# Transmission Lines As Impedance Transformers

Bill Leonard  N0CU

285 TechConnect Radio Club

2017 TechFest

# Topics

- Review impedance basics
- Review Smith chart basics
- Demonstrate how antenna analyzers display impedance data
- Demonstrate some important transmission line characteristics

# Impedance

- Impedance (Z) is a measure of the opposition to current flow
  - Unit of measure = Ohm = Ω
- Impedance describes a series circuit
- Impedance has two components:
  - The DC component = Resistance = R (ohms)
  - The AC component = Reactance = X (ohms)

Inductive Reactance

$X_L$ (ohms) = **+** $j2\pi fL$

Phase = **+** $90^o$

(Voltage leads current)

Capacitive Reactance

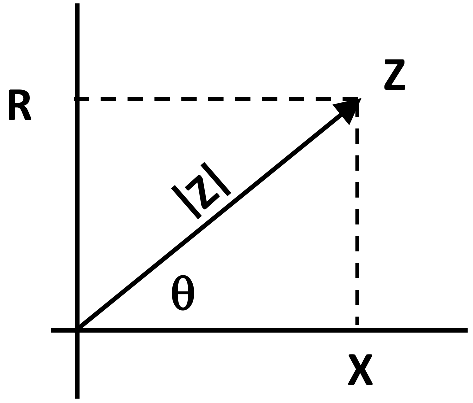
$X_C$ (ohms) = **-** $j[1/(2\pi fC)]$

Phase = **-** $90^o$

(Voltage lags current)

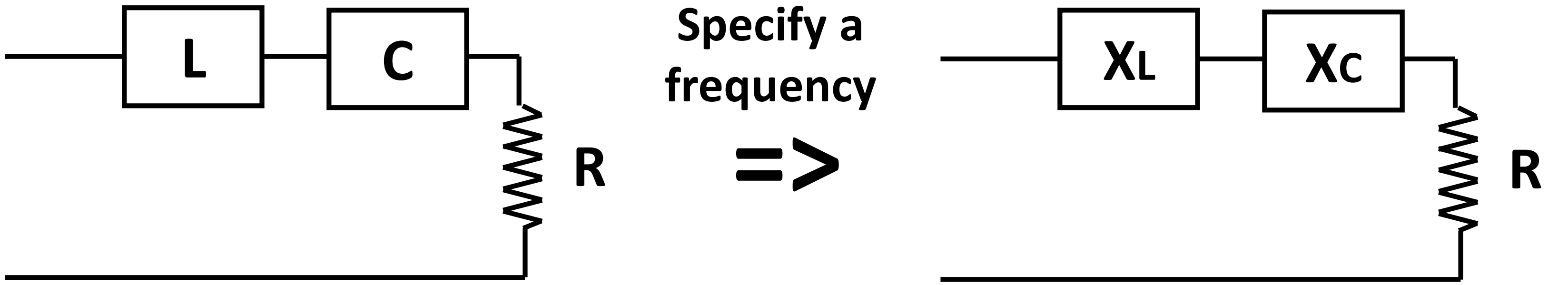
# Impedance – cont'd

- Impedance can be expressed in two ways:
  1. **Resistance** and **reactance** => **$Z = R + jX$** (Complex Number)
  2. **Magnitude** and **phase** => **$Z = |Z| \angle\theta$**
     - Magnitude of Z (ohms) = $|Z| = \sqrt{R^2+X^2}$
     - Phase of impedance (degrees) = $\theta$ = arctan(X/R)

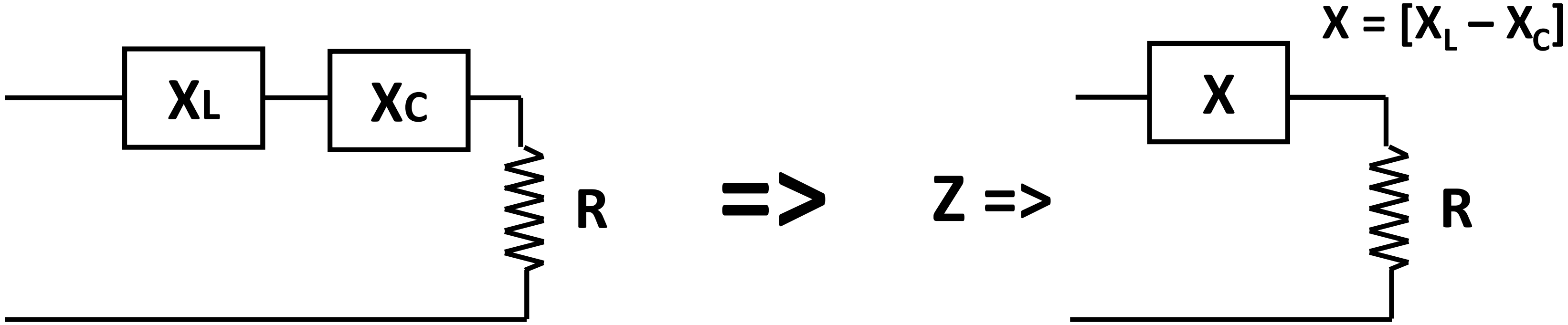


# Impedance of a Series Circuit

Step 1




Step 2



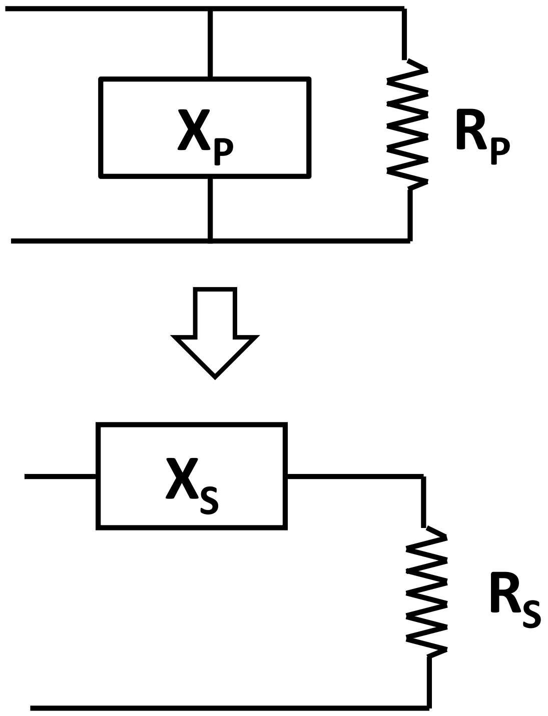

1. $Z = R + j\,X = R + j(X_L - X_C) = R + j[(2\pi fL - 1/(2\pi fC)]$
2. $Z = |Z|$ and $\angle\theta$

# Impedance of a Parallel Circuit

- Z is defined only for a series circuit
  - Must convert a parallel circuit to a series circuit
    - Frequency must be known to do the conversion
    - Both component values change when converted

$Z \neq R_P + jX_P$

$= ?$

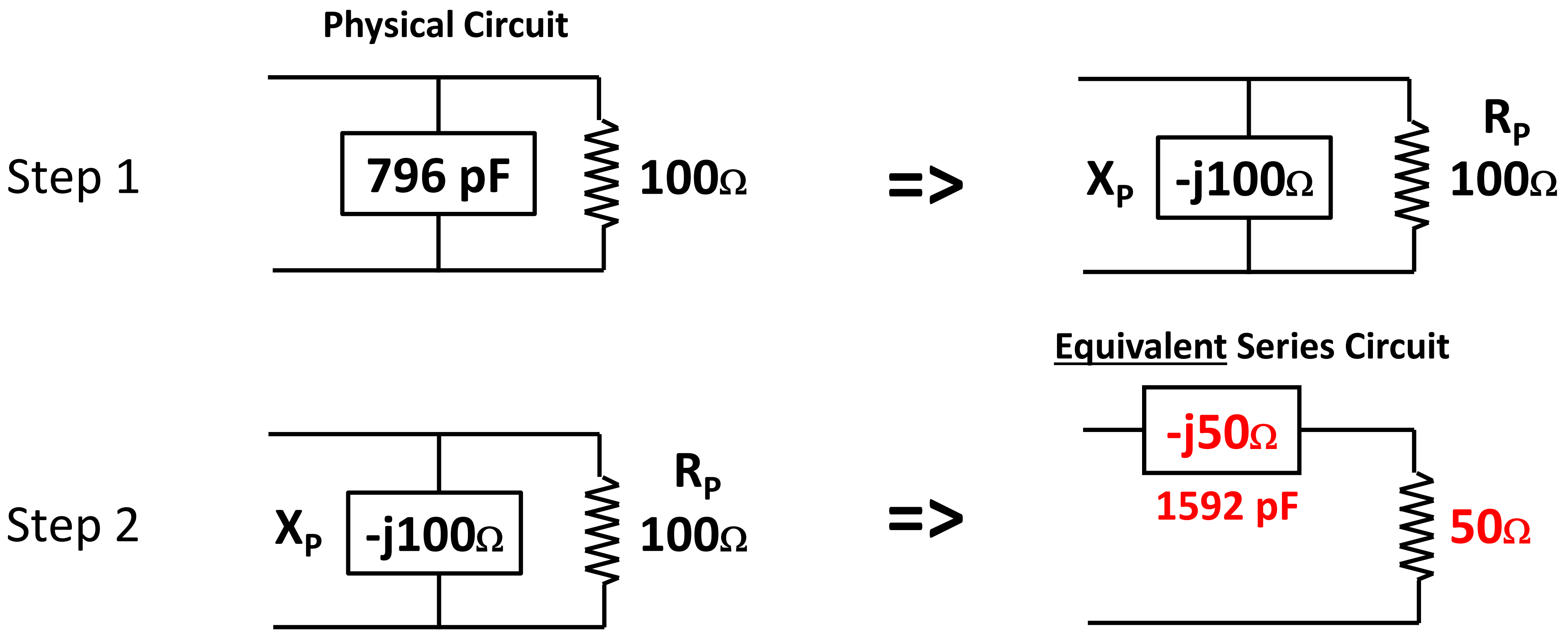



$Z = R_S + j\,X_S$

$$R_S = \frac{R_P \times X_P^2}{R_P^2 + X_P^2}$$

$$X_S = \frac{R_P^2 \times X_P}{R_P^2 + X_P^2}$$

# Example 1: Impedance at 2 MHz

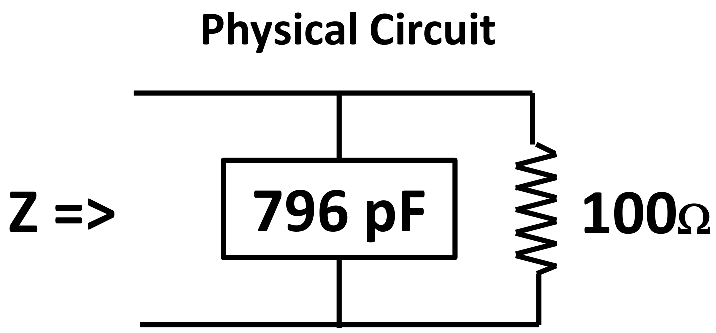



Note: Two different circuits have the same impedance **at 2 MHz**:

$Z = 50\Omega - j50\Omega = 70.7\Omega$ @ $-45^{o}$

# Example 1: Impedance at 2 MHz - cont'd

- What an MFJ-259B measured at 2 MHz:

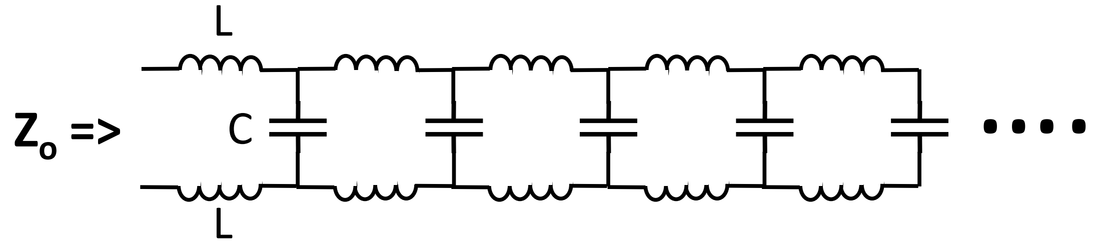



| | **Calculated** | **Measured** |
|---|---|---|
| Rs= | 50 Ω | 56 Ω |
| Xs= | -50 Ω | 48 Ω |
| \|Z\| = | 70 Ω | 74 Ω |
| Phase = | $-45^{o}$ | $40^{o}$ |
| SWR = | 2.6 | 2.4 |
| "Impedance" Meter = | 70 | 70 => \|Z\| |

**Note: The MFJ-259B does not display $R_P$, $X_P$, or the sign of a reactance**

# Transmission Lines Are Lowpass Filters

- "Lumped element" circuit <u>approximation</u> for <u>lossless</u> transmission line:




- $Z_O$ is called the "Surge Impedance" or "Characteristic Impedance" of the line
  - When $Z_{LOAD} = Z_O$
    - The line is "Matched"
    - The input impedance of a transmission line equals $Z_O$ and is independent of length
  - $Z_O \approx \sqrt{L/C}$
  - Example: Belden RG-58/U (9201)

Zo = 52Ω

C = 27 pF/ft

L = 94 nH/ft

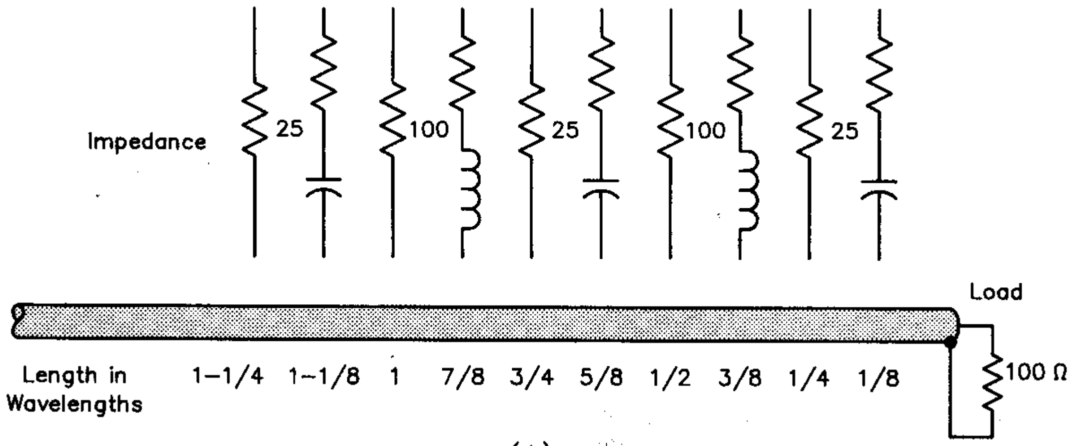
VP = 0.66

# When $Z_{LOAD} \neq Z_O$

## Input impedance of a 50 ohm line when the SWR = 2.0:

$R_{\mathbf{LOAD}}$ = 100 ohm

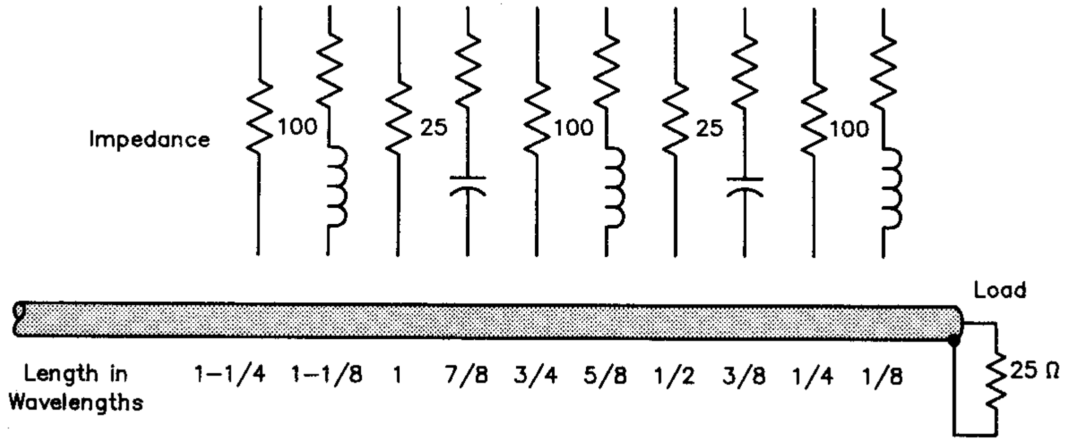
**$Z_{IN}$ =>**




(A)

$R_{\mathbf{LOAD}}$ = 25 ohm

**$Z_{IN}$ =>**

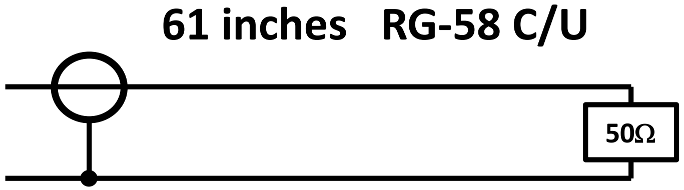



(B)

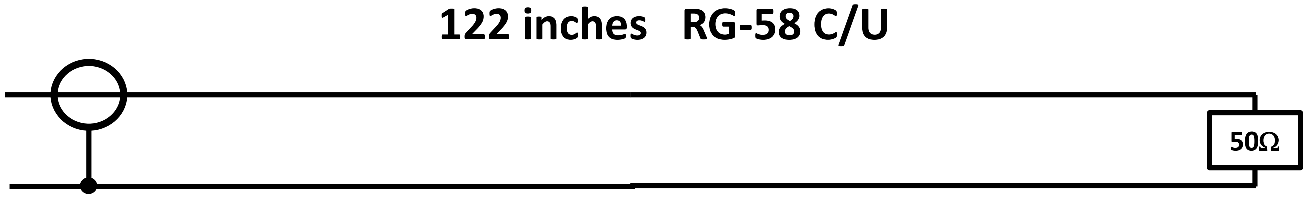
# Example 2

- What is $Z_{IN}$ at **32 MHz** ?

**$Z_{IN}$ = 50Ω**




**$Z_{IN}$ = 50Ω**



# Example 2 (cont'd)

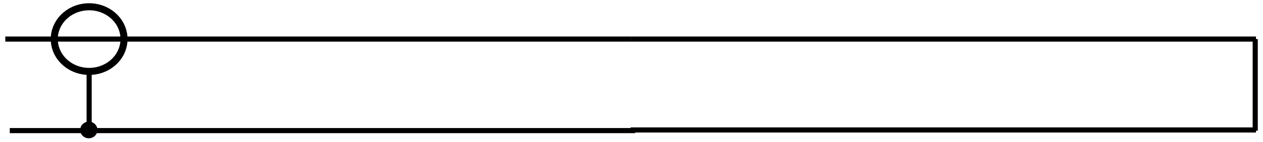
- What is $Z_{IN}$ at **32 MHz** ?

**61 inches RG-58 C/U**

**$Z_{IN}$ = ?**

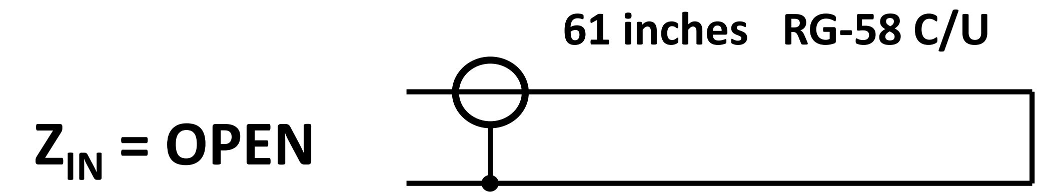
**122 inches RG-58 C/U**

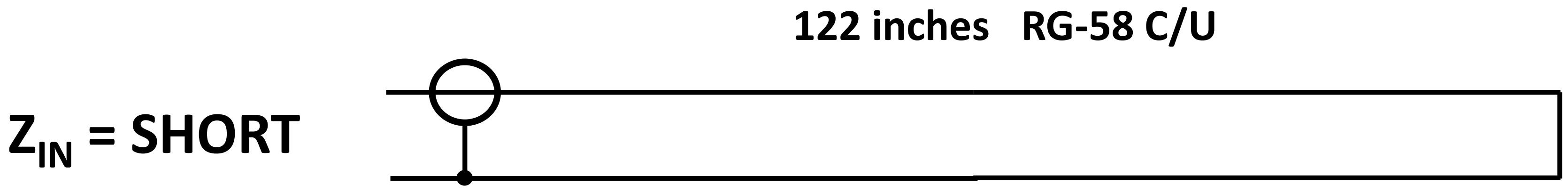
**$Z_{IN}$ = ?**



# Example 2 (cont'd)

- What is $Z_{IN}$ at **32 MHz** ?

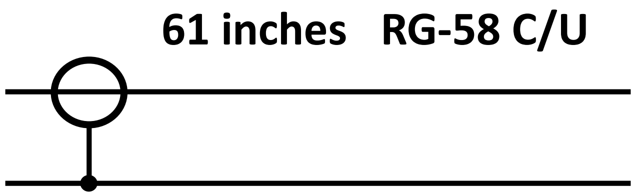


# Example 2 (cont'd)

- What is $Z_{IN}$ at **32 MHz** ?

**$Z_{IN}$ = SHORT**



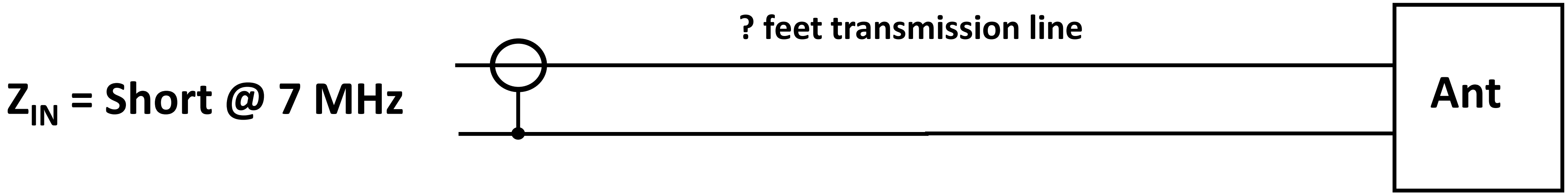

**$Z_{IN}$ = OPEN**

# Example 2 (cont'd)

- The electrical lengths at **32 MHz** are:
  - **61 inches = ¼ wavelength**
  - **122 inches = ½ wavelength**

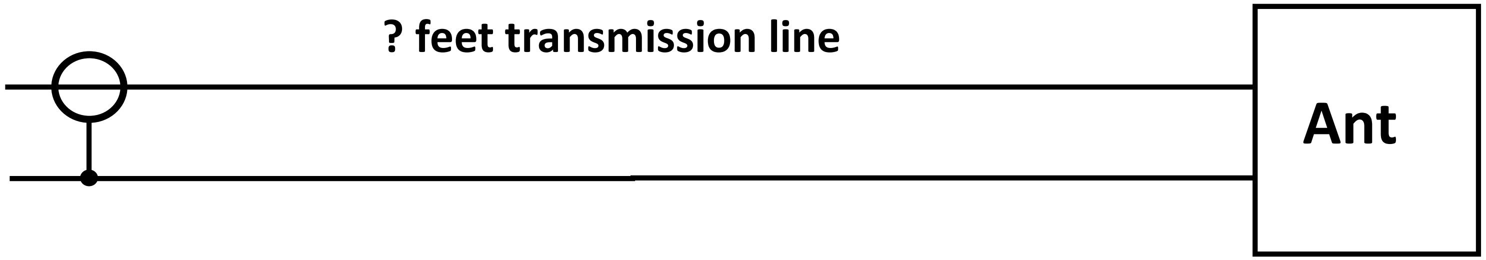
  } Electrical length ≠ physical length
  - Electrical length = VP x physical length
    - "VP" = velocity of propagation
- When $Z_{Load} = Z_O$:
  - $Z_{IN} = Z_O = Z_{Load}$ (for any length of line)
- When $Z_{Load} \neq Z_O$:
  - ***<u>Transmission lines become impedance transformers</u>***
  - When length = $n_{\mathbf{odd}}$ x ¼ wavelength, transmission lines **invert** the load impedance
    - "Invert" => high goes to low and low goes to high
    - Quarter wave transformer: $\mathbf{Z_{IN} = (Z_O)^2 / Z_{LOAD}}$
  - When length = n x ½ wavelength, transmission lines **replicate** the load impedance

# Quiz: High SWR




**Is the antenna shorted?**

# Quiz: High SWR – cont’d



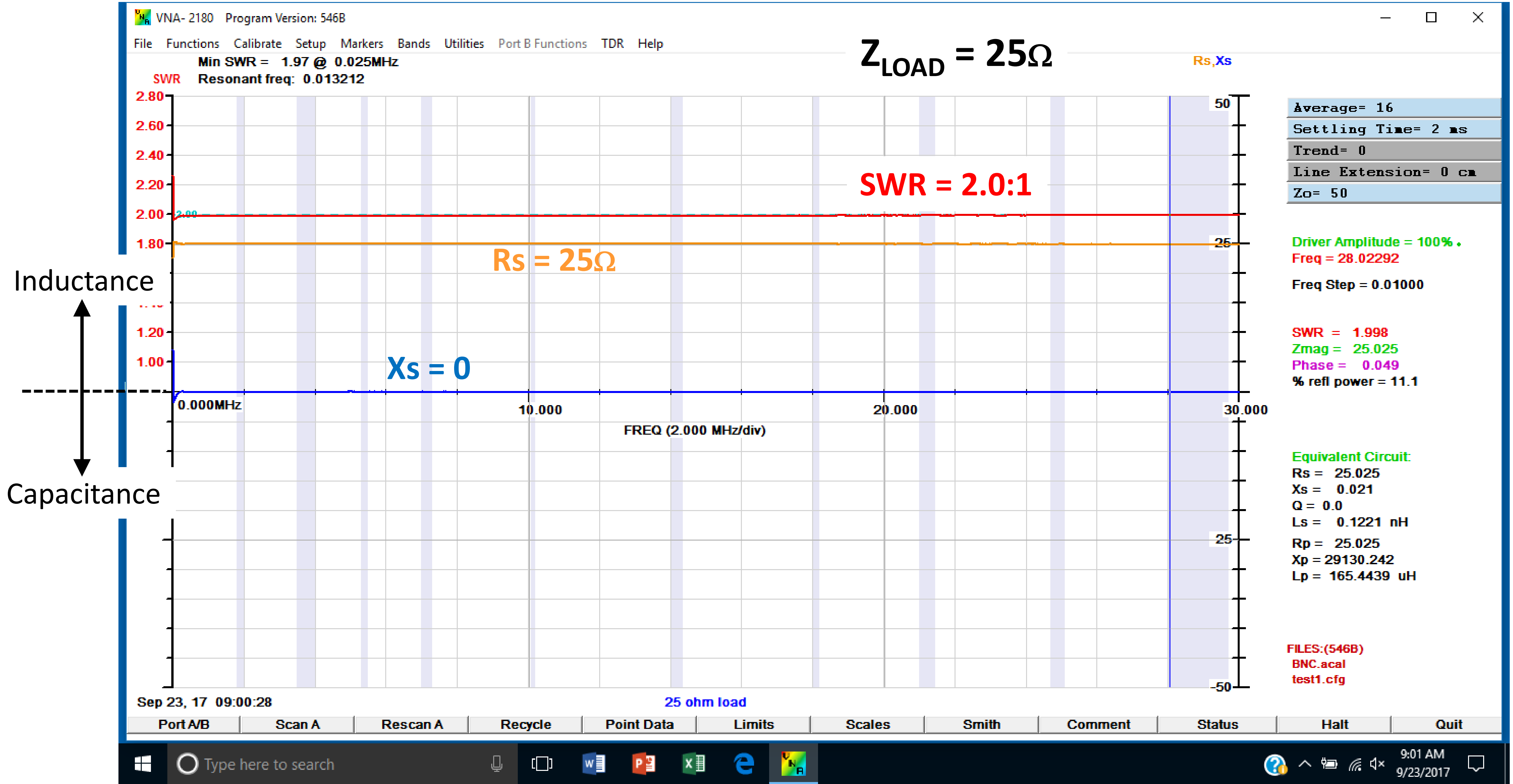

**$Z_{IN}$ = Short @ 7 MHz**

**Is the antenna shorted?**

**Don’t know:**

- **Need to know the <u>electrical</u> length of the transmission line at 7MHz**
- **The antenna could be an open circuit**

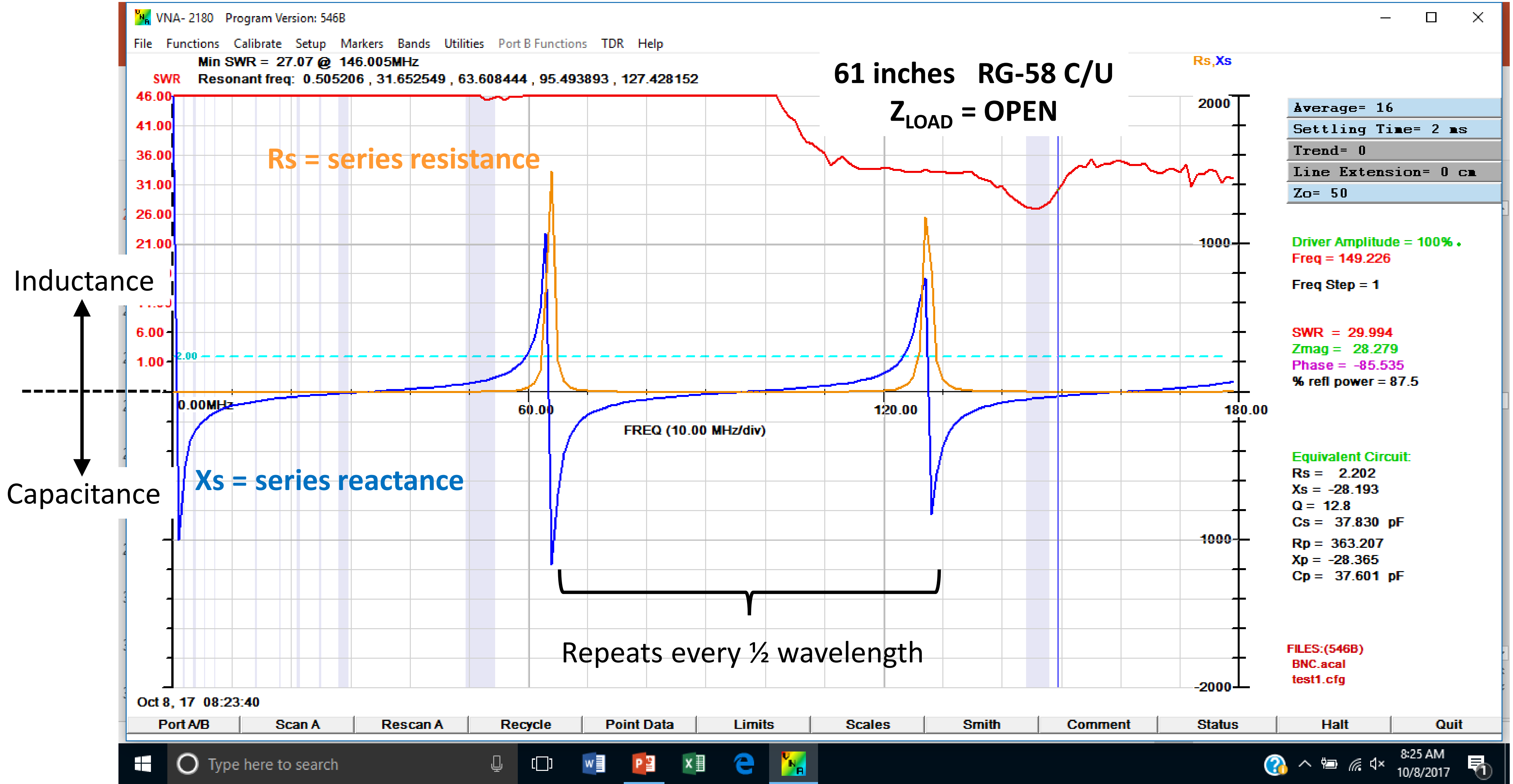
# Vector Network Analyzer: VNA 2180



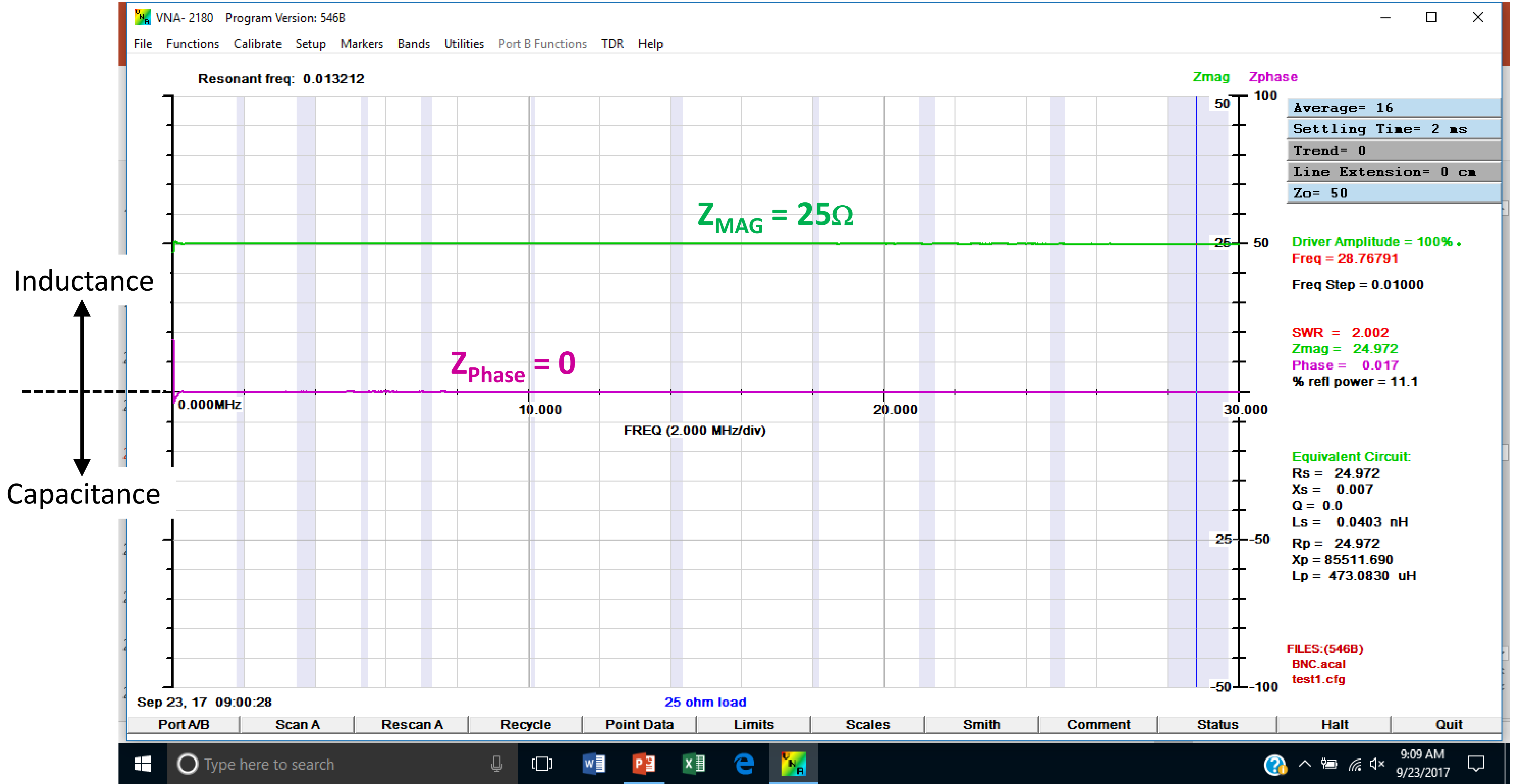
# Example 3: $Z_{IN}$ vs Frequency

- Use a VNA2180 to plot $Z_{IN}$ vs frequency

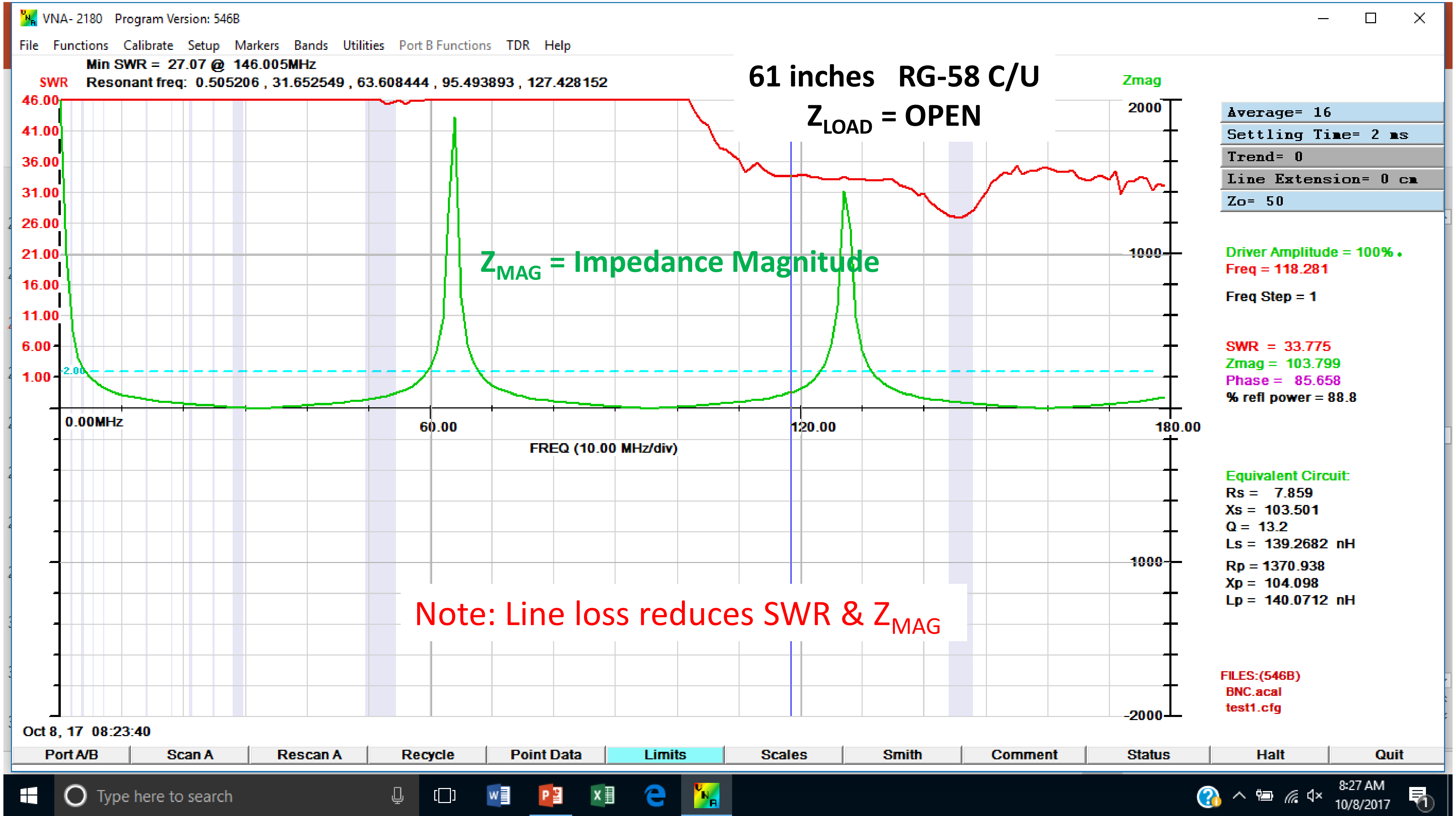
# Example 3: $Z_{IN}$ vs Frequency (cont'd)



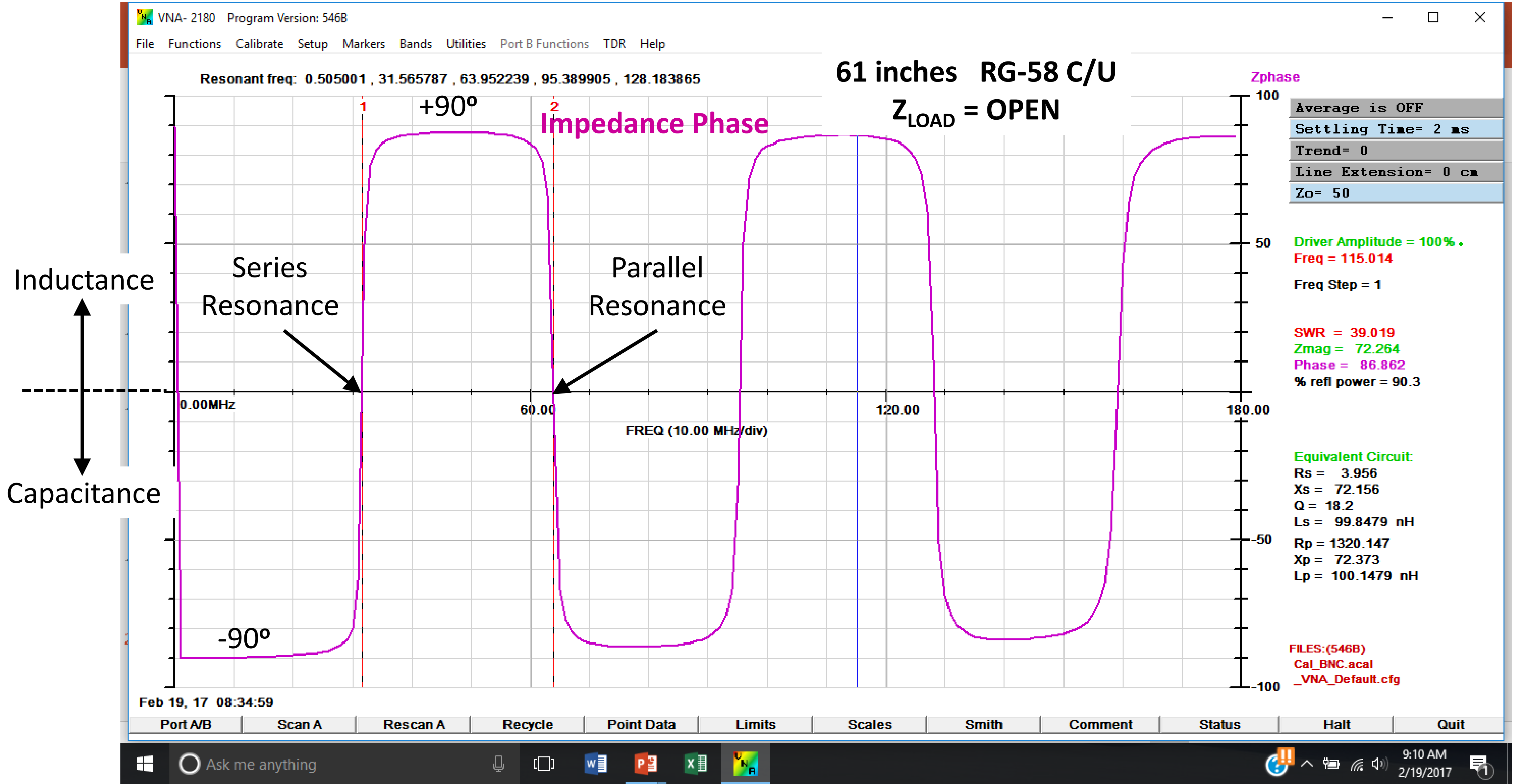
# VNA 2180 With 25Ω Load



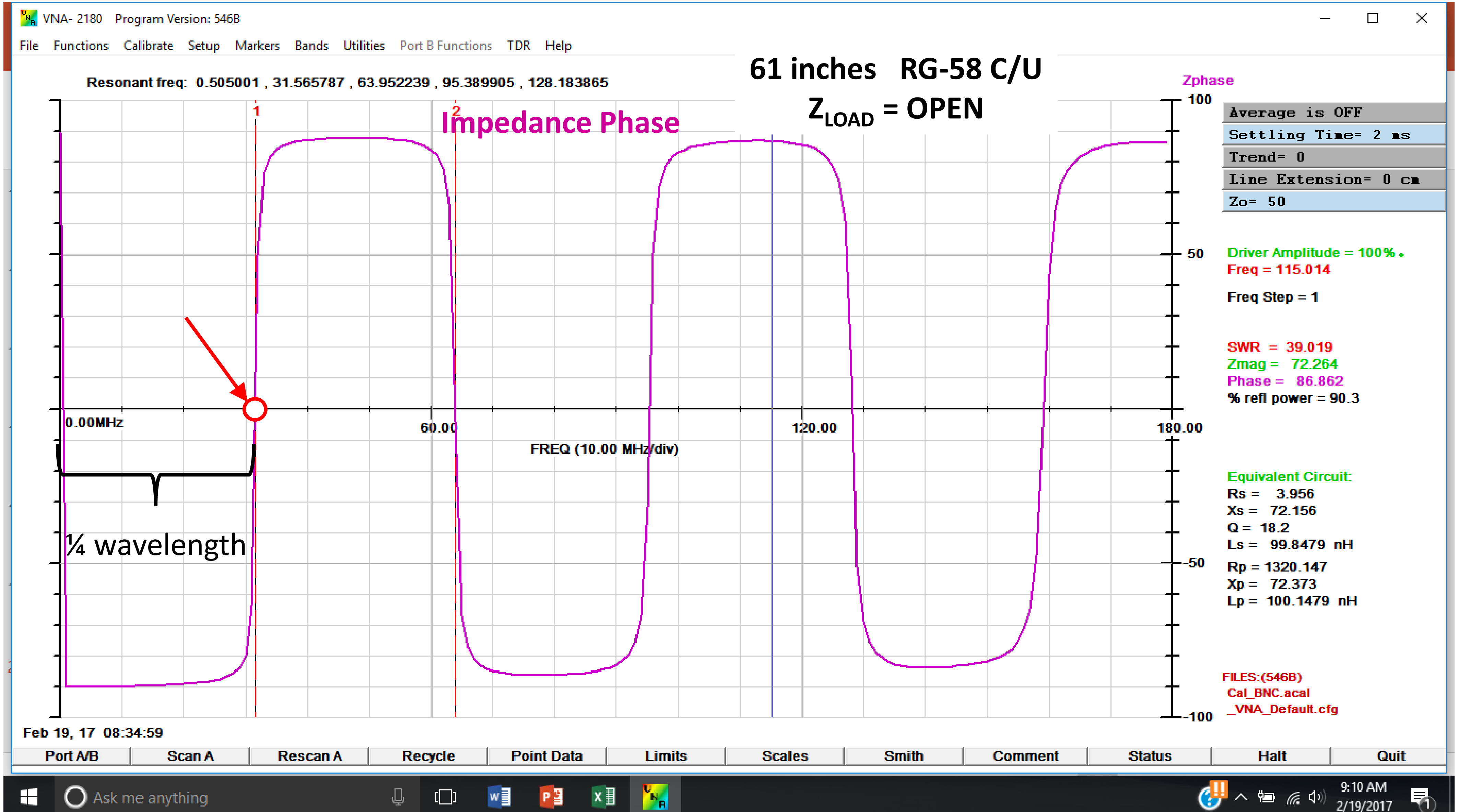
# Example 3: Plot $Z_{IN}$ vs Frequency (cont'd)



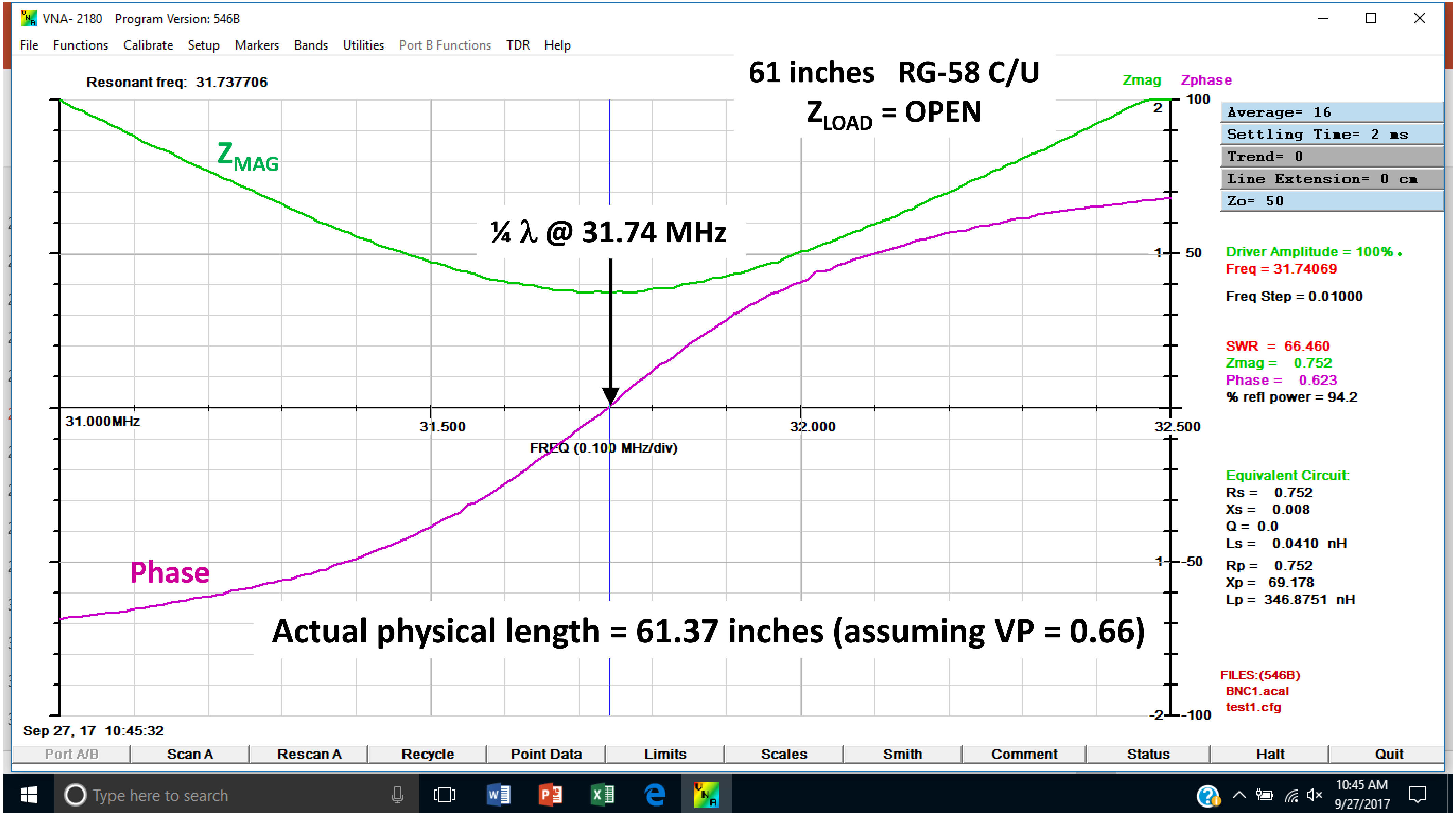
# Example 3: Plot $Z_{IN}$ vs Frequency (cont'd)



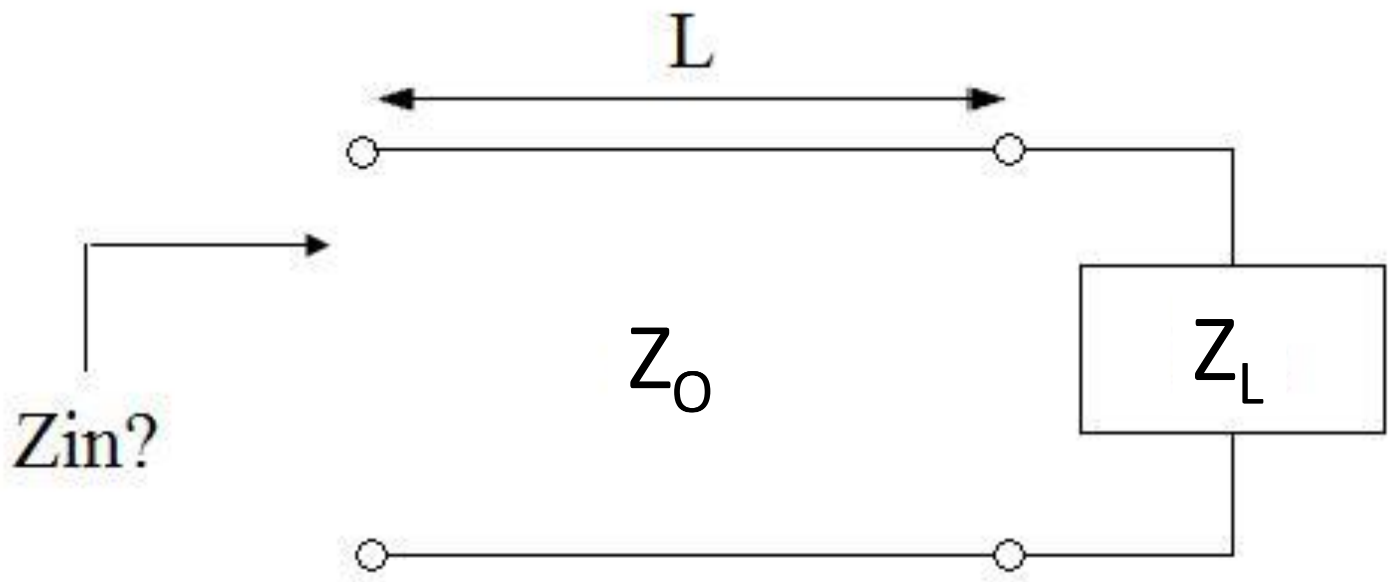
# Example 3: Plot $Z_{IN}$ vs Frequency (cont'd)



# Finding the Electrical Length of a Transmission Line



# Finding the Input Impedance of a Transmission Line



# Why Was The Smith Chart Developed?

*Frank Lynch, W4FAL*

## The Formula!

**Impedance Looking Into A Transmission Line**

**Hyperbolic Tangent**

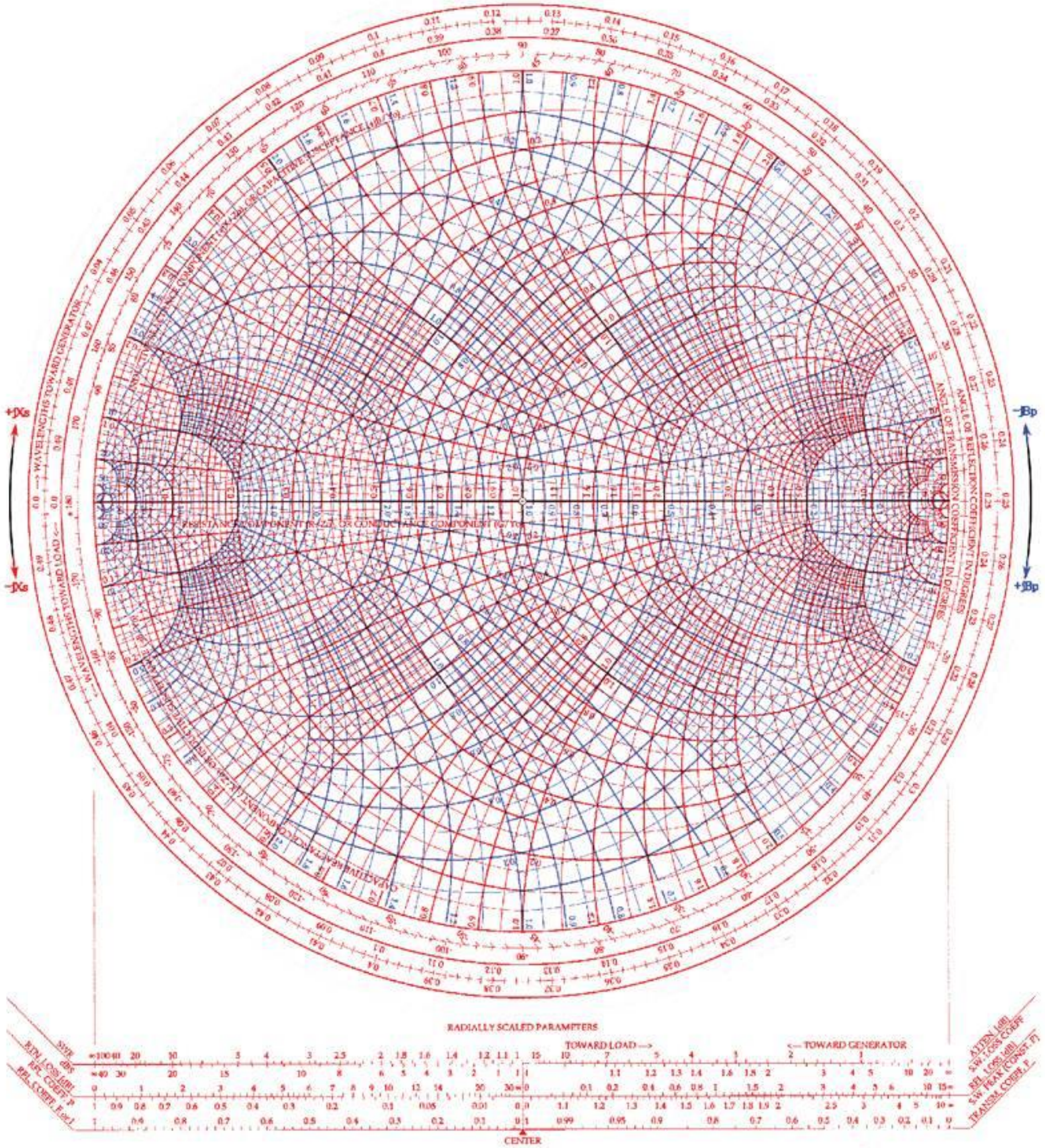
$$Z_x = Z_0 \frac{Z_L + Z_0 \tanh \gamma x}{Z_0 + Z_L \tanh \gamma x}$$

$$\gamma = \alpha + j\beta$$

**Complex Numbers**

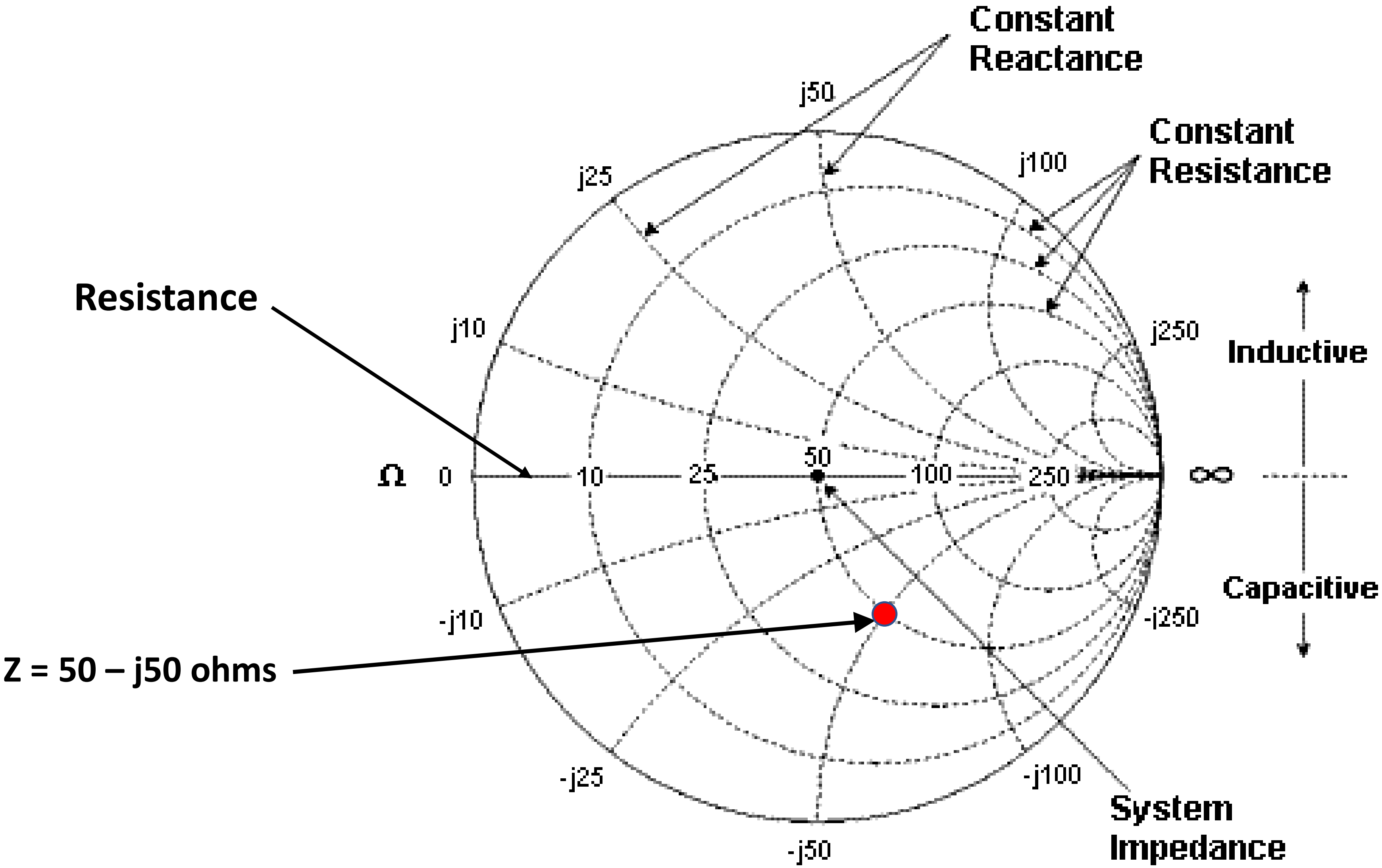
This is why the chart was developed.. Before calculators and computers the above formula's were impossible! They're still not easy today.

# Smith Chart

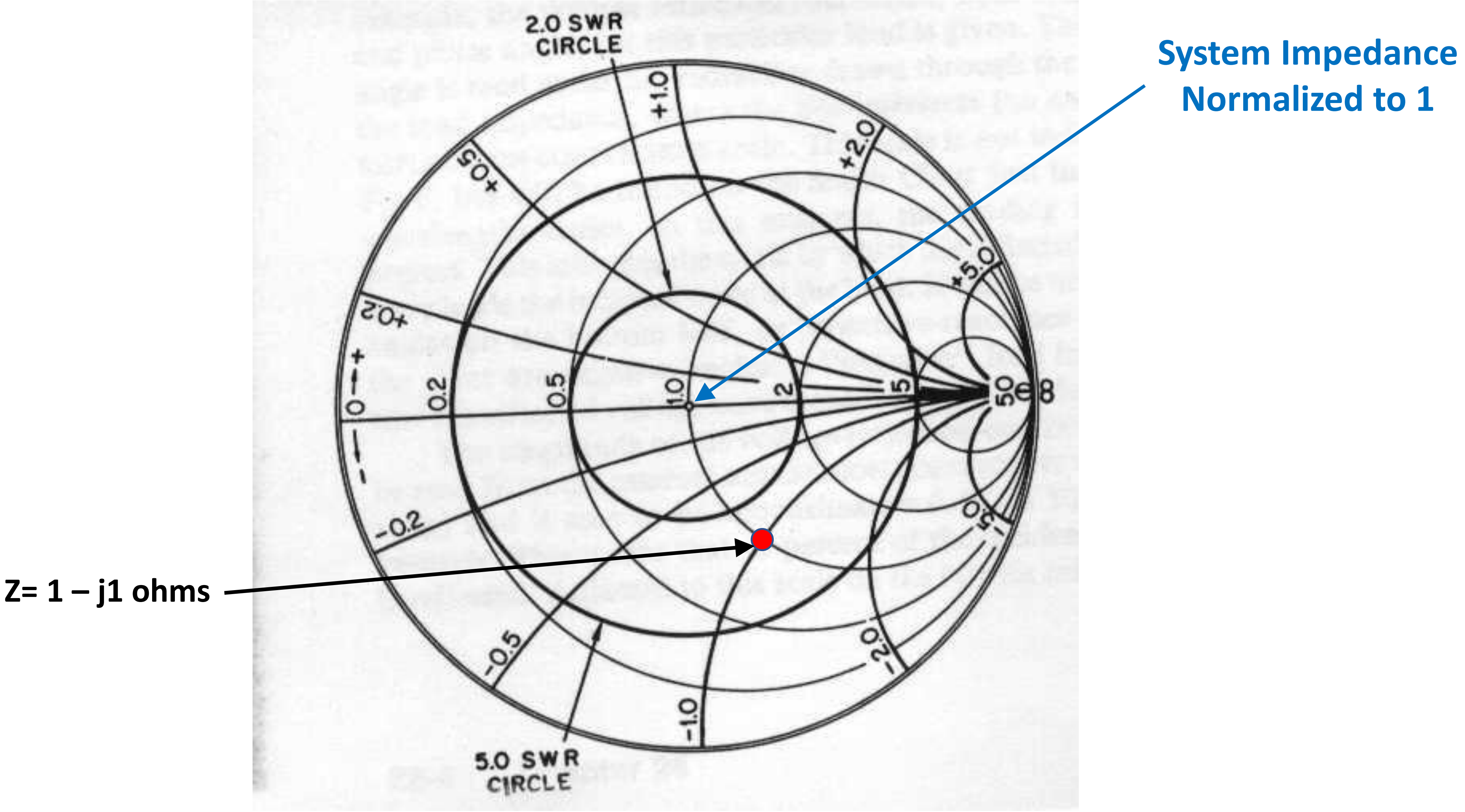


+jXs
-jXs
-jBp
+jBp
RADIALLY SCALED PARAMETERS
TOWARD LOAD
TOWARD GENERATOR
CENTER

# Simplified Smith Chart

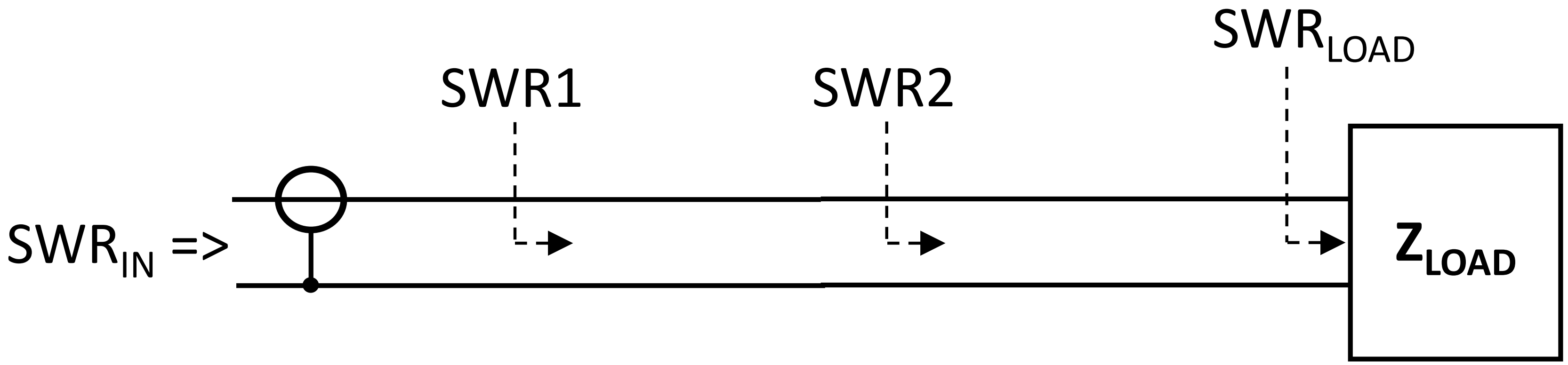


# Normalized Smith Chart



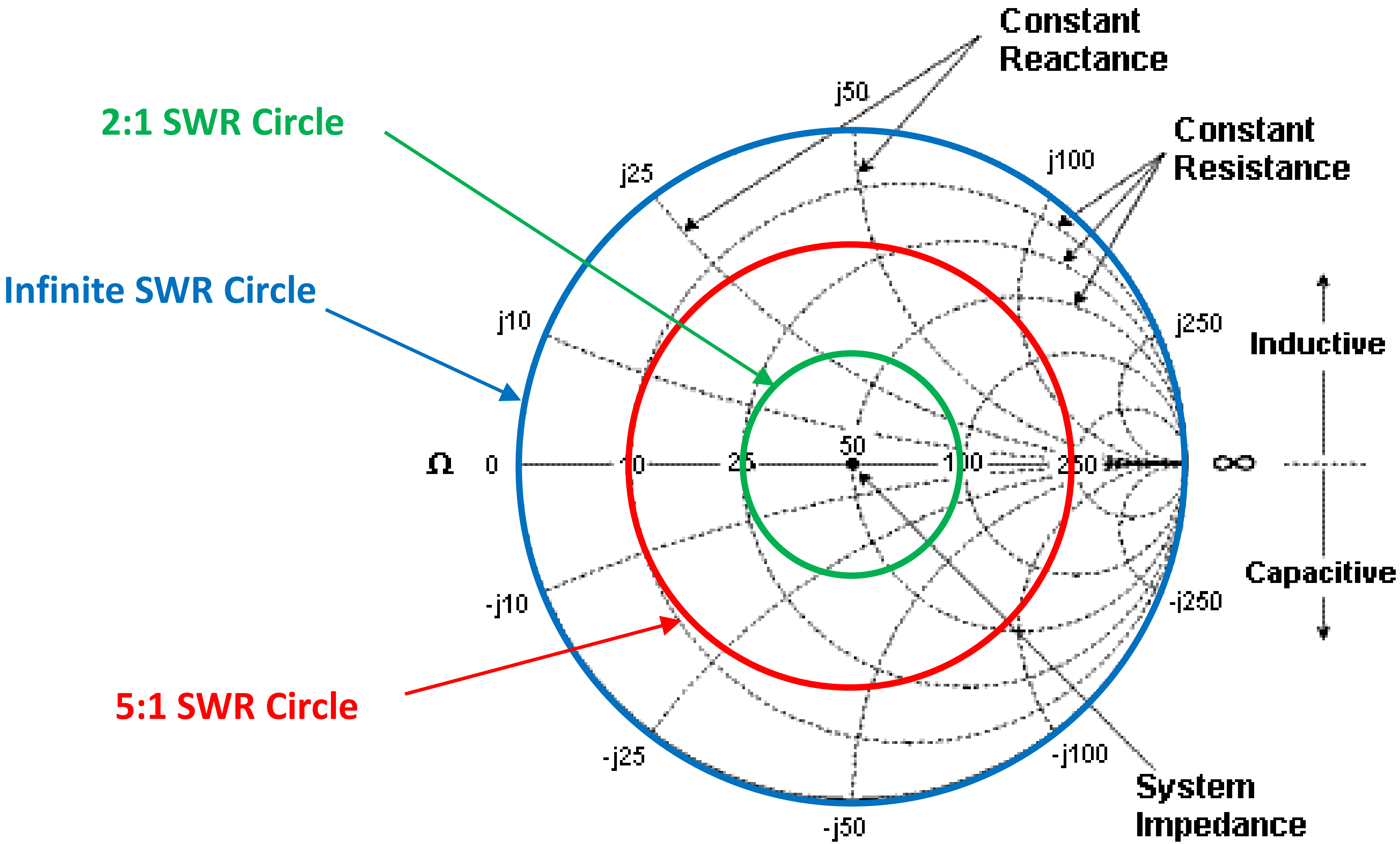
# SWR vs Transmission Line Length

For Lossless Transmission Line:




- SWR is determined solely by $Z_{\mathbf{O}}$ & $Z_{\mathbf{LOAD}}$
- SWR is constant along a lossless transmission line
  - $SWR_{IN} = SWR1 = SWR2 = SWR_{LOAD}$

# Simplified Smith Chart – Constant SWR Circles




1. **Adding Length to a <u>Lossless</u> Transmission Line Causes Clockwise Rotation Around a Constant SWR Circle**
2. **Z changes but SWR is constant**
3. **One Full Rotation Equals ½ Wavelength**

# Problem: Antenna Tuner Can't Find A Match

- Many built-in antenna tuners can only match up to a 3:1 SWR
  - External tuners have much better range than built-in tuners
- It is easier for most antenna tuners to match a high impedance
  - Ex: MFJ-993B spec'd matching range is 6 – 1600Ω
    - SWR:

      1600Ω => 32:1

      6Ω => 8:1
  - Many antenna tuners become very lossy at very low impedances
    - Obtaining a match is only part of the solution
    - Example: Palstar AT-Auto
      - Loss matching 6.25 ohms on 160M is **42%**! (QST Aug 2006)

# Problem: Antenna Tuner Can't Find A Match

- Many built-in antenna tuners can only match up to a 3:1 SWR
  - External tuners have much better range than built-in tuners
- It is easier for most antenna tuners to match a high impedance
  - Ex: MFJ-993B spec'd matching range is 6 – 1600Ω

**Common recommendation: add a short length of coax to reduce the SWR**

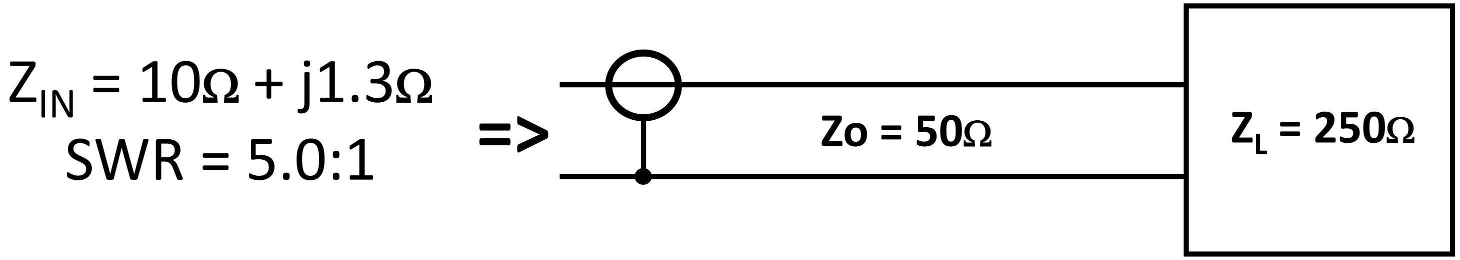
1600Ω => 32:1

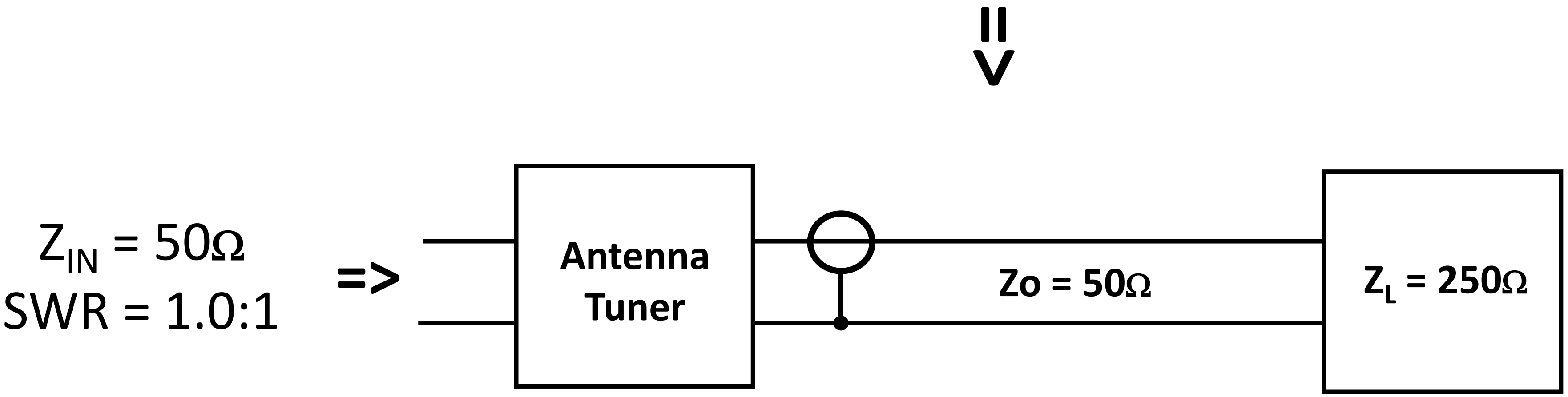
6Ω => 8:1

  - Many antenna tuners become very lossy at very low impedances
    - Obtaining a match is only part of the solution
    - Example: Palstar AT-Auto
      - Loss matching 6.25 ohms on 160M is **42%**! (QST Aug 2006)

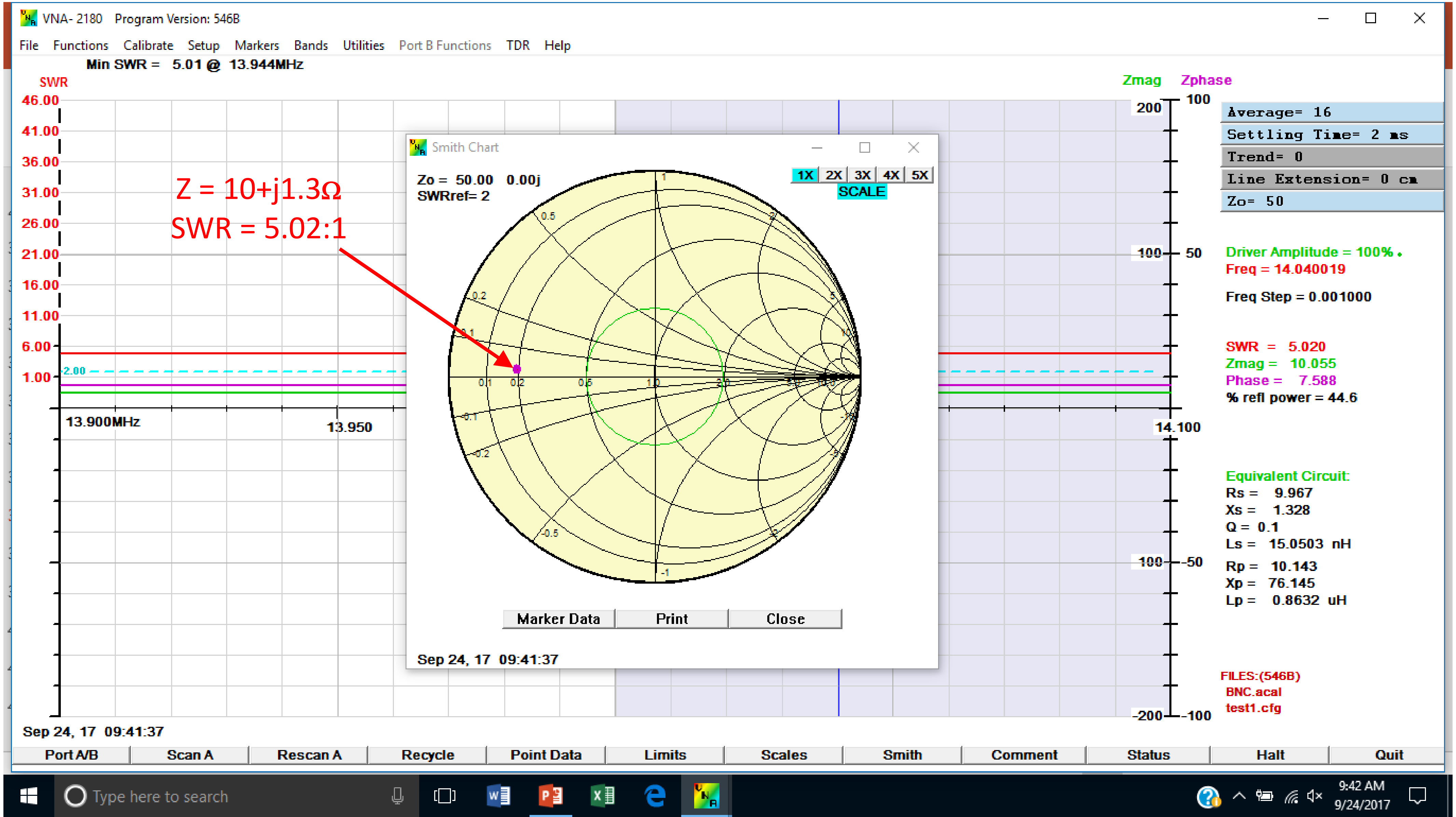
# Example 4: Antenna Matching Problem

- Problem: Antenna Tuner Can't Find A Match At **14.0 MHz**:

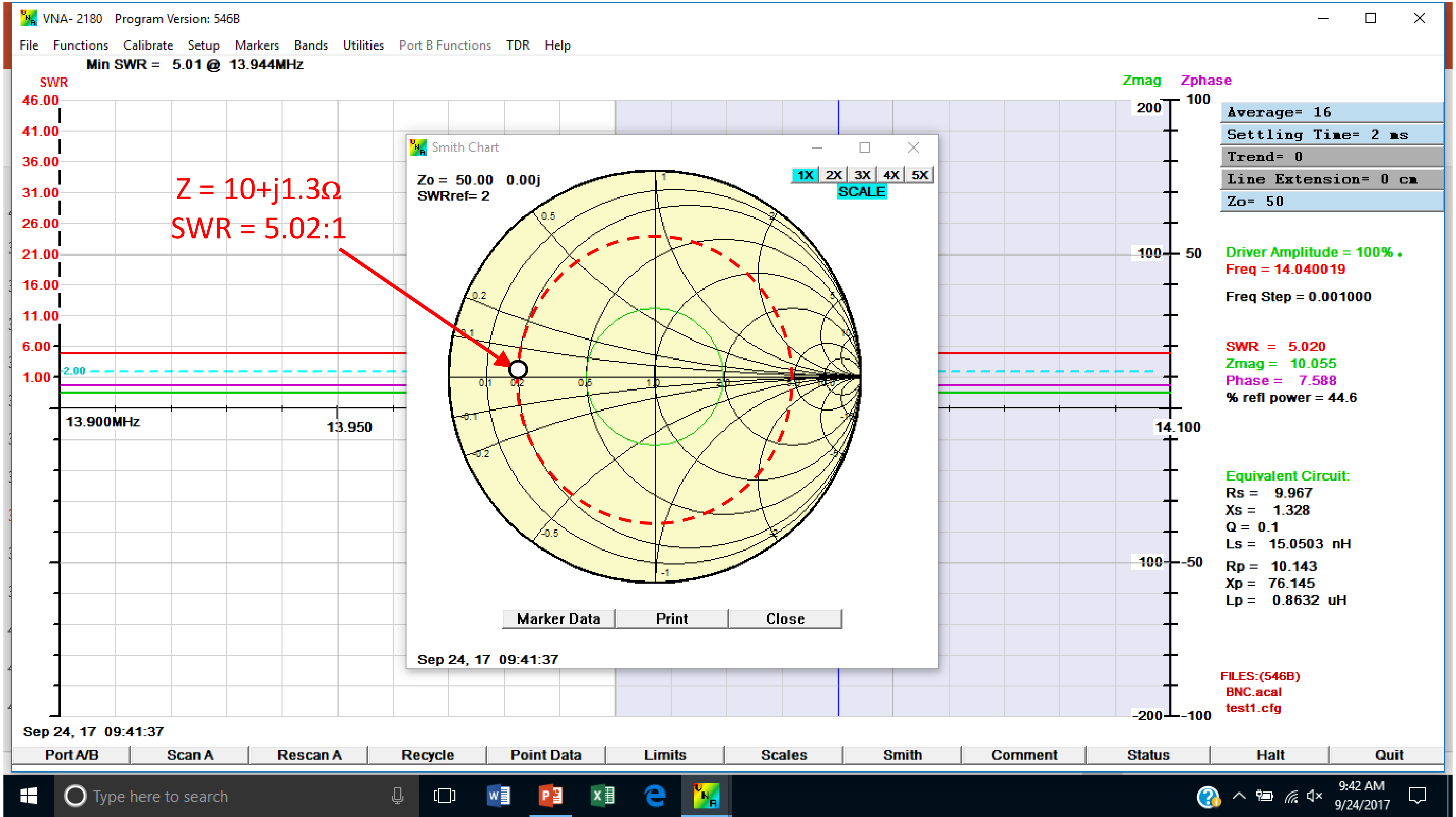


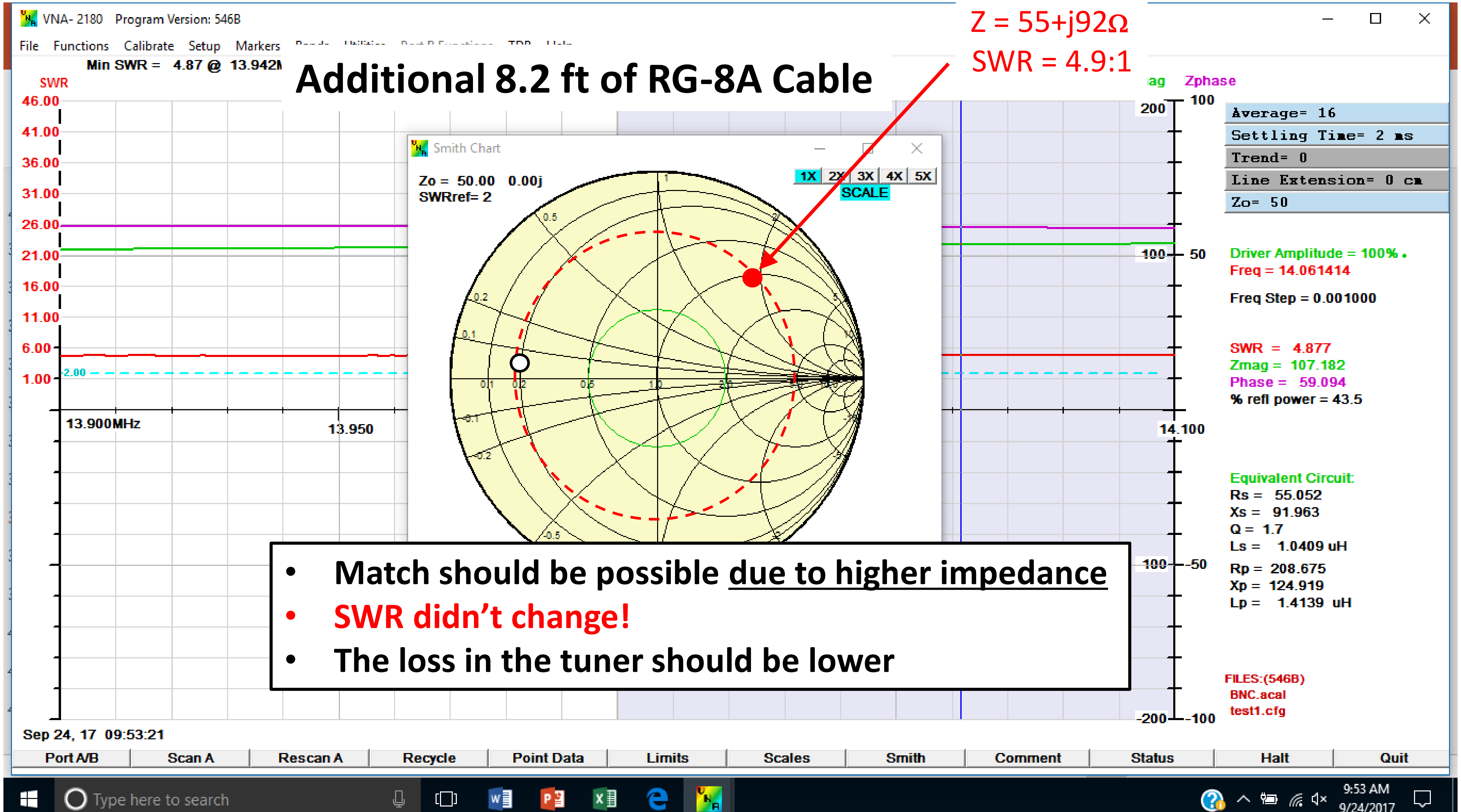
# Example 4: Antenna Matching Problem (cont'd)



# Example 4: Antenna Matching Problem (cont'd)



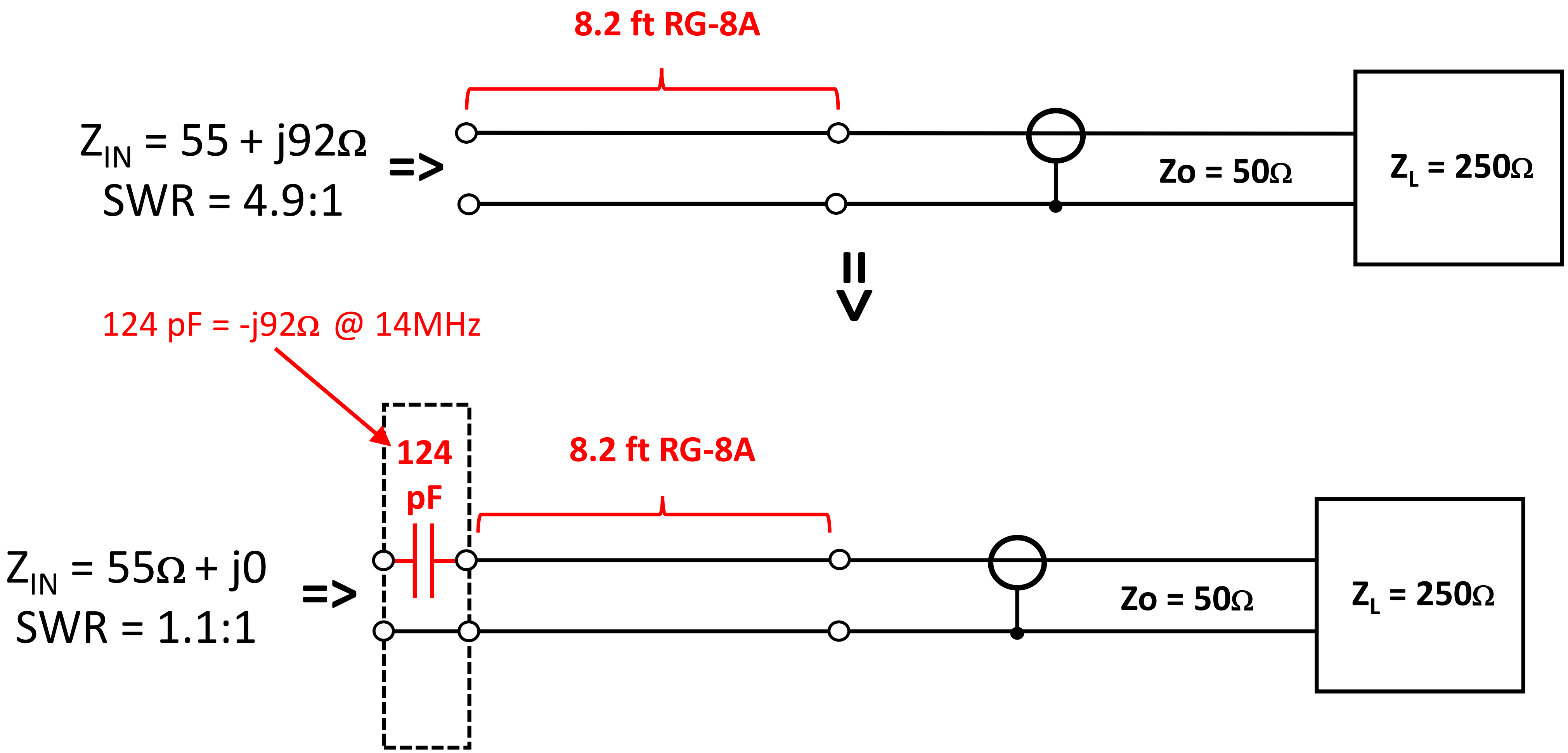
# Example 4: Antenna Matching Problem (cont'd)




- **Match should be possible <u>due to higher impedance</u>**
- **SWR didn't change!**
- **The loss in the tuner should be lower**

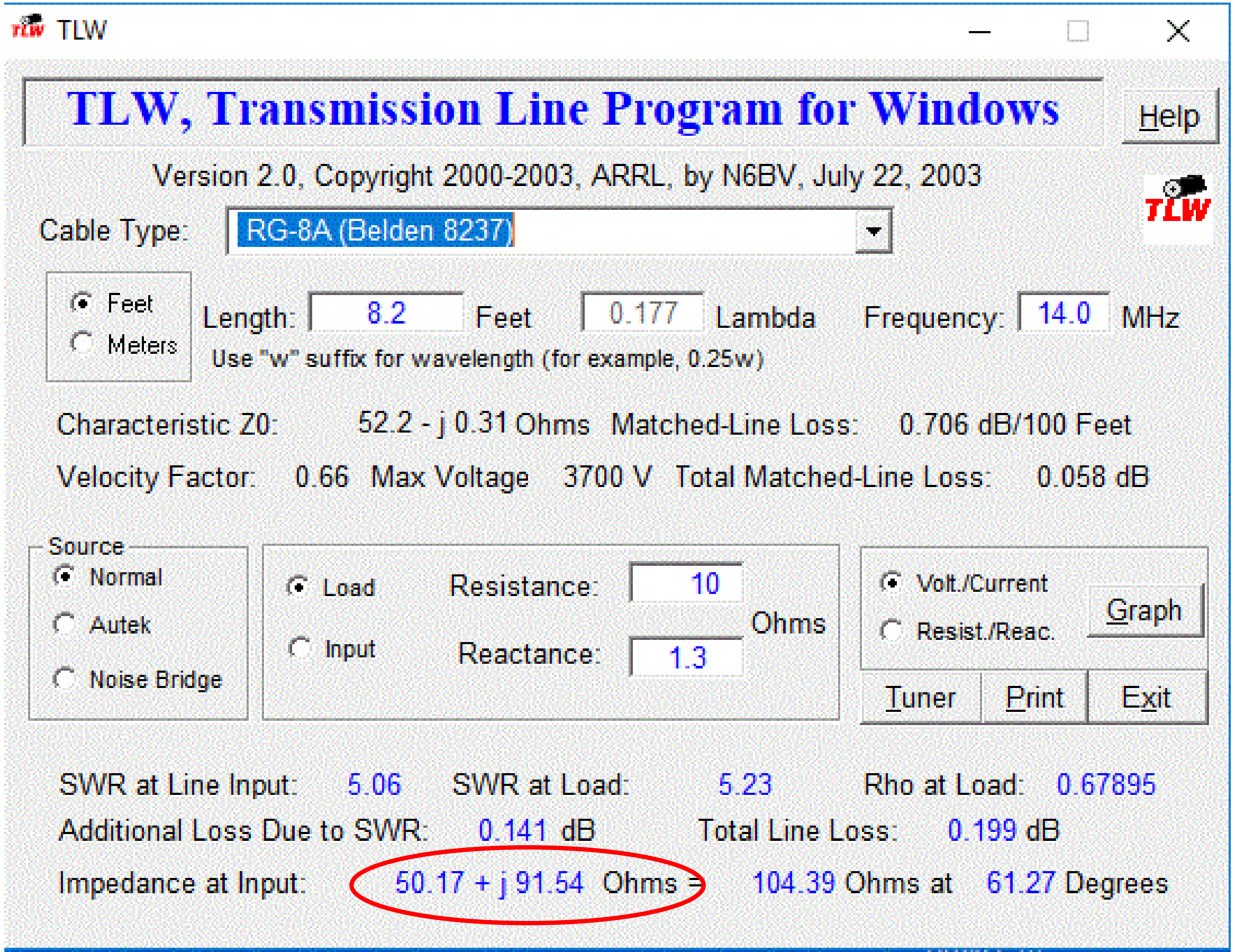
# Example 4: Antenna Matching Problem (cont'd)

- Simple (Single Band) Solution:



# ARRL Transmission Line for Windows (TLW)

- Free software with ARRL Antenna Book

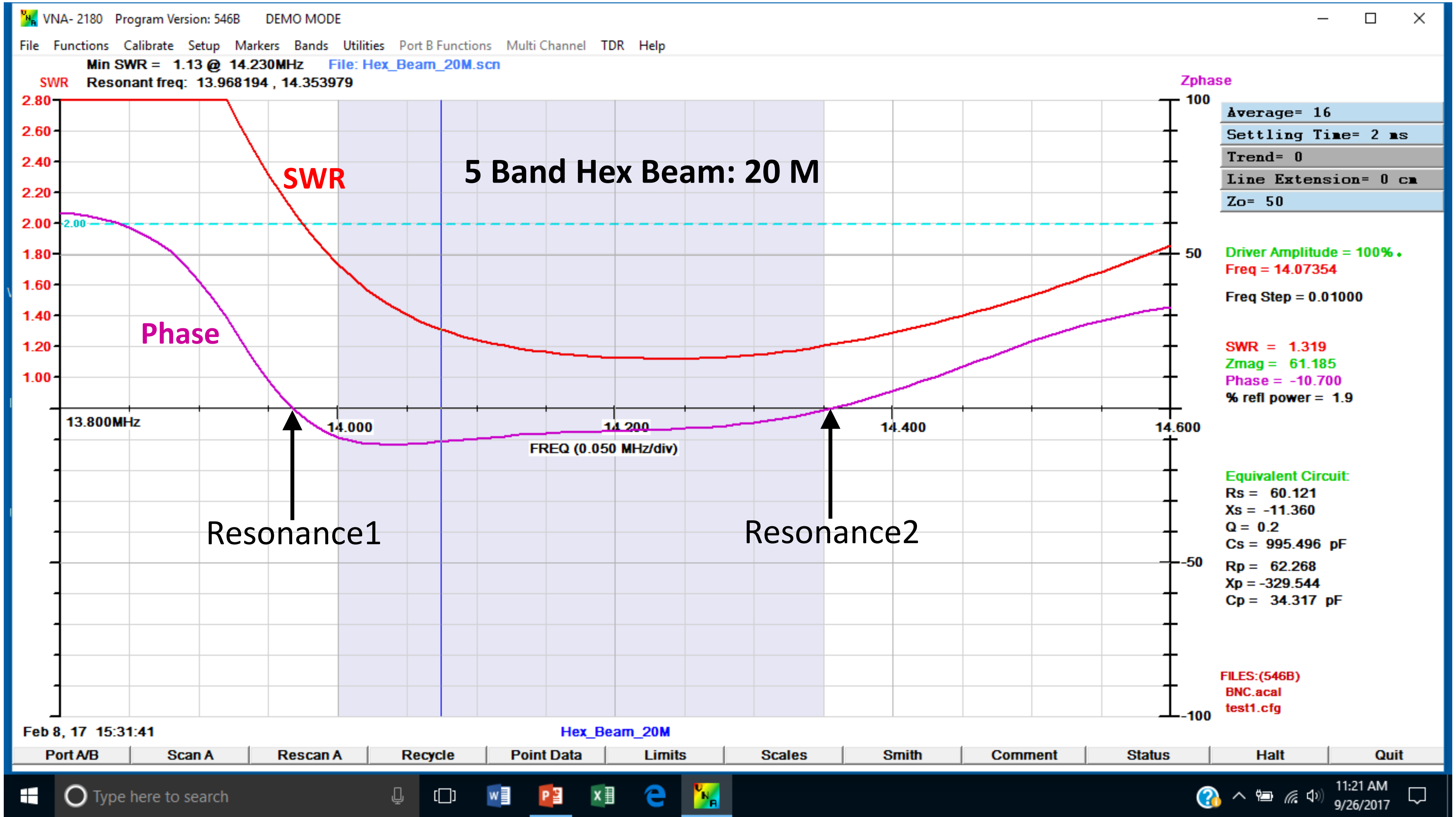


# Example 5: Antenna Tuning

- Should an antenna be tuned to resonance, or for lowest SWR?

# Example 5: Antenna Tuning – cont'd

- Should an antenna be tuned to resonance, or for lowest SWR?



# Example 5: Antenna Tuning – cont'd

**40 M Dipole**

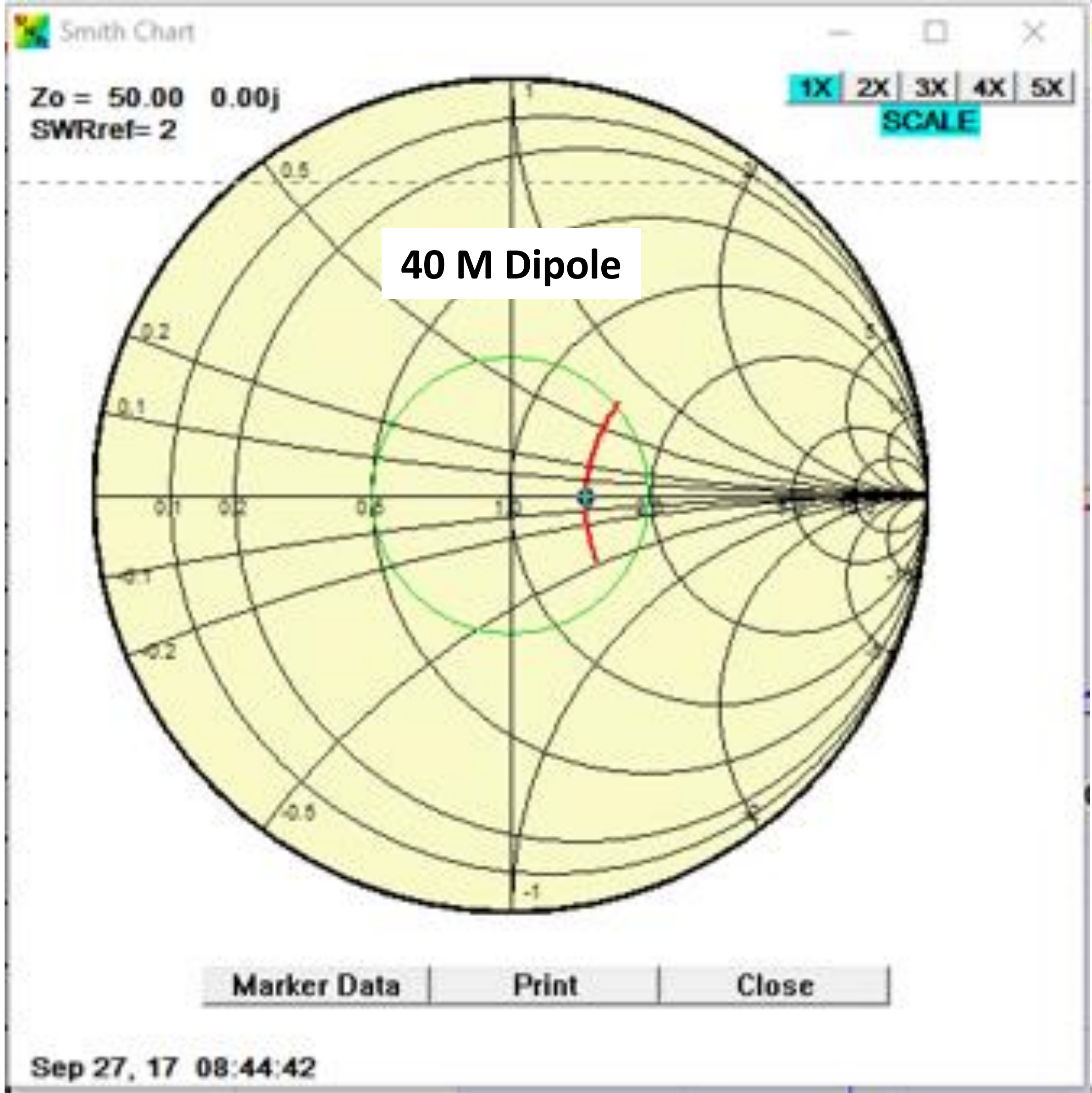
# Example 5: Antenna Tuning – cont'd

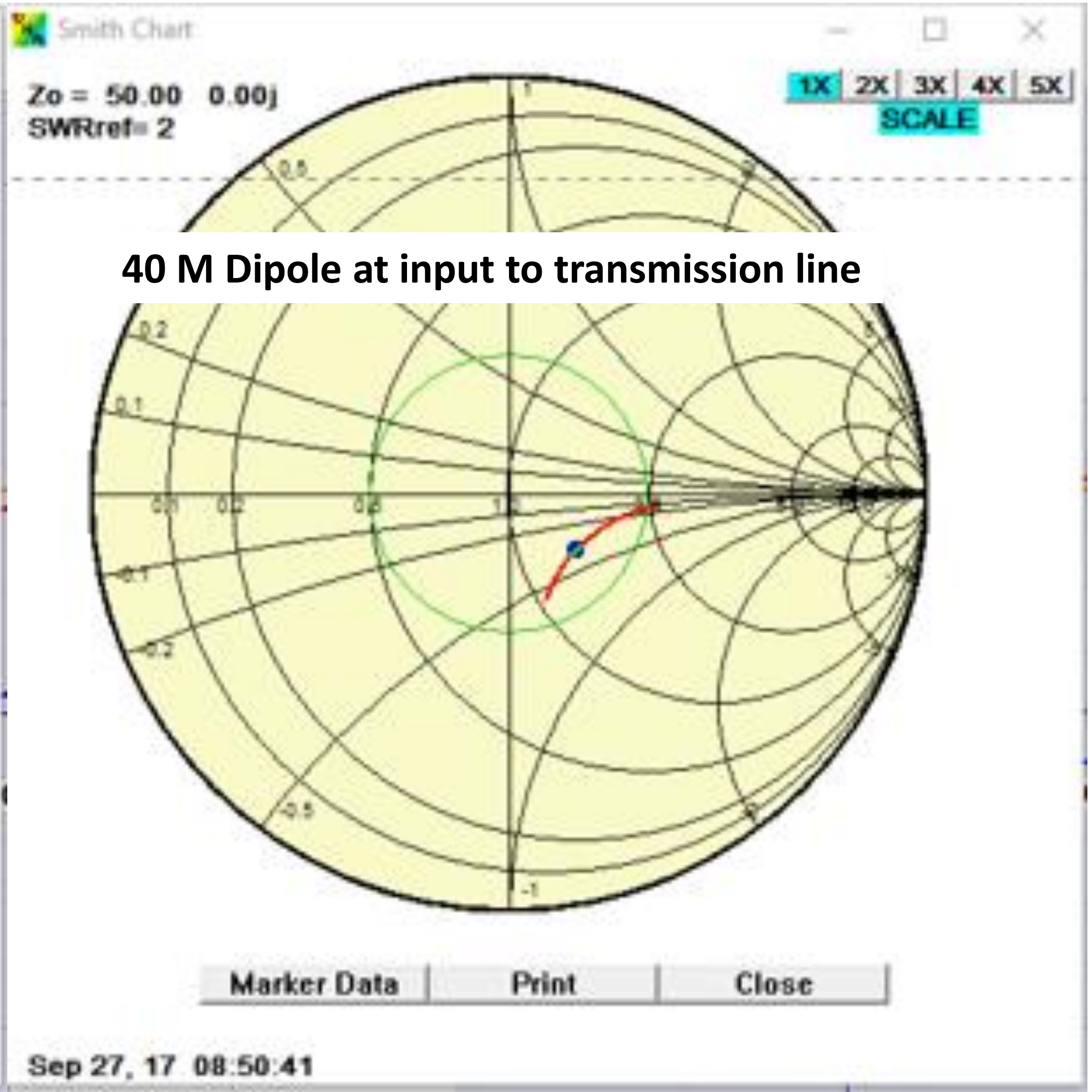
**40 M Dipole**


**40 M Dipole at input to transmission line**

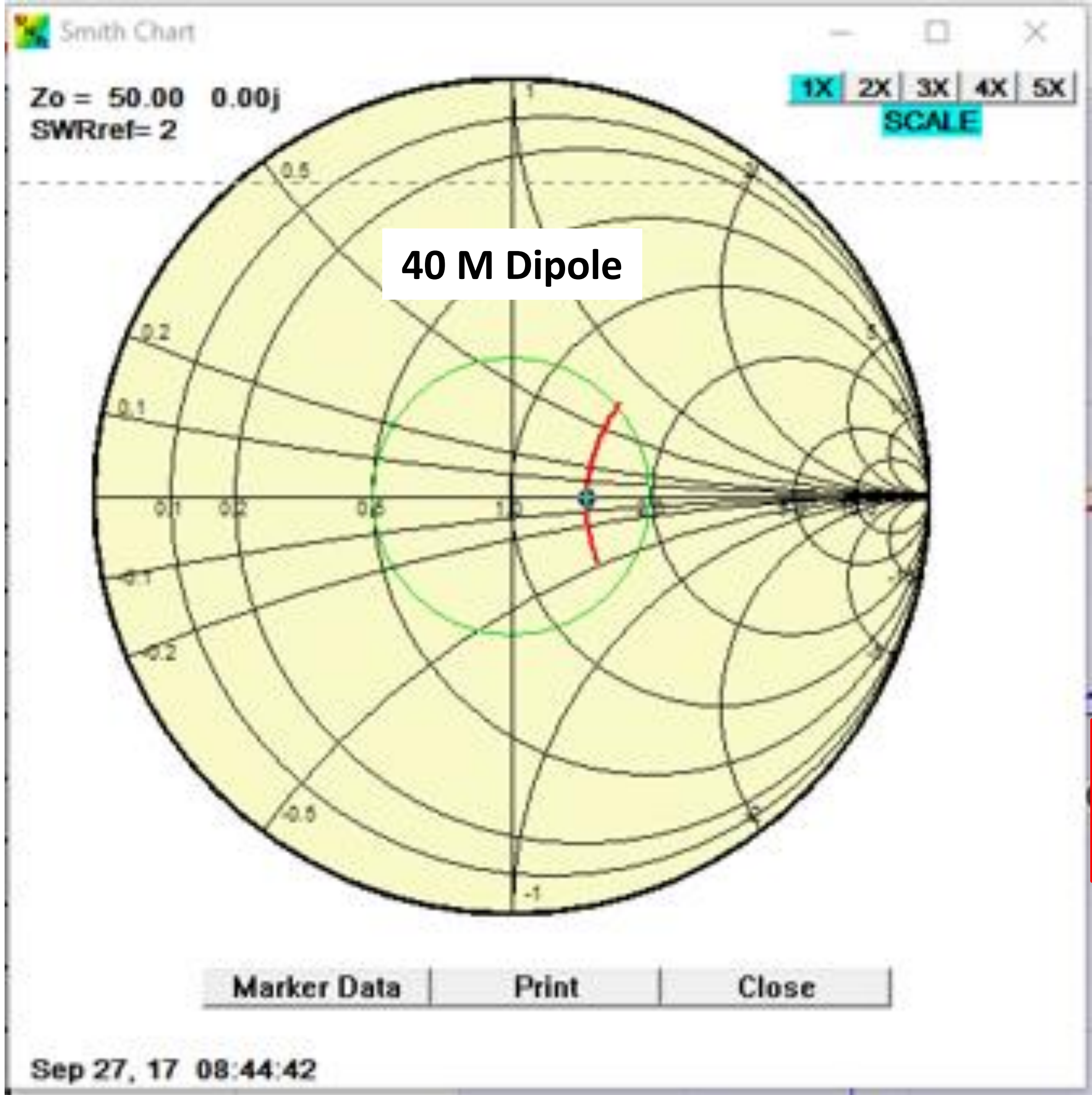

**Is the antenna no longer resonant?**

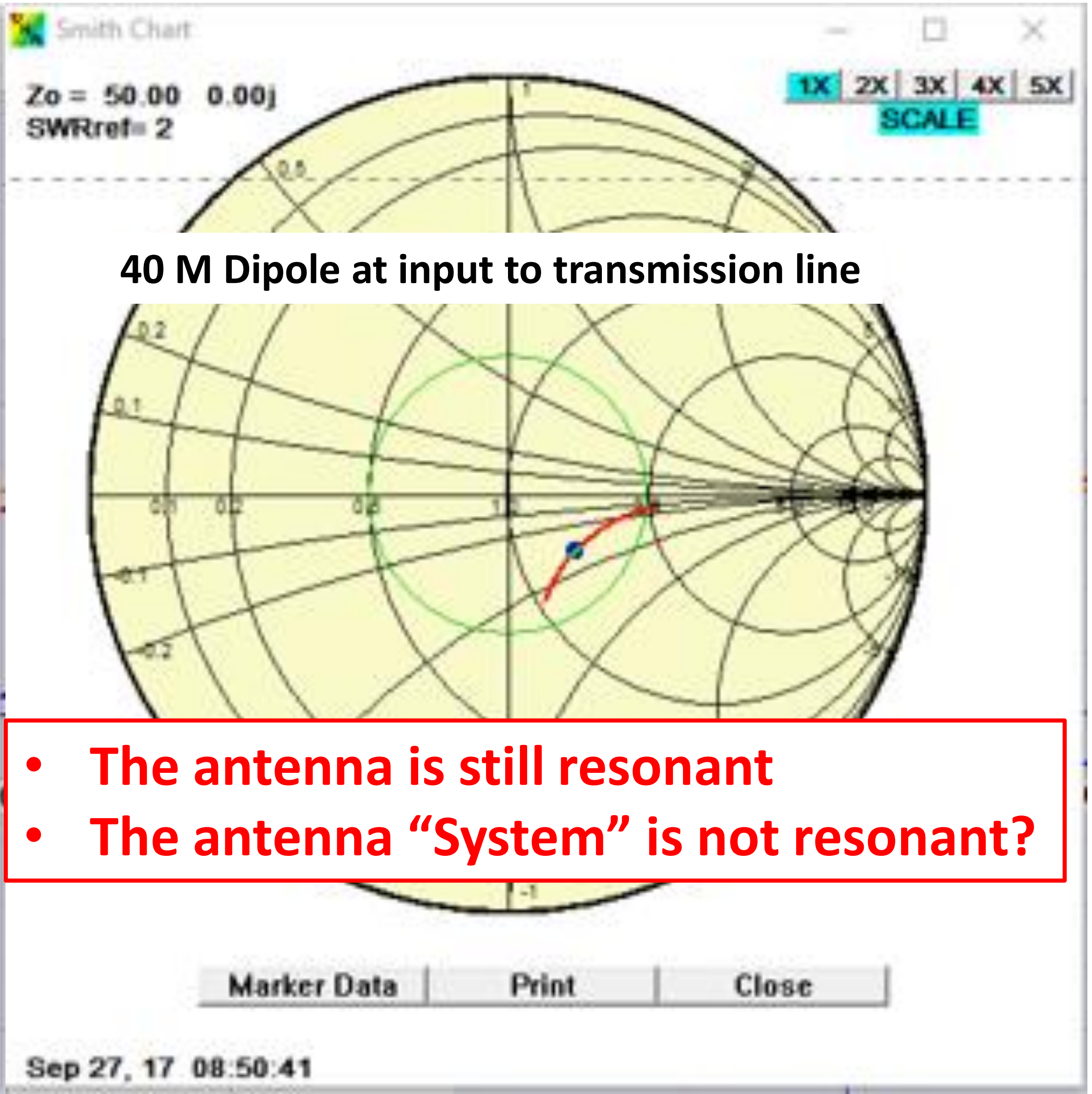
# Example 5: Antenna Tuning – cont'd



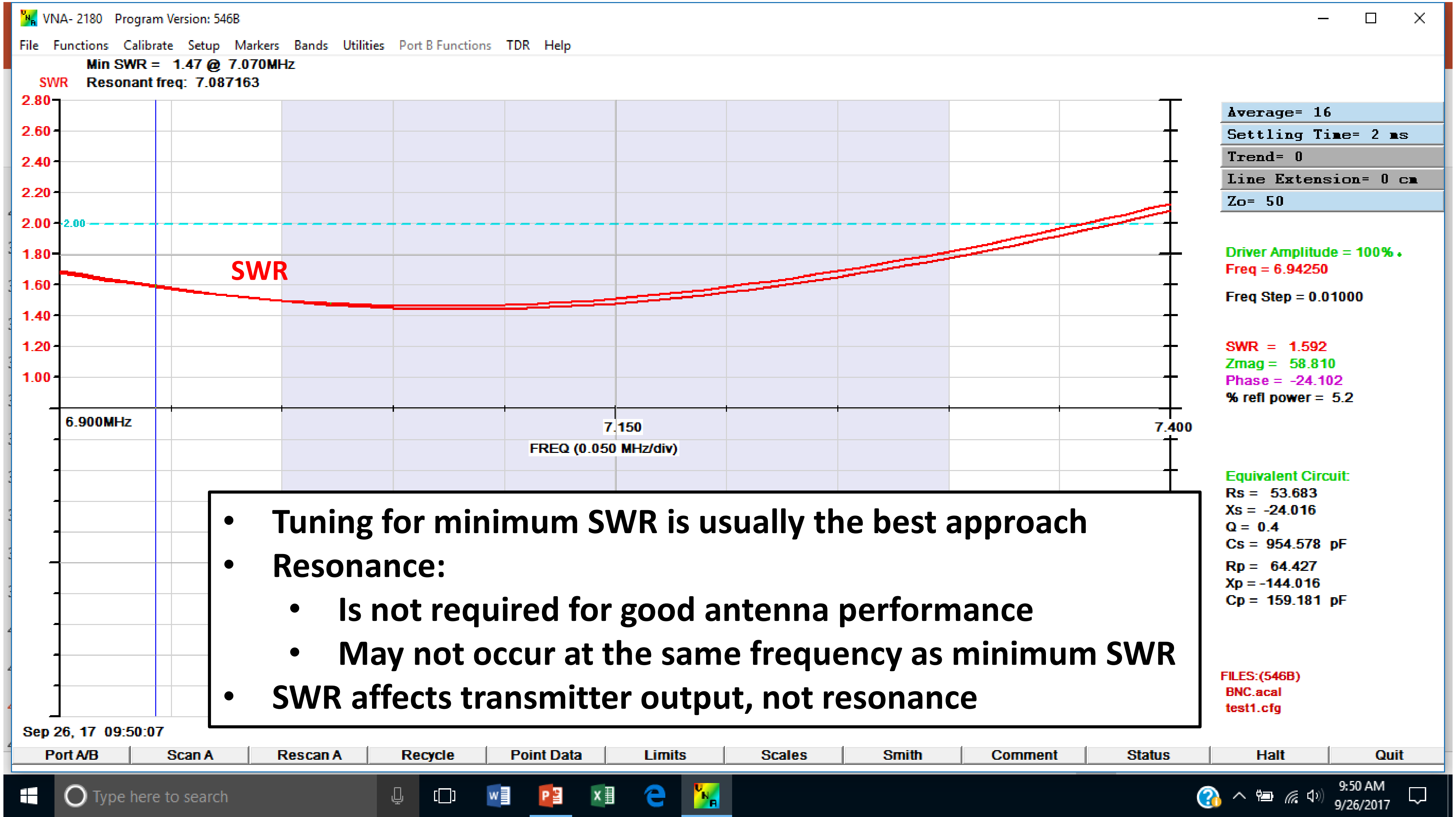
# Example 5: Antenna Tuning – cont’d



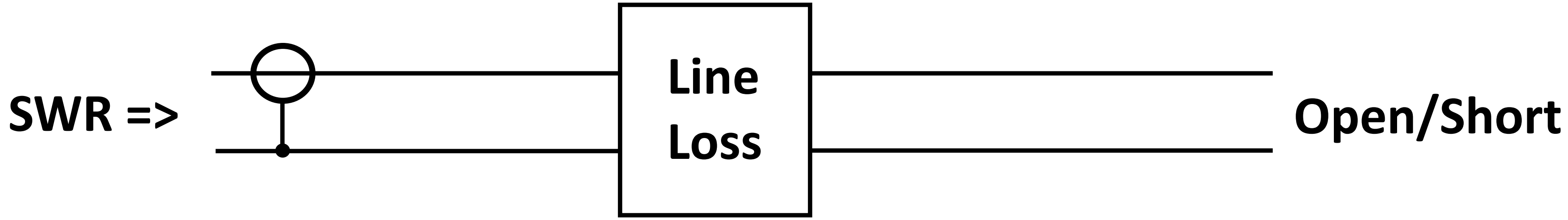

- **The antenna is still resonant**
- **The antenna “System” is not resonant?**

# Example 5: Antenna Tuning – cont'd




- Tuning for minimum SWR is usually the best approach
- Resonance:
  - Is not required for good antenna performance
  - May not occur at the same frequency as minimum SWR
- SWR affects transmitter output, not resonance

# SWR vs Transmission Line Loss




| Loss (dB) | Measured SWR | |
|---|---|---|
| 0 | Infinite | |
| 1 | 8.8 | |
| 2 | 4.4 | (75 ft RG-58A @ 28 MHz) |
| 3 | 3.0 | |
| Infinite | 1.0 | |

**Transmission line loss reduces measured SWR**

# Summary

- Make sure you understand the impedance measurement you are getting from your antenna analyzer
- When $Z_{LOAD} \neq Z_O$, transmission lines can become impedance transformers
  - This behavior can either be helpful or harmful
- The Smith chart:
  - Is a good learning tool
  - Is not the easiest way to solve impedance problems
- Adding a short length of transmission line might help an antenna tuner achieve a match
  - Because it raises the impedance (it does not lower the SWR!)
- It is usually better to tune an antenna for best SWR rather than resonance
- Transmission line loss lowers the measured SWR