AD5X

Determining Short HF Antenna Efficiency

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Short Antenna Efficiency

Search for the Ideal Antenna

- Unobtrusive
- Very Small
- Cheap
- 100% Efficient

TANSTAAFL

- ***T***here ***A***in't ***N***o ***S***uch ***T***hing ***A***s ***A*** ***F***ree ***L***unch
- Everything is a Tradeoff

Short Antenna Trade-offs

Positive

- Small
- Light
- Easy to Transport
- Less Expensive
- XYL-Friendly (Maybe most important!)
  - I.e., not as much of an eye-sore

Negative

- Efficiency

AD5X Why an Efficiency Penalty?

Radiation Resistance is what you want to get your power into to get it radiated. However…

- Radiation Resistance ≈ Height^2
- Radiation Resistance ≈ Frequency^2

Therefore, as Height and Frequency are reduced, the Radiation Resistance Plummets!

- So Who Cares – Just match to the lower radiation resistance, right?

Efficiency Loss

- Theoretically, matching to a low impedance is no problem.
- But, if there are other losses in low impedance systems, your efficiency will suffer.
- And there <u>ARE</u> other losses.
  - Coil Losses
    - matching and loading coils
  - Ground Losses
    - Because you won't have a perfect ground system

Simple Antenna Equations

First let's consider some simple equations.

- Capacitance of a short antenna
  - C_b = 3.75 pf/ft (base loading)
  - $C_c = 1/2C_b$ (center loading)

- Radiation Resistance of a short antenna (< 1/8λ)
  - Base Loading: $R_{Rb} = 2.73 \text{ X } 10^{-6} (hf)^2$
  - Center Loading: $R_{Rc} = 6.7 \text{ X } 10^{-6} (hf)^2$

Where: h = height in inches, f = frequency in MHz

Simple Equations (Cont.)

- Antenna Q = $360f_{MHZ}/(2{:}1\ VSWR\ BW_{KHZ})$
- Inductance L = $1/[(2\pi f)^2 C]$
  - Not totally accurate for calculating loading coil. But very close.
  - Tends to give a slightly greater inductance value than necessary.
- Coil Q = $2\pi fL/R_L$
- Coil Loss = $R_L = 2\pi fL/Q$

Simple Equations (Cont.)

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- R_T = Total System Resistance ($R_R + R_L + R_G$)
  = $2\pi fL$/Antenna Q
- Ant. Efficiency (%) = $[R_R/(R_R + R_L + R_G)] \times 100$
  = $[R_R$/(Total System Resistance)] x 100
- Power Loss (dB) = 10 LOG $[R_R/(R_R + R_L + R_G)]$
  = 10 LOG $[R_R$/(Total System Resistance)]

Simple Example

8-Foot Base-Loaded 40 Meter Antenna, Coil Q = 300

- C_b = 3.75pf/ft x 8 ft = **30 pf**
- $L = 1/[(2\pi f)^2 C] = 1/[(2\pi 7.2X10^6)^2 (30X10^{-12})]$
  = **16.3 uhy**
- $R_L = 2\pi fL/Q = 2\pi(7.2)(16.3)/300 =$ **2.5 Ω**
- $R_{Rb} = 2.73 \text{ X } 10^{-6} (hf)^2 = 2.73 \text{ X } 10^{-6} (96x7.2)^2$
  = **1.3 Ω**
- High-Q Coil Loss is Almost *TWICE* the Radiation Resistance. With a **PERFECT** ground, you still lose 2/3rds of your power do to the coil loss! Your antenna is **34%** efficient!
- With 10 Ω of ground loss, your efficiency is only **9%**!

Simple Example (Cont.)

What Does Center Loading Buy You?

- $R_C = 6.7 \times 10^{-6} (hf)^2 = 6.7 \times 10^{-6} (96x7.2)^2$
  $= 3.2\ \Omega$
- $R_L = 2\pi fL/Q = 2\pi(7.2)(32)/300 = \mathbf{5}\ \Omega$
- Radiation Resistance increases 2.5 times, but your coil losses double (twice the inductance).
  - With no ground losses, your efficiency is now **39%**.
  - With 10 Ω ground loss, your efficiency becomes **17.5%**.
- In the real world with finite ground losses, center loading generally doubles your antenna efficiency.

Loss vs Freq. vs Efficiency

- Losses get worse fast if ground losses and/or coil losses increase because of the low antenna radiation resistances.
- Things get much better as you go higher in frequency because the radiation resistance increases as **frequency^2** and so the other losses don't hurt you as much.
- Conversely, efficiency can get much worse when you go lower in frequency.

Determining Efficiency

- Measure the 2:1 SWR bandwidth of your antenna
  - Typically 30-80 kHz for a 7-foot long antenna.
- From the above, determine the antenna Q.
- Measure the antenna length and calculate the antenna capacitance
  - Using 3.75 pf/ft for base loading, 1.9 pf/ft for center loading.
- Calculate the inductance needed for resonating the antenna.
- Calculate the radiation resistance (base loaded or center loaded).
- Determine the Total System Resistance.
- Calculate the antenna efficiency.

AD5X Mobile Antenna Comparisons

Type	2:1 SWR BW (40m)
Carolina BugKatcher	30 kHz
Hustler "Standard"	40-50 kHz*
Hamstick	50 kHz
Outbacker	50 kHz
Big DK3	50 kHz
Hustler "Super"	50-80 kHz*

* From Data Sheets

AD5X Ex: Carolina BugKatcher

- Measure the 2:1 VSWR bandwidth of your antenna
  - 30 kHz
- From the above, determine the antenna Q.
  - Antenna Q = $360f_{MHZ}/(2{:}1\ VSWR\ BW_{KHZ}) = 360(7.2)/30 = 86.4$
- Measure the antenna length and calculate the antenna capacitance using 1.9 pf/ft (antenna is center loaded).
  - 7ft x 1.9 pf = 13.3 pf
- Calculate the inductance needed for resonating the antenna.
  - $L = 1/[(2\pi f)^2C] = 1/[(2\pi 7.2\text{x}10^6)^2(13.3\text{x}10^{-12})] = 36.74\ \mu\text{Hy}$

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Carolina BugKatcher (Cont.)

- Calculate the radiation resistance (center loaded).
  - $R_{Rc} = 6.7x10^{-6}\ (hf)^2 = 6.7x10^{-6}\ (84x7.2)^2 = 2.45\ \Omega$
- Determine the Total System Resistance.
  - $R_T = 2\pi fL/\text{Antenna Q} = 2\pi(7.2)(36.74)/86.4 = 19.24\ \Omega$
- Calculate the antenna efficiency.
  - Power Loss (dB) = $10\ \text{LOG}\ [R_R/(R_R + R_L + R_G)]$

    $= 10\ \text{LOG}(2.45/19.24) =$ **<u>-9 dB</u>**

Other Antennas

Antenna	40m 2:1 VSWR BW/Q	Length	C(pf)	L(uhy)	$R_R(\Omega)$	Eff.%	Loss
CBKatcher	30 kHz/86	7'(84")	13.3	36.74	2.45	12.7	-9 dB
Antenna B	50 kHz/52	7'(84")	13.3	36.74	2.45	7.7	-11 dB
Antenna C	80 kHz/32	7'(84")	13.3	36.74	2.45	4.7	-13dB

What are the actual ground losses?

- Carolina BugKatcher Coil Q Measured: 210

$R_L = 2\pi fL/Q = 2\pi(7.2)(36.7)/210 = 7.9\ \Omega$

$R_{Rc} = 6.7 \text{ X } 10^{-6}\ (hf)^2 = 6.7\text{x}10^{-6}\ (84\text{x}7.2)^2 = 2.45\ \Omega$

$R_T = 2\pi fL/\text{Antenna Q} = 2\pi(7.2)(36.74)/86.4 = 19.24\ \Omega$

$R_G = R_T - R_R - R_L = 19.24 – 2.45 – 7.9 = 8.9\ \Omega$ (typically 7-15 ohms)

160M Antenna Efficiency

- What type of efficiency does a home-brew center-loaded 160 meter antenna have?
- Measured Information
  - 1.2:1 VSWR at resonance (1817 KHz).
  - 2:1 VSWR Bandwidth = 10 KHz
  - Antenna length = 33 feet
- Assumptions
  - Antenna capacitance = 62 pf
    - 1.9 pf/ft
  - Air wound coil has Q_U = 300

AD5X 160M Efficiency (10 kHz BW)

- $L = 1/[(2\pi F)^2 C] = 1/(2\pi 1.82\text{x}10^6)^2(62\text{x}10^{-12})$
  $= 123\ \mu Hy$
- $R_L = 2\pi FL/Q_U = 2\pi 1.82\text{x}123/300 = 4.7\Omega$
- $R_R = 6.7\text{x}10\text{-}6(h_{in}F_{MHz})^2 = 3.5\ \Omega$
- $Q_L = 360F_{MHz}/(2{:}1\ \text{SWR BW}_{kHz}) = 360\text{x}1.82/10$
  $= 65.5$
- $R_{Total} = X_L/Q_L = 1407/65.5 = 21.5\ \Omega$
- $R_G = R_{Total} - R_L - R_R = 21.5\text{-}4.7\text{-}3.5 = 13.3\ \Omega$
- **Efficiency = 3.5/21.5 = 16%**

Base-loaded 160M Antenna

- What would the efficiency be if this antenna were base-loaded?
- $R_R = 1.3\ \Omega$
- $R_L = 2.35\ \Omega$
- Half the inductance has half the loss
- $R_G = 13.3\ \Omega$
- Efficiency = $R_R/(R_R + R_L + R_G) = 1.3/17$

  = **8%**

AD5X Auto-Tuners & Short Antennas

- Auto-tuners provide flexibility
  - You don't have to re-tune antenna every few KHz.
- Auto-tuner must be located directly at the base of a <u>non-resonant</u> antenna for best operation.
  - The auto-tuner is now the loading coil of a base-loaded short antenna.
- Auto-tuner should be connected to the base of the non-resonant antenna with a very short piece of wire – NOT COAX.

Auto-tuners (Cont.)

- Unfortunately, most auto-tuners do not have hi-Q inductors.
  - Auto-tuner inductors are typically close-wound inductors with much lower Q than the air-wound inductors often used as the base loading coil.
  - Your losses will be higher due to the low-Q auto-tuner inductors.
- So again, TANSTAFFL
  - You are trading off efficiency for QSY convenience.

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Auto-tuners (Cont.)

- Coax interconnects from an antenna tuner to a non-resonant antenna lead to very poor efficiency.
  - A short antenna capacitance ~ 30 pf (depends on length).
  - A one-foot length of coax cable has about the same capacitance.
- So you will shunt the antenna capacitance plus radiation/loss resistances with a similar amount of capacitance and loss resistance.
- This loss resistance could be even lower than the loss-plus-radiation resistance of the antenna
  - You could be throwing away half of your power or more, just by putting a 1-foot section of coax between the tuner and non-resonant antenna!

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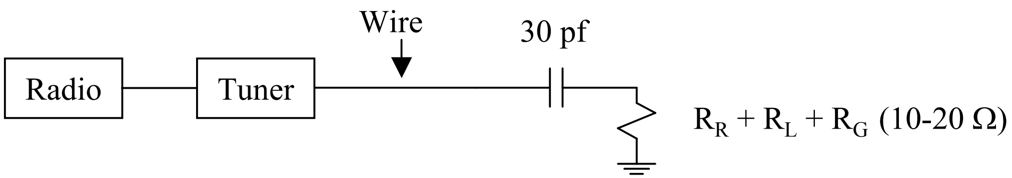
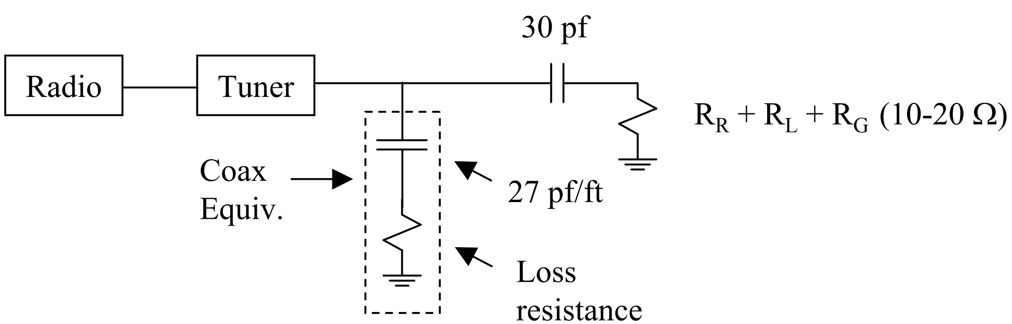
Auto-tuners (Cont.)



Tuner with short wire interconnect



Tuner with 1-ft coax interconnect

Build Efficient Short Antennas

- Use 3/8” diameter brass rods from your local hardware Store.
- Or 3/8” or ½” diameter aluminum tubing from Texas Towers or your local hardware store.
  - You can solder to aluminum with aluminum solder paste from www.solder-it.com.
- Make brass coupling interconnects for the rods and coils.
  - Use 1/8 NPT brass nipples and couplings.
  - Ream out couplings (use 3/8” drill bit) to fit over 3/8” diameter brass rods and wood/fiberglass insulators.

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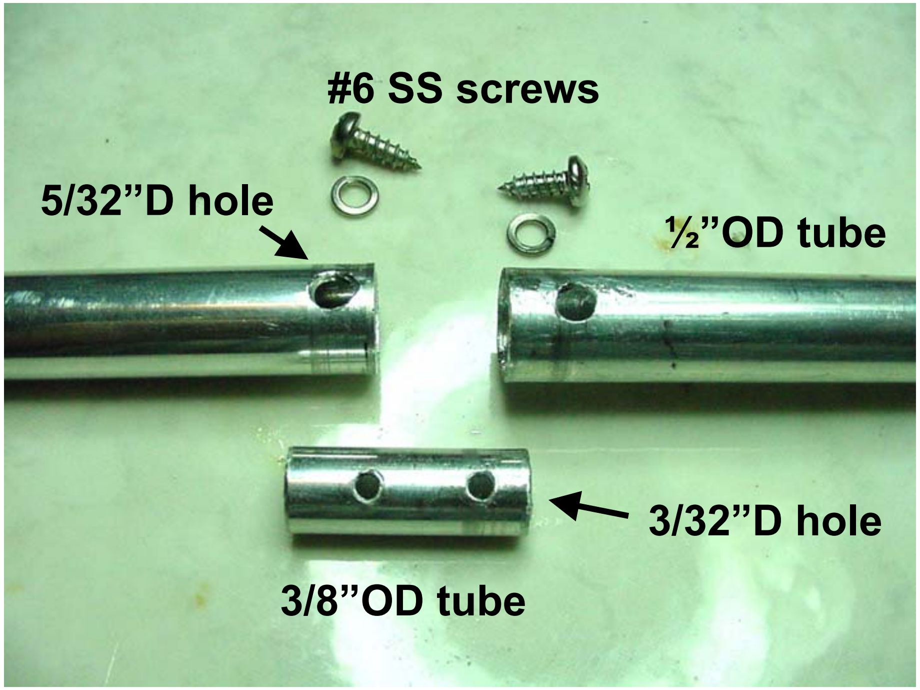
Joining Shorter Tubes



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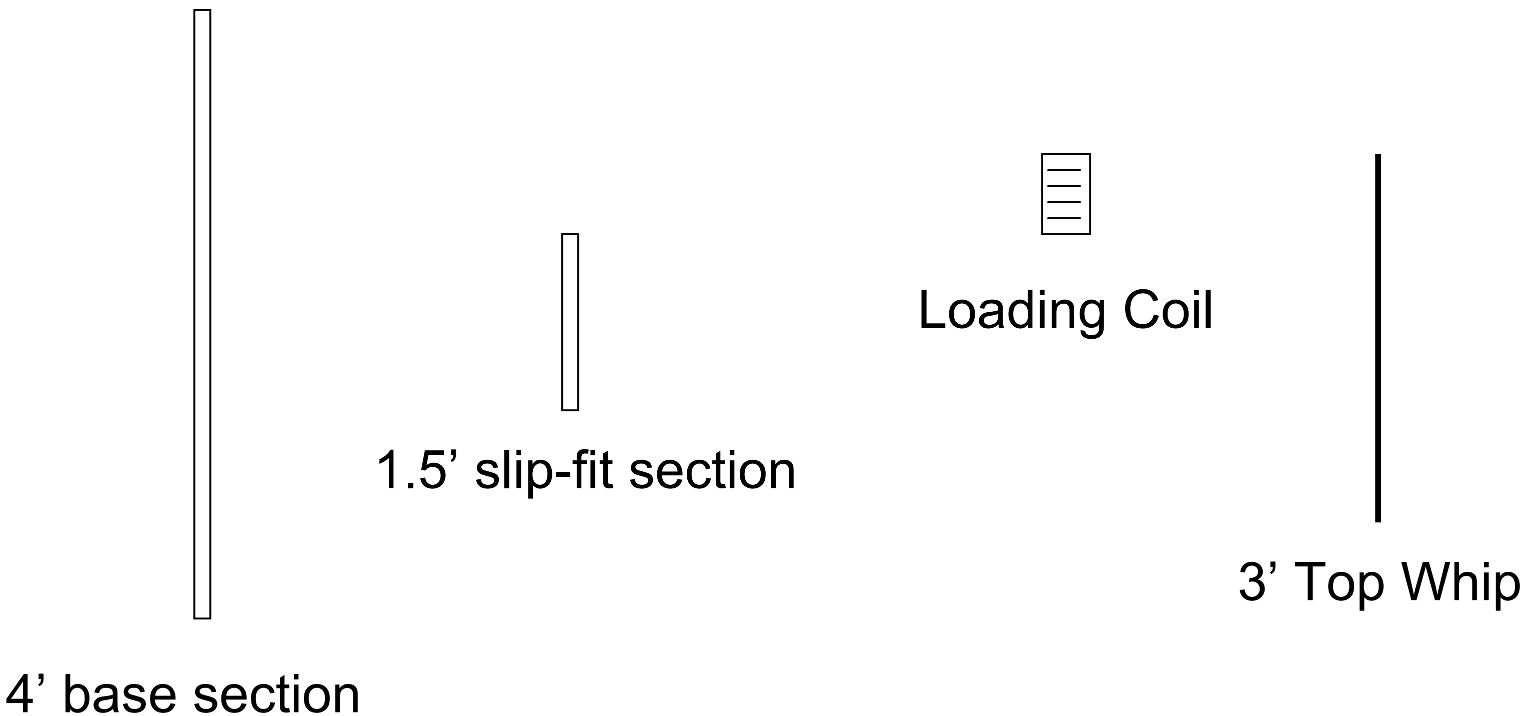
8-ft Mobile Antenna



Nipples, Couplings, 3/8x24 Studs

1/8NPT Nipple & Coupling

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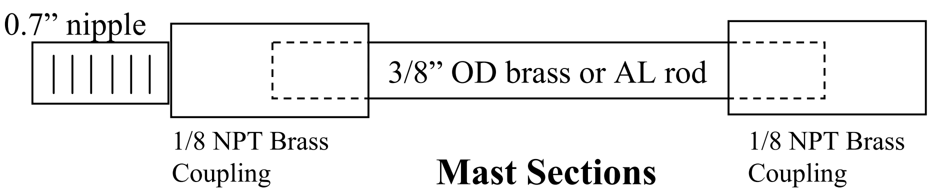
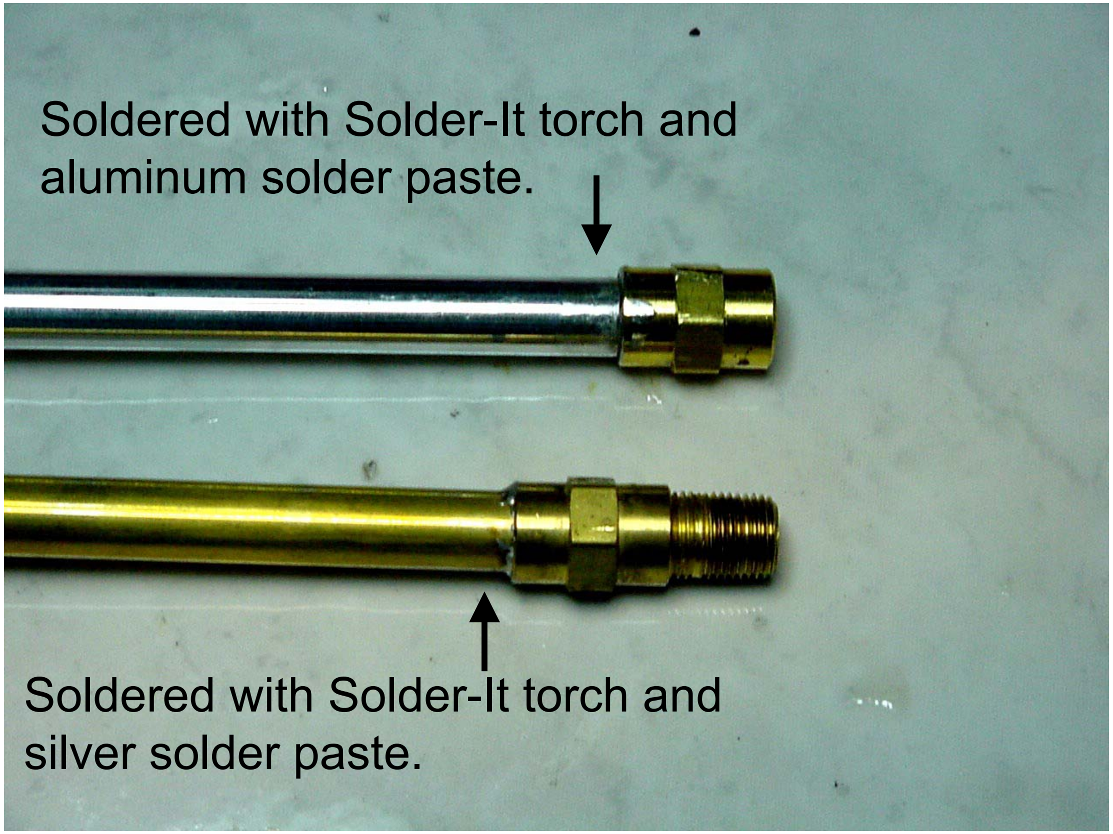
3/8" Diameter Mast Details





Alternative Attachments

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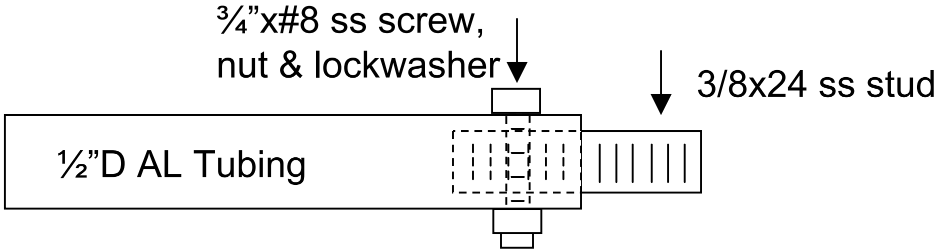
½”D Mast Details (Base)



½”D Mast Details (Top)

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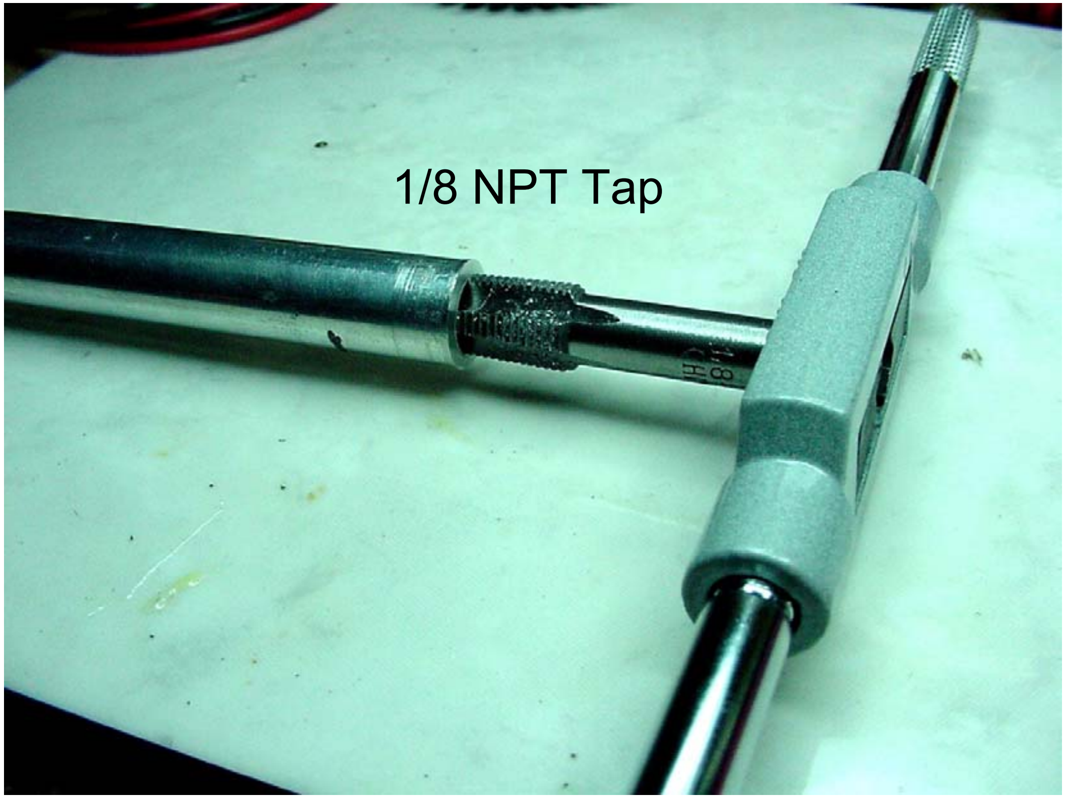
Harbor Freight 39391-0VGA Tap & Die Kit @ $12.99

<u>Sizes</u>: 4-40, 6-32, 8-32, 10-32, 10-24, 12-24, 1/4-20, 1/4-28, 5/16-18, 5/16-24, 3/8-16, 3/8-24, 7/16-14, 7/16-20, 1/2-13, 1/2-20, 1/8" NPT pipe tap.



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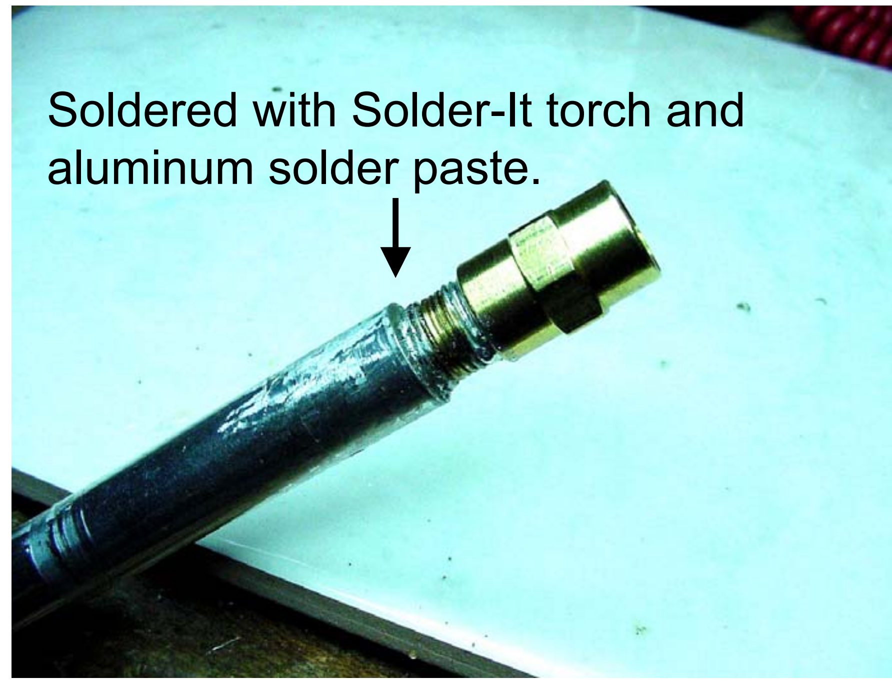
½”D Mast Details (Top)



Butane Torches

SolderPro 50/70/100/120
- Solder-It Company

SolderPro 50
- ACE Hardware
- Radio Shack
- Fry's Electronics

Silver Solder Paste
- Solder-It Company
- Radio Shack

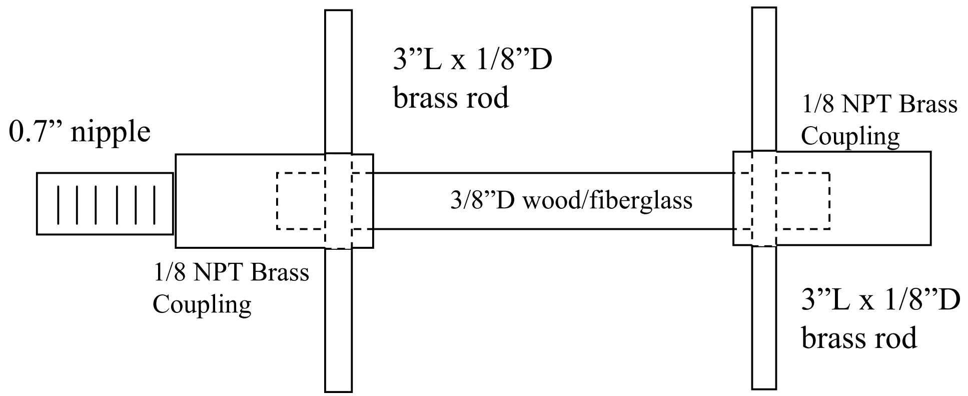
Aluminum Solder Paste
- Solder-It Company

Building Loading Coils

- Use 3/8" diameter wood dowel or fiberglass rod for the coil support.
- ¼"D fiberglass Bicycle Flags are also good.
  - Use ¼" compression-to-1/8 NPT Male/Female brass adapters
  - ***Be careful when working with fiberglass!***
- B&W 3027 Coil (~60 uHy)
  - 2"D x 10"L
  - Surplus Sales of Nebraska (www.surplussales.com)
  - $15 ea
- MFJ-404-008 (~60 uHy)
  - 2.5"D x 5"L
  - $15 ea.

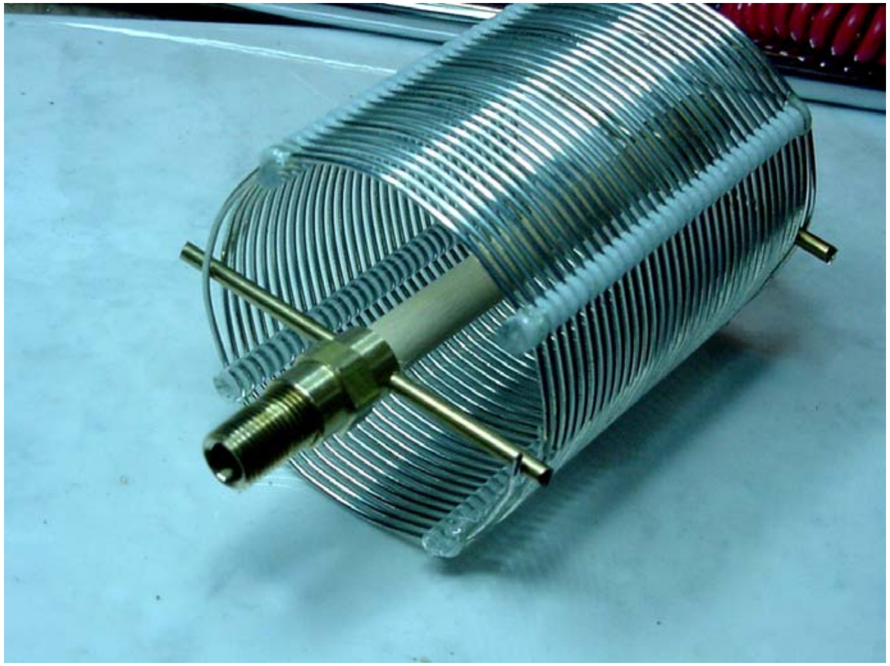
Note: Reinforce ends of coils with Home Depot 2-part quick setting clear epoxy.

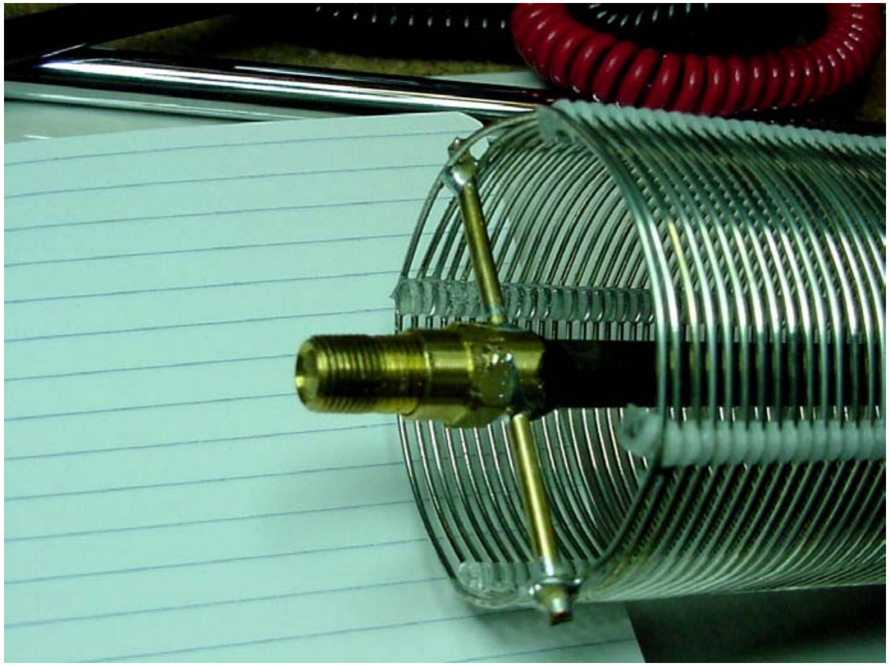
AD5X 3/8"Dia. Rod Coil Support



Coil Support Section

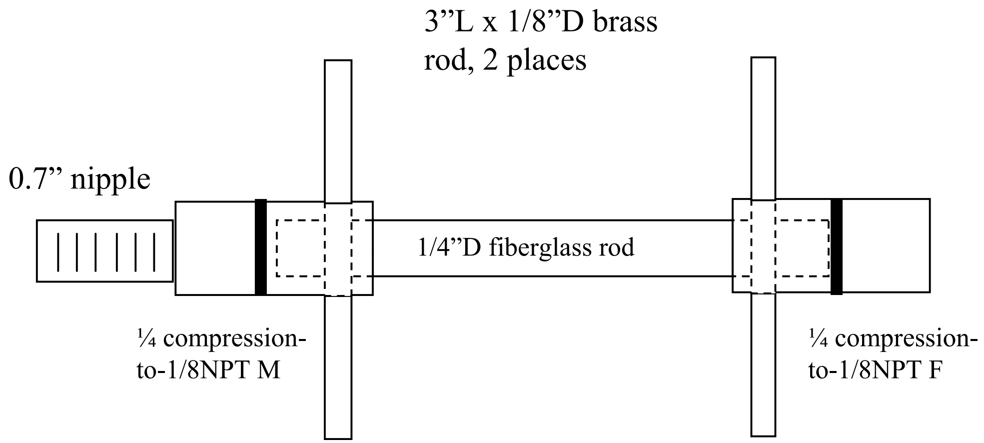
Coil Details





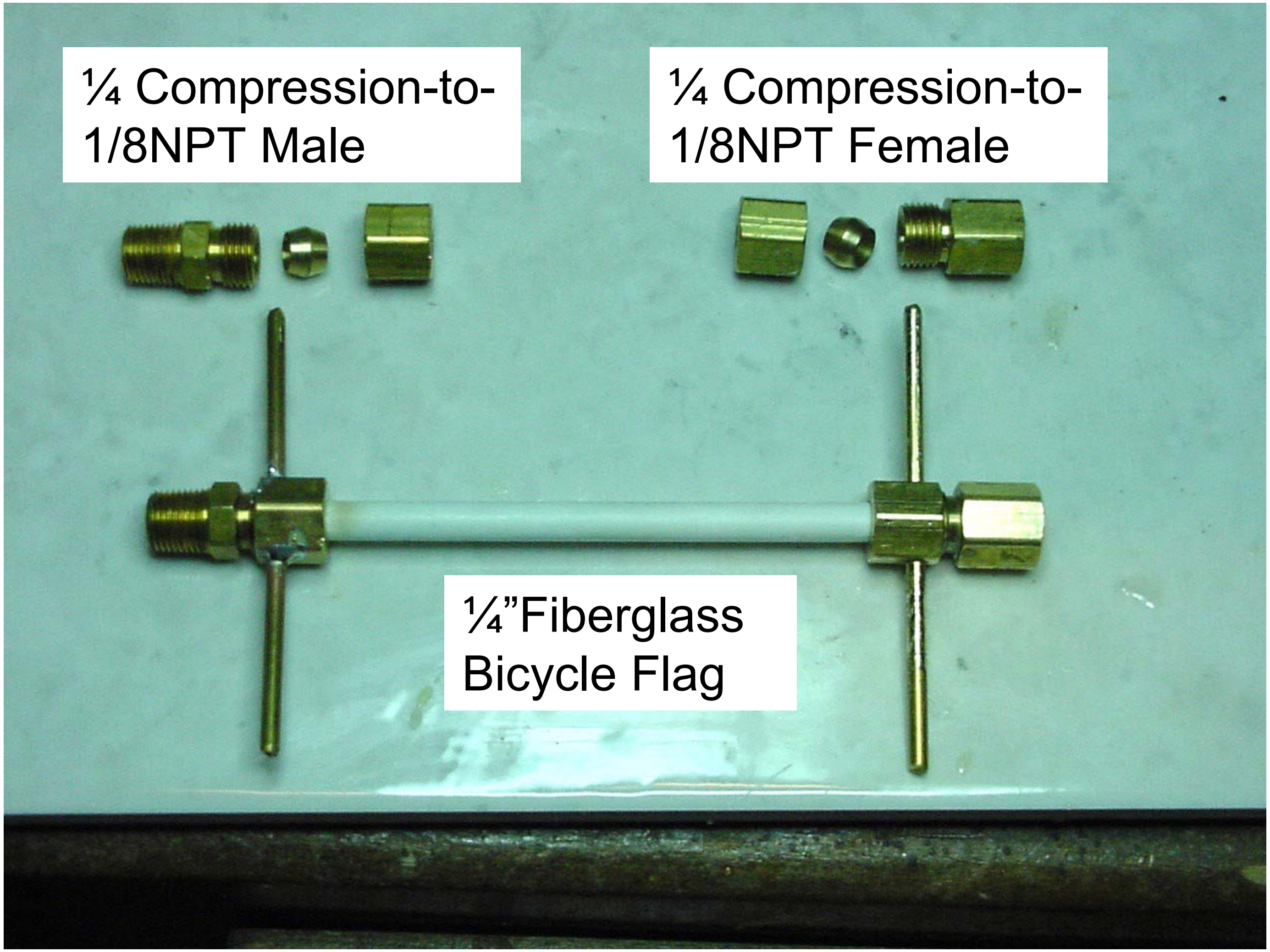
Coil: MFJ-404-008 @ $14.95
2.5"D x 5"L

AD5X ¼" Fiberglass Rod Coil Support



Coil Support Section - Bicycle fiberglass rod

¼" Fiberglass Coil Support



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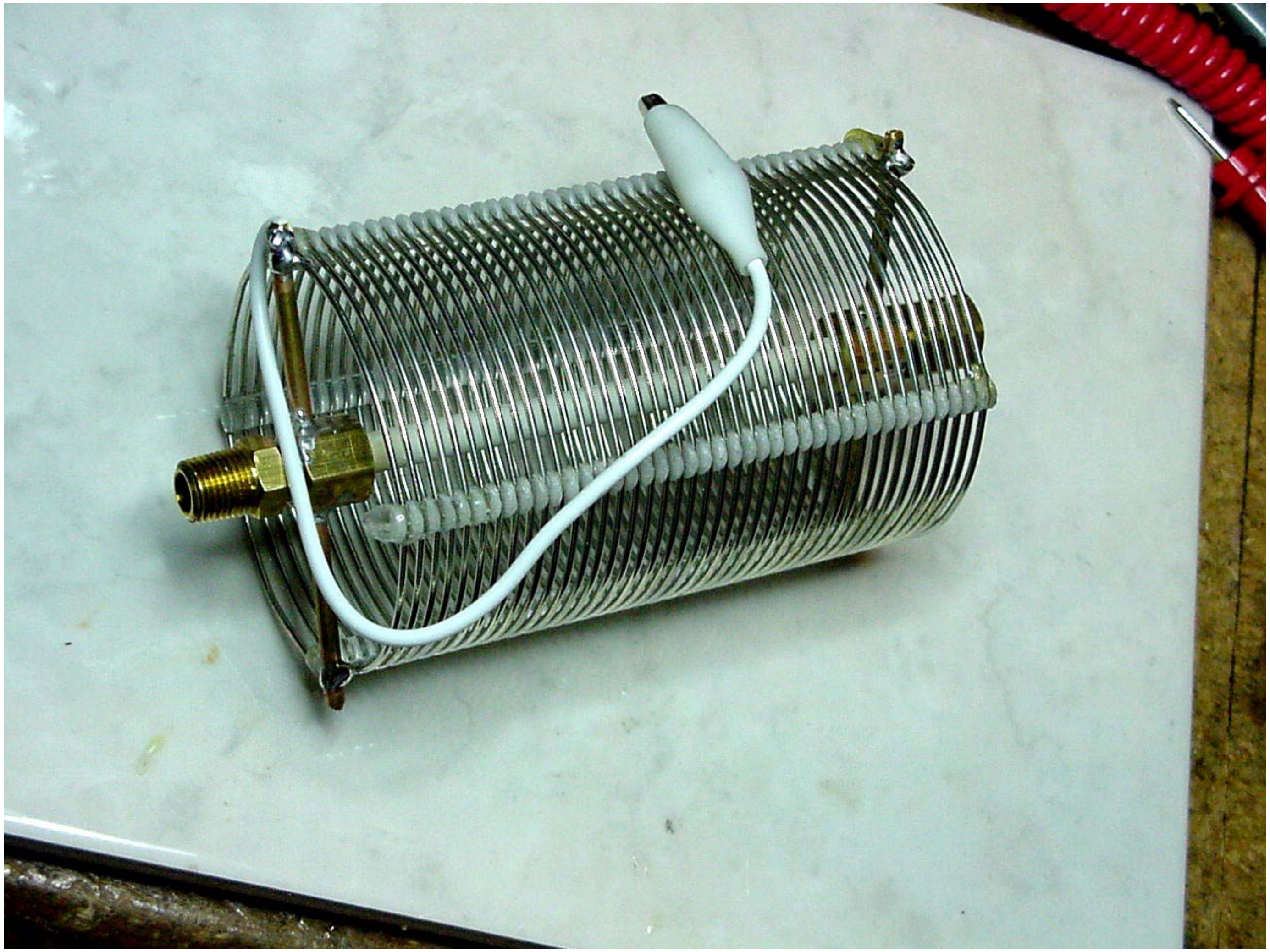
¼" Fiberglass Support Coil



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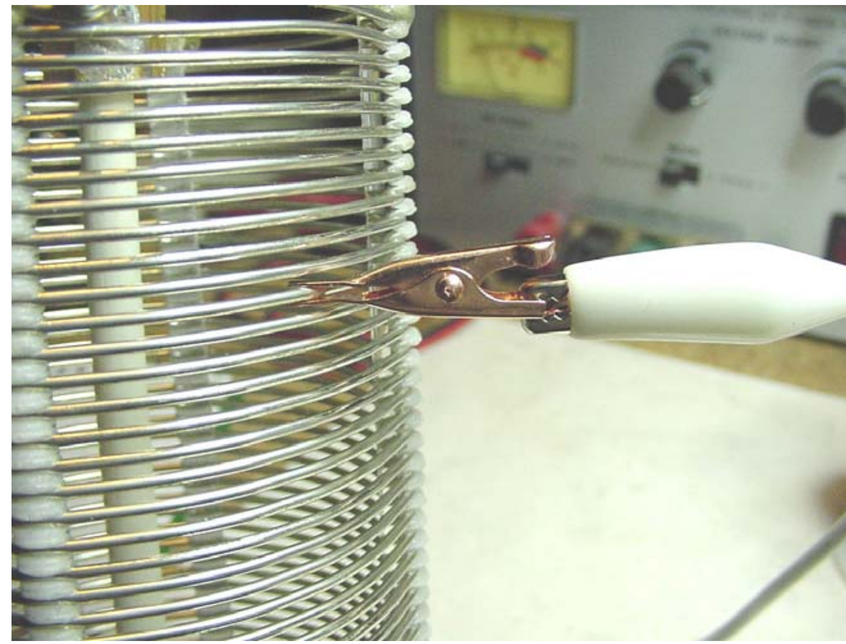
Find the Tap Point



Final Tap Point

Build your Own Coil

Items needed:

- Desired PVC pipe form (OD and length)
- Nylon Edge Trim (8-TPI)
  - McMaster-Carr 85085KB, $10.29 for 25x12-3/4” strips
- 14 Gauge bare copper wire
  - McMaster-Carr 8873K51, $10.20 for 80-feet
- Tie Wraps
  - To hold ends of Nylon Edge Trim to PVC pipe
- Hot Glue

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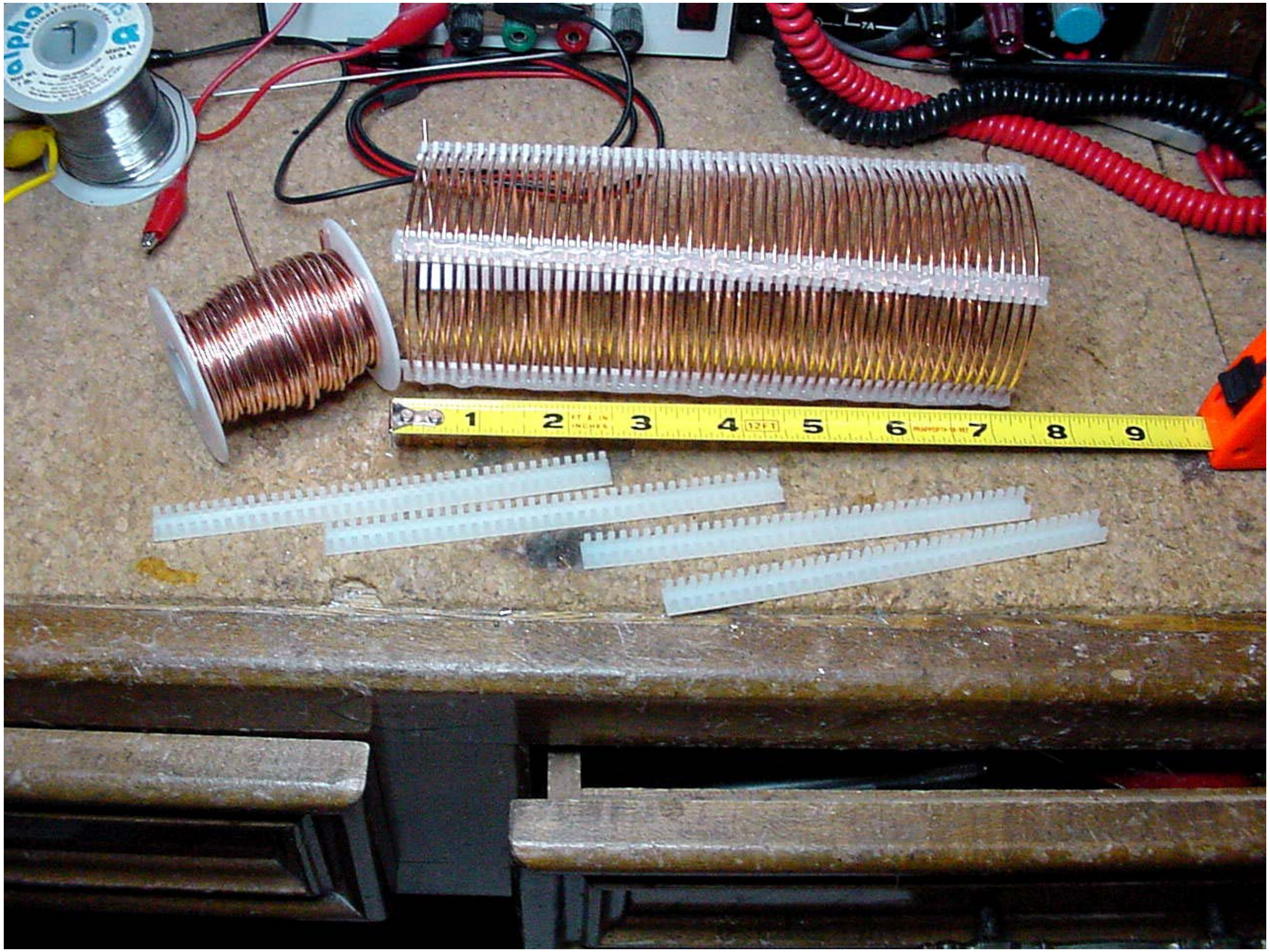
Build Your Own Coil



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Build Your Own Coil

$L(uhy) = d^2n^2/(18d + 14l)$

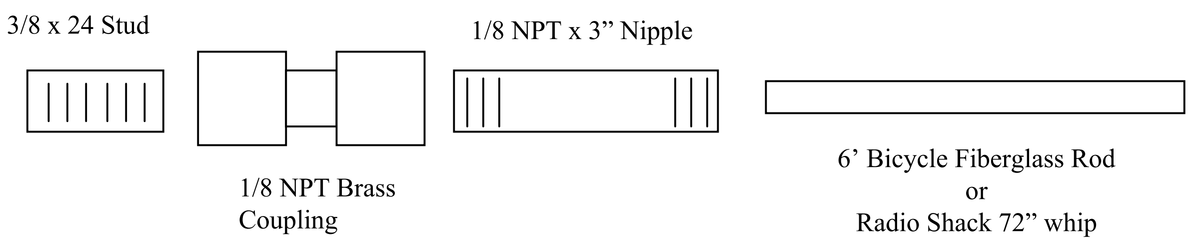
where:

- d = diameter (wire center to wire center in inches)
- n = number of turns
- l = length of coil (inches)

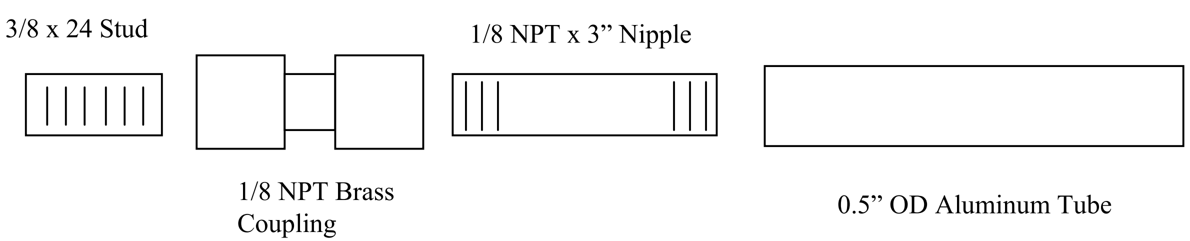
AD5X Top Whips or Dipole Elements

- 1/8 NPT Nipple has a 1/4” ID
  - Will take a 1/4” OD fiberglass bicycle flag pole
  - Or a Radio Shack 72” telescoping whip (RS270-1408)
    - May need to ream nipple with 9/32” drill bit
- 1/8 NPT Nipple will screw solidly into a 0.5” OD aluminum tube.
- To make a 3/8X24 stud, screw a 3/8X24 stainless steel bolt firmly into a 1/8 NPT coupling. Then cut off the head of the SS bolt.

AD5X Top Whips or Dipole Elements



OR



Radio Shack 72" Whip Interface

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RS whip and 3/8 x 24 thread

Fixed and Sliding Whips

- Top whips can be made with 1/8” rods
  - 3-feet brass rod @ Home Depot for $2.29 each
  - 4-feet steel rod @ Home Depot for $1.19 each
  - 12-feet stainless steel rod from Jacob Schmidt
    - www.jschmidtstainless.com
    - 12-feet for $2, but shipping ~$10.
- Couplers made with 1/8 Compression-to-1/8NPT Male brass adapter
  - Drill out center hole to 1/8” diameter
  - Use compression collar for fixed whip
  - Throw away compression collar for sliding whip
    - Drill and tap brass adapter for #6 thumbscrew
    - And/or solder on #6 nut over tapped hole for extra support

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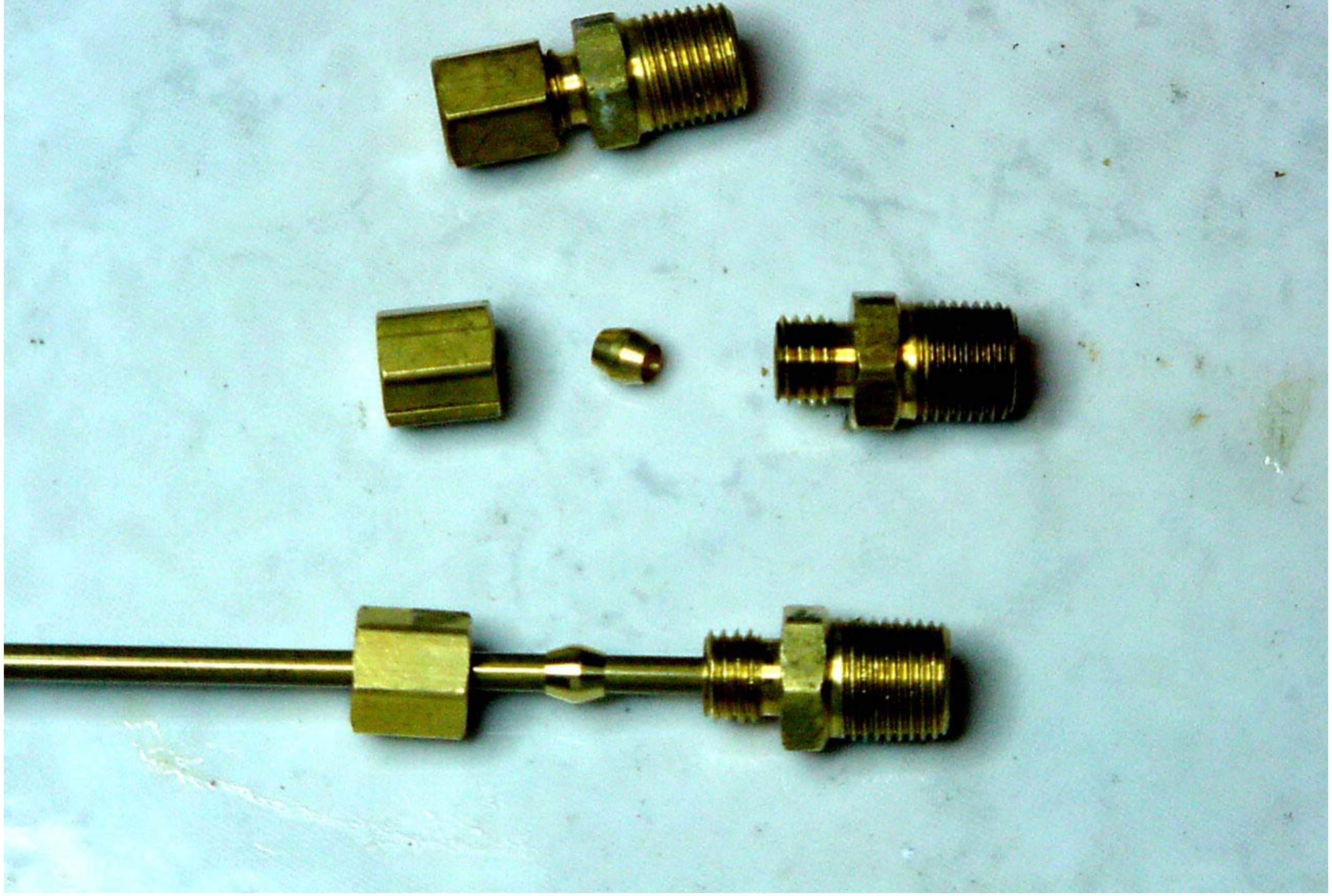
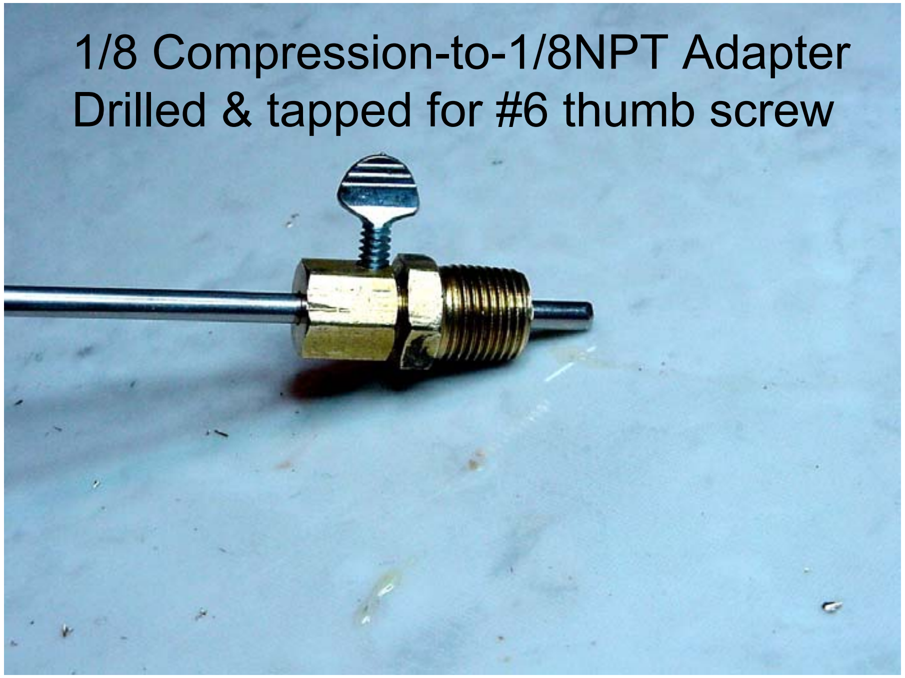
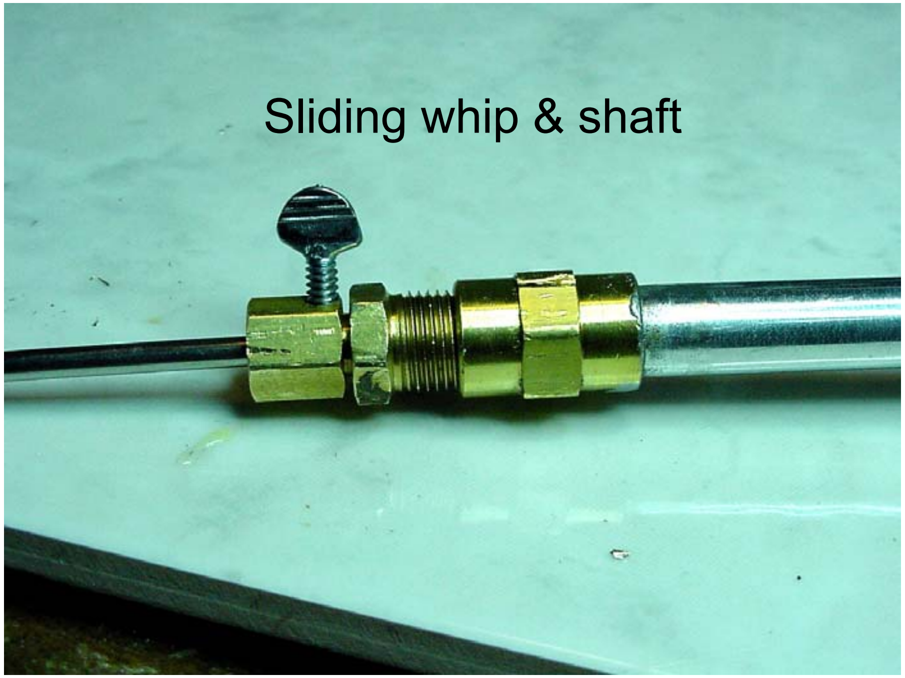
1/8" Steel or Brass Whip Intfc

1/8 Compression-to-1/8NPT Male Adapter

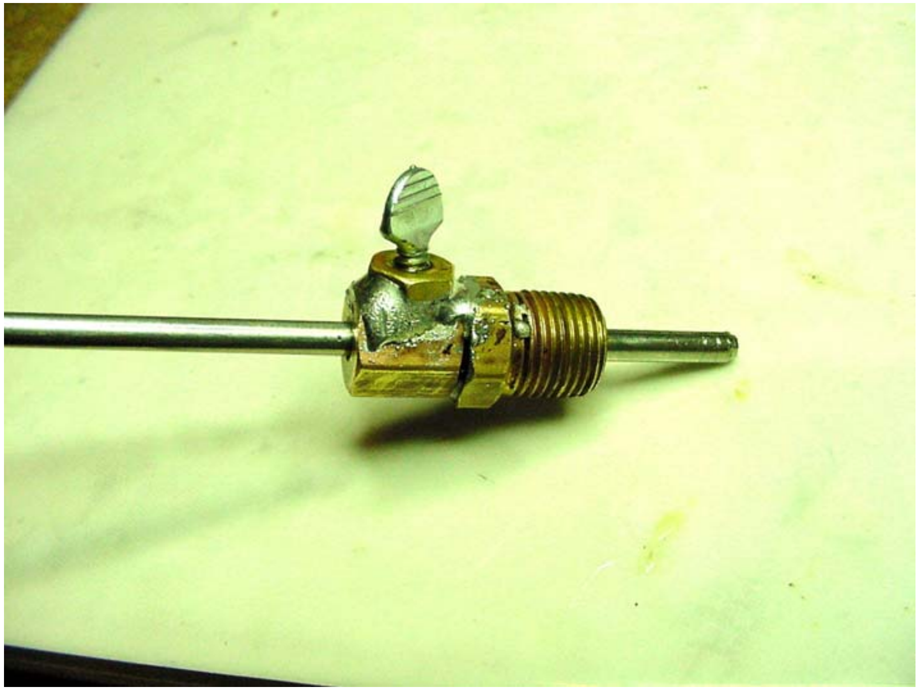


Sliding Whip Adapter

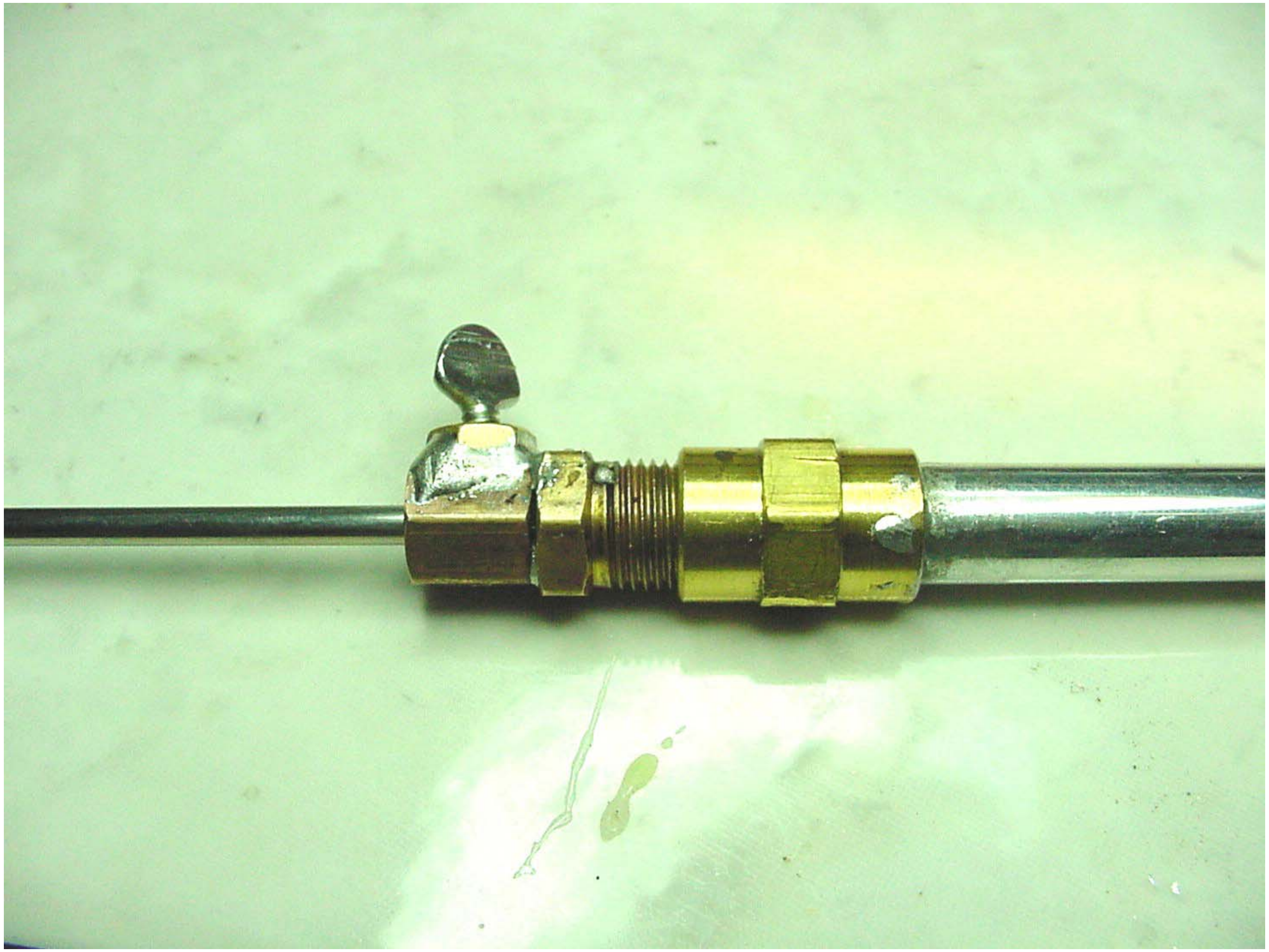




More Robust Whip Adjust



More Robust Adjust & Shaft



Corona Ball

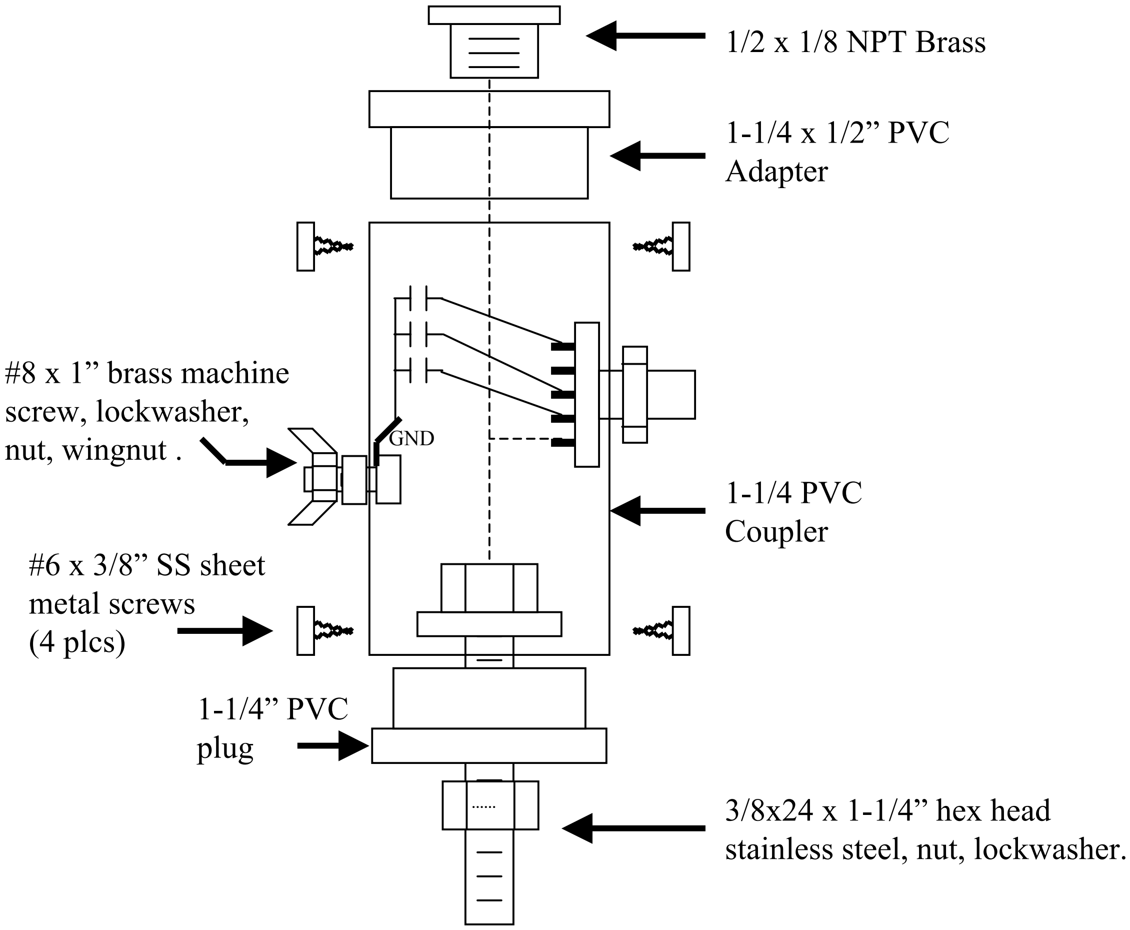
- Corona Discharge effectively gives you a varying antenna length, with a varying VSWR.
- To eliminate corona discharge, you need to eliminate any sharp points at the antenna end.
  - Also keeps you from poking your eye!!
- Taper the end of the 1/8” rod with a file.
- Screw on a #6 nut just enough so that it is firm on the end of the whip.
- Solder it in place.

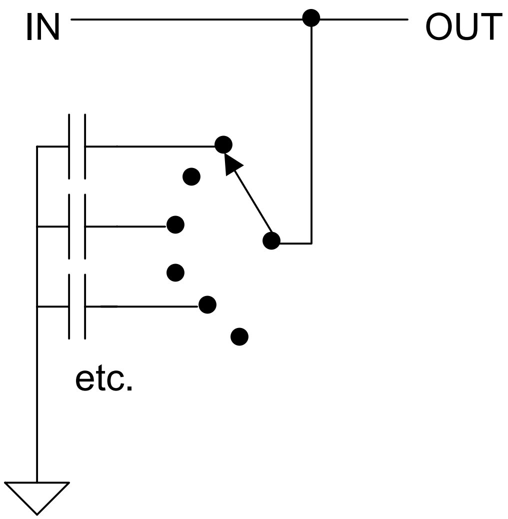
Corona Ball

Short Antenna Matching

- Short antennas have low radiation resistance.
- Sum of radiation resistance, coil loss and ground loss typically less than 25 ohms.
- Inductive, capacitive, or transformer matching will give you a good VSWR.
- ***If you don't need base matching on your short antenna, you probably have excessive losses!***

Capacitive Base Matching





Capacitor Matching Assembly
Not all internal capacitors shown

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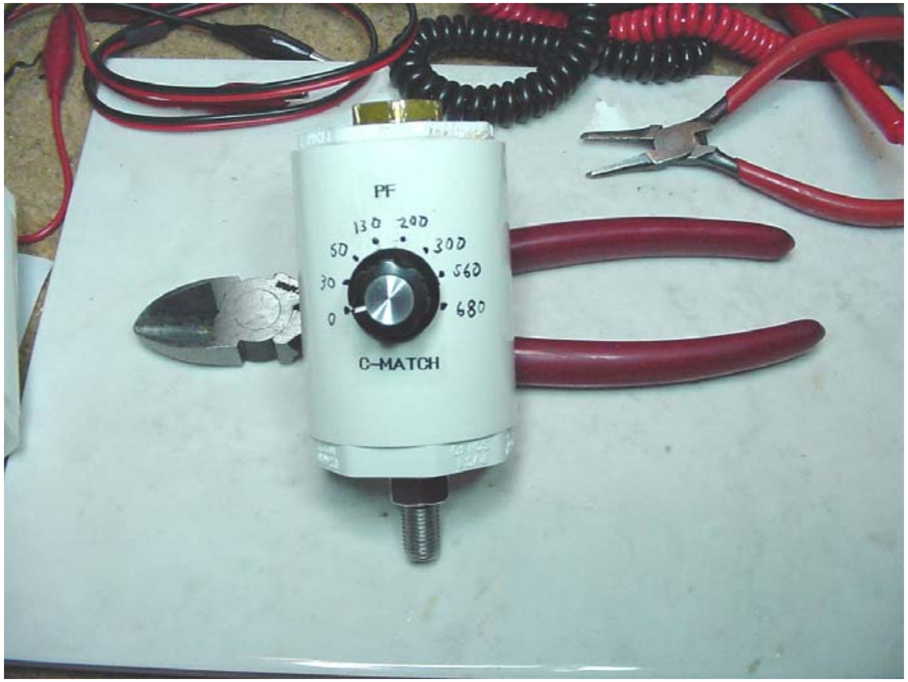
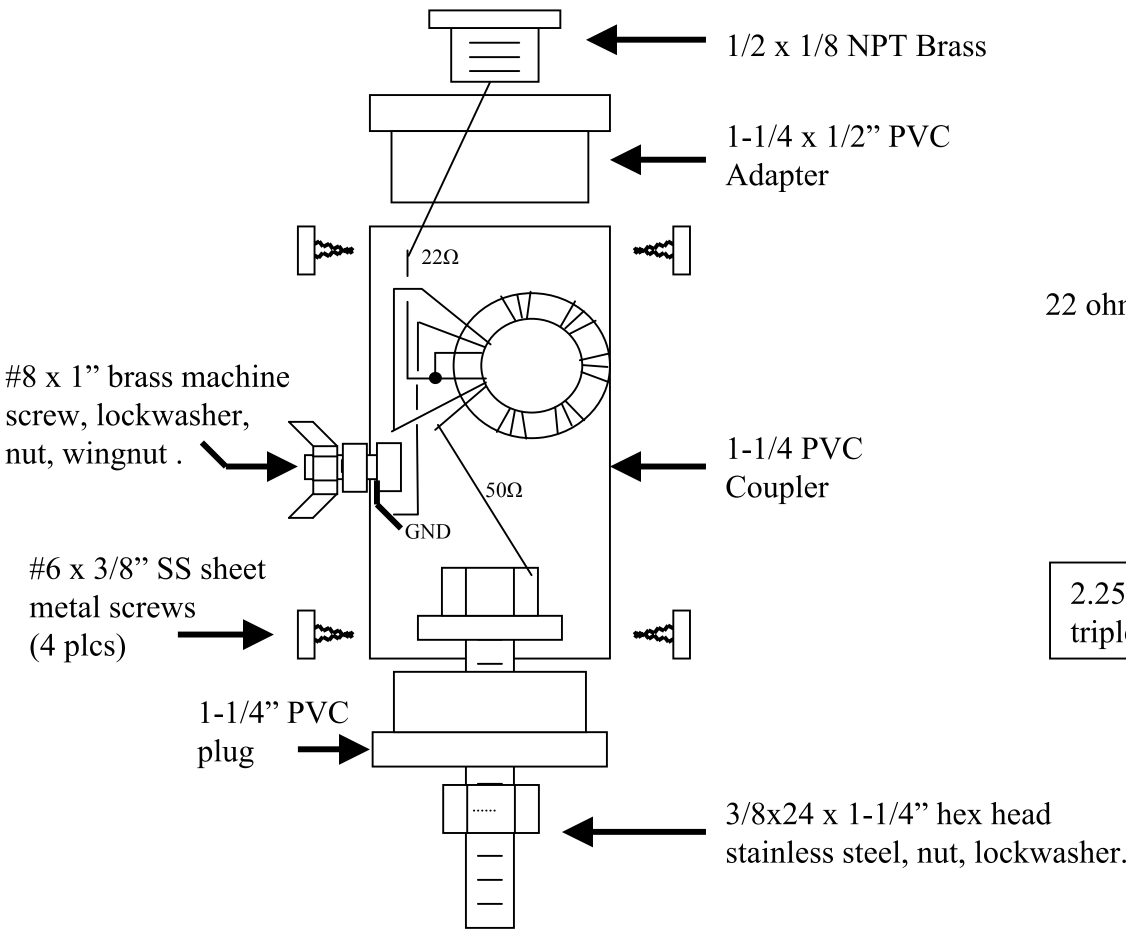
Capacitive Base Matching

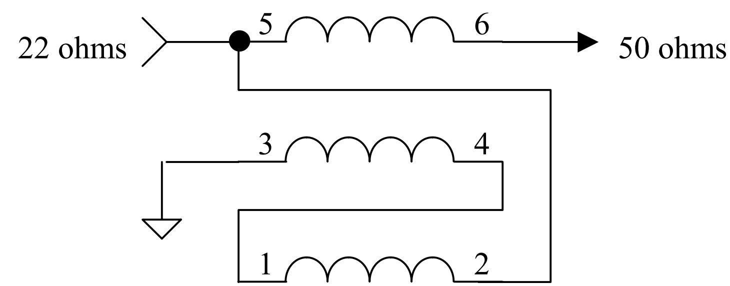


Capacitive Base Mount

XFMR Base Matching

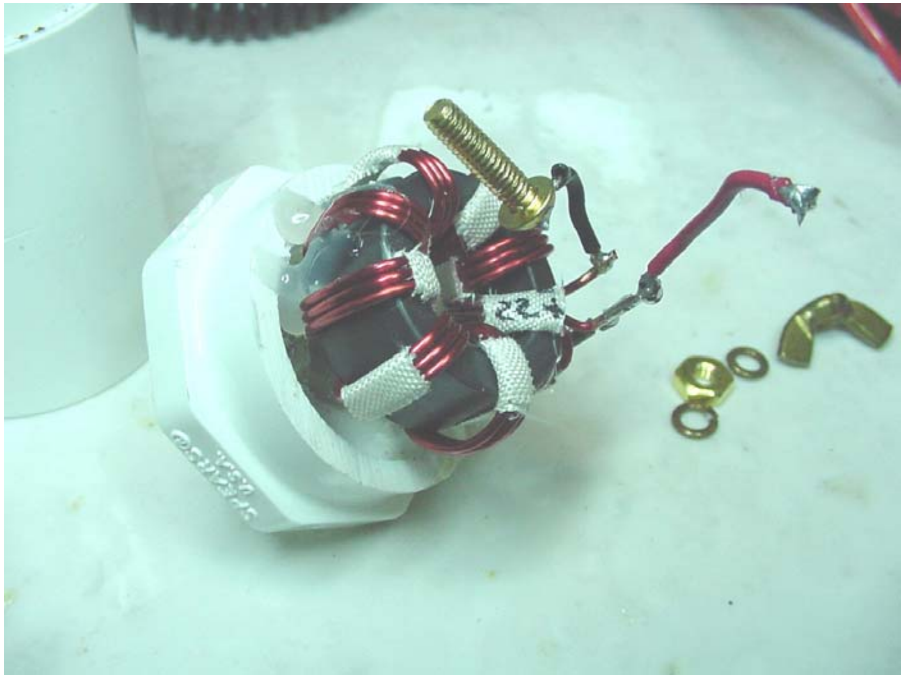


XFMR Matching Assembly

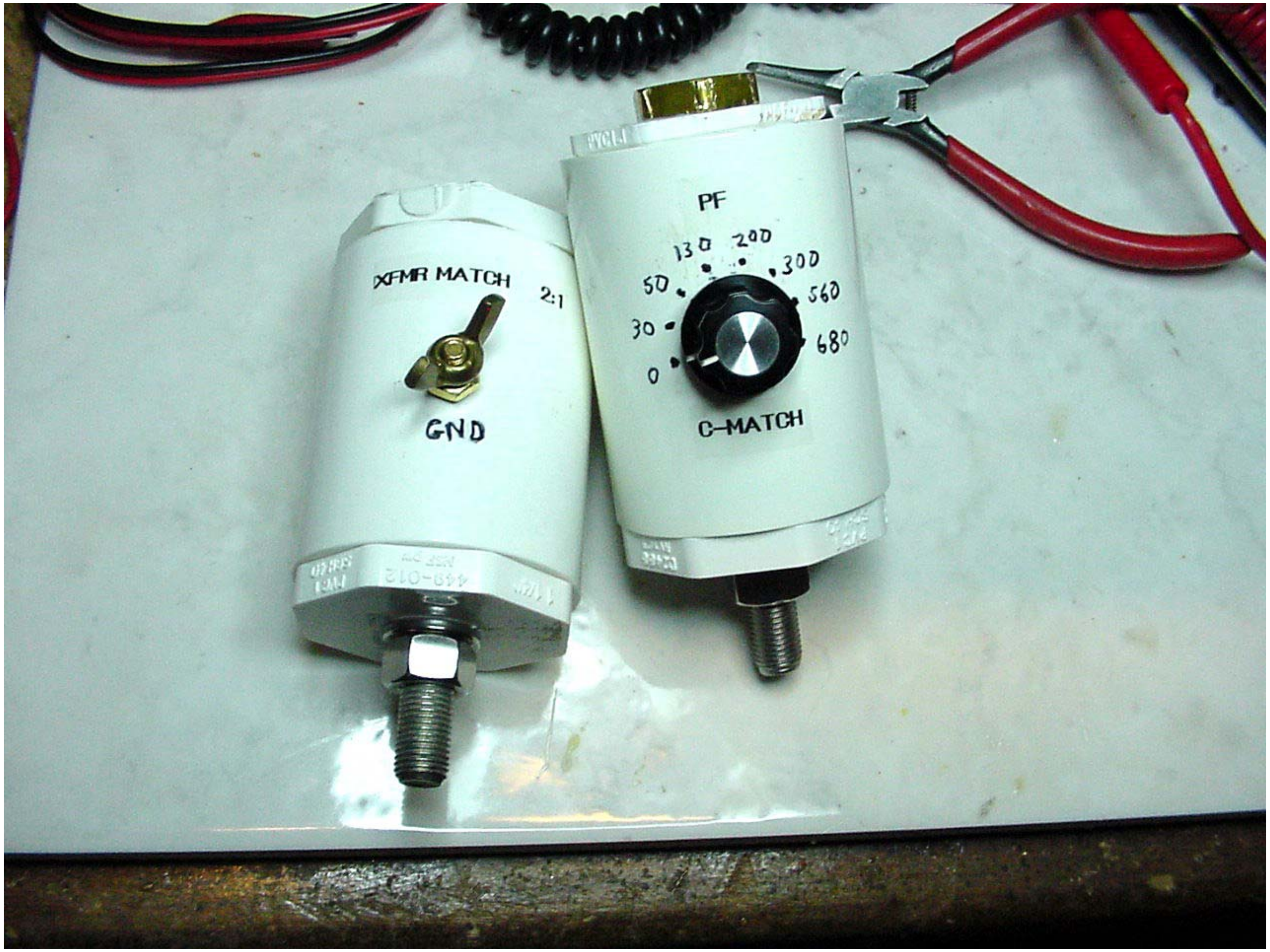


2.25:1 Broadband Matching Transformer. 8-turns triple #16 enameled wires on FT-114A-61

XFMR Base Matching



X- and C-Match



Efficiency Summary

- Use center loading
  - Typically doubles the efficiency of base loading
    - 3 dB or ½ S-Unit improvement
- Use high-Q coils
  - Large wire (with at least 1-turn wire separation)
  - Air wound
- High-Q means reduced operating bandwidth!
  - But more power is radiated
- Use the highest frequency HF band available
  - Doubling the frequency (7→14 Mhz) ***quadruples*** the radiation resistance.
- Make your antenna as long as possible.
  - Increases radiation resistance.

Efficiency Summary (Cont.)

- In mobile applications, mount the antenna as high as possible.
  - Reduces Ground losses.
- Keep capacitive hats well-above loading coil.
  - Hat-to-coil capacitance reduces coil Q.
- If you don't need some sort of base matching to achieve a good VSWR with a short antenna, you probably have high coil and/or ground losses.
  - The better the antenna/ground is, the worse the VSWR at resonance becomes for an efficient antenna.

Efficiency Summary (Cont.)

- If you use an auto-tuner with a non-resonant antenna, use a short wire interconnect to the base of the antenna.
  - For reasonable VSWR conditions (< 5:1 VSWR) coax losses will be minimal if the antenna tuner is located away from the antenna.
    - Coax losses are not too bad at these VSWR levels if the coax run is reasonably short.

So make a few measurements with your ruler and VSWR bridge and see how efficient your antenna really is!

It's not what you don't know, it's what you know that ain't so.

- Will Rodgers

AD5X

Parts Suppliers

- Aluminum tubing – Texas Towers, ACE, Home Depot, McMaster-Carr (www.mcmaster.com).
- Fiberglass rods/tubes
  - Max-Gain Systems: http://www.mgs4u.com/
  - Walmart/Bicycle shops: ¼” diameter fiberglass bicycle flag
- PVC, brass plumbing parts, tubing, stainless steel hardware
  - ACE/True Value/Home Depot/Elliott’s/McMaster-Carr
- Air-wound coil & coil taps
  - MFJ-404-008 coil, MFJ-605-4001 coil tap
  - B&W coils (Surplus Sales of Nebraska)

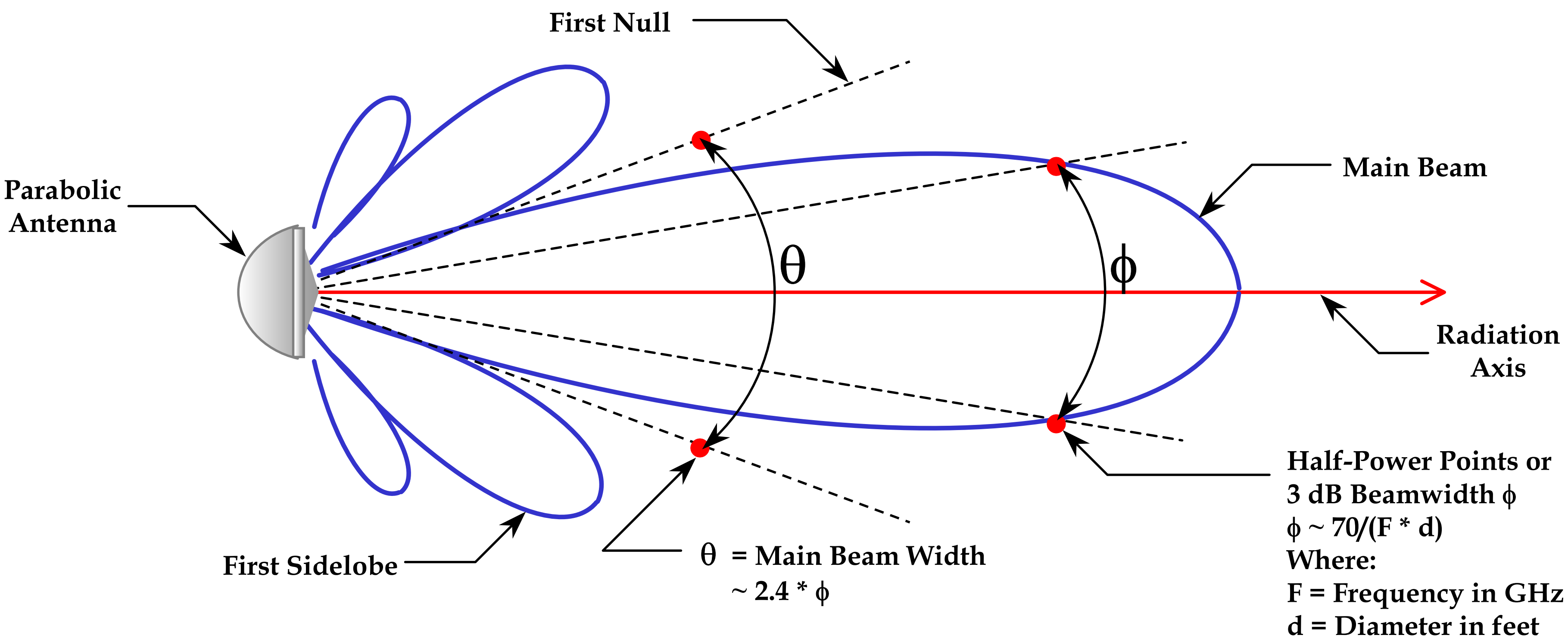
Parts Suppliers (Cont.)

- Tools: Solder-It Company: http://www.solder-it.com/
  - SolderPro torches (SolderPro 50 is $19.95 @ Radio Shack)
  - Aluminum Solder Paste
  - Silver Solder Paste (Silver Solder Paste is $4 @ Radio Shack)
- Hand Tools
  - Harbor Freight 39391-0VGA Tap & Die Kit @ $12.99
  - 11/64” cobalt drill bit (for drilling #8 clearance hole in stainless steel): ACE Hardware Store
- Stainless Steel hardware
  - Jacob Schmidt & Son (www.jschmidtstainless.com)
  - ACE Hardware store
  - McMaster-Carr (www.mcmaster.com)

AD5X

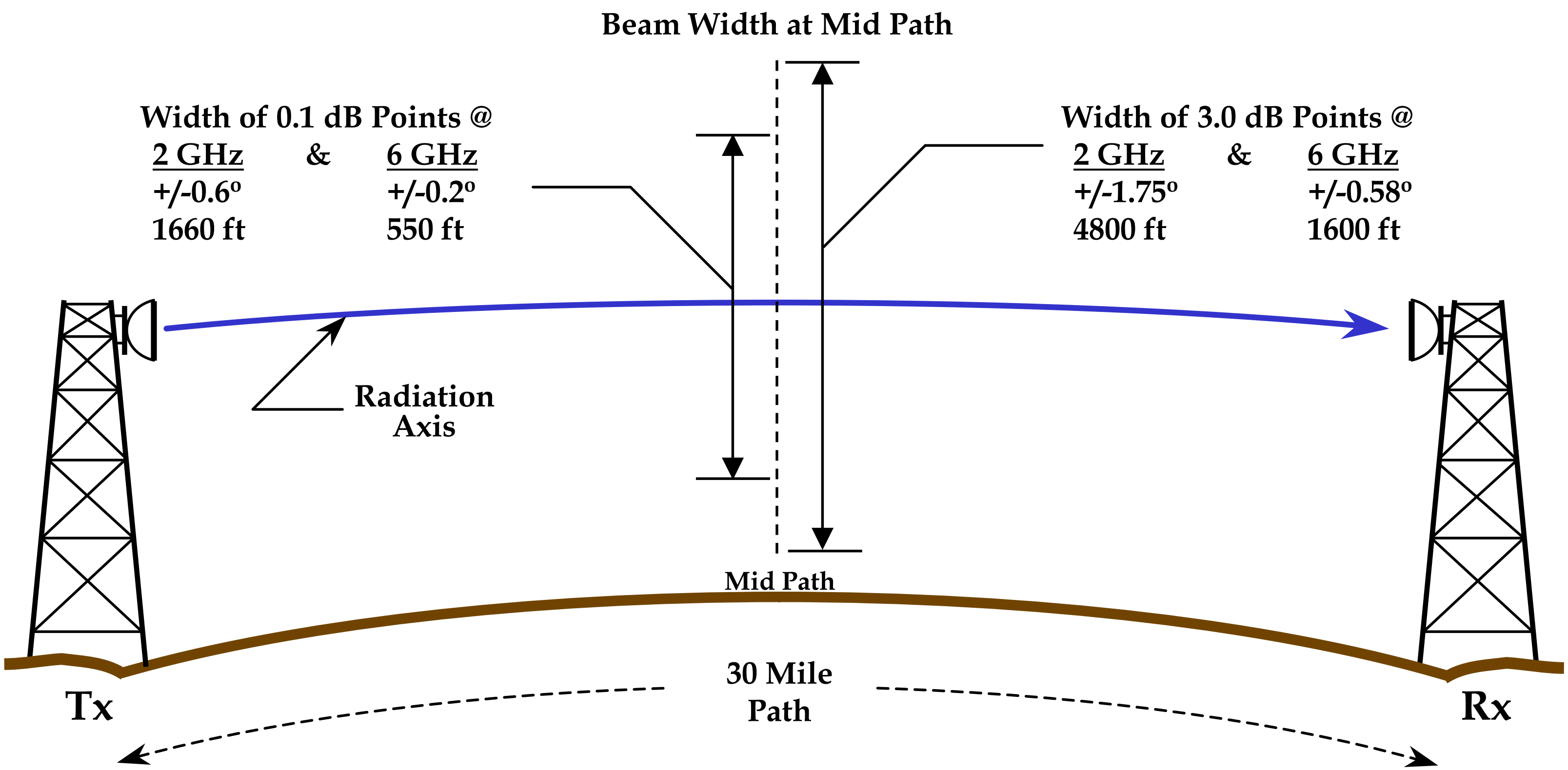
Parabolic Antenna Patterns

- Ten foot dish @ 2 GHz -- 3 dB BW ϕ = 3.5 deg.
- Ten foot dish @ 6 GHz -- 3 dB BW ϕ = 1.2 deg.
- Ten foot dish @ 11 GHz -- 3 dB BW ϕ = 0.64 deg.



Antenna Beam Width @ 15 miles

For 10 ft. UHX Antenna Operating in the 2 or 6 GHz Band

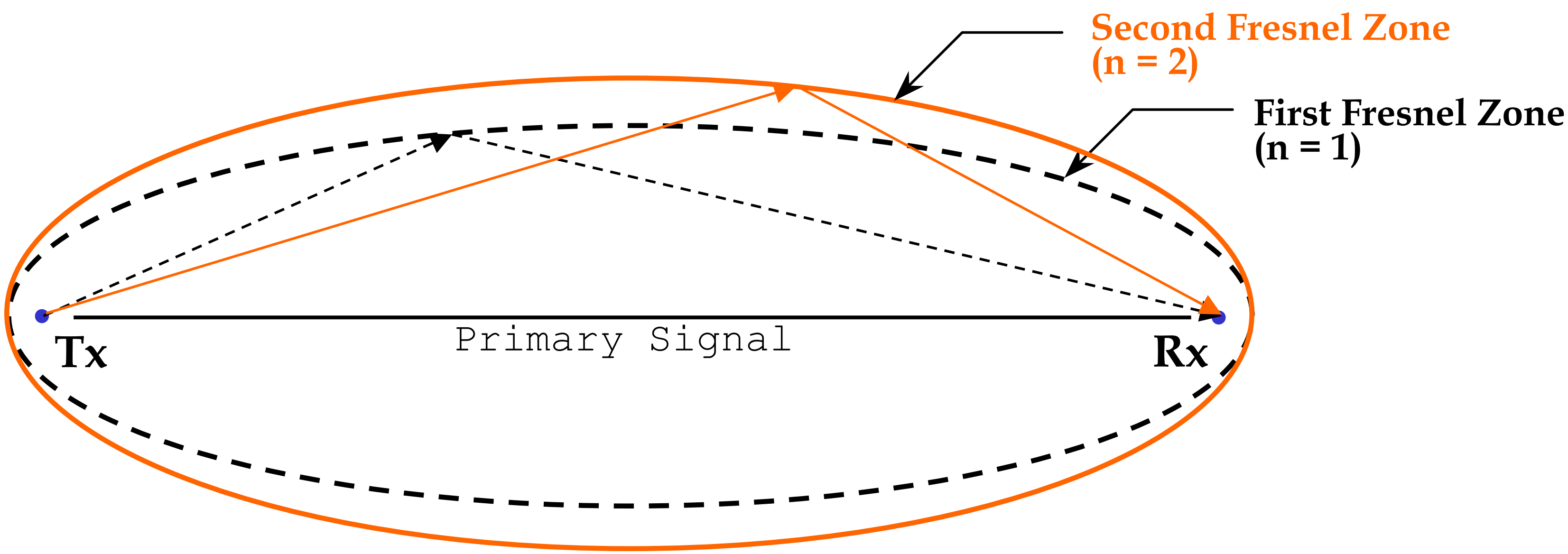


Fresnel Zones

- Path clearance is described in terms of Fresnel zones.
  - Fresnel zones - Families of ellipsoidal boundaries described by points at which a reflected radio wave would travel $n(\lambda / 2)$ further than by a direct route between the transmitter and receiver.
- If a spatial region corresponding to 0.6 first Fresnel zone is clear of obstruction, the received signal level should approach that expected in free-space propagation.

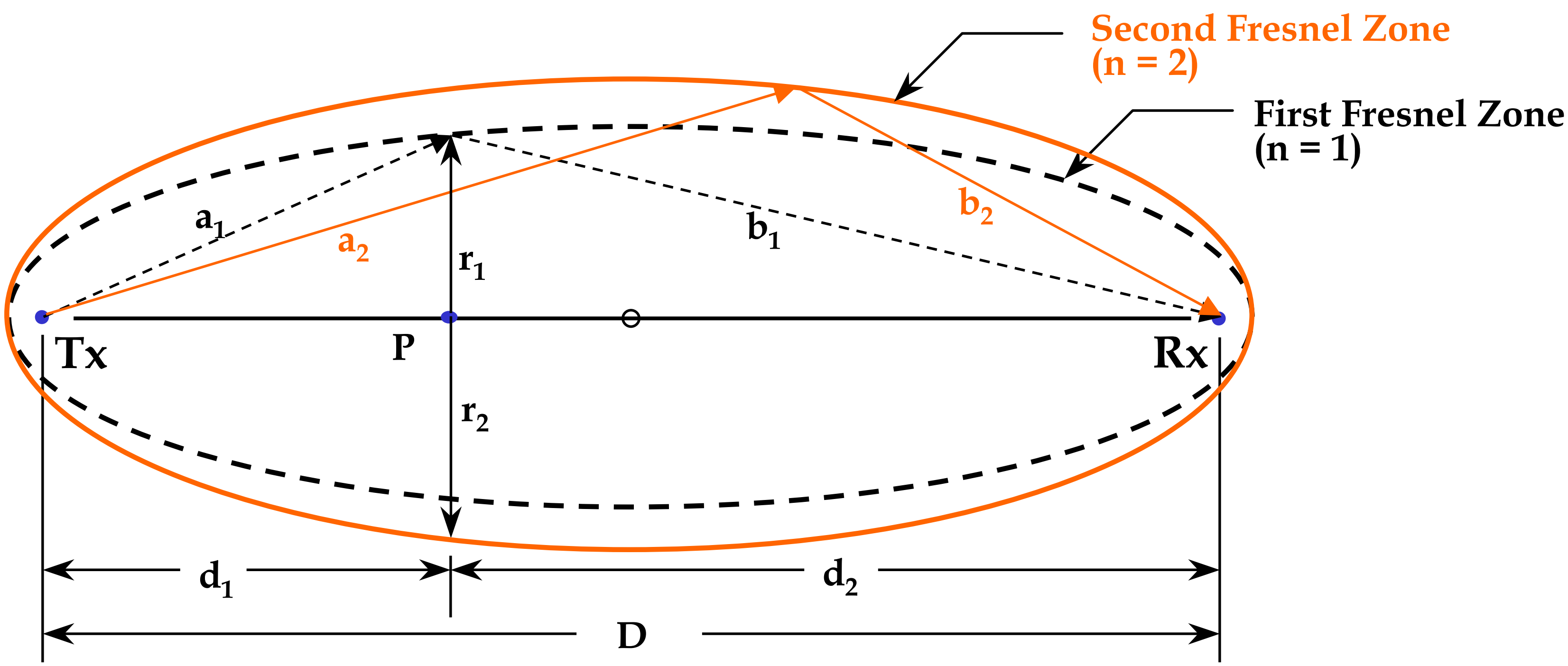
*Augustin Fresnel (1788-1827), French Physicist.

Fresnel Ellipsoides



1st Fresnel Zone: Reflected signal travels λ/2 farther than primary signal.
2nd Fresnel Zone: Reflected signal travels 2(λ/2) farther than primary signal.
3rd Fresnel Zone: Reflected signal travels 3(λ/2) fartehr than primary signal.
Etc..

Fresnel Ellipsoids



$r_1 = 72.1\ [(d_1 * d_2)/(f * D)]^{1/2}$

Where:

r_1 = the first Fresnel zone radius in feet at point P

d_1 & d_2 are distances from Tx & Rx in miles

D = path length in miles &

f = operating frequency in GHz

$a_n + b_n = D + n(\lambda/2)$ &

$r_n = r_1\ [n]^{1/2}$

Where:

n = the nth Fresnel zone

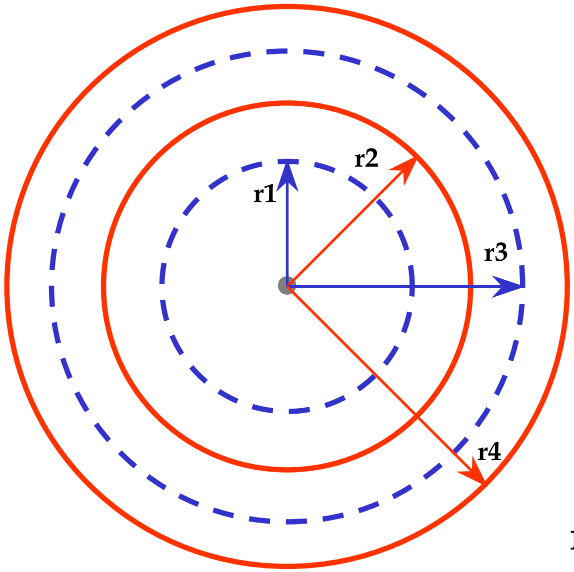
r_n = the radius of the nth Fresnel zone &

λ = operating frequency wavelength

Fresnel Ellipsoids - Cross Section

AD5X

If a cross section is taken of the Fresnel zones, looking from the receiver towards the transmitter, the results will be a series of concentric circles.



Mid-Path Fresnel Zone Radii For 30 mile Path:

@ 6 GHz	@ 2 GHz
r1 = 81 ft	r1 = 140 ft
r2 = 114 ft	r2 = 198 ft
r3 = 140 ft	r3 = 242 ft
r4 = 161 ft	r4 = 280 ft

$$r_n = r_1 [n]^{1/2}$$

Where:

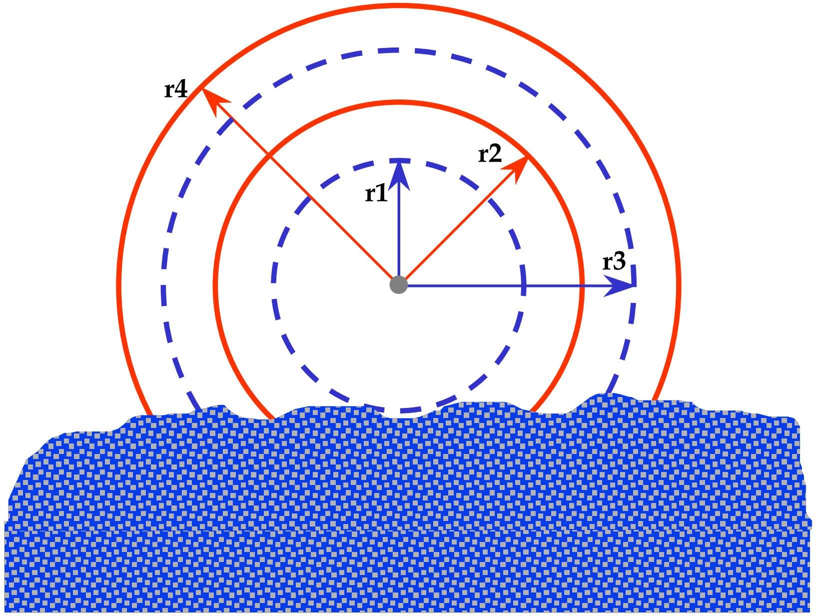
n is the nth Fresnel zone

r_n is the radius of the nth Fresnel zone

Fresnel Zones Cross Section

AD5X

- Reflections from odd numbered Fresnel zones will add in phase at the receiver.
- Reflections from even numbered Fresnel zones will be at anti-phase at the receiver and will cancel the primary signal.

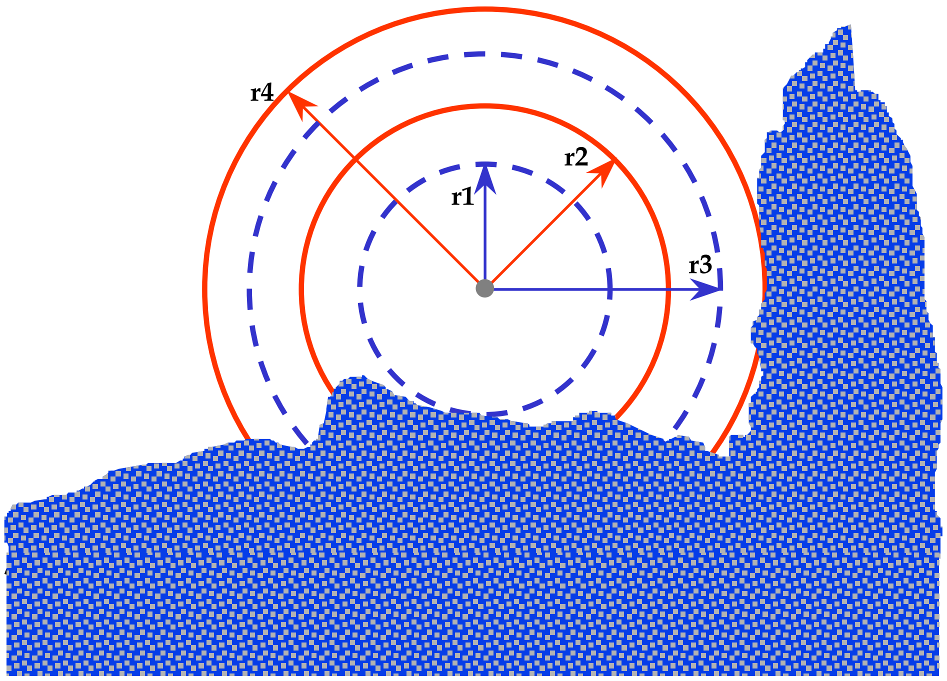


Cross section of typical path at point of least clearance.
Note: The path has first Fresnel zone clearance.

Second Path Cross Section

AD5X

- Reflections from odd numbered Fresnel zones will add in phase at the receiver.
- Reflections from even numbered Fresnel zones will be at anti-phase at the receiver and will cancel the primary signal.



Cross section at point with least clearance.

The path has first Fresnel zone clearance below the path line, but fourth Fresnel zone clearance on a vertical surface adjacent to the path line.

The vertical surface could be the side of a mountain, or a man made structure such as a building, cars on a rail-road track, trailer trucks, ships etc..