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Postage stamp garden 80 m NVIS antenna
Postzegeltuin 80 m NVIS antenne

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Summary

Small antennas for 80 m that work are a challenge. This document discusses a short (10m long) dipole with dedicated tuner for 80 m band NVIS communication. It may even fit a postage stamp garden.

The setup is analyzed first, taking into account wire loss, tuner loss, ground loss, bandwidth and high voltage issues. This is to know whether it is worth to build, and what can be done to improve its performance.

It seems feasible. Receive S-point will be almost 6 dB less compared to a halve wave dipole at same height. With good construction voltages stay below partial discharge limits when applying 100..400 W. As voltages are in the 5 kV range and currents in the 6 Arms range (at 100 W), this antenna with tuner will not be a weekend project.

A fixed tuned and remote tuned version is actually built and documented here. Various setups are simulated and basics of high-Q inductor design are given. This enables home builders to deviate from the implementation discussed here.

Hopefully this document will encourage people to build their own small size antenna.

Wim Telkamp, PA3DJS

Content

1. Introduction

Radio amateurs with large gardens can “grow” large antennas. Unfortunately, many radio amateurs have postage stamp size gardens.

Building and erecting a halve-wave dipole for 80 m, can be an evening project. Building a 10 m long dipole for 80 m including all matching components, not being a leaky dummy load, is a challenge.

When reducing the antenna size well below a half wavelength, both voltage and current levels increase rapidly, converting your valuable RF power into heat or sparks if not designed well.

There is more, you can only pick two items from the list below:

1. wide band
2. small
3. efficient

You can’t have all three at the same time. “magnetic loop” builders know this. Good efficiency comes with small bandwidth. Bandwidth can even be below the occupied bandwidth of an SSB signal at 80 m band.

This document discusses an electrically small dipole as it provides maximum horizontally polarized radiation for “local” NVIS communication.

The example 10 m long dipole uses

- vertical end extensions
- a wide-spaced balanced feed (30…40 cm)
- single-band fully balanced tuner directly under the balanced feed line.
- 1:1 balun for 50 Ohms system impedance

High Voltage
The analysis will show that voltages between the balanced feed line are in the 4 kVpk range at 100W input (or in the 8 kVpk range at 400W input). At these voltage levels, any sharp edge or thin protruded metal will lead to at least partial air breakdown (corona discharge), or full breakdown via air or surface.

Complex impedance notation.
This document uses complex notation for impedances. You don't need complex calculus to read this document, but it is necessary to understand the notation.

Impedances are presented in a form as:

$$Z = a + jb$$

Where **a** = real (ohmic, resistive) part of the impedance. **b** = imaginary (reactive) part of the impedance. A negative reactive part indicates a capacitive reactance. A positive reactive part indicates inductive reactance. Real and imaginary parts are frequently denoted as Re(Z) and Im(Z).

Example $Z = 5 + j300$ or $Z = j300 + 5$

The real part (Re(Z)) is 5 Ohms. The imaginary part (Im(Z)) is +300 Ohms. This indicates a series circuit of a resistance of 5 Ohms and an inductive reactance of 300 Ohms.

Example $Z = 5 – j200$ or $Z = -j200 + 5$

Re(Z) = 5 Ohms, Im(Z) = -200 Ohms. This indicates a series circuit of a resistance of 5 Ohms and a capacitive reactance of 200 Ohms.

The modulus of the impedance (that is |U|/|I| = |Z|) is:

$$|Z| = \sqrt{[Re(Z)]^2 + [Im(Z)]^2}$$

"|..|" = magnitude or amplitude of the so called "complex number" between the vertical bars.

2. Analysis

2.1. Antenna plus feed line

2.1.1. Simulation setup

The graph below shows the configuration that is simulated with NEC2D using the 4NEC2 pre and post processor.

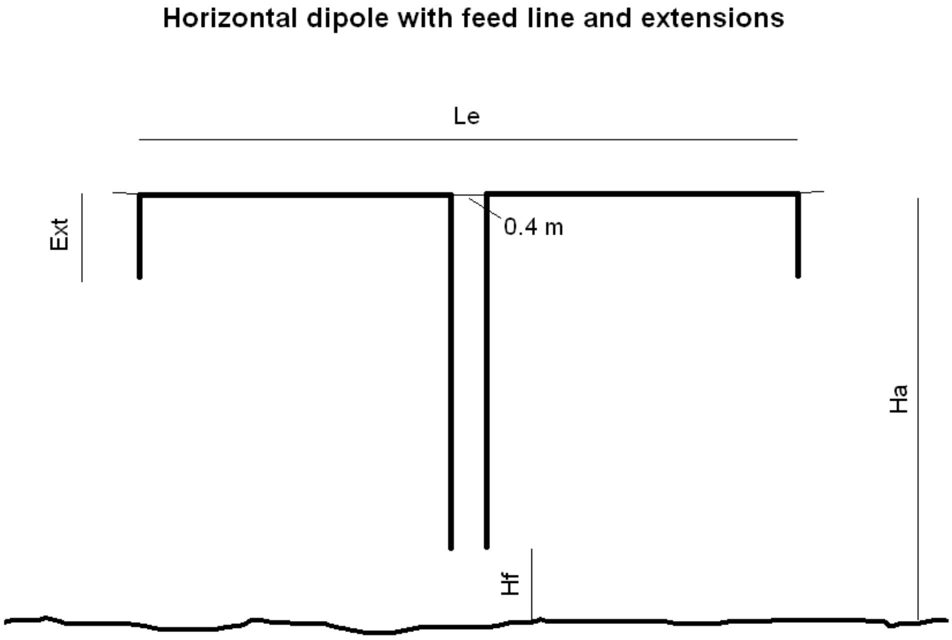


Figure 2.1: horizontal dipole with size references

The size references are used in the table on the next page (all in m, unless otherwise noted).

Ext = length of vertical extension

Le = length of dipole (this does not equal the wire length)

Ha = height of dipole above ground

Hf = height of feed point above ground

The spacing between the conductors of the balanced feed line is 40 cm (0.4 m).

For all configurations:

- Antenna height (Ha) = 7 m
- Feed line length = 6 m (so feed point is 1 m above ground)
- Wire thickness (d) = 2 mm (antenna and feed line), unless otherwise noted.
- Copper resistance is not added, unless otherwise noted
- All over NEC2 average ground, unless otherwise noted

No	**Configuration**	**Gi [dBi]**	**Eff [%]**	**Zant [Ohms]**	**Current [Arms]**	**Voltage [kVpk]**
1	Le = 40m No extensions (reference)	4.6	42			
2	Le = 8m Ext = 0	1.5	24	0.37-j835	16.4	19.4
3	Le = 10m Ext = 0	2.1	27	0.67-j743	12.2	12.8
4	Le = 10m Ext = 0 D = 1 mm	2.1	27	0.68-j818	12.1	14.0
5	Le = 10 m Ext = 2 m NEC Good ground	4.0	38	0.9-j595	10.5	8.9
6	Le = 10 m Ext = 2 m	2.2	28	1.5-j595	8.2	6.9
7	Le = 10 m Ext = 2 m Cu resistance	0.6	19.4	2.2-j595 $R_{cu.eff}$ = 0.7	6.7	5.7
8	Le = 10 m Ext = 3 m Cu resistance	0.7	20	2.9-j525 $R_{cu.eff}$ = 0.75	5.9	4.4
9	Le = 12 m Ext = 2 m Cu resistance	1.2	22	3.1-j523 $R_{cu.eff}$ = 0.75	5.7	4.2

Table 2.1: properties of several dipole configurations

Notes to the table

Gain [dBi] is the power gain for zero theta (that is 90^0 elevation or Zenith), referenced at the feed line input power. The Gain for Zenith direction is important as short range (say < 300 km) require almost 90 degrees elevation for NVIS sky wave propagation.

Eff [%] is the ratio of radiated power in the upper hemisphere over the net input power, referenced at the feed line input Efficiency never reaches 100% as some of the downwards radiated power is converted into heat in the soil below the antenna.

Zant [Ohms] is the impedance at the input of the feed line. The "-j" part indicates that the series reactance is capacitive.

Current [Arms] is the current that would flow into the feed line when the net input power is 100 W

Voltage [kVp] is the peak voltage in kV at the input of the feed line when the net input power is 100 W. Each wire carries half the voltage referenced to ground

2.1.2. Analysis of simulation results

No 1 is the full size half wave dipole, 7 m above ground. It is used as reference. When increasing the height (Ha) gain increases, but beyond about 0.2 lambda, zenith gain reduces.

No 2 simulation (8 m dipole size) shows impractically low real part of impedance (0.37 Ohms) with a very high reactive part (835 Ohms), making a low loss match impossible. The Q-factor of the antenna impedance is 2300. This is beyond any practical inductor-Q. Trying to get a descent match to any practical real impedance will lead to significant loss. Only solution here is to use many spaced wires in parallel to reduce the reactive part.

No 3 shows that even relative small change in length increases real part of impedance significantly and lowers the capacitive component, now Qant = 1100. Antenna Q reduces to below 50% of No 2 setup. Also input voltage for 100W input reduces significantly.

No 4 shows that thin conductors give some increase in capacitive component. Note that the AC resistance of 1 mm wire is twice as high as for 2 mm thick wire.

No 6 shows the effect of adding 2 m long extensions. Real part of impedance goes from 0.67 to 1.5 Ohms, and the capacitive part reduces significantly,
Now Qant = 400. Antenna Q reduces from 1100 to 400, and is now in the range that can be matched with acceptable (but still significant) loss.

No 5 shows the effect of better soil conductivity. There is about 1.8 dB gain increase, but Re(Z) goes down from 1.5 to 0.9 Ohms increasing matching loss.

No 7 adds copper loss into the simulation. The AC resistance is 0.081 Ohms/m (valid for a 2 mm thick soft copper wire). Though total AC resistance for 26 m of wire is 2.1 Ohms, effective loss resistance is 0.7 Ohms. This is because of current tapering towards the ends of the wires.

No 8 is same as no 7, but extensions are 3 instead of 2 m. Though impedance is easier to match with low loss, the gain increase will not be that much as the soil loss increases.

No 9 is same as no 7, but dipole length is 12 instead of 10 m. Impedance is easier to match with low loss, and soil loss decreases, hence gain including matching loss increases more than one would expect.

As the radiation resistance is 1.5 Ohms (see No 7), overall efficiency goes down with about -10log(1.5/2.2) = 1.6 dB. In other words 32% of the input power is converted into heat just because of the copper resistance of the 2 mm thick wire.

Due to the increase of Re(Zant), voltage for 100W input is now 5.7 kVp

No 8 and No 9 both increase the total wire length with 2m (1 m on both sides). Both setups show higher Re(Z) (resistive part of impedance) that will give easier matching (lower loss, lower current and voltage). Bandwidth increases in both cases. The difference is in the gain. Extending the dipole gives better gain increase. Of course best is to do both (that is increasing dipole length and increasing the extensions).

2.1.3. More on copper loss

No 7 shows the antenna that is actually built. Even with 2 mm thick wire (12 AWG), there is 0.7 Ohms effective AC resistance that eats 32% of your input power that you apply at the feed line.

Due to the weight, one may use thin wire. When going to 1 mm thickness, AC resistance goes to 1.4 Ohms, “eating’ almost 50% of your input power.

Some people may use cheap CCA (Copper Clad Aluminum) speaker wire, as it is light-weight (compared to copper). You pull the wires apart and you have the dipole wires. Reels of 15..25 m of 2.5 mm2 thickness with thick soft PVC insulation are sold at home improvement stores, hardware shops and various web shops. But.....

CCA wire with PVC insulation is not recommended for this short dipole.

Changing from 2.5 mm2 stranded CCA/PVC wire to 3.1 mm^2 stranded tinned copper with mPPE (Noryl) insulation gives an Re(Zant) reduction of 1.7 Ohms. This indicates that the CCA wire has an effective loss resistance of about 2.4 Ohms compared to 0.7 Ohms for copper.

2.4 Ohms wire loss resistance together with 1.5 Ohms radiation resistance introduces a loss of 4.1 dB.

Some of the loss is due to conductor loss, but another part will be because of dielectric loss of the thick soft PVC insulation on red-black speaker wire.

Because of the low radiation resistance of short dipoles, it is also not recommended to use galvanized steel or stainless steel wire.

A single thick copper wire, or well-spaced thin copper wires is the way to go if you want maximum efficiency given the small size of the dipole. ¡Circumference counts, not cross section (skin effect)!

2.2. matching

2.2.1. Matching strategy

When using setup No 7 (10 m dipole with 2m extensions, 2 mm copper wire thickness, copper loss included), we can Expect:

Zant = 2.2 - j595 Ohms

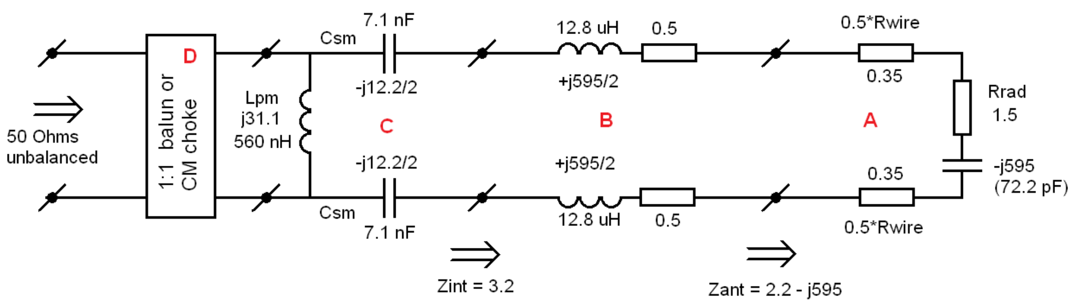
Measured at the input of the feed line at 1 m above ground, wire loss included

Due to the high antenna Q factor of 270, you will not find any transformer that transforms this impedance to something that gives a non-excessive SWR in an unbalanced feed line. Even if it were possible to find a nice transformation ratio, designing/building such transformer with 5.7 kVp operating voltage at 3.7 MHz is hard to impossible. A resonating approach is a better choice.

An option is to use a dedicated (single) band balanced matching circuit, see figure 2.2. This circuit also shows the additional losses.

Part A shows the equivalent single frequency antenna circuit including copper loss
Part B shows the inductor to counteract the capacitive component, including loss
Part C shows the L-match circuit to convert the low impedance to 50 Ohms
Part D shows the 1:1 balun to enable connection to a coaxial feed line.

Matching circuit for postage stamp garden 80 m short Dipole



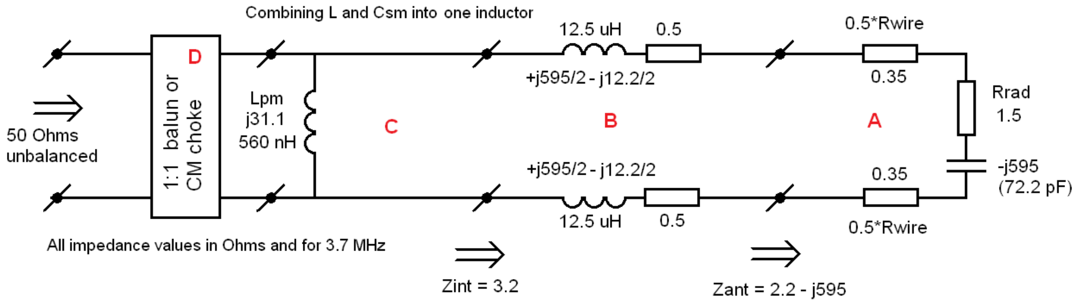


Figure 2.2: Matching circuit and antenna model (3.7 MHz)

To counteract the -j595 Ohms capacitive reactance, about 12.7 uH inductance in series with each feed line wire is required to get the impedance to 2.2 Ohms (without any reactive component). Due to inductor loss, the total impedance (Zint) will be above 2.2 Ohms.

Inductor calculation (for your own setup):

$Z_L = j \cdot \omega \cdot L$ or $X_L = \omega \cdot L$

$L = X_L / \omega$

Z_L = complex impedance of an inductance in Ohms, X_L is the imaginary part of the impedance in Ohms, (the number right of “j”).

Example:

Antenna impedance = Zant = 2.2 – j595 [Ohms]
To counteract the capacitive reactance of the antenna +j595 is required (or an inductive reactance of 595 Ohms

$L = X_L / \omega$ = 595/(2·pi*3.7M) = 25.6 uH

As we have one inductor in each feed line, we need two, 12.8 uH inductors. Use some larger inductance to have some margin.

A bigger reactive part in the antenna requires a bigger inductor.

From measurement inductors with Q > 600 can be made using "amateur" materials and tools. For a Q > 600, coil diameter should be > 90 mm (will be discussed in the implementation section). So we may add an additional 0.5 Ohms in series with each inductor.

Then a simple L match circuit can be used to convert Zint = 3.2 Ohms into 50 Ohms balanced. As we are now at 50 Ohms impedance level, a simple balun or CM choke can be used to connect to a 50 Ohms coaxial cable.

For the Lmatch with a parallel inductor (Lp):

Z_{high} = 50 Ohms,
Z_{low} = 3.2 Ohms

$Q_{match} = \mathrm{sqrt}(Z_{high}/Z_{low} - 1) = \mathrm{sqrt}(50/3.2 - 1) = 3.82$

$Xp = Z_{high}/Q_{match} = 50/3.82 = 13.1$ Ohms (inductive)
$Xs = Z_{low} \cdot Q_{match} = 3.2*3.82 = 12.2$ Ohms (capacitive

C_{sm} (with Z = -j12.2 Ohms) can be taken together with the series inductance as is shown in the lower graph. We now have a matching circuit with inductors only.

The copper loss of Lpm can be neglected as the loaded Q factor is just 3.8 and the inductor Q will be well above 100.

2.2.2. Overall gain and evaluation

Now we know the gain for the lossless situation and the losses, we can calculate the overall gain.

From table 1, No 7:

Re(Zant) = 1.5 Ohms (that is the radiation resistance)

Gain = 2.2 dBi (for 90^0 elevation).

Losses

Rloss = 2·(0.5 + 0.35) = 1.7 Ohms (inductor and wire loss)

Zint = 1.5 + 1.7 = 3.2 Ohms. (Intermediate impedance)

"gain" due to copper loss:

Gain = 10*log(1.5/3.2) = -3.3 dB

Overall antenna gain (including copper loss and tuner loss):

Gi = 2.2 + -3.3 = -1.1 dBi

Power balance

47% of the RF input power is radiated in a full sphere
28% of the full sphere radiation is radiated into the sky (due to ground absorption)

Therefore

13 percent of the input power (at the balun) is radiated into the upper hemisphere.

The reference dipole has gain of 4.6 dBi and 42% of the input power is radiated into the upper hemisphere.

Is this Postage Stamp Garden antenna worth to be built?

Yes, you will lose about 1 S-point (5.7 dB) compared to a half wave dipole at 7 m above ground. You will not be the strongest 100 W station, but you will be heard!

2.2.3. Useful bandwidth

You can only have 2 out of:

1. small size
2. good efficiency
3. large bandwidth

We have a small antenna with reasonable efficiency, so you will NOT get large bandwidth.

The antenna together with the series inductor behaves as a series resonator with a relative high Q-factor

Q = Xs/Rs = 595/3.2 = 186

Xs = reactive component of the series L or C, Rs = total series resistance in the LC series circuit.

BW(swr=2) = 0.707·fc/Q = 14 kHz (at f_{center} = 3.7 MHz).

To enable use across the complete 80 m band, some form of tuning is required. This should be done by modifying <u>both</u> series inductors to maintain balance.

The bandwidth of the matching section (Csm, Lpm) is large enough as Q = 3.8. Csm is not present in the actual circuit.

2.2.4. High voltage issues

Zint = 3.2 Ohms, and the antenna reactive component is –j595

100 W into 3.2 Ohms generates

I = sqrt(P/R) = sqrt(100/3.2) = 5.6 Arms.

|Zant| = 595 Ohms, hence

Vrms = 595*5.6 = 3300V

Therefore

Vpk = 3300V*1.414 = 4.7 kV across the feed line

Each wire is 13 m long, that is 65% of a quarter wave (58.5 degrees from the extremity). Each wire receives 2.35 kV (assuming perfect balance).

When the wire would be fully straight, the (feed point)/tip voltage ratio would be sin(32) = 0.52. That would generate:

Vtip = 2.35/0.52 = 4.5 kVpk.

These are voltages you normally do not encounter in antenna systems with 100 W input (except small “magnetic” loops). They are far into the region were partial air discharge (corona discharge), full break down, or tracking may occur.

When the E-field at the surface of a conductor becomes too high, ionization occurs (that is electrons are ripped off gas molecules). For thin round wires, the E-field at the surface must be further increased to get visible corona.

At RF, you don’t want ionization at all. First ionization occurs at a field strength of about 3 kVp/mm (2.1 kVprms/mm).

For clean straight air-spaced ladder lines, the voltage between the wires where ionization starts depends on distance between wires and diameter of wires. It can be calculated using Peek’s formula.

Some results relevant for small straight ladder lines

C-C spacing [mm]	Wire diameter [mm] ionization voltage [kVp]	
	1	**2**
20	11	18
100	16	27
400	20	36

Table 2.2: ionization voltage for balanced feed lines

Sharp bends, rough / polluted surface and low air pressure (mountains) lower the ionization voltage.

Ionization voltage depends heavily on wire diameter and weakly on spacing as long as spacing >> wire diameter.

As we have 4.7 kVp between the wires, and 2 mm wire diameter, ionization and even visible corona discharge will not occur (even 400 W instead of 100 W would be safe).

Strong E-field occurs at pointed objects. They are frequently the weakest link in an electrically small transmitting antenna. A single filament protruding out of a stranded wire will lead to corona discharge.

Approximation formula for ionization voltage of round tips (think of needles, wire filaments, etc).

$$U_{ion}[kVpk] = 3 \cdot Radius[mm]$$

Tip radius [mm]	Ionization voltage [kVpk]
0.1	0.3
0.2	0.6
0.5	1.5
1	3

Table 2.3: ionization voltage for sharp tips.

A wire can have a tip radius of maximum half its diameter!

So a 2 mm thick wire with rounded tip will cause ionization at 3 kV. For visible corona higher voltage is required, especially for thin tips.

Just cutting a 2 mm thick wire to the desired length will lead to visible corona as we have about 4.5 kVp at 100W input. This is undesired. Your RF energy is converted into some blue light and lots of heat. In addition the antenna impedance becomes power-dependent. In other words, SWR will change with RF input power to the antenna. This will lead to out-of-band emissions and/or damage to the PA section of your transceiver.

To avoid these problems, the tip of the wire should be formed into a loop, see figure 2.3.

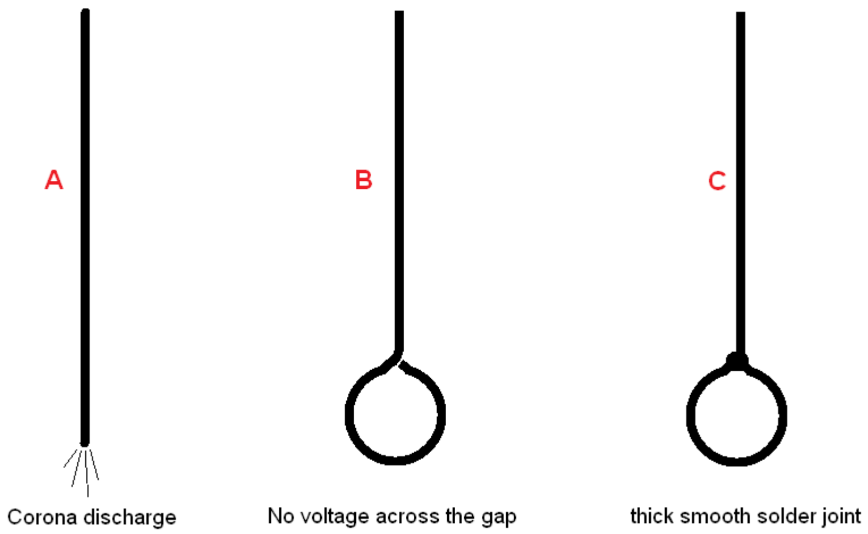


Figure 2.3: Reducing corona discharge

The A figure shows the corona discharge at the end of the antenna wire.

The B figure shows the basic principle. The voltage left and right of the air gap in the loop is the same, so there is no voltage across the gap.

The C figure shows the practical implementation where the tip is wound around the wire and soldered. One must use lots of solder to get a smooth thick joint.

The diameter of the loop should be large compared to the wire diameter (think of factor 10 or more). The solder blob must also be large to avoid local ionization.

2.3. Conclusion of feasibility

A small 80 m NVIS dipole of about 10 m long, 7 m above ground and 6 m long wide spaced feed line seems feasible.

Some findings

- Gain is almost 6 dB (1 S-point) below that of a full size half wave dipole at same height, including copper loss.
- You need copper conductors with a circumference > 6 mm. This can be a single conductor, but also spaced multiple smaller conductors.
- When using hard drawn aluminum, the circumference should be at least doubled.
- Avoid soft PVC insulation due to dielectric loss. Use bare wire, or low dielectric loss insulation (XPLE, PPE, PTFE, etc).
- The dipole wire should extend downwards over a distance of about 2 m to increase the radiation resistance to a value that can be matched without excessive loss.
- Voltage at feed point is in the 4.7 kVp range for 100W input, tip voltage is in the 4.5 kVp range.
- Due to relative high voltage, sharp edges should be avoided to avoid (non-visible) corona discharge.
- Matching inductors should have good quality factor (Q > 600) to keep matching loss acceptable.
- Bandwidth is small (about 14 kHz for SWR = 2), some form of tuning is required.
- Increasing the dipole length and/or the extensions, even with 1 m, gives easier match (less current, less voltage, lower loss).

3. High-Q inductor design

3.1. Introduction

We have an inductor-only matching circuit with two high-Q inductors.

As the actual inductance depends on each individual antenna installation, inductance should be adjustable. For now tuning is done using non-ferro-metallic clips on bare copper wire. Ferrite tuning experiments are underway.

We also need to take into account high voltage issues.

3.2. Design guidelines for the inductors

There are many sources on high Q inductor design. Here some general guidelines are given that will give you an inductor with a Q-factor very close to the absolute maximum.

3.2.1. Inductance

The graph below (figure 3.1) shows the dimensions as used in the formulas.

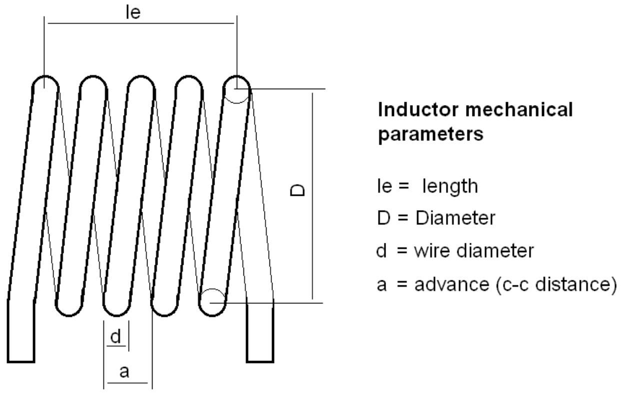


Figure 3.1: geometry of single layer coil

For inductors with many turns, you can use the distance between the terminations as length (le).

We are metric, so use meters (or mm when indicated).

Wheeler Inductance Formula:

$$L = 2.5 \cdot \pi \cdot \mu_0 \cdot \frac{D^2 \cdot n^2}{4.5 \cdot D + 10 \cdot le} \qquad le > 0.4 \cdot D \qquad [H, Vs/A] \qquad \textbf{3.1}$$

D = Average diameter, in m, n = number of turns, le = length, in m, $\mu_0 \approx 1.2566 \cdot 10^{-6}$ H/m, L = inductance, in H, Vs/A.

For Le/D = 0.2 the error is about -4% (so formula underestimates the inductance. It is generally within 1% for Le/D > 0.4.

Formula is not valid for coils with very few turns

For Le = D, the formula simplifies to

$$L[\mu H] = 0.681 \cdot D \cdot n^2 \qquad le = D \qquad [uH, uVs/A] \qquad \textbf{3.2}$$

For Le = 1.5·D, the formula simplifies to

$$L[\mu H] = 0.506 \cdot D \cdot n^2 \qquad le = 1.5 \cdot D \qquad [uH, uVs/A] \qquad \textbf{3.3}$$

With a certain advance per turn (a, in m), we get

$$Le_W = \pi \cdot D \cdot \frac{Le}{a} \qquad [m] \qquad n = le/a \qquad 3.4$$

$$L[\mu H] = 0.420 \cdot \frac{D^3}{a^2} \qquad le = 0.7 \cdot D \qquad [uH, uVs/A] \qquad \textbf{3.5A}$$

$$L[\mu H] = 0.681 \cdot \frac{D^3}{a^2} \qquad le = D \qquad [uH, uVs/A] \qquad \textbf{3.5B}$$

$$L[\mu H] = 1.14 \cdot \frac{D^3}{a^2} \qquad le = 1.5 \cdot D \qquad [uH, uVs/A] \qquad \textbf{3.5C}$$

Le_W = total wire length in m, n = number of turns

Due to self-capacitance, the inductance measured at the operating frequency (L_{OP}) increases with a factor:

$$\frac{L_{OP}}{L_{LF}} = \frac{1}{1-\left(\frac{f_{OP}}{SRF}\right)^2} \qquad \textbf{3.7}$$

L_{OP} = inductance at operating frequency f_{op}, L_{LF} = low frequency inductance (that is inductance very well below SRF), SRF = first Self-resonant frequency of the inductor.

For inductors with Le/D = 1, and optimum wire thickness, self-resonant frequency (SRF) is just above the frequency where the wire length = 0.25·λ.

The SRF is the frequency where the inductor reaches parallel resonance with its parasitic capacitance, when one side is grounded. At SRF the impedance is high and real (no reactive part, purely resistive).

An inductor having wire length (Le_W) = 5 m, has SRF = 15 MHz. When f_{OP} = 3.8 MHz, the inductance at 3.8 MHz is 1.069·L_{LF}.

3.2.2. Q-factor

Coils for resonators or filters are designed differently compared to inductors that are used as an inductor. Inductors for resonators can be operated even at their self-resonant frequency (SRF) enabling very high resonator Q (well above 1000).

The inductor is used as an inductor here, not as part of a resonator. At the self-resonant frequency (SRF), Q = Im(Z)/Re(Z) = 0. The self-resonance phenomenon is caused by stray capacitance (between windings and across windings).

For a single layer air coil with Length over Diameter ratio of one (Le/D = 1), the self-resonant frequency is just above the frequency where the wire length (Le_W) is 0.25·λ. So a coil with a wire length of 5 m and Le/D=1, has a SRF of about 15 MHz.

Maximum Q is reached when f_{op}/SRF = 0.45. Above 50% of SRF, apparent inductance increases rapidly and Q drops rapidly. This is because of the self-capacitance.

As a guideline for high Q single layer air core inductors, wire length should be maximum 0.12·λ at the operating frequency (f_{op}). A single layer coil operated as an inductor at 80 m band, should have a wire length of maximum 10 m.

Best Q factor for coils operated well below SRF can be obtained with Le/D = 0.45, When the operating frequency of the inductor is no longer small compared to SRF, Le/D = 0.7 gives better Q (ref: *Coil Length-to-Diameter Ratios For Maximum Q in LFMF Antenna Loading Inductors, Rudy Severns N6LF*). Le/D = 1, is a good compromise. You get larger number of turns, but therefore less voltage drop per turn.

For an air cored single layer inductor with Le = D, ignoring self-capacitance effects, using optimum wire diameter (d), and bare copper wire, Q is about:

$$Q = 5.2 \cdot D \cdot \sqrt{f} \qquad le = D \qquad [] \qquad \mathbf{3.8}$$

D = coil average diameter in m, f = frequency in Hz

At f_{OP}/SRF = 0.45, Q factor is about 80% of value based on the above formula.
At f_{OP}/SRF < 0.25, Q factor nearly equals the value based on the formula.

The “complete formula for Q based on geometry is (ignoring parasitic capacitance, bare copper, and optimum wire thickness):

$$Q = \frac{\sqrt{f}}{\frac{0.138}{D} + \frac{0.054}{Le}} \qquad [] \qquad \mathbf{3.9}$$

f in Hz, D, Le in m.

Wire diameter
One would expect to use the thickest wire that fits (so turns almost touching each other). In a single wire, the RF current distributes uniformly around the circumference of the wire (skin effect). So using thicker wire, reduces the RF resistance.

However when wires are close together as in an inductor, current concentrates at the outer and inner side of the winding, reducing the effective area where current flows. So AC resistance increases.

Wires sitting very close next to each other are affected mostly (Proximity effect). Therefore you need space between the windings to reduce/overcome this undesired effect.

The wire diameter (d) should be 50…70% of the advance (optimum: d = 0.6·a, for Le/D = 1). Above 75% and below 30% Q drops rapidly.

Insulation
Air is the preferred insulation. Do not use PVC (as used for electrical installation wiring). A thin layer of (spray) coating has only small effect on Q and avoids oxidation of the copper. Enameled wire can also be used (but making electrical connections requires some effort).

Thin sheets of epoxy glass laminate with holes for fixing the windings have negligible effect on Q (as it is thin sheet material). Even PVC thin sheets can be used.

3.2.3. Examples

Online calculator used is from:
https://hamwaves.com/inductance/en/index.html#input

20 uH inductor with Le/D = 1, D = 150 mm, f = 3.6 MHz

Using formula 3.8, Q = 1480

Using formula 3.5B gives a = 15 mm

As we have Le = 150 mm (Le=D), n = 10

Optimum wire diameter (60% of advance) = 9 mm.

Wire length = 0.15*pi*10 = 4.71 m

SRF = 3e8/(4*4.71) = 15.9 MHz

What can we expect?

f_{OP}/SRF = 0.23, well below 0.45, so it is not required to add a correction for Q and or the inductance. Deviation is under 5%.

It is likely that you well get a Q-factor > 1100 when using wire (tube) diameter of say 7...10 mm.

12.8 uH inductor with Le/D = 1, D = 90 mm, f = 3.6 MHz

Using formula 3.8, Q = 888

Using formula 3.5B gives a = 6.2 mm

As we have Le = 90 mm (Le=D), n = 14.4

Optimum wire diameter (60% of advance) = 3.7 mm.

Wire length = 0.15*pi*10 = 4.07 m

SRF = 3e8/(4*4.07) = 15.9 MHz

Now some practical issues
It is an experiment; 1.8 mm thick wire is available. This gives d/a = 29%. This is well outside the 50% to 70% range.

Using an online calculator gives Q = 709 for d = 1.8 mm

The same online calculator gives Q = 892 for d = 3.7 mm

Hence using the thin wire reduces the Q-factor.

I need about 3 mm space between edges of windings to allow connection of clips onto the wire so that I can vary the inductance. Then an advance of about 5 mm is convenient.

We have two options: reduce the diameter and length to keep Le = D. This does increase the number of turns, hence advance reduces. But both D and Le reduces, given relative large reduction of Q factor.

When looking to the complete formula; D has larger effect on Q compared to Le. This is because D has constant 0.138 and Le has constant 0.054. As long as Le/D does not go below 0.45, you will get a good Q-factor. So it is better to make a coil with somewhat smaller Le/D for the 1.8 mm thick wire.

When using Le/D = 1, D = 90 mm, f = 3.6 MHz, a = 5 mm

Using formula 3.8, Q = 888

Using formula 3.5B L = 19.9 uH.

d/a = 1.8 mm / 5 mm = 36%.

Now we place the clip on the position where L = 12.8 uH.

Playing with the Wheeler formula in a spread sheet gives:

Le = 0.065, D = 90 mm, n = 13 (instead of 14.4) L = 13 uH.

Using formula 3.9, Q = 803

Actual Q will be below this, as d/a = 36%, but this is not as worse as 29%.

You lose Q due to the shorter length (le), but gain some Q due to the reduced wire length.

The same calculator gives Q = 713 for d = 1.8 mm

The same calculator gives Q = 811 for optimum wire thickness

So it is not that critical, as the inductor with Le = D = 90 mm has Q = 709.

3.3. *Conclusion on High Q inductors*

- There is a design difference between inductors, and inductors for resonators. This is due to the self-capacitance that causes self-resonance (SRF).
- Q-factor for practical coils can exceed 1000.
- The largest size gives highest Q factor, so use large diameter coils. Le = D is a good compromise, but actual Q is not strongly dependent on Le/D ratio, as long as Le/D is above 0.4.
- Wire thickness needs to be about 50...70% of the advance. Somewhat less thickness is allowed but large (close to 1) wire diameter / advance ratio reduces Q significantly. Though not discussed here, it is not good to use two wires in parallel, always use a single round soft copper wire.
- Operating frequency should be maximum 50% of SRF. Beyond this value, Q drops fast and apparent inductance increases fast. For Le/D = 1, SRF is about $3 \cdot 10^8/(4 \cdot le_W)$. That is the quarter wave frequency of the wire length.
- Use bare copper wire with a thin coating if required. Don't use thick PVC insulation.

4. Implementation, fixed tuning

The picture below shows the fixed single frequency tuner with a dummy load (trimmer capacitor with 2.2 Ohms resistor).

Figure 4.1: Photo of fixed frequency tuner test model.

Note that the matching coil has 4 turns. The coil in the second version has 5 turns to be more flexible in case of having longer dipoles.

This is the test setup for experimenting whether it is worth to invest in a mechanical remote tuning system. The trimmer capacitor is there for testing only and is not present in the actual tuner.

The construction is made to be disassembled easily (all screw connections).

We need to make

- 2, > 12.8 uH inductors (for frequency tuning), Q>600
- 1, > 560 nH (for matching to 50 Ohms), Q > 100
- 1, 1:1 balun that operates at low SWR in a 50 Ohms system

4.1. >12.8 uH inductors

A picture of the inductor is shown below:

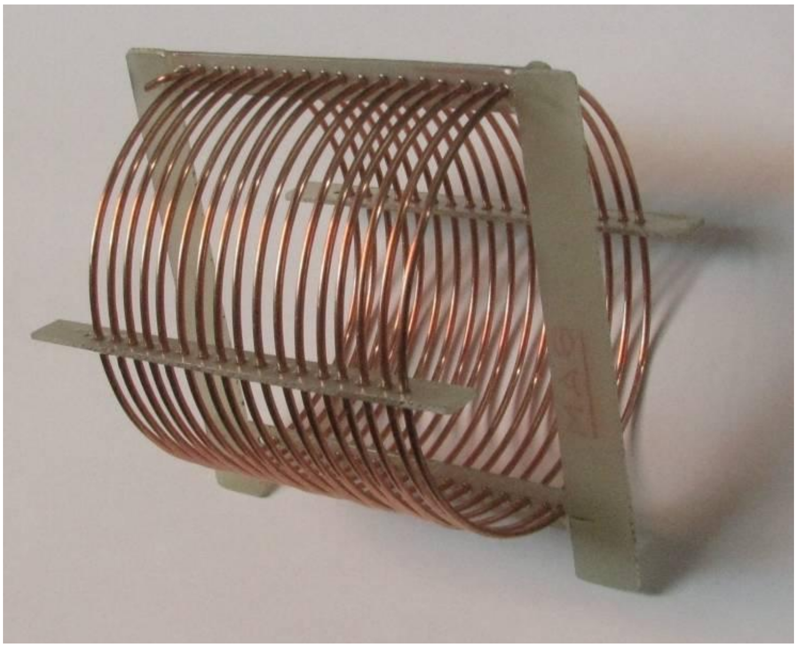


Figure 4.2: Photo of one of the two large inductors.

Putting some numbers in the formulas showed that a diameter of > 80 mm should give Q > 600. Some aluminum is available that is used to wind the coil. When releasing, the coil diameter was about 90 mm.

The inductor shown has:

D = 90 mm, n = 17, Advance = 5 mm, le = 85 mm,
d_{wire} = d = 1.8 mm (2.5 mm^2)

How to make the inductor

4, 10 mm wide strips of 1.5 mm thick FR4 epoxy laminate are put together. 18, 2 mm holes were drilled (when using 1.8 mm wire). Break the edges on both sides of all holes using a countersink drill bit. This is to assure good fixing of the windings. Sand the strips for good adhesion of the resin or glue.

Make two flat strips that are several cm longer then the coil diameter. The excess length is to fix the final coils onto the base.

Glue (2 comp. epoxy glue) the flat vertical sections onto two of the strips. Make sure the distance of the array of holes is 90 mm, clean and sand before adding the resin/glue. Note that if your diameter is somewhat different, match the distance to the diameter of the coil instead of using 90 mm.

The tough thing is to put the coil onto the reinforcement strips. You first wind the coil onto a rigid round tube. Then turn the coil into the strips. Yes, this will take some time. Use clean hands to avoid a fatty layer on the copper, as this will guarantee bad adhesive joints between copper and strips.

Add little thin slow curing epoxy glue onto the strips (use a pencil). This sucks into clearance between the wires and the holes in the strips. When using fast curing epoxy, you don't the time to apply it.

Fix the coil and let it cure. After curing (this may take some days) you have a very rigid coil!

Measurement using resonance with high Q air dielectric capacitor showed
Q > 600 @ 3.4 MHz.

Terminations
The inductance needs to adjustable. Adjustability is also required when adding the tuning option, as the tuning range is limited to the 80 m band. Brass clips are used on the low impedance (input) side to select the desired inductance.

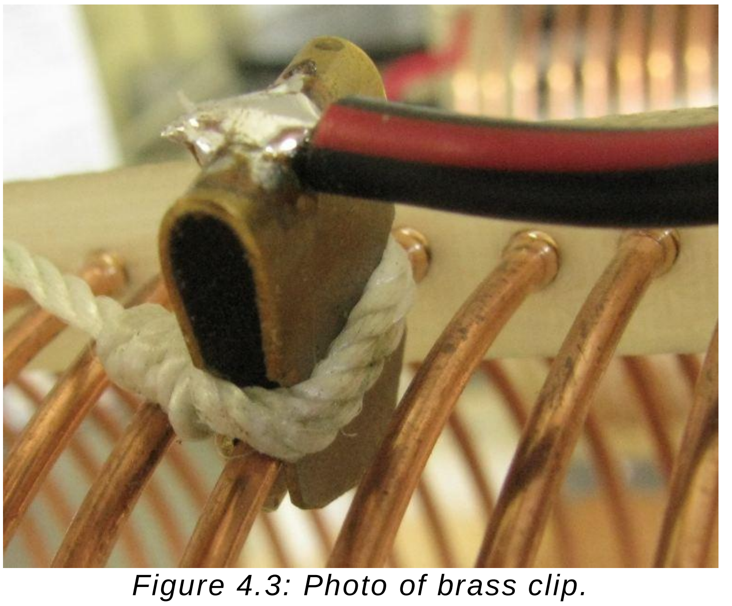


Figure 4.3: Photo of brass clip.

The clips are made from brass strips of 0.5 mm thickness and about 10 mm wide. Edges are rounded before bending the strip into the U-shape. Then notches for the wire are made (using a round file). This keeps the nylon (PA) wire on its intended position. The friction knot gives additional clamping force. On top a third notch is made to ease soldering. There are sure better solutions for the clips…

The output side (high voltage side) has a soldered fixed connection, see picture below. Sharp clips would provoke air breakdown.

Figure 4.4: Photo of brass seat for feed line connection.

Actual dipole connection goes via a clamping system where the dipole wire is clamped onto the brass seat. Make sure to round all edges of the brass seat to avoid air breakdown. A 5 mm long, 3 mm wide slot in the brass seat receives the flexible copper wire. Excess solder can be removed mechanically (file, knife or sanding paper).

Note that the brass seat should not touch the screws. The plastic can be PE, PA, PP, PVC, etc. Be careful when using carbon black colored plastic (this is frequently sold as acceptable for outdoor applications).

The picture also shows how the tuning coils are mounted onto the 30*30 mm^2 supports (press fit).

For ease of installing the feed line wires, it is better to cut thread into the plastic and use screws, or use wood stud screws (Dutch: stokeind).

4.2. >560 nH inductor (for matching)

A picture of the coil is shown below (without the tap).

Figure 4.5: Photo of matching coil.

The inductor is at the low voltage side of the tuner, so here sharp edges are acceptable. It has an inductance of about 1.2 uH. This enables matching of longer dipoles (that have larger radiation resistance). When you plan to use short dipoles only, 4 turns is fine.

As the loaded Q is below 5, High Q factor isn't required.

D = 55 mm, n = 5, le = 35 mm, d = 2.8 mm (6 mm^2 tinned ground wire)

The coil is rigid so it doesn't need any support between turns. It is bolted onto a plastic support using M4 nuts and bolts. The heads of the bolts do not touch the wood. The complete assembly is mounted onto the wooden base with self-tapping screws.

When using low temperature plastic (such as PP or HDPE cutting boards) it is best to first solder the connection wire onto the coil, and then assemble the coil with the plastic support.

It is not recommended to bolt the coil directly onto wood, unless you live in a dry area.

Terminations
One side of the coil is connected directly onto a terminal of the balun (via the flexible wire). A brass clip is used to vary the inductance to get the best match (not shown on the picture of the inductor.

When tuning within the 80 m band, it is not required to change the tap on this coil.

4.3. Balun

As the antenna and tuner is fully balanced and matched to 50 Ohms, a simple 1:1 balun or CM choke can fulfill the balanced to unbalanced transition.

A real air balun (not a choke) is used in the first fixed-frequency tuner:

Figure 4.6: Photo 1:1 "air cored" voltage type balun.

A ferrite loaded balun is much smaller and consumes less coax. It is used on the tunable version to make space for the sledge that is part of the tuning mechanism.

Below a real 1:1 balun is shown (epoxy for water proofing not applied yet for clarity).

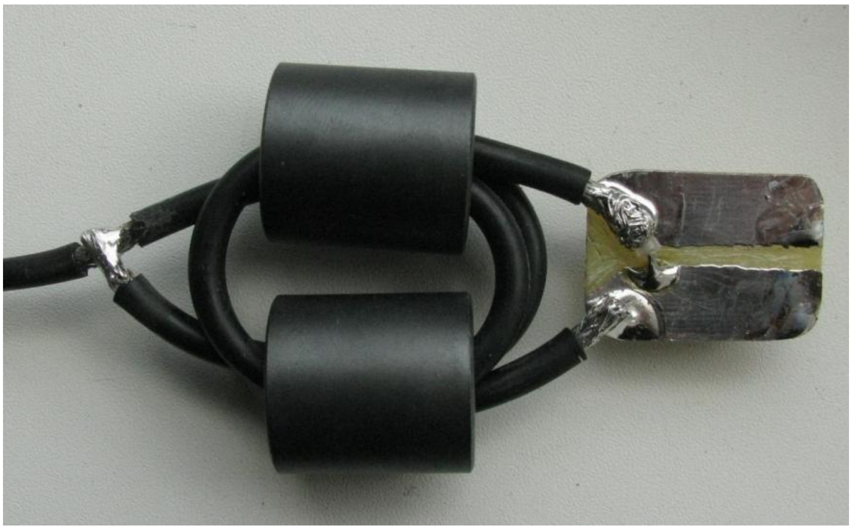


Figure 4.7: Photo 1:1 ferrite voltage type balun.

Cores are 28 mm long and the material is 28B (Steward / Laird). Most EMC materials for HF or VHF can be used. It has a relative permeability of around 400…1000. Of course, one can also stack smaller cores to get similar or more core length (that is > 28 mm).

Flux density at 100 W input with 50 Ohms load is < 5 mT (peak) at 3.5 MHz using the 28 mm long cores. The core cross section (single core) is 180 mm^2. When using other cores (or a stack), keep about 180 mm^2. Of course you can use smaller cross section, but then you may need more turns to keep losses acceptable.

Cable routing through the cores
The coaxial cable carrying the signal (RG58) enters from the left into the upper core and passes through it. It then goes down and goes through the lower core (from right to left). It goes up and goes through the upper core again. Then it enters the PCB. The center conductor passes the gap and is soldered onto the lower part of the PCB.

The compensation winding uses the braid only. It is connected to the braid of the signal cable and goes through the lower core. Then it goes through the upper core (from right to left), and goes through the lower core again. It enters the PCB and is connected to the lower part of the PCB only.

The compensation winding assures perfect balance as seen from the balanced side. As seen from the balanced side, there are three full turns that pas through 2 cores. This provides more than sufficient impedance. Instead of coaxial cable, you can use other (stranded) wire.

No load: SWR > 23 at 3.7 MHz, 50 Ohms load: SWR < 1.1, all with 2 m RG 58 cable included. This is a wide band design, and can be used to at least 80 MHz with SWR < 1.2. So it is useful for a multi-band fan dipole.

CM choke instead of real balun
This balun is used for measurement purpose, but strictly spoken it is not required. A simple common mode choke is also fine.

One can just pass the signal coaxial cable three times through a similar core, then three times through a second core and connect the coaxial cable to the balanced tuner. This saves you from making the braid-braid connection and gives sufficient common mode suppression.

When using large aperture ring cores, you need more than three turns to get sufficient impedance as impedance for a single turn is less compared to the impedance for these cores.

Air cored balun
When you don't have (or don't like) ferrite, you can use the air cored balun as shown, as long as its inductance as seen from the balanced side is above 1.5 uH. The turns may touch, or even bound together. It provides higher inductance.

An air cored CM choke isn't recommended unless you are fully sure how to design/build it.

Construction
Construction of the ferrite loaded balun shown in the photo is relatively straight forward. The connection of the braid can be troublesome.

Best is to use "fresh" coaxial cable with a shiny braid. Remove about 10 mm black jacket from the cable where the compensation cable will connect.

Before soldering at 260 degrees C, a very small amount of Chemtronics CW8300 water soluble flux is applied. This flux can be mixed with regular flux cored solder. Add lots of solder during tinning. This tins the braid quickly. Make sure not to press hard, as this will cause a short circuit between the braid and the center conductor. When you can, tin the braid without additional flux. It is better. You may try a liquid rosin based no clean flux on a sample piece. For Dutch builders: do not use S39 flux together with rosin flux cored solder! It makes a real mess.

When soldering the compensation winding onto the signal cable, first tin the compensation cable, than make contact with the braid of the signal cable. Use sufficient tin so the braid is fully soaked with tin. You may add a ground termination at the connection of the braids (for example for DC feeding, or RF grounding).

When ready, remove solid flux, clean with some solvent and leave the balun about a day on a warm surface to remove all moisture/water. Scratch the black jacket at the jacket/braid interface to get good adhesion. You may do this already before soldering, but the adhesion reduces when heating the jacket.

Then apply epoxy glue or other coating to seal the solder joints. This also avoids corrosion in case of some flux residue is still present. If present, leave the ground termination blank.

4.4. The dipole

The dipole requires 26 m of wire and is shown below:

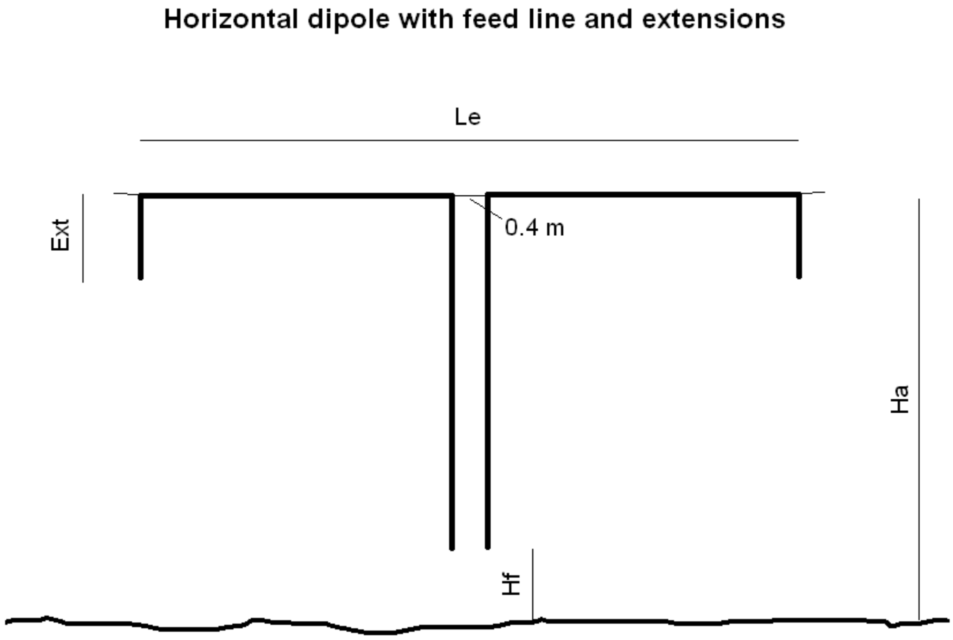


Figure 4.8: Dipole with extensions and balanced feed line.

Overall length is 10.4 m (Le), The extensions (Ext) are 2 m. Height (Ha) is 7 m. The feed line is 6 m. Therefore the matching circuit is 1 m above ground. If you want your tuner on the ground, you need additional wire! If you have more length available, you may increase the length. Series inductance (in the tuner) will be less as well as voltage and current). Going below 10 m is not recommended, unless reduced efficiency is acceptable (for example when using weak signal digital modes only).

I used Alpha Wire, 12 AWG (about 3.3 mm^2) tinned stranded copper wire with mPPE insulation (Alpha Wire product number: 6718 BK005, ECO wire).

H07V-K <HAR> switchboard stranded wire is also suitable, as it has relatively thin PVC insulation, is easy to get, and cheap compared to “specialty” wiring. When possible, use 4 mm^2. Remind yourself that this is heavy wire compared to 2.5 mm^2.

You may use real copper speaker wire of 2.5 mm2 or more. You may lose some efficiency due to the thick PVC insulation. You will notice this when measuring the SWR=2 bandwidth (it will increase).

Do not use cheap Copper Clad Aluminum speaker wire, unless reduced efficiency is acceptable.

You may also use heavy gauge special antenna wire, but check the price before buying!

Don’t forget to create a small loop at the wire terminations (see figure 2.3). A loop that has D = 50 mm is sufficient.

You may need one or two spreaders to keep the feed lines spaced. Do not use more spreaders then needed as they may introduce loss. I used square lashings (Dutch: kruissjorring) to fix glass fiber rods (D = 2 mm) onto the feed lines. The knots were impregnated with petrolatum.

I didn’t use special insulators, but just knotted 3 mm polyester rope onto the wires. Then I applied a thick layer of petrolatum (Vaseline) and used a heat gun to soak the petrolatum into the polyester rope. Petrolatum avoids penetration of moisture/water between the fibers.

Polyester rope from recycles PET bottles is very fine, and has good UV protection.

4.5. Balancing

Though the tuner is fully balanced, it doesn’t automatically mean that the complete antenna system is fully balanced.

In many practical situations the dipole isn’t fully balanced.

- One side is close to a large metallic object (for example metal drainage components, concrete wall, roofing material with metallic moisture barrier, etc).
- One side is elevated (so the antenna is sloping)

So the dipole may look fully balanced, but it is likely not due to coupling with nearby structures.

When the antenna system (that is antenna + tuner) is not balanced, there will be a common mode voltage between the tuner and ground (see the A-figure of figure 4.9). A short piece of cable (say about 1 m) is too short to support significant common mode current at 80 m band. So you will not notice this unbalance when using a battery powered analyzer.

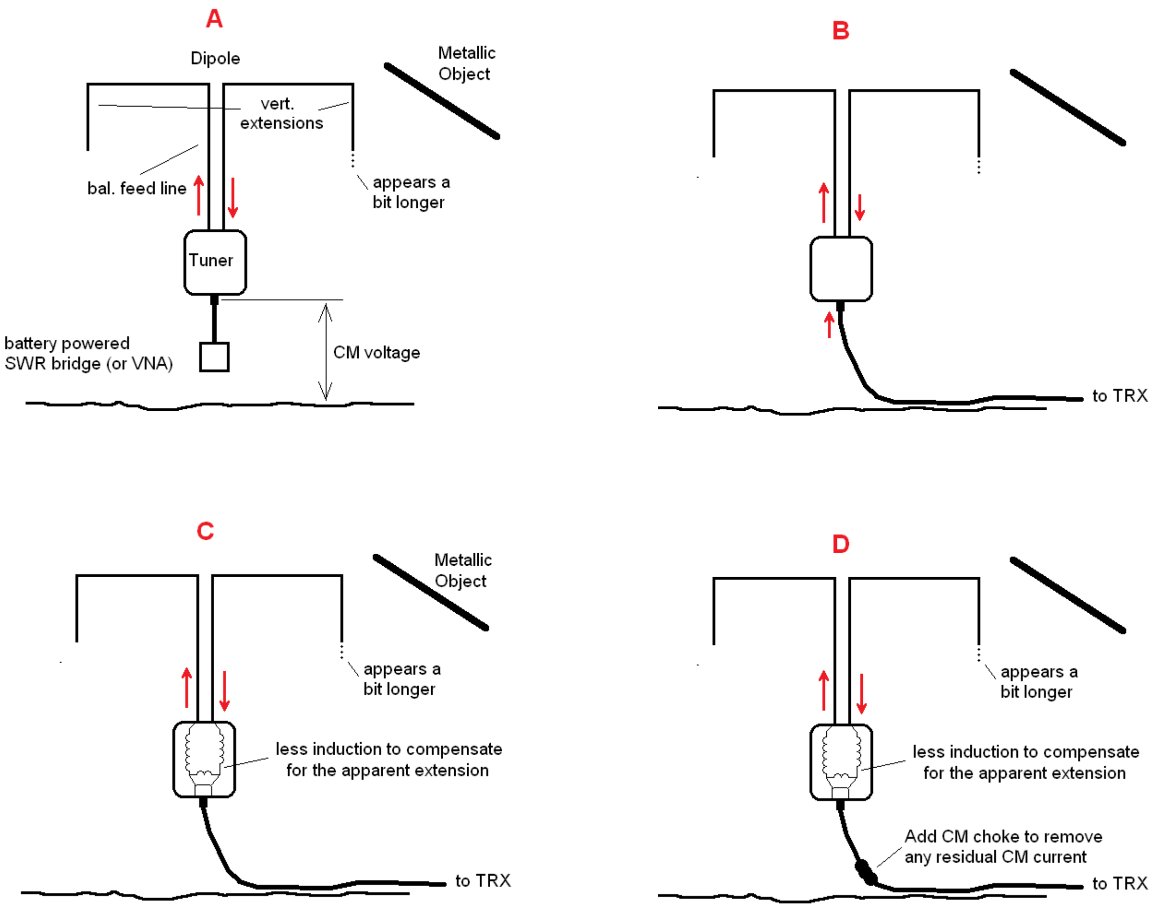


Figure 4.9: Antenna System Unbalance and Balancing with the tuner.

When you install the (long) cable between tuner and transceiver, a common mode current may flow in both the cable and the balanced feed line between the tuner and the dipole. This is shown in the B-figure.

Common mode current is not desired because of:

- A common mode current in the balanced feed line will introduce vertically polarized radiation that isn't useful for NVIS, it is wasting of power and may cause RFI.
- The cable will also radiate, this is also wasting of valuable RF power.
- From an RX point of view, the balanced feed line and cable may pick-up noise.

As the voltage across the feed line is relatively high (about 4.7 kVpk), relative small unbalance will generate several hundreds of Volts between the tuner and ground. So it is best to get reasonable balance first. The remaining unbalance can be corrected with a good common mode choke.

There are several ways to measure the unbalance in the system:

SWR measurement
When you have a battery powered SWR meter or battery powered VNA, tune the antenna via a short cable between tuner and instrument (the A-figure).

When done, connect the coaxial braid to a ground stake, large/long metal part, or the braid of the coaxial cable that goes toward the TRX. This allows flow of common mode current. When SWR change (say with more then 0.1 point), you have significant common mode current.

Common mode current measurement
When a long cable is connected to the antenna, or the tuner is grounded, one can measure the current through the ground conductor or the cable common mode current. Easiest way is by using a current probe based on a large (split) ferrite (see annex). You may need several Watts of input power to be able to measure the current using a passive (diode detector) current probe.

SWR measurement with Common Mode Choke
If you have a good CM choke (that is > 5 kOhms at 80m), observe the change in SWR when adding/removing the CM choke (see the D-figure). Adding or removing a CM choke (close to the tuner) should not change SWR with more then 0.1 point.

There are two ways of balancing the antenna system:

1. Modifying the length of one of the dipole halves
2. Creating intentional unbalance in the tuner.

Method two is shown in the C-figure.
Due to the capacitive coupling between the right dipole half and the metallic object the right dipole half appears a bit longer. That means the inductance of the coil in that arm should be reduced a bit. This is easy, just move the clip a bit. To maintain tuning you may need to increase the inductance of the coil in the left dipole arm.

Check for CM current and repeat until SWR no longer depends on cable length or grounding of the tuner.

When done you may add a CM choke as shown in the D figure. When you opt for the remote tunable version, the DC wiring also needs choking. When using a ferrite choke, one can run the DC wiring together with the coaxial cable through the ferrite.

5. Implementation, tunable version

5.1. Introduction

Tuning requires change of geometry. We don't want to change the length of the dipole (for example with a pulley system), but this can be an option.

As we have an inductor-only tuner, we need to change the inductance of the two 12.8 uH inductors. Options:

1. Compressing the coils (that is changing the length).
2. Splitting in two coils and change the orientation/coupling (variometer)
3. Movable ferrite
4. Single turn secondary winding with varying coupling. This looks like a variometer, but one coil is a short circuited single turn.
5. Tunable series or parallel capacitor

Coil compression is mechanically demanding.

A variometer is an option as there are many examples around. Relative large Lmax/Lmin is possible.

A sliding ferrite seems possible also. Calculation is carried out together with small signal measurement. Flux density is acceptable, but there are doubts about the variation of ferrite permeability vs peak flux density.

From another project I know that the resonant frequency slightly changes with increasing flux density. It initially goes down, and at excessive flux density it goes up. Q-factor is relatively high in the 80 m antenna project. SSB modulation may result in small phase modulation.

Single turn shorted secondary I used in UHF tuners. It is frequently used in so-called "helical filters". It is a fully linear system, and you don't need to modify the geometry of the inductors. Depending on the requirement for Lmax/Lmin ratio, you may experience reduction of Q-factor.

The tunable capacitor requires a larger inductor and the voltage across the inductor (and capacitor) increases. A parallel capacitor requires a smaller inductor, current through both inductor and capacitor increase.

What inductor tuning range do we need?

As resonant frequency is proportional to rt(1/LC), Lmax/Lmin ratio should be in the range of:

Lmax/Lmin = (3.8/3.5)^2 = 1.18.

This is not the complete story, some of the inductance is in the antenna itself, and therefore the reactive part of the antenna impedance varies with frequency.

From simulation:

Le = 10 m, Ha = 7m, Hf = 1m, dwire = 2 mm, copper loss included,
Ext = 2 m, NEC moderate ground

Freq [MHz]	Z	Eq. Cap. [pF]	Req. Ind. for resonance. [uH]
3.50	2.05 – j657	69.2	29.9
3.65	2.18 – j610	71.5	
3.80	2.33 – j565	74.2	23.6

The capacitance appears to increase with factor 74/2/69.2 = 1.072 (from 3.5 to 3.8 MHz). To counteract this, the inductor tuning range needs to be:

Lmax/Lmin = 1.18·1.072 = 1.27 (or use values from table above).

When you connect an RC load (for example 2.2 Ohms, 71.5 pF), the tuning range should have Fmax/Fmin = rt(1.27) = 1.127. This can be from 3.5 to 3.944 Mhz (that is a range of 440 kHz).

NOTE:

When using a larger dipole, the relative inductor tuning range has to increase, as larger part of total inductance is in the antenna.

5.2. Tuning experiments

I started with the ferrite option, but the short-circuited turn is cheaper, and material is in stock (aluminum tubing, copper foil, etc).

The same 90 mm diameter coils are used, but one leg is removed to enable entry of the single short-circuited turn.

The single short-circuited turn is just aluminum tubing with D = 50 mm and length = 85 mm.

The figure below shows the setup. Basically it is the fixed-frequency tuner, but a sledge is added that carries the single short-circuited turns (the tubes).

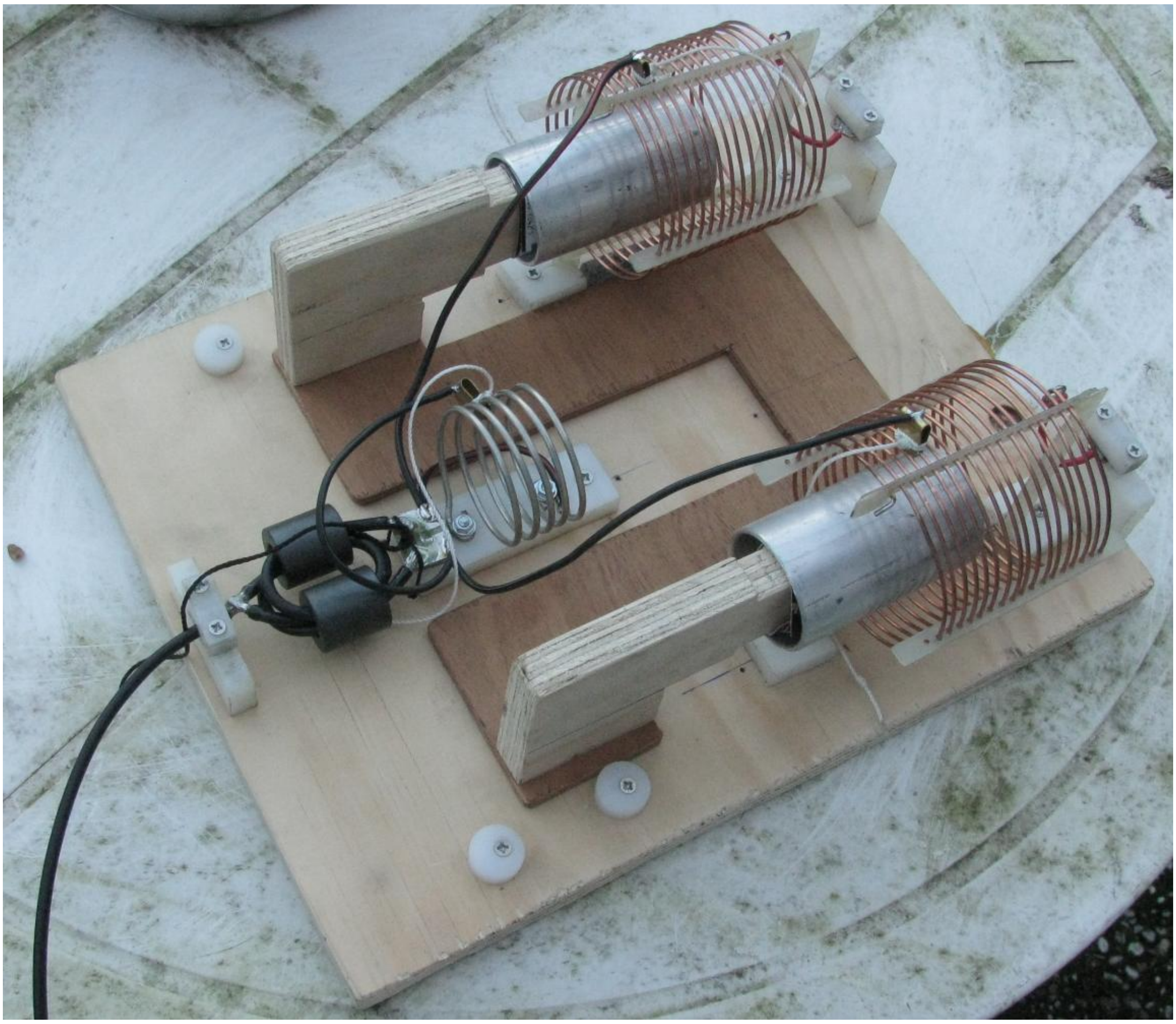


Figure 5.1: manual tunable tuner using short circuited turn, test model.

When the tubes are brought into the coils, the inductance reduces, hence the antenna resonant frequency increases.

The white disks are for guiding the sledge. The screw holes are off-centered to enable adjusting of the clearance and the path of the sledge. Of course many other options are available to make a sledge guide.

Some test results.

The tuner is terminated with a fixed RC Load (2.2 Ohms in series with 70 pF Sledge is move fully left (so tube are not in the coils). Tuner is tuned to 3.5 MHz using the clips. SWR = 1.

Tubes are moved into the coils and resonant frequency increases with 420 kHz, SWR remains near 1. This is just insufficient as 442 kHz is required.

When 300 kHz is absolutely required, one may use 55 mm tubing when using 90 mm coils. Using 60 mm may increase the loss resistance of the coils.

Increase of loss resistance.
Some increase of loss resistance was expected due to eddy current loss in the aluminum. The loss resistance, when moving the tubes into the coils, increase < 10%. SWR remains near 1 at 3.92 MHz.

When increasing the tube diameter to 60 mm, it may be better to use copper foil instead of aluminum tubing. Soft copper has significantly less surface resistance.

5.3. Practical notes

Mechanical
The sledge should have small guiding clearance so that both tubes go in and out the inductors simultaneously. The off-center mounted white rings enable easy adjustment of sledge guiding clearance. Of course other solutions are possible (and may be better).

When using HDPE plastic (cutting boards) for both sledge and base, you don't need provisions for reducing friction, as HDPE has very low friction coefficient.

When using wood, you need some PE interface to reduce friction. wood on wood (or painted wood on painted wood) gives relative high friction, making tuning difficult. You may overshoot the point of good match (from experience). I used PE tape on top of the base and at the bottom of the sledge.

You may install some grip to have easy one-handed access to the sledge (so that you can use your other hand to operate the transceiver or analyzer). Design it such that you hand is always on the left side (balun side) of the tuner so that your hand is not at the high voltage side.

When using wood in an outdoor environment, you definitely need to apply several layers of paint. You don't want high amount of moisture in the sledge or base.

You may add frequency markings on the base to ease tuning.

Initial position of the wire taps
When tuning for the first time, move the tubes out of the inductors and tune the antenna using the taps at the lowest frequency (that is 3.500 MHz). Make sure to check for lowest common mode current. When moving the tubes into the inductors, the resonance frequency of the antenna increases. If you don't do CW and/or digital modes, you may do the initial tuning at say 3.590 MHz instead of 3.500 MHz.

Tuning procedure
As this is a narrow band antenna (BW = 14 kHz for SWR=2), you need to check the step size of your antenna analyzer if you use SWR sweep mode. RigExpert analyzers have typically 80 steps in one sweep. When you select a 1 MHz span, you have 12.5

kHz steps. You will very likely miss the resonance dip and you may think that you SWR is bad.

During normal operation, you don’t need an analyzer. First tune by listening to the noise (maybe with AGC off), or tune for maximum noise reading on the S-meter. Then fine-tune with low power key-down and observing the SWR. So you don’t need to switch between transceiver and analyzer. Adjust the tap on the matching inductor (4..5 turns), and repeat until SWR is fine.

If you have an analyzer with Smith Chart presentation
When tuning at the lowest frequency, adjust the matching coil so that the S11 curve encircles the origin with SWR of about 1.2. That means the input impedance at the balanced side of the balun is somewhat less then 50 Ohms.

When tuning at a higher frequency the impedance increases gradually to somewhat above 50 Ohms giving a very well match over the complete 80 m band.

When having SWR only indication
First tune at the lowest frequency for best SWR (tubes out of coils, use the taps). Then tune to mid band using the sledge. Adjust the tap on the matching coil, and tune again with the sledge. Repeat this until you have best SWR around the mid band frequency. This will give you good SWR across at least the complete ITU region 1 80 m band.

6. Implementation, Remote tunable version

6.1. Introduction

For operating directly below the antenna, one can have the tuner close to the operating position. Manual tuning is possible then. In other situations every time going outside for tuning will be frustrating after some time.

One can extend the feed line somewhat, but making it too long will result in poor tuning range, and/or you need series capacitors.

There are several means to make the remote tuning. Next section will give some information on the requirements.

6.2. Required power, torque, force and speed

The displacement of the sledge is about 120 mm, so the tube can be moved fully inside the inductor and far enough away. The weight of the sledge + metal tubes is less the 0.5 kg.

Assuming a friction coefficient of 0.3, the force to move sledge will be about:

$$F_{move} = 10 \cdot 0.5 \cdot 0.3 = 1.5 \text{ N}$$

Assuming the tuner is horizontally oriented.

Required energy, $E = F \cdot s$

$$E = 1.5 \cdot 0.12 = 0.18 \text{ J}$$

How fast should the sledge move?

We have a tuning range of about 300 kHz, and a Bandwidth (SWR=2) of about 14 kHz. When the sledge moves too fast, tuning will be troublesome, or you need some form of proportional control (for example with a stepper motor and control logic).

For the time being, a simple on/off control with push buttons is assumed using a DC brushed motor. So direction of travel is determined by polarity. An SWR meter (external or part of the transceiver) is used as indicator during normal operation.

The guess is that when the region with SWR<2 takes about 1s, tuning should be easy. In case of linear relation between position of sledge and frequency, we have 300/14 = 22 bins with a 14 kHz width. So tuning time from lowest to highest frequency would be 22s.

It is sure the sledge position isn't linear related to tuning frequency, so it is a good idea to have some margin. Let us say tuning takes 30 s. That means the sledge should move about 0.12 m in 30 s.

Then the required power to move the sledge will be:

$P = E/t = 0.18/30 = 6$ mW

Vsledge = 0.12/30 = 4 mm/s

This is not equal to the required shaft power of an electric motor. There is friction and some power is required to accelerate the sledge. When using an optimized reduction with rotation to linear movement conversion, a motor with about 12 mW shaft power would be possible. Assuming 30% efficiency, the electrical input power would be in the 40 mW range.

Using a lead screw drive

When using a lead screw drive, efficiency can be very low. The reason is the friction in the "lead screw – nut" system. A ball screw is way too expensive and not necessary.

Calculation for M6 threaded rod with a PE (polyethylene) lead screw nut, friction coefficient of 0.3 between steel and PE.

Common M6 threaded rod has an advance of 1 mm/revolution. So to move the sledge 120 mm in 30 seconds, the rod has to do 120 revolutions in 30s. That are 4 rev/s, or 240 RPM.

The rod has to push the sledge forward (via the PE nut). The required axial force is Fmove = 1.5 N.

The tangential friction force to rotate the rod would be 1.5N·0.3 = 0.45 N. For an M6 mm rod, that would require a torque:

Trod = 0.45N·6m/2 = 1.4 mNm (14 gr·cm)

$P = T\cdot\omega = = 2\cdot pi\cdot T\cdot(rev/s) = 2\cdot pi\cdot 1.4m\cdot 4 = 35$ mW

The rod has to transfer the force on a bearing that is fixed to the base. This will likely be a friction bearing. I used a 3 mm home built friction bearing and that requires a torque of about 40% of Trod.

So there will be 35*0.4 = 14 mW loss in the friction bearing. We still have the 6 mW to move the sledge.

Required shaft power = Pleadscrew + Pbearing +Psledge

Required shaft power = 35 + 14 + 6 = 55 mW, at 4 rev/s (240 RPM)

Assuming that everything is well aligned (and that isn't a trivial task). When there is some misalignment, required torque increase rapidly (from experience).

These simple calculations show that a very small motor can be used. I used a MABUCHI RF-300EA-1D390 DC motor with metal brushes, provided by PE1NWK (Marco). They are used frequently in CD-ROM drives to open/close the tray.

It provides 170 mW shaft power at 3520 RPM / 0.47 mNm, at an electrical input of 3.9V / 84 mA / 327 mW.

Note that these motors have a friction bearing. When applying radial force on the shaft, available torque drops rapidly (from experience).

Fixed nuts on the lead screw (the M6 threaded rod) limit the travel of the sledge.

Required electrical power
This is taken from the MABUCHI FR-300EA datasheet; 3.9V, 84 mA at 170 mW output, 21 mA no load current.

We require 55 mW (instead of 170 mW), so the motor current will be likely in the 45 mA range. Measurement showed about 60 mA / 4.2V / 250 mW.

Once the lead screw nut reaches the end stops (fixed nuts with a thick plastic washer), current increases. With current limitation and a current limit indication, no additional means are required to monitor the position of the sledge.

6.3. *Practical implementation.*

Everyone has its own experience, knowledge, available materials and available tools. I used the lead screw drive as it doesn't require gears. Sure, other, better solutions are possible. It all depends on your creativity and available materials.

Below pictures of the actual implementation are shown.

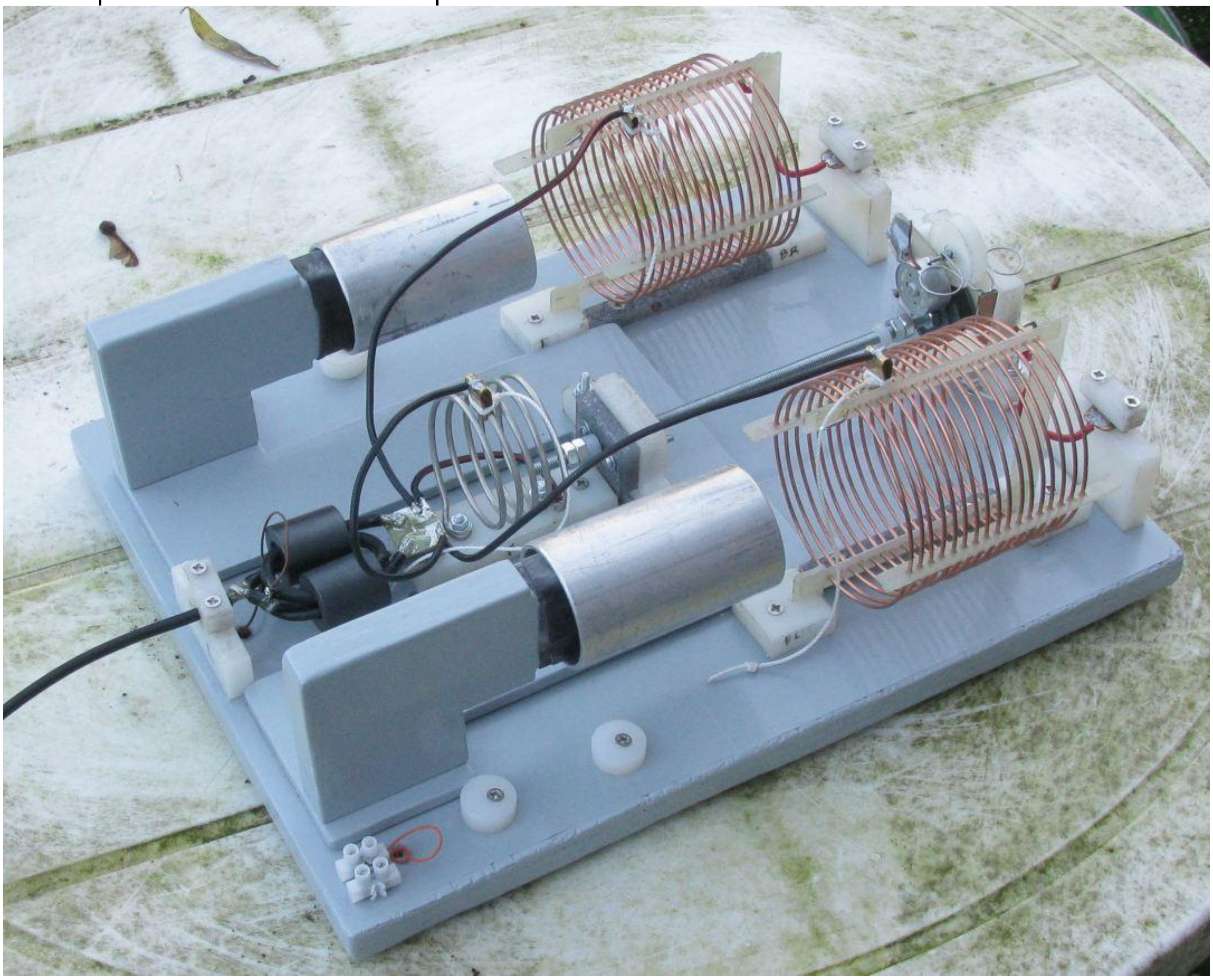


Figure 6.1: remote tuner, perspective view, highest tuning frequency.

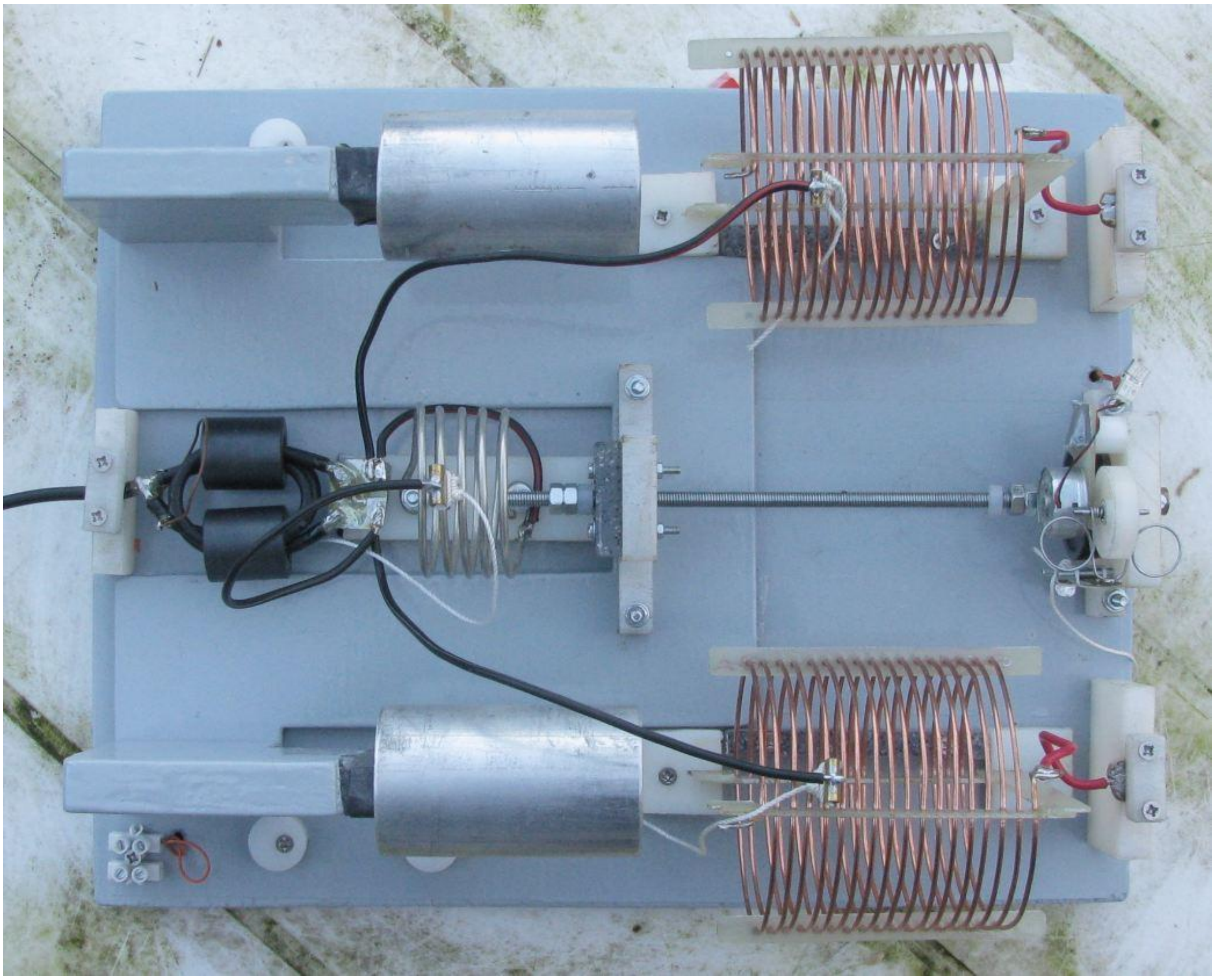


Figure 6.2: remote tuner, top view, highest tuning frequency.

The terminal block down left is for connecting the DC wire from the motor controller. The wire has been connected to the coaxial feed line with many whippings. The braid is used as return. Note that the wires that go to the motor run in the symmetry plane at the underside of the base.

6.4. Implementation, mechanical

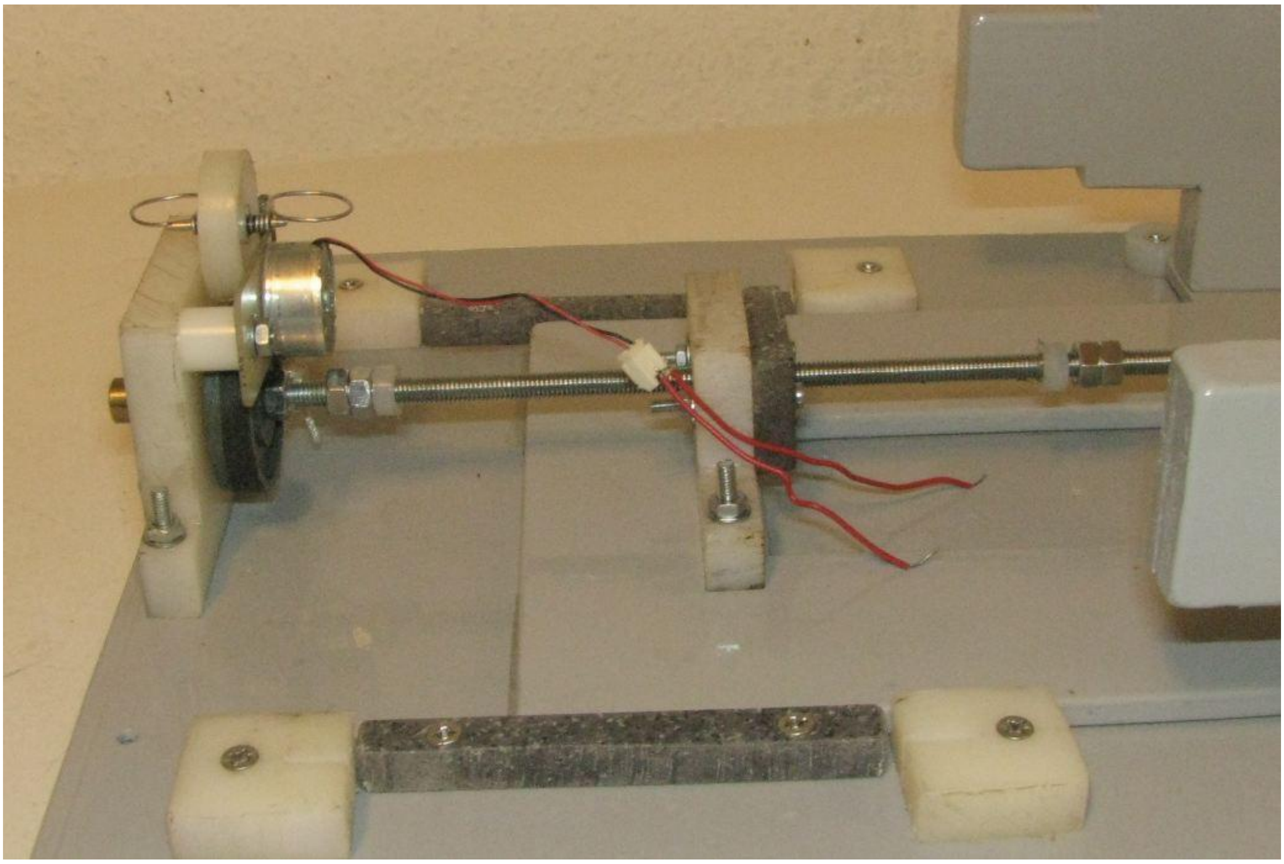


Figure 6.3: lead screw drive, detailed view, inductors and tubes not shown.

The white support on the sledge (figure 6.3) carries the lead screw nut (dark part, made from a HDPE cutting board). The "nut" is mounted on the right side of the support. It can be moved with respect to the support to enable fine adjustement. You may experience too much friction after cutting the M6 thread. If so, you may cut thread in a refrigerated piece of HDPE. It gives some additional clearance. The additional backless is more than acceptable for this tuner application.

The dark 40 mm disk (here PVC) with rubber ring on it (from a bicycle tube) drives the M6 rod. The 2 mm shaft of the motor is pressed onto the 40 mm disk (here PA6) via the white disk with spring suspension. The motor itself can freely move up and down. The "2 mm motor shaft / 40 mm disk" combination gives a reduction of factor 20.

Pushing the shaft onto the 40 mm disk (via force at the motor body) introduces significant radial force onto the bearing inside the motor. This significantly raises the current consumption due to friction. The range between good operation and stall is very small. Therefore the white ring on top of the motor shaft "removes" radial force from the motor's bearing.

To reduce friction between sledge and base, both base and sledge have PE adhesive tape on them.

The motor runs at 4.2V, and it isn't fully loaded, therefore RPM = 4000 (66.6 rev/s). The "2 mm motor shaft / 40 mm disk with rubber" combination reduces this to 66.6/20 = 3.3 rev/s for the lead screw (M6 threaded rod). As it has an advance of 1 mm, the sledge speed will be 3.3 mm/s. So it takes 120/3.3 = 36 seconds to move the two aluminum tubes fully in and out.

This is slightly slower then my initial guess, but I can grow old with that.

The bearing in the most left white support is just a 3.2 mm hole carrying a 3 mm shaft (so it is a friction bearing). A 3 mm hole is drilled in the lead screw and a 3 mm thick short piece of stainless steel is pressed into the hole (press fit). The excess length goes through the white support at the left part of the base. A brass piece with small screw secures the 3 mm shaft.

If you plan to copy this drive, you need a means to drill holes perpendicular to surfaces. This is very important to have a smooth running lead screw drive system. You can use pieces of round bar for the 40 mm disk and white disk. All holes for bolts have some clearance to enable adjustment for smooth running.

The white support on the base and the white support on the sledge need be perpendicular to their surfaces, otherwise you will get additional friction.

6.5. Implementation, electrical

There are many ways to do this. Several people may opt for a stepper motor. Here the solutions are limited to a DC brush motor. So you need polarity reversal to tune up and down in frequency.

The goal is to have remote tuning that can be coarse tuned by listening to the noise and/or looking to the S-meter. So the electronics should not produce too much noise. Final tuning is based on SWR during key-down with low power.

First step to reduce noise is to put the motor in the symmetry plane of the tuner, and to put a capacitor across the wires. I used 100 nF film capacitor.

The electronics should provide a near constant voltage (with polarity reversal) and a fast current limiting action. The current limiting is to have smooth start-up and to avoid excessive force when the sledge encounters the end stops. It is also desired (better read as "must have") to have an indication when current limiting is active. This shows you that the sledge reached the end stops. Of course a current meter can also be used, but I prefer a LED solution.

The MABUCHI RF-300EA-1D390 DC motor with metal brushes requires about 3.9V with current limiting of about 100 .. 150 mA. Final current limit setting will be made based on experiments.

There are several solutions

1. Full bridge switching voltage / current limited circuit, with push button control
2. Full bridge linear voltage / current limited circuit, with push button control
3. Single polarity switching voltage / current limited regulator with push button control
4. Single polarity linear voltage / current limited regulator with push button control

Given the low power requirements, switching topologies were rejected (noise and complexity).

A full bridge circuit can be fed from the transceiver's supply, provided that you have an isolated motor. That means you need two wires that go together with the 50 Ohms coaxial cable.

A single polarity solution can only be used when having double pole push buttons, and an isolated motor. When having an isolated supply, the motor may be grounded. The advantage is that the coaxial screen can be used as return path and you may even use the center conductor as DC conductor via bias tees.

I took the single polarity linear voltage / current regulator and an isolated supply with two, double-pole push buttons. At this moment the braid is used as return conductor, so I need a separate wire in parallel with the coaxial feed line. This may be changed in the future.

Some pictures

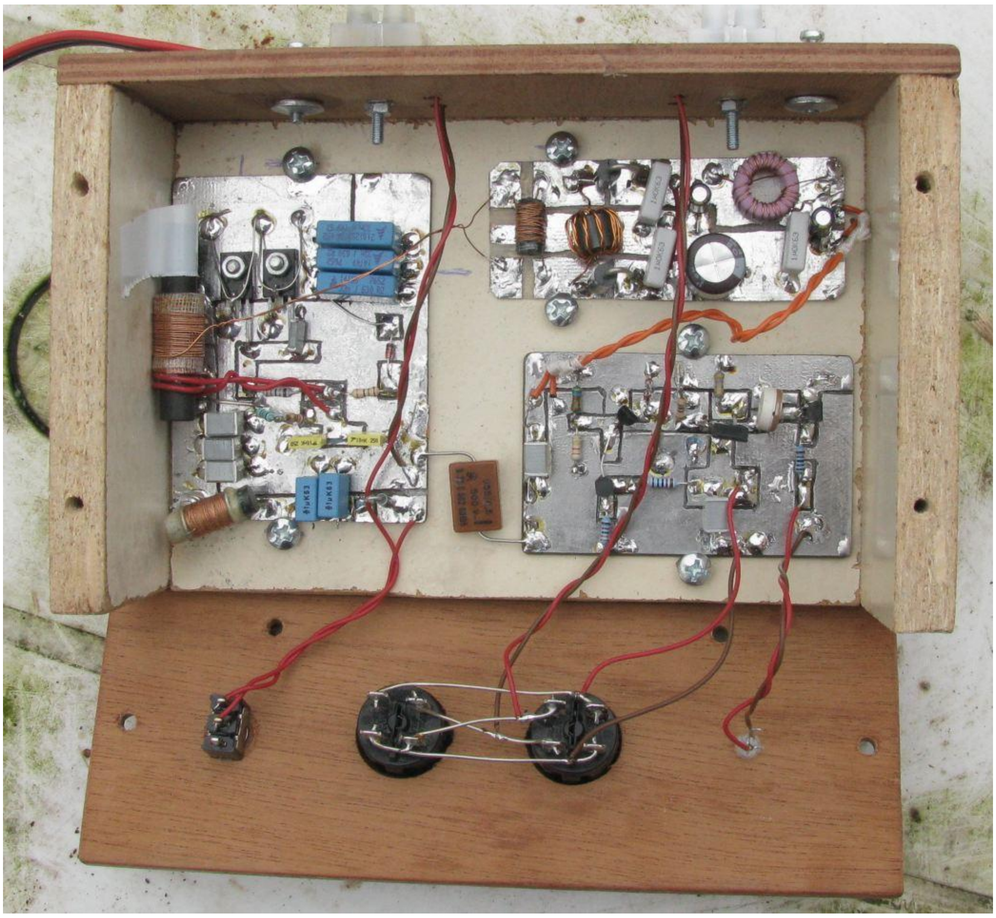


Figure 6.4: Overview of Motor Controller.

Figure 6.5: Assembled Motor Controller.

Figure 6.4 shows the complete circuit in its housing. The voltage / current regulator is on the lower right PCB.

The push buttons for the polarity reversal are shown. A main rocker switch is present, and a LED for indicating overcurrent condition. Figure 6.5 shows a perspective view.

The left circuit in picture 6.4 is a power sine wave oscillator (200 kHz / 5W) that is part of the isolated DC/DC converter. The upper right circuit is a low noise reactive power limited balanced rectifier. The isolated DC/DC converter will not be further discussed here.

Linear Voltage / current regulator

A fully discrete circuit is used as shown in figure 6.6.

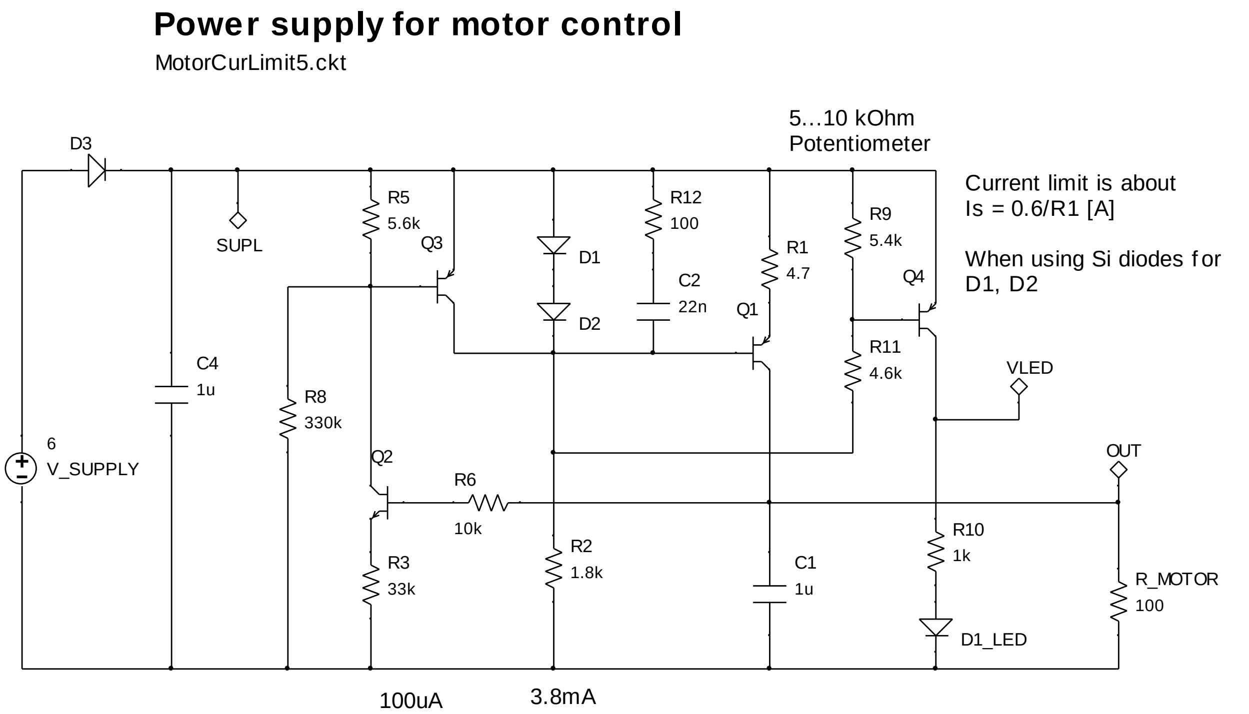


Figure 6.6: circuit diagram of voltage / current regulator. .

Q2: BC546...548, or equivalent small signal NPN transistor
Q3, Q4: BC556...558 or equivalent small signal PNP transistor
Q1: BD 136 or equivalent, see also transistor note
D1, D2: 1N914, 1N4448, 1N4148, or equivalent, 1N400x is also usable
D3: 1N400x, or medium current schottky rectifier, or replace for short circuit if reverse protection is not required (as in my motor controller).
C1, C2, C4: use film capacitors (MKS, MKT, etc), or X7R ceramic.
R9, R11: this is a trimmer potentiometer of 5 .. 10 kOhms.
R_MOTOR: is just for simulation

The circuit is built around a fast acting current source (D1, D2, R2, R7, Q1).

Current is limited to about I_{lim} = 0.6/R1. You need to test this, as it depends on what component you use for D1, D2. Use 4.7 Ohms as an initial guess for a short circuit current of about 130 mA.

The input voltage (V_SUPPLY) needs to be above the required output voltage plus 1.8V. If you don't use the reverse polarity protection (D3), input voltage should be about 1.1 V higher then the required output voltage. Maximum input voltage depends on transistors used, but 16V is generally safe.

The voltage control loop (around Q2 and Q3) reduces the current limiter setpoint by (partly) shorting D1-D2 via Q3. When the output voltage exceeds the setpoint, collector current of Q2 will cause current through de BE junction of Q3. Collector current of Q3 will steal current from R2, hence voltage across D1-D2 drops.

C2-R12 are to make sure the voltage control loop is stable. R8 is to make Vout virtually independent of input voltage. There is sufficient stability margin, but when you reduce C1 below 220 nF, step response shows ringing.
Do not make it very large as that negatively impacts smooth operation during startup. Something between 0.56 uF and 3 uF is fine.

Where is the zener diode?
There isn't one. The BE voltage "to open" Q3 (about 0.7V) is used as a reference. It is not very temperature stable, but that isn't important as it doesn't matter whether the output voltage is 3.9 or 4.5V.

Output voltage is determined with R3. When output voltage with R3 = 33 kOhms is too low, just increase R3 to get more output voltage.

If you plan to use a relative high supply voltage (say 13.8V), you may recalculate R2 based on R2 = 1000·(SUPL – 1.2)/3.8. For 13.8V, R2 = 2.7 kOhms.

Transistor note (for Q1):

> If you don't have a BD136 .. 140, or near similar transistor, you can use small signal transistors. Just use 3 PNP small signal transistors in parallel (bases connected together and collectors connected together). Each transistor has its own emitter resistor. If you would need 4.7 Ohms for a single BD136, then each transistor needs R = 3·4.7 = 15 Ohms emitter resistor. This guarantees excellent current sharing.

Adjusting of the trimmer (5…10 kOhms) for the overcurrent indicator circuit.
This trimmer is for correct operation of the over current LED indicator. Set the wiper at midpoint. Short circuit the output and slowly move the wiper towards R2, until the LED intensity doesn't increase anymore. Now turn the wiper a little bit back until the LED intensity just start to dim.

Now the LED will act as a current indicator with an analog behavior. Before the current limit is reached, the LED will blink with reduced intensity. This is a useful feature to see whether or not the current consumption of the motor increases due to wear of pollution. When during normal operation the LED lights with increasing intensity, the tuner needs maintenance.

Direction reversal

The output from the regulator goes to the circuit below:

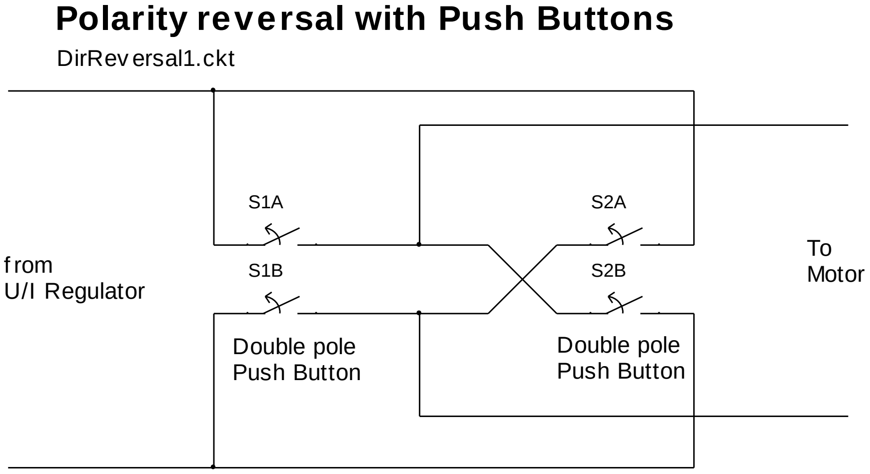


Figure 6.7: circuit diagram of polarity reversal circuit.

You just need two double pole push buttons to reverse the turn direction of the motor. When pressing S2, the output voltage reverses. When you push both buttons at the same time, the LED should lighten, showing good operation of the circuit.

Supplying the motor control circuitry

When you supply from the power supply that is used for the transceiver, you need two wires that go to motor. No wire or the motor may touch ground.

If you want to use the coaxial braid as return, you need to supply the circuit from an isolated supply.

When you have AC mains at hand, old AC to DC adapters (“wall warts”) with a transformer are very useful. As long as they supply the minimum required input voltage (in my case 6V), it is fine. You need to test this with the motor controller short circuited. The wall wart doesn’t need to be regulated, as long as it provides DC (including a capacitor to reduce the ripple). It is no problem when the no-load voltage reaches say 15V, as it drops rapidly when some current is drawn from the adapter.

You may try a switching AC to DC regulator, but check for noise!

As I also want to operate from DC 12V, I used a home brew isolated DC/DC converter (that was part of another experiment). Be careful if you buy a COTS isolated DC/DC converter. Many produce lots of noise and additional filtering is required to be able to use them in an RF receive environment.

Use adequate fusing to avoid fire in case of failure.

For temporary (field) use, you may supply the motor controller from (rechargeable) batteries. In that case a main switch is really useful as the circuit draws several mA of standby current.

When Q1 has good HFE, you may reduce current through R1.

Example:

> When you use 3, BC 557B transistors in parallel and the current limit is set to 120 mA, Each transistor has to supply 40 mA. At these current levels, you can expect HFE>150 at room temperature.
>
> That means total required base current is 120/150 = 0.8 mA. It is then fully safe to reduce current through R1 to 2 mA. For minimum supply voltage of 10.6 V,
>
> R1 = (10.6-1.2)/2m = 4.7 kOhm.

When using modern mesh ("low VCE(sat)" transistors), guaranteed HFE can be over 200 and base current of 0.5 mA may be sufficient.

When optimizing for low standby current, use a 10 kOhm trimmer potentiometer for R9, R11.

7. Does this tuner work?

Yes it does, but everyone that builds something says it does work, even if it doesn't, isn't it?

Building the tuner as shown in figure 4.1 is not recommended. Tuning by changing the taps on the inductors is demanding. Even when using fixed frequency operation only, small changes of the environment may require tuning. Keep in mind that the BW (SWR=2) is just 14 kHz.

If you want a minimum usable tuner, then build the tuner as shown in figure 5.1, or 6.1 and 6.2, but without the motor drive. Add a grip on the balun-side to enable manual tuning. Such setup is suitable if you don't require frequent tuning.

You need to tune once using the taps. This is for determining the lowest frequency and for minimum common mode voltage / current. When done, you can use the sledge to tune the antenna. You may even put marks on the base so you know where to position the sledge for a certain frequency.

Remote tuning
In case of frequent tuning and or physical limitation, you need to go for the motor drive to enable remote tuning. It is a pleasure. The small wooden box (figure 6.5) is sitting adjacent to the Kenwood TS 590SG and tuning goes smoothly.

The sledge may even go faster. The current limitation gives a kind of slow start. So by pressing shortly on the buttons, the sledge displacement is very small as the motor doesn't reach its nominal RPM. This enables pleasant fine tuning (better than originally expected).

What about the signals?
With good conditions and a superstation on the other side, one can work large distance with a leaky dummy load. This antenna is just for NVIS communication at 80 m (say an area with a radius around you of about 200 .. 400 km). acceptable conditions are near guaranteed. Only in the evening (2020), critical frequency may sometimes drop below 3.6 MHz, making short distance circuits impossible (at 80 m).

Comparing with people with full-size half-wave dipoles at around 10m height, with same input power, my signal is about 10 dB less.
So my signal is in the S8…S9+10 dB range when received with a half wave dipole.

You may compensate some of the loss by using more power (for example 400 W, the Dutch standard limit). It will help you overcome noise at the amateur that receives your signal.

Is it wise? In case of SSB and good construction, the tuner can handle 400W, but what about the electronic equipment of the neighbors? Such short antennas produce very high near field. The advantage is that this near field drops very rapidly. So if you have sufficient physical separation, or there is a reinforced wall between possible “victim” electronics and the antenna, 400W may be possible.

Hopefully this document inspires others to build an electrically small 80 m band antenna that can be used for SSB voice communication.

Good luck with the construction and let your waves travel around the world and beyond!

Wim Telkamp, PA3DJS

8. Annex

8.1. Current probe for measuring common mode current

When you really want to measure your common mode current, you can use a ferrite current transformer with some components and DC current meter.

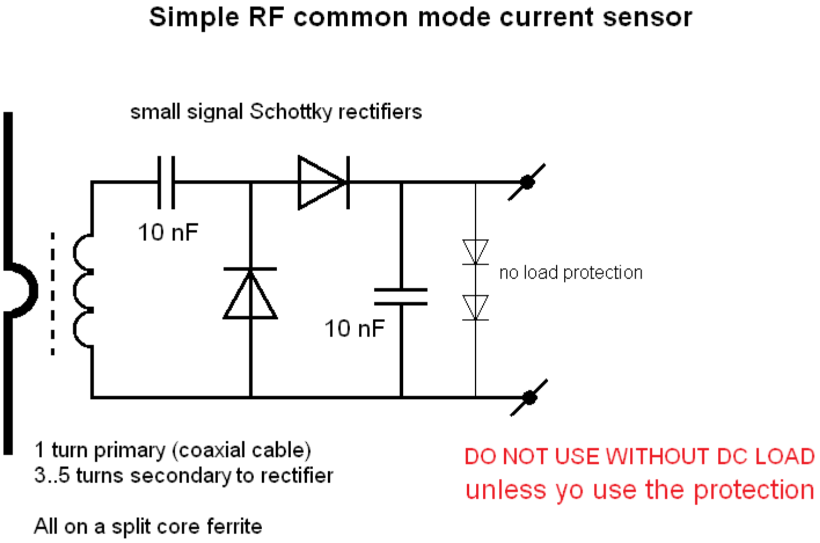


Figure 8.1: simple current transformer with ferrite.

Use a big 12 …15 mm split core ferrite intended for HF interference suppression. They have a diameter and length in the 30 mm range and have impedance in the range of 30…60 Ohms at 3.6 MHz.

Sensitivity
For 80m band use 3 turns. In that case the primary voltage has to be 0.15..0.2 Vrms to have diode conduction. This equals a primary current of about 3 mArms. So you may expect a minimum detection limit of 3..4 mArms for 3 turns and small signal Si junction rectifiers.

When using small signal low voltage Schottky rectifiers, detection limit will be about 1.5 mArms. Below the detection limit, you meter will indicate near zero current.

For large RF current:

$$Idc = 0.45 \cdot Irms/N, \text{ or: } \quad Irms = 2.2 \cdot Idc \cdot N$$

Where: Idc = indication on DC ampere meter [A], Irms = common mode current flowing through cable that passes the ferrite [Arms], n = number of secondary turns.

When you read 4 mA on the DC amps meter, and you have three turns, Irms = 27 mA. This is well above the detection limit.

The cable that you will measure goes only once through the hole in the core. When you use 3 secondary turns, the secondary wire goes three times through the core.

Rectifiers
You get best sensitivitywhen using low voltage small signal schottky rectifiers (BAT85, BAT48, BAT54, BAT15, etc). Other options are regular small signal junction diodes like 1N4148, 1N914, 1N4448, etc, but in that case you will lose sensitivity. Do not use power diodes like 1N400X series.

Important note
You need to connect a current meter before applying the current through the primary, otherwise you will blow low voltage schottky rectifiers like BAT14, BAT15, etc.

You may add two 1N4148 in series parallel to the output as indicated in the figure. This limits the DC output voltage to about 1.4 V.

If your instrument requires < 500 mV for full deflection, you can use one rectifier (1N4148/4448/914/etc).

For best voltage rejection of the current probe, keep short connections (< 1 m) between the circuit and the DC current meter.

When done, remove the current probe as the rectifiers may generate some harmonics.

People that have a spectrum analyzer may skip the detector and go straight into the analyzer. You need to convert voltage back to current in that case. I prefer blowing some rectifiers instead of the input circuit of a spectrum analyzer. . . .