Understanding Resistance, Reactance, Resonance and Impedance

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Why Do We Have Two Kinds of “Resistance”?

A Resistor resists the flow of current and drops voltage. We tend to analyze resistance in a DC environment because a resistor is not an active element that changes value with frequency.

Radiation Resistance is the value of the ***imaginary resistor*** that would consume the amount of power **actually radiated by the antenna.**

In an antenna system, Radiation Resistance is the ***beneficial*** value that we wish to maximize. The two non-beneficial resistances that we wish to **minimize** *are Ground Loss and Coil Loss (a.k.a. Material Loss).*

The Hidden “Resistance” Many Ignore

Assume that I have an SWR meter connected at the transmitter, and it shows SWR of 1.5:1.

What does that tell me about the antenna?

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

Absolutely NOTHING.

All cables have loss. If we have a cable with 3 dB loss per 100 feet of cable (i.e., 50% of power), we see: 100 Watts forward and 4 Watts reflected = SWR of 1.5:1.

SWR at source = (1+((4/100)$^{0.5}$))/(1-((4/100)$^{0.5}$)) = 1.5 NOTE: *$X^{0.5}$ (or X^0.5 in Excel) is square root of X.*

Consider that we have one half of the 100 Watts reaching the antenna, and two times the power we read as reflected (reading at the transmitter). We discover that eight watts is reflected from 50 Watts applied to the antenna and our ***actual*** VSWR is 2.33.

SWR at load = (1+((8/50)$^{0.5}$))/(1-((8/50)$^{0.5}$)) = 2.33

We now can say that we have Transmitter outpower ***minus cable loss*** at the antenna, and the value of reflected power at the antenna ***minus cable loss*** at the transmitter. Thus:

- Transmitter Power minus cable loss equals antenna input power.
- Reflected power at antenna minus cable loss equals reflected power seen at transmitter.

Belden 9258 has a matched loss of 4.086 dB per 100 feet at 146 MHZ. At 1.5:1 SWR, we add 0.151 dB SWR loss for 4.237 dB total. Thus, our power delivered to the load with 100 Watts transmitter output power is about 37 Watts (37%). Obviously, we would like to have a less lossy cable.

*Think of cable loss as “another resistor” that eats power in **both** directions.*

The Real Measuring Tool

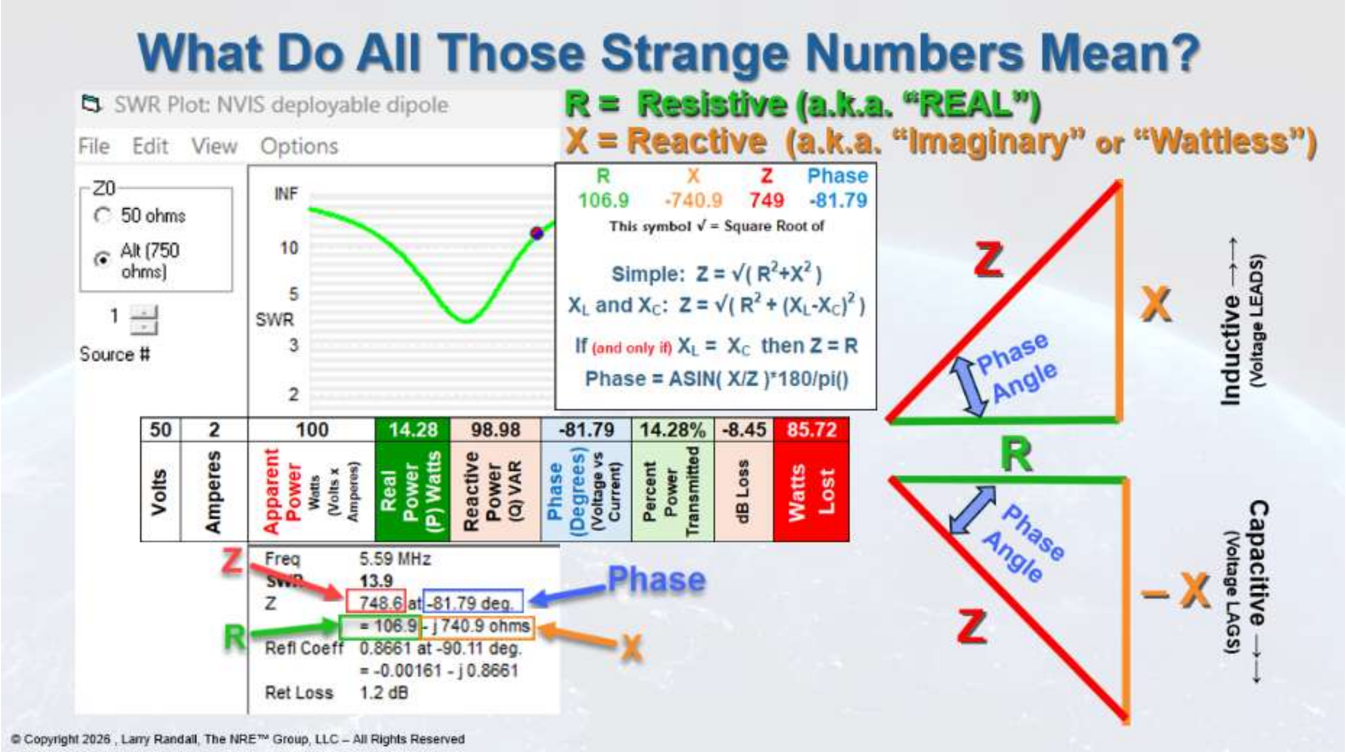
We rely upon directional Watt Meters so that we can translate the reading of 100 Watts forward and 4 Watts reflected into a ***true*** value of SWR at the antenna.

For the SWR meter, there is an issue of where in the line it is inserted, because its readings will change with location in the line. Thus, our SWR reading might look **great** on a lossy cable, even though actual VSWR is off the charts.

There is no such dependency when we use a directional wattmeter, because the wattmeter measures *actual power in each direction, not SWR*.

The above scenarios assume that the antenna is at or near resonance and MATCHED to the 50 Ohm feedline. That is a **really, really poor assumption.**

The next image is from one of my presentations that illustrates the relationship between Radiation Resistance, Capacitive and Inductive Reactance, and Impedance. Many to most hobbyists (and lots of professionals) see the numbers and go absolutely numb with “Math-itis”.



What Do All Those Strange Numbers Mean?

R = Resistive (a.k.a. "REAL")

X = Reactive (a.k.a. "Imaginary" or "Wattless")

R	X	Z	Phase
106.9	-740.9	749	-81.79

This symbol √ = Square Root of

Simple: $Z = \sqrt{(R^2+X^2)}$

X_L and X_C: $Z = \sqrt{(R^2 + (X_L-X_C)^2)}$

If (and only if) $X_L = X_C$ then $Z = R$

Phase = ASIN(X/Z)*180/pi()

50	2	100	14.28	98.98	-81.79	14.28%	-8.45	85.72
Volts	Amperes	Apparent Power Watts (Volts x Amperes)	Real Power (P) Watts	Reactive Power (Q) VAR	Phase (Degrees) (Voltage vs Current)	Percent Power Transmitted	dB Loss	Watts Lost

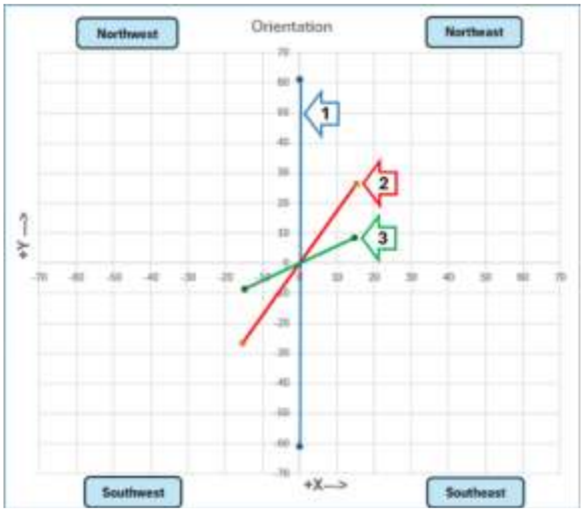
Freq	5.59 MHz
SWR	13.9
Z	748.6 at -81.79 deg.
	= 106.9 - j 740.9 ohms
Refl Coeff	0.8661 at -90.11 deg.
	= -0.00161 - j 0.8661
Ret Loss	1.2 dB

Let's Clarify Those "Mysterious Numbers"

Very basic math deciphers these numbers quite easily.

Notice that the formula for Z is the formula for the Hypotenuse of a Right Triangle. *That's because that is exactly what we are solving.*

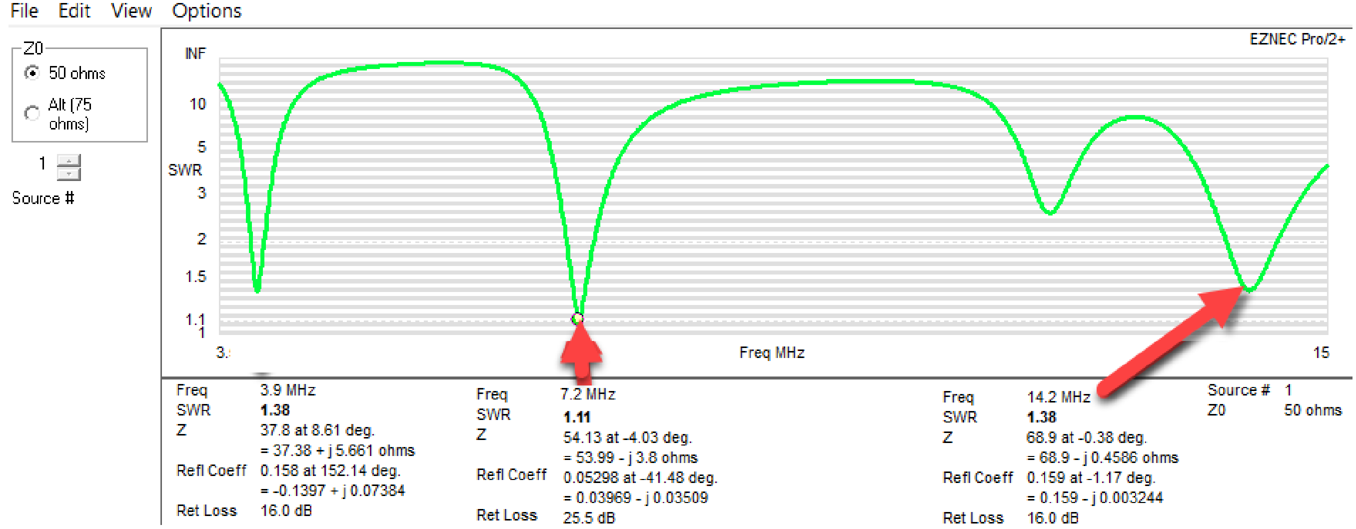
- **"R" is the REAL portion of impedance.**
  - That means zero reactance.
  - This is what is called is called **Radiation Resistance (R_R).**
- **"X" is the Reactance portion of impedance.**
  - It also may be called either "**Imaginary**" or "**Wattless**".
  - Reactance does not contribute to power radiated.
    - **Positive value of X** indicates **Inductive**, because **Voltage leads current**.
    - **Negative value of X** indicates **Capacitive**, because **Voltage lags current**.
- **"Z" is the Impedance value in Ohms** (***but it is NOT a resistance***).
  - **Z = Square Root of (R^2 +X^2)** $Z = \sqrt{(R^2 + x^2)}$
- **Phase Angle is the difference in time between voltage and current.**
  - Phase angle = **ASIN (X / Z) x (180 / pi())** NOTE: "180 / pi()" converts Radians to degrees.
  - Phase Angle =ASIN(-740.9/748.6)*(180/PI()) = -81.79
    - In this case, minus 81.79 degrees indicates Capacitive Reactance.
    - Only 14.28 Watts is available to be transmitted
    - 85.72% of power is lost.



Here, we see a physical layout of 3.9, 7.2, and 14 MHZ dipoles with common feedpoint. We have 30 degrees azimuth between elements, and all are flat-topped at 30 feet AGL.

- Dipole 1 is 75 meters
- Dipole 2 is 40 Meters
- Dipole 3 is 20 Meters

Below right is the 3.5 to 15 MHZ sweep for 50 Ohm feed. The impedance and SWR for each point are shown below the plot.



Freq 3.9 MHz
SWR **1.38**
Z 37.8 at 8.61 deg.
= 37.38 + j 5.661 ohms
Refl Coeff 0.158 at 152.14 deg.
= -0.1397 + j 0.07384
Ret Loss 16.0 dB

Freq 7.2 MHz
SWR **1.11**
Z 54.13 at -4.03 deg.
= 53.99 - j 3.8 ohms
Refl Coeff 0.05298 at -41.48 deg.
= 0.03969 - j 0.03509
Ret Loss 25.5 dB

Freq 14.2 MHz
SWR **1.38**
Z 68.9 at -0.38 deg.
= 68.9 - j 0.4586 ohms
Refl Coeff 0.159 at -1.17 deg.
= 0.159 - j 0.003244
Ret Loss 16.0 dB

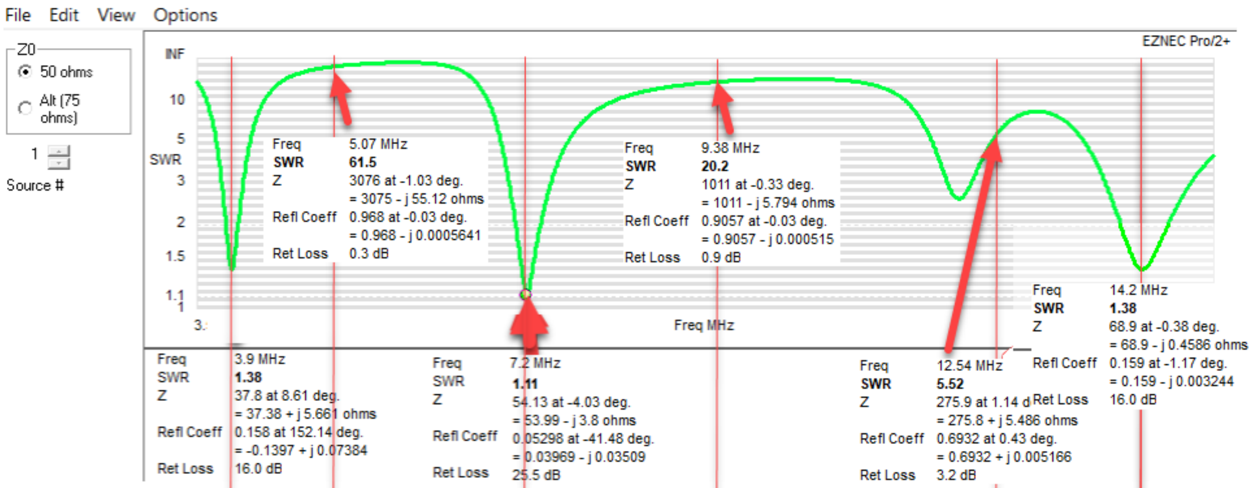
Source # 1
Z0 50 ohms

We see lowest SWR of 1.11 at 7.22 MHZ, SWR of 1.38 at 3.9 MHZ, and SWR of 1.38 at 14.2 MHZ

SWR is nearly the same at 3.9 and 14.2, but IMPEDANCE is 37.8 Ohms at 3.9 and 68.9 Ohms at 14.2.

(See next page.)

When we change nothing but feedpoint impedance (e.g., put a transformer in line) to feed at 1200 Ohms, we get a wildly different plot.



Freq	5.07 MHz
SWR	**61.5**
Z	3076 at -1.03 deg.
	= 3075 - j 55.12 ohms
Refl Coeff	0.968 at -0.03 deg.
	= 0.968 - j 0.0005641
Ret Loss	0.3 dB

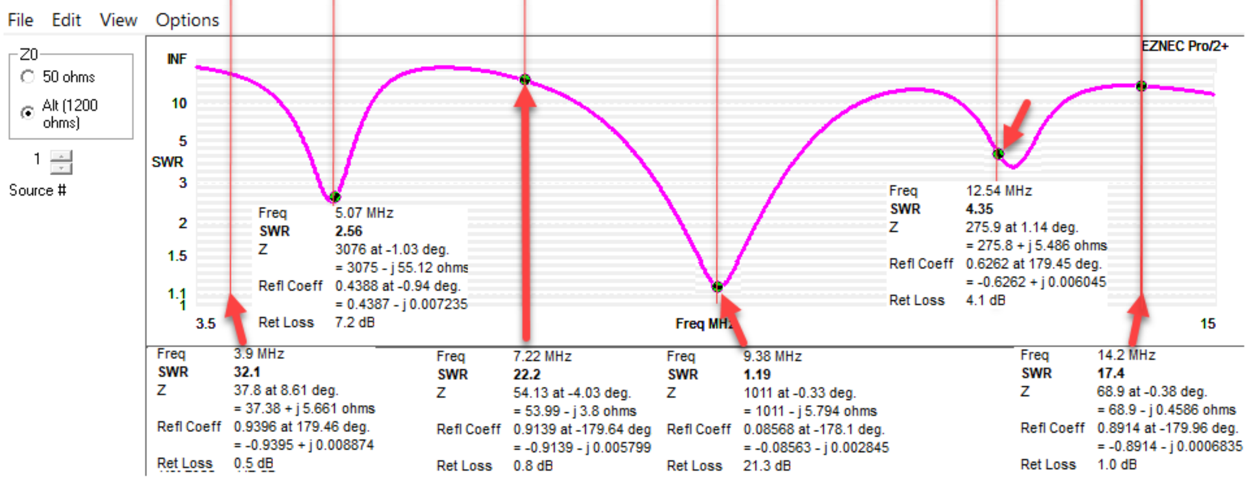
Freq	9.38 MHz
SWR	**20.2**
Z	1011 at -0.33 deg.
	= 1011 - j 5.794 ohms
Refl Coeff	0.9057 at -0.03 deg.
	= 0.9057 - j 0.000515
Ret Loss	0.9 dB

Freq	14.2 MHz
SWR	**1.38**
Z	68.9 at -0.38 deg.
	= 68.9 - j 0.4586 ohms
Refl Coeff	0.159 at -1.17 deg.
	= 0.159 - j 0.003244
Ret Loss	16.0 dB

Freq	3.9 MHz
SWR	**1.38**
Z	37.8 at 8.61 deg.
	= 37.38 + j 5.661 ohms
Refl Coeff	0.158 at 152.14 deg.
	= -0.1397 + j 0.07384
Ret Loss	16.0 dB

Freq	7.2 MHz
SWR	**1.11**
Z	54.13 at -4.03 deg.
	= 53.99 - j 3.8 ohms
Refl Coeff	0.05298 at -41.48 deg.
	= 0.03969 - j 0.03509
Ret Loss	25.5 dB

Freq	12.54 MHz
SWR	**5.52**
Z	275.9 at 1.14 d
	= 275.8 + j 5.486 ohms
Refl Coeff	0.6932 at 0.43 deg.
	= 0.6932 + j 0.005166
Ret Loss	3.2 dB



Freq	5.07 MHz
SWR	**2.56**
Z	3076 at -1.03 deg.
	= 3075 - j 55.12 ohms
Refl Coeff	0.4388 at -0.94 deg.
	= 0.4387 - j 0.007235
Ret Loss	7.2 dB

Freq	12.54 MHz
SWR	**4.35**
Z	275.9 at 1.14 deg.
	= 275.8 + j 5.486 ohms
Refl Coeff	0.6262 at 179.45 deg.
	= -0.6262 + j 0.006045
Ret Loss	4.1 dB

Freq	3.9 MHz
SWR	**32.1**
Z	37.8 at 8.61 deg.
	= 37.38 + j 5.661 ohms
Refl Coeff	0.9396 at 179.46 deg.
	= -0.9395 + j 0.008874
Ret Loss	0.5 dB

Freq	7.22 MHz
SWR	**22.2**
Z	54.13 at -4.03 deg.
	= 53.99 - j 3.8 ohms
Refl Coeff	0.9139 at -179.64 deg
	= -0.9139 - j 0.005799
Ret Loss	0.8 dB

Freq	9.38 MHz
SWR	**1.19**
Z	1011 at -0.33 deg.
	= 1011 - j 5.794 ohms
Refl Coeff	0.08568 at -178.1 deg.
	= -0.08563 - j 0.002845
Ret Loss	21.3 dB

Freq	14.2 MHz
SWR	**17.4**
Z	68.9 at -0.38 deg.
	= 68.9 - j 0.4586 ohms
Refl Coeff	0.8914 at -179.96 deg.
	= -0.8914 - j 0.0006835
Ret Loss	1.0 dB

The Myth of SWR and Resonance

Note that actual impedance is unchanged, but 7.2 MHZ SWR skyrocketed from 1.11:1 to 22:1.

- The system also is RESONANT at 9.38 MHZ at an impedance of 1011 Ohms.
- It is RESONANT at 5.07 MHZ at an impedance of 3076 Ohms.

We see here that there are multiple points where the antenna system actually is resonant, as noted by the vertical lines. The IMPEDANCE at resonance varies from 37 Ohms to over 3000 Ohms.

I say this to make a very critical point: **High SWR *does not indicate* lack of resonance, and low SWR *does not indicate resonance.***

- Resonance occurs ONLY when voltage and current are in phase.
- Resonance occurs at one value of impedance for that frequency.

So, can we have a single wire (with an equal counterpoise) for all frequencies 2 to 30 MHZ ?

YES!

Fixing the Phase Angle

In the prior case, (Phase Angle =ASIN(-740.9/748.6)*(180/PI()) = -81.79 degrees), we can bring the phase angle to (or very near) zero by applying an inductance of 740 Ohms Reactance in parallel at the feedpoint. A value of 21.09 μH is required.

- **$L = X_L / (2\pi \times \text{Freq in Megahertz})$**
  L = 740.9/(2*PI()*5.59)) = 21.09 μH
  - The input becomes **resistive** at the value of the REAL portion (106.9 Ohms).
  - Full power (minus losses) is available to be radiated.

R	X	Z	Phase
106.9	-740.9	749	-81.79

This symbol √ = Square Root of

Simple: $Z = \sqrt{(R^2+X^2)}$

X_L and X_C: $Z = \sqrt{(R^2+(X_L-X_C)^2)}$

If $X_L = X_C$, then $Z = R$

Phase = ASIN(X/Z)*180/pi()

By balancing the inductive or capacitive Reactance at the chosen frequency with the opposite sign Reactance, *we align voltage and current in phase at the antenna*.

When is an "Antenna Tuner" NOT a REAL Antenna Tuner?

Note that a "tuner" at or inside the transmitter adjusts to present 50 Ohms ***impedance*** to the transmitter (*which may be mostly reactance*), *without regard to the voltage and current phase relationship at the transmitter or at the antenna.*

An Antenna Matching Unit (AMU, a.k.a. "Tuner") must be located ***at the feedpoint of the antenna.*** The AMU supplies a 1:1 non-reactive match to the transmitter *and* supplies a *conjugate match* (i.e., opposite sign reactance) at the feedpoint to create a *resonant feed* to the antenna at that frequency. (i.e., Voltage and current are fed to the antenna in phase.)

Since reactance is cancelled by the tuner at the feedpoint, the input Impedance equals Radiation Resistance (R_R) + Ground Loss (R_G) + Material Loss (R_C). Therefore, for a simple wire, essentially we have *power applied times* $R_R/(R_R+R_C+R_G)$ **=** *power transmitted*

Assume: 100-Watt transmitter. Coax and tuner losses of 10 Watts. R_R 35 Orms, R_C 3 Ohms, R_G 10 Ohms. We have 90 Watts x (35/(35+3+10) = 90 x 0.73 = 65.7 Watts transmitted.

Simply, ***higher*** R_R and **lower** R_C and R_G, means <u>*greater percentage of power transmitted*</u>.

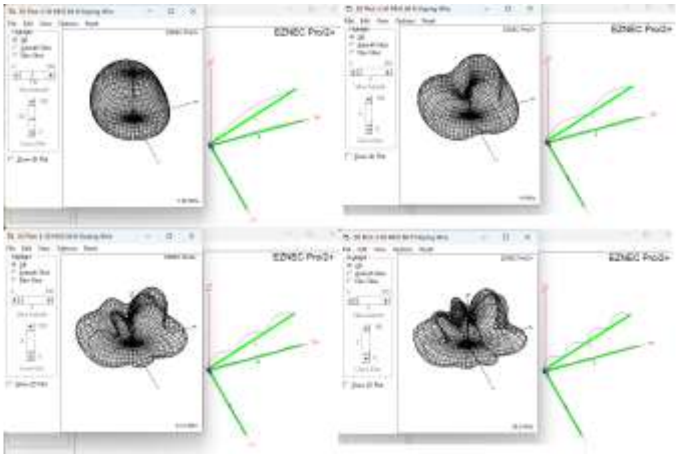
Up to a point, wire length in wavelengths, frequency of operation, and ground losses determine the percentage of applied power that is transmitted. However, *wire lengths of half wavelength are to be avoided because the near infinite impedance is beyond the 4000 Ohms to 5500 Ohm maximum impedance range of a tuner*.

- For **40-30-20-15 meters**, 35 feet is good.
- For ***40-30-20-17-15-12-10 meters***, 40 feet or 60 feet are clear of half wavelengths and work well.
- For ***160-80-40-30-20-17-15-12-10 meters***, 70 feet, 106 feet, or 136 feet are safe lengths.

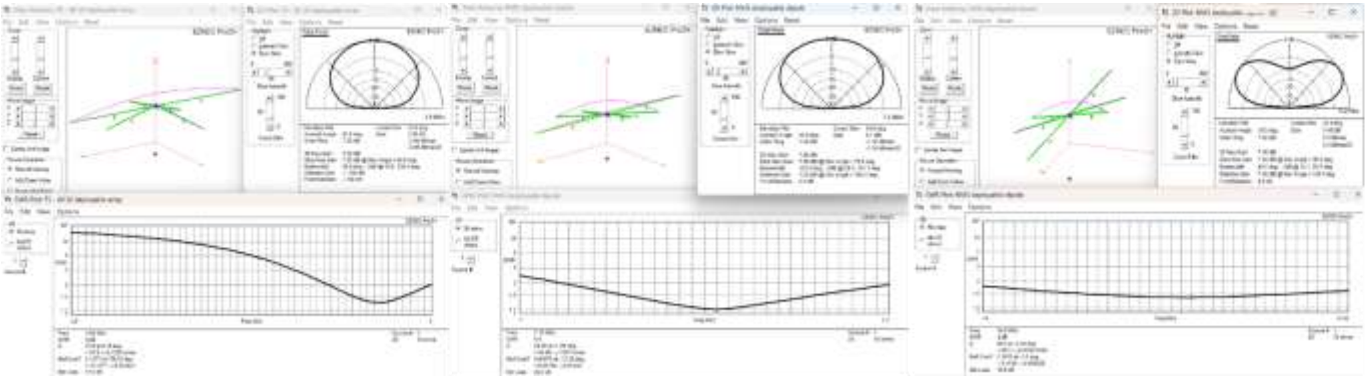
CREDIT: https://udel.edu/~mm/ham/randomWire/indexOld.html

Since Radiation Resistance increases with increasing radiator length up to near 1/2 wavelength, typically we **might** get higher efficiency on higher frequencies; ***HOWEVER, the longer the wire in wavelengths, the greater the pattern distortion at higher frequencies -- AND low height above ground*** **very significantly increases Ground Loss.**

Note that the pattern diverges wildly



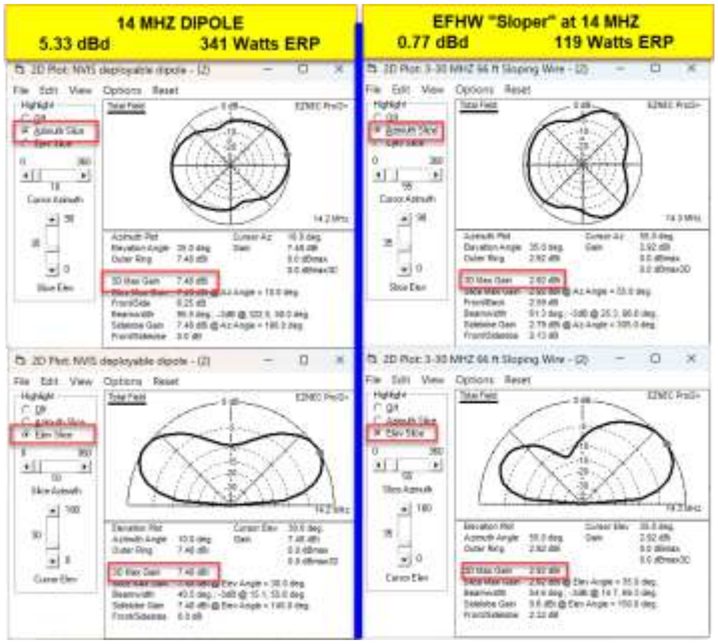
For the above reason, I recommend a SET of antennas – some or all of which may share a common feedpoint. The design below uses dipoles mounted flat-top 30 feet over average soil, elements spaced at a minimum of 30 degrees of azimuth from each other and fed by a single feedline. (The design could be adapted easily for another set of bands.)



NOTE: The red arc is the current distribution. The green lines are the antenna elements. As you can see, there is very low interaction between elements. We see that 3.9 and 7.2 are good NVIS antennas, with the 7.2 offering DX possibilities, and the 14.2 element is a reasonable DX antenna**.**

14 MHZ Dipole vs 66 Foot "EFHW"

Notice that the 14 MHZ dipole in the array above has 7.48 dBi (5.33 dBd) gain, while the "EFHW" has gain of 2.92 dBi (0.77 dBd). The maximum 0.77 dBd gain of the "EFHW" wire is at 55 degrees (i.e., 35 degrees from the plane of the wire) while the 5.33 dBd dipole gain is at 80 to 90 degrees to the wire in both directions.



Summary

Antenna designs are not really mysterious, though much study may be required to understand the relationships that are important to them.

The required basic math is nothing not seen in a high school classroom, and the free EZNEC Pro allows you to look at an idea to see how it should work in the real world.

The key to successful modeling is to ensure that the ***real world*** is considered.

One person modeled a dipole array and installed it – only to find SWR off the charts. When we looked at the installation, there was a long metal walkway within very few feet of one end of the antenna. We moved that end, and SWR dropped to designed value.

There ALWAYS is a reason why something does not work as designed. Sometimes it is a design flaw – but most often it is failure to consider the ***real world*** when modeling and installing the antenna.

Be curious. Be aware. BE SAFE.