic, inductive, capacitive, or a combination
(The last one we call: 'complex')

- Mathematically the different Z-combinations make circles in the Chart
- This Chart is still in use. It is a valuable tool. That's why it is in incorporated in the software of the nanoVNA.
  As it turns out, it's also very useful for radio amateurs.

reflection

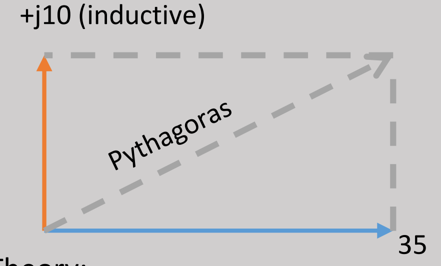
Sidestep: What is the Z_{load}

(back to the hamradio course)

Z_{load} → Ohmic part, R

Z_{load} → Capacitive or Inductive part, X_C or X_L

} Complex



Theory:
vectordiagram from a hamradio course

- X_L = 10 ohm inductive → **+ j** 10 ohm
  X_C = 10 ohm capacitive → **– j** 10 ohm

  Antenna with impedance: 35 + j 10 ohm
  35 ohm is called 'Real' part, j10 ohm 'Imaginairy' part

- the Smith Chart is *normalised* on the Z_o (in normal language scaled), mostly on 1:50
  - so 50 + j 25 ohm → Smith Chart : 1 + j 0,5 ohm
  - so 100 ohm → Smith Chart : 2 ohm

Excercise:

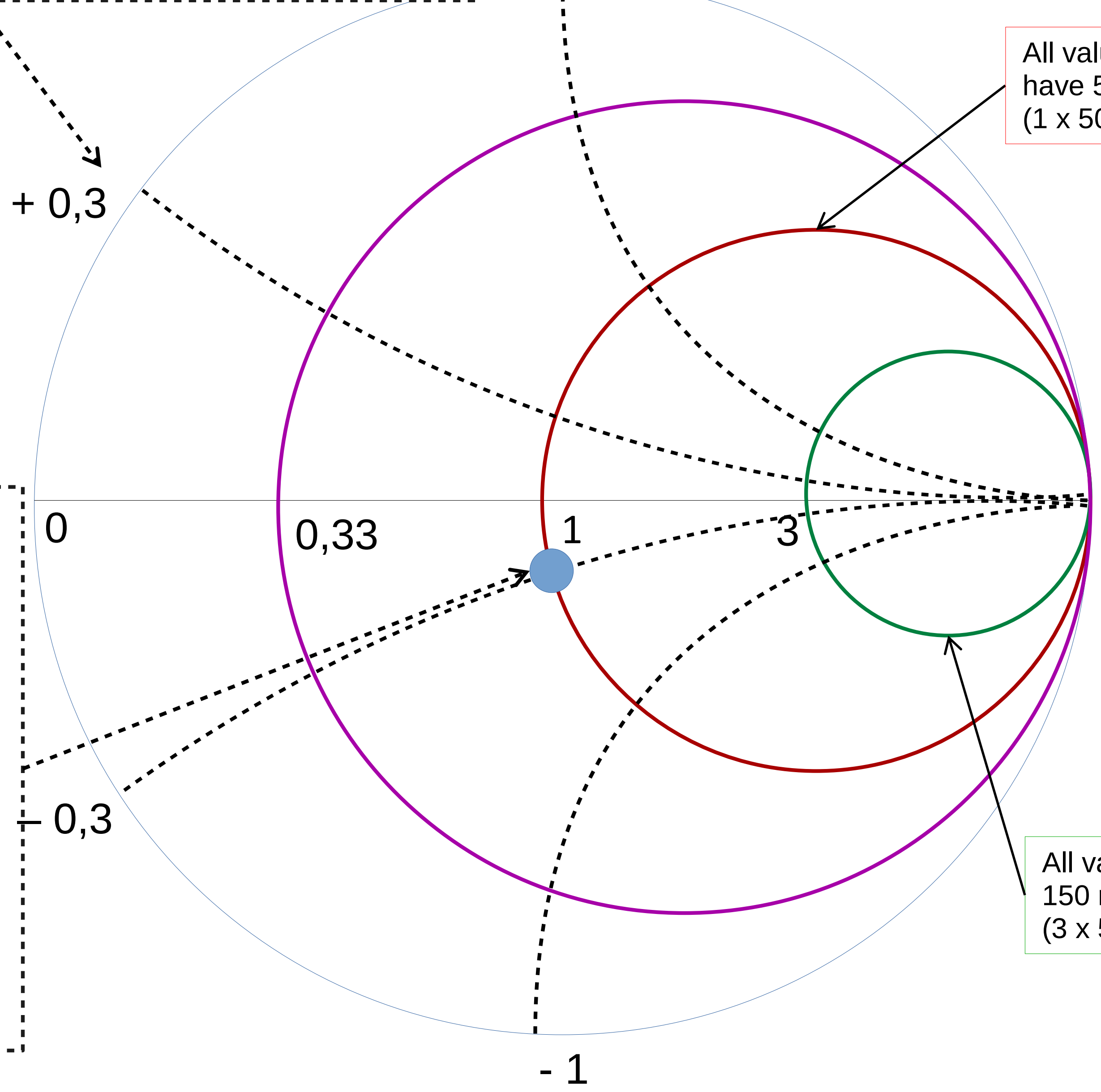
- so 300 – j 100 ohm is … - j …. ohm in the Smith Chart
- Is this capacitive of inductive?

(So 300 – j 100 is a COMPLEX number, with REËEL part 300 and IMAGINAIRY (capacitive) part –j 100)

Smith&Z_L

To plot the Z_{load} on the Smith Chart

All values on this line have + j 15 ohm imaginair part (0,3 x 50)
= … + j 15   (inductive)



All values on this line have 50 ohm real part
(1 x 50)   = 50 +/- j ...

Blue dot is on real 50 ohm line (1 x 50) and on the imaginairy (capacitive) - j 15 line (0,3 x 50)

so

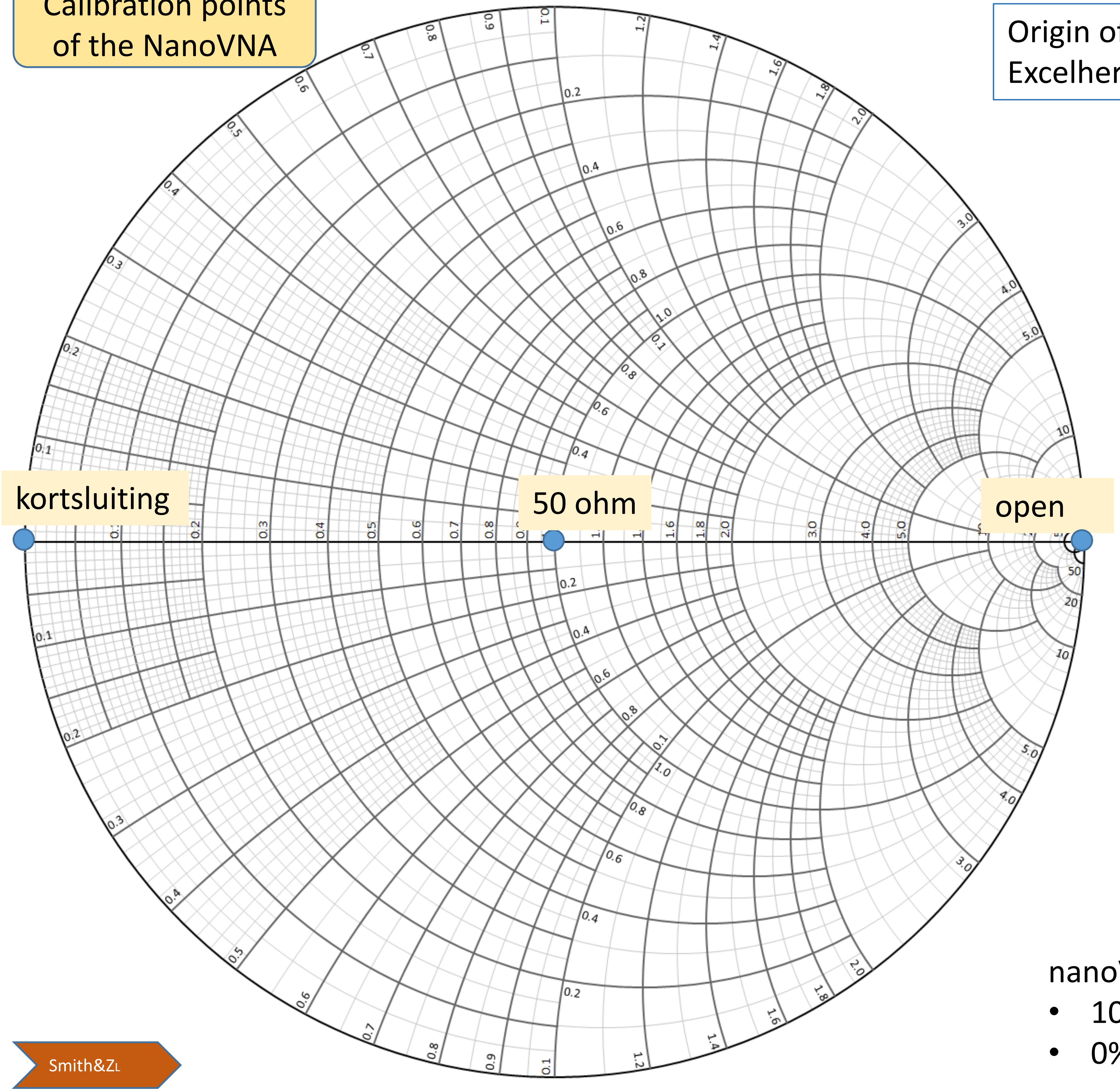
Zload = 50 – j 15 ohm
(capacitive behaviour)

Looking at the position of the dot, the reflection that presents itselfs here (a relatively small percentage at a phase angle of nearly 90°, comes from a measurement of 50 – j15 ohms

All values on this line have 150 real part
(3 x 50)   = 150 +/- j ...

Smith&Z_L

Calibration points of the NanoVNA



Origin of this Chart: Excelhero.com

the Smith Chart

… on a fine schaal

… and still shown in the basic format (as on the NanoVNA).

the rest is still to come…

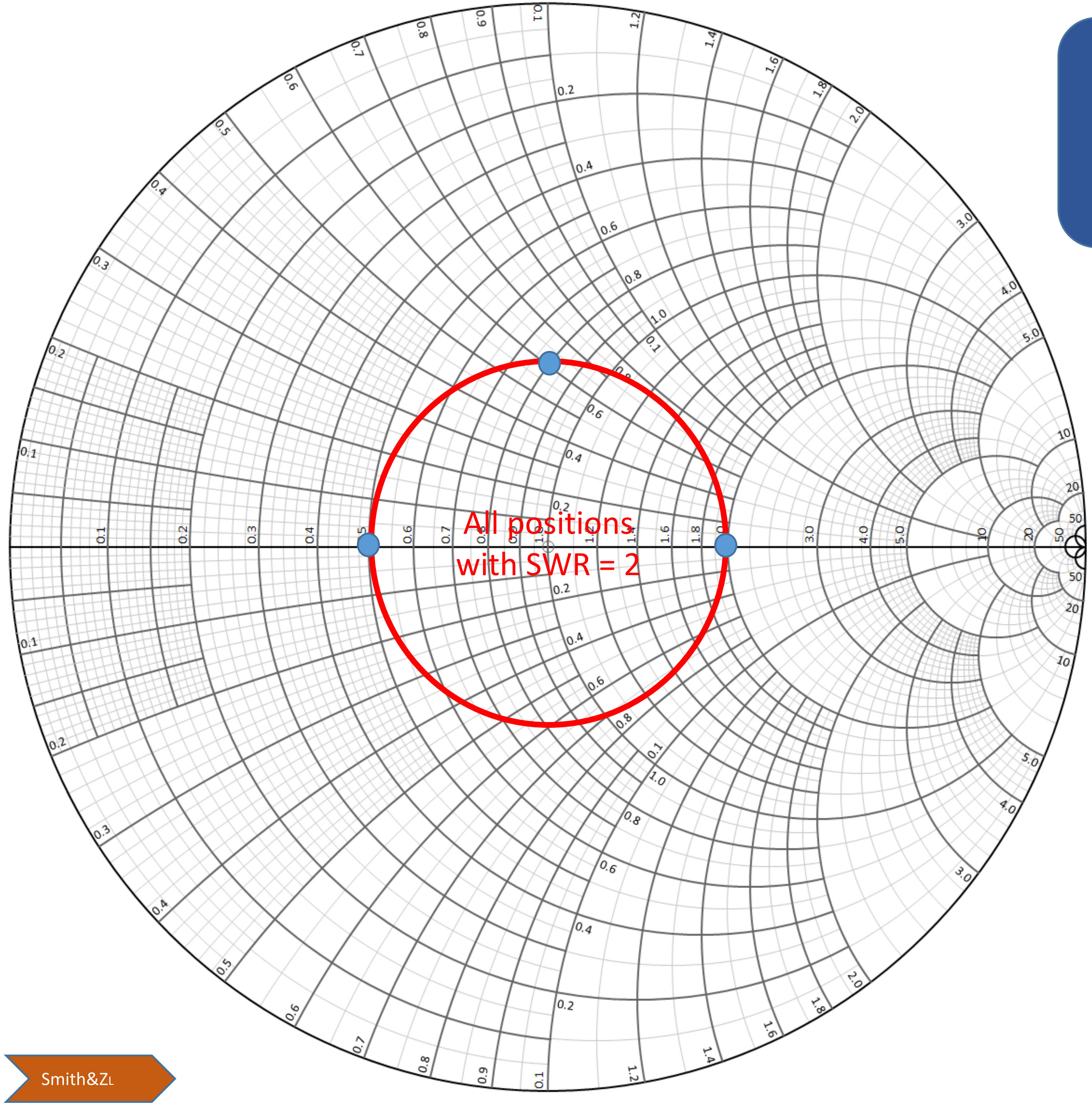
Now you can plot the reflections of different measured impedances by hand… if you like

nanoVNA calibratione on:

- 100% reflection: open or short
- 0% reflection: 50 ohm load

Smith&ZL

Measurements with equal SWR are on a circle around the centre of the chart.



E.g. SWR = 2
100 ohm and 25 ohm ofcourse…

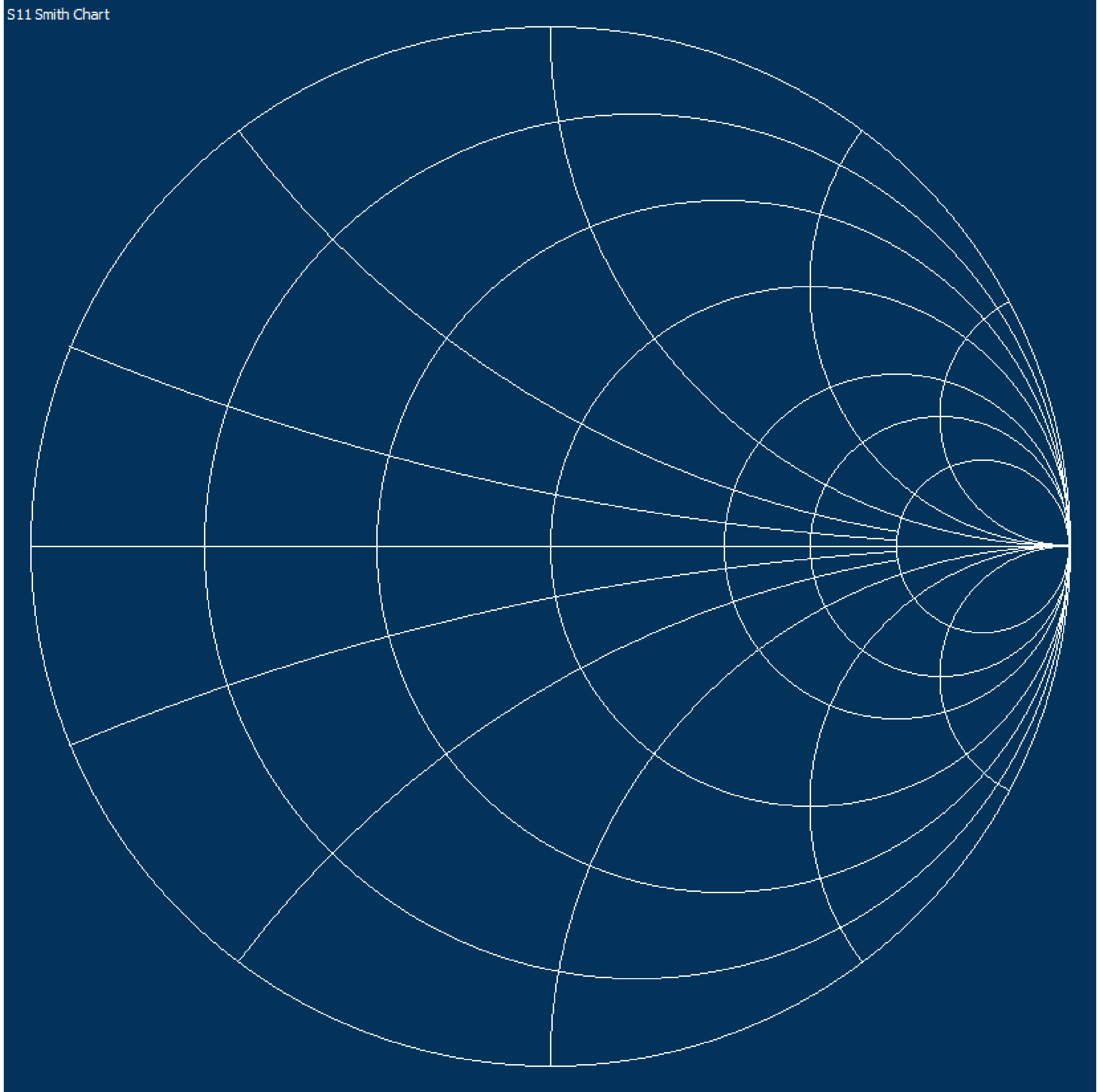
There ar many loads producing SWR = 2, but now you can see whether it is caused by a resistor only or something with inductance or capacitor as well.

the dot: 40 + j 30 ohm also has SWR = 2

(40 = 0.8 x 50
30 = 0.6 x 50)

Smith&ZL

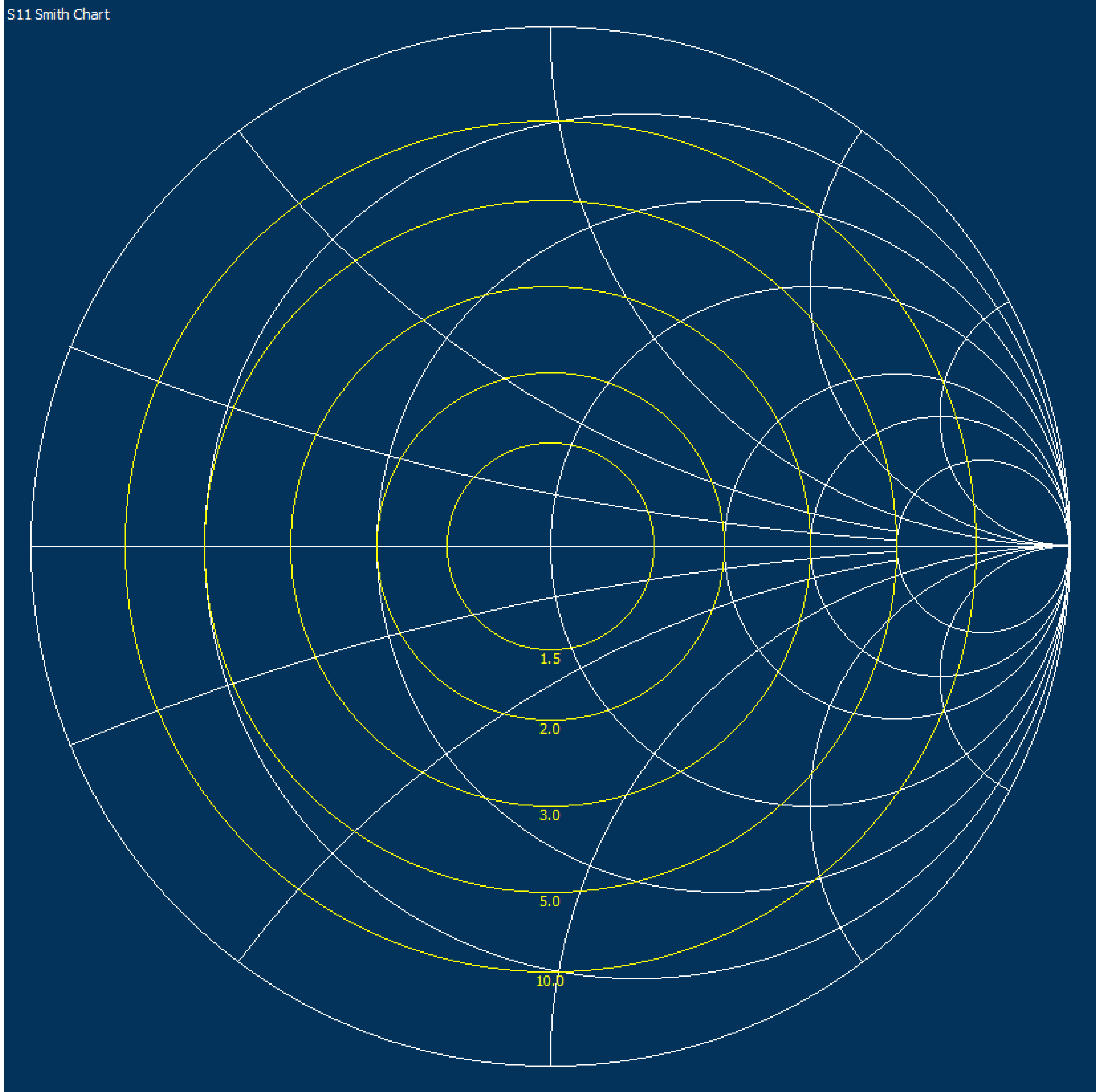
Smith Chart from NanoVNAsaver software



Smith&ZL

Smith Chart from NanoVNAsaver software

SWR cirles added



Smith&ZL

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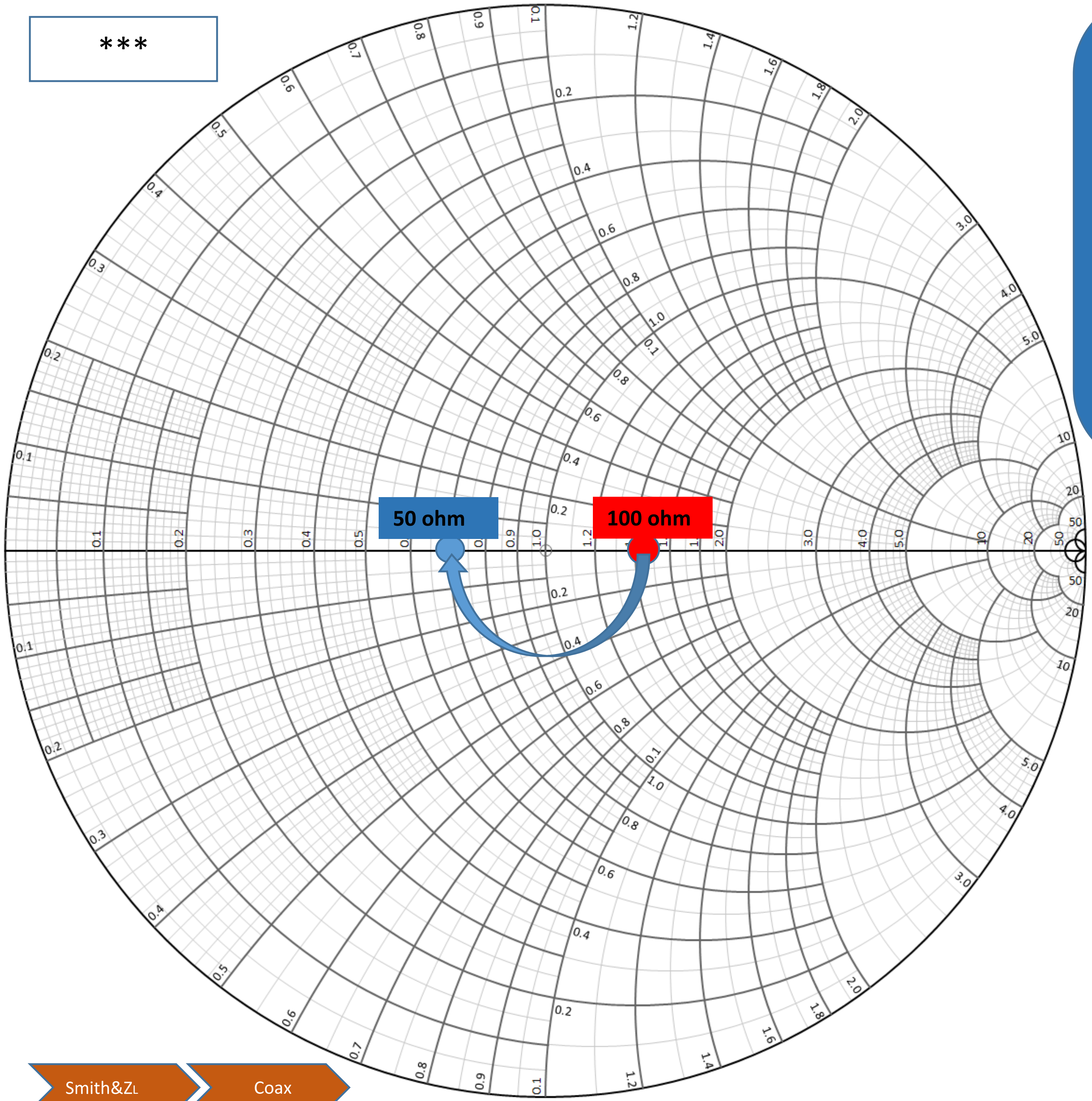


Smith Chart and the quarter wave transformer:

Transformation from 100 ohm to 50 ohm;
We do this using a ¼ wavelength
70 ohm cable

SO the CENTRE OF the SMITH CHART IS 70 OHM NOW.

From 100 ohm (e.g. single quad loop) to 50 ohm using a quarter wavelength cable coax of about 70 ohm.
Suppose the used coaxial cable Z_0 is 70 ohm:
So **100 ohm = 100/70 = 1,43**
So **50 ohm = 50/70 = 0,71**

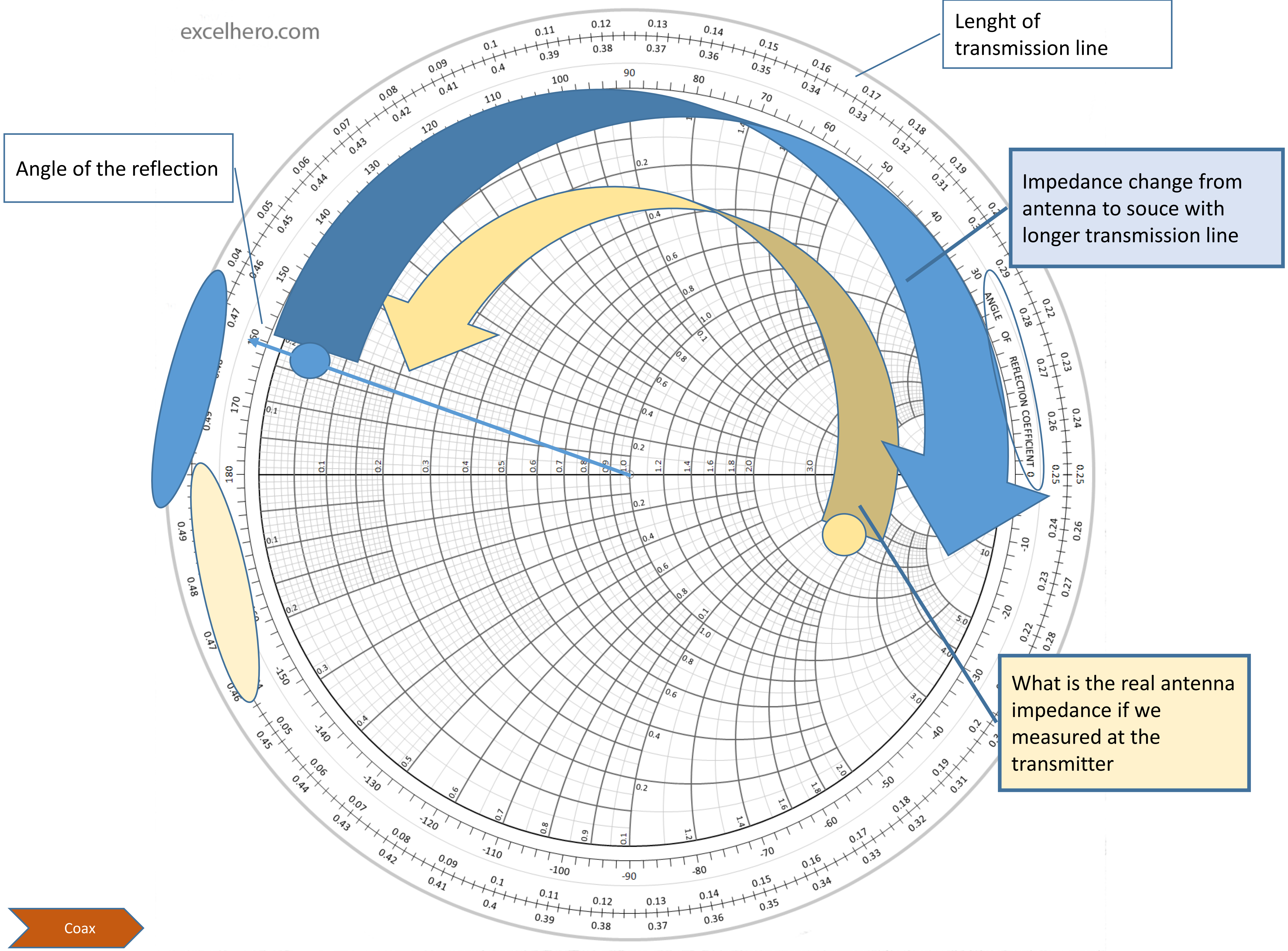
Attention!

- System is 70 ohm
- SWR in both dots is equal
- A 180 degree turn around the centrepoint (70 ohm) is the result of a quarter wave (90 dgs in the transmission line)
- Using a half wave line (one full wavelength round to load and back) we will come back to where we started!!

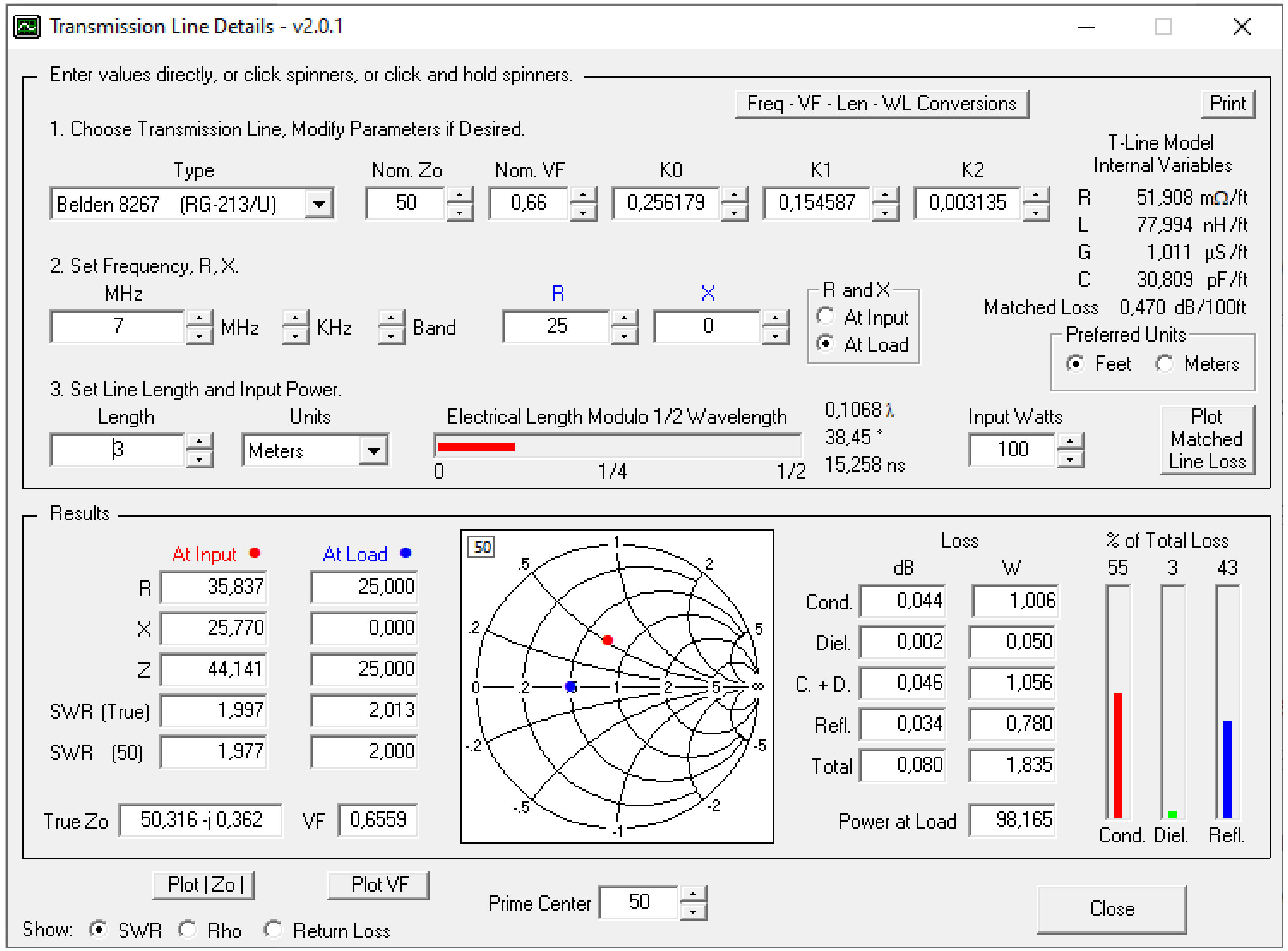
- Underway (on the blue arrow) you see the impedances you encounter if you start with a zero length transmissionline and increase its length bit by bit until it is a quarter wave length long.

- QUESTION: how long will the quarter wave 70 ohm coax be on say 14 MHz?

Smith&ZL Coax


excelhero.com
Lenght of transmission line
Angle of the reflection
Impedance change from antenna to souce with longer transmission line
What is the real antenna impedance if we measured at the transmitter
ANGLE OF REFLECTION COEFFICIENT
Coax

TL Details by AC6LA (this will calculate everything ☺)
(https://ac6la.com/tldetails1.html)



Conclusions on the Smith Chart (up till now)

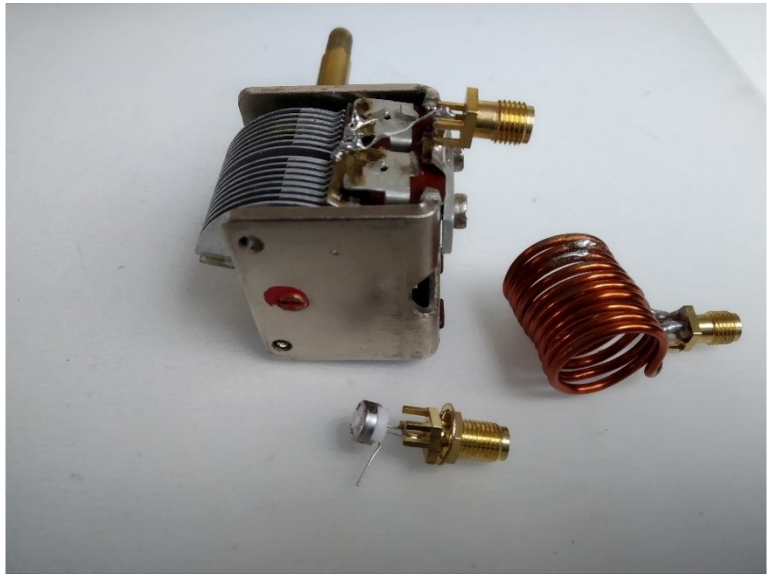
- Whatever the length of the transmission line: same SWR everywhere (zero or very low loss line)
- Sometimes a tuner can not tune the antenna, BUT with another length of transmission line it there's a chance it could, because the shown impedance changes with the length of the cable. The Smith Chart shows grafically how much.
- Reflection is shown in reflection Coëfficiënt (S_{11}) and is the percentage reflected *voltage at a certain phase angle*. Percentage reflected power is the percentage of the Reflection Coefficiënt squared.
- The closer to the '1' (the middle) = the smaller the reflection = the lower the SWR.
- There are many formulas about reflection with cables and loads.
  The radio amateur can already do a lot with: SWR = R_{load} / Z_{cable} (as a general idea)

Let’s play with the NanoVNA (1)

- Work with a 50 ohm calibrated NanoVNA
- Choose different frequencies
- Sweep an antenna
- Connect an open ended coax
- Connect a variable resistor
- Connect a capacitor or an inductance

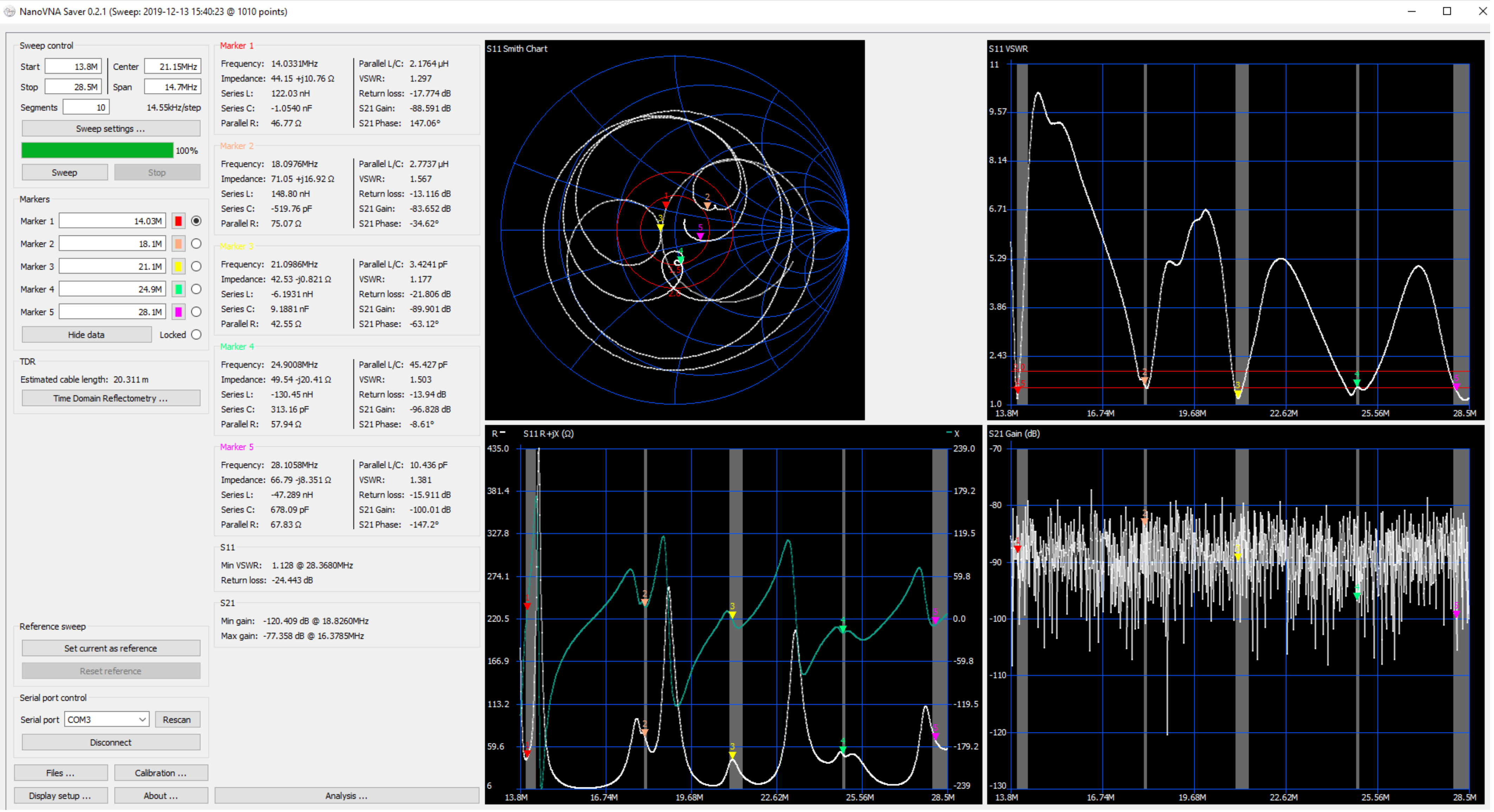
- DEMO with Smith Chart:
  inductance, capacitor, resistor

- Some measurements @ PA3A



2m/70cm vertical: 140MHz-150MHz   (@PA3A)

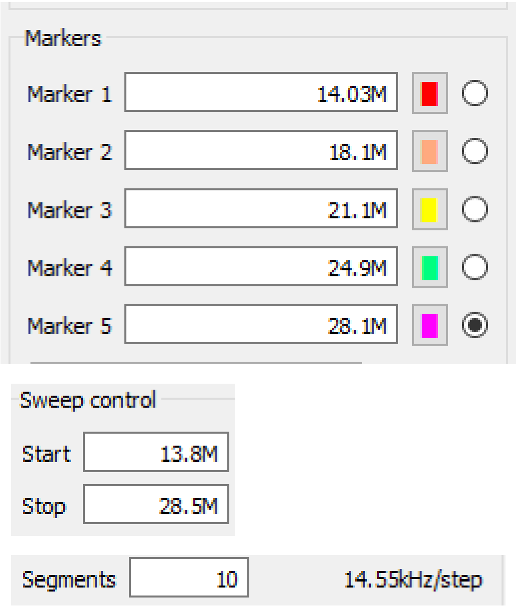
Screenshot NanoVNA Saver: 5 band antenna MA5B @PA3A
Markers in several amateur bands. (Software nanoVNA saver 0.2.1)

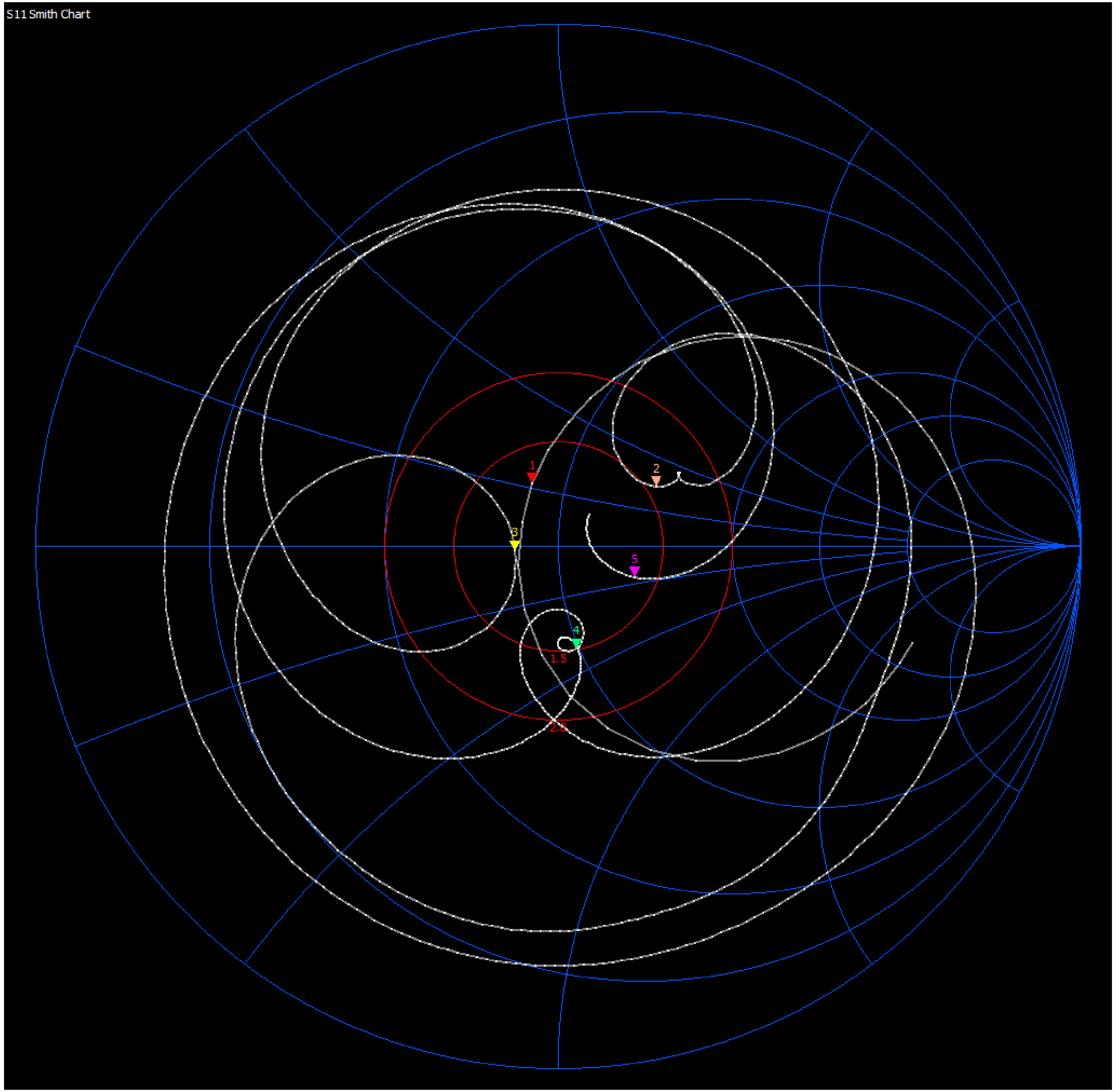


Next slides more readable

MA5B sweep
@ PA3A

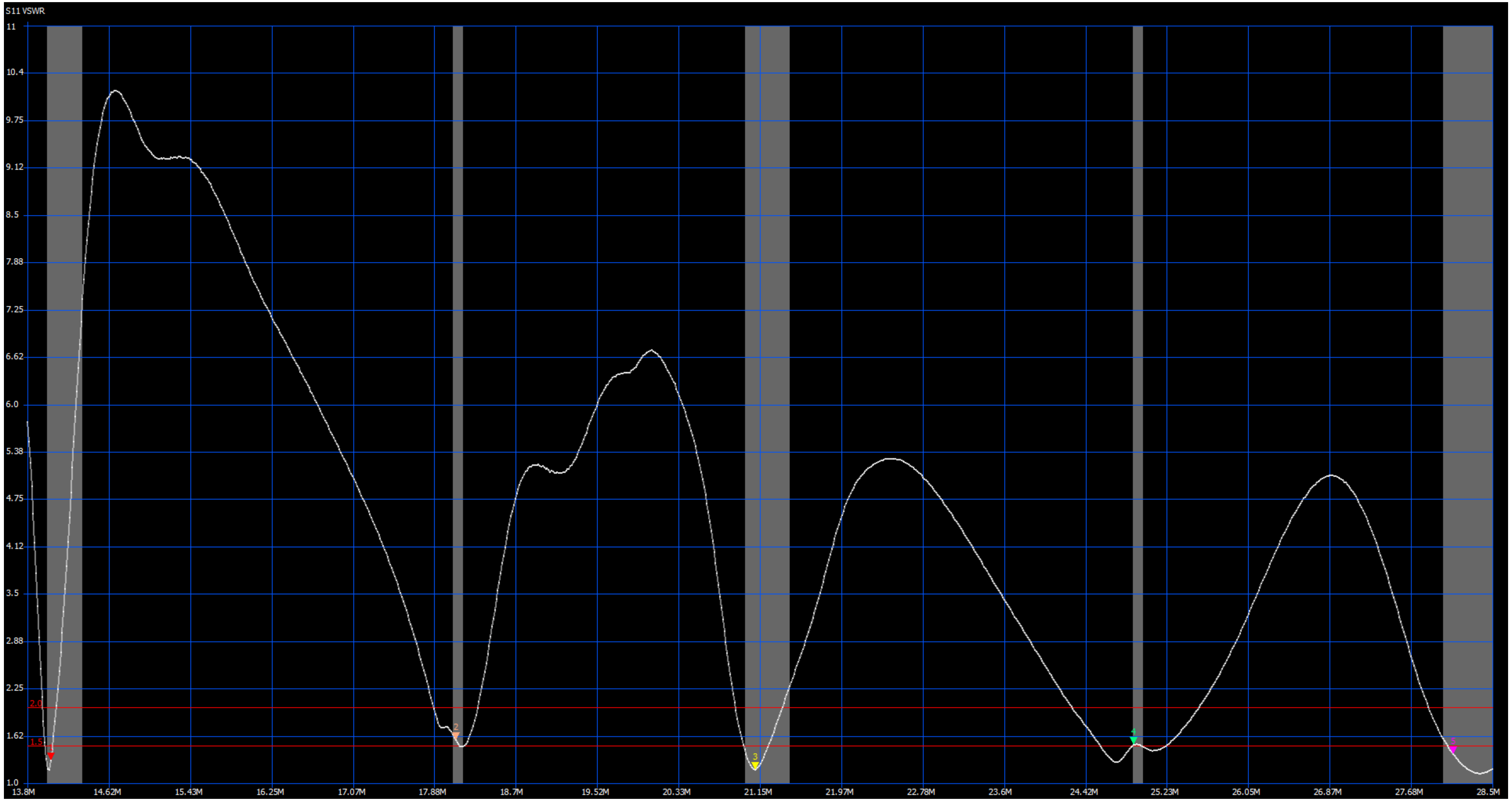
'Smith Chart MADNESS' ☺





Let me tell you why this is madness

MA5B VSWR radio amateur **'common sense'**



Who was Mr. Smith

Bron: Smithchart.org

Phillip Hagar Smith
Lexington, Massachusetts
1905 – 1987
Engineer at Bell Telephone Laboratories

1939: Made the chart (Smith Chart) as a calculation tool for calculating complex parameters of a transmission line, the reflectioncoëfficiënt and impedances.

In short: without formulas and computer:
a graphical calculator

Pause, and in part 2: the APPLICATION of it all

- the design of a matching network with a Smith Chart (e.g. an antenna tuner …)

  - impedance & admittance
    ('admittance' is the reverse of impedance)

  - the Smith Chart with impedance and admittance

  - Tune an antenna impedance to 50 ohm with the Smith Chart
    (so: tune a random impedance to 50 ohm)

- Easy free online tooling on the internet

VSWR | reflectio n | Smith&ZL | Coax | **PAUSE** | admittance | Tuners | Demo L | software

Admittance: have we seen that before?

- Parallel set of resistors
- In fact the adding of conductors in parallel so you can add up the amount of conductance
- the total conductance is sum of all conductances

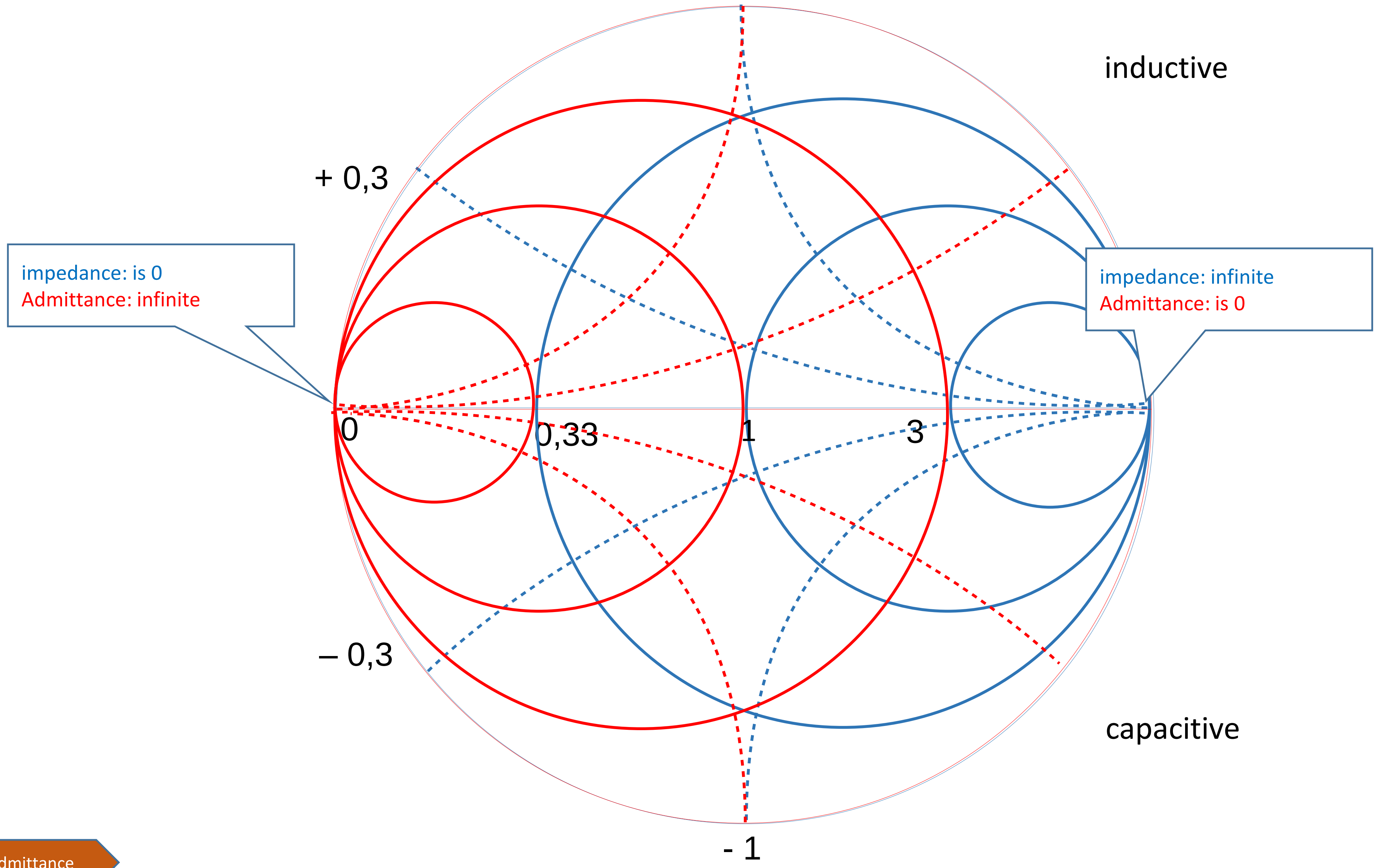
$$\boxed{\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$$

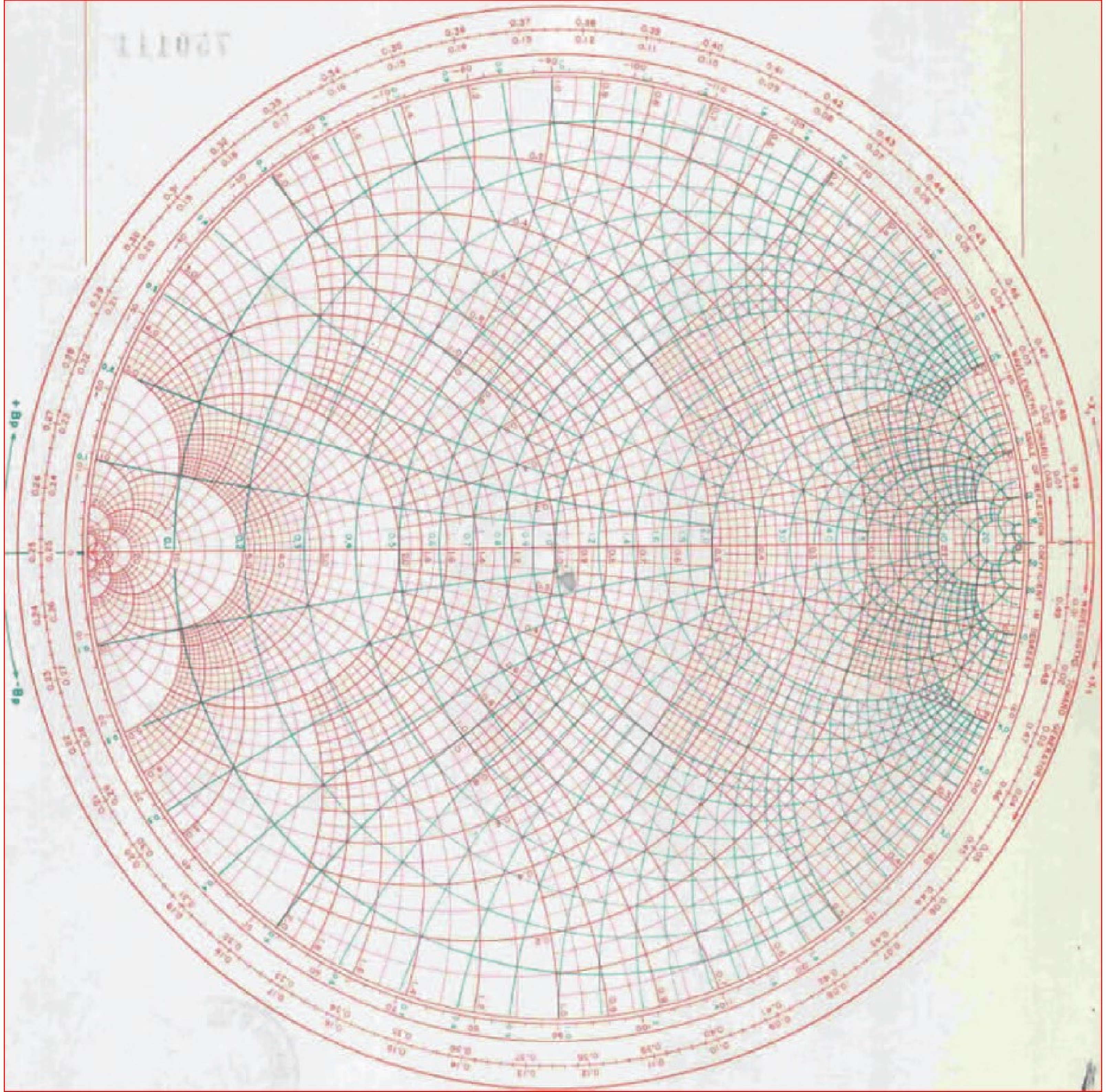
with a parallel resistor we add conductance

this is also true for inductances and capacitors (X_L and X_C)

- this formula is for all impedances
- the reverse of impedance (Z) is called admittance ($Y = \frac{1}{Z}$)

impedance in the Smith Chart with the impedancelines
and
admittance in the Smith Chart with the admittancelines

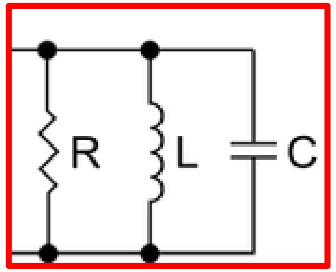


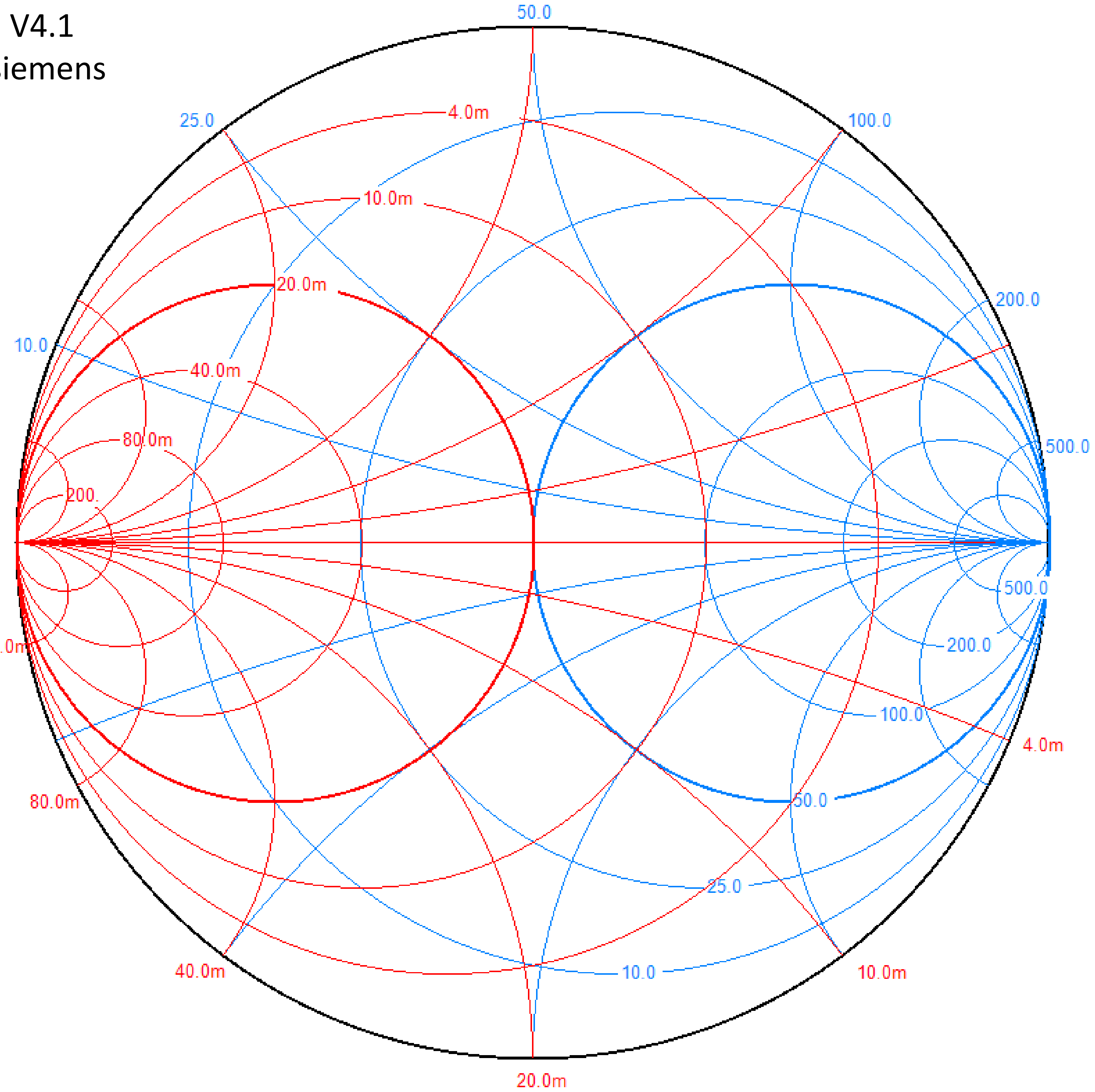


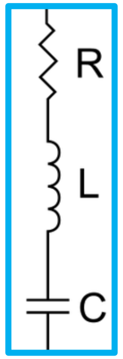
Old copy, as used in the
‘good ole days’
(found on the internet)

admittance

Source: Smith V4.1
In ohms and siemens







admittance

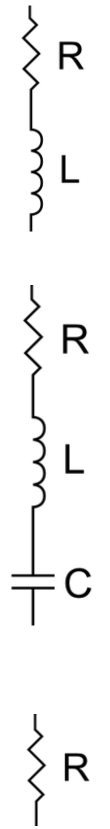
Tuner: TRICK 1 with the Smith Chart *...here we go...*

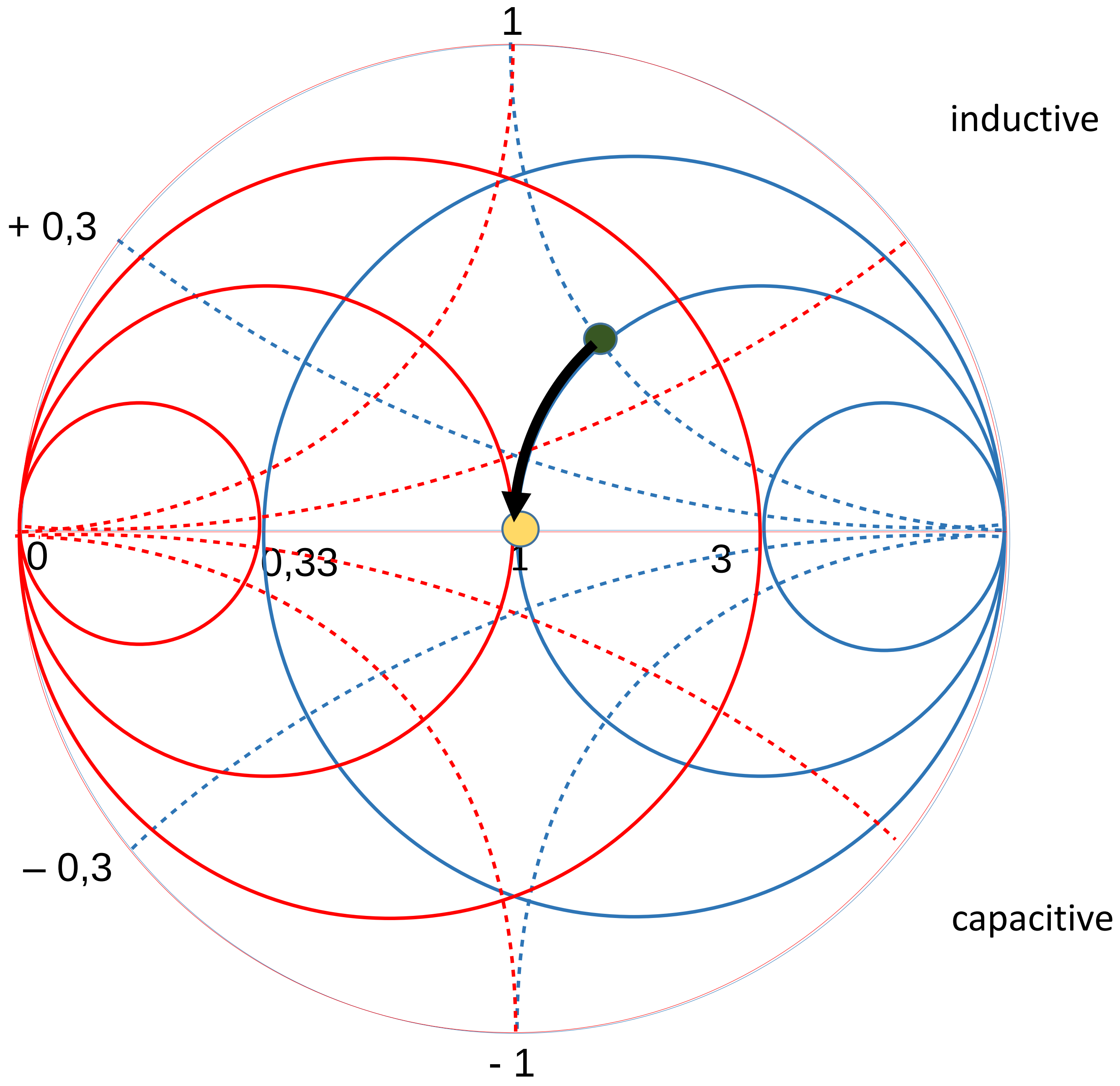
Capacitor in series: Direction to capacitive side along the series/resistive lines

Suppose a Z: 50+j50 ohm
1 + j1 in the chart
SWR = 1 : 2.6

Tuning the +j50 ohm with a capacitor with value -j50 ohm in series
(= series resonance)
Then you arrive at a clean 50 ohm without any reactance

In the Smith Chart:
Anti-clockwise down over the resistor lines ('series lines') in direction of capacitive part of the chart.

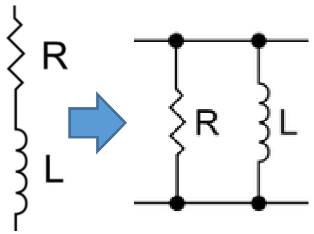


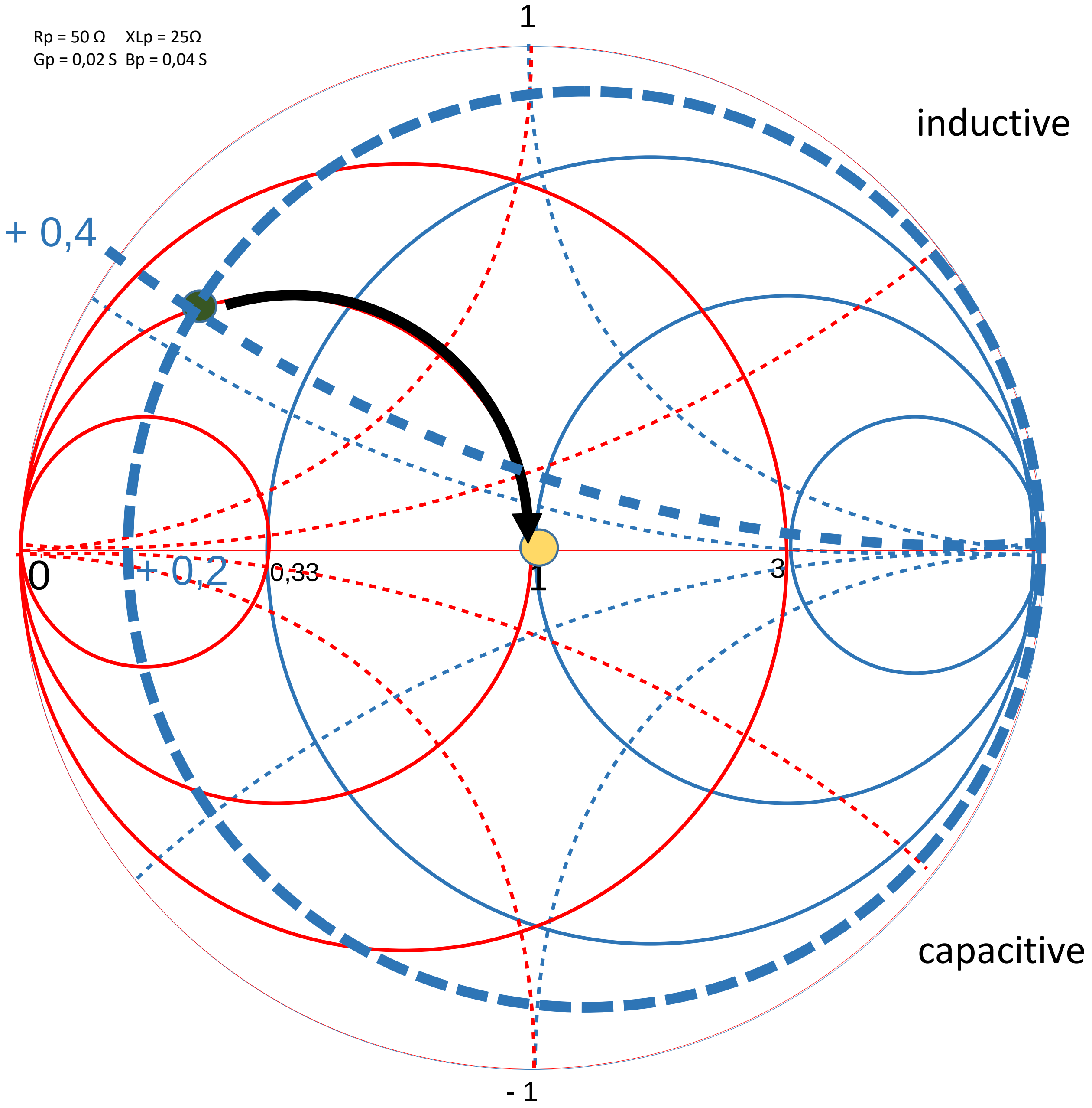


Tuner: TRICK 2 with the Smith Chart

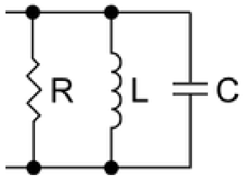
Capacitor parallel: Direction capacitive part along the red admittance lines

Z = 10+j20 ohm
in the schart: 0,2+j0,4
SWR = 1 : 10





We will match this with a capacitor in parallel (adding of capacitive reactance)



In the Smith Chart: Clockwise over the red **admittance lines** ('parallel lines') in direction of capacitive part of the chart.

We have just matched 10+j20 ohm (SWR=10) to 50 ohm (SWR=1) with ONE capacitor in parallel!

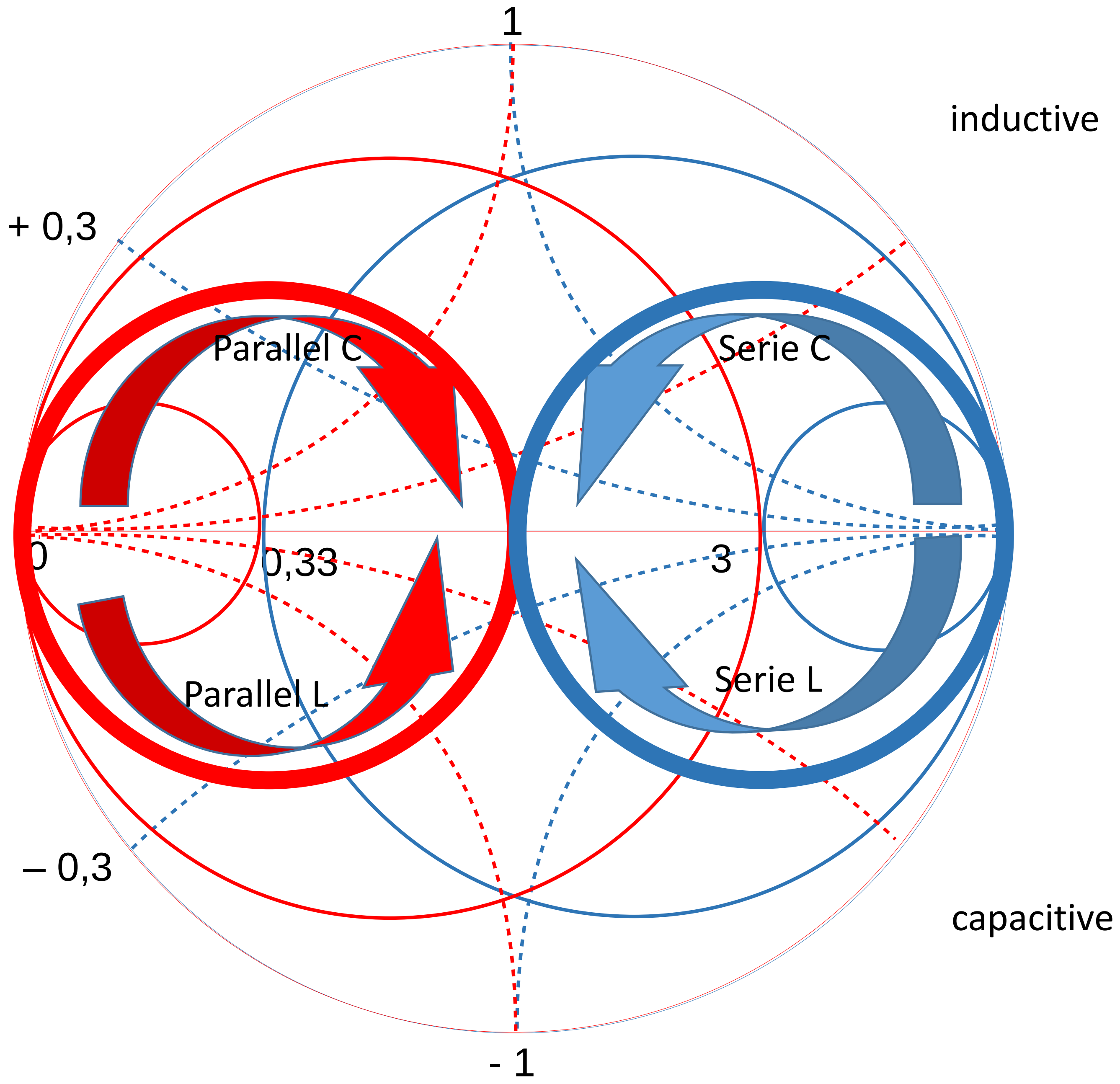
We have seen that we could match several impedances to the 50 ohm value with one single Capacitor.

The other way around with a variable inductance is the opposite

So this is simple….

ONLY when the impedance we have to match is on the circles through 1 (=50 ohm).

These are the 50 ohm line (blue) and the 1/50 ohm = 20 milli siemens line (red)



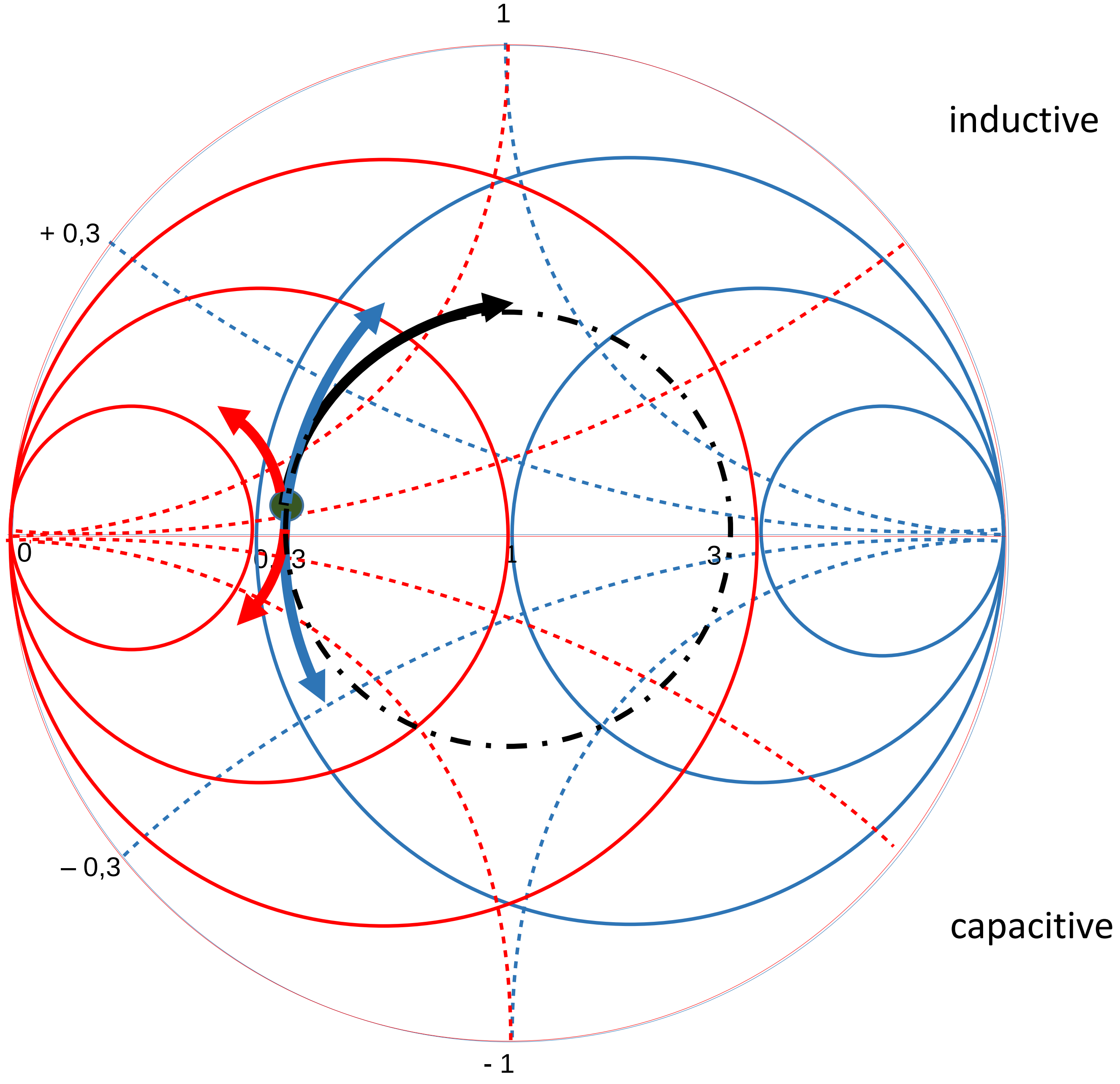
Wrapping up the adding of components

Random impedance is given (see dot).

transmission line in series: Clockwise over the so called constant SWR circle where you are adding extra phase lag (circle around the middle)

Parallel L or C:
Along the red admittance (parallel) lines

Series L or C:
Along the blue impedance (series) lines



Tuners

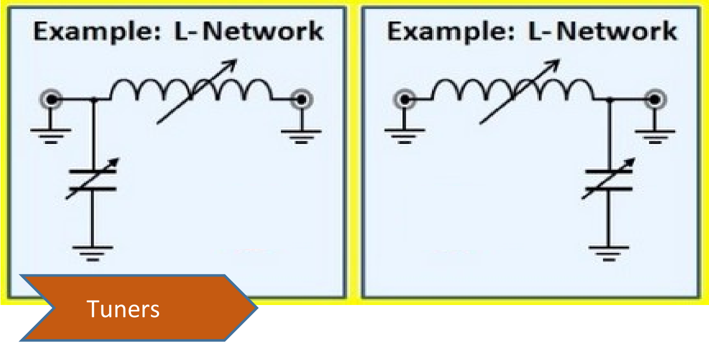
Excersice:

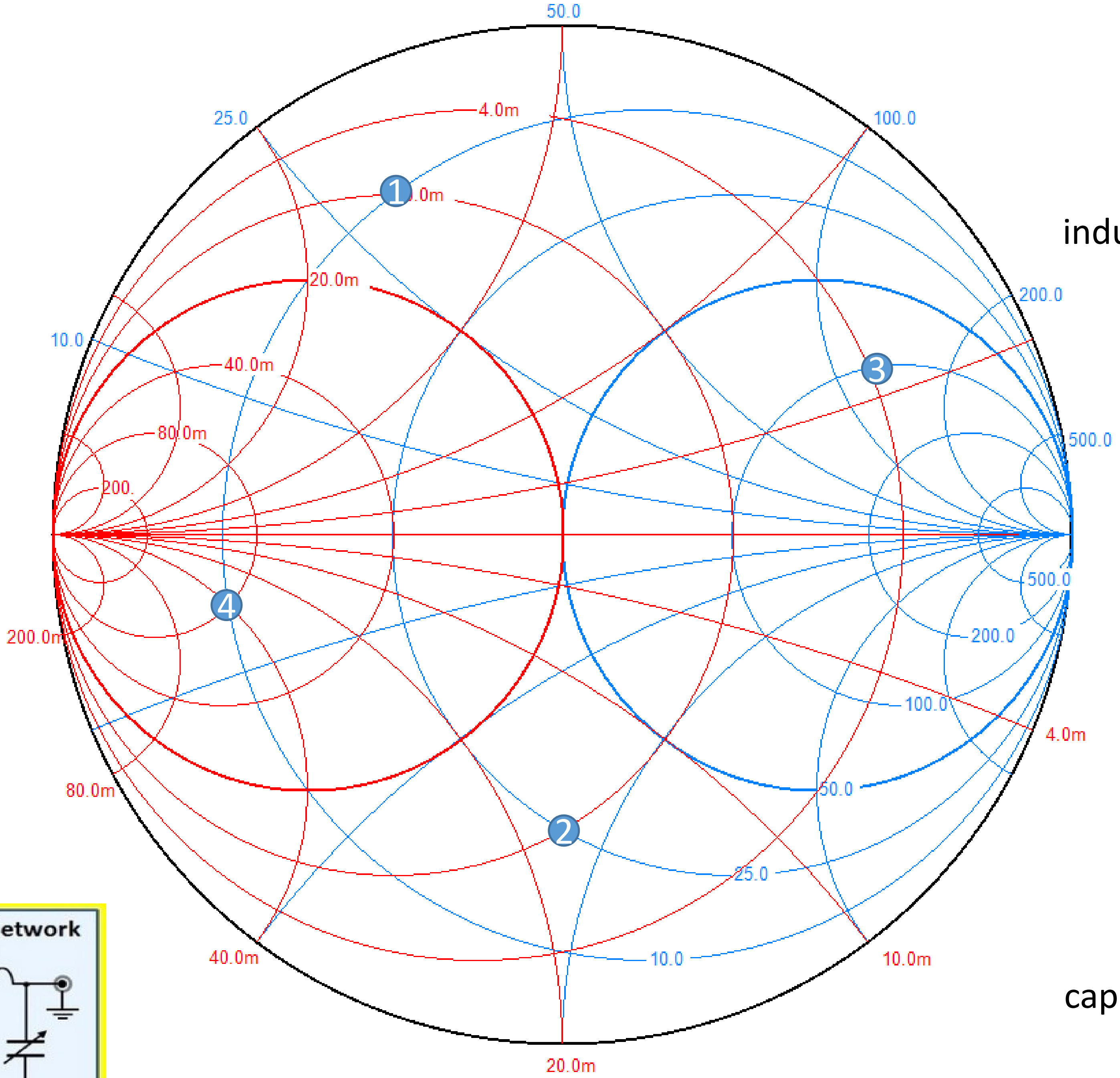
How are we gonna tune dot 1 to 4 to a 50 ohm value

Tip 1:
Move your impedance to one of the two 50 ohm / 20mS circles first

Tip 2:
With two components try a Low-Pass configuration (good practice):
- series-L and parallel-C
  or
- parallel-C and series-L

(This can always be done)

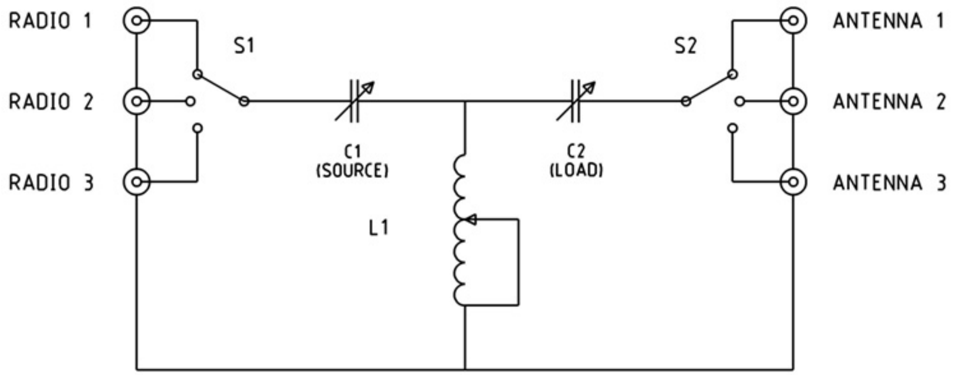




inductive

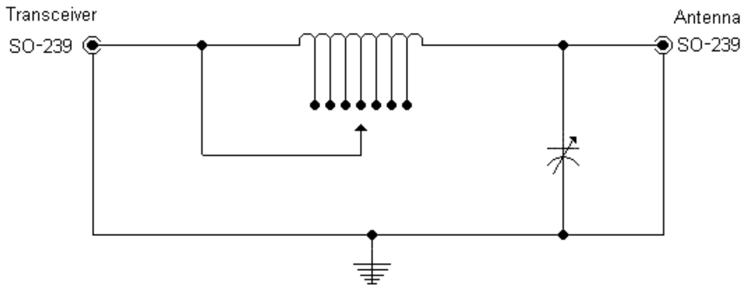
capacitive

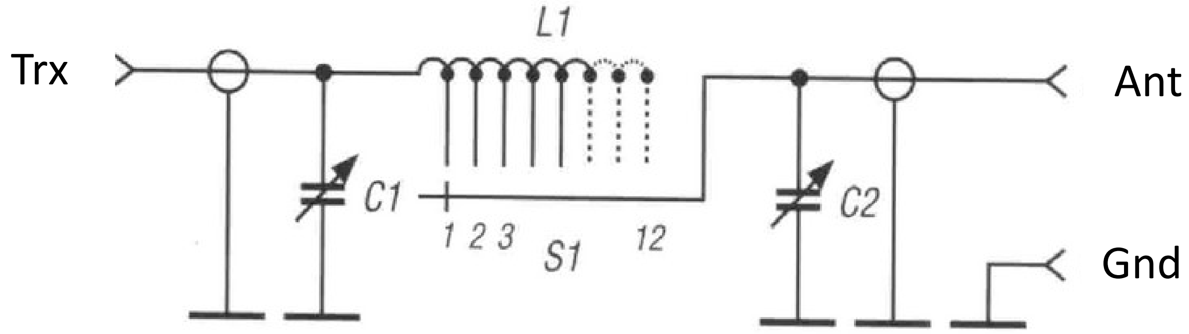
The usual tuner networks → T-, L- and PI-



T-tuner

L - Network Tuner





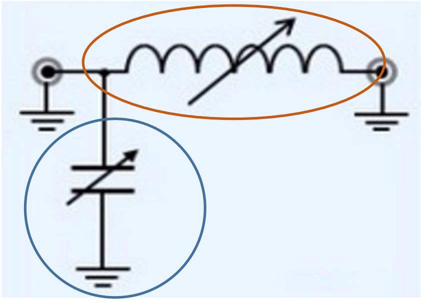
Pi-tuner

Solution 1

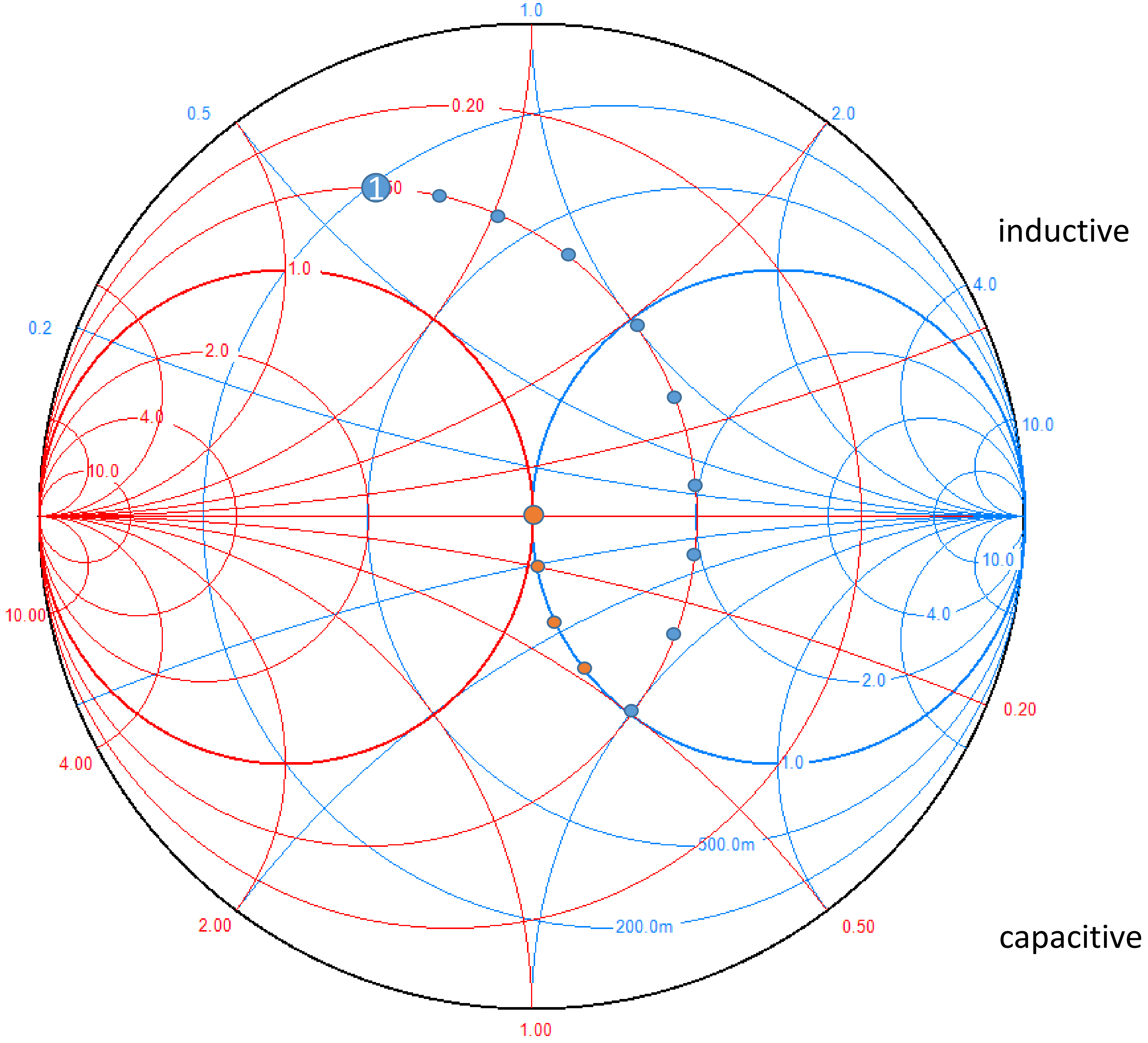
with **L-network**:

with Parallel C
and
Series L

(in low-pass)



First parallel C and then series L .
Here is only *one* possible solution.



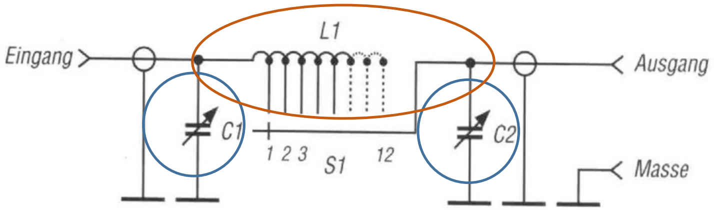
Tuners

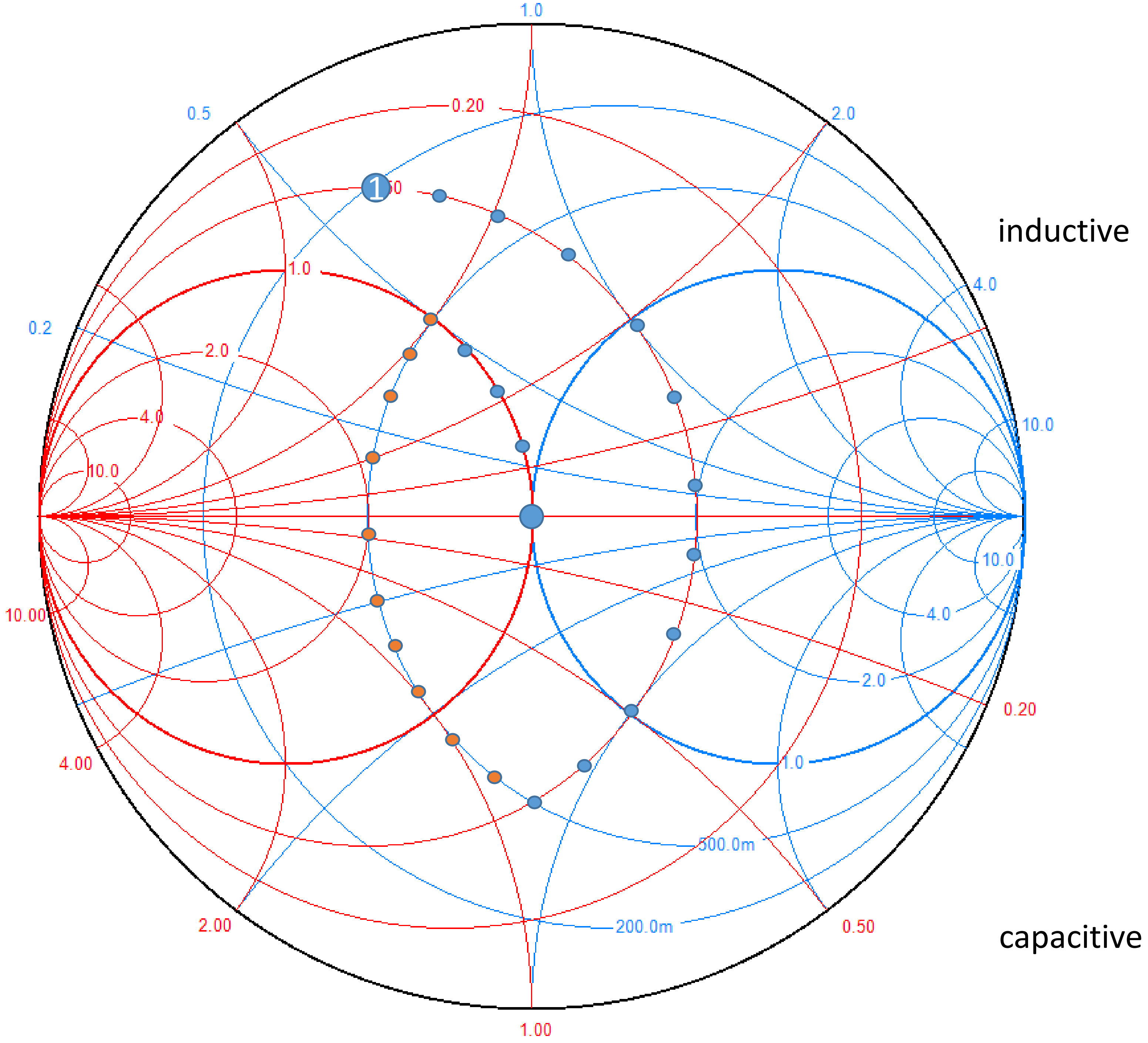
Solution 1

with **PI-network**:

with Parallel C
and
Series L
and
Parallel C

this is a <u>possible</u> solution;
there are more 'paths' to the 50 ohm centre than the one shown here





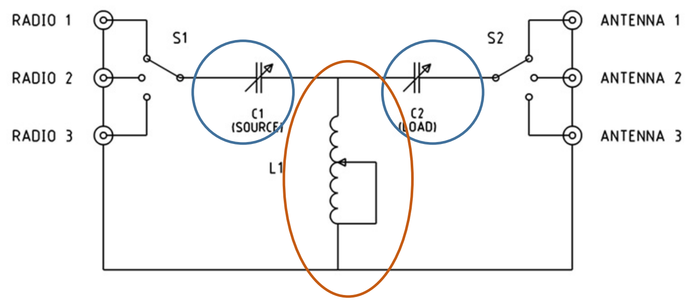
Tuners

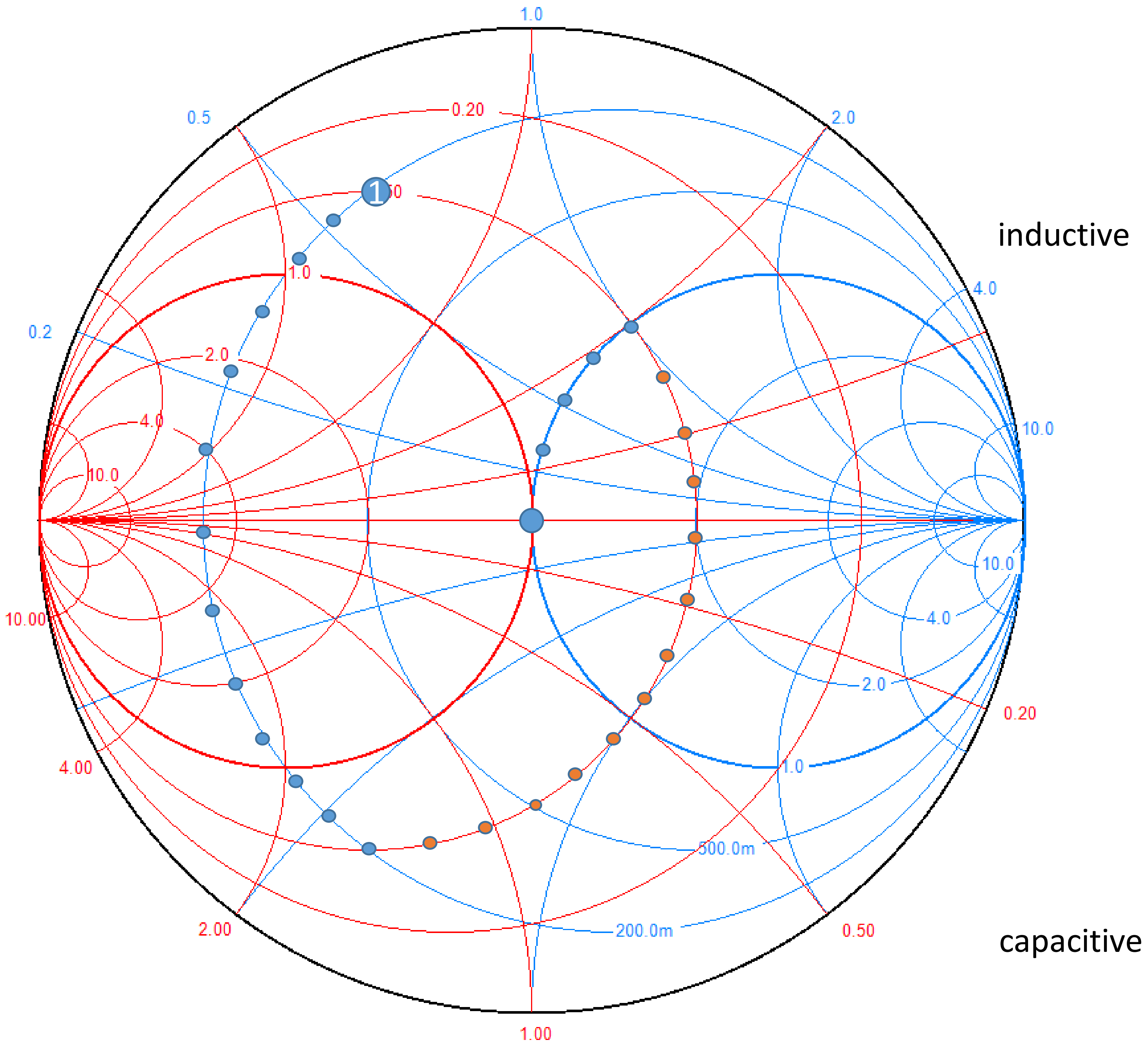
Oplossing 1

with **T-network**:

with Series C
and
Parallel L
and
Serial C

Also: many combinations possible.

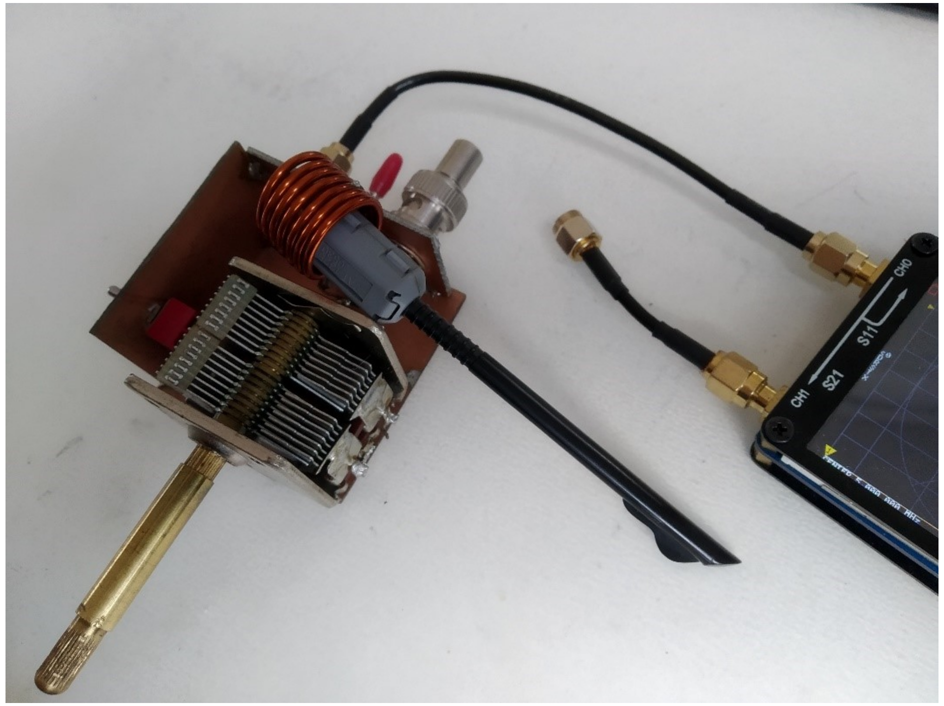


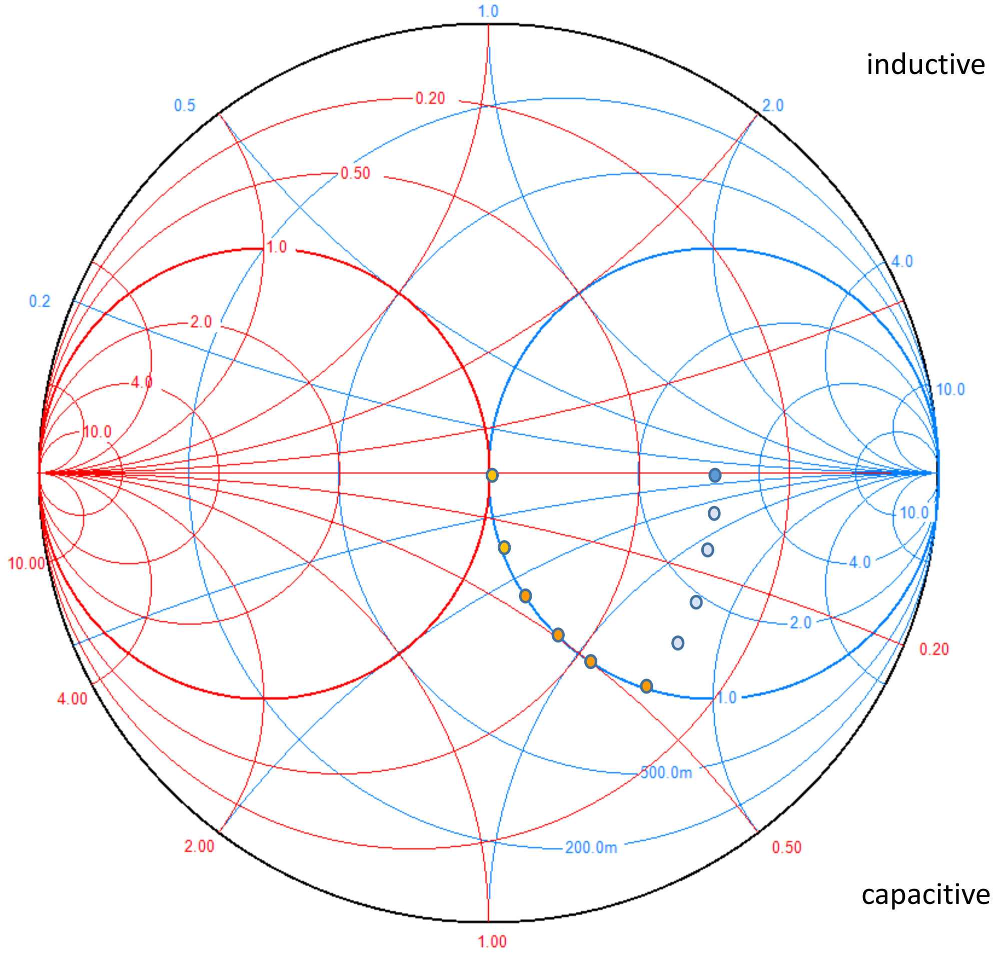


Tuners

Demo

- 150 ohm (SWR = 3) tune to 50 ohm (SWR = 1)
- With tuner (L-network) and the nanoVNA





Tuners

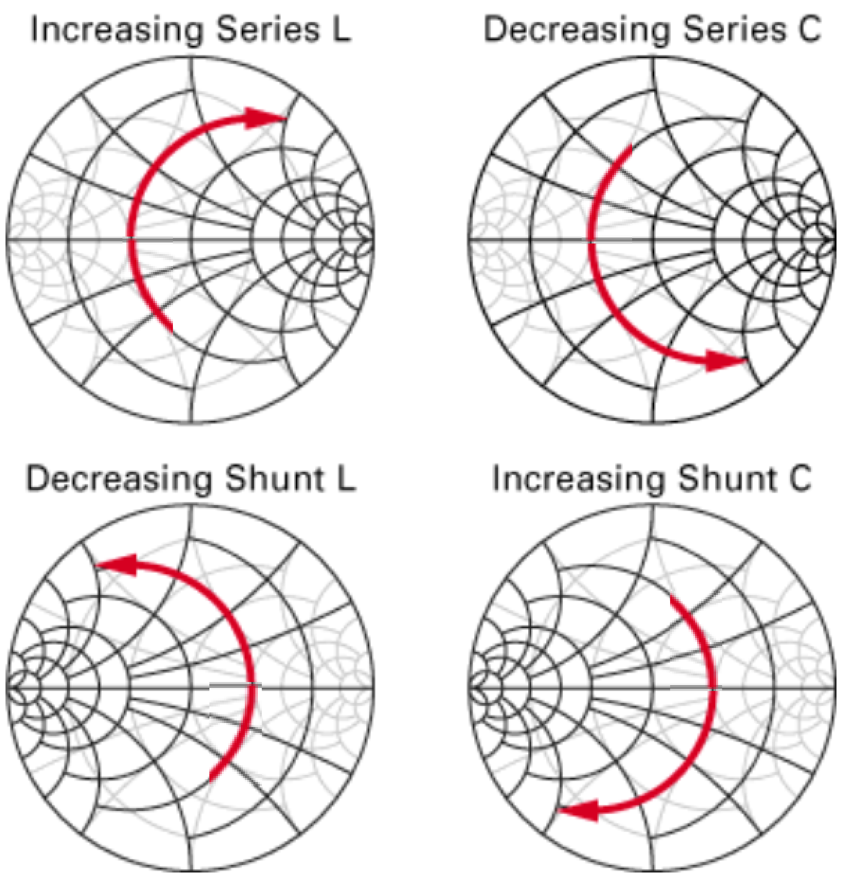
L and C– network

source: certifytech.tripod.com
http://certifytech.tripod.com/references/electronic/electronics/impedance.html modified

A helping hand??
The picture is true but:

Easy mixed up and / or forgotten

Stay away from these pictures.
It’s far better to go over this presentation again and know what you are doing.

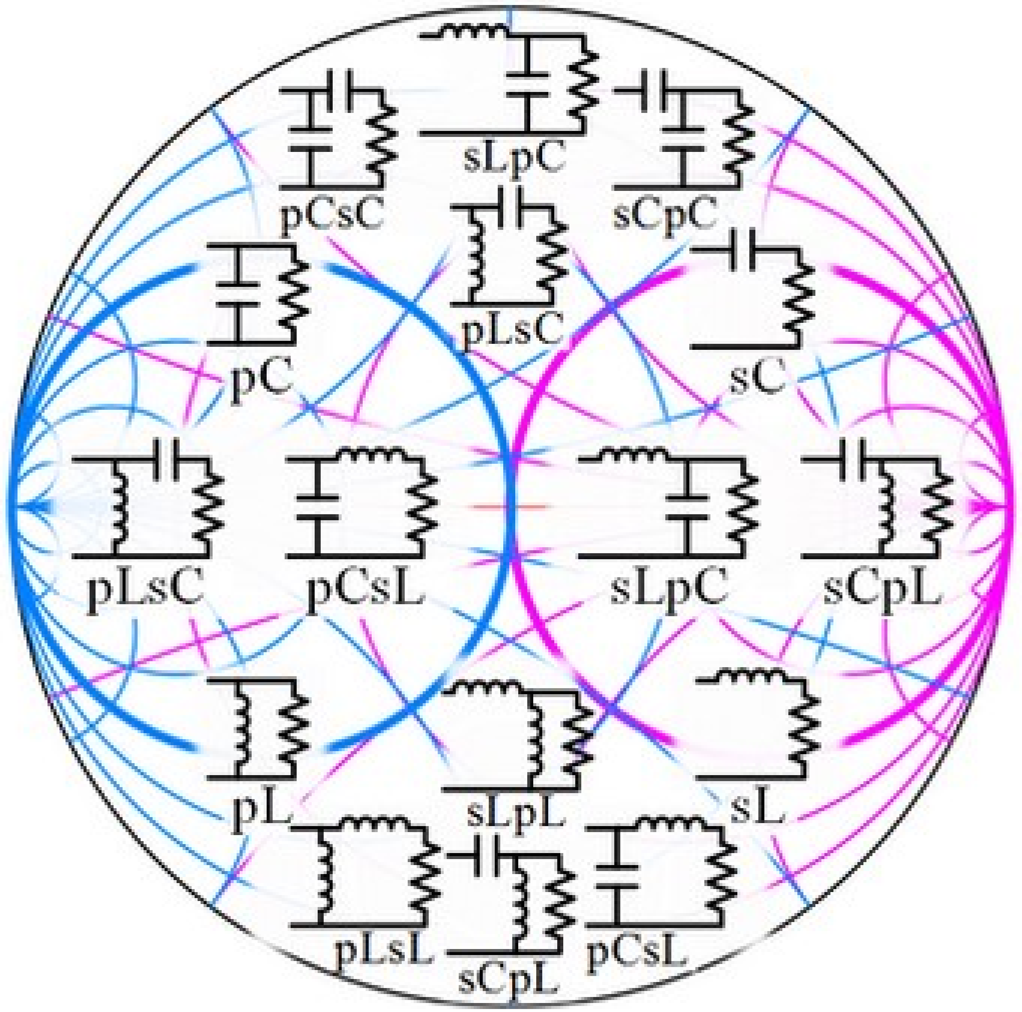


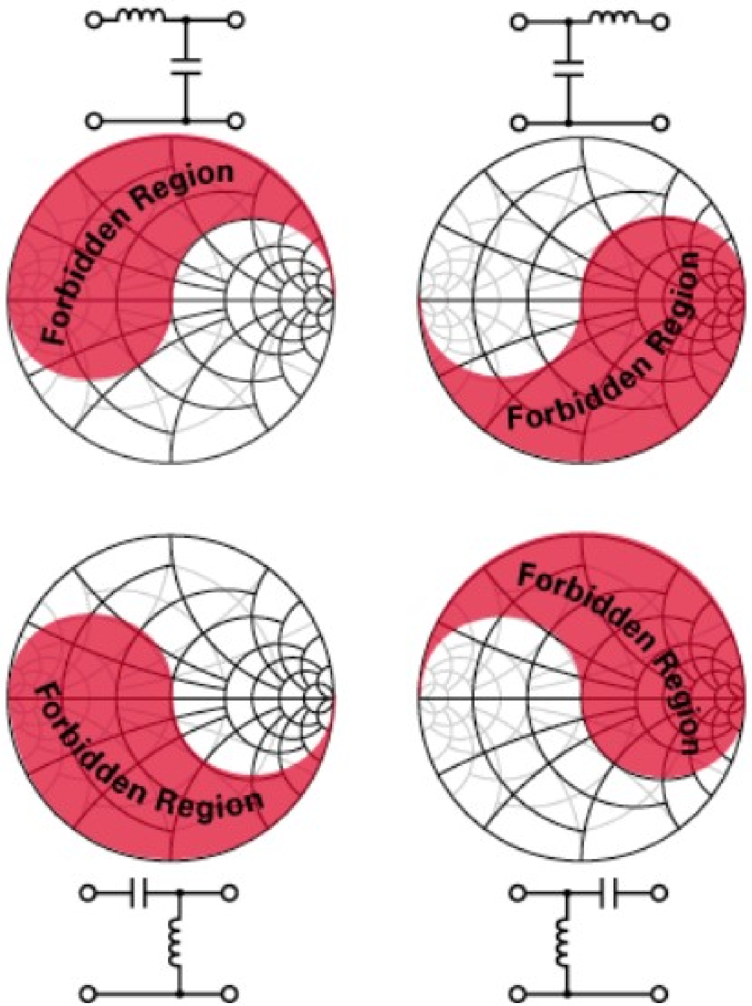
Tuners

More of the same: matching with two components.

Stay away from these, they won't help you.

Trust what you have learned from this presentation.





Sources:
https://www.researchgate.net/publication/324837507_An_Ultrasonic_Through-Metal-Wall_Power_Transfer_System_with_Regulated_DC_Output
http://home.sandiego.edu/~ekim/e412f04/e412lab06.pdf

Tuners

Online tooling to WILL help you

- Website RF mentor:
  https://www.rfmentor.com

Use this to practise and learn the Smith Chart. This will help you to remember the 'moves' and make further steps.

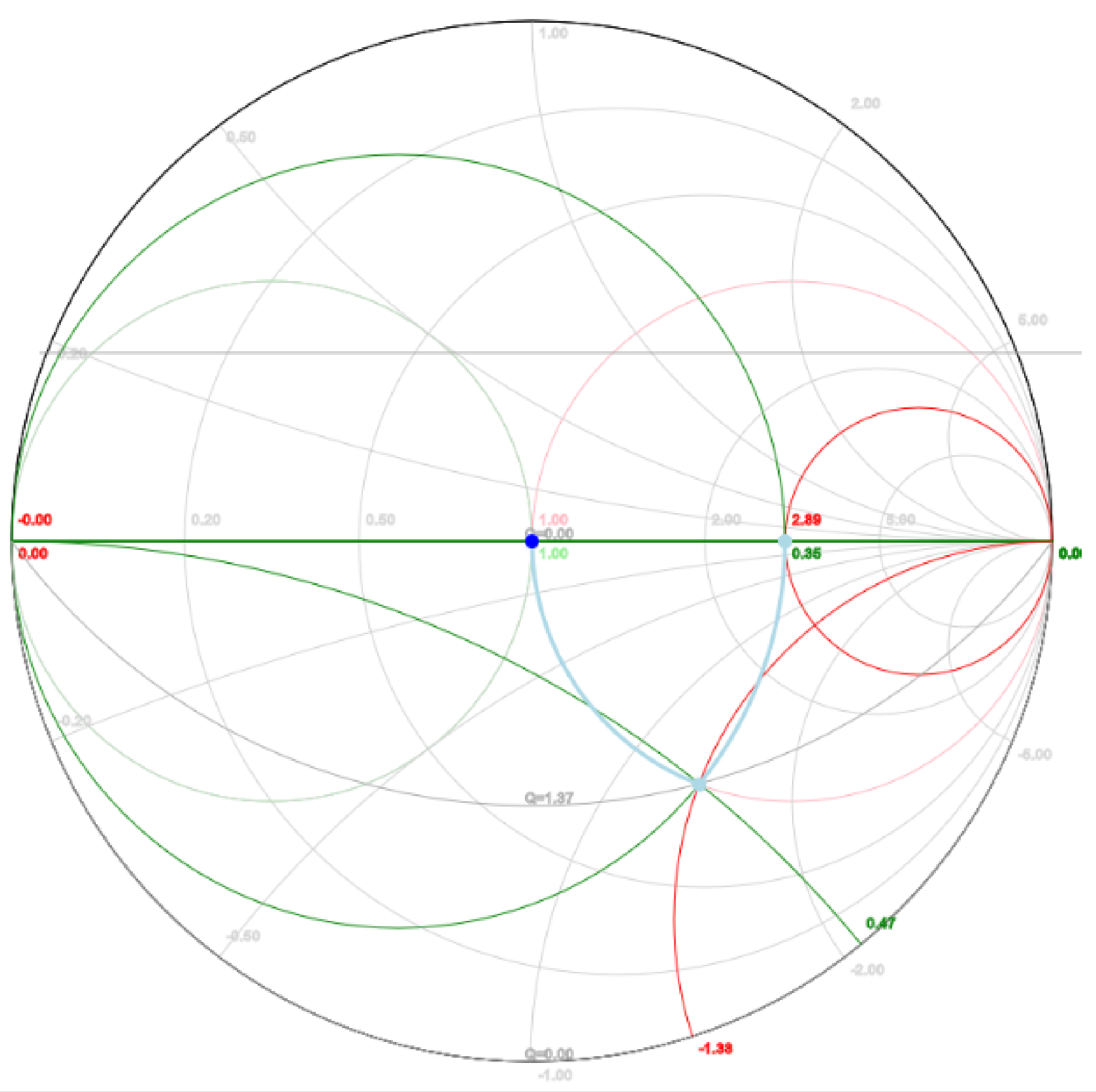
- Smith Chart software:
  - SimSmith: http://www.ae6ty.com/Smith_Charts.html

    (of SimSmith there is a beautiful series of tutorials on YouTube by Larry N0QE !!)
  - Smith: https://www.fritz.dellsperger.net/smith.html
  - PASAN: http://www.science4all.nl/?Electronics___Pasan

Tuners

Drag-n-Match Smith Chart Matching

Add Circuit | Ser Cap | Ser Ind | Ser Res | Ser TL | Sht Cap | Sht Ind | Sht Res | Sht Short TL | Sht Open TL | Delete Item



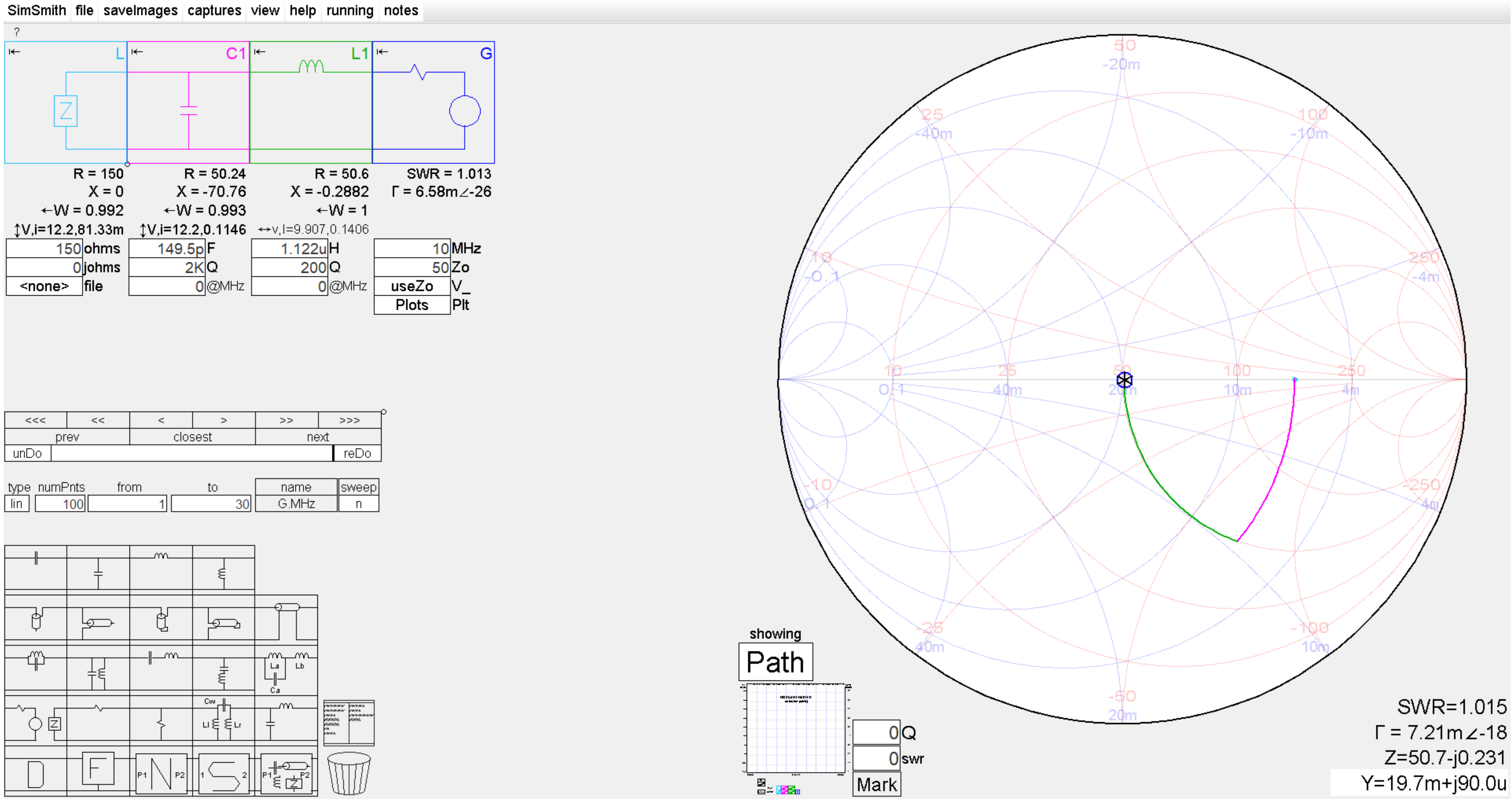
Element	Value	Gamma (mag,ang)	Impedance (r,jx)	Admittance (g,jb)
Starting Gamma	(0.49@ -0.00°)	(0.49@ -0.00°)	(2.89,j0.00)	(0.35,j0.00)
Shunt Capacitor	151.14 pF	(0.57@ -55.40°)	(1.00,j-1.38)	(0.35,j0.47)
Series Inductor	1095.87 nH	(0.00@ -0.00°)	(1.00,j-0.00)	(1.00,j0.00)

Subscription:

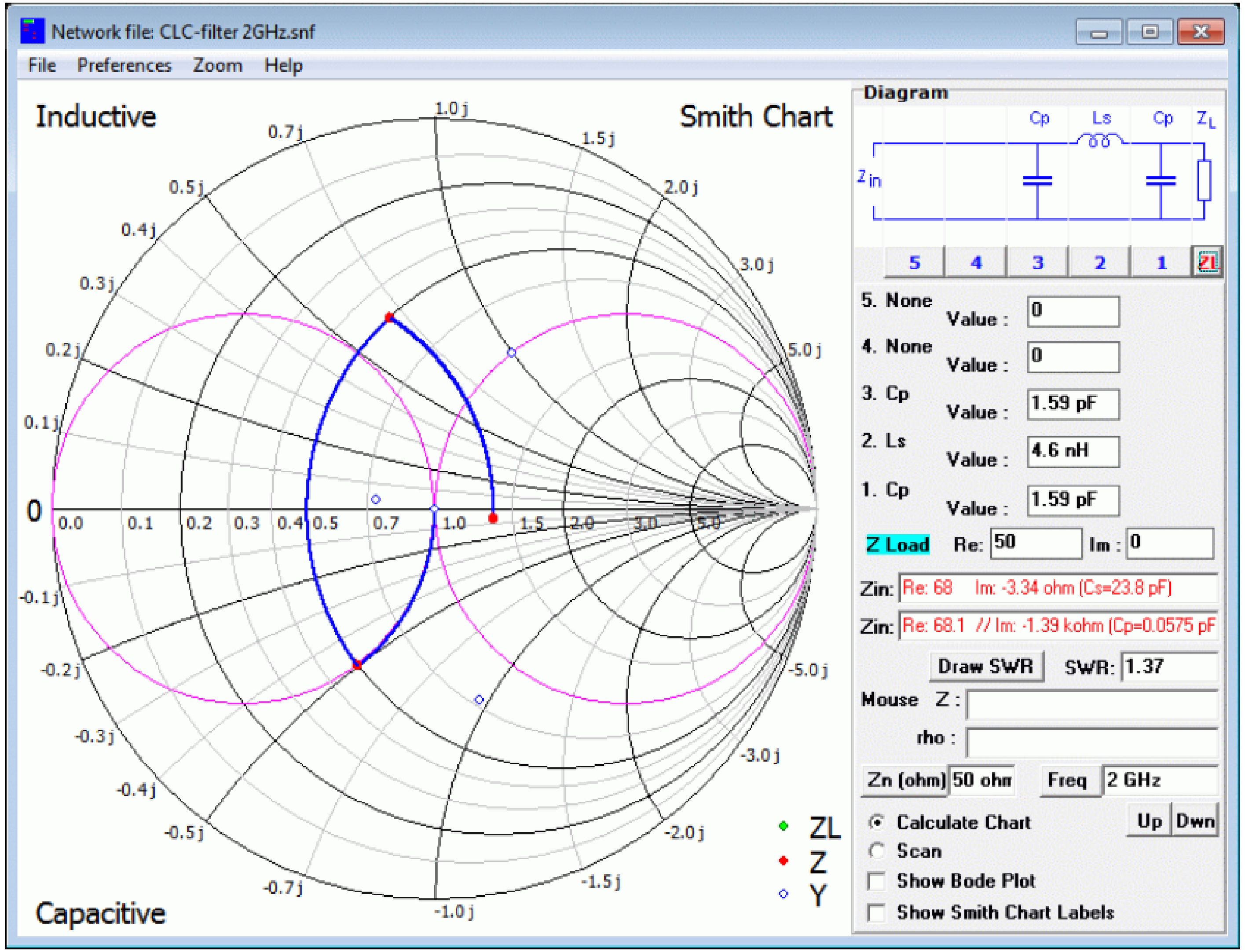
RF Mentor

Smith Chart

SimSmith


SimSmith file saveImages captures view help running notes
L C1 L1 G
R = 150
X = 0
←W = 0.992
↕V,i=12.2,81.33m
R = 50.24
X = -70.76
←W = 0.993
↕V,i=12.2,0.1146
R = 50.6
X = -0.2882
←W = 1
↔v,I=9.907,0.1406
SWR = 1.013
Γ = 6.58m∠-26
150 ohms
0 johms
<none> file
149.5p F
2K Q
0 @MHz
1.122u H
200 Q
0 @MHz
10 MHz
50 Zo
useZo V_
Plots Plt
prev closest next
unDo reDo
type numPnts from to name sweep
lin 100 1 30 G.MHz n
showing
Path
0 Q
0 swr
Mark
SWR=1.015
Γ = 7.21m∠-18
Z=50.7-j0.231
Y=19.7m+j90.0u

Pasan



Network file: CLC-filter 2GHz.snf
File Preferences Zoom Help
Inductive
Smith Chart
Capacitive
Diagram
Cp Ls Cp ZL
Zin
5 4 3 2 1 ZL
5. None Value : 0
4. None Value : 0
3. Cp Value : 1.59 pF
2. Ls Value : 4.6 nH
1. Cp Value : 1.59 pF
Z Load Re: 50 Im : 0
Zin: Re: 68 Im: -3.34 ohm (Cs=23.8 pF)
Zin: Re: 68.1 // Im: -1.39 kohm (Cp=0.0575 pF
Draw SWR SWR: 1.37
Mouse Z :
rho :
Zn (ohm) 50 ohm Freq 2 GHz
Calculate Chart Up Dwn
Scan
Show Bode Plot
Show Smith Chart Labels
ZL
Z
Y

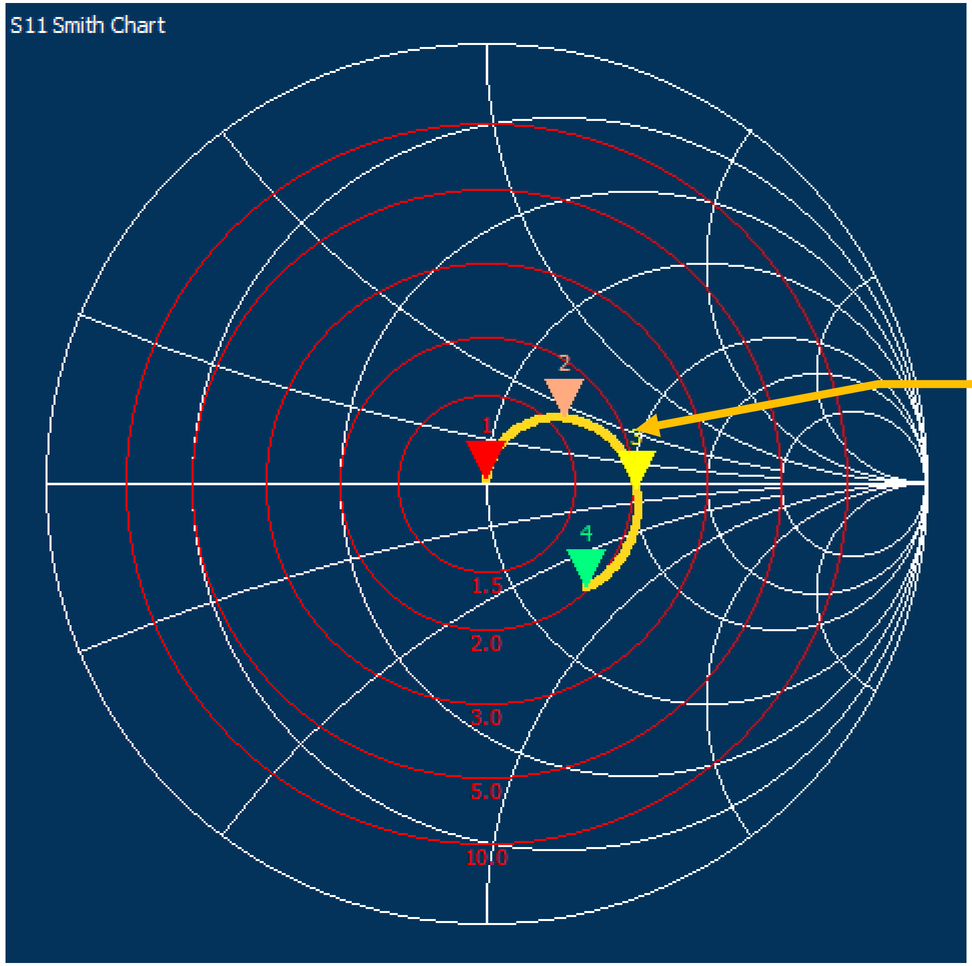
Nice special case:

Measuring of a **50 ohm dummyload** for frequencies 1 – 150 MHz

Haha, Murphy strikes…

- Not a 50 ohm coax used but ***75*** ohm tv coax,
- About 40 cm long

marker	Freq (MHz)
1	1
2	50
3	100
4	150



- In ideal case *circle* through 50 ohm and 112 ohm (1/4 wave transformer)
- length variation: on different frequencies the cable has a different length in degrees.
- You don't see an exact circle because there are other losses
- The expected constant SWR of the dummy is varying – oscillating because of the 75 ohm cable

To prevent certain mis-understandings.

- the Smith Chart is a plot of the measured Reflection Coëfficiënt of a Load that is connected to a transmission line. The Smith Chart Zo is the Zo of the transmission line, in hamradio world mostly 50 ohm.

- the reflection Coëfficiënt is the RATIO of two voltages: reflected signaal off the Load (Urefl) and the signal of the transmitter sent to that load (Ufwd).
  This is often called the 'Gamma' (Greek capital Γ) and is equal to Urefl / Ufwd.
  The phase angle in the chart is the measured phase difference between the Urefl and Ufwd .

- For the impedance circles that are projected on the the Smith Chart (as Reflection Coeffient projection): these are the reflection causing impedance values R+jX for every reflection point in the Smith Chart.

To be stressed:
the phase shift of the **reflection coefficient** in the Smith Chart (difference between **voltages** Ufwd and Urefl) is different from the phase shift between **voltage and current** at the load R+jX.

SWR related formulas

Have a party ☺ !

$$\Gamma = \frac{ZL - Z0}{ZL + Z0}$$

$$\mathrm{SWR} = \frac{|V_{\max}|}{|V_{\min}|} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

$$VSWR = \frac{Vmax}{Vmin}$$

satoms.com

$$\mathrm{SWR} = \frac{R_L}{R_0} \text{ or } \frac{R_0}{R_L}$$

VSWR = (1+ $10^{RL/20}$) / ($10^{RL/20}$ - 1)

Where:

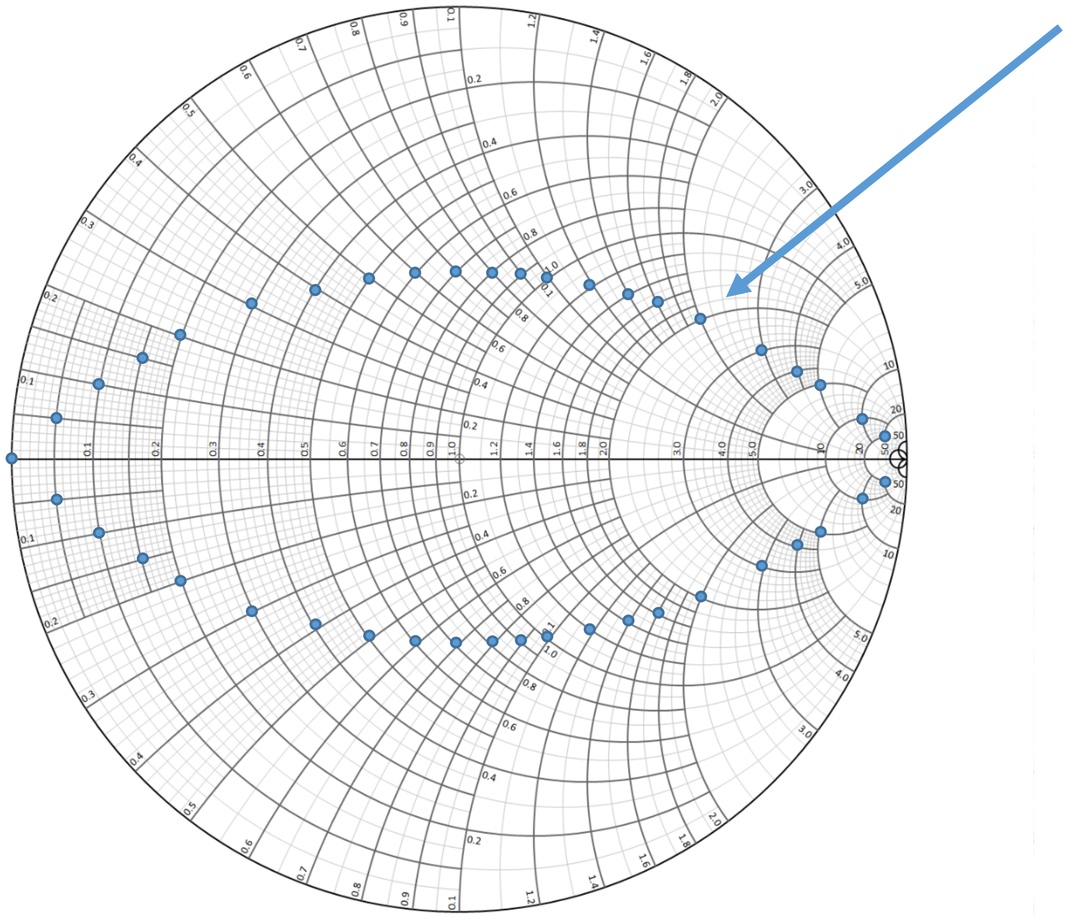
R_0 = line impedance

R_L = load resistance

$$\mathrm{SWR} = \frac{1 + \sqrt{P_r/P_f}}{1 - \sqrt{P_r/P_f}}.$$

Interesting for a radio amateur:
What's the bandwidth of the carefully designed matching network?

- the Q-cirkels in the Smith Chart go from zero up to a high number → the spots in the chart where X /R = constant



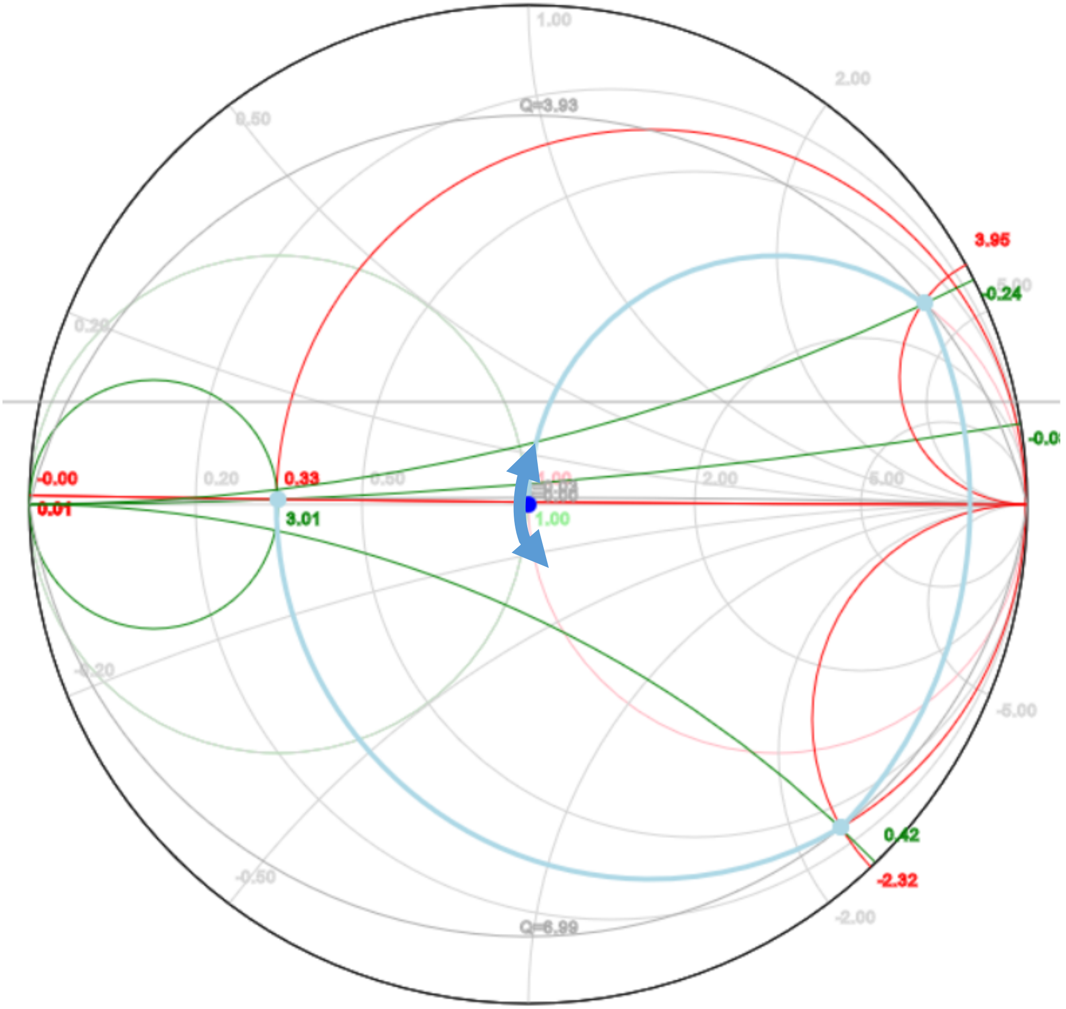
- Drawn Q = 1, so |X|= R *in the Smith Chart*
- You can plot them for all different values of Q

Attention:

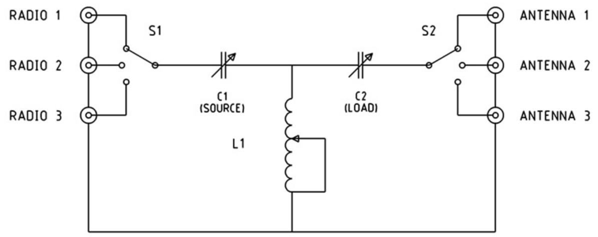
- This Q in the Smith Chart is NOT the Q of a standard LC-circuit. It is a helping tool for the bandwidth of the matching network, the so called '**Loaded Q**' of the matching network
- This bandwidth is influenced by the impedances on both sides of the tuner and the 'spots you pass on the Smith Chart' when matching.
- The closer you stay near the horizontal (ohmic) axis (so away form the outer region of the Smith Chart), the more bandwidth the tuning network will have.

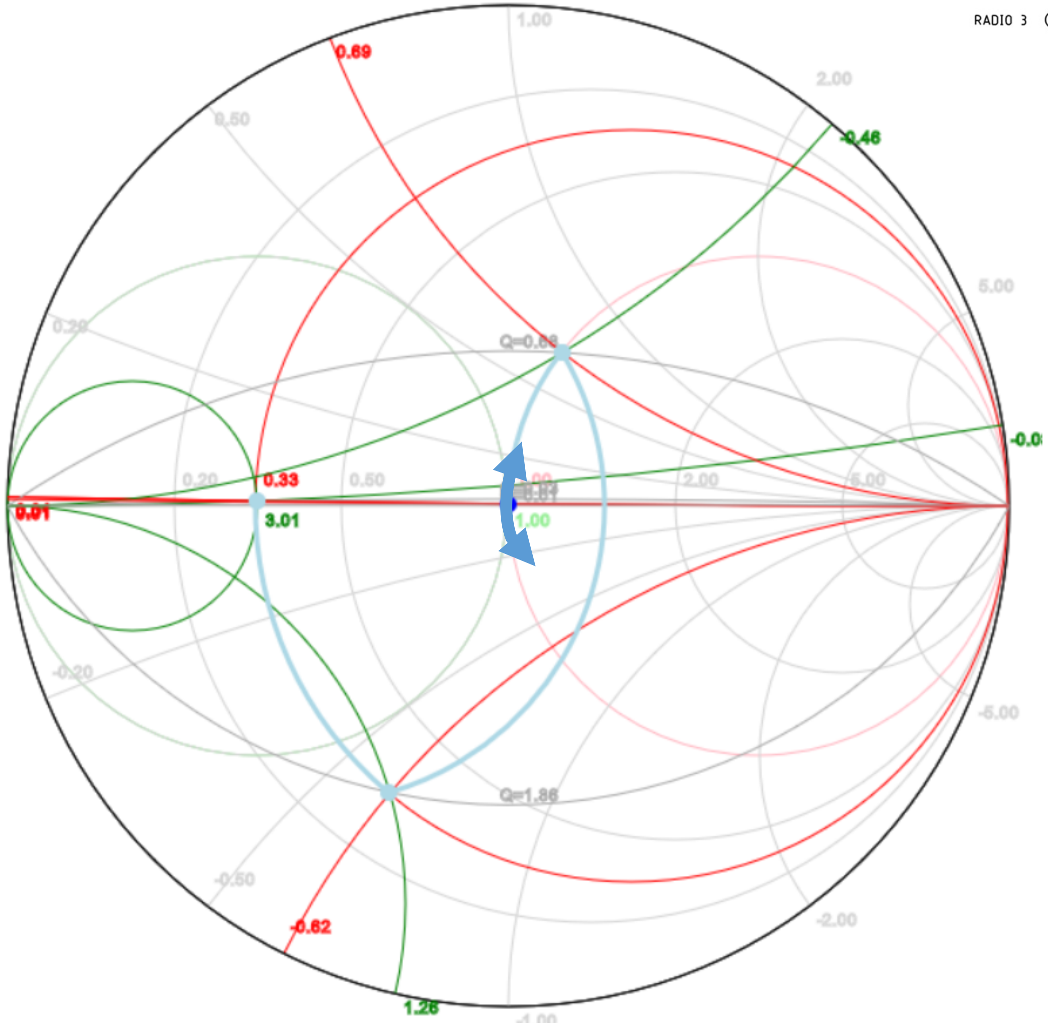
So What? Two examples with a T-tuner C-L-C: 16 → 50 ohm

<u>Case 1 → tuning along the 'outer border'</u>
Last C value: 80pF, the blue arrow length below is caused by an 8 pF change. The tuning is very 'touchy' Experts say that this can easily cause arcing by high voltages and heating by high currents.



<u>Case 2 → tuning closer to the 'middle'</u>
Last C value: 450pF, the arrow length is now caused by about 300 pF change.





Which tuningpath you use can also depend on available L and C ranges in the tuner.

More info on measurements with the nanoVNA:

https://pa3a.nl/nanovna-metingen-and-smith-chart-articles/

Sources:

Pictures of the Smith Chart:

http://certifytech.tripod.com/references/electronic/electronics/impedance.html

https://www.researchgate.net/publication/324837507_An_Ultrasonic_Through-Metal-Wall_Power_Transfer_System_with_Regulated_DC_Output

http://www.excelhero.com/blog/2010/08/excel-high-precision-engineering-chart-1.html

http://home.sandiego.edu/~ekim/e412f04/e412lab06.pdf

General info:

https://Smithchart.org

Software, and Smith Chart pictures:

https://www.fritz.dellsperger.net/smith.html (Smith V4.1 , trial version)

https://github.com/mihtjel/nanovna-saver/releases (nanoVNAsaver v0.2.1)