Antenna Fundamentals
Antenna Matching
and
SWR

May 2021

k3eui

Overview of Topics

Antenna Feed Lines

Characteristics of a dipole antenna

Resistance, reactance, impedance

Resonance and SWR

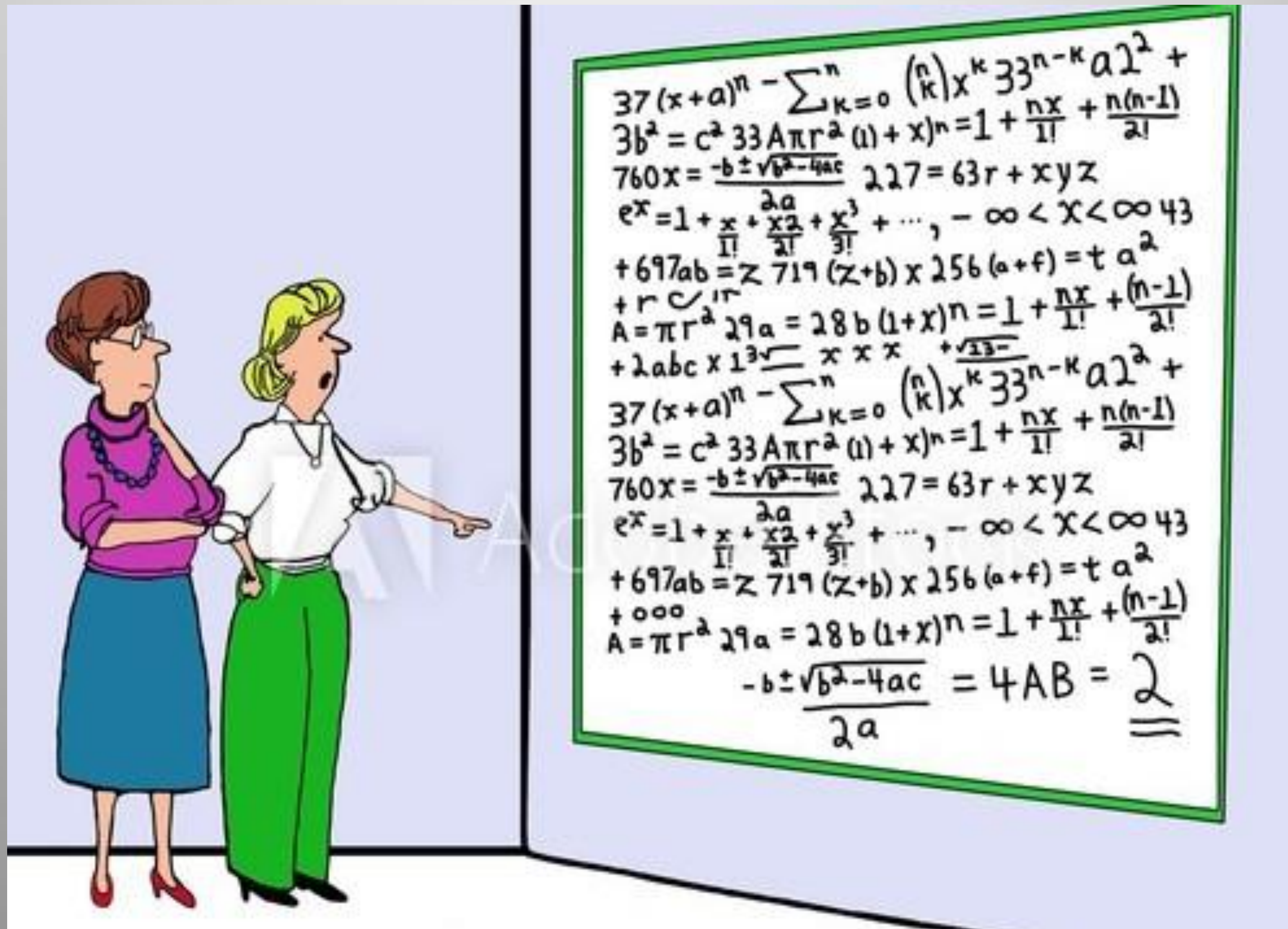
Antenna Tuners: when might you need one

How they function and what they look like

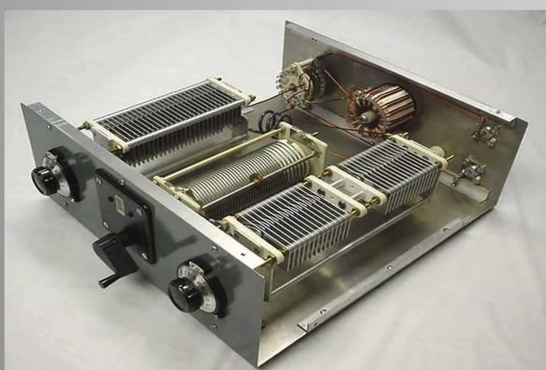
What do all of these share in common?

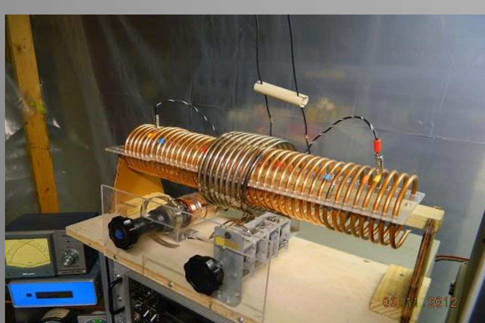
How do you know if/when you need one?

I think I need an antenna tuner

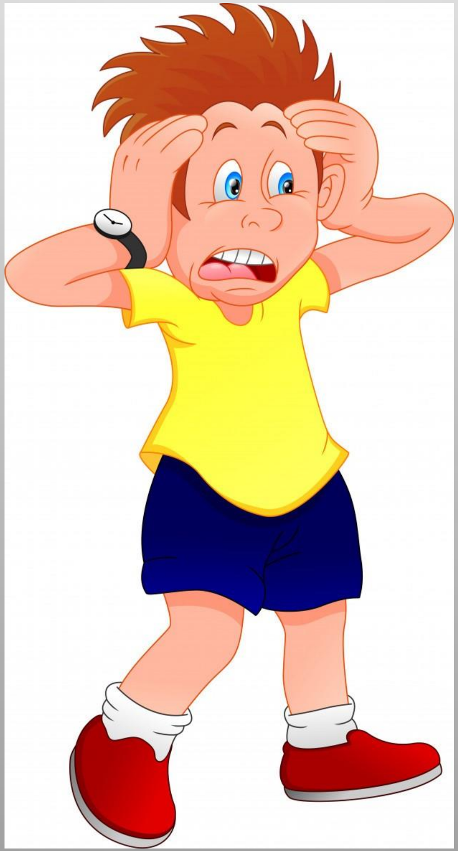


They all contain inductors and capacitors to provide a way of canceling the **REACTANCE** on your feed line



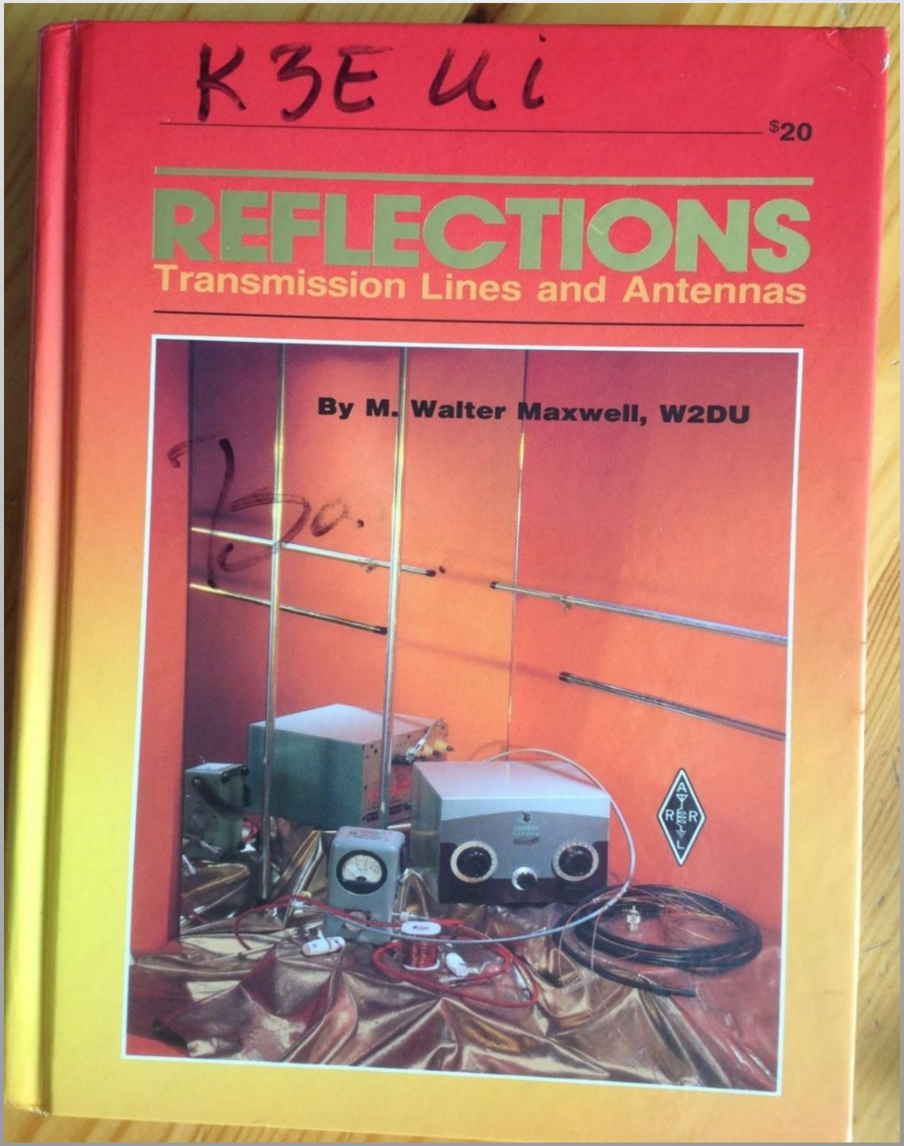


Why does my feed line have **REACTANCE?**



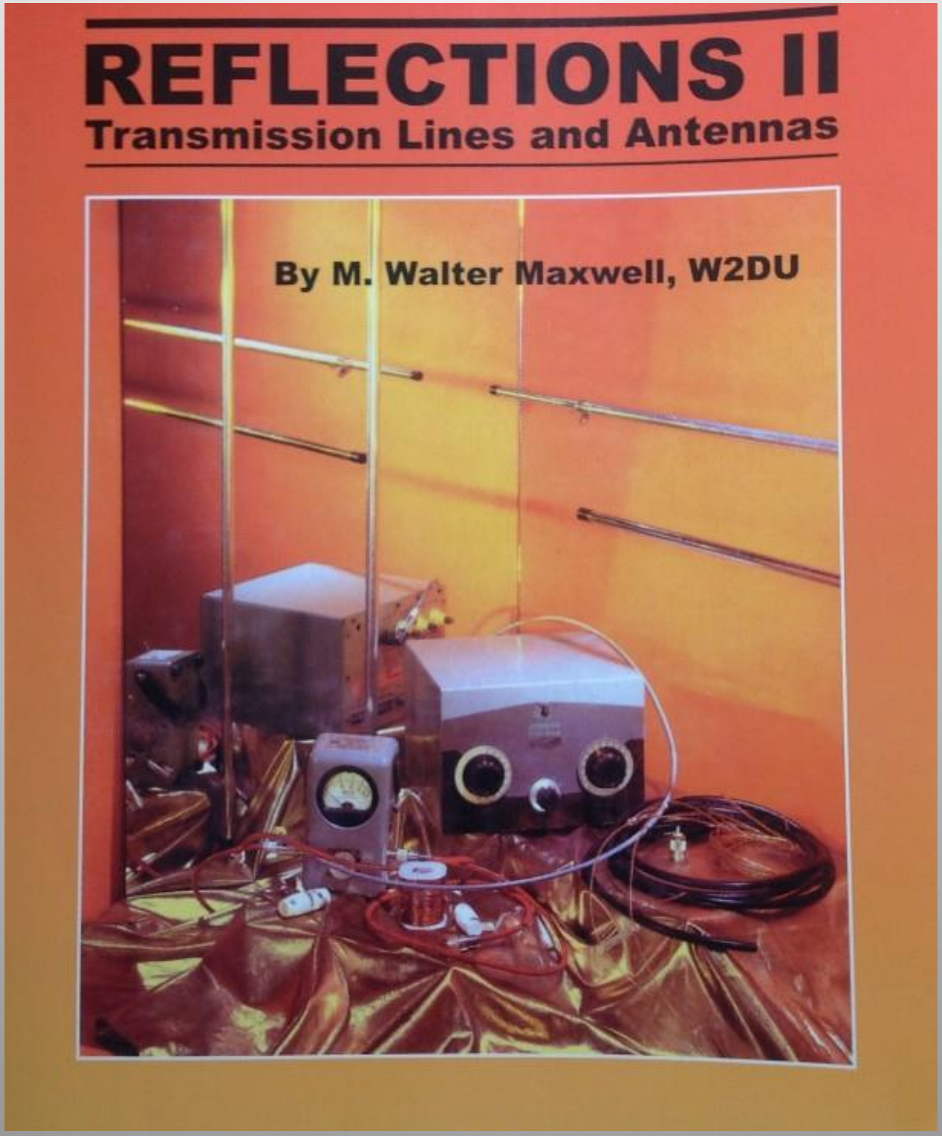
Reflections by W2DU Walt Maxwell

many chapters reprinted from QST series

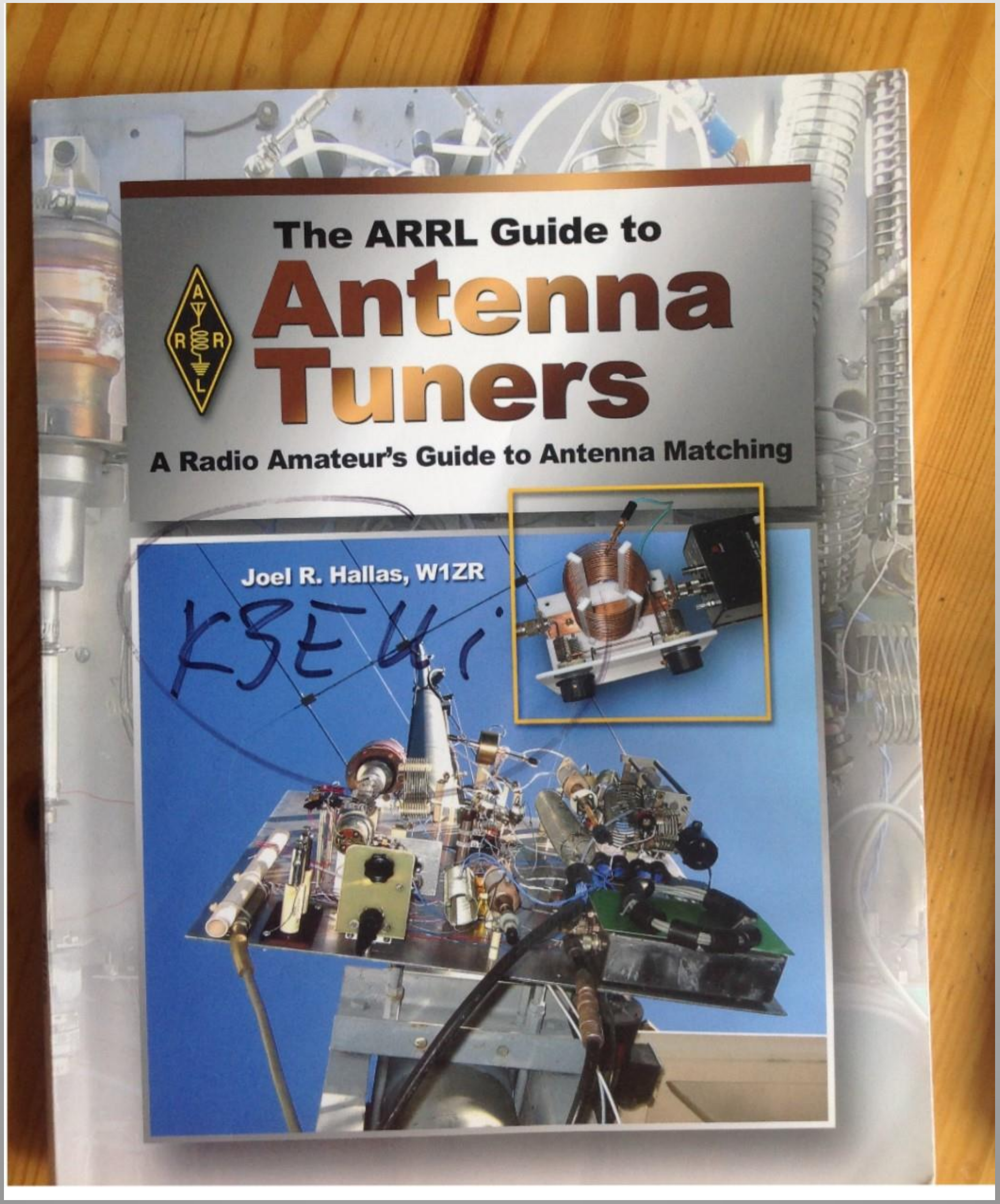


Reflections II (much more detail) by W2DU

(lots of math and formal proofs of the ideas in Reflections I)

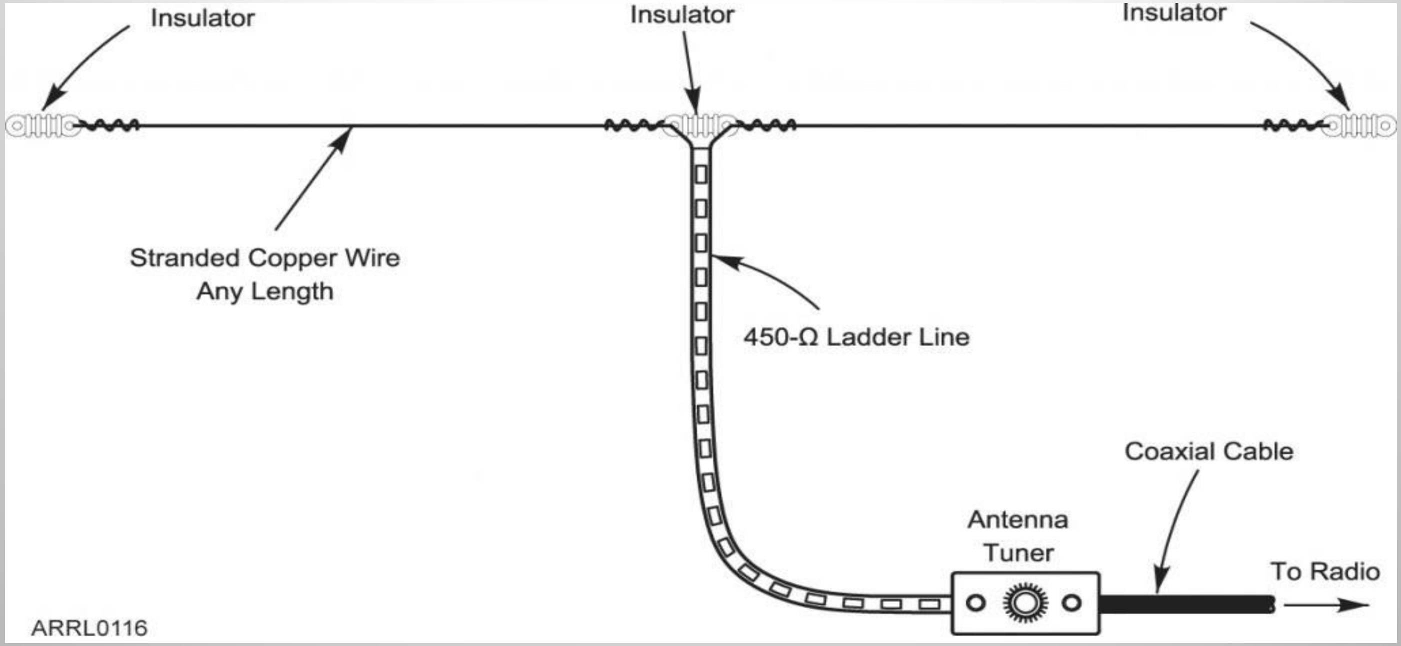


Antenna Tuners: W1ZR Joel Hallas



What is the function of a

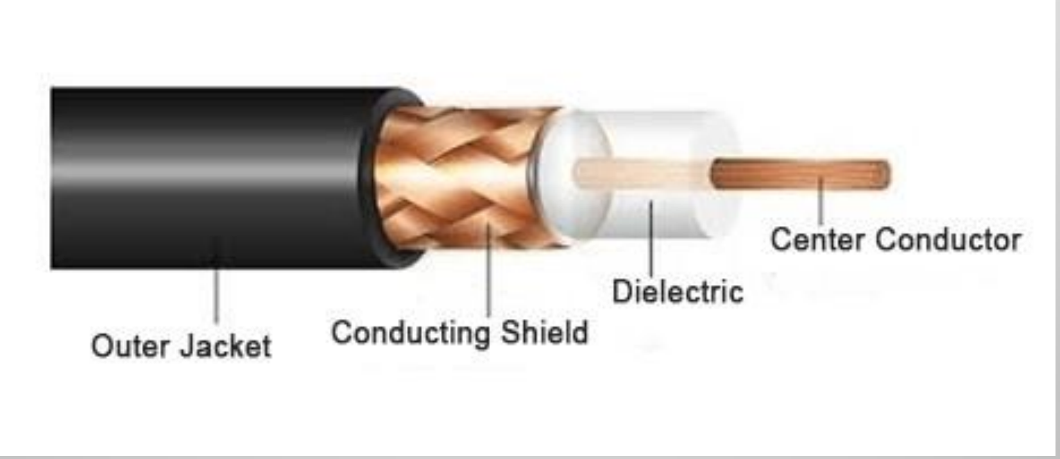
FEED LINE ?



Transfer RF power from the transmitter to the antenna with the <u>least amount of loss</u>

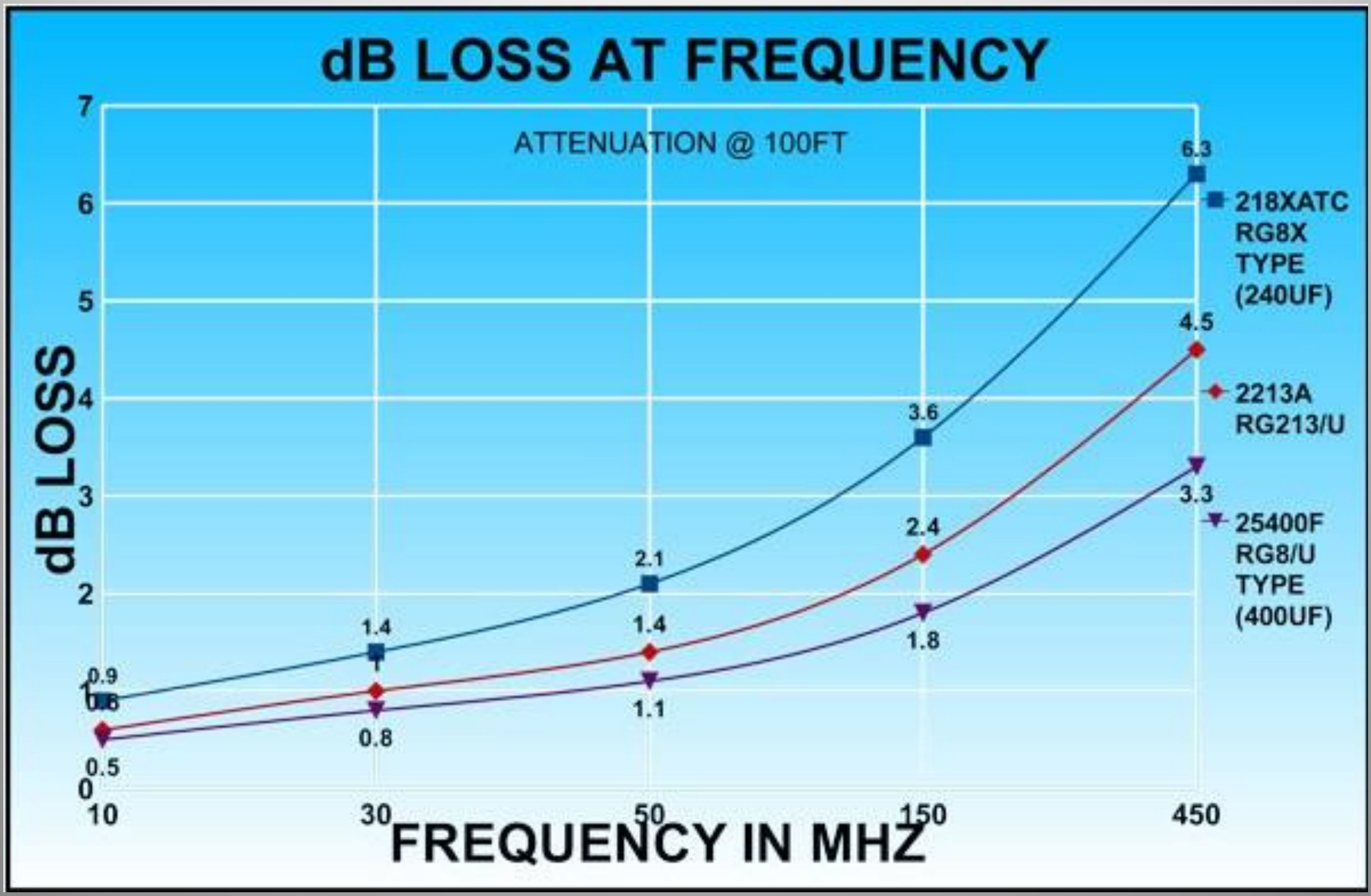
BALANCED LINE vs. COAX

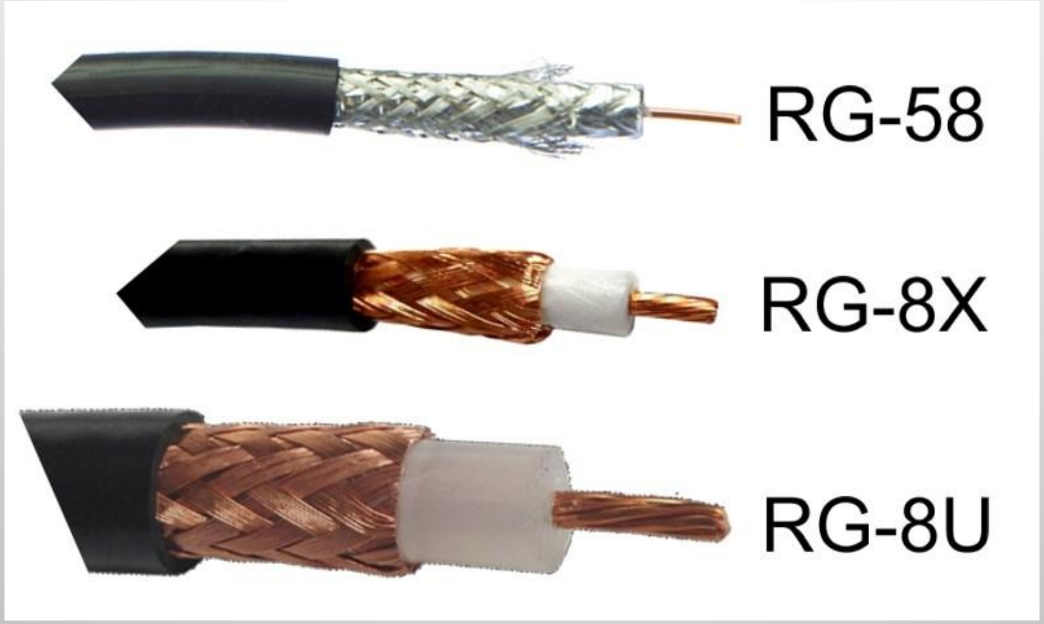
Coaxial vs. Balanced Lines



LMR coax types

ATTENUATION vs. FREQ
RG213: **Loss per 100 ft at 4 MHz is about <u>0.4 dB</u>**





What causes Feed Line “loss” ?

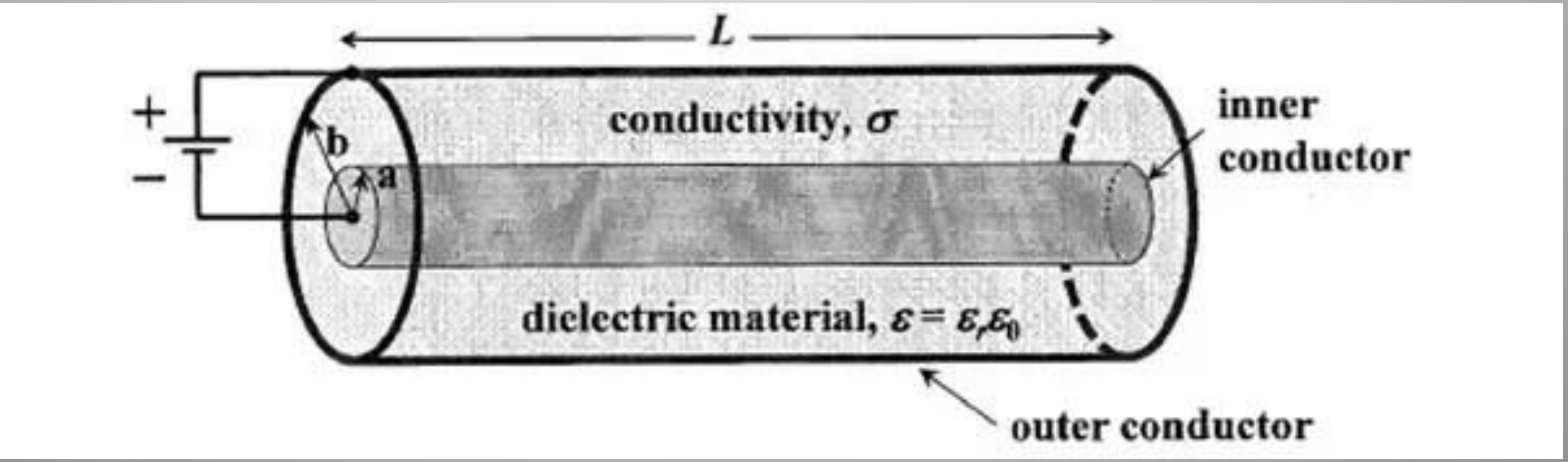
Why does loss increase at higher frequencies?

Why do smaller diameter conductors have more loss than larger diameter conductors?

Attenuation (dB per 100 feet)

Coax Cable Signal Loss (Attenuation) in dB per 100ft*								
Loss*	RG-174	RG-58	RG-8X	RG-213	RG-6	RG-11	RF-9914	RF-9913
1MHz	1.9dB	0.4dB	0.5dB	0.2dB	0.2dB	0.2dB	0.3dB	0.2dB
10MHz	3.3dB	1.4dB	1.0dB	0.6dB	0.6dB	0.4dB	0.5dB	0.4dB
50MHz	6.6dB	3.3dB	2.5dB	1.6dB	1.4dB	1.0dB	1.1dB	0.9dB
100MHz	8.9dB	4.9dB	3.6dB	2.2dB	2.0dB	1.6dB	1.5dB	1.4dB
200MHz	11.9dB	7.3dB	5.4dB	3.3dB	2.8dB	2.3dB	2.0dB	1.8dB
400MHz	17.3 B	11.2dB	7.9dB	4.8dB	4.3dB	3.5dB	2.9dB	2.6dB

Two Types of "loss" in coax
I^2R loss in conductor's **resistance**
V^2 / R loss in dielectric (insulator)



Attenuation in Feed Lines
what can YOU live with?

You have a 100 watt transmitter (50 ohm coax output jack) operating on 80 meters feeding 100 ft of RG213 coax (50 ohm) into a 80 meter dipole (50 ohm) at 50 feet above ground

The coax manufacturer claims a loss (attenuation) of

0.5 dB/100 feet

at a frequency of 4.0 MHz

HOW MUCH POWER GETS TO THE ANTENNA?

Efficiency of a Feed Line

RG213 has an “attenuation” (loss) of about

0.5 dB/100 ft (at a frequency of 4 MHz)

How many watts get to the antenna (100 ft distant)

How do you convert <u>dB loss</u> to <u>watts lost</u>?

dB loss in coax converted to **watts** to the antenna

Assume rig output is 100 watts

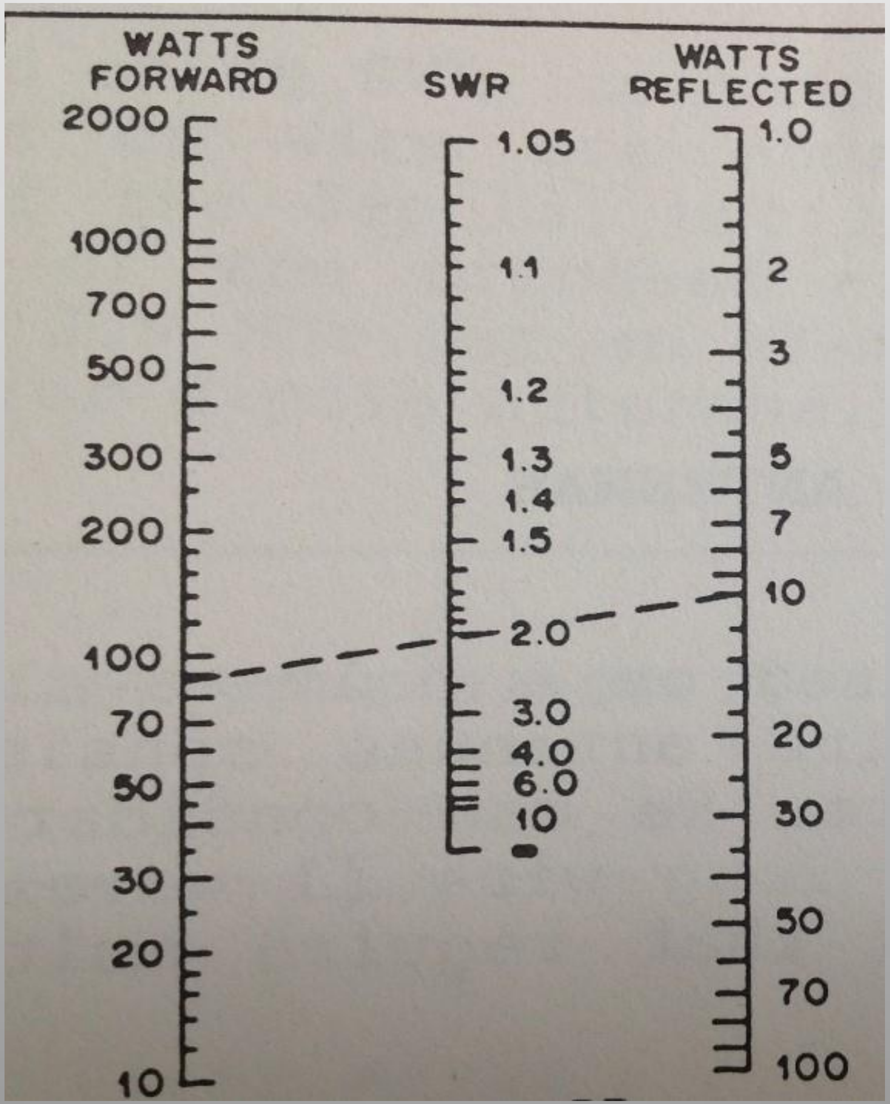
Power to antenna (watts)

$$P(\text{antenna}) = 100\ W \times [\ 10^{-0.1\ \text{dB loss}}\ ]$$

How much loss will you accept?
Let's assume one S – unit = 6 dB

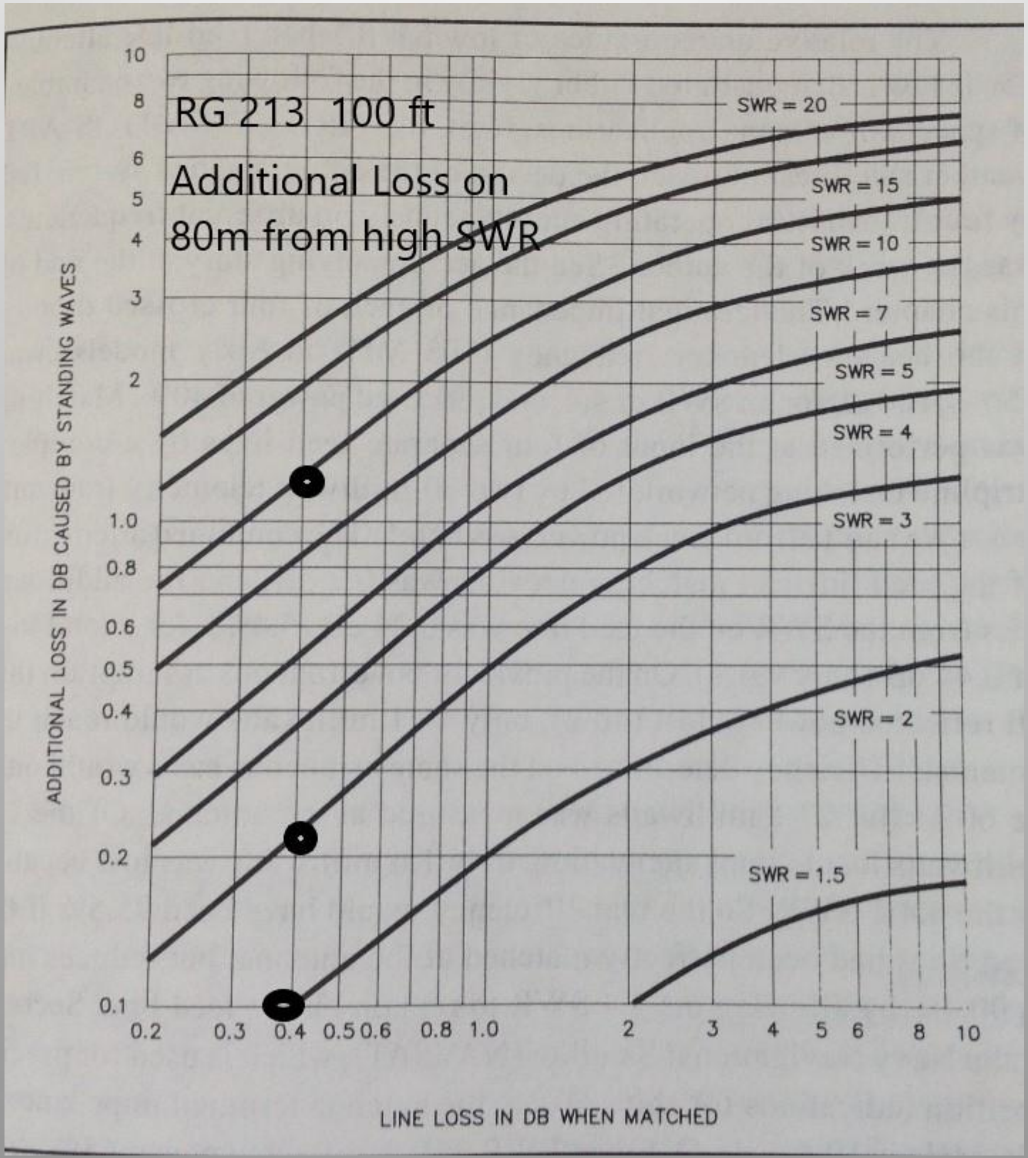
A	B	C	D
Attenuation (loss) in feed line		100 watt output	
dB (decibels)	% power lost	POWER to Antenna	S unit loss (6 dB/S unit)
0.5	11	89	1/12
1	21	79	1/6
2	37	63	1/3
3	50	50	1/2
4	60	40	2/3
5	68	32	5/6
6	75	25	1
10	90	10	
12	94	6	2

If the SWR is 2:1 what happens to this "reflected" power?



2:1 SWR at **4 MHz** results in an **additional 0.1 dB loss**

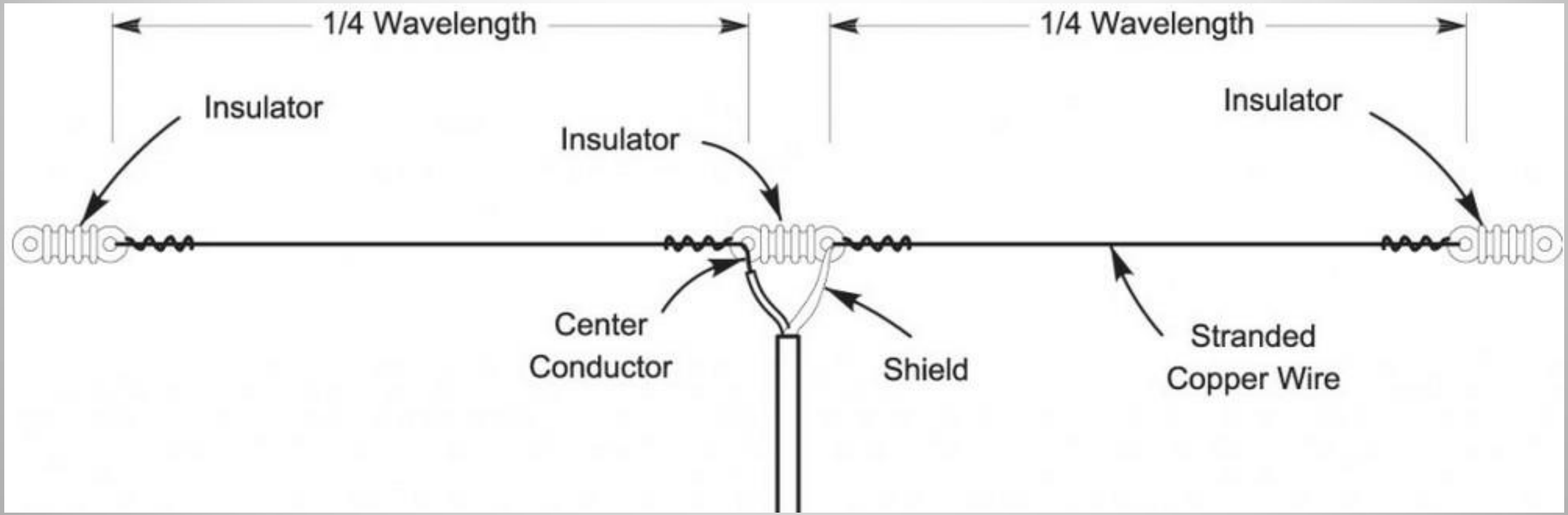
10:1 SWR at **4 MHz** results in an **additional 1.3 dB loss**



What is the **SOURCE** of all Radio Waves?

Sources of EM radiation

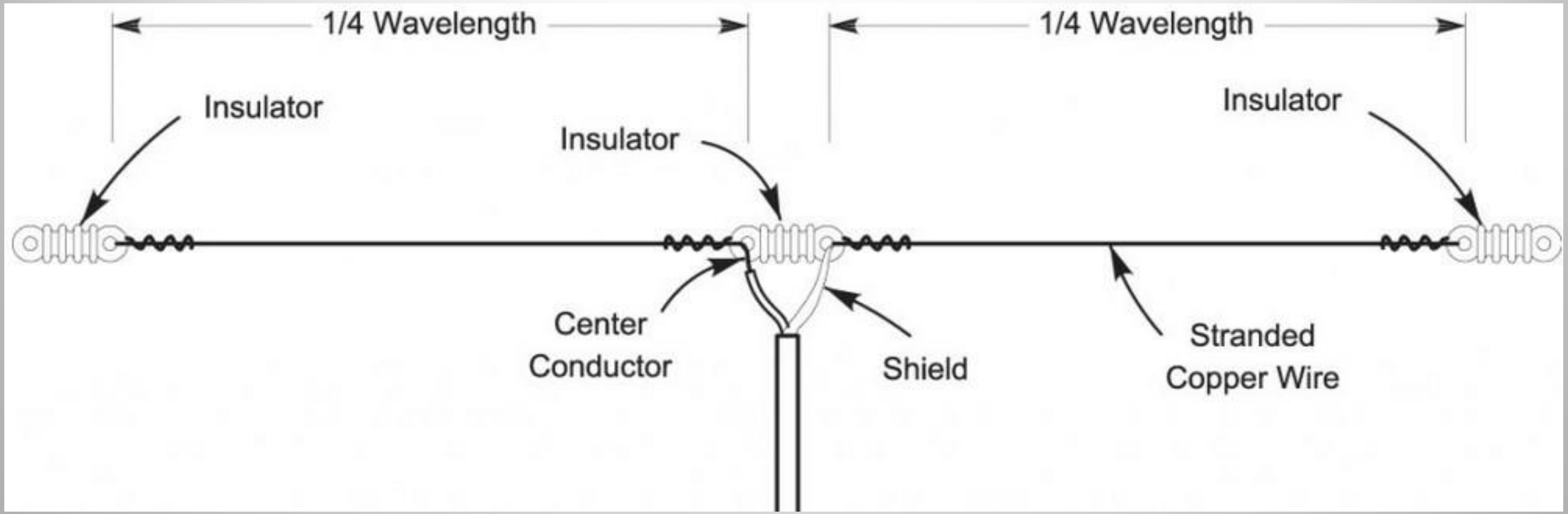
Type	Source
Radio	*Vibrating electrons e.g. AC current*
Microwaves	*Excited semiconductors or vibrating electrons*
Infra-red	*Electrons transitions between energy levels*
Visible	*Electrons transitions between energy levels*
Ultraviolet	*Electrons transitions between energy levels*
X Ray	*Emitted when decelerate rapidly electrons e.g. when they hit a metal target*
Gamma	*Emitted by nuclei after a nuclear reaction*



Is the frequency of the oscillating ELECTRONS

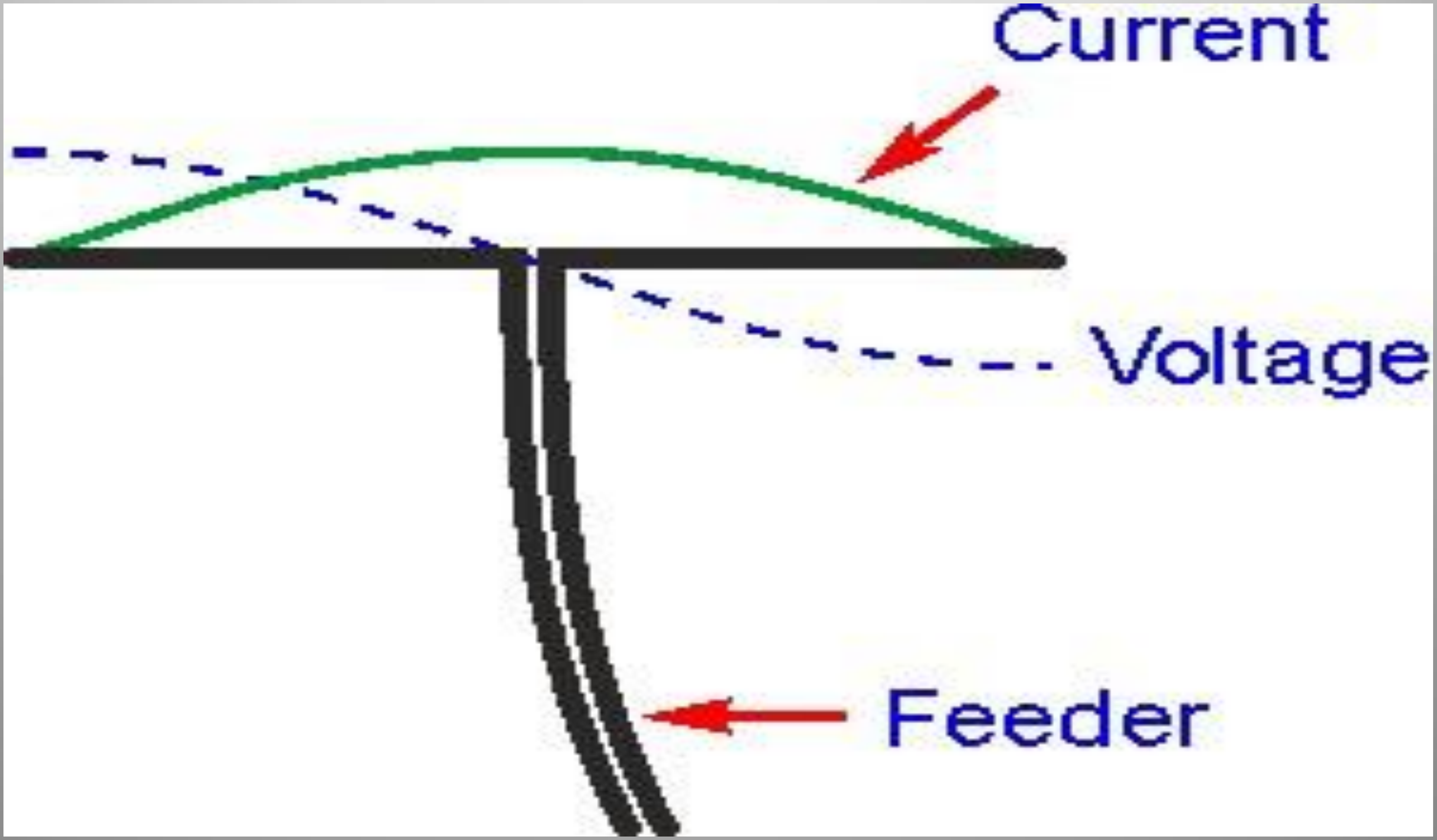
is the same as

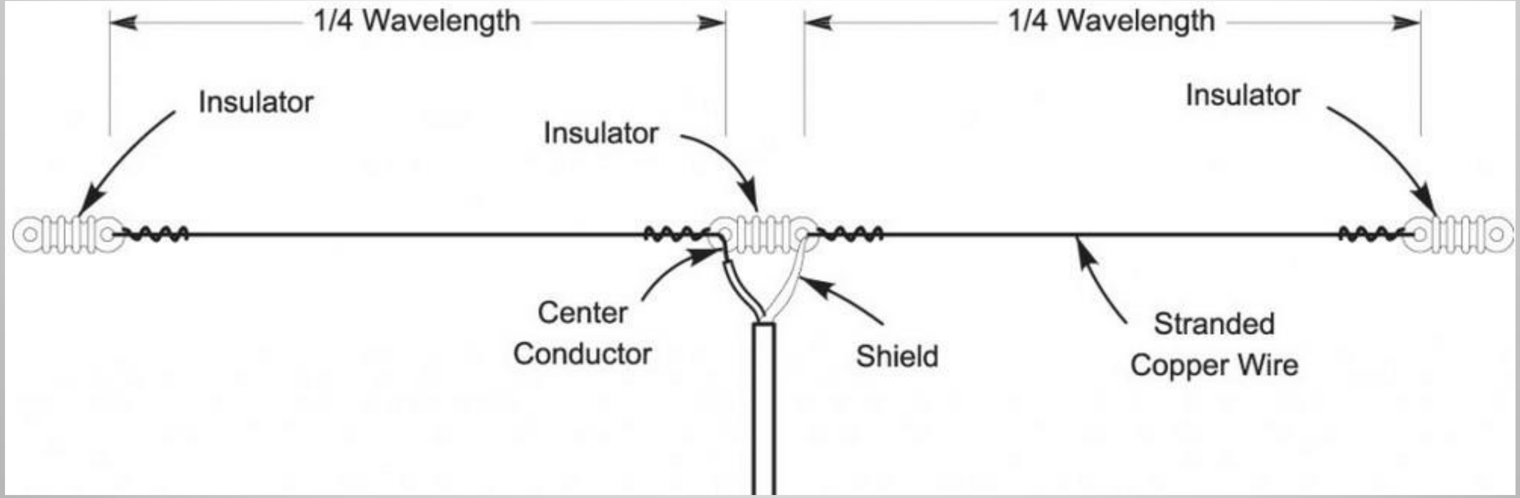
the frequency of the EM wave radiated?



What does the VOLTAGE and CURRENT Distribution look like on a typical dipole?

Where does the maximum radiation occur?
CURRENT is maximum at the center, zero at the ends
VOLTAGE is maximum at the ends





Do the <u>electrons</u> that wiggle and giggle on your dipole

<u>come FROM the transmitter</u>?

NO

The electrons were already in the antenna

(a conductor)

The transmitter supplies the

ELECTRIC FIELD or ENERGY

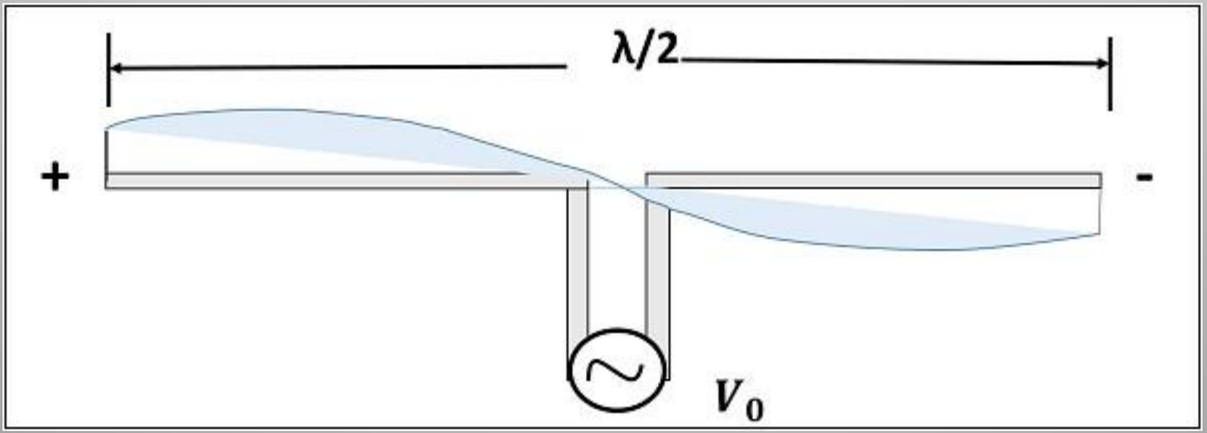
that accelerates the electrons to/fro

What is an “antenna?

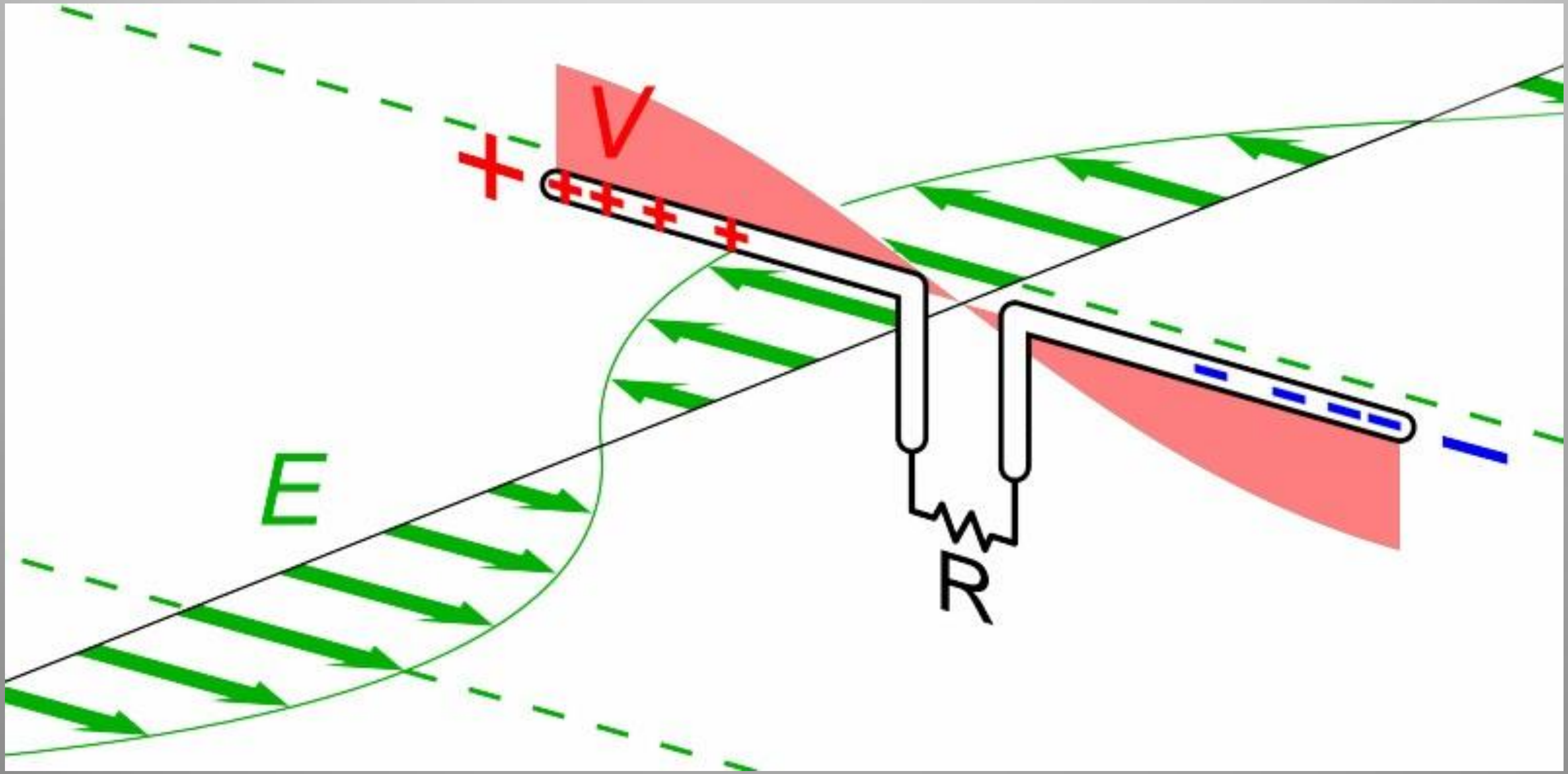
Transmitting: Any conductor that can convert **oscillating electrons** into an Electro-Magnetic (EM) Wave

Receiving: Any conductor that can capture an E-M wave and generate a current (oscillating electrons) to your receiver and be amplified

How do the electrons actually oscillate on a dipole? When one side is + (missing electrons) the other side is negative (excess electrons)



Charge accumulates at the **ENDS** of the dipole
hence the voltage is GREATEST there
What is the **OVERALL NET CHARGE** on the dipole at this moment?



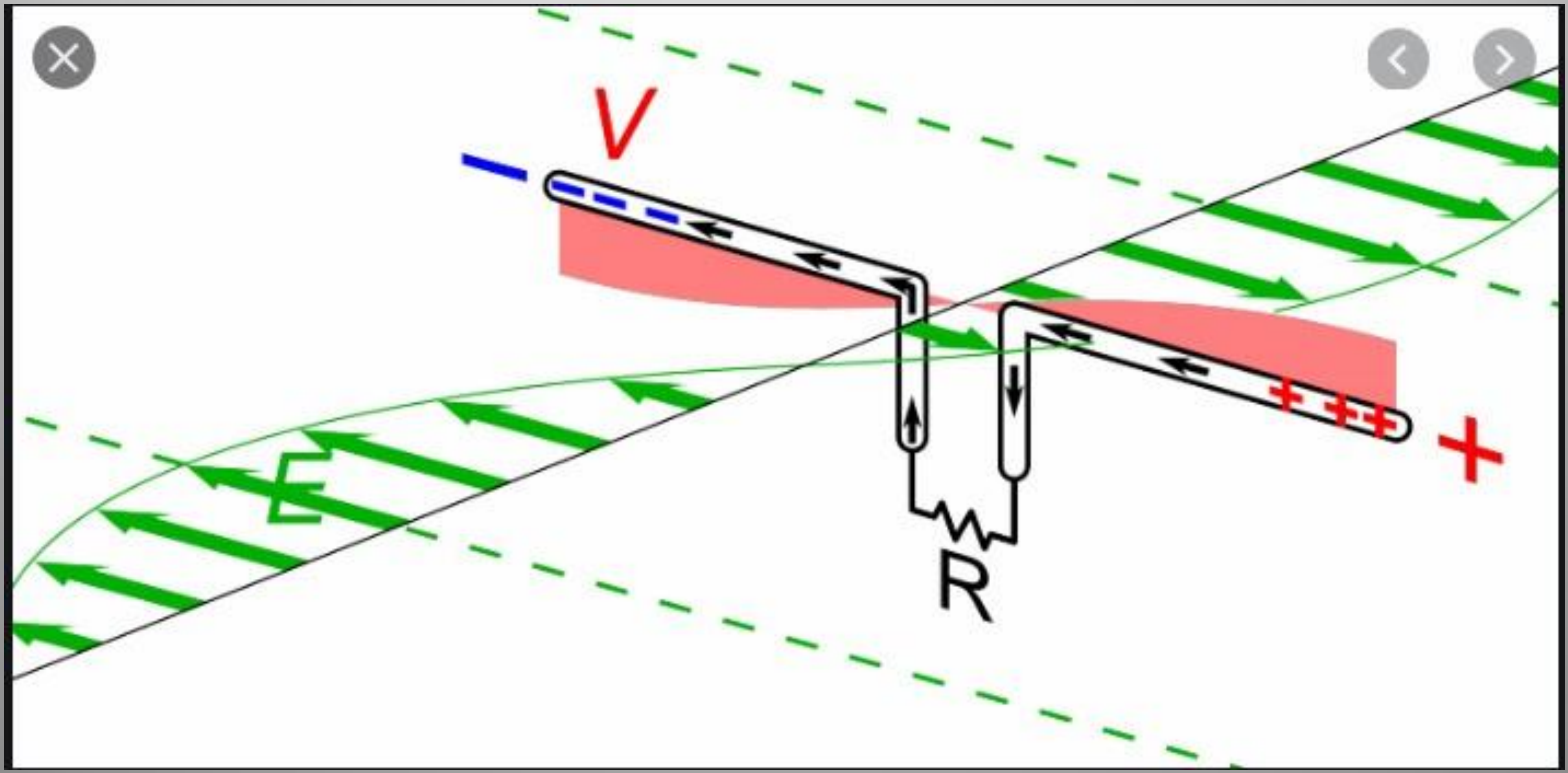
In ½ of the RF cycle

The + and - charges have switched sides (poles)

Left side is now negative - Right side is now positive

How much time elapsed to complete this reversal?

Is there an optimum length of dipole based on the frequency?



WHAT IS RESONANCE

How does Grampy know WHEN to push?

Gramps, if your push is IN-PHASE with my natural frequency on the swing ==> my amplitude increases

Natural Swing: Period and FREQUENCY

Frequency = 1 / period   Period = 1/ frequency

If child's swing (back and forth) takes 4 sec

T = Period = 4 sec   then   F = ¼ Hz

If child's swing takes 2 seconds

Period = T = 2 seconds then Freq = ½ Hz

<u>Shorter PERIOD results in higher FREQUENCY</u>

Check out Sound Resonance of Metal BARS

Why do **LONGER** bars produce **LOWER pitch** tones?

Which soda bottle produces the **highest pitch** sound? WHY?

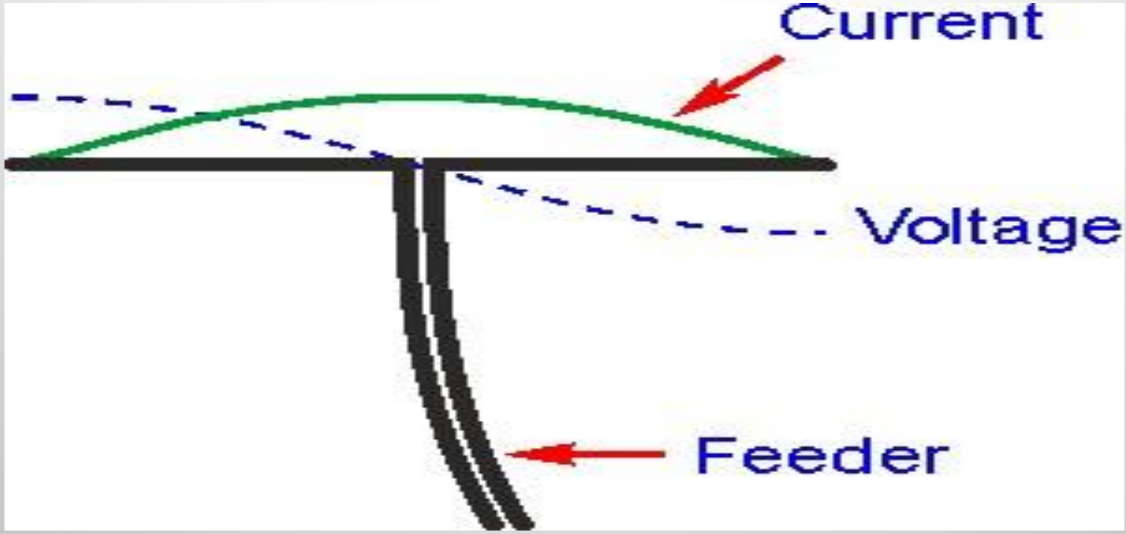
Resonance: Sound Waves

Live DEMO

3 tuning bars of unequal length

Let’s get back to looking at

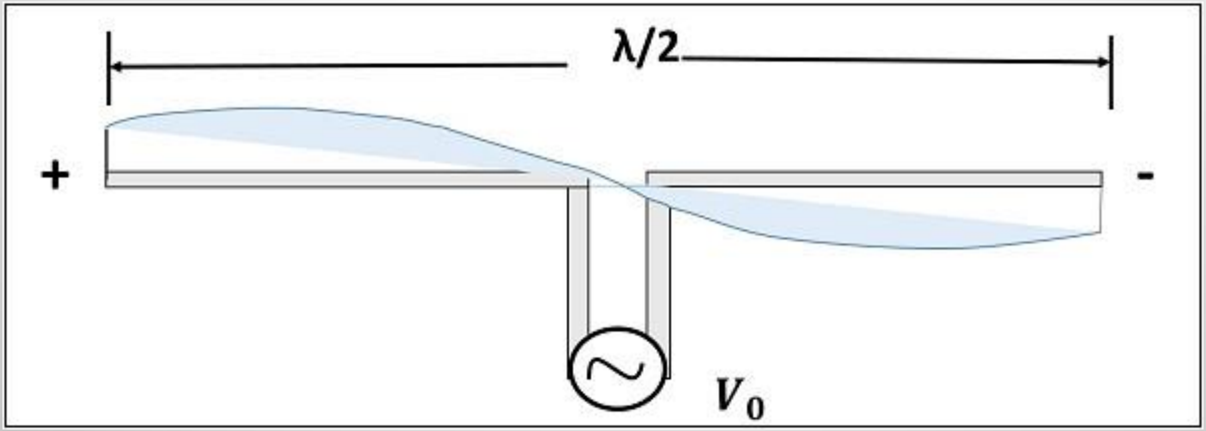
RESONANCE in a ½ wave DIPOLE antenna



Resonance in a Dipole Antenna

A transmission line must exert an electric field at the feed point that keeps the electrons oscillating at just the right timing based on the length of the dipole

At the feed point the VOLTAGE and the CURRENT must be **IN-PHASE** for resonance and maximum current



The electron current actually traverses **TWICE** the length of the dipole in one complete RF cycle

2 L = one cycle = 1 wavelength

Leads to the famous formula for resonance dipole length:

½ wavelength dipole **LENGTH = 468 ft / frequency (MHz)**

Consider a dipole **130 ft long**

At what frequency will it **naturally resonate**?

The current has to travel TWICE the length of the dipole (260 ft) in one "oscillation" period (one RF cycle)

Wave moves about **1 ft per nanosecond** **(v = 1 ft /10^{-9} seconds)**

Period = time for one cycle => **260 nanoseconds to travel 260 feet**

Frequency = 1/period = 1 / (260 x 10^{-9}) = 3.8 x 10^{6} Hz = 3.8 MHz

Resonant Frequency of 130 ft dipole ==> 3.8 MHz

as a ½ wavelength antenna

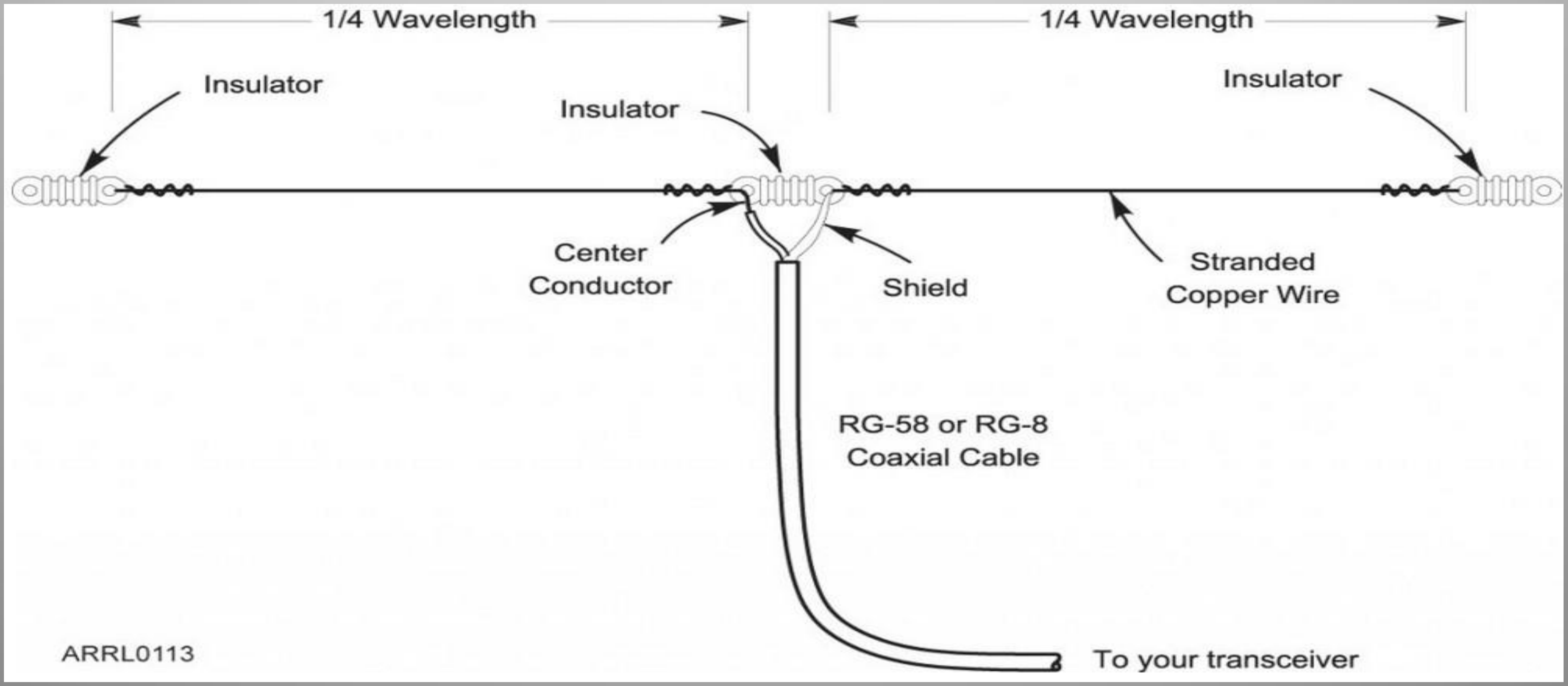
Standard ½ wavelength antennas
Lengths are in feet

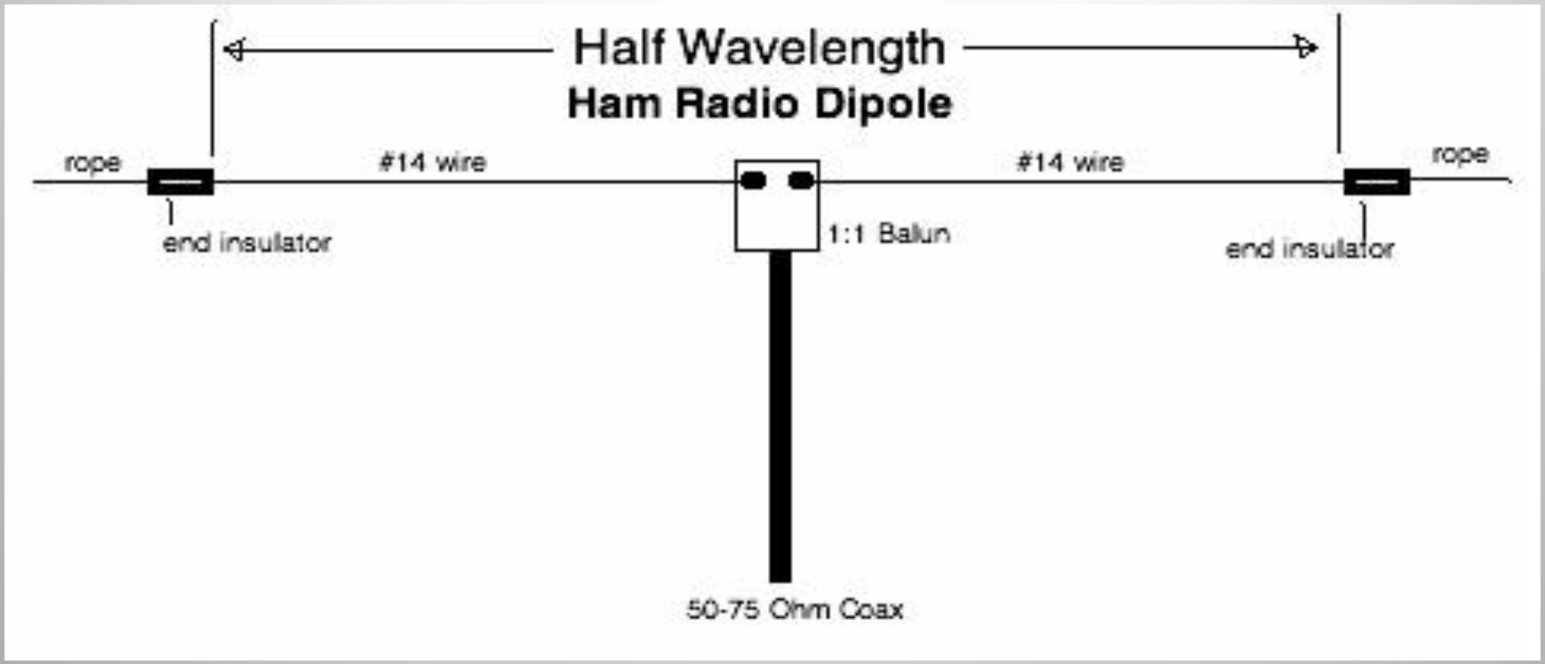
Band	Target Frequency	Total Length
160	1.900	246.32
80	3.800	123.16
60	5.365	87.23
40	7.150	65.45
30	10.300	45.44
20	14.175	33.02
17	18.118	25.83
15	21.225	22.05
12	24.940	18.77
10	28.500	16.42
6	52.000	9.00

Resonant Lengths 80 meter Half-Wave Dipole

L = 468/f

Frequency	Resonant Length
3.5 MHz	134 feet
3.6 MHz	130 feet
3.7 MHz	126 feet
3.8 MHz	123 feet
3.9 MHz	120 feet
4.0 MHz	117 feet





If you operate at a frequency BELOW resonance

The reactance is negative (capacitive) X_c

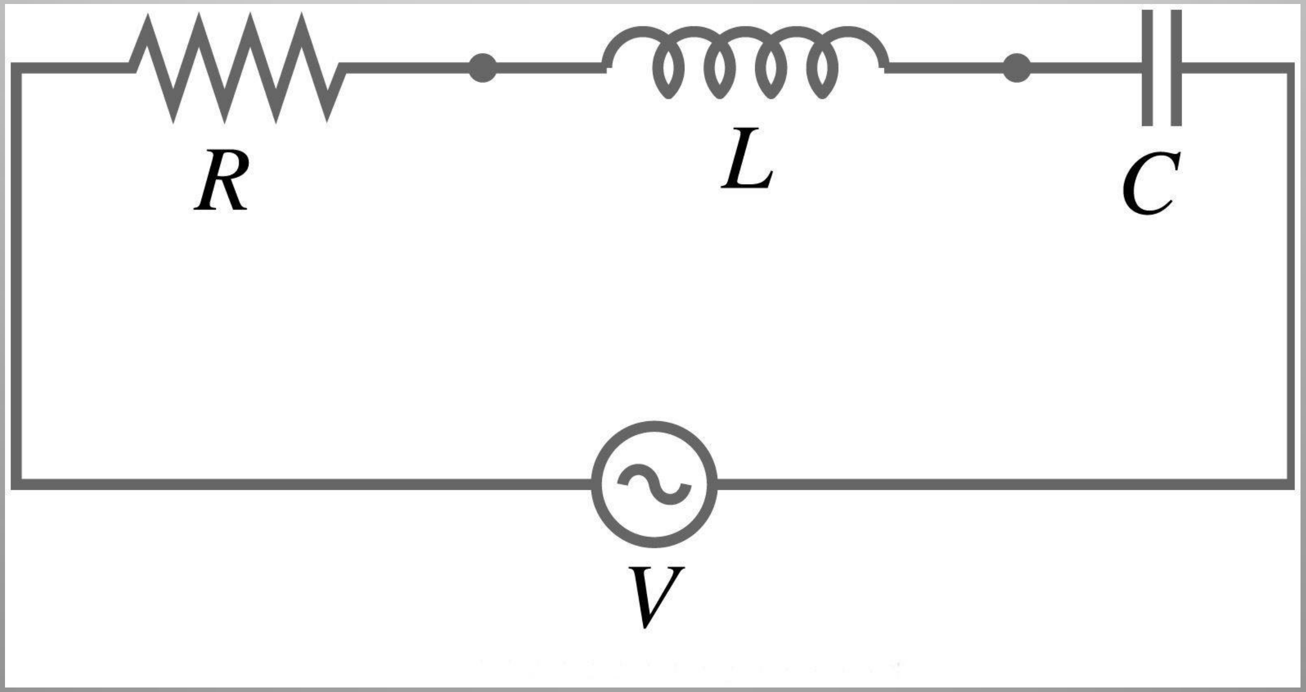
If you operate at a frequency ABOVE resonance

The reactance is positive (inductive) X_L

Model of a Dipole Antenna

Resistor **R** Inductor **L** and Capacitor **C**
in **series** with an AC generator (transmitter)

Capacitors restrict **LOW** frequencies (why?)
Inductors restrict **HIGH** frequencies (why?)



<u>ELI</u> the <u>ICE</u> man

In an **INDUCTOR** (L) the voltage (E) **leads** the current **(I)**

Voltage => emf **E** Current **I** (intensity of charge)

Ampere thought current as the "<u>intensity</u>" of the electricity, thus **I** for current

In a **CAPACITOR**, the current (I) **leads** the voltage (E)

Thus, the PHASE (time relationship) is <u>opposite</u> in

Inductors and Capacitors

RESONANCE in a RLC Circuit

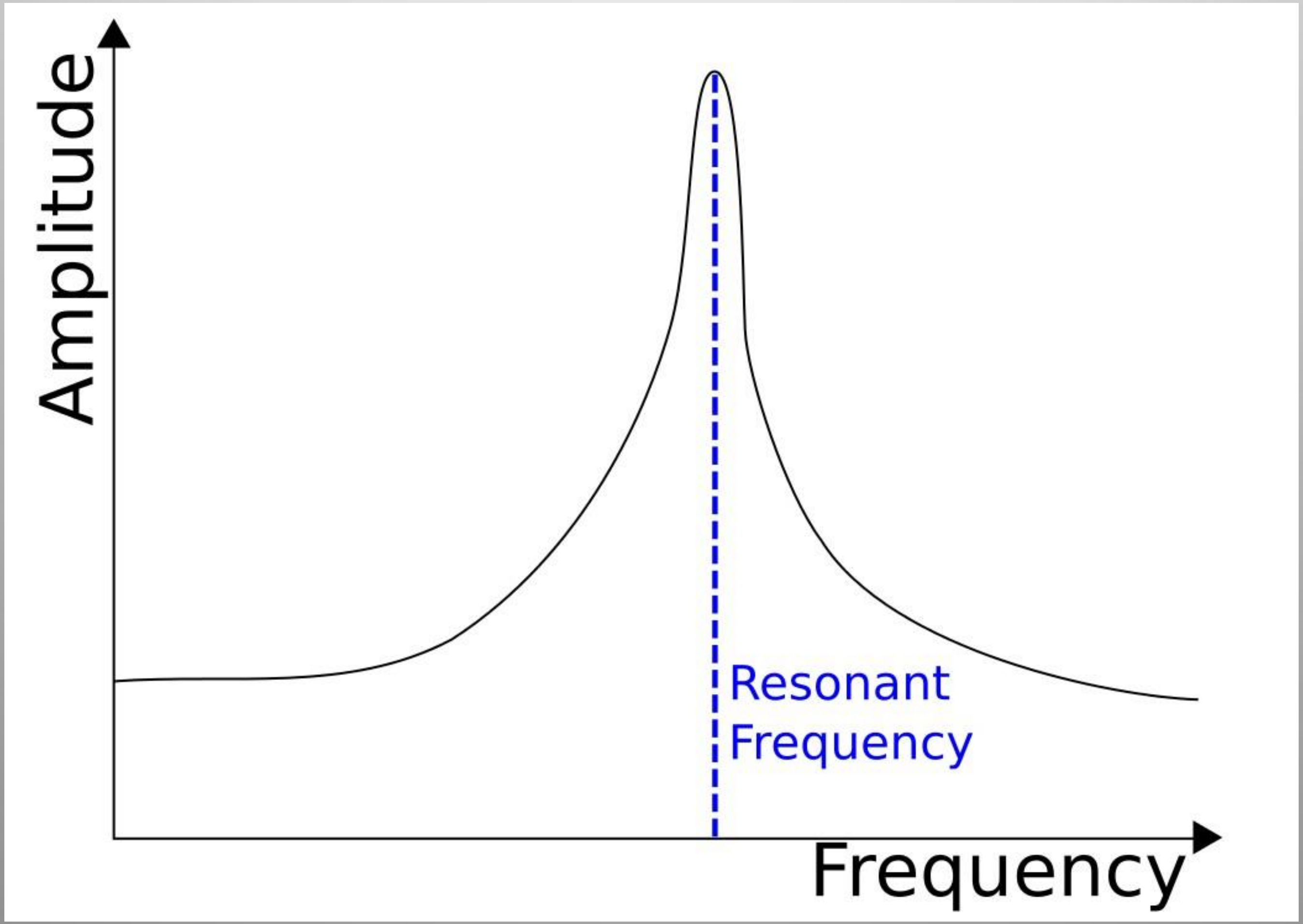
A condition where the inductive reactance **(X_L)** (ohms) is equal in value (but opposite sign) to the capacitive reactance **(X_C) (ohms)** and they **CANCEL** each other

$$X_L - X_C = 0$$

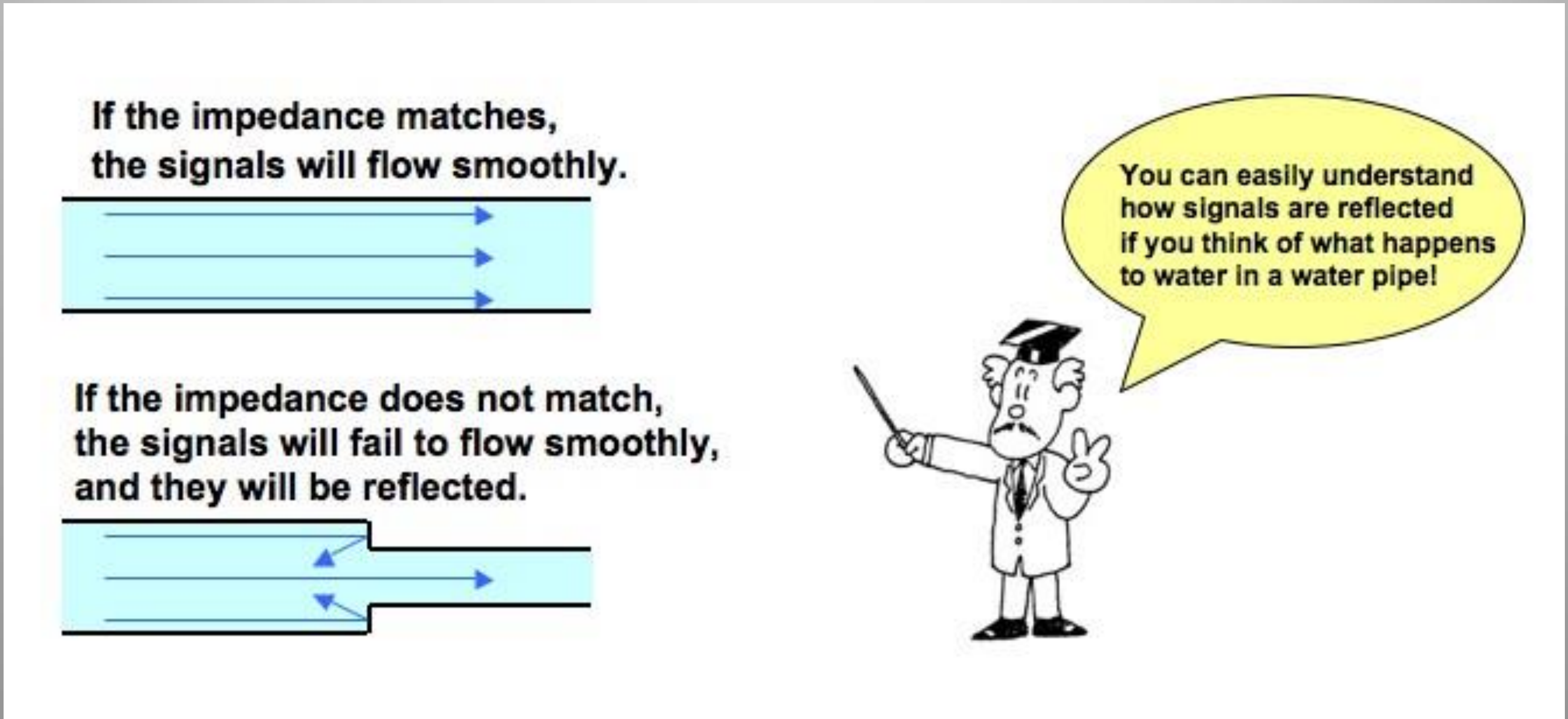
Leaving the IMPEDANCE **Z** as a pure resistance **R**

A RLC circuit has the maximum current and minimum resistance

at its resonant frequency (reactance is zero)



You do NOT want an impedance "bump" which causes REFLECTIONS of voltage and current



SWR meters indicate an impedance BUMP
FORWARD power (1 W) and REFLECTED power (0.8W)
This one looks dreadful!!

SWR: Standing Wave Ratio

Indicates the degree of “match” (or mismatch)

Feed line to antenna: ideal is 50 ohm to 50 ohm

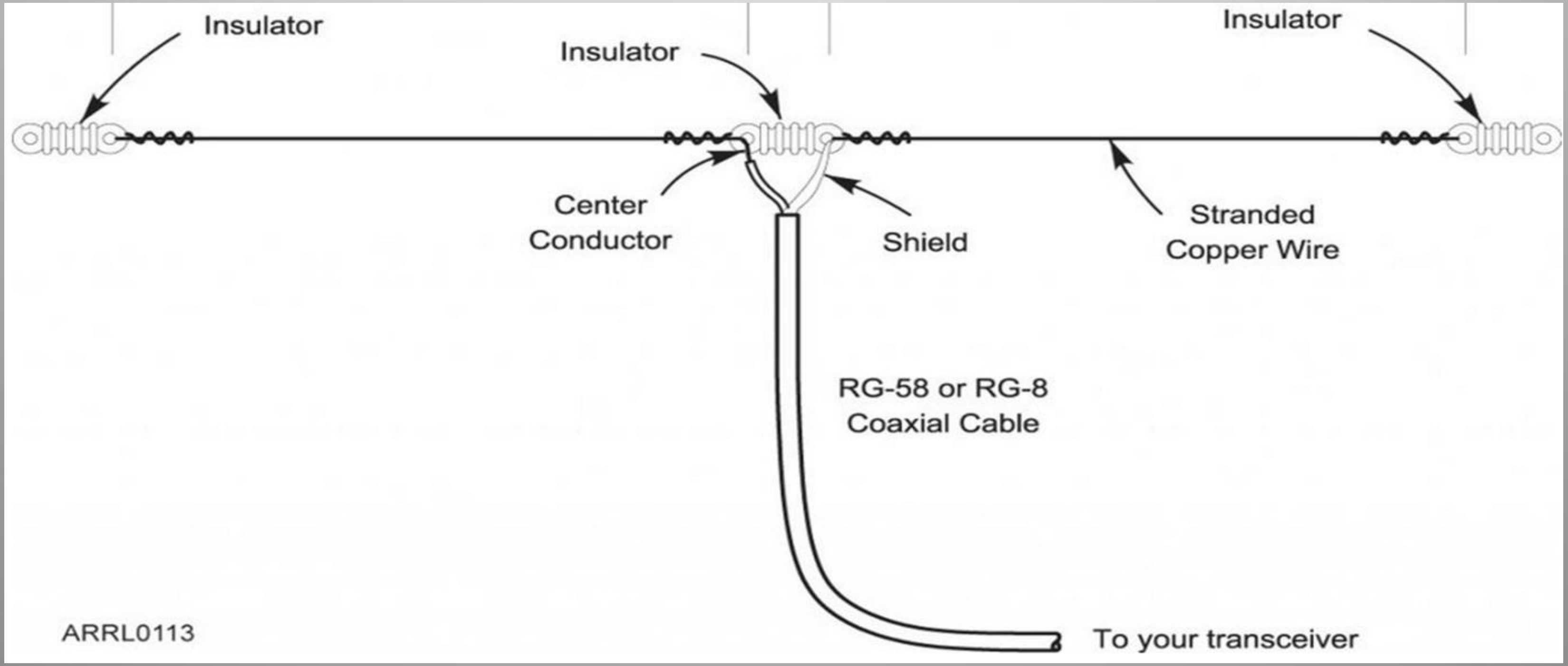
Rig to feed line: ideal is 50 ohm to 50 ohm

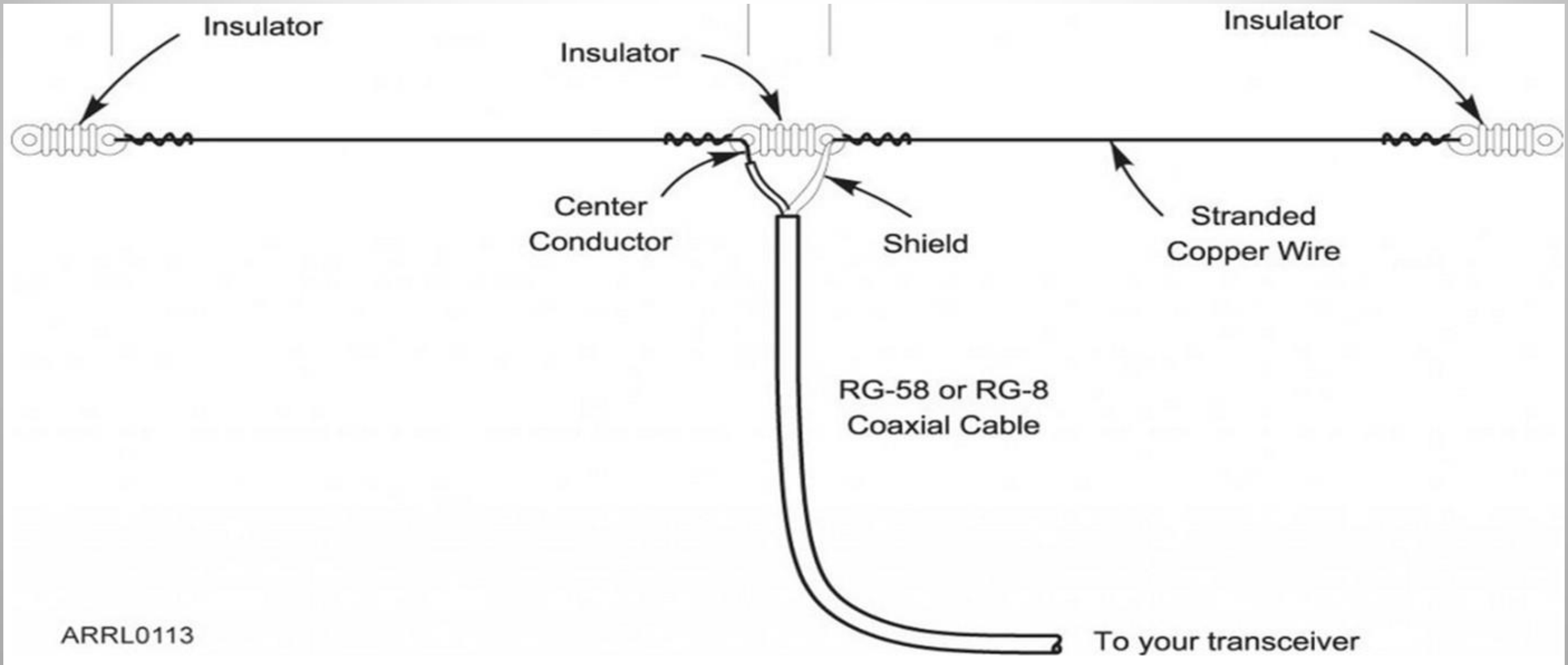
SWR = Ratio of impedance

50 ohm/50 ohm = 1:1

MAXIMUM TRANSFER OF POWER occurs if the SWR is 1:1

A center-fed dipole at ½ wavelength above ground has an impedance of **about** 50-70 ohms
(a good match to 50-70 ohm coax)

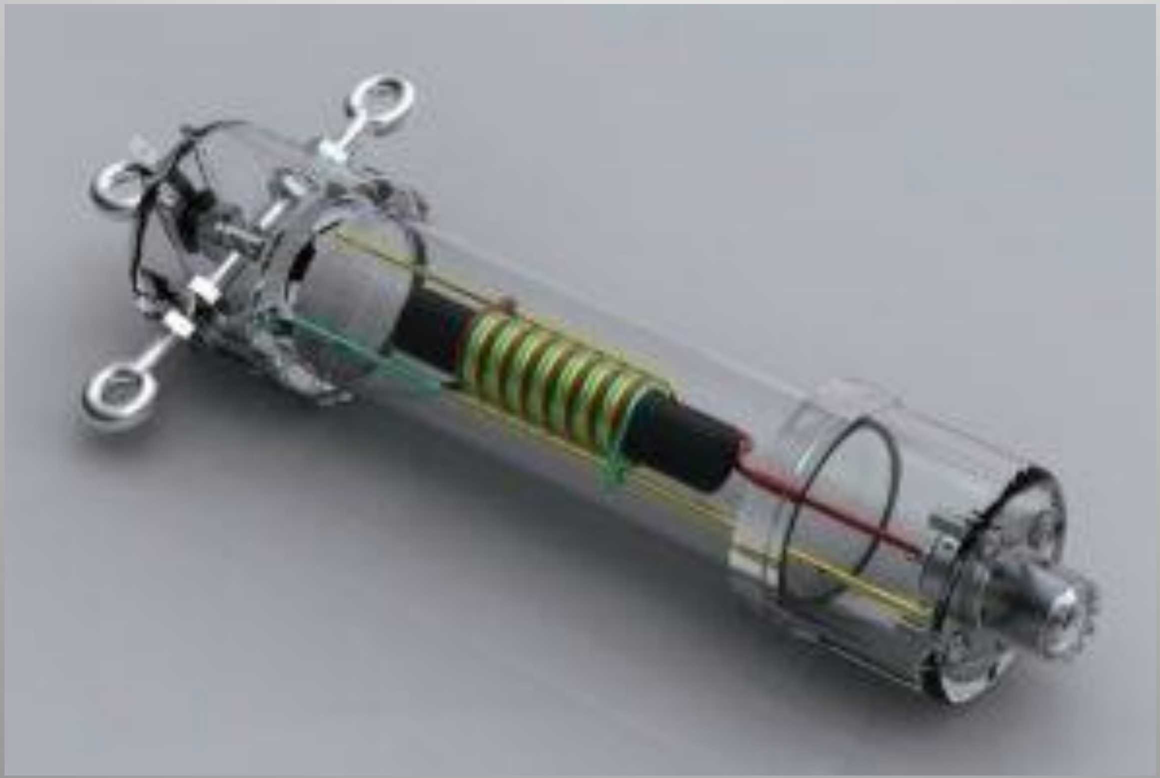


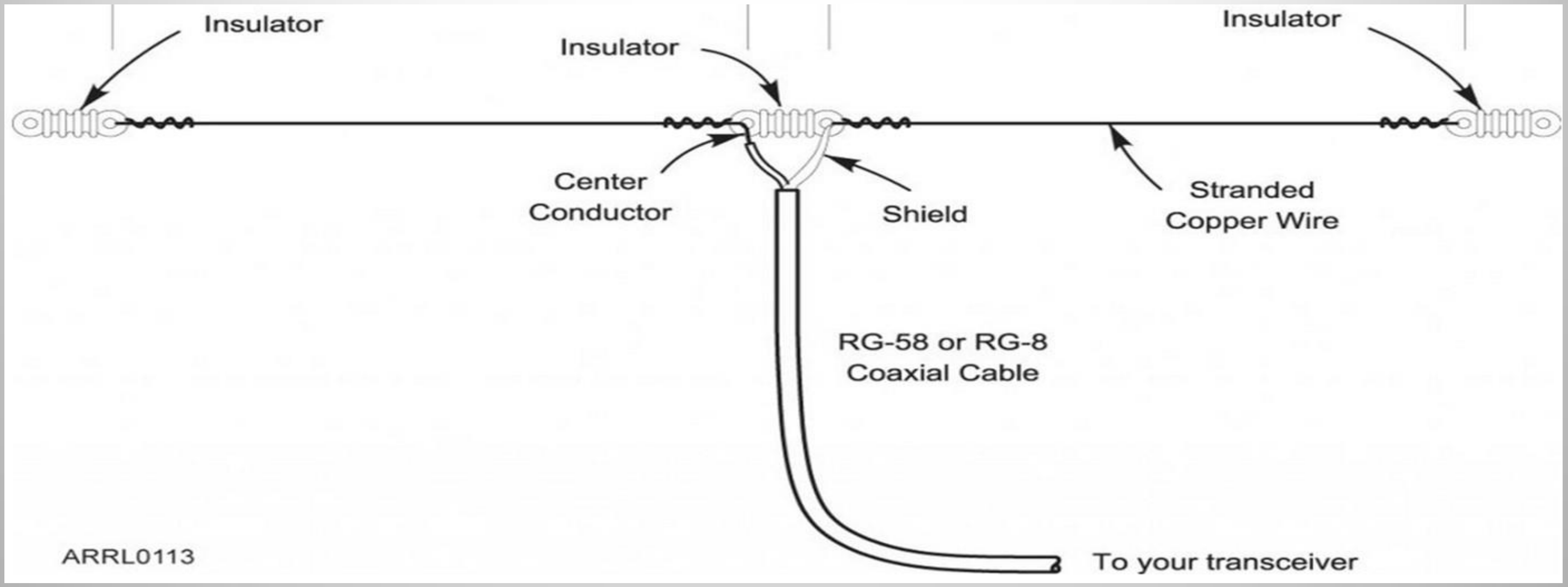


Ideally you want to "match" the
transmitter output impedance (50 ohm)
to the feed line impedance (50 ohm)
to the antenna impedance (50 ohm)

Balun

(balanced antenna to unbalanced coax)





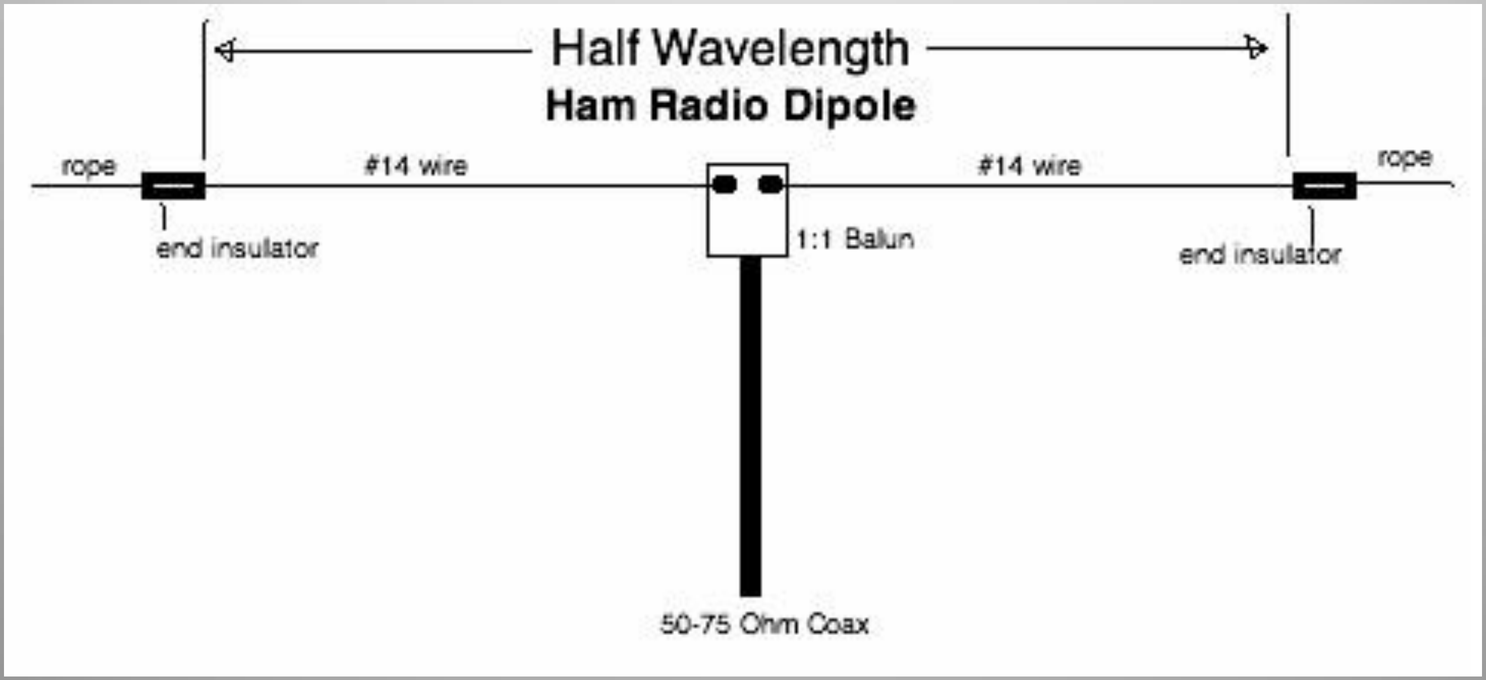
A dipole that is <u>TOO SHORT</u> will exhibit **CAPACITIVE REACTANCE**
A dipole that is <u>TOO LONG</u> will exhibit **INDUCTIVE REACTANCE**

At "resonance" the dipole is just the right length
the reactance CANCELS
the current and the voltage are IN-PHASE at the feed point

Various combinations of R and X to yield Z

Resistance R	Reactance X	Impedance Z	SWR
50	0	50 + j0	1
25	0	25 + j0	2
100	0	100 + j0	2
40	30	40 + j30	2
16	0	16 + j0	3
150	0	150 + j0	3
30	40	30 + j40	3
10	0	10 + j0	5
250	0	250 + j0	5
10	50	10 + j50	10

How can you operate over the **entire 80m band** if the rig needs to “see” a 50 ohm load and an SWR under 2:1?



Cancel the **reactance** (**X**)

in the antenna feedline

and

convert the resistance component

R to **50 ohms**

<u>to match your 50 ohm coax</u>

So how is this magic accomplished?

QUIZ

Do antenna TUNERS really

"tune" your antenna?

YES ?   NO?

How does a Tuner "match" impedances?

An "antenna tuner" takes the

reflected wave on the feed line,

and by means of coils and capacitors,

creates a

"conjugate match"

inside the tuner…

This combination of inductors and capacitors then **RE-REFLECTS** the reflected wave from the tuner back towards the antenna,
adding to the FORWARD power going to the antenna

Creating a **REFLECTION GAIN**

REALLY …. Is it that simple?

It is MAGIC (almost)

Is this possible?

Assume the feed line has zero loss. Transmitter puts out 100W.

The antenna has a 3:1 mismatch to the feed line

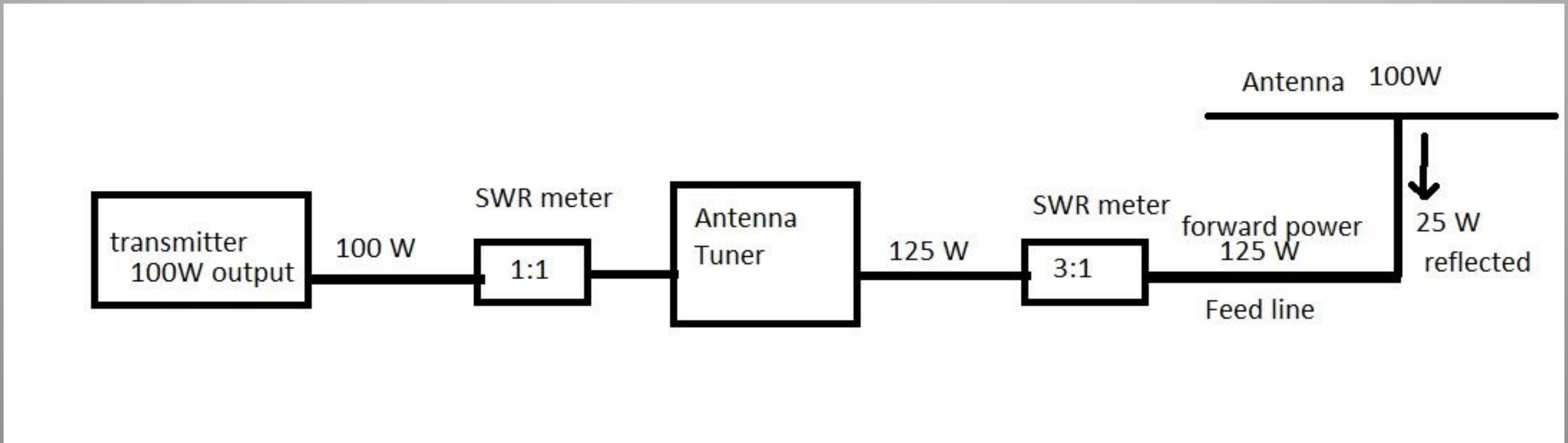
reflecting 25W back towards the transmitter.

The antenna tuner **RE-REFLECTS** this 25W back towards the antenna

Thus, now 125W is in the forward direction

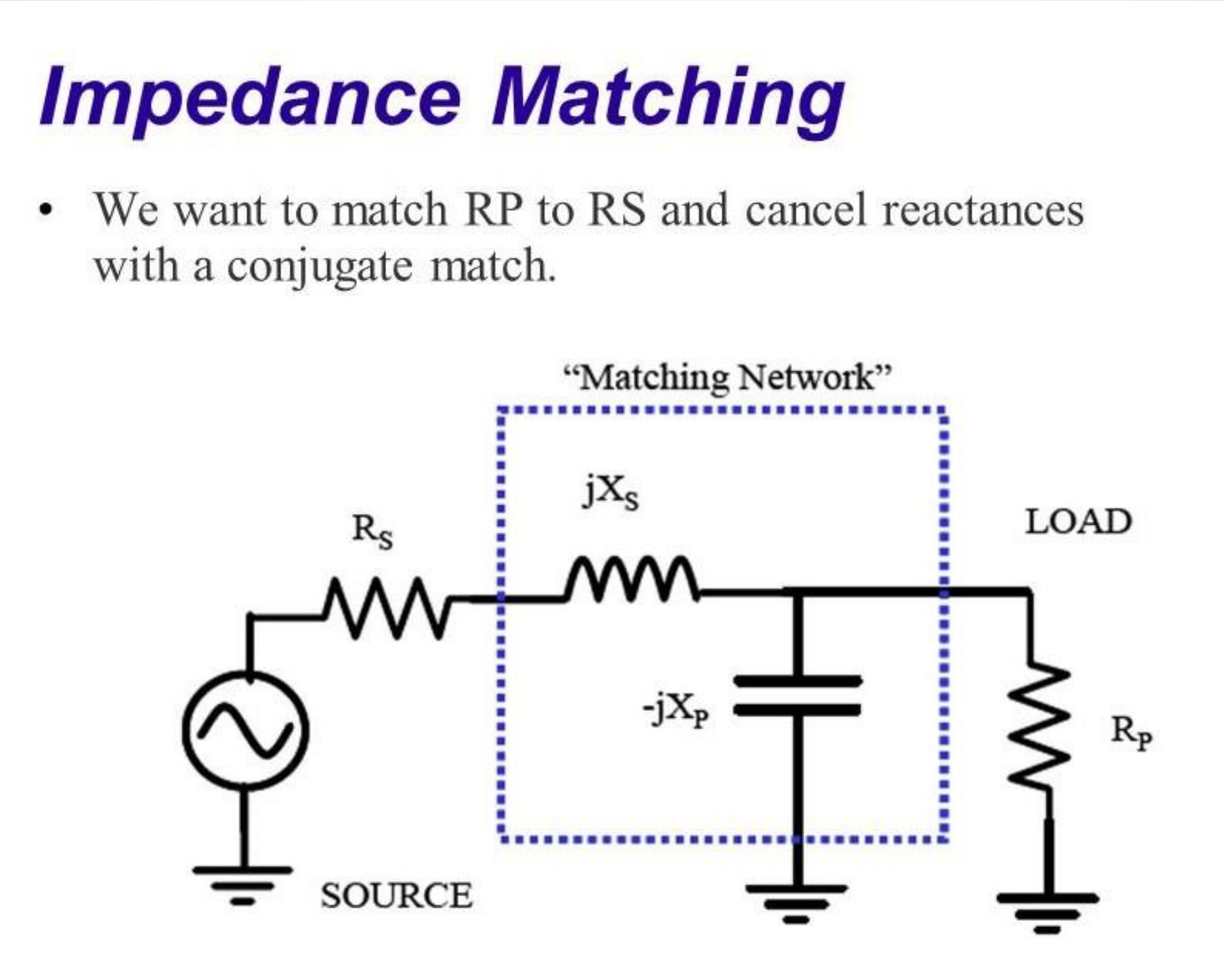
Then antenna then absorbs and radiates the 100W

"THE ANTENNA SYSTEM IS NOW RESONANT"

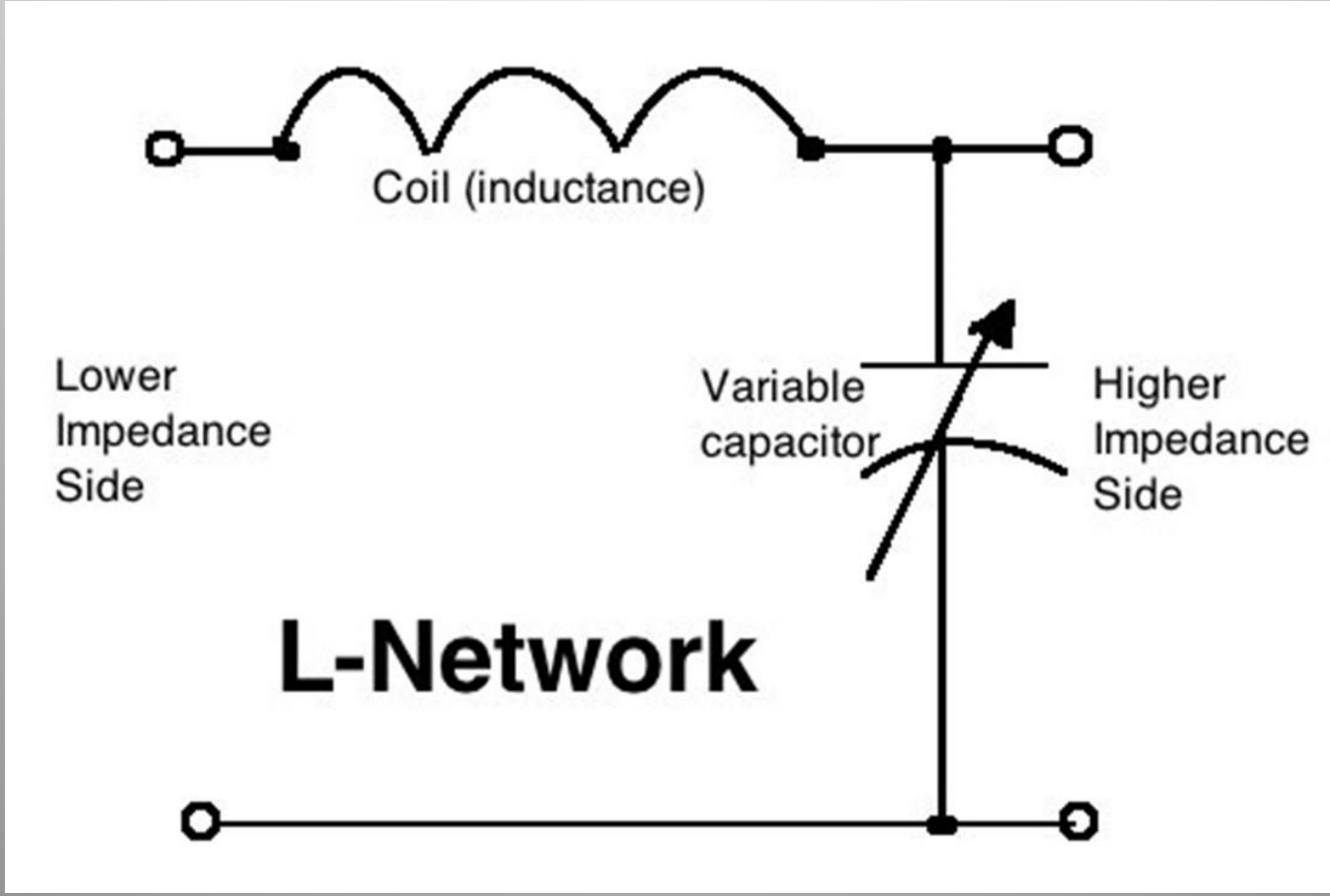


Let’s now look INSIDE
a variety of antenna tuners

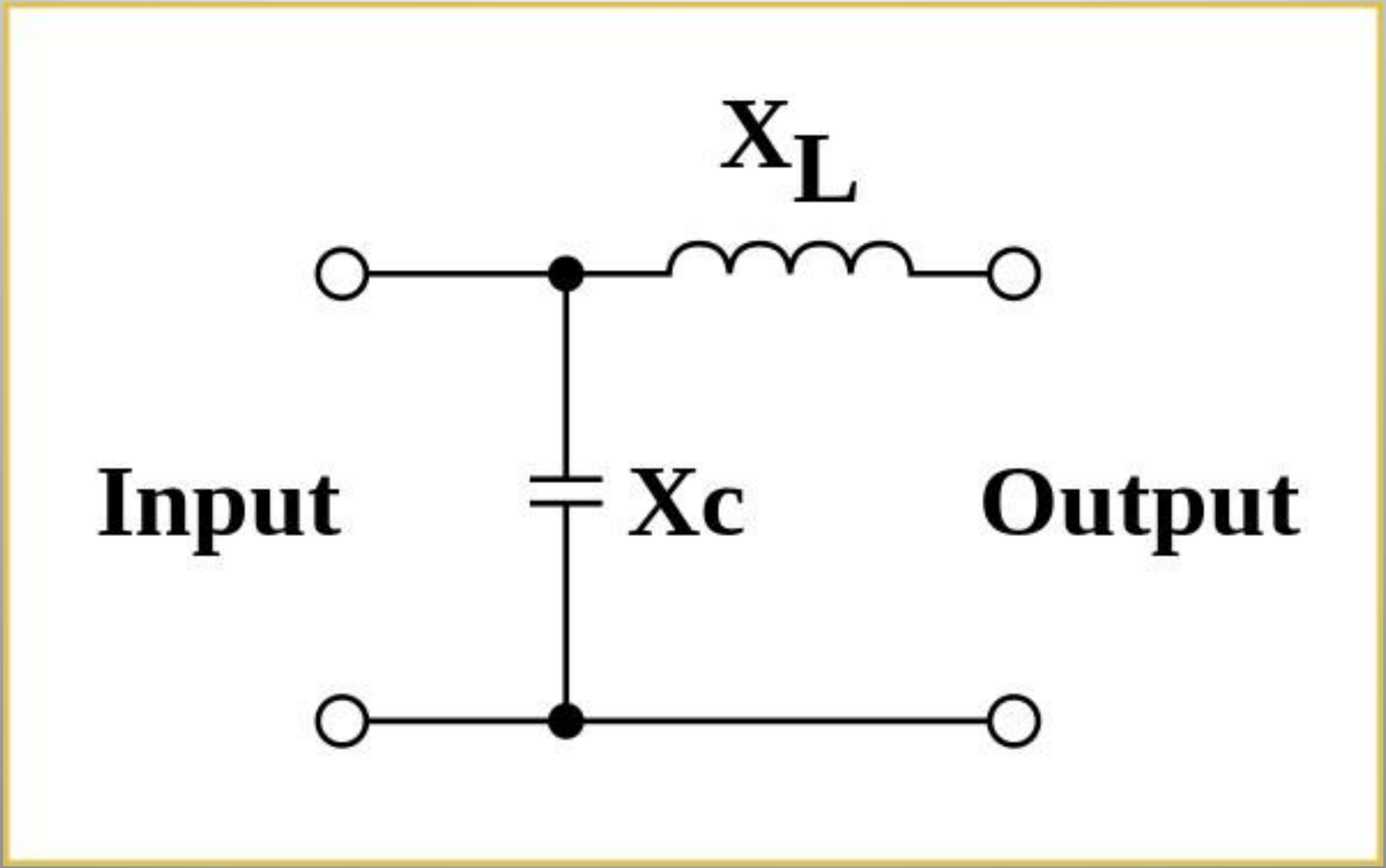
Tuner Function: Cancel reactance and convert the feed line impedance value to
50 ohm resistance for the rig



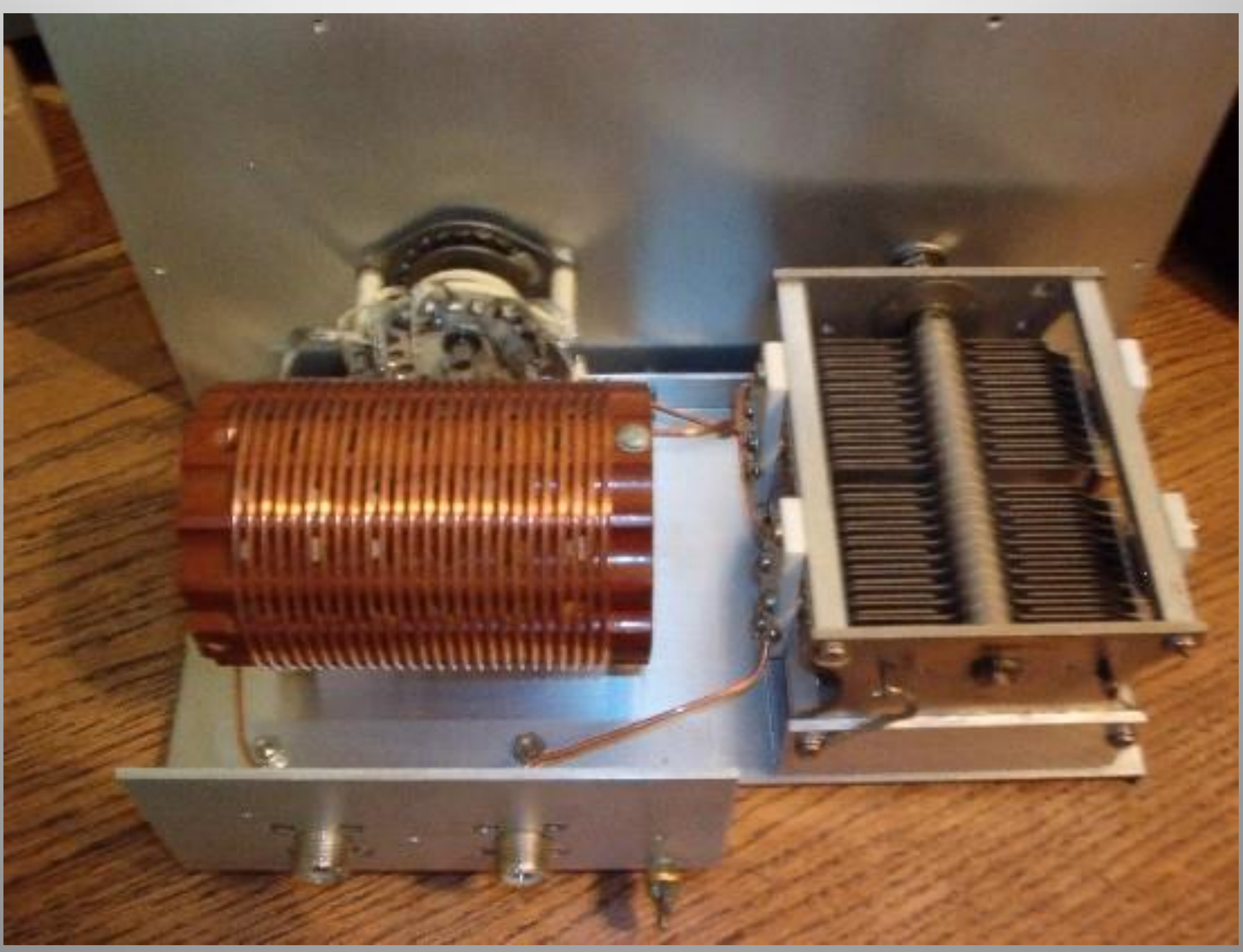
A simple **L network** matches transmitter to a higher impedance and cancels reactance



L network can match to a **low** impedance antenna by placing the capacitor on the INPUT side



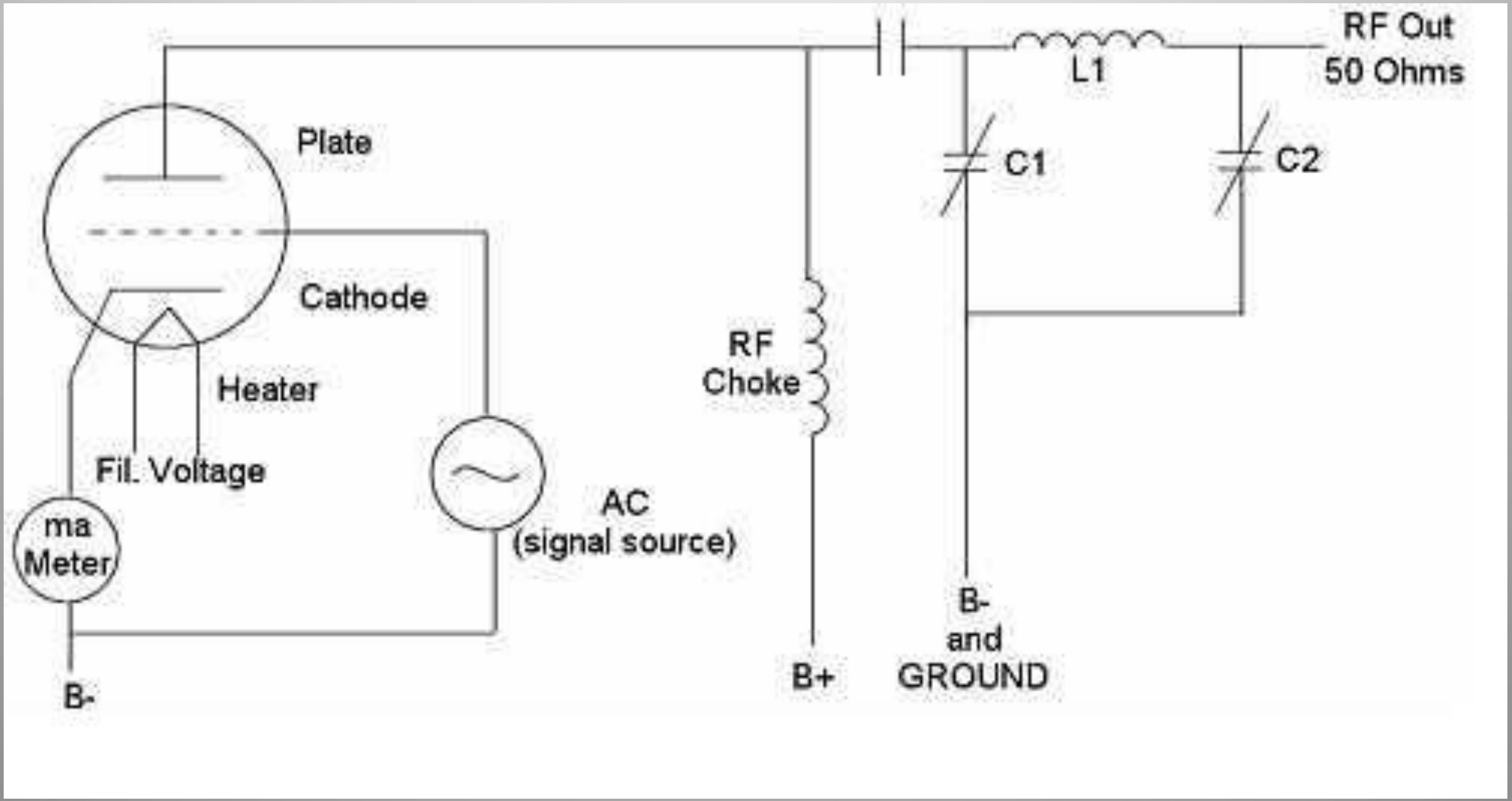
L network: only two components



Ten-Tec 2 kW L network Tuner
1 capacitor, 1 inductor
switch reverses capacitor connections

Inside the TenTec L network tuner
Capacitor can be switched to either side of roller inductor

"Pi" network in vacuum tube amps was its own "tuner"
CLC transforms high impedance at tube plates 2000 – 5000 ohms
to low impedance 50 ohm coax feedline
C1 = plate current dip (**tune** to resonance) C2 = **load** adjust
L1 was adjusted by taps to each band



Drake MN-2000 2 kW **Pi-Network** Tuner coils switched by BAND switch

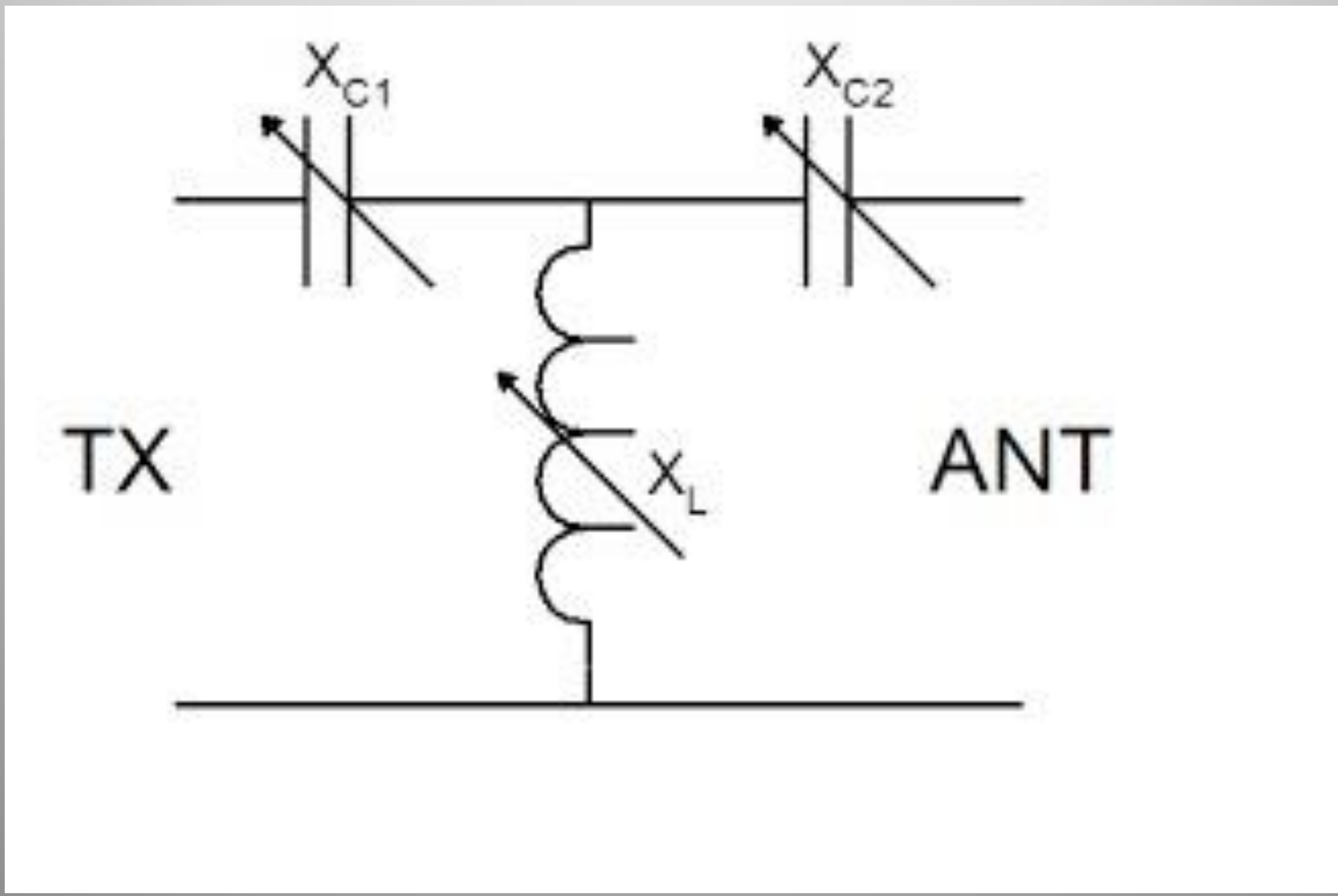
Inside the Drake MN2000 tuner
Why two coils and two capacitors?

A very common design **T network**

Two capacitors (neither side grounded)

and one roller inductor (to ground)

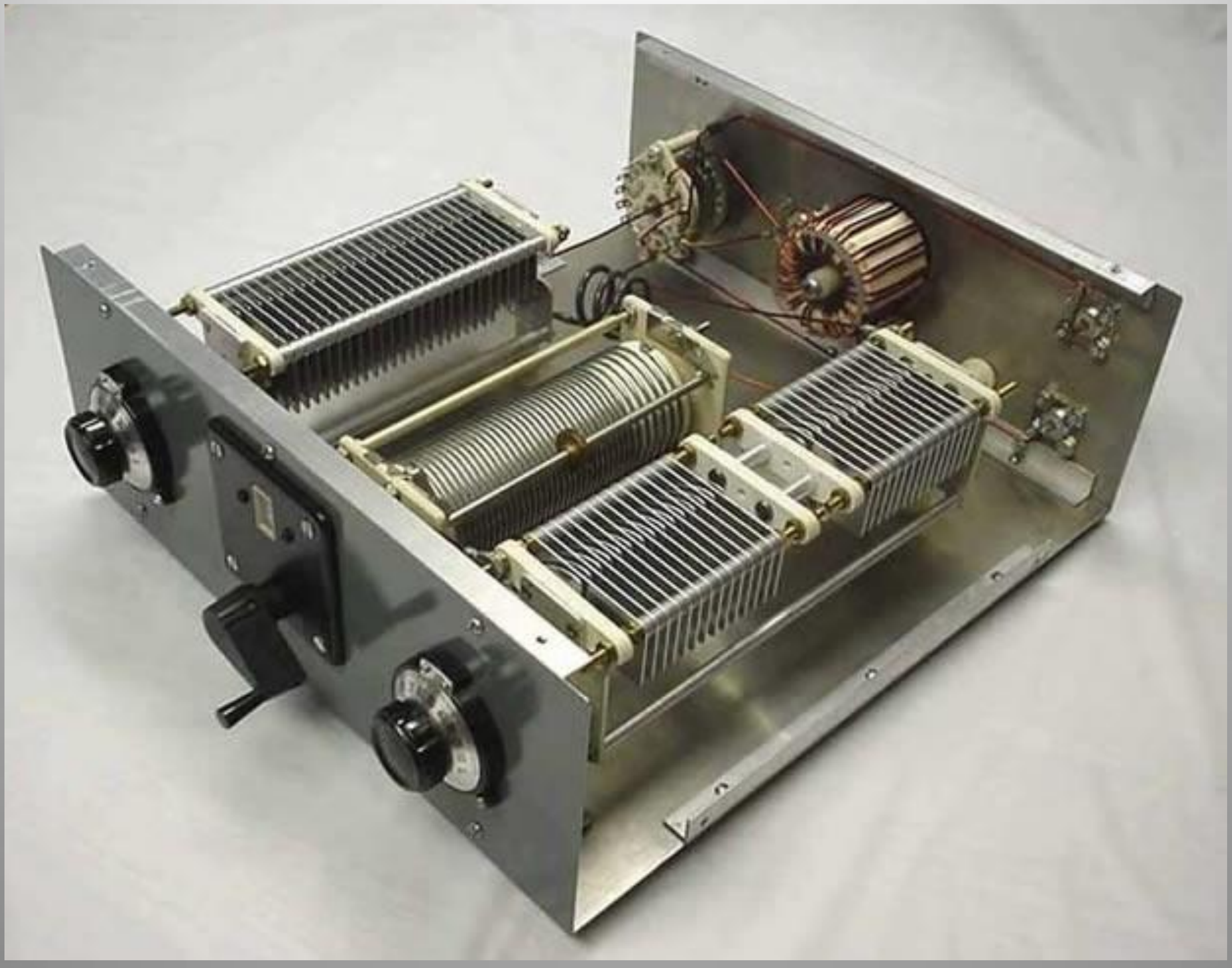
Do you see two L networks?



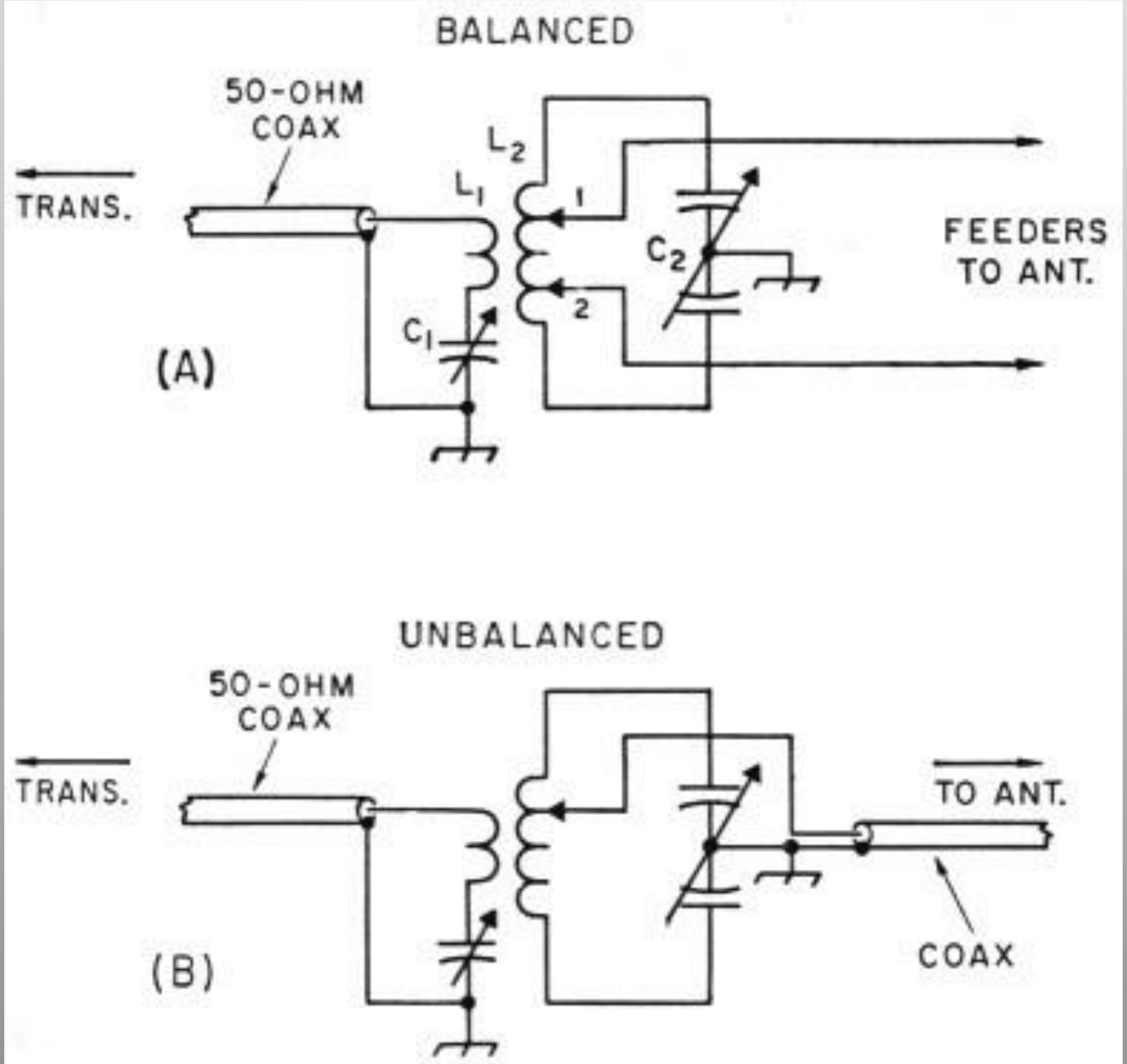

TRANSMITTER
SWR/WATTS
300
30
SWR
INDUCTANCE
ANTENNA
MFJ VERSA TUNER II
MODEL MFJ-941


ANT. 2
ANT. 1
ANT. 1
ANT. 2
WIRE/BAL
BYPASS
BYPASS ANT.
TRANSMITTER
ENTERPRISES
MS, U.S.A.

2 kW T network manual tuner

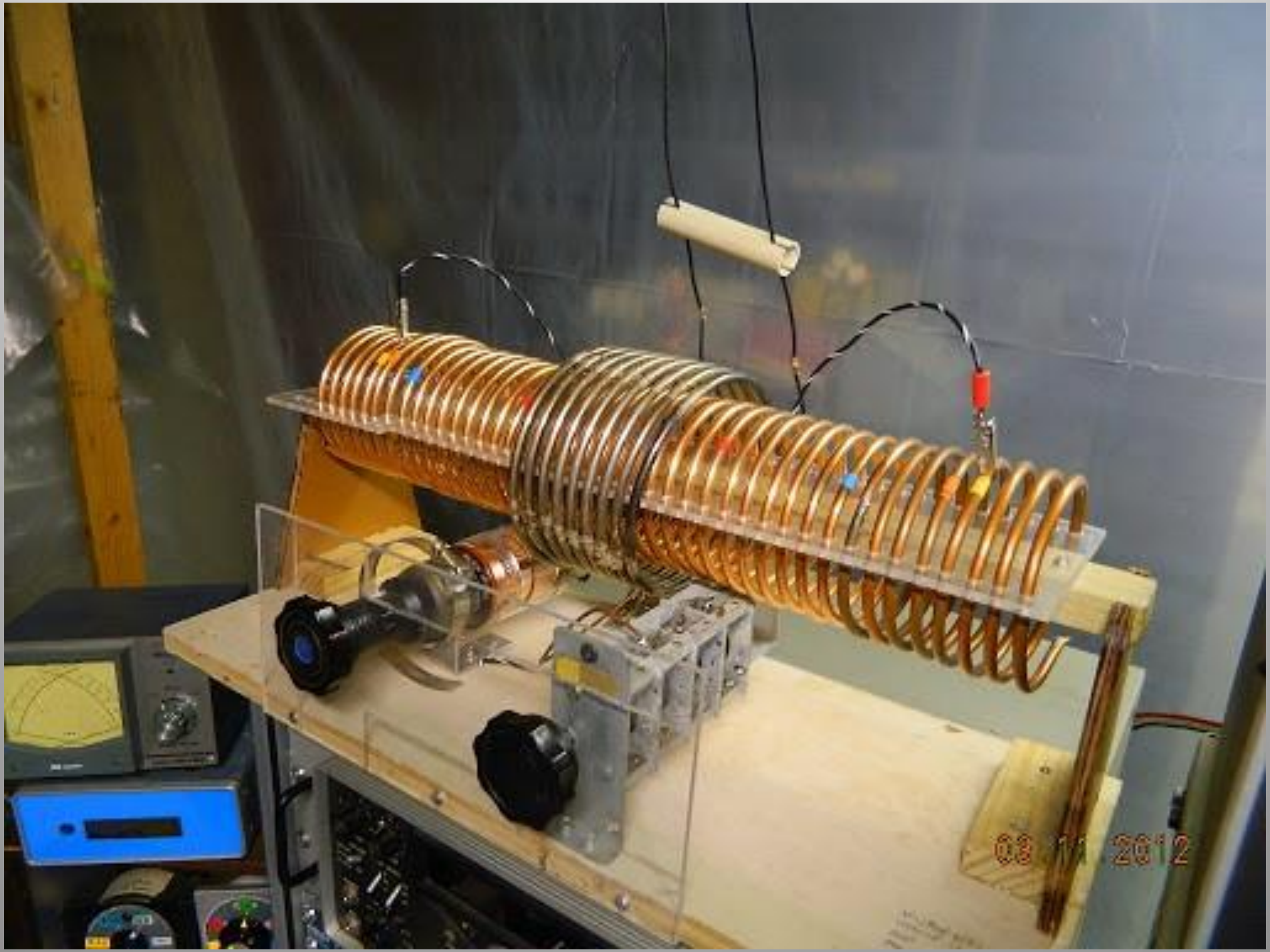


LINK-COUPLING: does power get from **L1** to **L2**



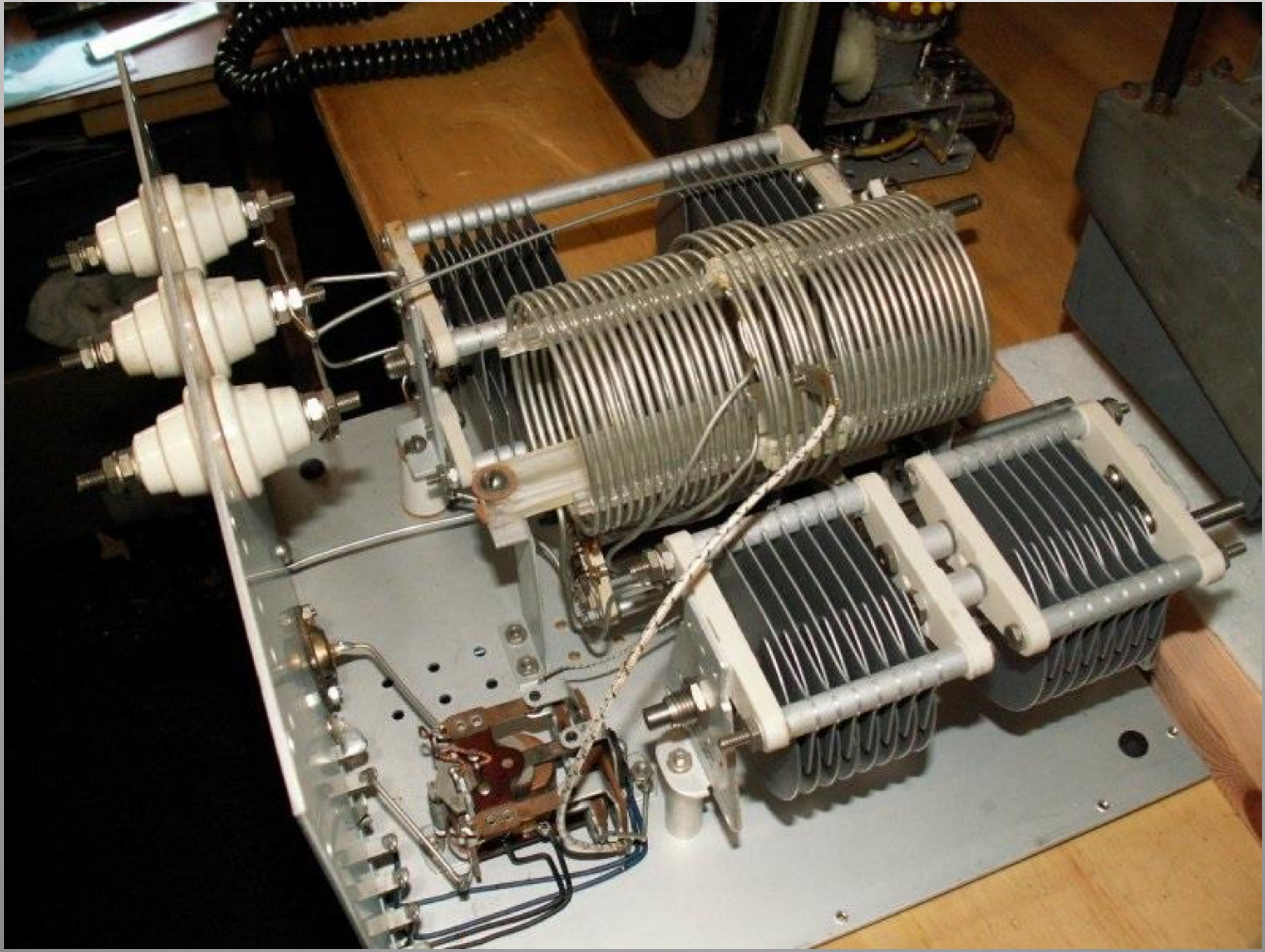
Link-Coupling
no physical contact between INPUT and OUTPUT

Extreme Link-Coupling
Output via a home made LADDER LINE

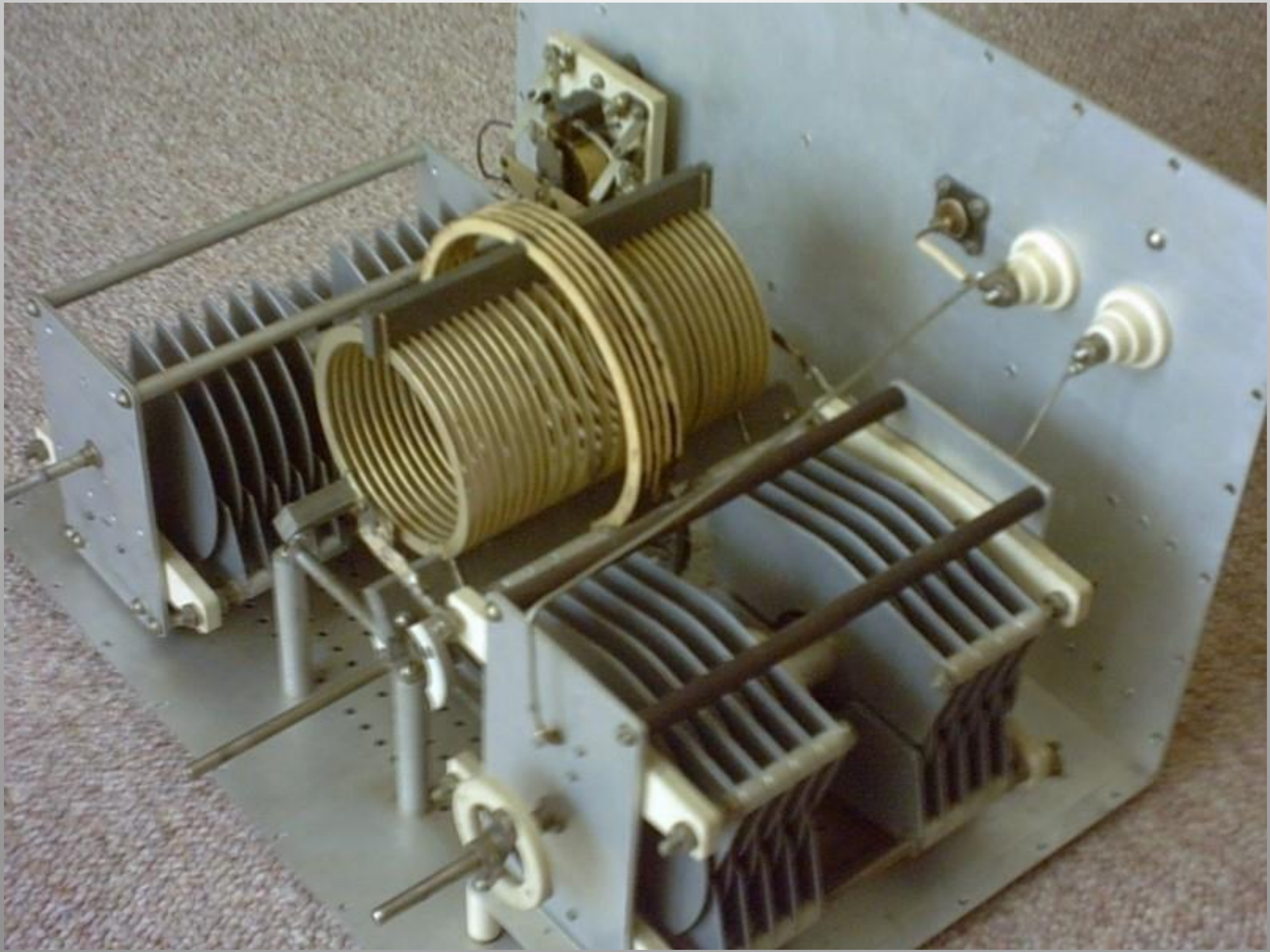


Johnson Viking Matchbox
1960 design for BALANCED FEEDERS

Johnson Viking Matchbox: 275 watt
Link Coupling used in TWO concentric coils



Viking Kilowatt MatchBox
also uses LINK COUPLING: BALANCED FEEDERS out

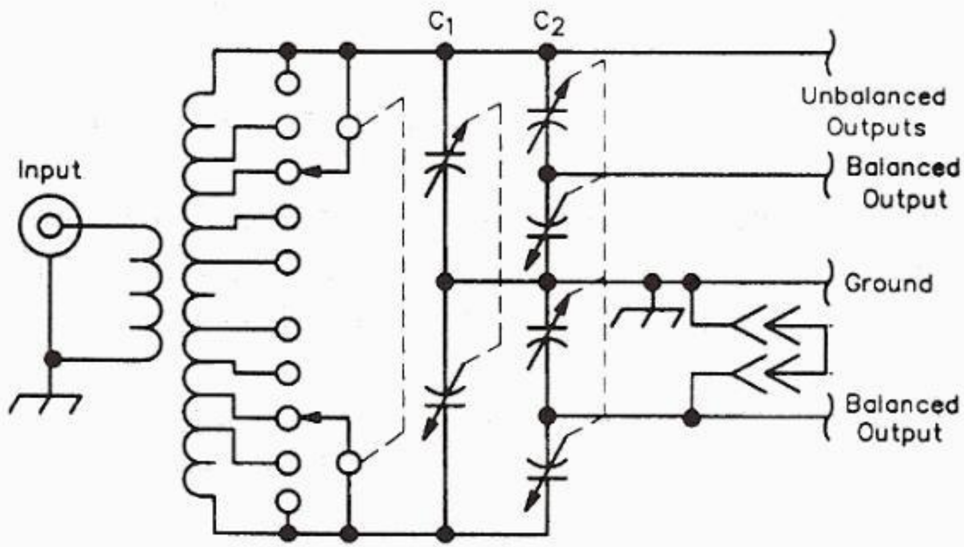


Johnson Viking MatchBox: **Balanced** Antenna Tuner

C1 tunes to **resonance** with band switch (80-10m)

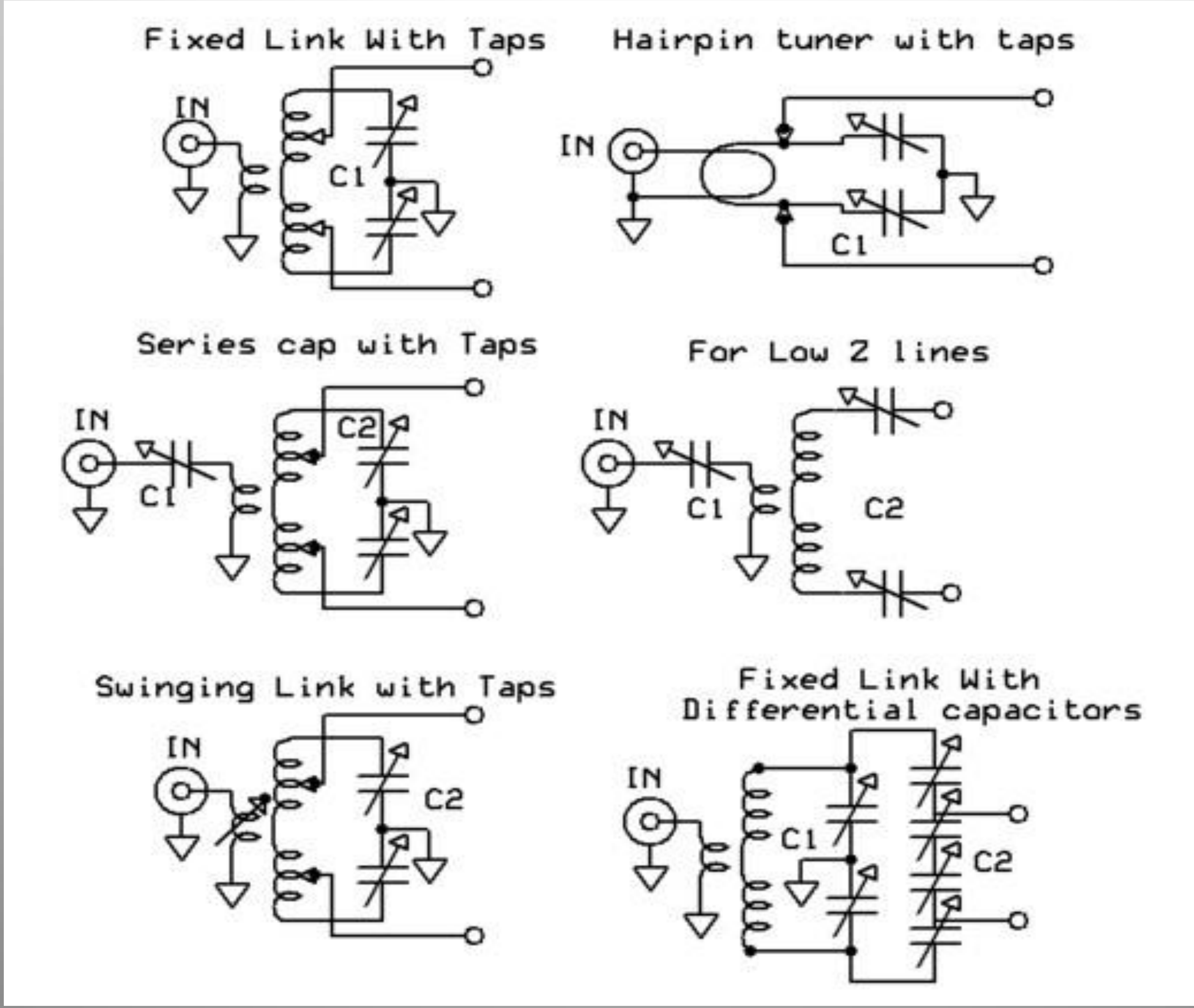
C2 matches **impedance** (voltage divider)

MATCHBOX ANTENNA TUNER



C1 is a split stator capacitor and C2 is a dual differential capacitor. The top unbalanced output connection is used for high-impedance unbalanced loads, and the other is used for low-impedance unbalanced loads. In the latter case, the unused balanced load connection is grounded.

Various “balanced” tuner designs



An Antenna Tuner for 440 MHz uses smaller value L and C

Rigs with built-in antenna tuners
(more properly called trimmers)
Can MATCH a 3:1 SWR (16 ohm – 150 ohm)

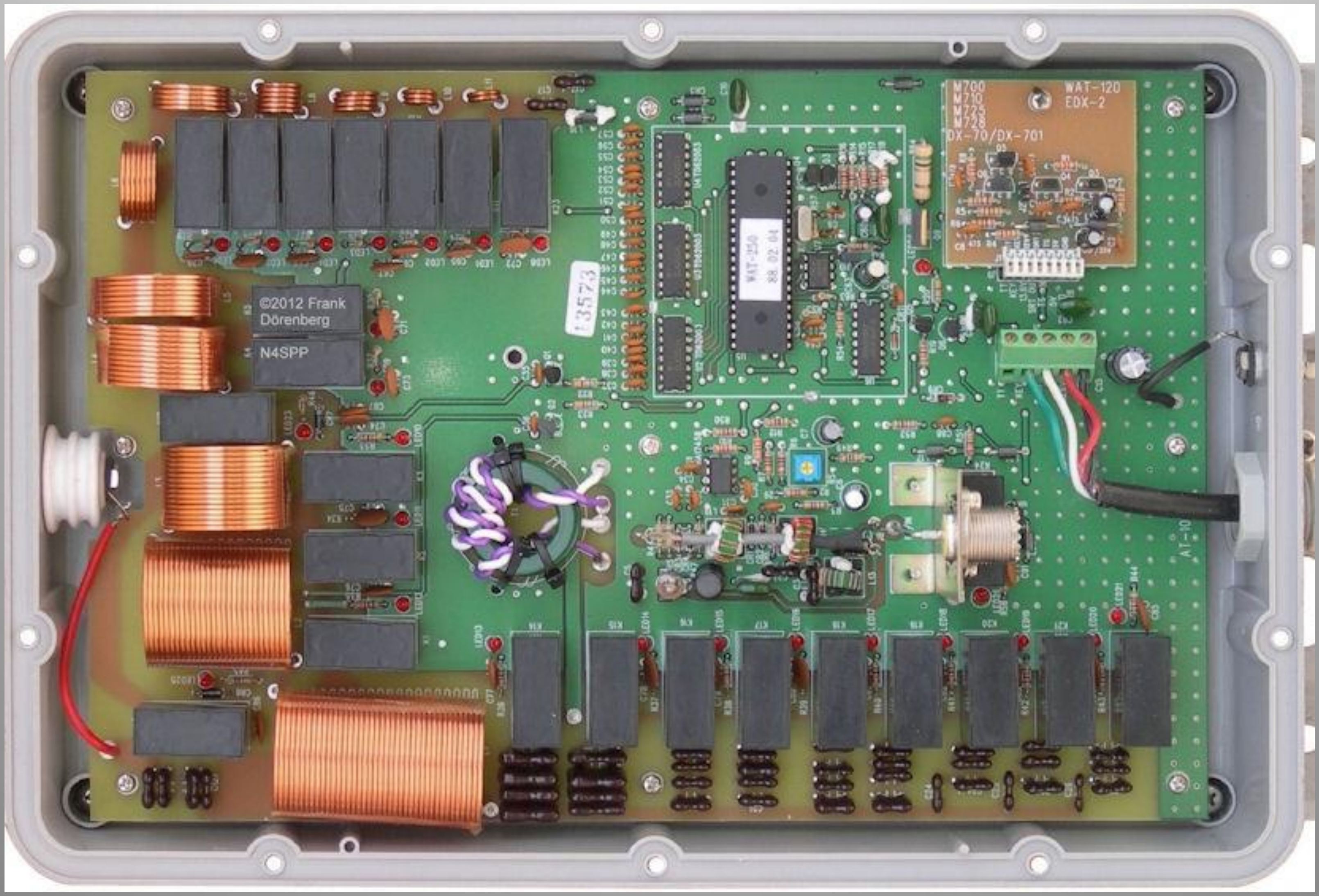
Automatic Antenna Tuners

Uses series and parallel capacitors and inductors to arrive at the “optimum” **conjugate match**

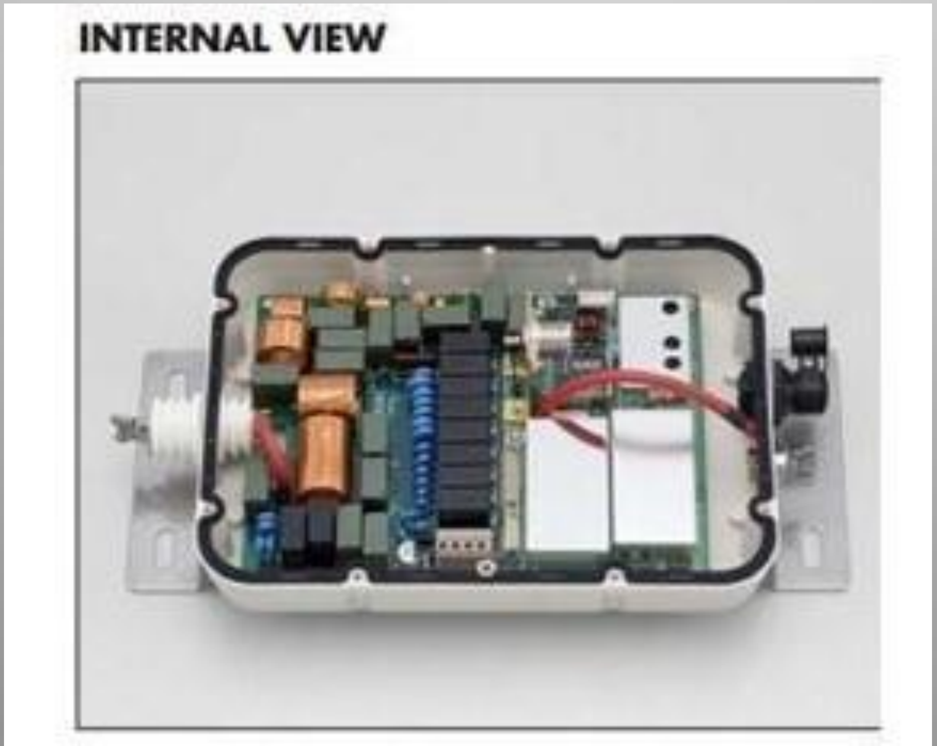
Cancel any reactance and transform impedance to 50 ohms

Memories store the best match of L,C at various frequencies

Combinations of coils (L) and capacitors (C) can match up to a 10:1 SWR




DANGER
HIGH VOLTAGE


INTERNAL VIEW

Do antennas need to be resonant
to radiate well?

NON-RESONANT (balanced)

all-band, very efficient, HF antenna (80-10 m)

with 130 ft long wire antenna, fed with **low-loss ladder line**

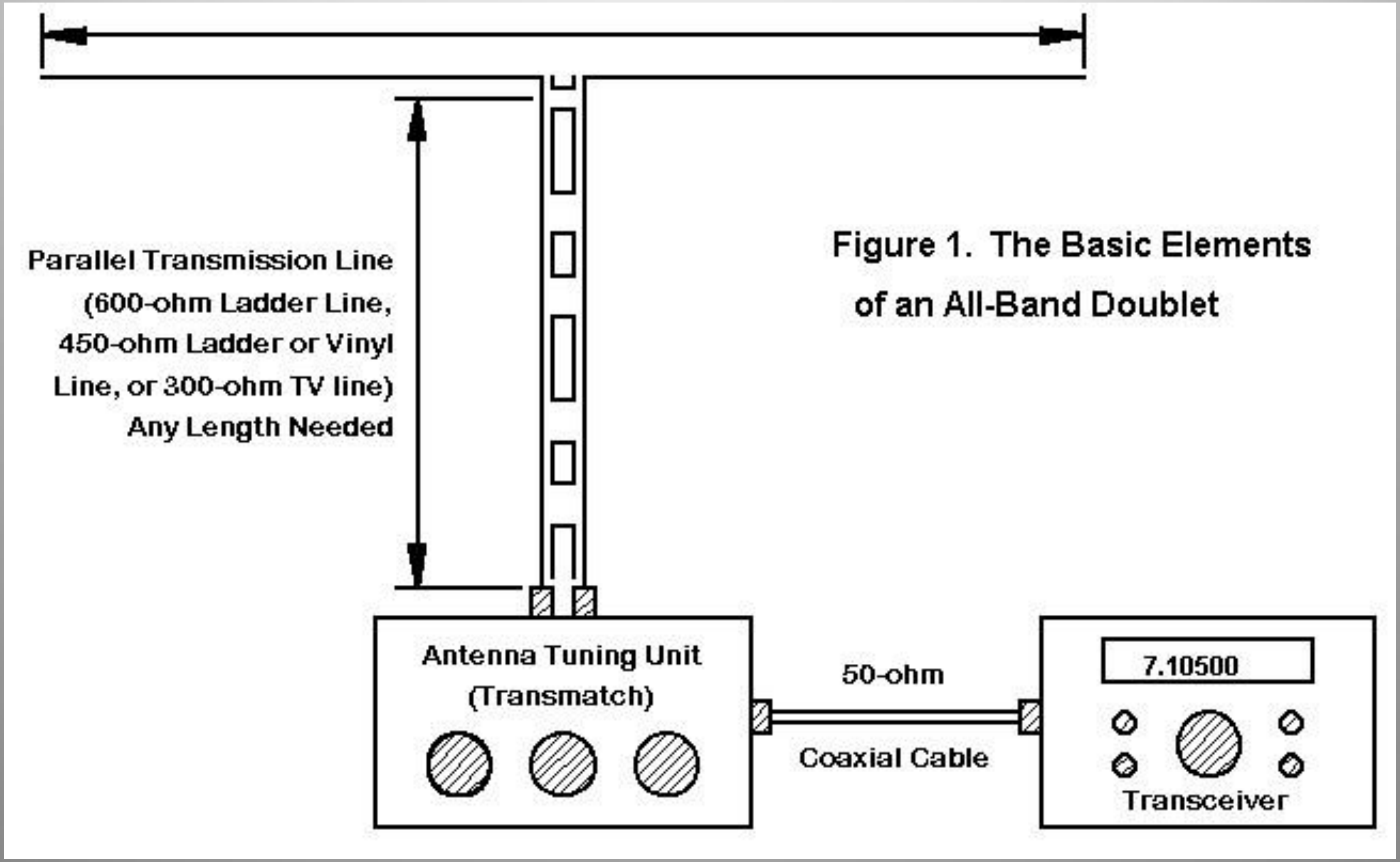
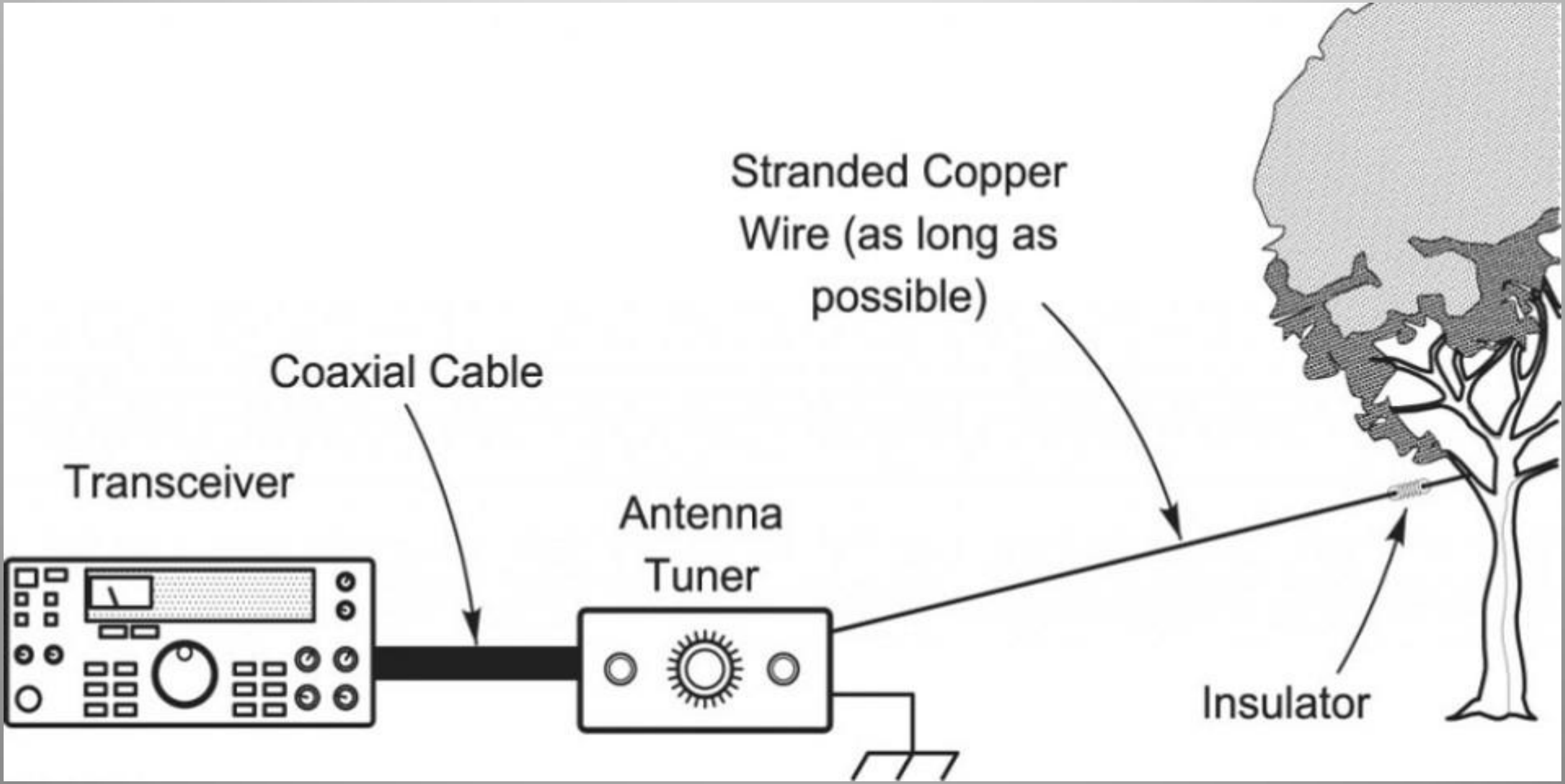


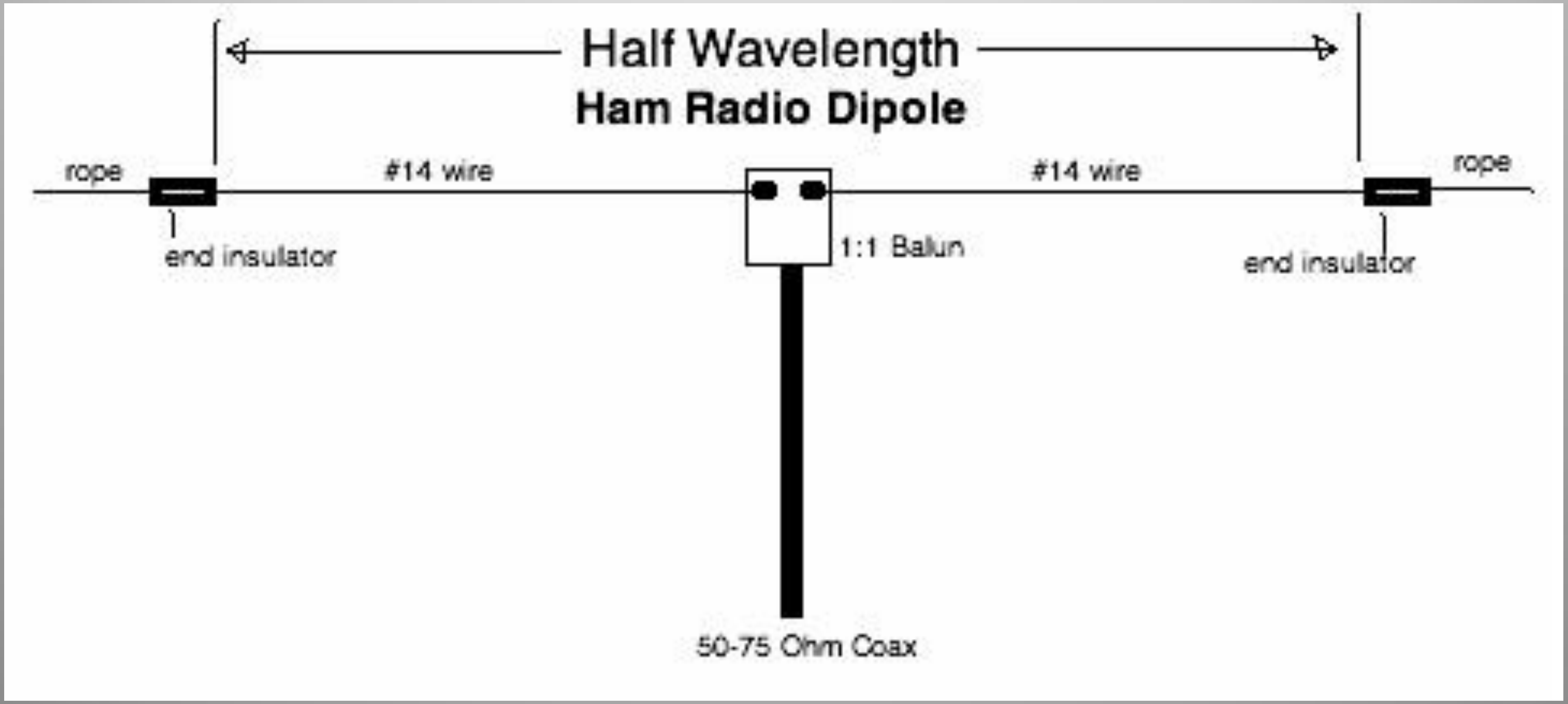
Figure 1. The Basic Elements of an All-Band Doublet

Non-Resonant, **random length** 100 ft long "long wire"
can be an efficient antenna on 80-10m
when worked against an RF ground

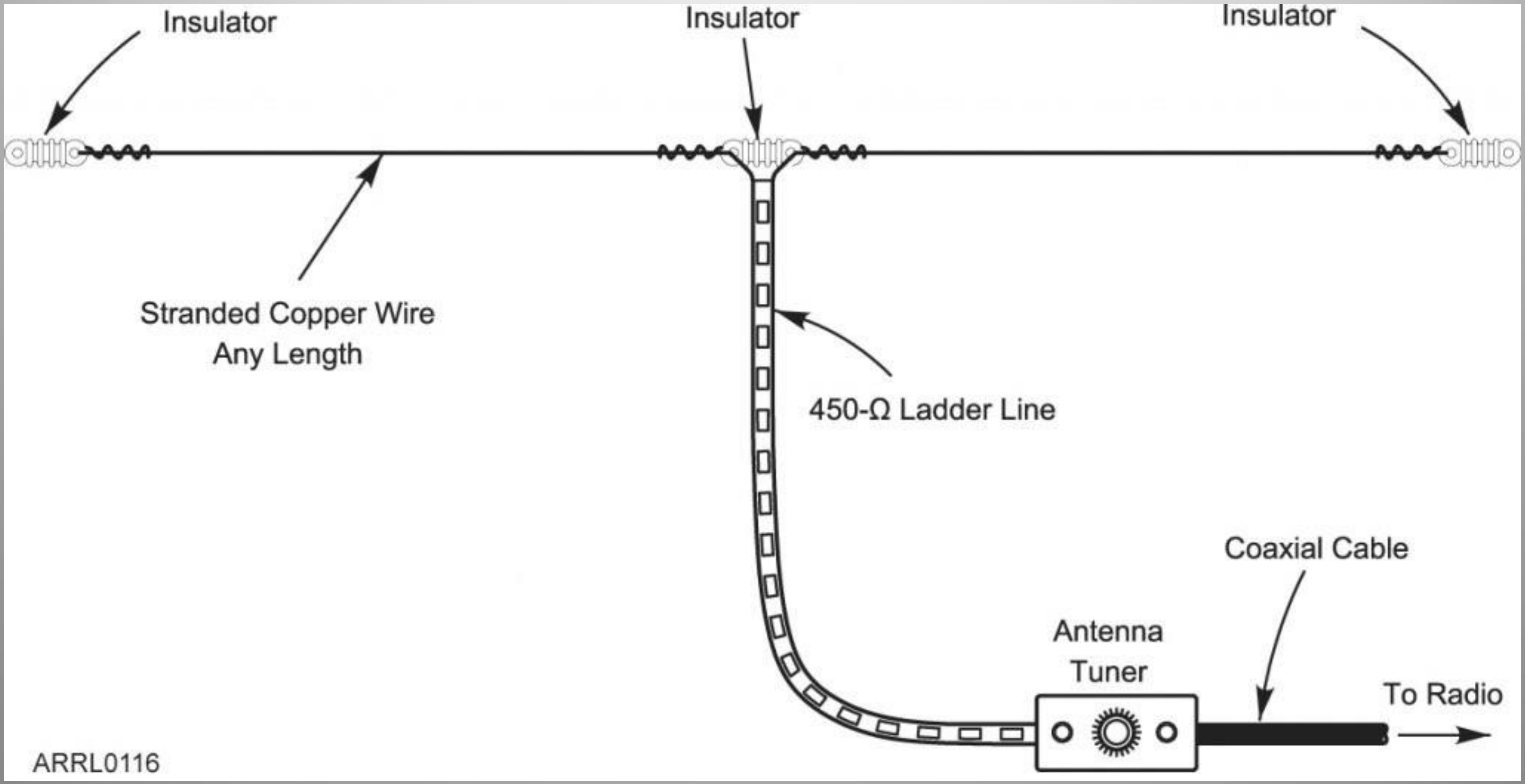


Only at integer multiples of the **resonant length** **L = 468/f** will the antenna have <u>zero reactance</u>

At **ODD** multiples of ½ λ the impedance is **LOW** (50-100 ohms)
At **EVEN** multiples of ½ λ the impedance is **HIGH** (1000 ohms)



IF the antenna tuner is operating properly **where** is the SWR equal to 1:1 (perfect match)



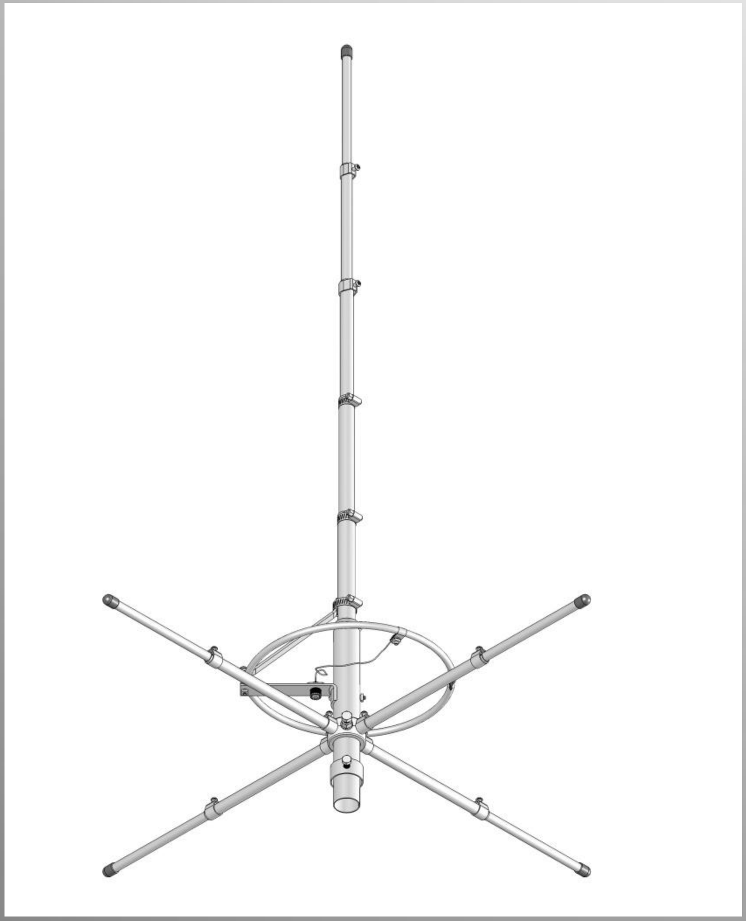
Is a 1:1 SWR a guarantee of a great antenna?

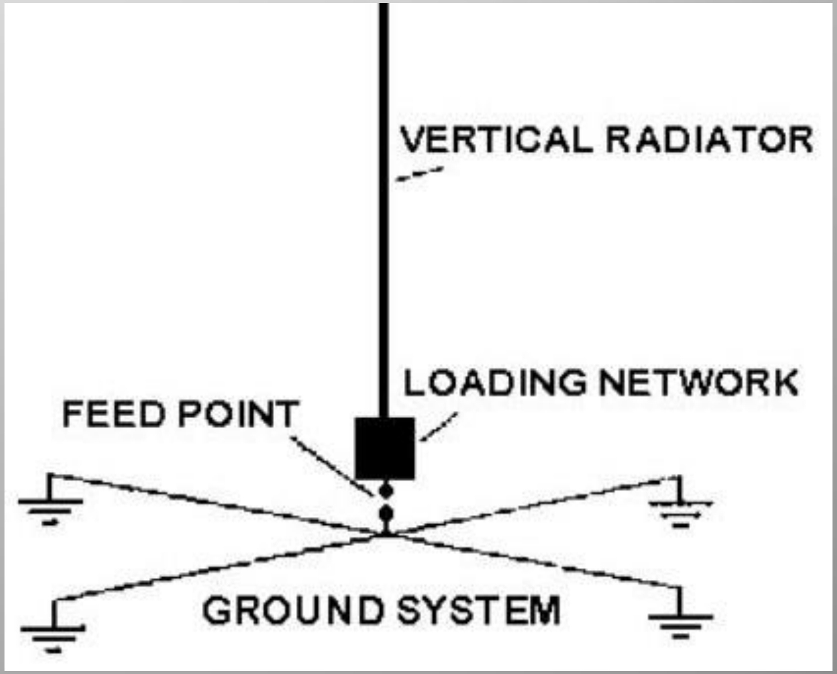
Even if you can achieve a 1:1 match **in your SHACK**

The feed line **to the antenna** still has the
SAME HIGH SWR as it had before you introduced
the antenna tuner

The "tuner" ONLY allows your transmitter to
"see" a 50 ohm resistance (impedance) and to deliver
its FULL power to the feed line

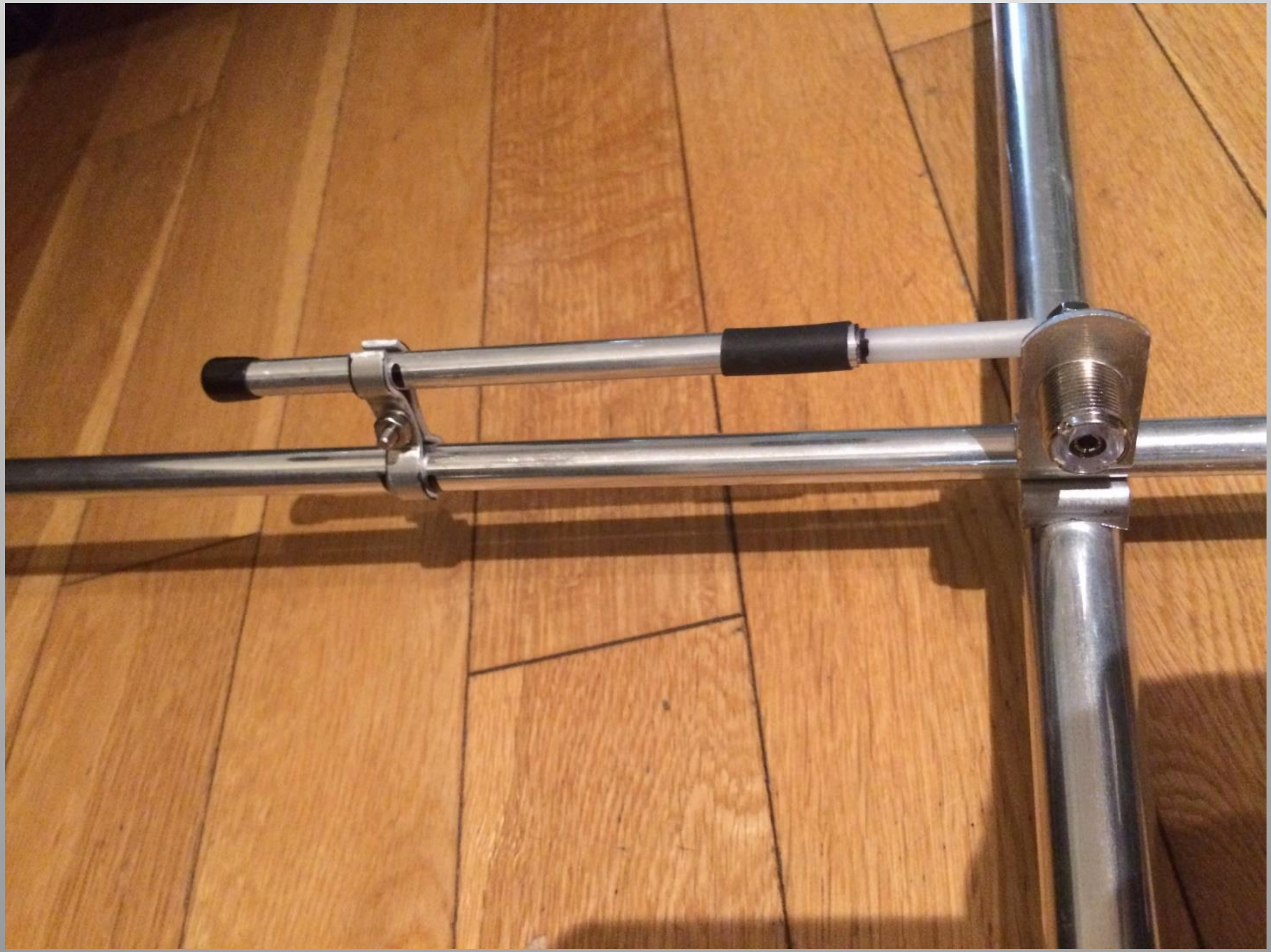
Perhaps the reactance can be cancelled right AT the antenna terminals



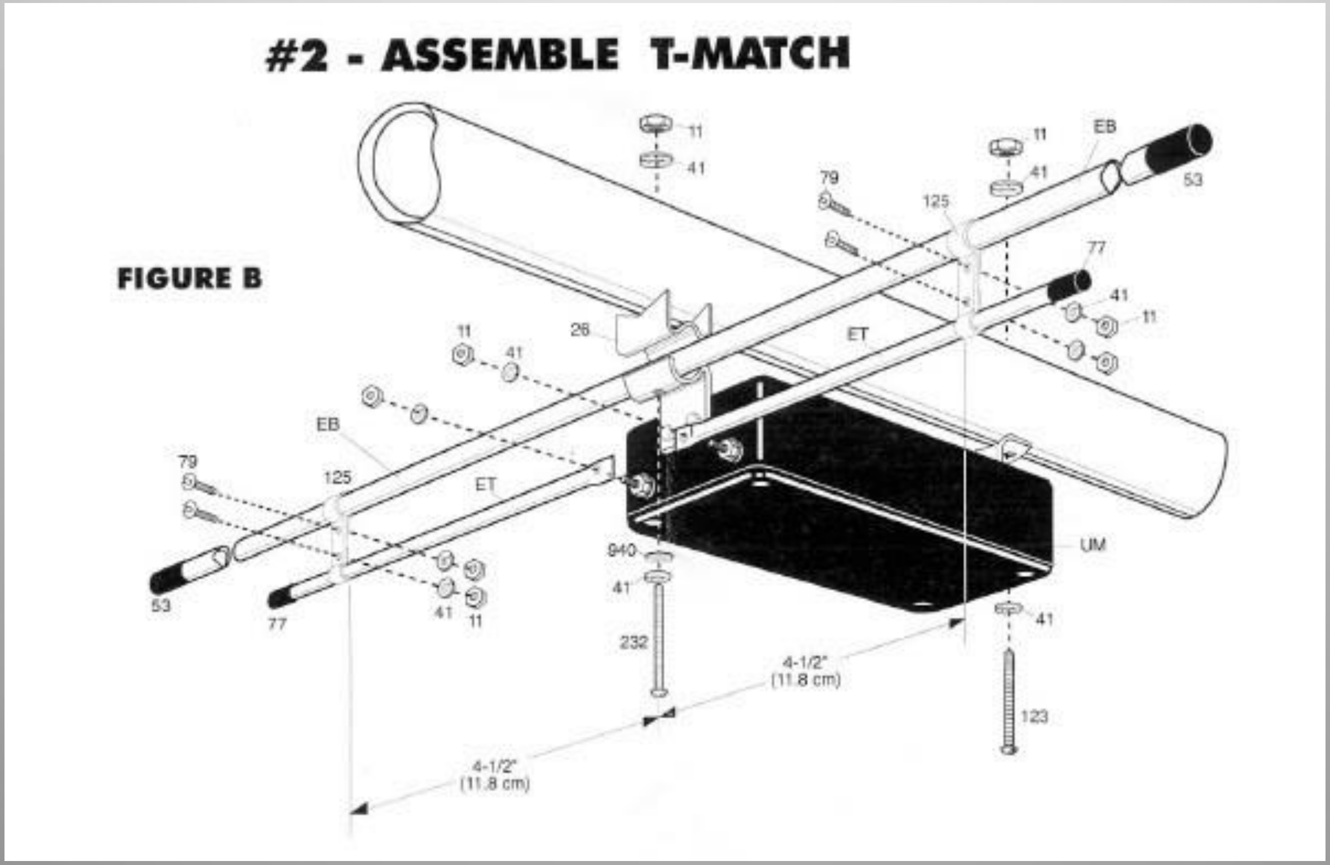


Base loading / matching coil

Cushcraft GAMMA match 2m beam
30 ohm to 50 ohm



T-Match common on beams (balanced wrt ground on boom)



J-POLE coax (50 ohm) to higher impedance

I'm glad my antenna SYSTEM is resonant