The Counterpoise: The **Other Half** of Your Antenna!

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How this program came about.

- I could not understand how the end-fed half-wave (EFHW) antenna could possibly work, because of its tiny, 0.05 wavelength, counterpoise.
- This led me into the rabbit-hole of learning about counterpoises and antennas. Now, your turn!
- It turns out the EFHW antenna does work, but the part we call the counterpoise isn't really the counterpoise. We'll get into that later.

AC gets a *lot* harder than DC Electricity

- Not all of us are electrical engineers, and the ones who aren't might only have an intuitive understanding of DC electricity, if that.

- It's a *big* step to go from DC to AC theory. RF is the ultimate AC, and not that we're going there today, but microwave is the ultimate RF; as shown by this RADAR PCB.

- But today, let's start *really simple!*
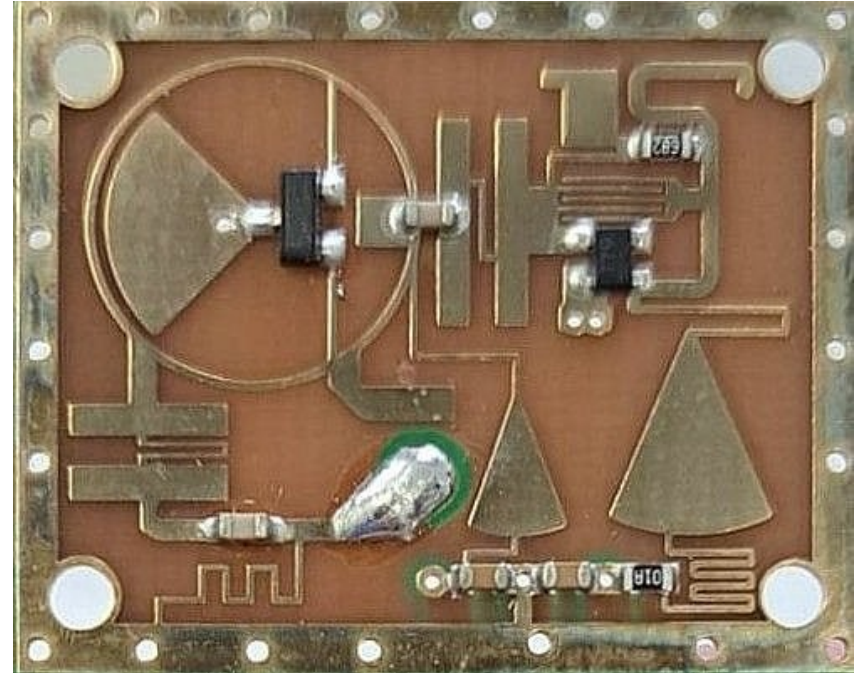
You Can't Force Current Through a One-Terminal Circuit

Closed Loop
(Current Flows -> LED On)

Open Loop
(LED Off)

1.5V

1.5V

NO RETURN PATH
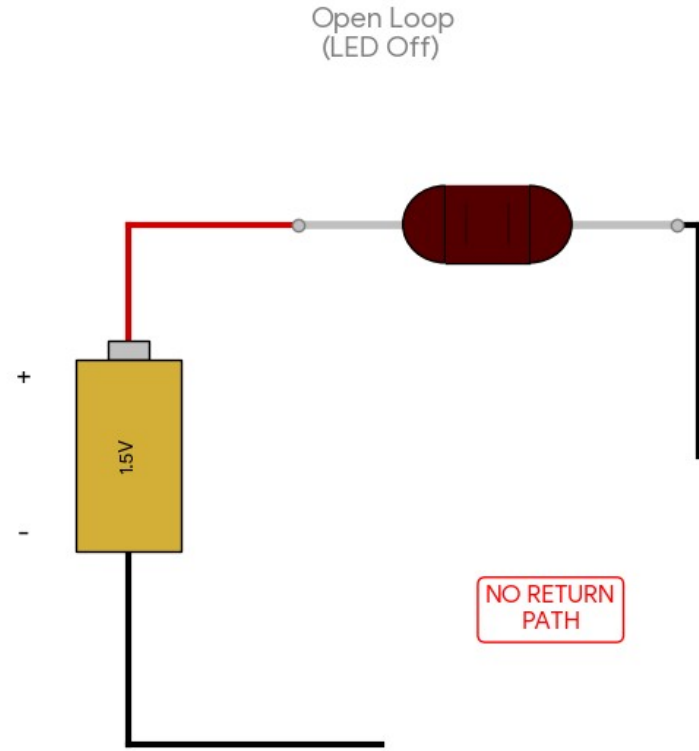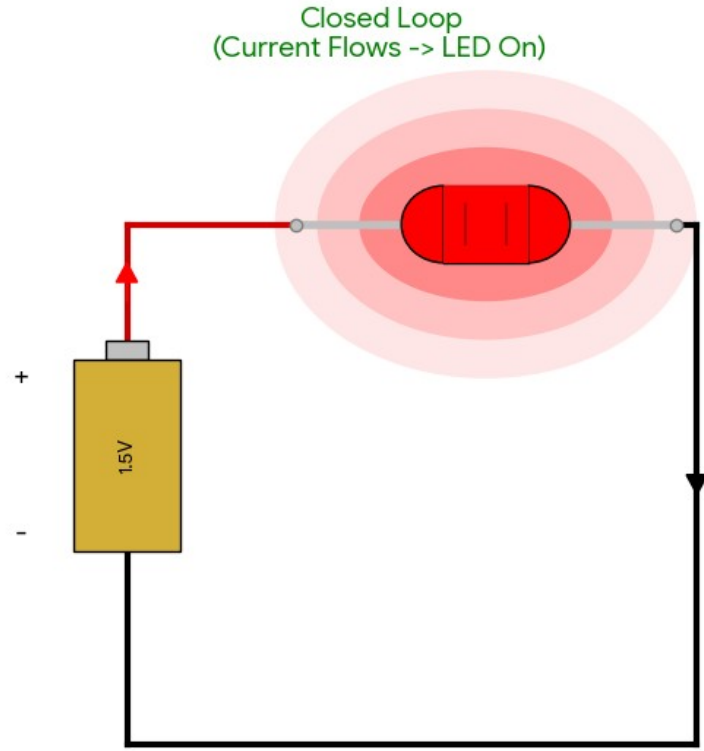
No One-Terminal Circuits

- There must always be two terminals:
- A current *supply.*
- A current *return.*
- Without both, no current flows.

Then, How Does Your Antenna Work?
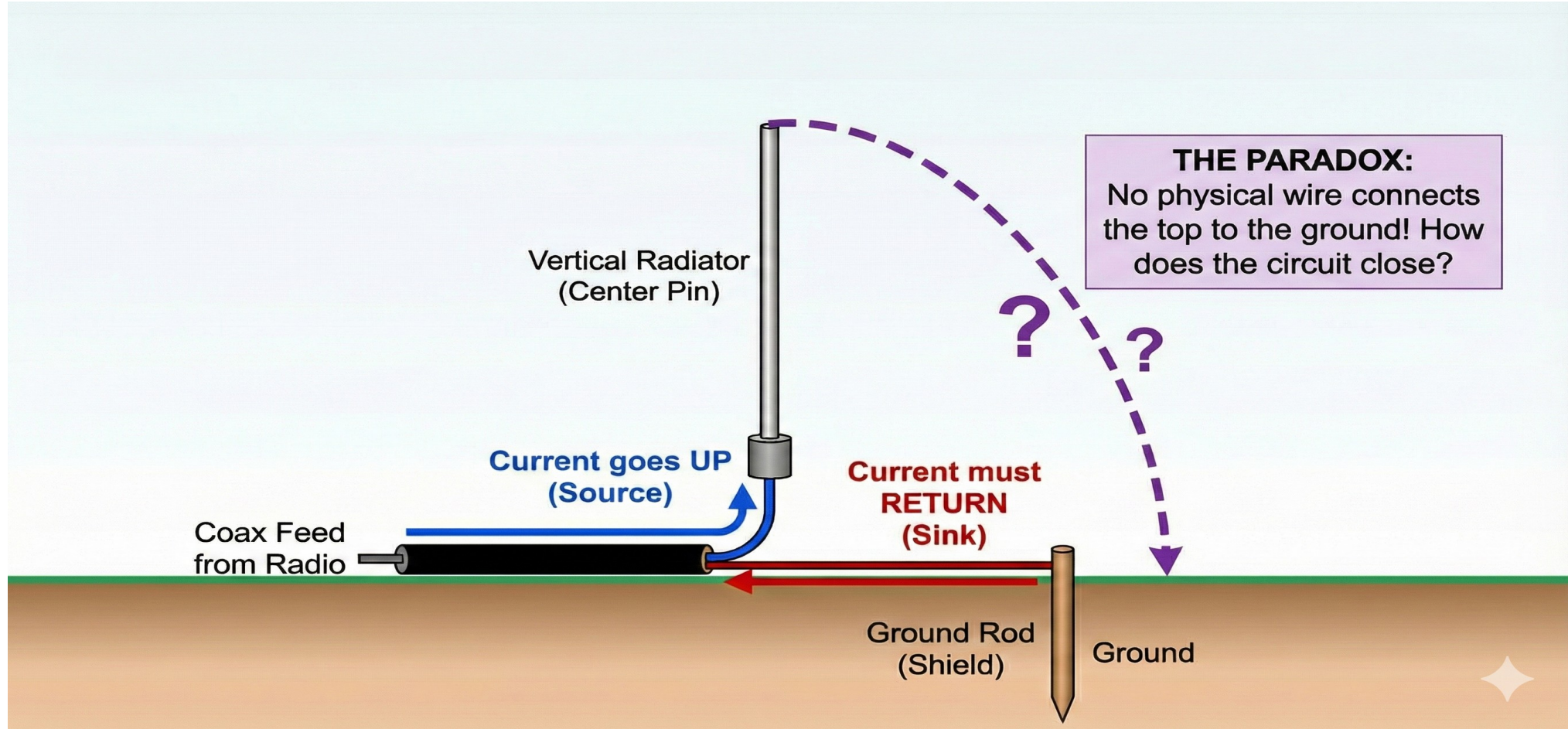
Antennas Must Always Be Two-Terminal Circuits!

- Current flows from the transmitter to the antenna on the center conductor of the coax.

- Current **must return** from the antenna to the transmitter, on the shield of the coax, to complete the circuit! *What invisible thing completes the circuit?*

- And if all of the current *returns to the transmitter,* how do we transmit anything?

There's a Third Component Connecting the Antenna Elements, *Space-Time!*

- The two elements of a dipole, illustrated, are connected to each other by space-time.

- Red: magnetic field in space time, Blue: electric field.

- Oscillating antenna current induces fields in space-time, oscillating ***fields induce current in the antenna.***

Electric Field (**E**)

Magnetic Field (**H**)

SO-239
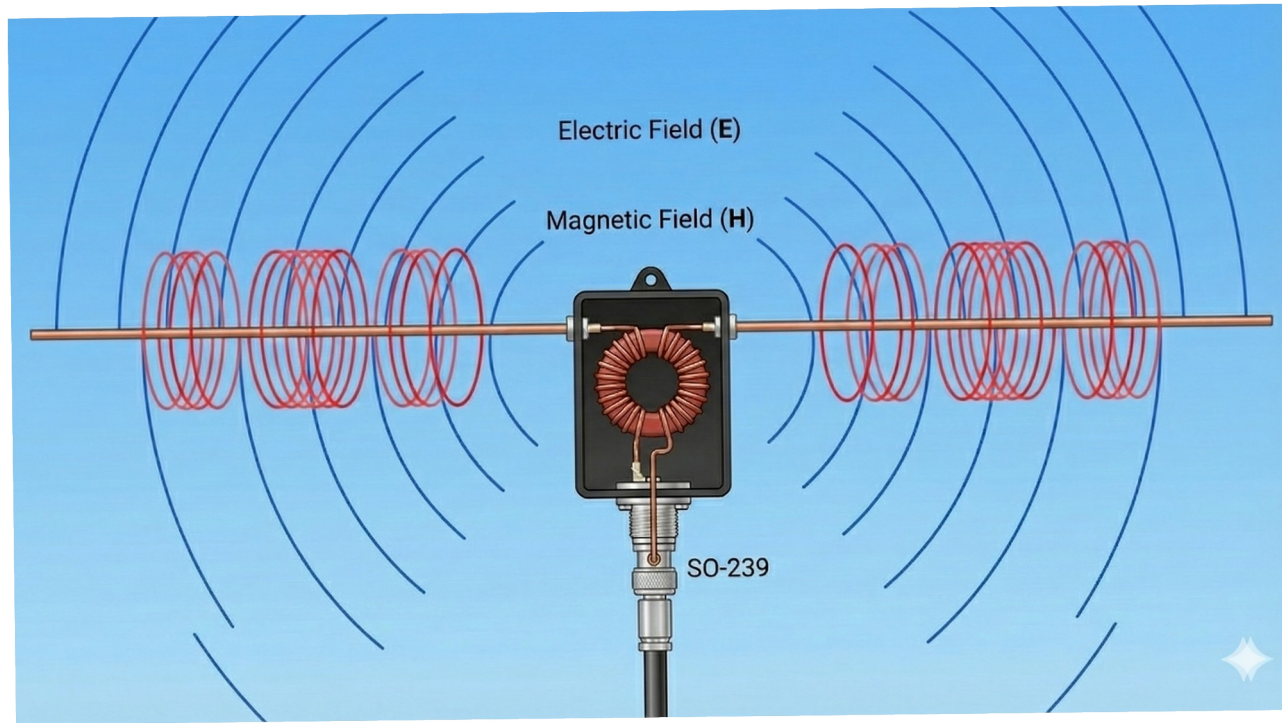
How Is Space-Time Part of the Antenna?

- You can think of space-time *as an electronic component that is* **everywhere.**

- Like a resistor or capacitor, space-time has *well-defined electrical properties that are useful in a circuit.*

- Of course, the image is imaginary. Space-time is everywhere, you don't have to solder it to your PCB.

Electrical Properties of Space-Time

- **Magnetic permeability:** the ability to support a magnetic field (related to inductance).
- **Electrical permissivity:** the ability to support an electric field (related to capacitance).
- A **propagation speed**, the speed of light. Wavelength comes from this (space/time).
- An **impedance** (377 ohms).

How Antennas Really Work

- Radio waves don't just fly off of the antenna.
- The antenna creates *fields. Electrical* and *magnetic*.
- The fields are in space-time.
- The two wires of a dipole, and space-time (and the transmitter and feedline) form a complete circuit! *Current returns to the transmitter.*

What Do The Fields Do?

- Just as a moving magnet can induce an electric current in a wire, changing magnetic fields induce electrical fields in space-time, *and vice-versa.*

- The oscillating electric and magnetic fields **sustain each other** and can propagate over a great distance.

- That's what radio waves are.

Coil or Loop

Direction of Movement

N   S

Magnet

0

Galvanometer
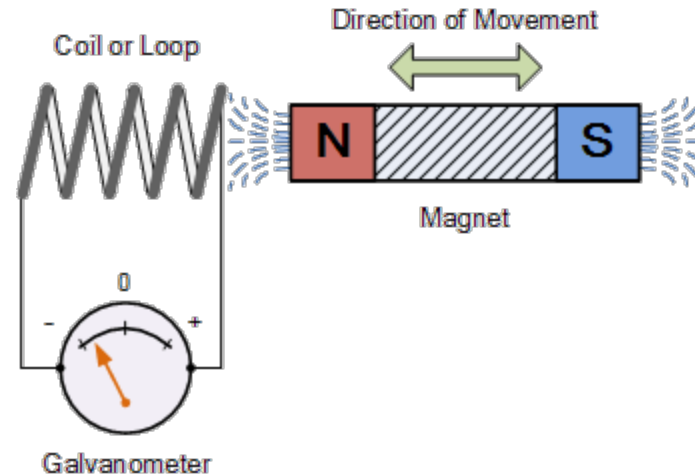
Compromise Antennas

- We're going to talk about why some antennas aren't so good. Why?

- A compromise antenna is always better than *no* antenna. But maybe it's not the best antenna you could have. You might make a better compromise, if you understood antennas better, did more work, etc.

- Most ham antennas are too small, too low height to avoid ground loss, not matched to the frequency, have wires too thin, have a bad counterpoise, etc. These are the ways we compromise.

Compromise Antennas (2)

- You will *always* hear from people who won contests with compromise antennas. So, it must be good, right?

- There is varying theoretical knowledge, use of modeling, and measuring procedures among antenna manufacturers. Some only do A/B testing, which can lead to self-deception (and deceiving the customer unintentionally) because there are too many variables.

# What is a Counterpoise?

- The part of an *unbalanced* antenna that returns current to the transmitter. This *¼ wave vertical* is a very common unbalanced antenna. It has a vertical element, and counterpoise radial elements. It is *unbalanced* because the two parts are not the same.

→
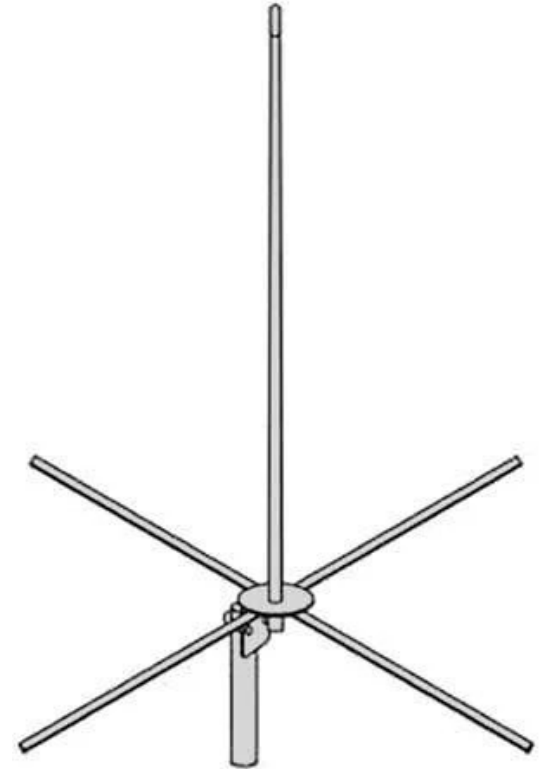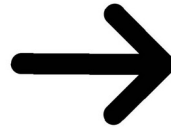
Well, What's a Balanced Antenna?

- A balanced antenna has *equal elements* (often wires) for each side of the circuit.

- This horizontal dipole has two *equal* wires, so it's balanced. The two wires are in a circuit with space-time (and the transmitter and feedline).

Electric Field (**E**)

Magnetic Field (**H**)

SO-239
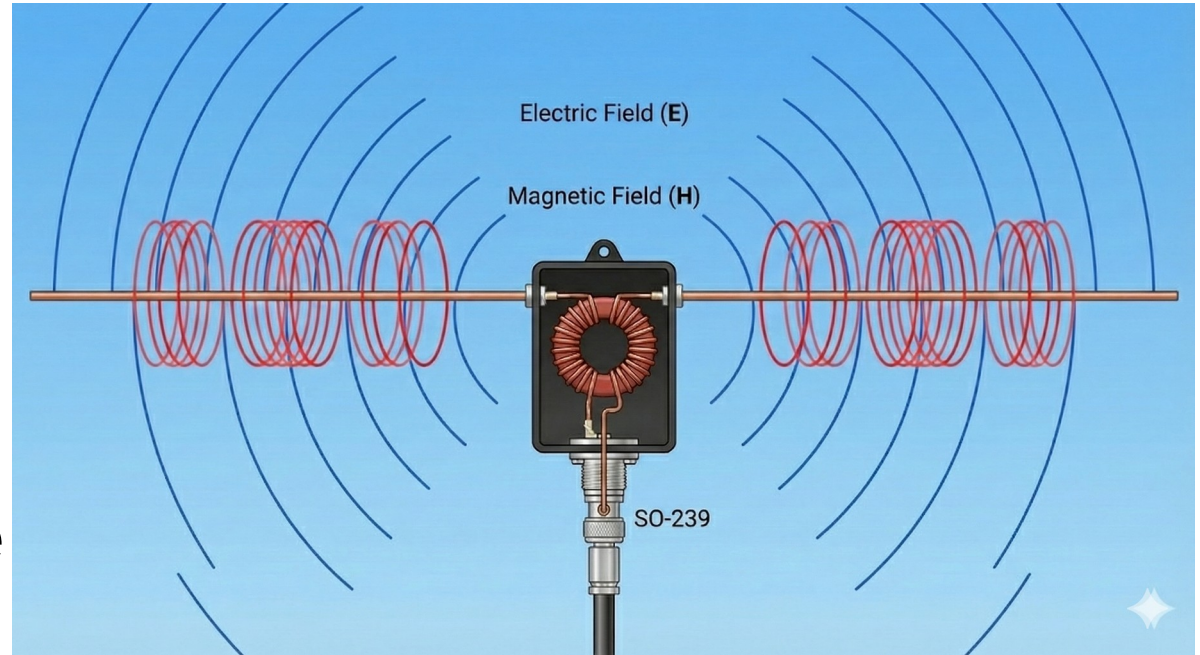
Loop Antenna

- A loop is a balanced antenna made of *one* wire with both sides connected to the feedline, so it more intuitively makes a circuit, and returns current to the transmitter. Although it makes a circuit on its own, the loop *is still in a circuit with space-time.*
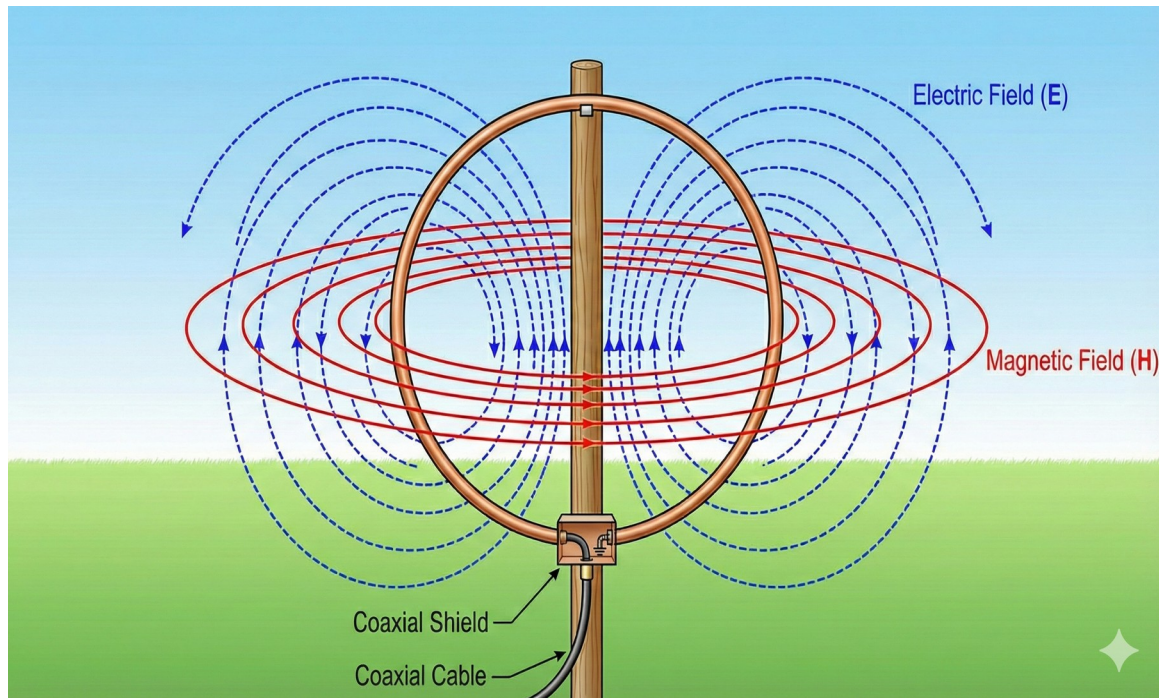
There are Balanced Feedlines Too

- Coax is unbalanced.

- Ladder-line is balanced.

- We often use a Balun (BALanced to UNbalanced transformer) to go from unbalanced feedline (like coax) to a balanced antenna.

Coaxial Cable with PL-259

Ladder-line
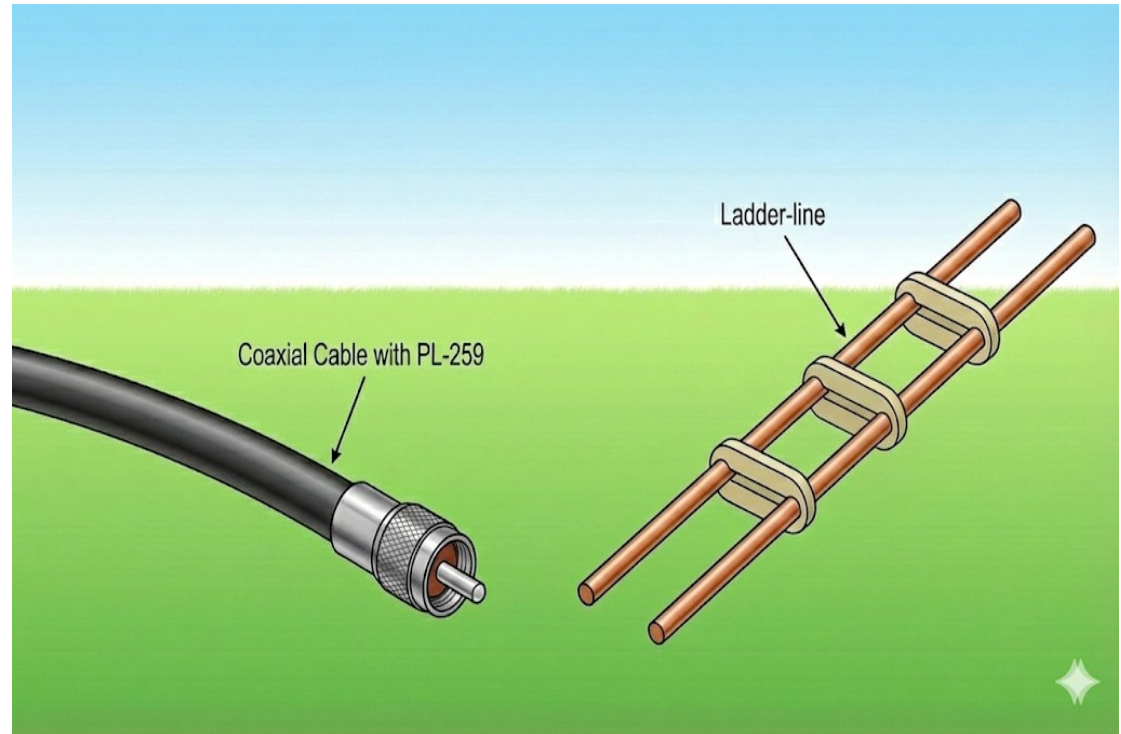
Unbalanced Antenna

- Verticals and random wire are examples of a *un*balanced antenna. We'll get into EFHW later.
- The "radiating element" and the counterpoise, the part that returns the current to the transmitter, are physically different.
- Unbalanced antennas can be modeled as dipoles with unequal parts.
- **It's the unbalanced antennas that often skimp on the counterpoise.**

Misconceptions about the Counterpoise

- "*The counterpoise is not important, because it is not the radiating element.*"

- FALSE! The counterpoise is necessary to return current to the transmitter. ALL of the current must be returned, none flows without returning. The antenna will work poorly unless the current is returned *efficiently.*

Misconceptions about the Counterpoise (2)

- "You only need 0.05% of the wavelength for the counterpoise", oft stated for EFHW.

- FALSE! The 0.05% wire on an EFHW is not the major counterpoise. The long section, because it's most of a half-wave long, *returns its own current*.

The Importance of Measuring Antennas *Accurately*

- Hams have historically been poorly equipped to measure their own antennas. *We only had really indirect methods,* like S-meter, the thickness of our QSL pile, and SWR doesn't actually measure antenna performance.

Effect of Lack of Accurate Measurement

- Because antennas were so difficult to measure, *craft knowledge took the place of science,* and there has been a lot of confusion and misconception about antennas. That continues today.

- But today, we have a new method to measure antennas acurately! Let's talk about how we've been doing it, and how we *should* do it.

What to Measure? Near Field vs. Far Field

- The fields emitted by an antenna are separated into *the Near Field* and *Far Field.*

- Near Field: The electric and magnetic field close to the antenna. These fields actually return significant current to the antenna, so this is also called the *reactive* field.

Near Field and Far Field

- Far Field: Farther from the antenna, the fields behave as plane waves and better represent what happens at a much greater distance from the antenna. This is also called the *radiative* field.

- **To understand antenna performance, we must measure the *far field.***

Near and Far fields. The field shapes are not mathematically accurate, and Poynting vectors not shown.
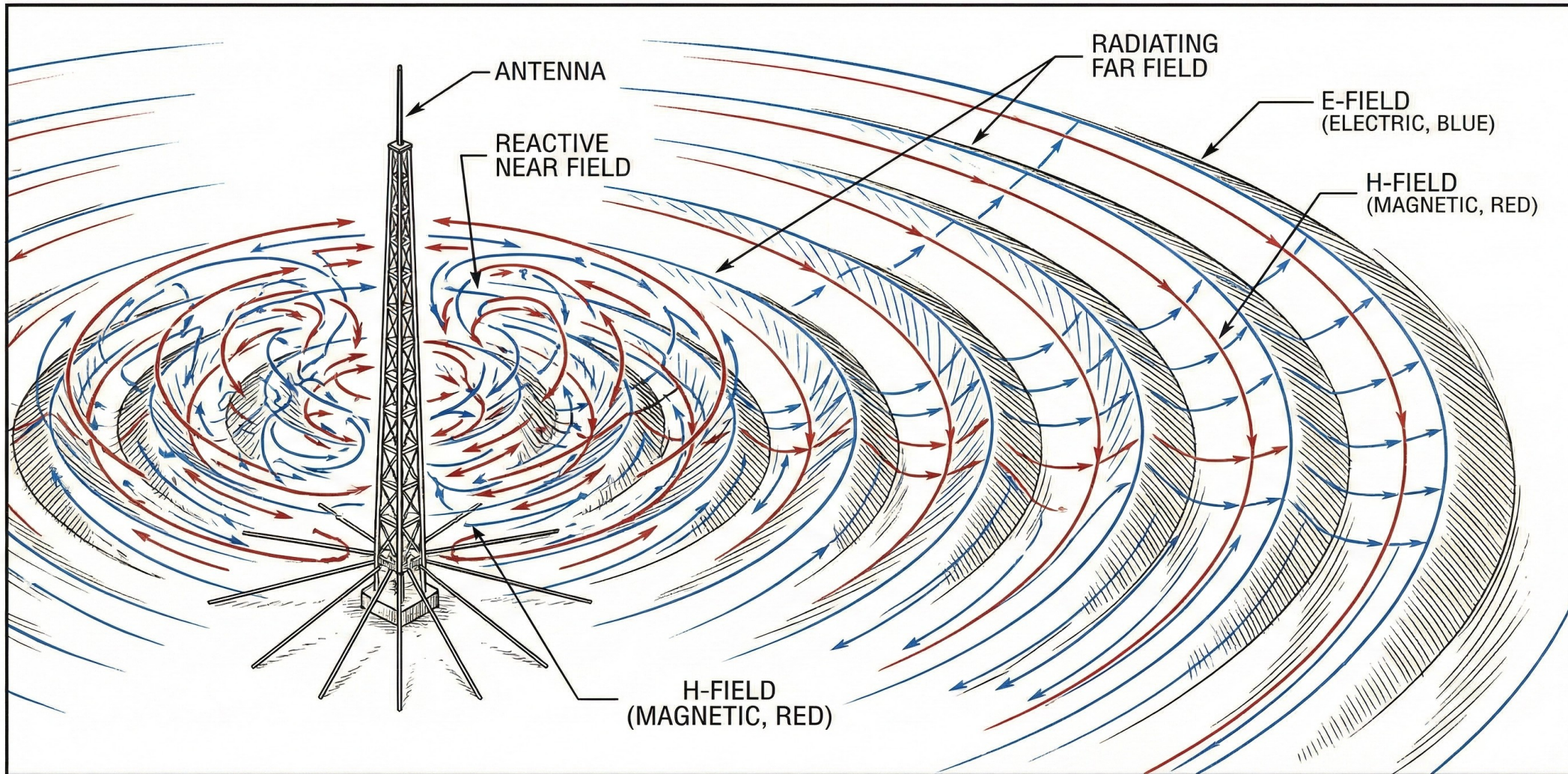
How Do We Measure Antennas?

- *Antenna measuring range:* A huge (for HF), flat, empty plot of land with the antenna in the middle, and a moving tower at a distance, from which far-field signal strength can be measured at various horizontal and vertical angles to the antenna, thus we can determine the antenna pattern.

- At UHF, this is practical to do in your backyard. At HF, significant acreage is required to measure the far field. Moving the tower for the measuring antenna may be elaborate.

- Advantages: This method can be very accurate and eliminates the variables in some other methods.

Antenna Measuring Range

- This RF-anechoic chamber is for far-UHF or microwave.

- The measuring antenna is to the left of center. It's a log-periodic to measure a broad frequency range. The device under test and its antenna can be rotated to measure the antenna pattern.

- Image credit: NSI-MI Ametek.
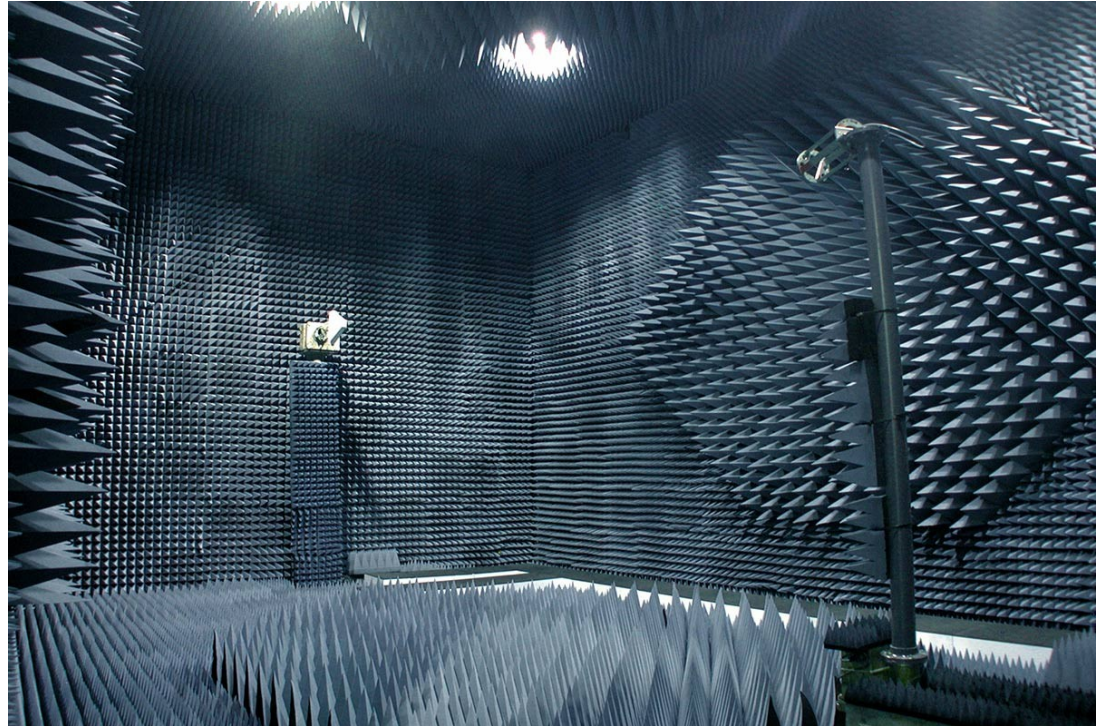
How Do We Measure Antennas? (2)

- *A-B testing:* Compare two antennas with the cooperation of a distant station.

- WSPR or the Reverse Beacon Network can help to automate this process.

- Advantages: uses the equipment you already have.

- Problems: *Too many variables to give a good answer,* for example propagation changes over time, fading from moment to moment; etc. **So, it's easy to deceive yourself.**

Self Deception

- This is the phenomenon of your car running better after it's been through the car wash. What actually happens is you *like* your car better that way.

- You want your antenna to be good, so it's easy to deceive yourself when using poor methods of measurement.

- Good scientific methods of measurement protect you from self-deception.

How Else Do We Measure Antennas?

- *SWR:* Indicate the reflected power at the transmitter.

- Advantages: Uses the equipment you already have, and very easy to do.

- Disadvantages: **SWR is *not* a measure of the antenna radiation at all!** So, you *are* deceiving yourself. We'll discuss why.

How Do We Measure Antennas (4)

- *Theoretical Modeling*: A mathematical model of a real-life phenomenon.

- Advantages: Can be done before the antenna is built, easy to change and re-try, tells us a lot. Uses the computer you already have.

- Problems: Learning the program and entering data take lots of time. The program misses real-world issues, so you can deceive yourself.

The Future of Antenna Measurement is *Airborne!*

- *Drones* are the solution!

- Programming a drone to fly to many points on a flattened hemisphere around your antenna (considering the 400-foot altitude limit), and sampling the signal strength at each point, is *within reach of hams today.*

- With drones, *we aren't guessing any longer!*

- You should still model before building your antenna.

Commercial Antenna Testing Drone!

Antenna Measurement with a Drone, Continued

- Issues to solve: making a sampling antenna that works through a 90° change in angle (from beside to above), or *adding a servo to turn it.*

- Manage electrical noise from the drone and environment.

- Consider RFI *to* the drone. Use low power.

- Consider reflection from the environment (but this is a real-world part of your antenna performance).

- Be aware of neighbors and regulation, the risk of losing the drone.

The Only Accurate Measurement

- The *only* accurate antenna measurement is radiated field strength *at a distance,* measuring the far field at many points to determine the antenna pattern.

- You *only* get this with a drone, or a measuring range.

- Consider it like putting a thermometer in the refrigerator, vs. just going by how the food tastes. The goal is the food, but the thermometer helps you understand how you are getting there.

Radiation and Loss

- Some of the power that goes to your antenna ends up as *radiation.* In other words, radio waves. This is the useful part.

- The rest ends up as *loss.* This becomes heat, although you probably don't notice the heat.

Where Does Loss Come From?

- **Mainly, the Ground.**

- In an unbalanced antenna, the ground is almost always the *main* path for current return to the transmitter. The soil has resistance, and it's part of the circuit, so power is lost there.

- A balanced antenna at a practical height for most hams will radiate into the ground.

Dipole Height and Loss

- A dipole ¼ wavelength from the ground or less has the ground as a lossy reflecting element. It could be considered *a two-element beam pointing straight up.* Thus, a "sky heater".
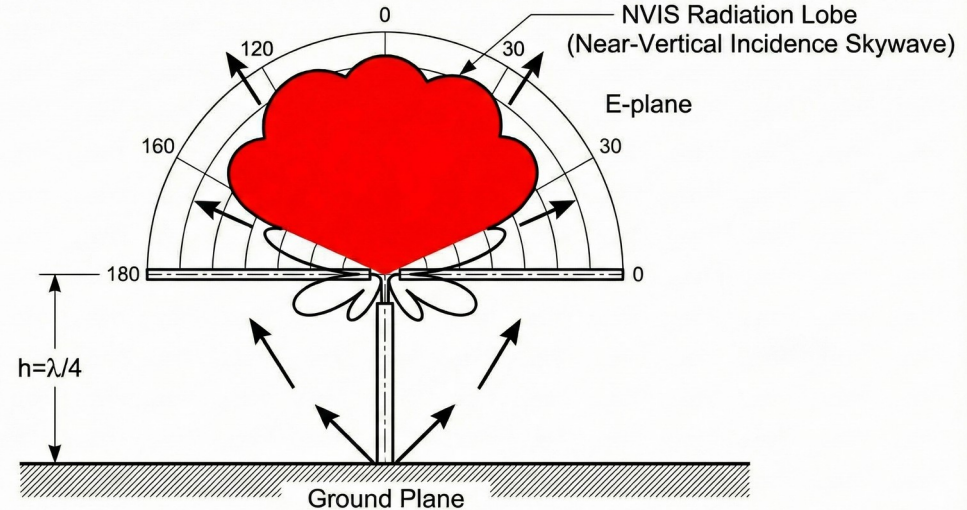
Dipole Height and Loss (2)

- Adding multiple parallel ground radials under that dipole would reduce the loss, and make it a good NVIS antenna, but it would still mainly radiate straight up.
- ½ wave high is better if NVIS isn't your goal. The higher you can get it, the more like a *theoretical* dipole it will perform.

Kinds of Loss in Your Antenna

- **Ground Losses Dominate.** This varies with each installation, but 36 ohms resistance in returning current to the antenna isn't unusual, and for a quarter-wave vertical, that's *half the power.*

- Electrically-short antennas: Effective radiated power dimishes approximately with the **square** of the ratio of the element's electrical length to ¼ wave, no matter how well you load it with your tuner. So, a half-size antenna is ¼ as effective.

Kinds of Loss in Your Antenna (2)

- Resistance losses: Because the wire or antenna element isn't a perfect conductor. Made worse by the *skin effect,* because *only the skin carries RF, not its whole diameter.*

- At 10 meters, 100 feet of wire: 24 AWG (American Wire Gauge): **20 ohms resistance!** 12 AWG: **5 ohms**. In contrast, the DC resistance would be a fraction of an ohm.

Kinds of Loss in Your Antenna (3)

- Dialectric Loss: complex (several different causes) loss in the insulating portion of your feed-line.

- Transformer loss: also a number of factors.

- **But ground loss almost always dominates.**

Measuring Radiation and Loss

- An antenna has *radiation resistance,* the effective resistance that comes from *the work of radiating radio waves.*

- An antenna has *loss resistance,* the resistance that comes from all of the losses in your antenna system that make heat rather than do real work.

- The second is often larger than the first.

Antenna Efficiency vs. Ground Loss Resistance
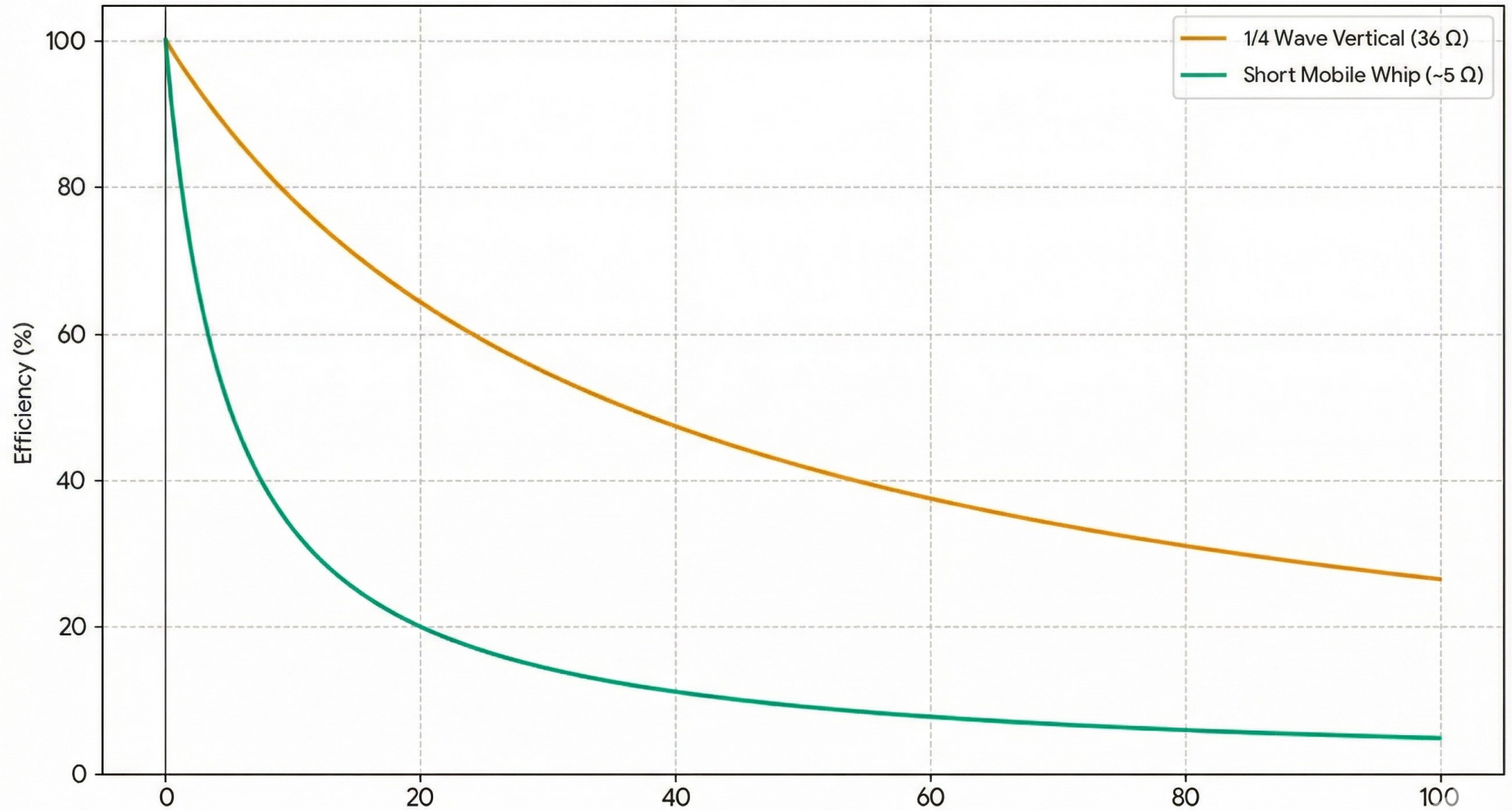
Power Distribution for 1/4 Wave Vertical (100W Input)
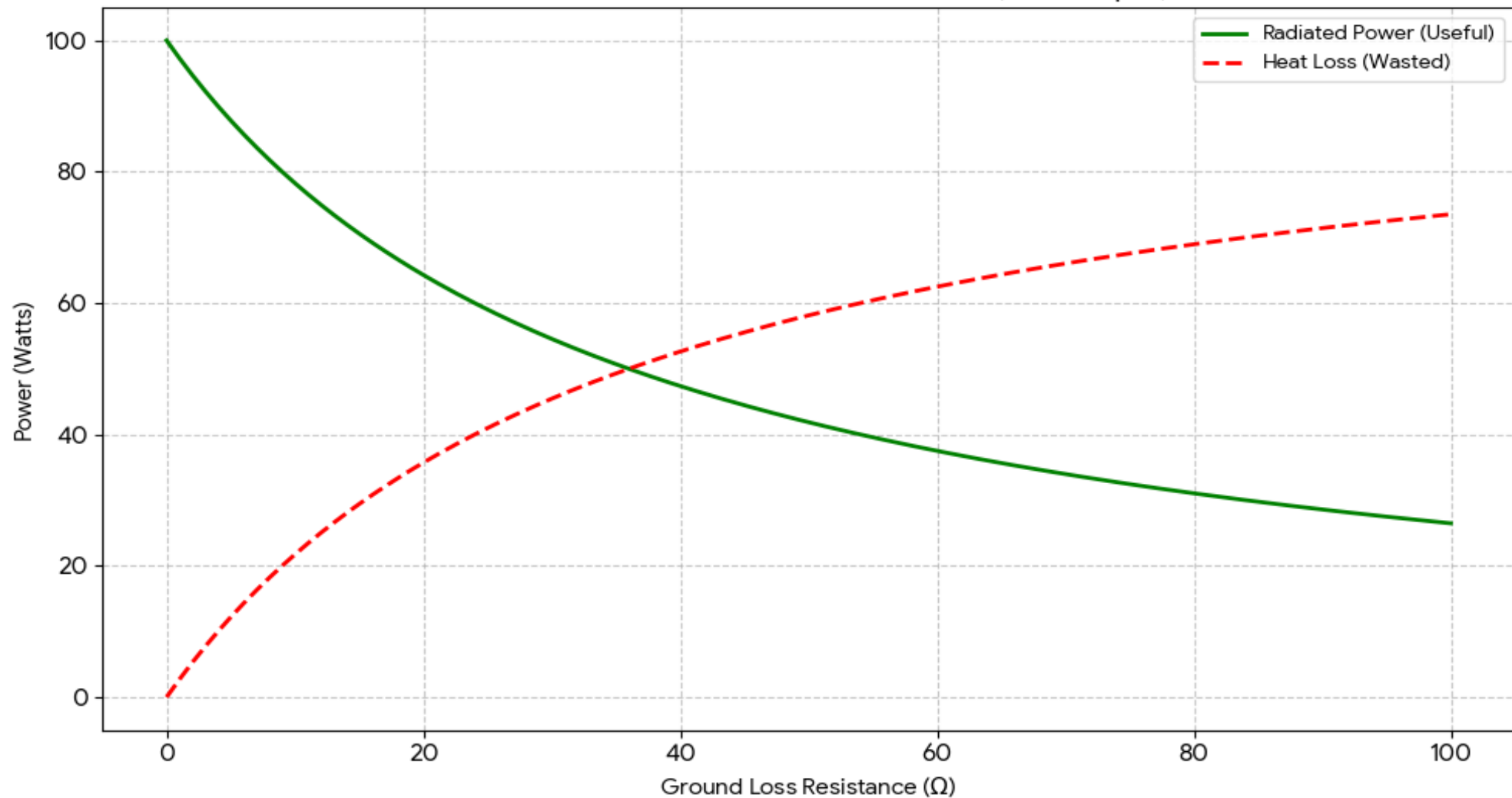
Measuring Radiation and Loss (2)

- We generally arrive at loss resistance and radiation resistance through theoretical modeling, but can derive it from accurate field-strength measurements.

Transmission line

V_{gen} (Generator)

I_{ant}

P_{rad} (Radiated Power)

R_r (Radiation Resistance)

I_{ant}

R_{loss}

P_{loss} (Heat Loss)

S

Antenna Efficiency $\eta = \dfrac{R_r}{R_r + R_{loss}}$

Real Antenna Circuit

Transmitter (Tx)

SWR Meter / Bridge

SWR 1.5:1

Forward Power P_{fwd}

P_{ref} Reflected Power

Coaxial Feed-line $(50\Omega, Z_0)$

Z_{ant}

SWR =

P_{rad} (Radiation Resistance)

R_{loss} (Loss Resistance)

P_{rad} Performance
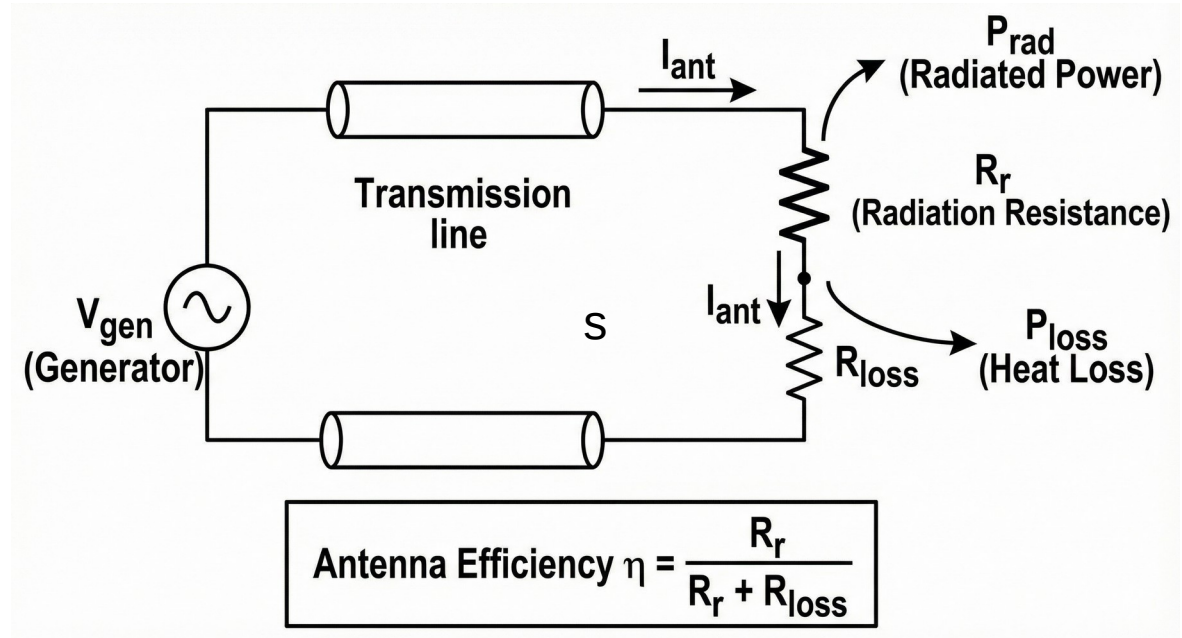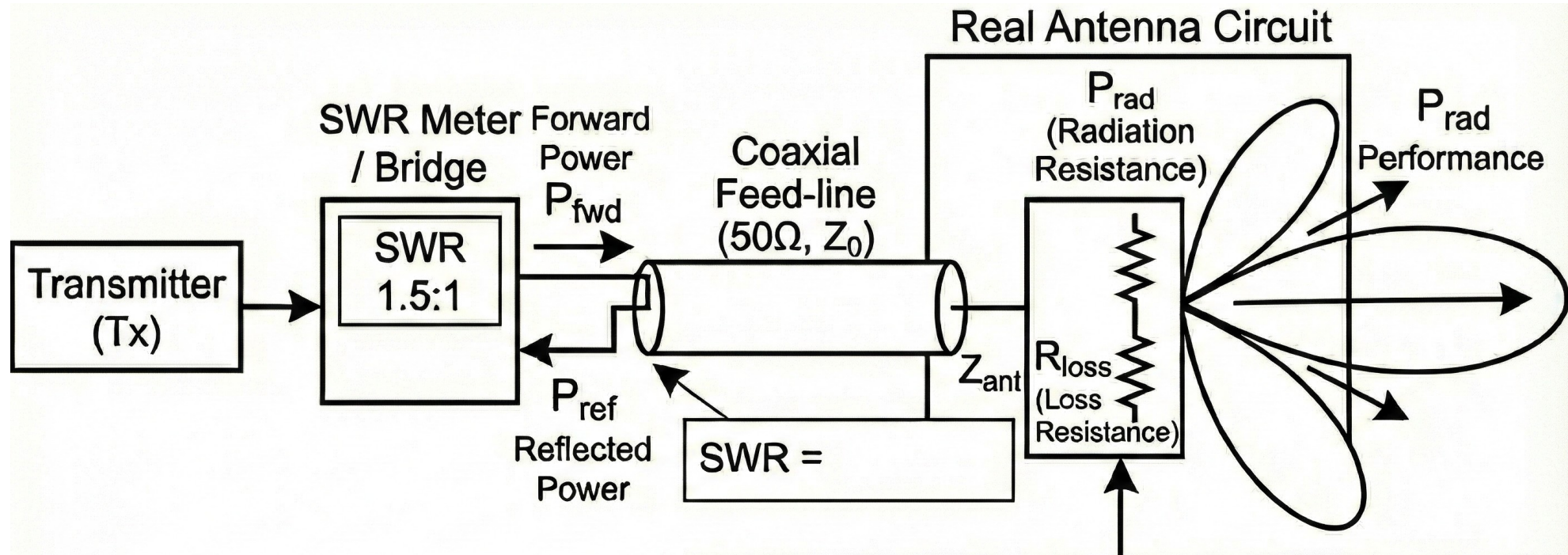
SWR is a function of Total Z_{ant}. A "good" SWR can exist where $R_{loss} \gg R_{rad}$, meaning most power is dissipated as heat ($P_{loss} = I^2 R_{loss}$) rather than radiated ($P_{rad} = I^2 R_{rad}$). SWR does NOT distinguish between coupling to Radiation or Loss Resistance.

So, SWR **Lies!**

- It can't tell you if you are matching the loss, or the radiation resistance.

- With a fixed antenna (not a tuner or SteppIR), *the flatter the SWR is over a wide band,* **the more suspicion that you are mainly matching the loss.**

- A 52 ohm RF resistor is likely to have *perfect* 1:1 SWR and *not radiate much.*

- Impedance matching is important. It's just not a radiation measurement.

This is Why We Need The Counterpoise

- The counterpoise helps us to reduce the ground loss, the resistance of the soil in returning current, *by replacing the soil with a more conductive wire*. Reducing the loss resistance makes the radiation resistance *most of* the resistance in the circuit, thus increasing the overall efficiency of the antenna.

Counterpoise for HF Vertical

- Elevated radials: 3 or 4 resonant wires per band you expect to operate.

- Ground radials: Wires ¼ wavelength or longer, the more the better. Diminishing improvement as you add more wires or make them longer.

Mobile and Marine Counterpoise

- Automotive antennas almost all **use the metal of the vehicle as a counterpoise.** Magnetic ones capacitively couple to the roof of the car. Permanent ones electrically couple through their mount.

- Mobile antennas need a counterpoise, so **don't work well without a big piece of metal or 4 or 5 quarter-wave radials under them.**

- At VHF, fiberglass boats generally use vertical dipoles, or the feedline as an unintentional counterpoise. Marine HF gets complicated enough for its own talk.

HALF an antenna! Must have a counterpoise!

Two Kinds of Radials

- *Resonant* radials are cut to ¼ wave for a particular frequency, and couple efficiently to the overall circuit of the antenna and space-time at that frequency. They must be elevated from the ground.

- Unresonant radials work over a broad bandwidth but require more material and space.

Transmission Lines

- Current going through a wire is not as simple as you might think. It behaves as a long reactive (inductive and capacitive) network. This is due to interaction with materials around the wire, and with space-time.

- **This is called a transmission line.**

Lumped-Element Model of a Transmission Line

In

R   L   R   L   R   L   Out

C   C   C

Neutral
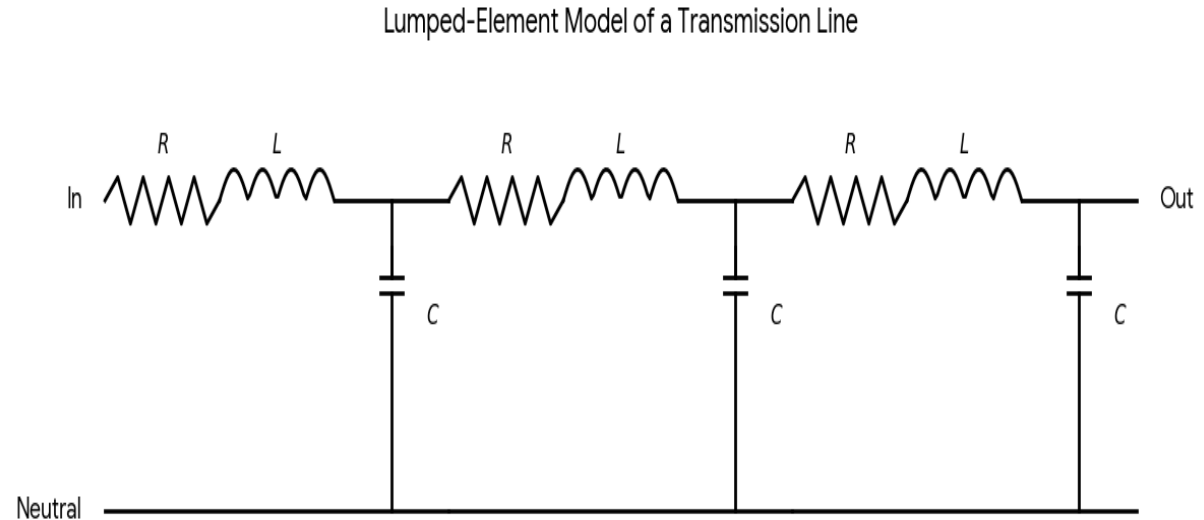
Practical Transmission Lines

- Coaxial cable, and ladder-line, are deliberately-constructed to be transmission lines, and to have a well-defined impedance along their entire length.

(photo credit: W7FG)

Transmission Lines

- The original understanding of transmission lines developed with the electric telegraph.

- AC power distribution uses transmission lines, and their issues are motivating a switch to long-distance distribution *using DC* (also, DC carries 1.4 times as much power as AC for the same voltage).

Propogation Speed and Velocity Factor

- The propogation speed through a transmission line is *slower* than the speed of light in vaccuum. It's the speed of oscillating electricity going through that network of inductances and capacitances.
- This is true for *all matter.* Matter interacts with light and electricity going through it, slowing it down.
- We call this difference in speed the ***velocity factor.***

Velocity Factor

- Light travels at 186,282 miles (299,792,458 meters) per second per second **in *vacuum.***

- Electricity travels more slowly through *matter* because of its interaction with the matter.

- This difference is the ***velocity factor.***

- Bare copper wire *in air* has a velocity factor around 0.95 .

- This effects the *electrical length* of the wire, and the size you cut it to match a wavelength.

Ground Radial Velocity Factor

- Ground radials will be *electrically longer* than the same wire in the air, as the effect of the ground reduces their velocity factor. A 1/8 wave radial on the ground may be electrically closer to ¼ wave.

- We still want them longer to catch as much of the near field as possible.

Ground Radial Velocity Factor (2)

- The velocity factor of wires on the ground *changes with ground conductivity, and that changes with rain.* Because we can't count on the electrical length, we just use a lot of radials, and we make them longer.

- A Beverage-on-ground antenna is electrically longer because of this effect.

Skimping on Elevated Radials

- Many VHF/UHF base antennas have radials much smaller than ¼ wave, that might provide an adequate impedance match, but a poor current return.

- Some or most of the current may be returning through the feed-line and mast, making a vertical dipole, or the vertical element may be acting as an EFHW.

Skimping on Elevated Radials (2)

- Where's the counterpoise? It's the PCB, any conductive part of the case, and *you!*

- "Tails", wires shorter than your height, connected to the shield part of the antenna connector, provide a better counterpoise, and are useful for improving range.

The Skin-Effect: Wires Carrying RF Don't Act The Way They Do For DC!

- The inductance of a wire forces RF to travel *along its skin, only.*

- *Common-mode* return current picked up by your feedline is on the **outer** skin of the coax. A clip-on choke can stop this.

- The return of current *from the antenna* is on the **inner** skin of the coax. A clip-on choke *does not effect it.*

- Because of the skin effect, the inner and outer skin are effectively two separate conductors! Of course, they are connected at the ends.

So, How Does the EFHW Work?

- A half-wave dipole has maximum current, minimum voltage, and lowest impedance at the center, and maximum voltage, minimum current, and very high (theoretically infintite) impedance at the ends.

- A half-wave dipole is *usually* fed from the center and has an impedance of about 72 ohms there. But you can feed it from any point along its length!

How the EFHW Works

- The radiation pattern *does not change substantially as you move the feed point,* <u>as long as you have a good choke or transformer isolating the feed-line.</u> Otherwise, the feed line radiates and the pattern is distorted.

- The *impedance* changes *a lot* as the feed-point moves.

- At the very end, it's a one-terminal circuit. Of course you could connect ground or radials, but the feed point would then be between them instead of *at the end.*
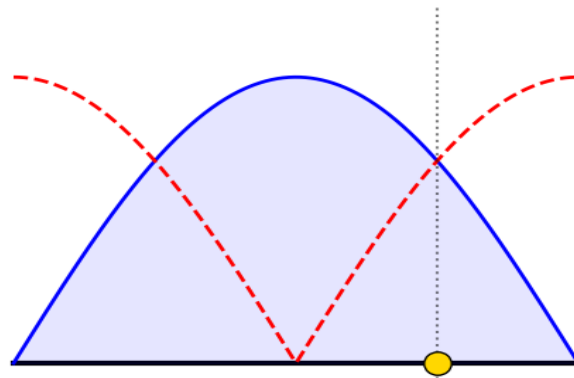
Dipole Current Distribution is *Unchanged* No Matter Where The Feedpoint Is (use a choke or xfmr).
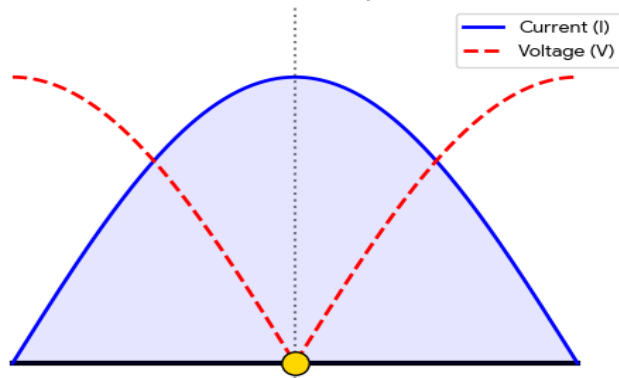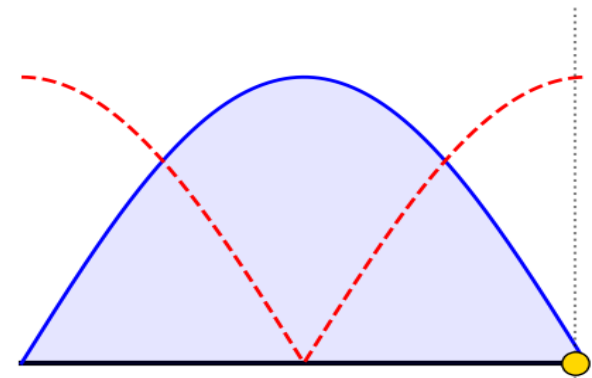
Half-Wave Dipole Antenna

Position along antenna

Impedance Meter

71 Ω
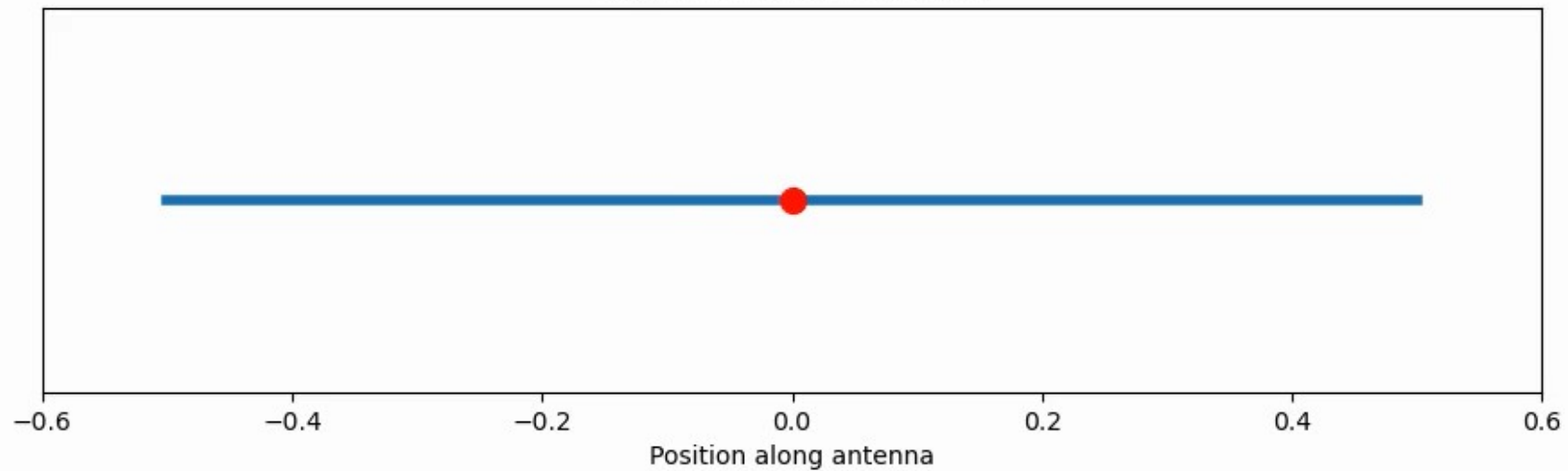
Impedance (Ohms)
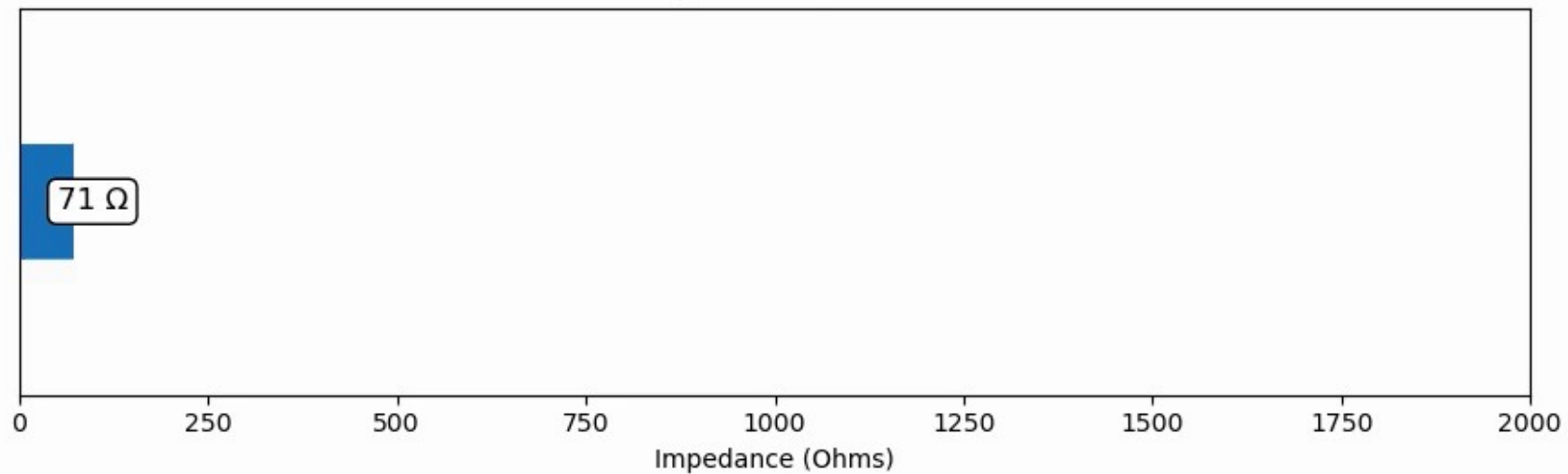
End-Fed Half-Wave Antenna

- As in the previous animation, this is a dipole fed close to one end.

- The short section *is not really a counterpoise.* Or much of one. It is mainly a capacitor against ground so that the transformer works.

- The short and long section together act as a dipole, and thus about half of the long section is the current return for the other half of the long section.

- Most EFHW don't have the variable capacitor shown.

- Image Credit AA5TB.
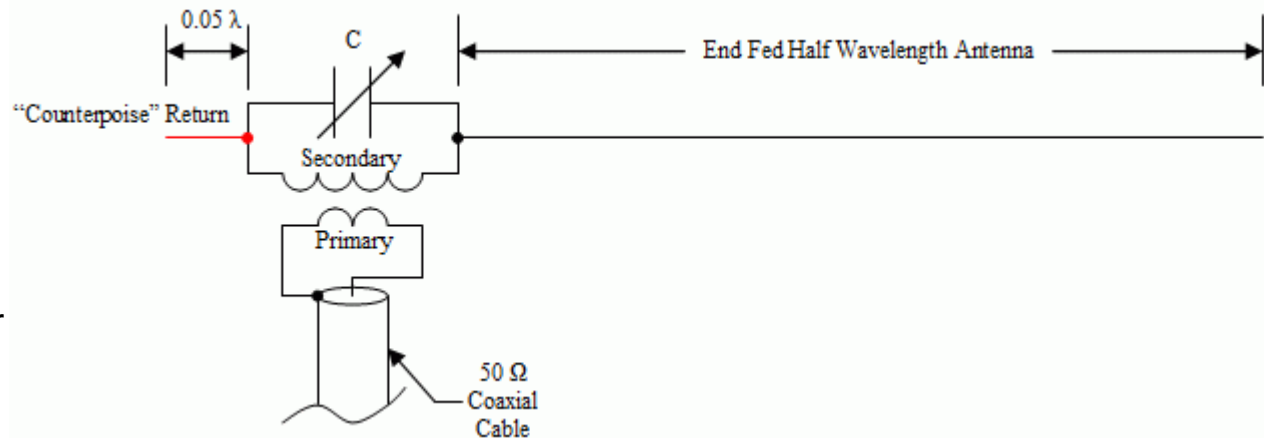
Current Distribution on the EFHW

EFHW Schematic Superimposed on Current Distribution

Source Portion
(Driven by Transformer)

Short
Counter...
(0.05...

49:1
Unun

Coax Feed
(To Radio)

Return Portion
(Acts as Counterpoise)

Start

0.25 λ
(Midpoint)

0.5 λ
(End)

Antenna Length (λ)
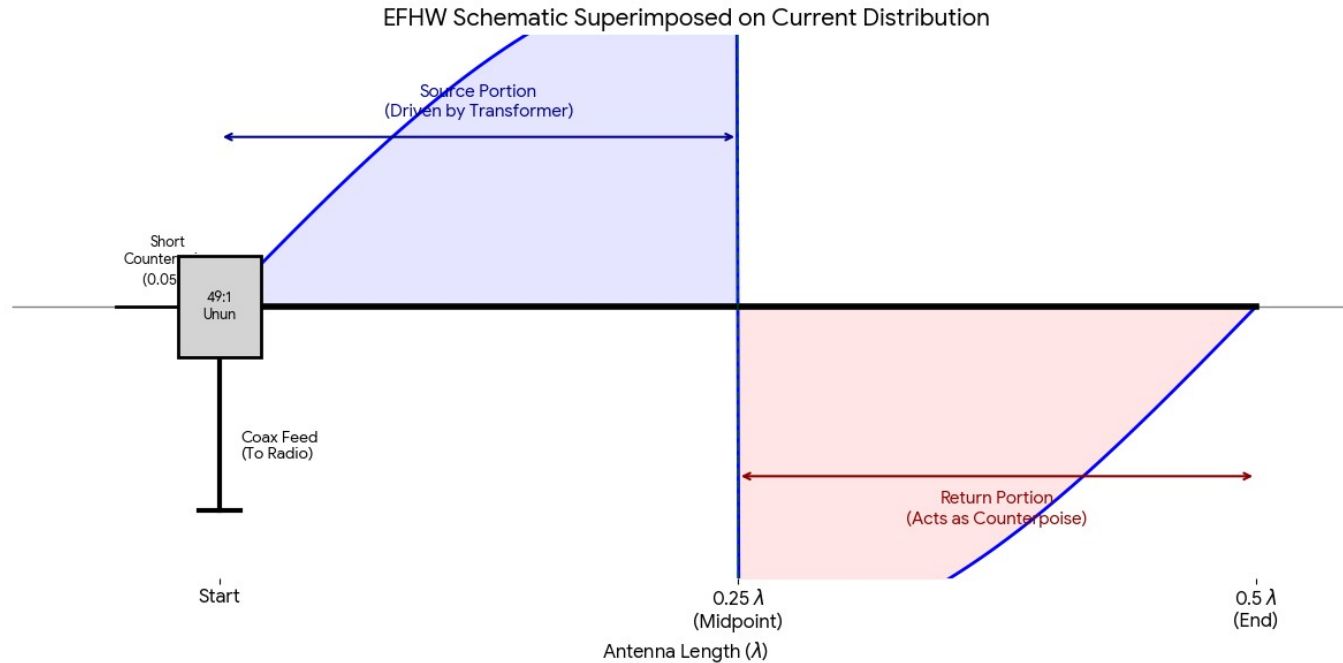
Antennas on *Lower Bands than the Fundamental Frequency*

- Now, let's try to use our 130-foot EFHW or 80 meter dipole on 160 meters! The best way is to short the feedline and use the feedline and antenna as a **T antenna** against any counterpoise you have, or failing that, ground. The feedline becomes part of the antenna. Shack RF may be severe.

Dipole Configured as a T-Antenna

Dipole Leg 1   Dipole Leg 2

Feedpoint Shorted
(Center + Shield)

Transmitter
(Driving against Ground)

To use a dipole on lower bands (e.g., 80m dipole on 160m):
1. Short the feedline leads together.
2. Drive the whole system as a vertical wire.
3. The dipole legs act as a 'Top Hat' (Capacitive Loading).
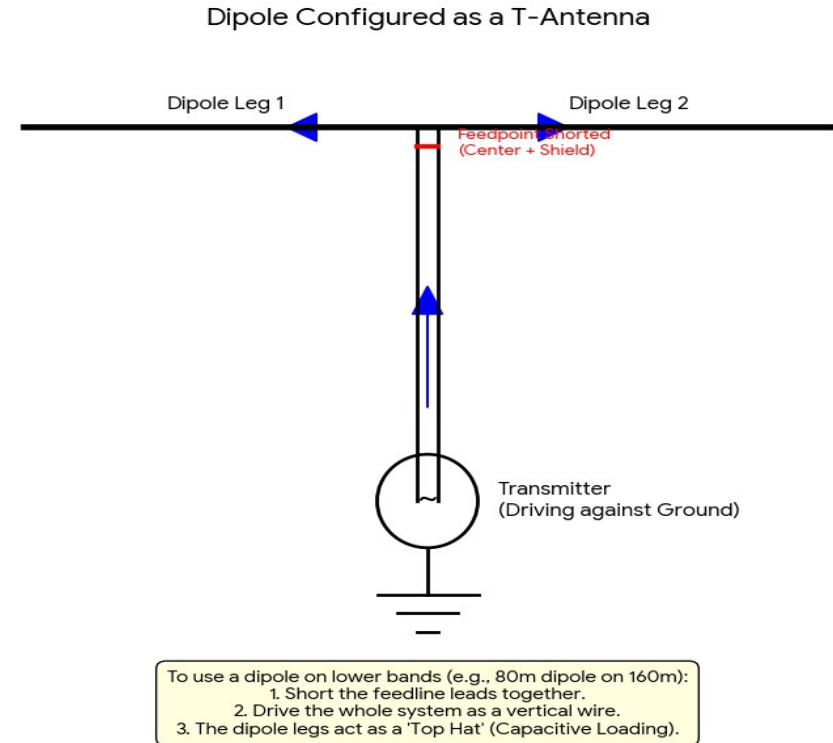
Dipoles on Higher Bands than the Fundamental Frequency

- Single-band dipoles, *fed at their center,* have a reasonable impedance on *odd harmonics of their fundamental frequency.*

- An 80 meter dipole thus *doesn't have useful harmonics,* as 40, 20, 10 meters are all even harmonics*.*

- A 40 meter dipole has a third harmonic at 15 meters.

- The G5RV antenna gets around this because the ladder-line feed is part of the antenna on most bands.
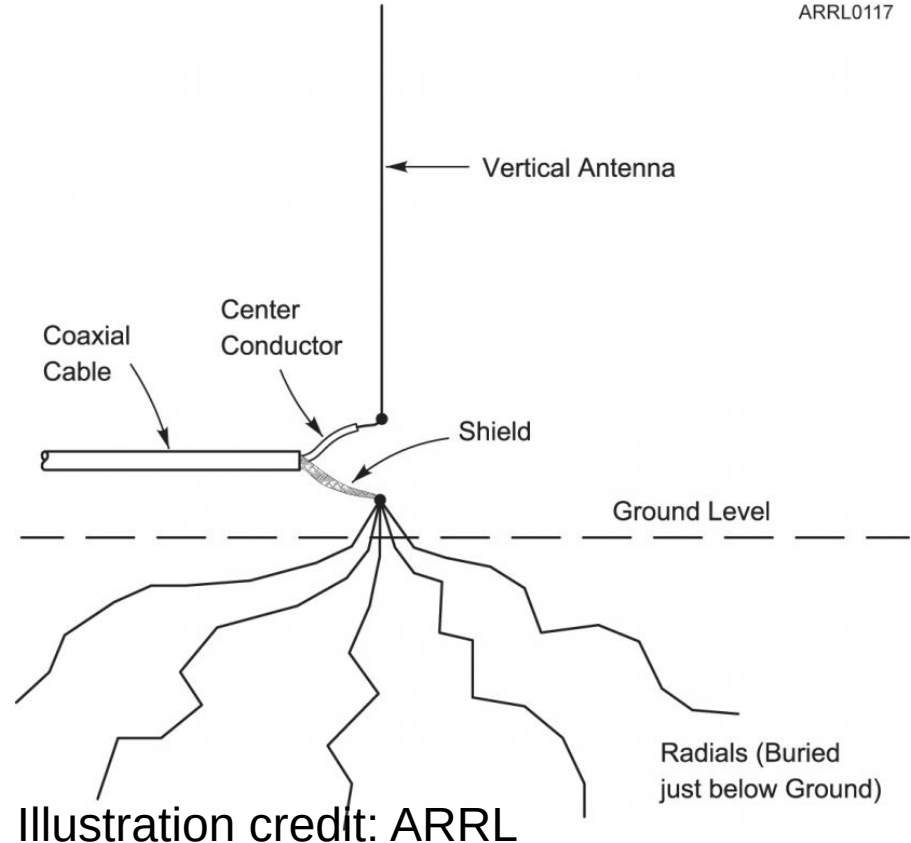
So, How To Do Multi-Band?

- An *off-center fed antenna* of the right length can have a *reasonable* impedance on most HF Amateur bands. This is why the EFHW can work well above its fundamental frequency (usually 80 meters).

- A *Windom* is another example of a multi-band off-center-fed wire antenna. It's fed 1/3 of the way to one end.

How To Do Multi-Band?

- An OCF antenna works best with a tuner *at the antenna,* so that there isn't loss on the feed-line from the high SWR*.* The old MFJ remote tuners are a good example, new remote tuners have been coming out from other companies.

- The 130 foot (39.6 meter) EFHW is resonant in the *digital* portion of 80 meters. *Don't cut it shorter* to get a perfect resonance on the voice section, unless that's the *only* band you will use it for. The resonance will then fall outside of the band on all harmonically-related bands.

HF Vertical Antenna and Radials on the Ground

- The importance of *this* counterpoise is acknowledged by many hams.

- There are a number of commercial HF antennas with a tiny counterpoise, with questionalble results.

ARRL0117

Vertical Antenna

Center Conductor

Coaxial Cable

Shield

Ground Level

Radials (Buried just below Ground)

Illustration credit: ARRL

What Is It About 120 Radials?

- In an AM broadcast station site application, FCC has historically required 120 radials, each ½ wave long, *or* theoretical modeling of the grounding system.

- This originated in a 1937 technical paper.

- 120 ½ wave is overkill for all but the most zealotly perfectionist of radio amateurs.

Diminishing Returns

- A length of ¼ wave at the lowest expected frequency is considered good for Amateur applications. This is still 65 feet (20 meters) for a frequency of 80 meters, and a 130 foot (40 meter) square lot, so compromise might be necessary. There is diminishing improvement with additional length.

- As the number of radials increase, there is diminishing improvement. 16 is a good minimum, you can feel good about 32, there isn't a limit.

HF Vertical with Elevated Radials

- In contrast to on-ground radials, 3-4 elevated radials, cut to resonance, for *each band* you expect to operate (sometimes considering harmonics), are considered sufficient.

In Closing: So, The Counterpoise is Important

- The counterpoise is as important as the part of the antenna you think of as the "radiating element", and takes part equally in making the radiation!

- Unfortunately, the counterpoise requires space and work, so it is often ignored, to the ham's disadvantage.

The Counterpoise is Important (2)

- Any antenna a ham is likely to encounter other than a loop or dipole will need a counterpoise.

- Compromise antennas tend to skimp on the counterpoise, in part because buyers think the radiating element is most important. It isn't.

Contact the Speaker

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```python
#Animation of impedance changing as dipole feed-point moves from center.
# GPT-5 wrote this for me. This prorgram is in the public domain. As an AI output, it can not be copyrighted.
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.animation import FuncAnimation
from matplotlib.animation import FFMpegWriter

# Antenna parameters
L = 1.0                    # normalized half-wave dipole length
x_positions = np.linspace(0, -L/2, 200)

# Impedance model (illustrative)
def impedance(x):
    eps = 0.02             # avoid infinity at the end
    return 73 / (np.cos(np.pi * x / L)**2 + eps)

Z = impedance(x_positions)

# Figure setup
fig, (ax_ant, ax_meter) = plt.subplots(2, 1, figsize=(9, 6))

# -------------------------
# Antenna plot
# -------------------------
ax_ant.set_xlim(-L/2 - 0.1, L/2 + 0.1)
ax_ant.set_ylim(-0.2, 0.2)
ax_ant.set_title("Half-Wave Dipole Antenna")
ax_ant.set_yticks([])
ax_ant.set_xlabel("Position along antenna")

# Dipole wire
ax_ant.plot([-L/2, L/2], [0, 0], linewidth=4)

# Feed point marker
feed_point, = ax_ant.plot(0, 0, 'ro', markersize=10)

# -------------------------
# Impedance meter
# -------------------------
ax_meter.set_xlim(0, 2000)
ax_meter.set_ylim(0, 1)
ax_meter.set_yticks([])
ax_meter.set_xlabel("Impedance (Ohms)")
ax_meter.set_title("Impedance Meter")

meter_bar = ax_meter.barh(0.5, 73, height=0.3)
meter_text = ax_meter.text(
    50, 0.5, "73 Ω",
    va='center',
    fontsize=12,
    color='black',
    bbox=dict(facecolor='white', edgecolor='black', boxstyle='round,pad=0.3')
)

# -------------------------
# Animation update function
# -------------------------
def update(frame):
    x = x_positions[frame]
    z = min(Z[frame], 2000)

    # Update feed-point (must be sequences)
    feed_point.set_data([x], [0])

    # Update meter
    meter_bar[0].set_width(z)
    meter_text.set_text(f"{int(Z[frame])} Ω")

    return feed_point, meter_bar, meter_text

# Create animation
ani = FuncAnimation(
    fig,
    update,
    frames=len(x_positions),
    interval=50,
    blit=True
)

plt.tight_layout()

writer = FFMpegWriter(fps=20, bitrate=1800)

ani.save("dipole_impedance_animation.mp4", writer=writer)

plt.show()
```