SMALL "MAGNETIC" TRANSMITTING LOOP FOR 80-20 MTRS

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INTRODUCTION

I wanted a **small transmitting loop** (STL) antenna that covers at least the 80 and 40 meter bands (preferable 80 - 20). Why?

- I want to do 80 mtrs DX, but I have no room for a decent 80 m wire-antenna, nor would I be able to install such an antenna high enough above ground. I have had some success with short, loaded vertical antennas with a single elevated radial, see here and here. But I cannot install those permanently at my QTH.
- Below 10 MHz, our apartment building generates a large amount of "electro-smog" QRM. An STL tends to be less sensitive to picking up electrical noise in the near-field (< 1 λ), which appears to be the reason why this type of antenna is also referred to as a "*magnetic* loop antenna".
- STLs have a radiation pattern with directivity. They are also small enough to rotate with a small motor, or TV-antenna rotor.
- They are less conspicuous (to my friends of the home-owners association "police") than a wire antenna that is strung along the outside of the building.
- I don't want to have to mess with radials, counterpoises, RF-grounds, etc. Loops are inherently symmetrical, like dipoles.
- Can be installed close to the ground (vertically oriented), without significantly losing efficiency. Yes, higher *is* better.

A loop antenna is generally considered "small", if its circumference is less than 10% of the operating wavelength. So in my case (for 80 mtrs), "small" would be a circumference of less than 8 mtrs, e.g., a circular loop with a diameter less than 2.5 mtrs (≈ 8.2 ft). To be more precise, we are talking about a small *resonant* loop. Note that a multi-band loop that is "small" in the lowest band, is not necessarily "small" in the higher bands (= higher frequency).

Clearly, as with all antennas, "radiation resistance" is very important parameter. As the graph below shows, the radiation resistance of an STL is very small - we are talking **milliohms** here! The radiated RF power is determined by the radiation resistance, multiplied by the square of the circulating RF loop current. As the radiation resistance is very small, a large loop current is required to get practical levels of radiated power. This implies that all losses (e.g., capacitor losses, contact resistance due to loop construction, losses due to coupling with the environment), even if only a couple of milliohms, are important in STLs!

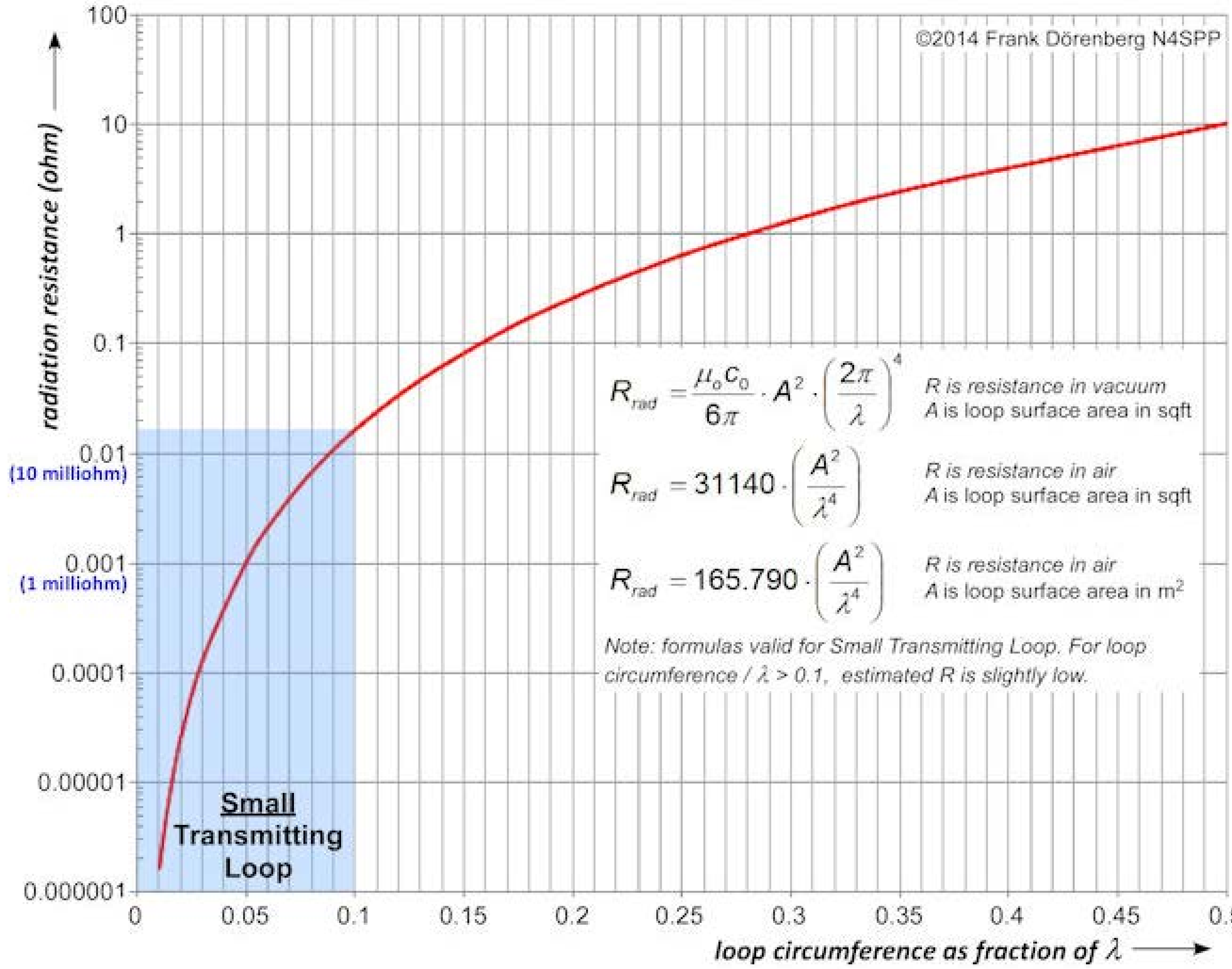


Fig. 1: Radiation resistance of a Small Transmitting Loop antenna

The radiation pattern of a Small Transmitting Loop antenna is shown below. The kidney-shape of the horizontal pattern (top view) becomes more pronounced (= deeper minimums) as the antenna circumference becomes a larger fraction of the wavelength. This is the case when operating a multi-band STL on the higher band(s). For large loops, the maximums of the horizontal pattern are actually in the directions *perpendicular* to the surface of the loop!

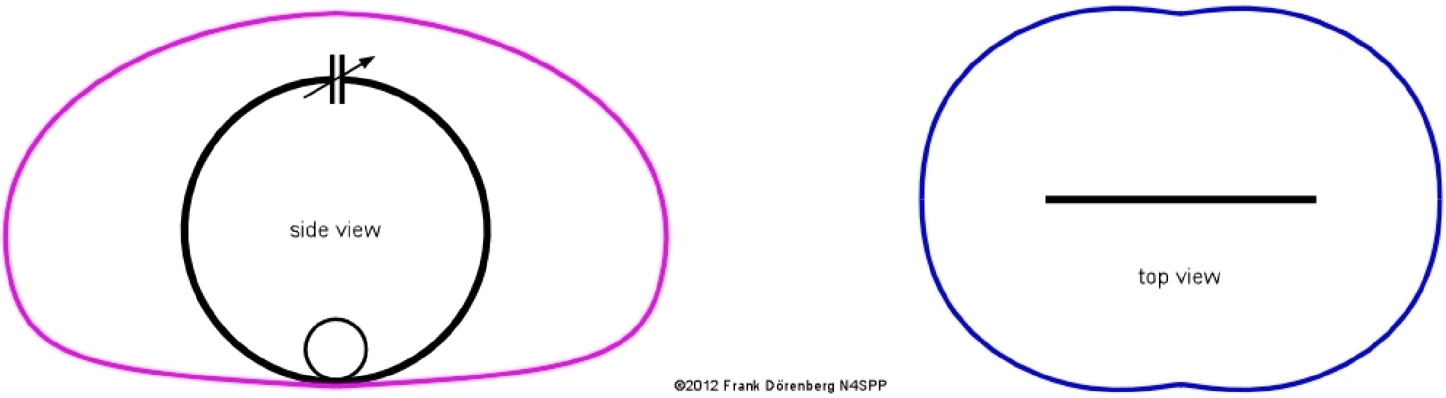


Fig. 2: approximate radiation pattern of a vertically oriented Small Transmitting Loop
(circumference = 0.15 λ, installed 0.08 λ above ground)

Due to the closed-loop shape, this type of antenna can be considered an extreme case of a "terminated folded dipole". A standard loop has a circular single-turn inductor. Of course, other shapes are possible: square, rectangular, octagonal, etc. There are variations such as multiple turns and configurations such as "figure-eight". As with dipoles, single-band directivity and gain can be increased by adding passive reflector and director loops, as in so-called multi-element "Yagi" beam antennas. This is all beyond the scope of this discussion.

Just to get a feel for some basic parameters, I have calculated the characteristics for a circular loop with a circumference of 5 m (diameter =1.6 m, ≈ 5.2 ft), made of copper tubing with a standard 16 mm outside diameter (5/8"). Input power is 100 watt (the limit of my transmitter).

Resonance frequency	Efficiency	Bandwidth	Tuning capacitor	Capacitor voltage	Q
3350 kHz	4%	3.6 kHz	503 pF (max)	2.9 kV	931
3580 kHz	5%	3.8 kHz	440 pF	3.1 kV	953
7040 kHz	36%	7.8 kHz	104 pF	4.2 kV	905
14800 kHz	88%	61 kHz	14 pF (min)	3.1 kV	241

Fig. 3: Calculated antenna characteristics for the given copper loop
(KI6GD calculator, ref. 2A; no additional losses assumed in the calculation - note: read ref. 2F for caveats about loop antenna calculators!!!)

Resonance frequency	Efficiency	Bandwidth	Tuning capacitor	Capacitor voltage	Q
3300 kHz	4%	3.6 kHz	500 pF (max)	3.0 kV	986
3580 kHz	5%	3.8 kHz	424 pF	3.3 kV	1015
7040 kHz	36%	7.5 kHz	110 pF	4.5 kV	963
14800 kHz	88%	58 kHz	14 pF (min)	3.3 kV	256

Fig. 4: Calculated antenna characteristics for the given copper loop
(AA5TB calculator, ref. 2B; no additional losses assumed in the calculation - note: read ref. 2F for caveats about calculators!)

If the input power is increased by a factor of *N*, then the maximum voltage across the capacitor is increased by a factor $\sqrt{N}$. E.g., doubling the power increases the capacitor voltage by ≈1.4. Conversely, the voltage is reduced by a factor of 1.4 when the input power is reduced by a factor 2.

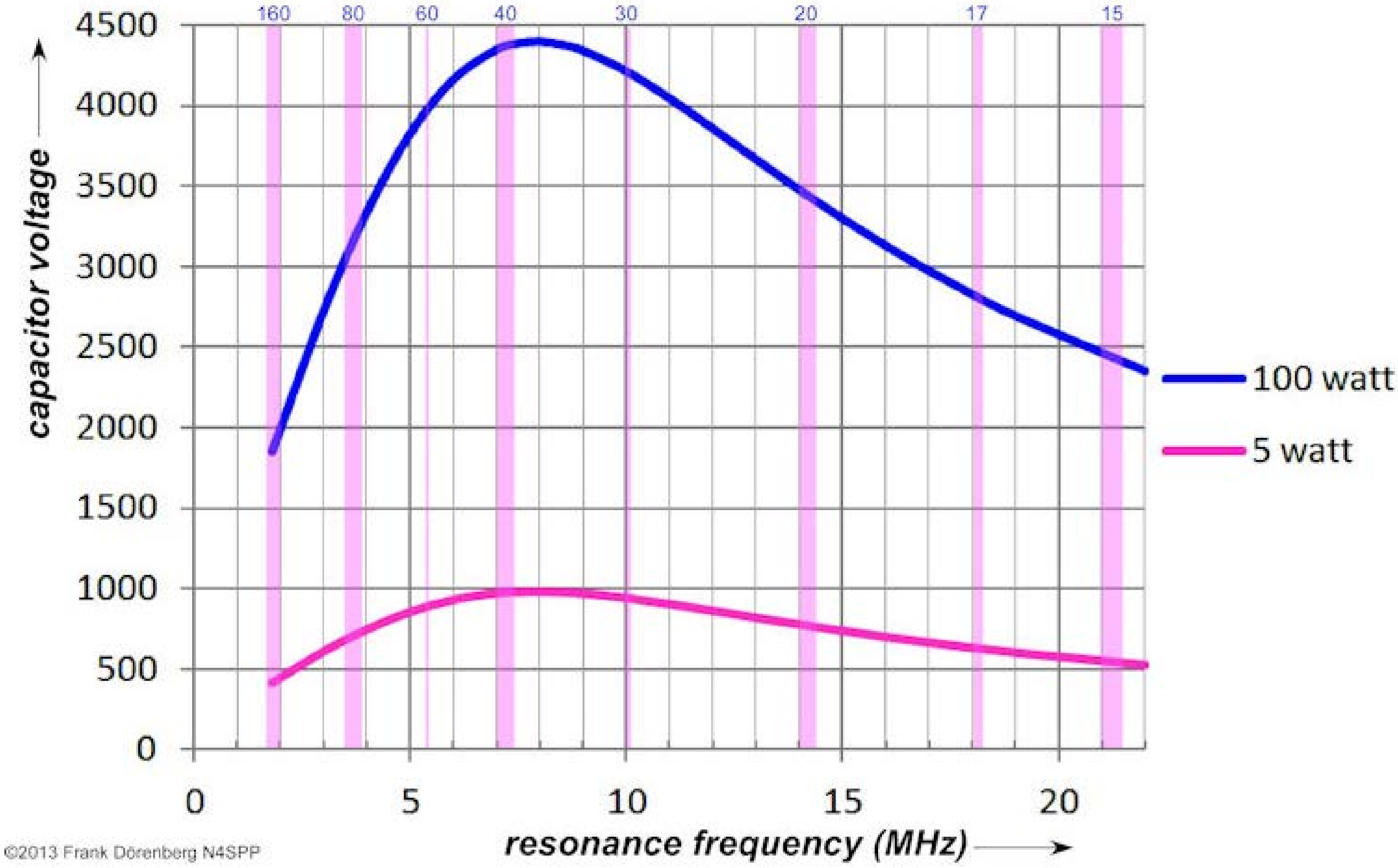


Fig. 5: Capacitor voltage as a function of frequency (1.6 mtr Ø loop made of 16 mm OD copper tubing)

(calculated with ref. 2B; assumes 5 milliohm loss resistance - note: read ref. 2F for caveats about calculators!)

"Efficiency" can be defined as "total power radiated by the antenna" divided by "net power accepted the antenna" [IEEE Std 145-2013 "Standard for Definitions of Terms for Antennas"]. The tables above show that the calculated / predicted efficiency for 80 mtrs is rather low (no surprise), but my other antennas for 80 mtr are (very) short verticals. I do not know what their efficiency is, but I am sure that it is very low. In the end, what counts is performance at *my* location, for the available space, for the prevailing conditions (proximity to the building, QRM levels, etc), and with respect to other antennas that I can (afford to) install there. The efficiency of STL antennas remains controversial (ref. 3).

As a rule of thumb, the optimum circumference of a multi-band STL is about 0.15 λ of the lowest operating frequency. With an appropriate variable capacitor, the resonance frequency of an STL *can* be tuned over a frequency range that covers at least two octaves (= factor 4x). However, from an antenna *efficiency* point of view, a factor of 2-3 is probably the practical limit. E.g., 80-40, 40-20, 30-10.

I have not looked into the assumptions that the calculators make, regarding installation height (free space?), coupling method, etc. As in all high-Q resonant circuits, calculated and actual performance is highly dependent on the losses in all components (loop, capacitor) and all interconnections. Losses in the milli-ohm range may be significant! In general, increasing the diameter of the tubing will reduce the (inductor) losses - up to a point.

Instead of the standard tubular conductor, loops can be made of a wide, flat conductor strip such as copper "flashing" or foil. The strip can be straight (ref. 4), or helically wound (hence, helically loaded, ref. 5A/B). Of course, helical/spiral "hula hoop" antennas can also be made of a Slinky™ coil, as I did late 2016. Ref 5C, 5F. Another option is a meandering or fractal loop circumference.

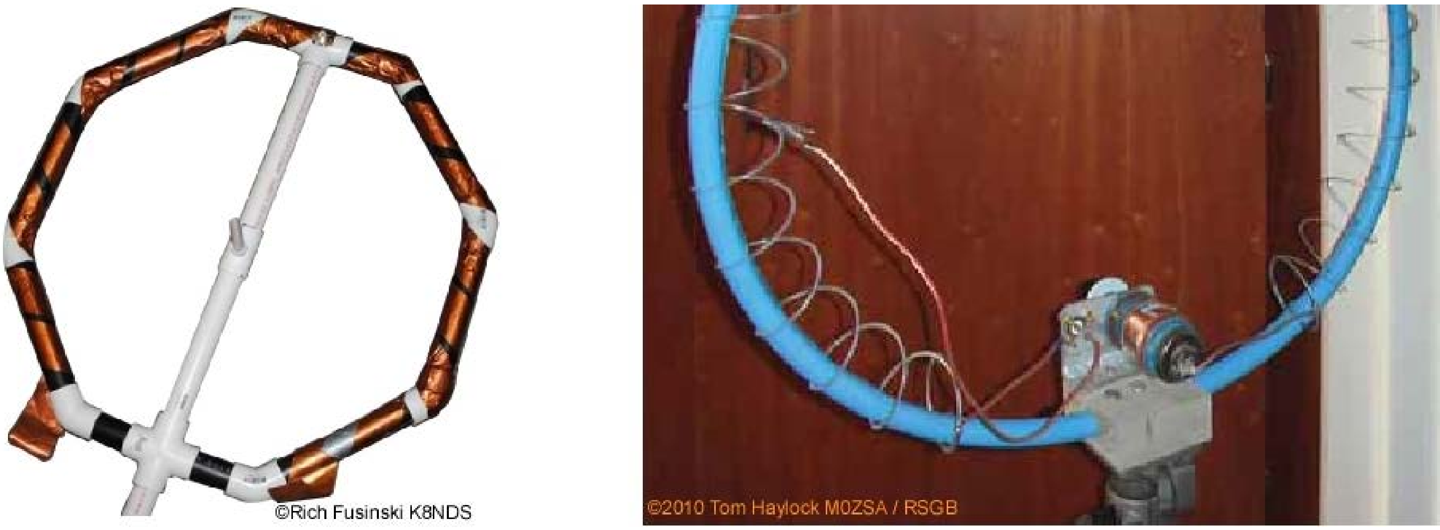


Figure 6A: Flat conductor loop (helically wound/loaded, shown without capacitor) and Slinky™ coil loop
(sources: ref. 5A/B and 5C)

Figure 6B: Flat conductor loop and meandering "fractal" loop
(source: ref. 4 and www.radioworld.co.uk)

Even on VHF (2 m band), the size of standard antennas such as HB9CV and Quads can still be sizeable or akward for portable operation. VHF loops can be made with the same construction techniques as for HF. However, for the 2m band, a 0.1 λ STL only takes an area of about 10x10 cm (4x4 inch). The main loop, and even the coupling loop, can be etched on a printed circuit board (PCB). This is what Thomas Schiller (DC7GB) did. Fixed capacitors can also be made of 2-sided PCB. However, Thomas' extensive experiments concluded that the dielectric properties of standard PCB material (e.g., FR4) varies too much (and on-linearly) with the main loop's E-field, even at low transmit power levels. At VHF, FR4 also has a large loss tangent δ. So he used a 4.7 pF 500V mica capacitor (yellow arrow in Fig. 7 below). That capacitance is too small to make variable for tuning. The latter is done by shaping a small (2-3 turn) coil (at the red arrow), placed in series with the coupling loop. Loop performance close to that of a full-size dipole.

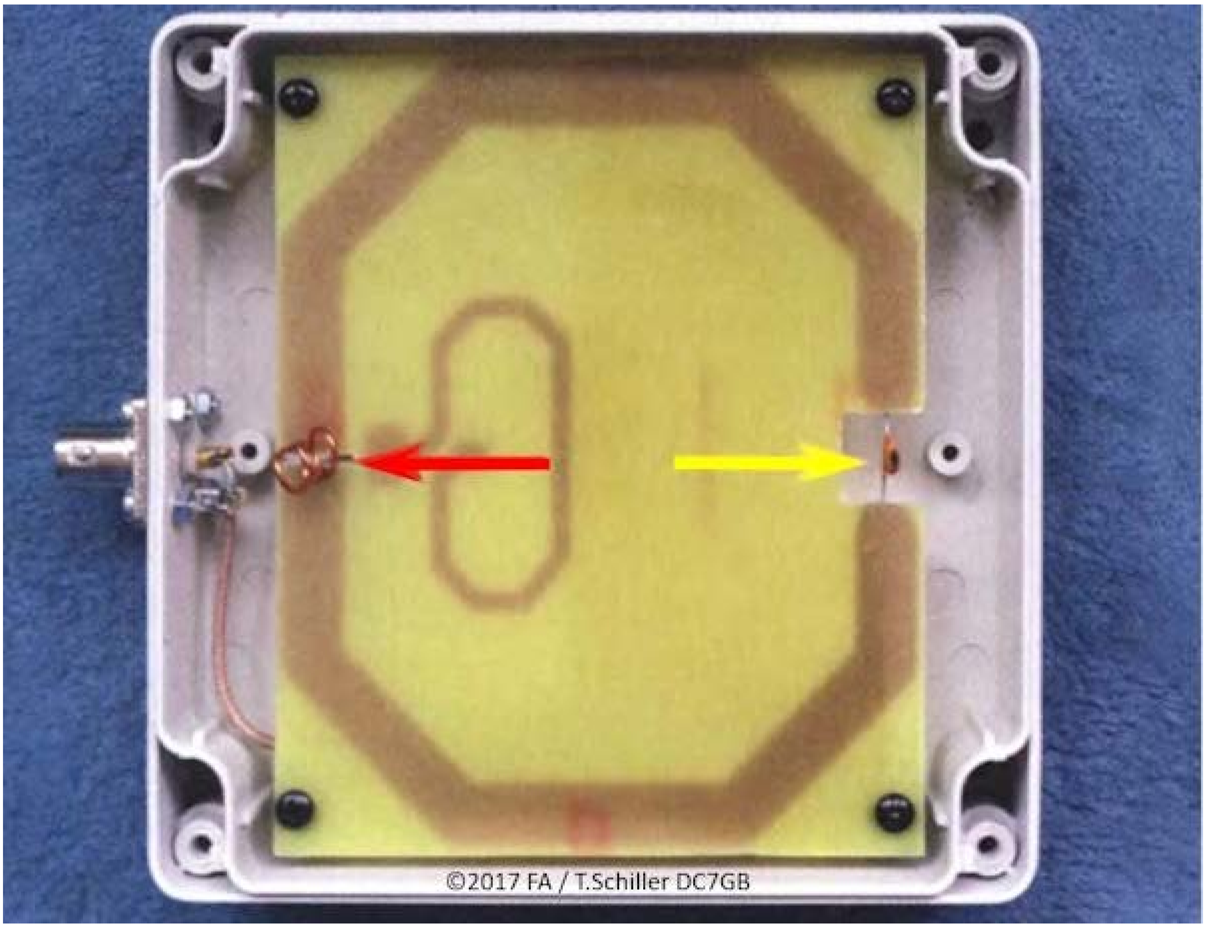


Figure 7: Printed circuit board loop for the 2m band
(source: ref. 4B)

SAFETY

Figures 3-5 above show that there is a **very high voltage** across the capacitor at resonance, even at QRP levels! This is not only important when choosing a suitable capacitor, it is also a **SAFETY** issue! When transmitting, **NEVER** touch the capacitor or the loop, and do not let any other person or animal touch it! RF burns do not heal well!

Exposure to RF radiation is also a health hazard to humans and (other) animals! Legal limits and guidelines for such exposure generally vary by country. The table below shows the minimum estimated safe distance for various transmit power levels. Ref. 14A, 14B, 14C.

Average power (watt)	Freq band (m)	Loop size (diameter)	Estimated *controlled* compliance distance (aware users, e.g. radio operators)	Estimated *uncontrolled* compliance distance (general public) ©2019 N4SPP
5	40-10	small	4 ft = 1.2 m (FCC)	5.6 ft = 1.7 m(FCC)
10	40-10 40-10	small 3.3 ft = 1 m	4.9 ft = 1.5 m (FCC) ≤ 6.9 ft = 2.1 m (ICNIRP)	6.9 ft = 2.1 m (FCC) ≤ 9.5 ft = 2.9 m (ICNIRP)
100	40-10	3.3 ft = 1 m	≤ 11.1 ft = 3.4 m (ICNIRP)	≤ 15.4 ft = 4.7 m (ICNIRP)
150	40-10	small	6.6-7.9 ft = 2-2.4 m (FCC)	9.2-13.8 ft = 2.8-4.2 m (FCC)
400	40-10	3.3 ft = 1 m	≤ 14.7 ft = 4.5 m (ICNIRP)	≤ 24 ft = 7.3 m (ICNIRP)
1500	80-10	3.3 ft = 1 m	9.9-19.4 ft = 3-5.9 m (FCC)	17.4-42.4 ft = 5.3-12.9 m (FCC)

Table 1: Estimated minimum safety distances for Small Transmitting Loop antennas
(sources: ref. 14A, 14B; distance is measured from the center of the loop)

TUNING THE LOOP'S RESONANCE FREQUENCY

The loop antenna is basically an LC-circuit that has to be tuned to resonance on the desired operating frequency. The loop by itself is an inductor that has the shape of a closed-loop. The generic formula for the resonance frequency of an LC-circuit is shown in Fig. 8 below. Note the duality of the "L" and the "C" in this formula. Based on this, the resonance frequency can be changed in two basic ways:

- by adding "C" to the circuit. This is typically done by opening the loop, and connecting a variable *capacitor* across the open ends of the loop. This is the standard way to "tune" the resonance frequency of a loop antenna.
- by adding "L" to the circuit. This can be done by opening the loop, and connecting a variable *inductor* across the open ends of the loop. Continuously variable inductors with a large value range, a high power rating, and low loss are rare. Also, a fixed-value capacitor may also have to be added to the loop, based on the value range of the inductor. This is why there are very few practical examples. The only example known to me, is described in ref. 13A. It uses a ferrite rod that is inserted into a 2-turn coil. This tuning method is not discussed in the rest of this article.
    - The "L" of the loop can also be changed, by changing the size of the loop. However, this is not very a practical method for tuing the resonance frequency - other than for a single-frequency application.

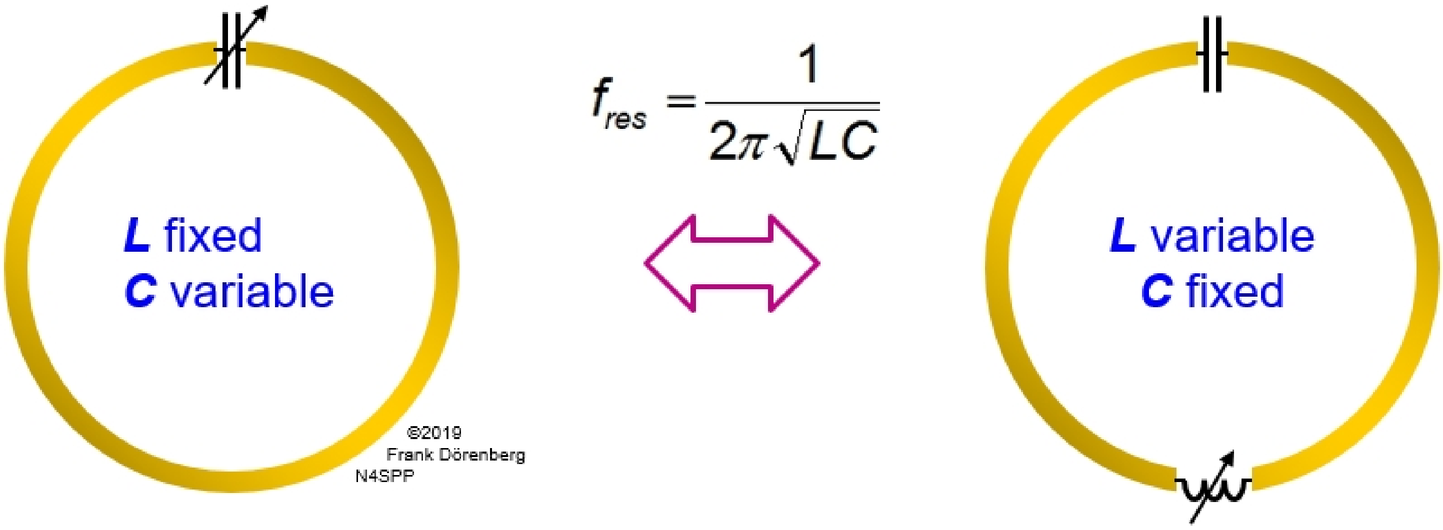


Figure 8: The duality of L and C in changing the loop's resonance frequency

Note that when "L" or "C" is *increased*, the loop's resonance frequency is always *reduced*. Also, the loop not only has inductance, but also stray (= parasitic) capacitance. This means that the loop has a self-resonance frequency, even without a tuning capacitor.

A simplified lumped-element diagram of a tunable LC-loop is shown below. The tuning capacitor is modeled as "non ideal", with equivalent series resistance (ESR) and inductance (ESL). Likewise, the loop's self-inductance includes loss resistance that represents skin-effect losses, construction losses (e.g., solder joints), etc. A "single-turn coil" loop is assumed, so no turn-to-turn stray capacitance is modeled. The model does contain parasitic capacitance, to represent coupling to ground below the antenna and to nearby objects. The "radiation resistance" is a fictitious conceptual resistance that relates the power that is radiated *by* the antenna, to the current flowing *in* the antenna. So it is directly related to antenna efficiency. It can be modeled, but unfortunately, it cannot be measured directly.

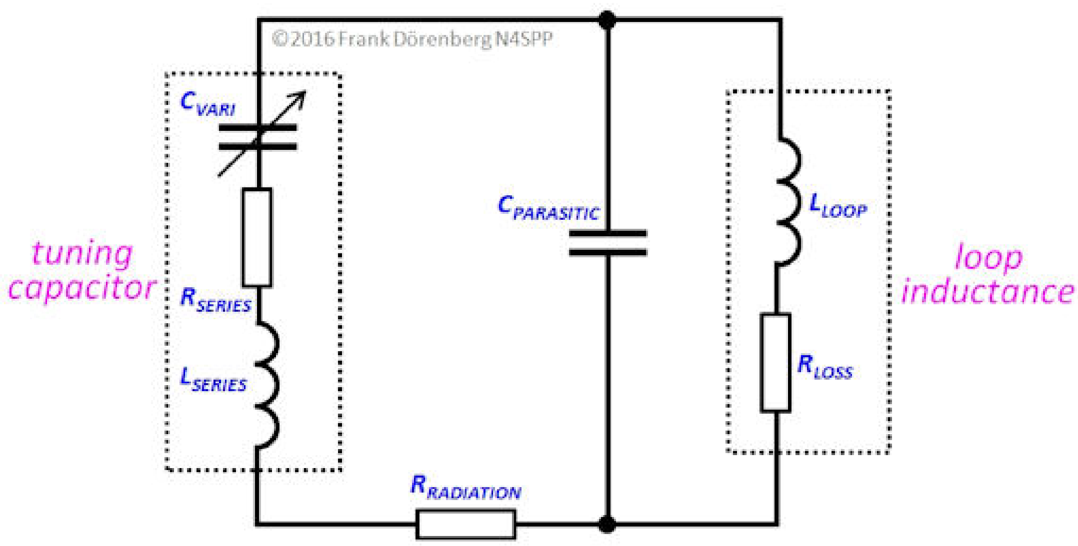


Fig. 9: Simplified equivalent lumped-element electrical circuit of an STL with tuning capacitor
(coupling to ground and objects near antenna is not shown; see Fig. 17 for tuning capacitor with dielectric other than air or vacuum)

"Tuning" the antenna is done by keying the transmitter (at low power setting) and observing the SWR-meter (or antenna-current meter) while adjusting the tuning capacitor. Alternatively, by tuning for maximum receiver noise level: there should be a sharp increase in the noise level when the antenna becomes tuned to the desired operating frequency.

An other important aspect to keep in mind, is the voltage and the current distribution along the loop - *at resonance*. As shown in the figure below, the voltage is highest at the capacitor, and zero at the point diametrically opposed (in a perfectly symmetrical loop + capacitor + capacitor connections + environment). In some coupling methods, the braid (= shield) of the coax feedline is actually connected to that neutral point.

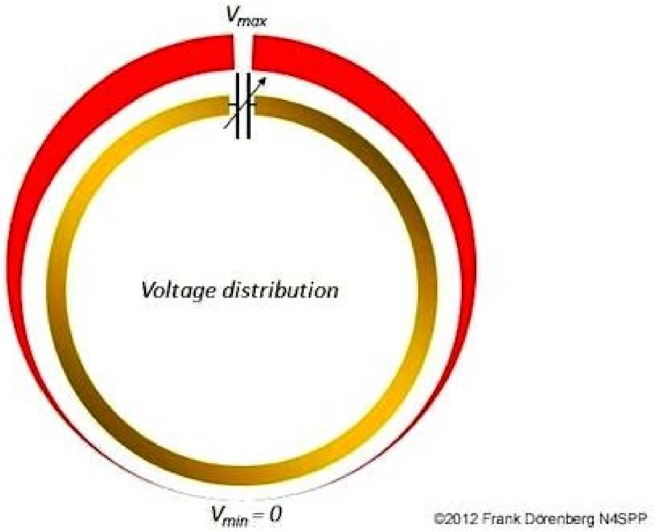


Figure 10A: Voltage distribution around a loop antenna

The current is highest at the point opposite the capacitor, and lowest *at* the capacitor. See ref. 1 for an illustration. Note that the minimum current is not zero! Unlike the voltage distribution, the current distribution depends on the size of the loop (circumference), as a fraction of the wavelength. For a small transmitting loop (circumference < 0.1 λ), the current distribution is nearly constant (uniform) around the loop. Both the voltage and the current distribution are symmetrical.

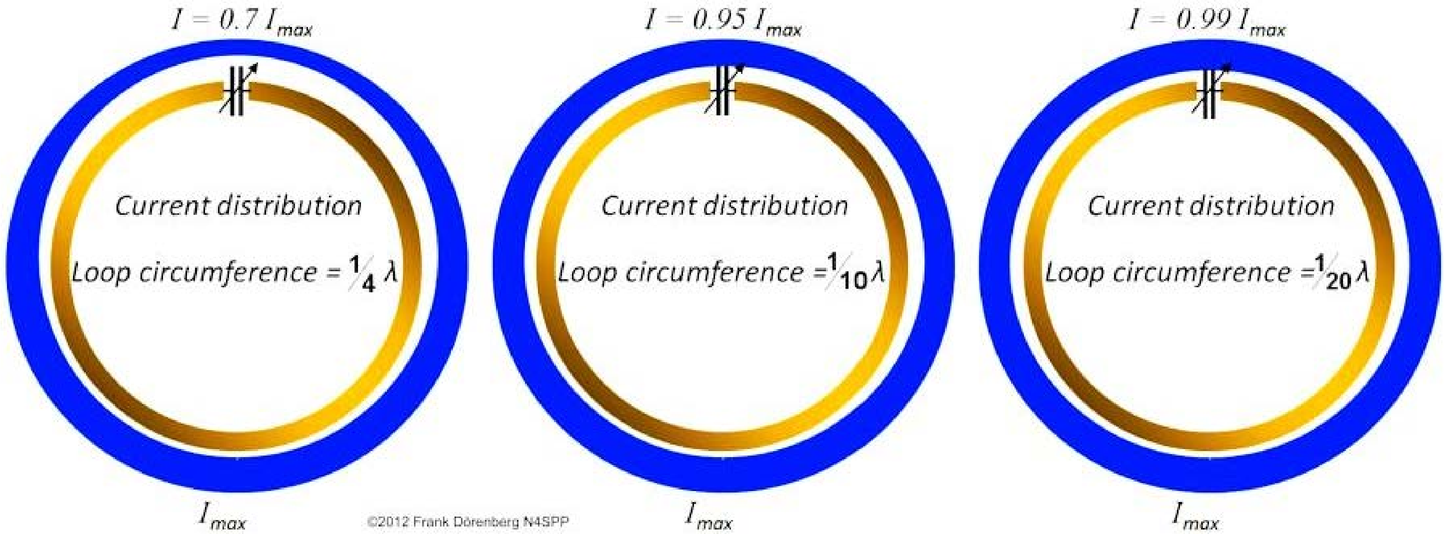


Figure 10B: Current distribution around a loop antenna
(note: a circumference > 0.1 λ is not "small")

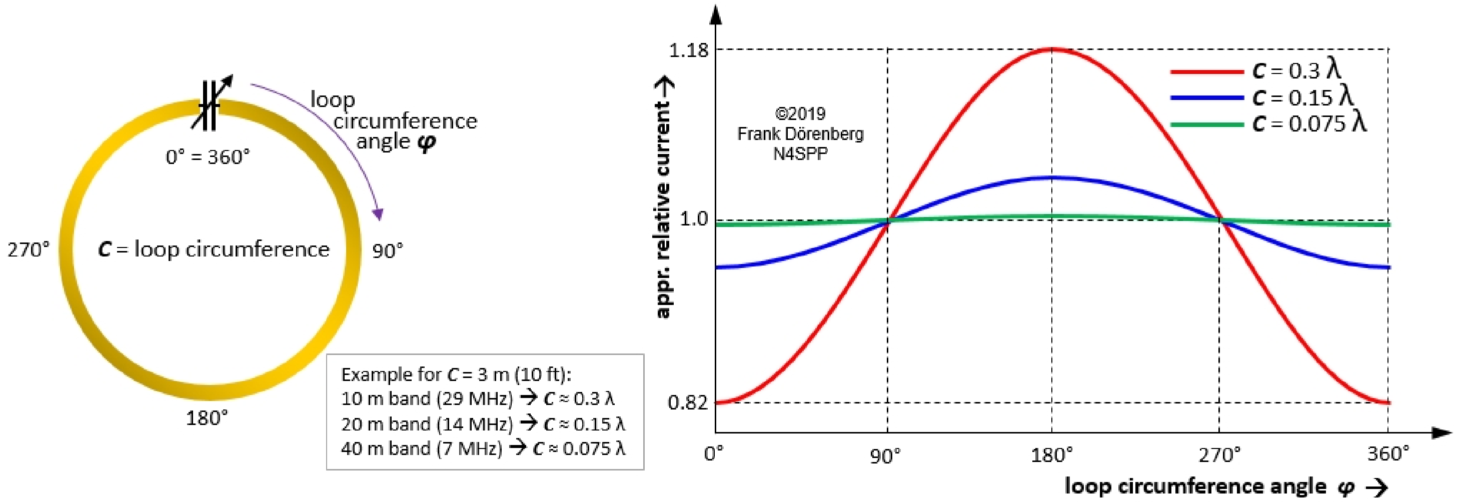


Figure 10C: first-order approximation of the amplitude of relative current around the loop - in free space

(source: adapted from ref. 8H)

The diagrams above shows that the largest current occurs at the point opposite the capacitor. This part of the antenna radiates the most. Some operators therefore install their loop with the capacitor at the bottom. Furthermore, placing the part with the highest voltage closest to the ground, increases losses due to parasitic capacitance to ground...

Based on the voltage and the current distributions, the impedance ($Z = V / I$) varies around the circumference of the loop. It is highest near the capacitor, and lowest at the point opposite the capacitor. E.g., there are two points, left and right of the neutral point opposite the capacitor, where the impedance is 50 ohm points with respect to that neutral point. This property is used in coupling methods such as Gamma Match and Delta Match.

THE TUNING CAPACITOR

A loop with a fixed-value capacitor is resonant at a single, fixed frequency. A well-constructed small loop antenna has a bandwidth that requires re-tuning when changing frequency across a band. Also, the resonance frequency will vary with temperature changes (sunshine/weather). In order to change the resonance frequency to the desired operating frequency, we need a *variable* capacitor.

The basic choice is between "air variable" capacitor and "vacuum variable" capacitor. Clean air has a dielectric strength of 0.8 kV per mm (at 20 °C and standard humidity). So, an "air variable capacitor" for 5 kV would need an air gap of 6.25 mm (1/4 inch) between the plates. High-vacuum has a dielectric strength at least 10x as high.

A typical air-variable capacitor is "rotary variable". It consists of a stack of stator plates (= stationary), and a stack of plates that are mounted on a rotor shaft. The rotor plates intermesh with the stator plates. Ideally, the rotor plate "vanes" are welded to the rotor shaft (rather than clamped) to reduce loss resistance. Connection to the rotor is either done via a sliding contact, and via a bearing to the frame of the capacitor. This always causes losses (series resistance)! Such moving contacts also tend to make tuning a bit "jumpy", cause receiver noise when changing rotor position, and limit transmit power during rotor movement. Such capacitors are generally to be avoided in "high Q" STL antennas. A discussion of losses in air variable capacitors is given in ref. 12M.

There are several basic types of air variable tuning capacitors:

- **Single-section**: a single rotor-stator section.
- **Multi-section**: basically two (or more) variable capacitors that are ganged (mounted side-by-

side), with a single conductive rotor shaft. Hence, the rotor vanes of all capacitor sections are electrically connected. The losses of the wiper contact can be eliminated by putting two capacitor sections in series: the rotor contact is not used, only the two stator contacts. This doubles the voltage rating, but at the same time halves the capacitance.

  - **Broadcast-band**: typically used in early AM/FM receivers. The rotational range (rotor "swing") is limited, typically to around 140°. This mechanical limitation makes motorized tuning more complicated. Plate distance is small, so only suitable for low power (QRP) transmission. As the plates and spacing are small, the sections are separated by a shielding wall.
  - **Split-stator**: a 2-section arrangement in which the two sets of rotor plates are mounted on opposite sides of the rotor shaft. Likewise for the two sets of stator plates.
- "**Butterfly**". The rotor vanes are typically shaped like a bow-tie ("butterfly wings"). There are two rotor/stator stacks. However, they not arranged side-by-side, but diametrically opposite of each other. Note that the full capacitance range is covered by 90° turn of the shaft. There is not always a rotor contact. The RF current passes through the two "wings" of each rotor plate, rather than through the rotor shaft. This reduces losses compared to split-stator and a regular 2-section capacitors.

Figure 11: Single-section and dual-section capacitor

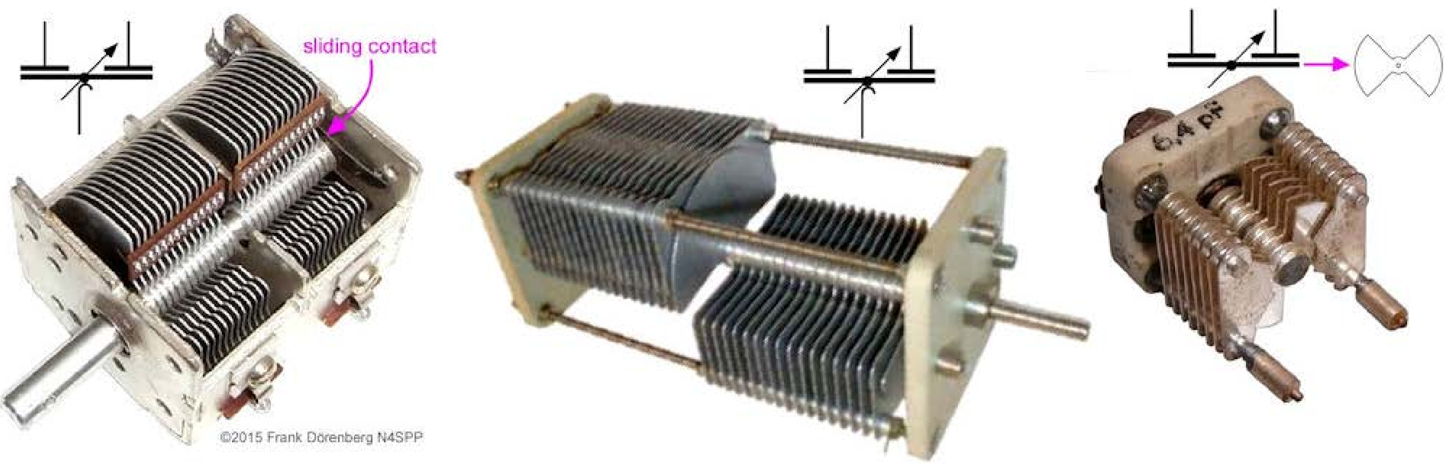


Figure 12: Broadcast receiver capacitor, split-stator capacitor, and butterfly trimmer

The dielectric constant of oil is about twice that of air. So an air-variable capacitor may be immersed in oil to double its capacitance. It also doubles the voltage rating. Use an oil-tight non-metal container, and pure mineral oil (a.k.a. paraffin oil), synthetic motor oil, or similar. I.e., <u>not</u> transformer oil, which is expensive and typically very toxic. Make sure that the capacitor plates are completely immersed!

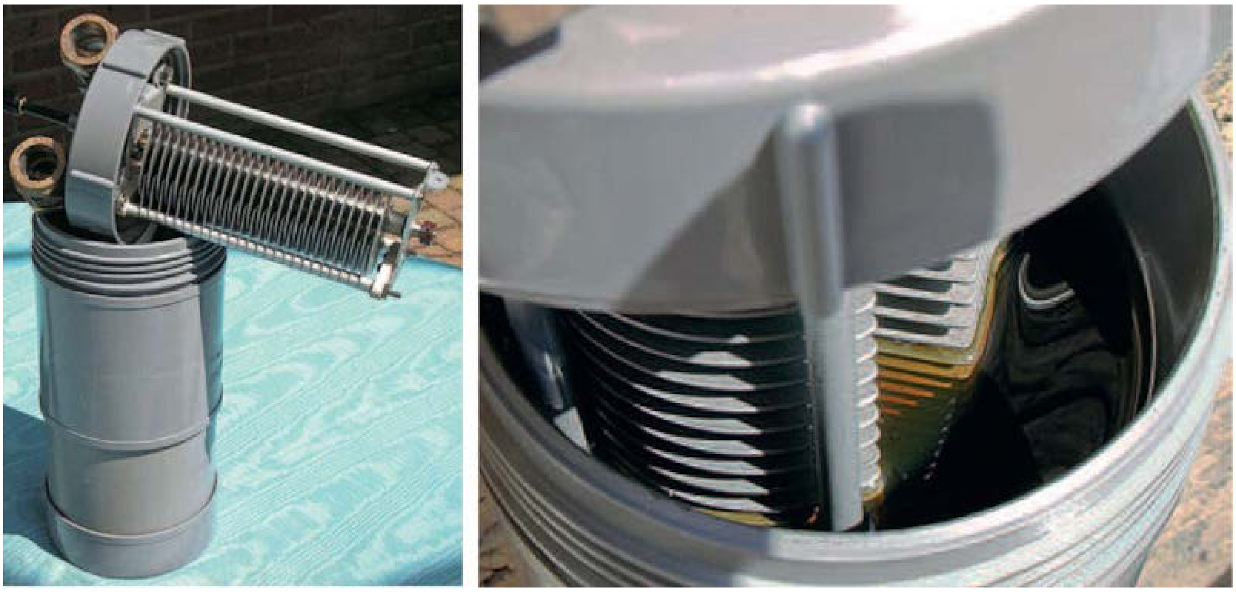


Figure 13: Air-variable capacitor immersed in oil - doubles capacitance and voltage rating
(source: ref. 12A)

Rather than meshing stacks of rotor and stator plates, a variable capacitor can also consist of "trombone-style" coaxial tubes: one tube is slid in and out of a slightly larger "stator" tube. This principle is also used in variable vacuum capacitors, see below.

On 15 June 1896, Nicola Tesla filed US Patent Nr. 567,818A (awarded three months later) for an “Electrical condenser”, with increased efficiency that is obtained by “practically complete exclusion of air or gas from the dielectric”. I.e., the vacuum capacitor! Nowadays, such capacitors typically use two sets of plates that are concentric thin-wall cylinders. In a vacuum *variable* capacitor, one of the two sets can be slid in or out of the opposing set of cylinders ("sleeve and plunger/piston"). The same concept is used in old fashioned air trimmer-capacitors that were made by Philips for several decades since the 1930s (a.k.a. "beehive" trimmer; German: "Tauchtrimmer"). Instead of intermeshing concentric cups, the electrodes may also consist of a continuous spiral (with a fixed pitch).

Figure 14: Philips tubular-piston "beehive" trimmer capacitors (5-30 pF, 0.3 mm plate distance)
(due to their shape, they are called "toltrimmers" in Philips-country (i.e., The Netherlands), meaning "spinning-top trimmer")

In the vacuum capacitor, spacing between opposing cylinders is several mm. The plates are sealed inside of a non-conductive envelope such as a glass or ceramic "bottle", and placed under a high vacuum. The movable part (plunger) is mounted on top of a flexible metal membrane (harmonica-style bellows). The membrane seals and maintains the vacuum. A screw-shaft is attached to the plunger. When the shaft is turned, the plunger moves in or out of the sleeve, and the value of the capacitor changes. The vacuum dielectric significantly increases the voltage rating of the capacitor, compared to an air-variable capacitor of the same dimensions and construction.

The tables in the previous section show that the assumed loop should be tunable from 80-20 mtrs with a 15-500 pF high-voltage variable capacitor. Note: a commercial air-variable capacitor for 15-500 pF and 5-10 kV is not necessarily smaller or less expensive than an equivalent vacuum variable capacitor! In 2010, I purchased a Russian-made capacitor. It is marked "10 kB 10-500 πΦ" in other words: "10 kV,10-500 pF". I measured 15-510 pF with a simple LCR-meter. This "bottle" is quite heavy: 2.2 kg (≈ 4.8 lbs). It takes 36 revs of the shaft to go from minimum to maximum capacitance.

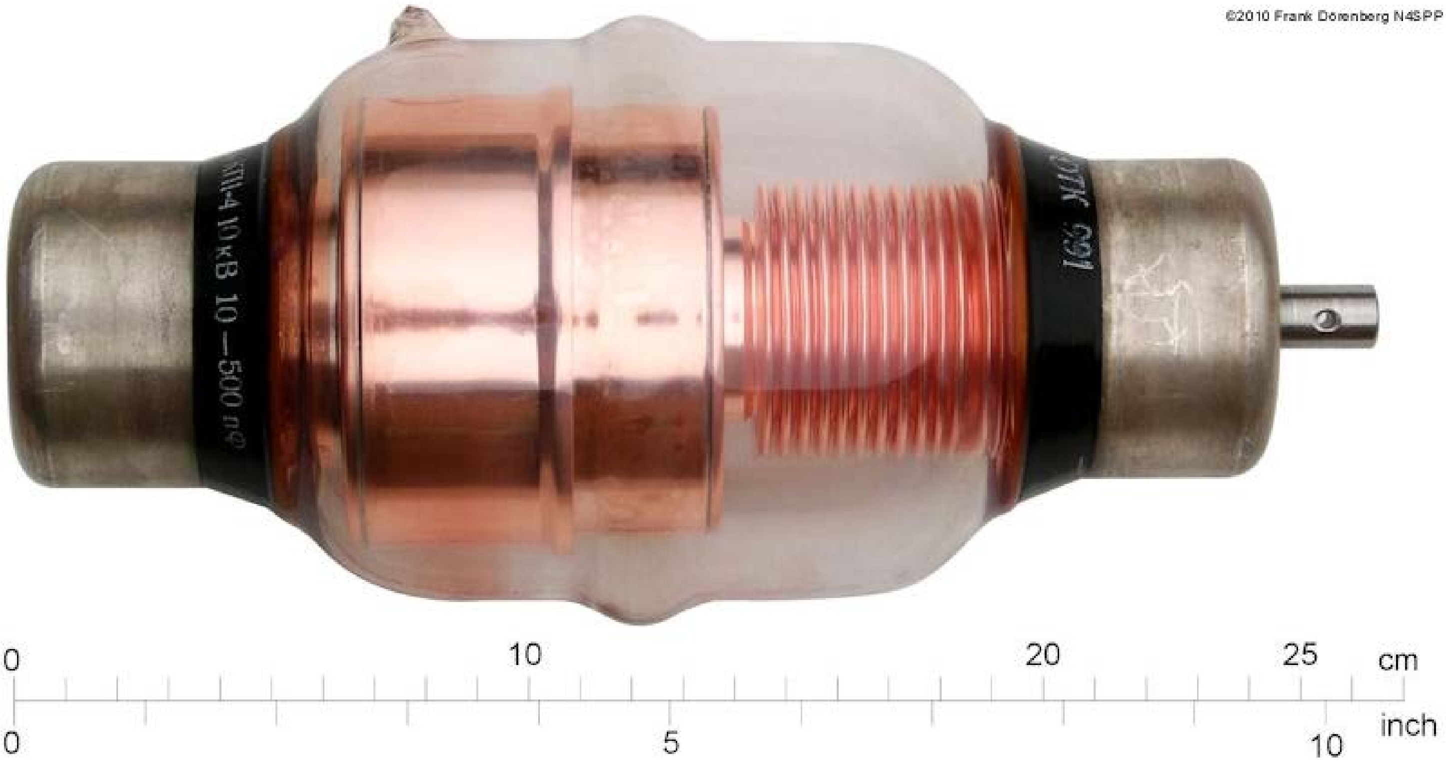


Figure 15: My vacuum capacitor

CAPACITOR RATINGS

Capacitors have two limits that are important in STLantenna applications:

- Voltage rating, which is the dielectric breakdown voltage (with some margin).
- Current rating, which is driven by losses that cause dissipation (= heating).

BREAKDOWN VOLTAGE. Dielectric strength is the maximum voltage that can be applied across a dielectric, without electrical breakdown occurring. Simply put, at the breakdown field strength, the dielectric becomes (locally) conductive: sufficient electrons are knocked out of the dielectric and/or electrode material, are sufficiently accelerated, and set free additional electrons via collisions. In capacitors with gaseous dielectric (such as air), the breakdown peak voltage as a function of plate spacing gas pressure is a non-linear relationship. It is critically affected by factors such as the geometry of the capacitor conductive parts, smoothness of edges, surface finish of the plates, ultraviolet illumination of the electrodes, etc. Breakdown results in a discharge, and can be limited to a luminous corona glow (low-current, high-voltage) around plate edges, or take the form of a "spark" (high-current, low-voltage). It is modeled by *Paschen's* law and associated curves.

Note that dielectric strength of practical vacuum is not infinite! Even deep space is not a perfect absolute vacuum. Ref. 12K. In vacuum electronic components, the vacuum level is typically on the order of 10^{-7} Torricelli ≈ 0.0133 mPa. The breakdown field strength of air is often given as VS = 30 kV/cm = 3 kV/mm = 3 MV/m. Note that this only applies for electrode (plate) spacing of about 2 cm = 20 mm! For smaller spacings, it is actually larger! E.g., for a spacing *D* around 1 mm, the following Townsend's formula is used in standard atmosphere: V_S = (30x*D* + 1.35) kV, where *D* is spacing in cm. For 1 mm (D = 0.1 cm), this yields V_S = 4.35 kV, i.e., ca. 43 kV/cm = 4.3 kV/mm = 4.3 MV/m. The breakdown field strength of air is actually on the order of 2-5 MV/m. Note: if a vacuum capacitor is kept in storage for a long time, or is only exposed to low peak voltage levels for a long time, some gas may be released into the vacuum. This reduces the breakdown voltage below the capacitor's specified test voltage rating. The capacitor may have to be reconditioned (treated with an increasing DC voltage).

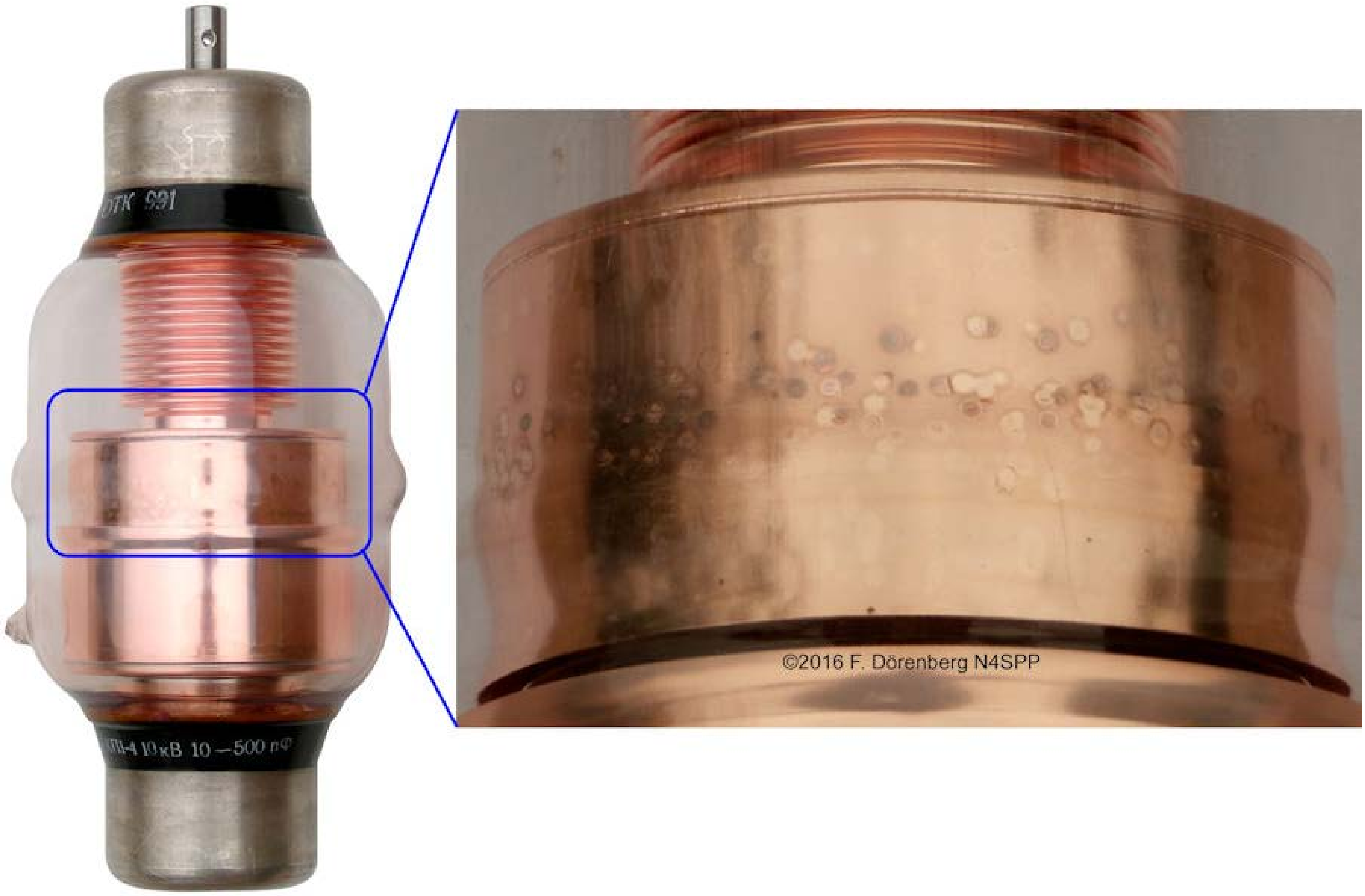


Figure 16: A vacuum capacitor with typical over-voltage arcing damage
(the round damage spots are about 4 mm (≈1/6 inch) in diameter)

The following lumped-element equivalent circuit diagram shows that a practical capacitor is quite a bit more than just an ideal, pure capacitance:

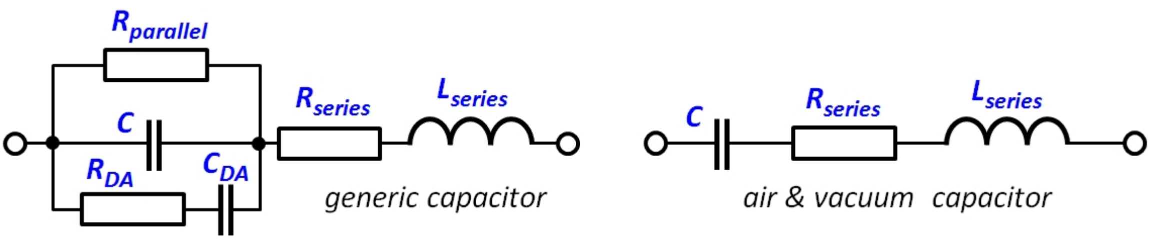


Figure 17: lumped-element equivalent circuit diagram of a capacitor

where

C = ideal, lossless capacitance
R_{series} = equivalent series resistance (ESR, loss)
L_{series} = equivalent series inductance (ESL)
R_{parallel} = insulation resistance
R_{DA} = resistive component of the dielectric absorption
C_{DA} = capacitive component of the dielectric absorption

When transmitting, the loop's tuning capacitor will heat up due dissipation in the capacitor's loss resistances. The latter can be summed into the Equivalent Loss Resistance, ESR. The dissipated power is:

$$P_{diss} = I_{rms}^{\ 2} \cdot ESR = \frac{V_{rms}^{\ 2}}{ESR}$$

ESR consists of metallic losses in the capacitor's electrodes and connecting leads, as well as dielectric losses. In a vacuum capacitor, the dielectric is "vacuum". Hence, the dielectric loss is negligible. At HF frequencies, the ESR of vacuum capacitors varies over a range of about 2 milliohms (at low HF frequencies) to about 20 milliohms (high HF). Ref.12G. The loss-resistance is primarily caused by the capacitor plates, the bellows and the structure that connects the movable electrode to its external mounting flange (in variable vacuum capacitors), and the transition between the rotor shaft and the rotor terminal (in air variable capacitor types, other than "butterfly" and "split-stator" with the stators interconnected). ESR is inversely related to the capacitor's (frequency dependent) Q. Manufacturers of vacuum capacitors typically provide a nomogram chart of max allowable I_{RMS} as a function of operating frequency at the specified peak operating voltage and max capacitance (= largest ESR). Ref. 12B shows the example of a particular vacuum capacitor with a temperature rise of about 40°C when operated at 6 MHz, 7.5 kV peak, and 10 amps RMS. Glass vacuum capacitors typ. have a max operating temperature around 90 °C (= 195 °F). Ceramic vacuum capacitors typically have a higher maximum: around 120°C (= 250°F).

Note that near resonance, a small transmitting loop may have a circulating RF current of several dozen Amps when transmitting at 100 W!

Some manufacturers of vacuum capacitors issue data sheets that include an RMS current rating graph. It typicaly shows a "continuous RMS current (amps) vs. frequency" curve for a fixed operating voltage (often the voltage rating). For *variable* vacuum capacitors, there may be two or more such curves, where the rating for lower capacitance values is lower than for higher capacitance values. The rating-curves normally increase (linearly on a logarithmic scale) with frequency, up to a certain frequency. For higher frequencies, convective heat-sinking capability becomes the limiting factor, and the curve(s) go down with frequency. The voltage rating is not frequency dependent.

Dielectric absorption is the effect by which a capacitor that has been charged for a long time, does not discharge completely when briefly discharged. In air capacitors and vacuum capacitors, this effect is typically too small to be measurable. The insulation resistance R_{parallel} accounts for leakage current through the dielectric. For variable vacuum capacitors, the latter is typically less than 10 microamps. This is extremely small, compared to the capacitor current when the loop is tuned to resonance.

The series self-inductance L_{series} of an air variable capacitor typically ranges from about 6 to 50 nH. For fixed vacuum capacitors, it ranges from about 2 to 10 nH. Variable vacuum capacitors have a bellows and a structure to connect the movable electrode to the external mounting flange. This increases the self-inductance to about 6 - 20 nH, and this inductance changes with the capacitance. The capacitor's self-resonance frequency that results from this series inductance, is normally well above HF.

EFFECTS OF TEMPERATURE, ATMOSPHERIC HUMIDITY & PRESSURE

(this section still needs some work...)

Have you ever noticed that the resonance frequency of your “Mag Loop” STL drifts when the capacitor’s temperature changes? The temperature change may be due to loss-dissipation in the capacitor when transmitting, the sun shining on the capacitor, or change in ambient temperature. Likewise, have you noticed a frequency drift when the relative humidity of the air changes significantly (foggy weather, temperature near the dew point)? Or you have noticed a change in the maximum transmit power you can apply, before a luminous corona discharge appears at the capacitor plates, or arcing occurs?

There is surprisingly little literature (including university textbooks) that discusses the effects of parameters such as humidity, atmospheric pressure, and temperature on the performance of tuning capacitors. General literature often considers the effects as “minimal” or “negligible”, and uses simplistic, approximate models such as that of an ideal capacitor that consists of two flat parallel plates or concentric cylindrical plates:

$$C_{parallel} = \frac{\varepsilon_r \varepsilon_0 A}{d} \qquad C_{concentric} = \frac{\varepsilon_r \varepsilon_0 2\pi \cdot l}{\ln\left(\frac{r_1}{r_2}\right)}$$

where

C = capacitance in Farad
ε_0 = absolute permittivity of free space ("pure vacuum"); $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m
ε_r = relative permittivity of the dielectric (a.k.a. dielectric constant)
A = area of plate overlap in square meters ("active area")
d between plates in meters (= dielectric thickness)
l = length of overlap between the electrodes in meters
r_1 = inner radius of the outer electrode in meters
r_2 = outer radius of the inner electrode in meters

These formulas ignore edge effects, and suggests that the capacitance C is a constant. However, the capacitance *does* change with temperature, as well as humidity and barometric pressure (air capacitors). Ref. 12B, 12C.

TEMPERATURE. The capacitance of a decent “glass bottle” vacuum variable capacitor typically varies no more than about 100 ppm/°C = 0.01%/°C (ref. 12G). Ceramic vacuum capacitors only drift about half as much, but an air capacitor may drift three times as much. That’s still not much, right? Well, in a “low-Q” filter application this may well be the case. But in a well-constructed “high-Q” loop? Let’s take a marginal vacuum variable capacitor and assume a temperature increase of only 10 °C (= 18 °F). Worst-case (!), the capacitance will change by 10 x 0.01% = +0.1%. What does this mean for the resonance frequency of a loop antenna?

$$f_{res} = \frac{1}{2\pi\sqrt{LC_0}}$$

where L = loop inductance, and C_0 = capacitance of the tuning capacitor at a particular temperature T_0. Note that, for the sake of simplicity, we are ignoring the stray (parasitic) capacitance of the loop inductance here. Based on the above formula, we can derive the change of the resonance frequency for a given shift in the capacitor temperature :

$$\Delta f_{res}(T_0 \rightarrow T_1) = f_{res}(T_0) \cdot \frac{1}{\sqrt{m} - 1}$$

where m = capacitance change-factor due to temperature change from T_0 to T_1. Hence, m = 1 + drift percentage. For ΔT = +10 °C, m = 1+0.01% = 1.01. Hence:

$$\Delta f_{res}(\Delta T = +10\,°C) = f_{res}(T_0)\cdot\left(\frac{1}{\sqrt{m}} - 1\right) \approx f_{res}(T_0)\cdot 0.995$$

I.e., a change of -0.5%: temperature increase causes a frequency decrease. For instance, at 28 MHz , the resulting frequency drift would be 28 MHz x -0.005 = -14 kHz. At 3.6 MHz, the resulting frequency drift would be 3.6 MHz x -0.005 = -1.8 kHz. This much drift is quite noticeable! Note that there are even small hysteresis effects associated with large temperature changes (ref. 12C).

In the discussion above, we used the standard equation for the resonance frequency of an LC circuit and approximate models for capacitance. Per the resonance frequency equation, a relative change in *C* clearly has the same effect as the same relative change in *L*. The standard approximate model for an inductance coil is given below. Instead of the capacitor's permittivity ε of the medium between the plates, we now have the magnetic permeability μ of the medium inside the coil winding(s). For a cylindrical coil with *N* turns (*N* = 1 for a standard STL antenna), the inductance is approximately:

$$L = \frac{\mu_r \mu_0 N^2 A}{l}$$

where

- L = inductance in Henry
- μ_0 = absolute permeability of free space ("pure vacuum"); $\mu_0 = 4\pi \times 10^{-6}$ H/m
- μ_r = relative permittivity of the dielectric
- N = the number of turns of the coil-winding
- A = area of plate overlap in square meters ("active area")
- l = average length of the coil in meters (= dielectric thickness)

A standard "Mag Loop" STL antenna is a 1-turn air-core inductor. Like a capacitor's relative permittivity, a coil's relative permeability depends on the operating frequency, and the temperature, pressure, and humidity of the dielectric (= "air" for a loop antenna)!

Before I bought my used vacuum capacitor, did a quick test to verify integrity of the vacuum: I put the capacitor in the refrigerator for about an hour. There should be no formation of condensation on the inside of the glass when in the fridge, or after taking it back out (on outside is OK). If the vacuum seal is compromised, the shiny copper will turn dull eventually. As heavy as the capacitor is, the glass is actually rather thin. I found this out when my first vacuum capacitor imploded when it rolled around on the tiles of my terrace floor.

HUMIDITY. Yes, the capacitance of vacuum capacitors is not affected by humidity: moisture can only affect the outside surface of such capacitors. But high ambient humidity may cause a small leakage current across the outside of the capacitor. However, for air capacitors, the capacitance change as a function of relative humidity of the air is actually so large, that such a capacitor can be used as a relative-humidity sensor (ref. 12D)! Note that air capacitors also exhibit small hysteresis effects associated with long exposure to high humidity (ref. 12F). Relative permittivity $\varepsilon_r = 1$ for vacuum. Dry air has an $\varepsilon_r \approx 1.0006$ (at standard temperature and pressure of 1 atm). This "constant" changes 2 ppm/°C for dry air, and 7 ppm/°C for moist air. Ref. 12H. Dry air has a relative permittivity $\mu_r \approx 1.000000037$. I'm still trying to dig up data on the relative permittivity of air as a function of temperature, humidity, and partial vacuum. With my own helical loop antenna with air variable capacitor, I have observed a frequency drift of 0.5% (20 kHz around 3.6 MHz) when fog moved in, while temperature only changed 0.5 °C.

COUPLING A LOOP TO THE FEEDLINE

The loop antenna will be connected to my transceiver via a coax feed-line. This means that the coax needs to be coupled to the loop, and the coupling must be wide-band enough to cover the tuning range of my antenna. As with other types of antennas, there are several ways to do this:

[Inductive coupling (coupling loop)] [Capacitive coupling]
[Magnetic transformer coupling (ferrite ring)] [Auto-transformer coupling (Gamma Match, etc.)]

Note: this is only a overview of the most common methods. The list is not exhaustive.

INDUCTIVE COUPLING

The most common coupling method is using a small inductive coupling loop (a.k.a. matching loop). The main loop and the coupling loop form a (rather) loosely coupled transformer:

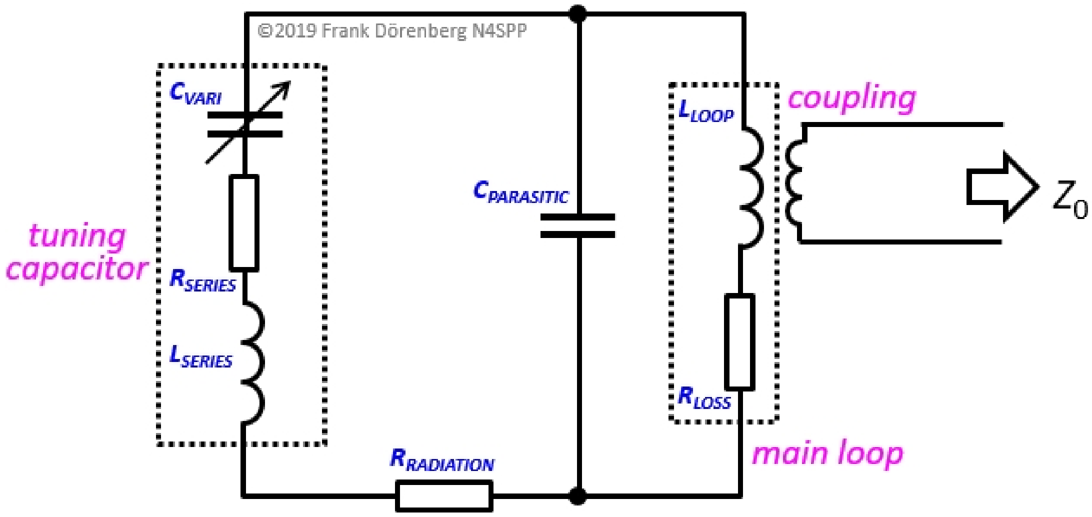


Fig. 18: Simplified equivalent lumped-element electrical circuit of an STL with inductive coupling
(coupling to ground and objects near antenna is not shown)

The turns ratio of this is fixed (1:1), but there are several coupling loop parameters that affect the coupling:

- The **size** of the coupling loop. Its standard diameter is 1/5 that of the main loop. However, I have seen designs with 1/3 to 1/8 the diameter of the main loop.
- The **shape** of the loop. The standard shape is circular. Obviously, like the main loop, other shapes can be used (square, octagonal, ..). To obtain the desired coupling, the coupling loop can be squashed or stretched into a vertical oval or egg-shape. This changes the aperture of the loop (area of the "opening"), as well as the distance to the main loop.
- **Placement** along the main loop. Standard is opposite the tuning capacitor. However, to adjust the coupling, it can be moved off-center, along the main loop.
- **Proximity** to the main loop. Normally, the coupling loop is placed opposite the tuning capacitor, close to the main loop.
- **Alignment** with the main loop. That is: whether the plane of the coupling loop coincides with that of the main loop. The coupling with the main loop can be varied by turning the coupling loop about its vertical axis (from where the coax is connected to the point at the top of the loop), such that it sticks through the main loop. Instead of turning, it can also be bent.

- The **gauge** of the conductor - as with all coils / inductors.

A distinction is made between "un-shielded" and "shielded" coupling loops.

Unshielded coupling loops are very simple:

- A heavy gauge wire or small diameter copper tubing; the conductor need not be heavier gauge than the center-conductor of the feed-line coax. However, heavier conductor will help retain shape of loop, and make it self-supporting.
    - I have used "extra heavy" single-strand (solid) installation wire of 2.5 mm^2, but these days I use soft copper tubing of about 6 mm diameter in my large loop (see Fig. 79 below), and thin brass tubing (see Fig. 9 of my small STL project). This is mechanically quite stable.
    - With such a simple coupling loop, I obtain very good SWR over a frequency range of up to 2 decades (factor 4), see Fig. 79 & 80 further below.
- The shield of a section of coax cable. The center conductor is left unconnected, or both ends of it are connected to the shield.
- The center conductor of coax, with outer insulation and braid fully removed. The dielectric material of the coax is kept, and provides rigidity.

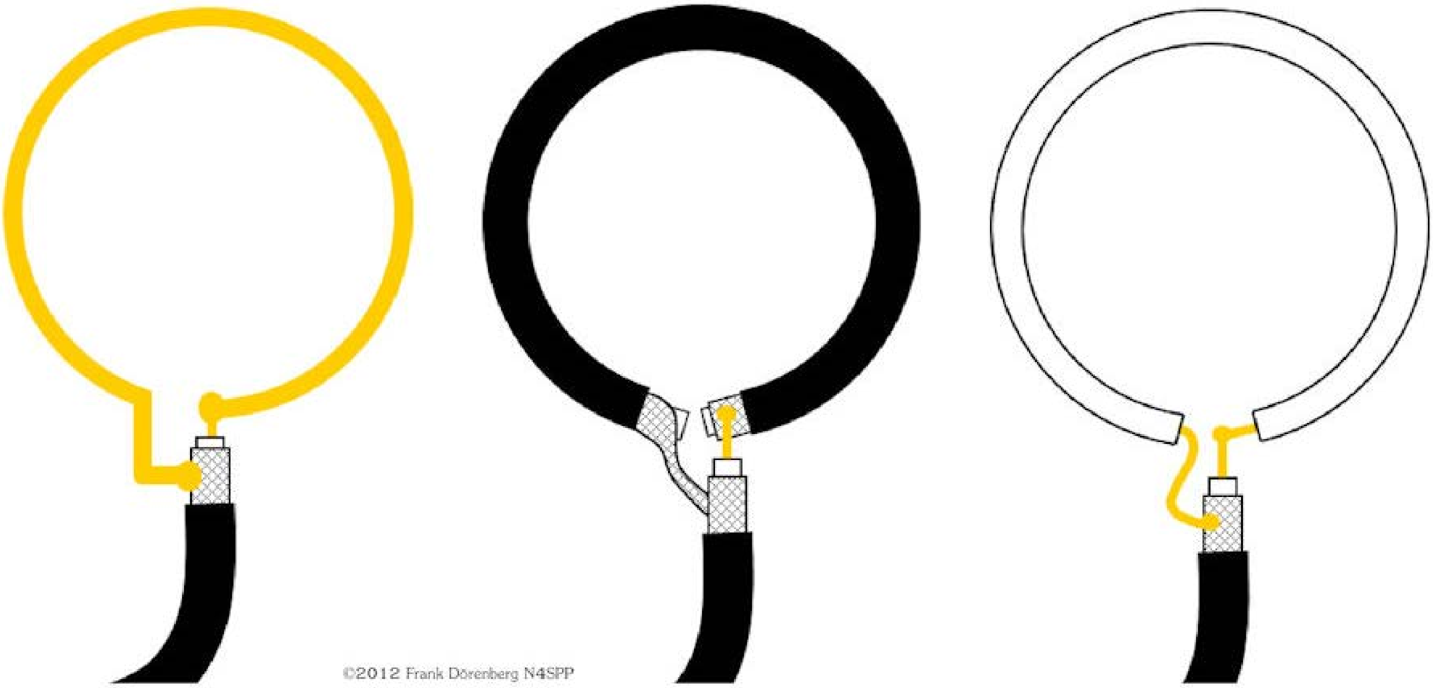


Figure 19: Un-shielded coupling loops
(solid wire, braid of coax, center-conductor of coax)

One variation of this is a "tuned coupling loop", but is does not appear to be popular:

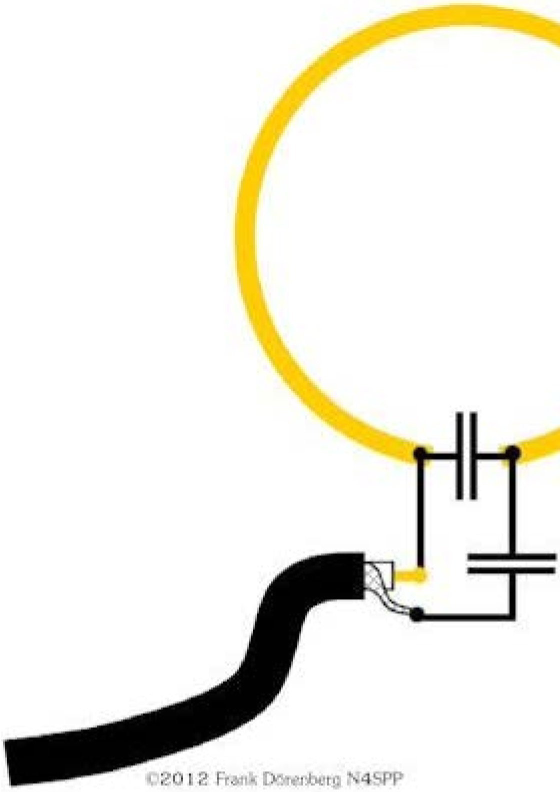


Figure 20: Un-shielded coupling loop with a tuning and a loading capacitor

Note that with the standard round coupling loop, the main loop and the coupling loop are close to each other, but only over a small part of the circumference of the coupling loop. Depending on the size of the coupling loop, better coupling ("lower SWR") can sometimes be obtained when the coupling loop is stretched or compressed into a more oval shape:

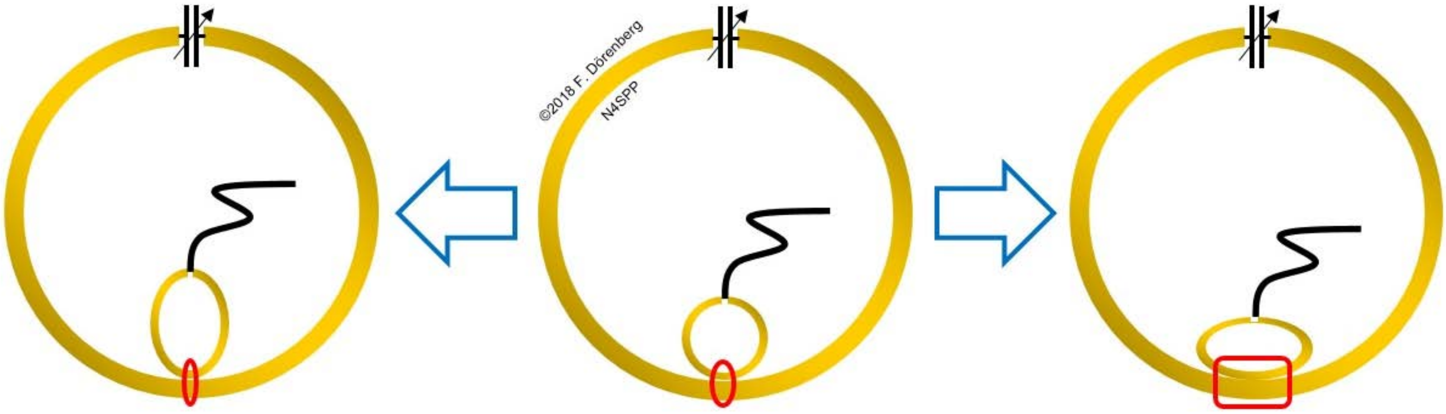


Fig. 21: Stretching or compressing a round coupling loop to change the coupling with the main loop

A variation of this method is what I call the "coat hanger" coupling loop. It consists of insulated wire (e.g., installation wire, or even heavy enameled copper wire). The overall wire length is a little more than the diameter of the main loop. The coupling loop is symmetrically placed onto (and affixed to) the main loop, over a distance equal to 1/2 the main loop's diameter (i.e., ≈ 1/6 the loop's circumference). Rather than connecting the coax at the bottom, it is connected at the top of the feed loop. I.e., an upside-down wire loop. The wire ends are folded towards each other, joined and twisted over a distance of about 10-12 cm (4-5"; not critical), and connected to the coax. A current choke "balun" is placed near the coupling. The point where the wire ends are twisted, is moved up or down, to obtain the desired matching.

I have only briefly played with this coupling method. The antenna's resonance frequency varied quite a bit when the twisted connection to the coax was moved up and down. SWR was relatively flat over a significant frequency range - about 200 kHz, quite a bit wider than with a regular coupling loop.

This is similar to the triangular feed-loop of [my (mono-band) spiral loop antennas](), where the coupling loop has a circumference that is 1/8 that of the spirally-wound 1/4 λ main loop.

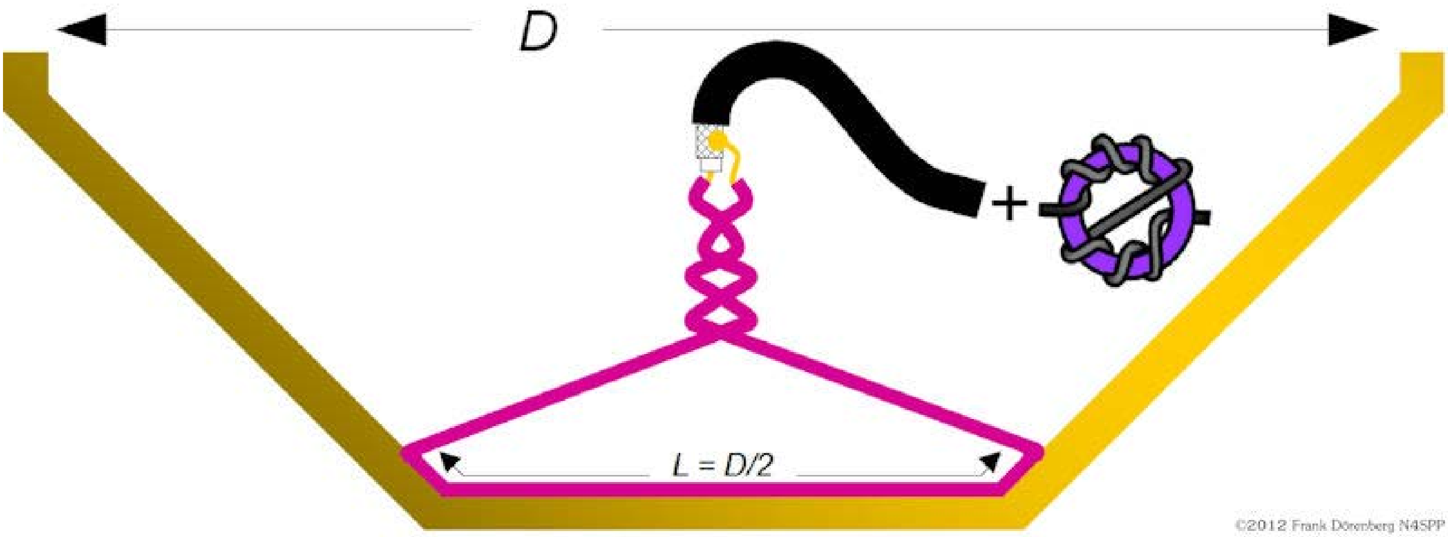


Figure 22: "Coat hanger" coupling loop

The coupling between the triangular coupling loop and the main loop can be made tighter, by winding the insulated wire of the coupling loop around the main loop, like Jo Lourenço (CT1ECW) has done for his 7-21 MHz loop (ref. 6M). This looks like a "twisted" delta-match. The same technique is used in the ["twisted" gamma-match]() that is shown further below.

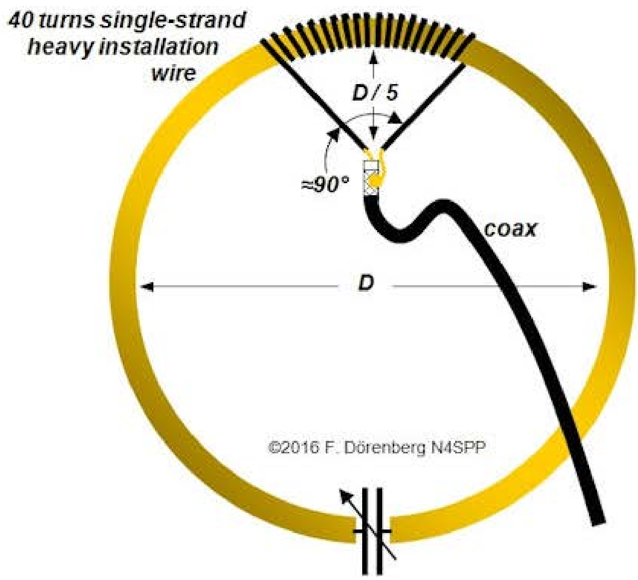


Figure 23: Spiral coupling
(photo: ©Jo Lourenço, used with permission)

The second type of inductive coupling loop is the **shielded** (= screened) loop, often referred to as a "Faraday Loop". As with the unshielded coupling loop, the typical diameter is 1/5 that of the main loop (though some people have better results with a coupling loop as small as 1/8 the size of the main loop). For ease of construction, this coupling loop is typically made of a section of coax cable. In my experience, it is difficult to make such a coax loop mechanically stable, especially with thin coax (RG58, RG8,...) and a "Faraday" configuration (= interrupted coax braid and center conductor).

There is number of variations that differ with regard to:

- whether the coax braid (= shield) is interrupted at the point half way around the loop,
-

- whether the center conductor is interrupted at that same point,
- how the braid and center conductor are connected at the starting point of the loop.

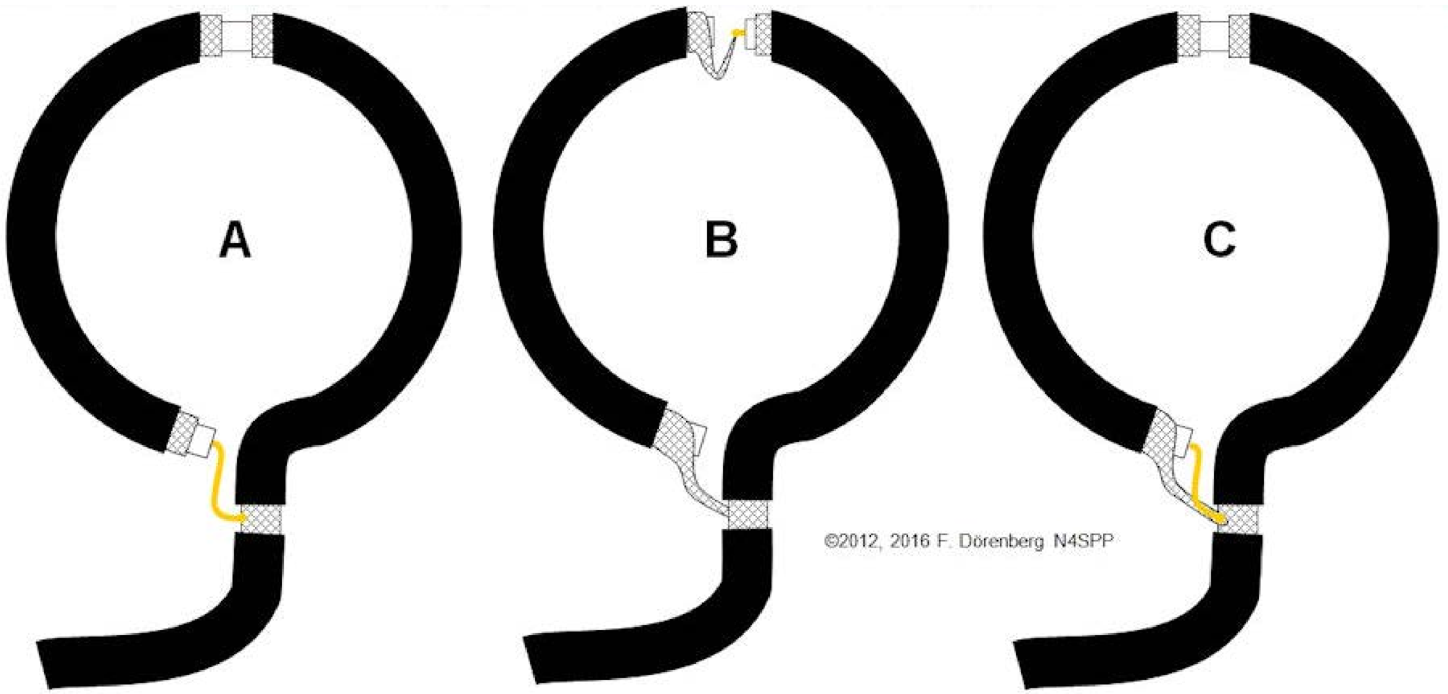


Figure 24A: Variations of shielded coupling loops

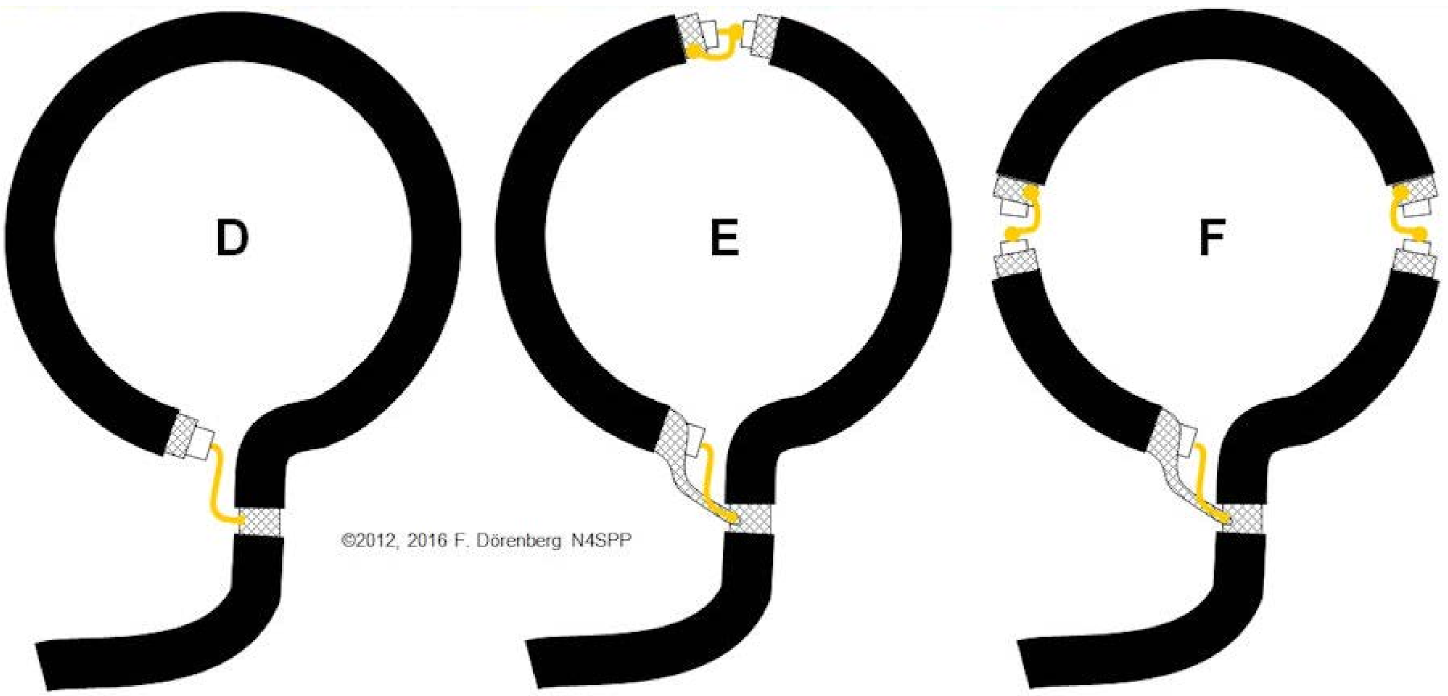


Figure 24B: Variations of shielded coupling loops (continued)

Let's have a closer look at variation **D**. The shield of the coax loop envelopes the flux that is created by the 1-turn coil formed by the center conductor of that coax. This induces a voltage across the looped shield. The maximum voltage occurs at the point where the shield ends. At the mid-point of the coax loop (i.e., at the top of that loop in the diagram), half of this maximum voltage is present. Hence, the loop as a whole, also has an average $V_{max}/2$ with respect to ground. This coupling loop generates an electrical field that is primarily vertically polarized (assuming the coupling loop is installed vertically), This is coupled into the shield of the feedline. Conversely, this loop "receives" vertically polarized E-fields, incl. from the feedline (which may carry any disturbances that the transmitter passes to ground from its power supply and main power). This problem is solved in variation **B** (which is actually a half-shielded loop). Here, the left-hand and right-hand half of the coupling loop generate opposite (= cancelling) voltages. In the *vertical* direction, the average is now zero. This eliminates receiving and generation of vertically polarized E-fields. Clearly, there still is reception and generation of *horizontally* polarized E-fields. In principle, *both* polarizations can be suppressed by opening the coax loop at the 3 o'clock and the 9 o'clock position, instead of only at the 12 o'clock position. See variation **F**. Ref. 6R.

The next two shielded loops are inherently balanced. Note that unbalanced coupling loops cause an asymmetrical radiation pattern of the main loop, even if positioned symmetrically with respectto the latter. Configuration **G** is another conventional "split loop". In configuration **H**, the center conductor of the coupling loop crosses-over to the shield on the opposite side of the gap. If you trace one of the terminal wires, it is clear that the signal goes around the coupling loop twice. Start, e.g., with the red terminal wire. Follow it via the first cross-over, then all the way around the shield, then another cross-over, and via the blue wire to the second terminal. This resembles a so-called "Möbius" strip. It is named after the 19th century German mathematician August Ferdinand Möbius (equivalently spelled as "Moebius"). This strip is a surface with only one side! In it simplest form, it is a strip of material, one end of which is twisted 180 degrees and then attached to the opposite end of the strip. The result is a loop with a twist. Hence, loop configuration **H** is also referred to a "Möbius (strip) loop". Note that the two-turn signal path doubles the (very small) path delay time. As a reception loop, the voltage across the terminals is double that of configuration **G**. See ref. 15A-15G.

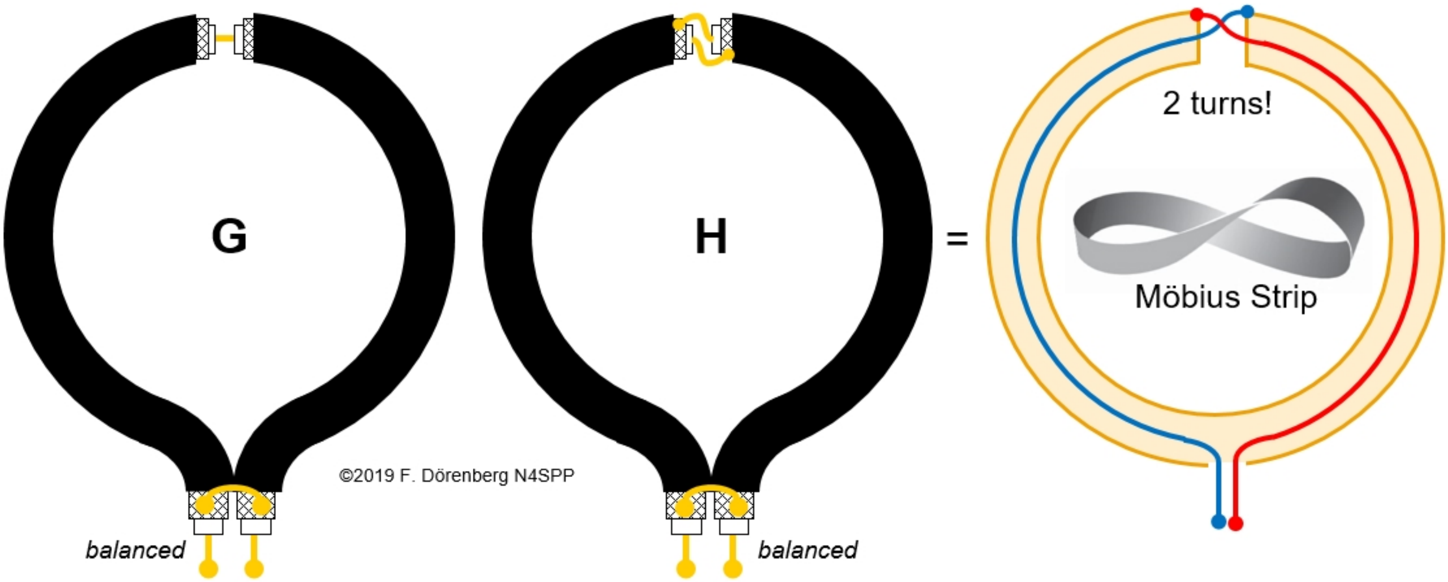


Figure 24C: Balanced shielded coupling loops

To connect the above balanced coupling loops to a coax feedline, a 1:1 balanced-to-unbalanced (Bal-Un) transformer must be used. The one shown in Fig. 24D comprises 11+11 bifilar turns on an FT-240-43 ferrite ring (an FT-140-43 should be fine upto 100 W or so - once the main loop is tuned!). I used 2x0.75mm^2 twin-lead wire (≈ 18 AWG) with relatively thin insulation, to maximize the number of turns. The green wire in Fig. 24D connects the shield of the coupling loop to the shield of the feedline coax. I intend to compare this coupling loop configuration (with and without green wire), to my standard unshielded loop. Results will be reported here in due time...

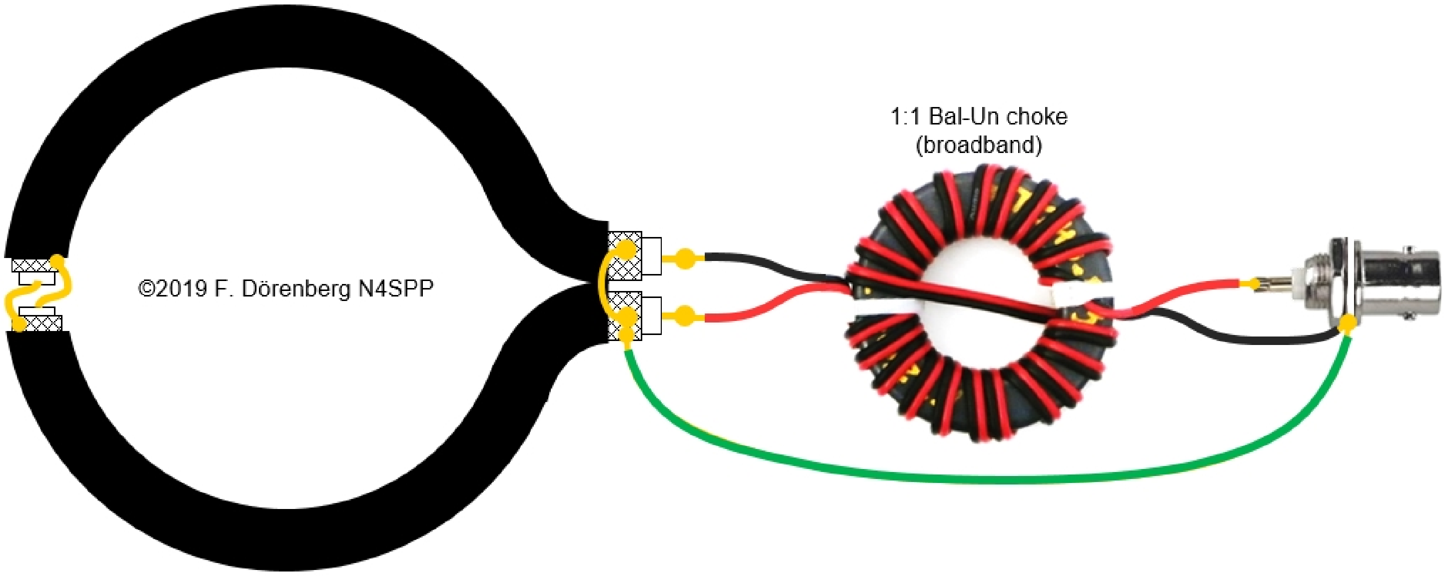


Figure 24D: Balanced shielded coupling loop - fed by (unbalanced) coax via a 1:1 BalUn

For the same diameter, the unshielded and the various shielded coupling loops all have a different self-resonance frequency (easily measured when not coupled to the main loop).

Jochen Huebl (DG1SFJ) has done some interesting comparative measurements with an unshielded coupling loop, and with shielded coupling loop variations D and E (ref. 6A). The coupling loop (in his case: 16.5cm (6.5"), 1/5 the diameter of the main loop) was placed in the same plane as the main loop, opposite the tuning capacitor. He then varied the distance ***d*** between the two loops: starting with the coupling loop against the main loop (with some insulation between them), then moving the coupling loop closer to the center of the main loop (max 10 cm / 4 inch). See the figure below:

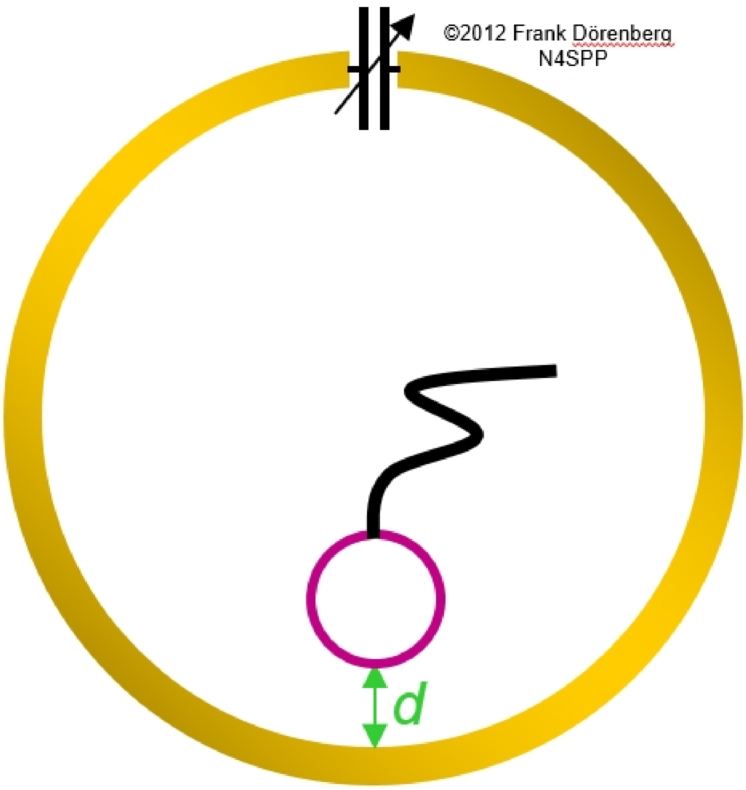


Figure 25: The experiment of Jochen Huebl (DG1SFJ)

As the induced magnetic field decreases with distance, the coupling between the two loops becomes weaker when the distance is increased. Note that it basically makes no difference whether the coupling loop is *inside* the main loop or *outside*. Jochen's **observations** are:

- SWR increased linearly with the distance between the coupling and main loop (from close to

1:1 to ca. 5:1).

- Lowest SWR was obtained with the coupling loop closest to the main loop.
- The shielded coupling loops had slightly better SWR than the unshielded coupling loop.
- Network parameter S11 is the magnitude of the Reflection Coefficient, expressed in dB. That is, *S11* = +20 x log(abs(Γ)), where Γ is a complex number (a vector entity). It has a magnitude that is commonly denoted *ρ*, and a phase angle *θ*. *S11* is 0 for a full reflection and negative for anything else. "Return-loss" is simply that same dB value of *S11*, but with the opposite sign (at least for passive devices such as antenna systems). "Return loss" does not mean loss *due to* reflection (= "return"), but rather means loss *of* reflection. Jochen observed that *S11* increased rapidly when the distance was increased from 0 to 2-3 cm (1"), then became more flat with further increase in distance. Over the initial distance increase, the shielded coupling loops had better coupling: *S11* was more negative by about 6 dB (= return-loss decreased by 6 dB). See the figure below.

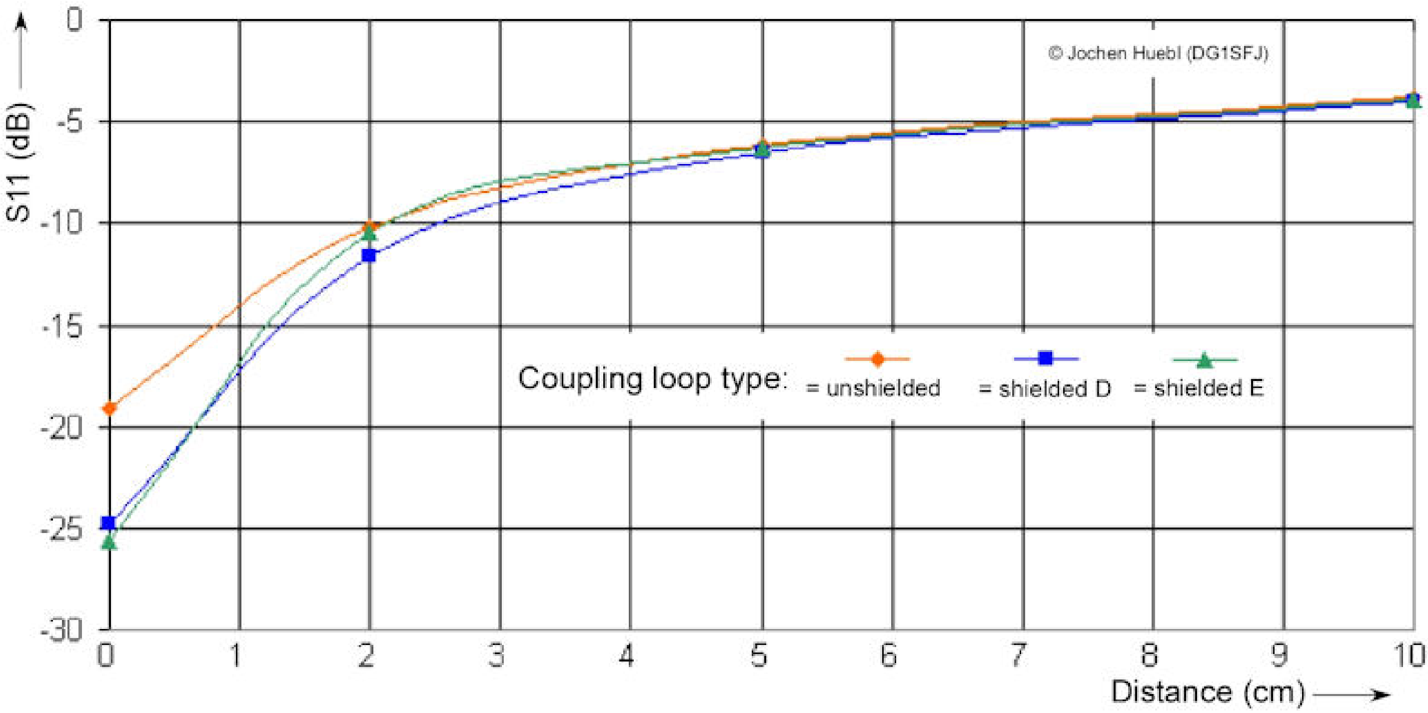


Figure 26: Return-loss S11 as a function of distance between coupling loop and main loop

The main loop and the coupling loop basically form an air-core transformer. Some literature claims that the transformation ratio only depends on the ratio of the surface area of these two loops. As shown above, this is simply not true - *unless* the two loops are round, concentric, and co-planar (= lie in the same plane), and the loop-current is uniform around the loop's circumference. Ref. 6Q.

Note that if the coupling loop is too large, moving it away from the main loop may improve the SWR. Likewise, if the loop is too large, coupling may be improved (= SWR lowered), by turning the coupling loop about its vertical axis, such that it no longer lies in the same plane as the main loop:

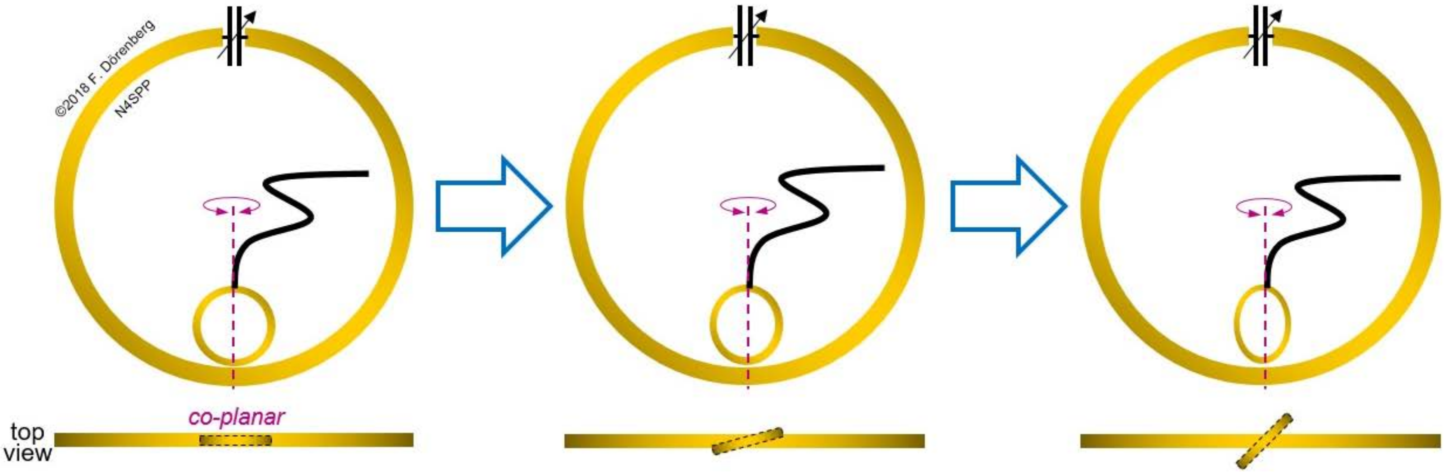


Figure 27: Turning the coupling loop about its vertical axis to change the coupling with the main loop

This rotation can actually be motorized with remote control (see this section further below), to maintain low SWR over a larger frequency range than is possible with a fixed-angle coupling loop. Assuming that the radiation pattern of the antenna is symmetrical, then the motor drive only has to be able to rotate the coupling loop about its vertical axis over 90° max, Actually, the required rotational range will be a lot less than 90°: when the two loops are close to perpendicular, the coupling will not be good. Note that asymmetrical coupling methods such as the Gamma Match make the radiation pattern somewhat asymmetrical. Objects close to the antenna may have the same effect.

CAPACITIVE COUPLING

The capacitive coupling methods basically consist of one or two tuning capacitors, and one or two loading capacitors. This suggests that there are several configurations, as is indeed the case. This type of coupling is much "tighter" than with the coupling loops described above. This may make the antenna system more effective, even though the "Q" of the loop is reduced.

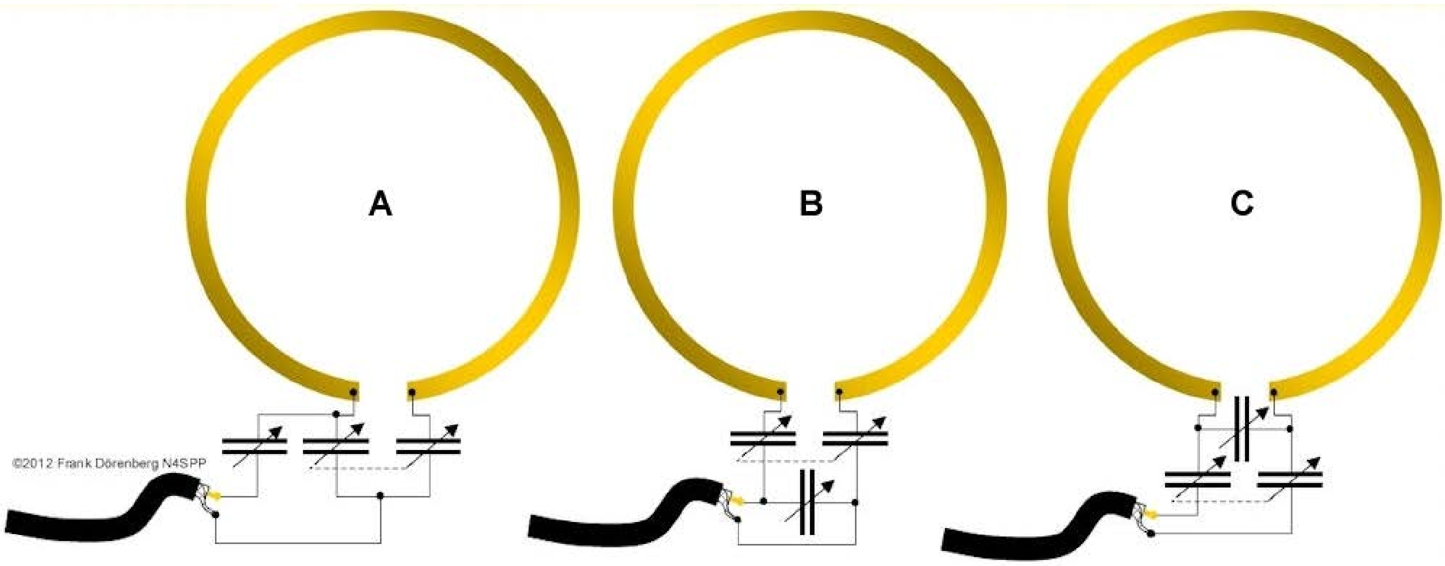


Figure 28: Capacitive coupling methods

Configuration B in the figure above is referred to as the "Patterson loop" (ref. 6B, 6P) or "Army loop". It was used in overseas adventures of the US army in the 1960s. The octagonal loop for 2-5 MHz consisted of 5 ft (1.5 m) sections of aluminium tubing (diameter: 1.75 ", 4.5 cm). The ends of the tubes were gold plated, to reduce contact resistance.

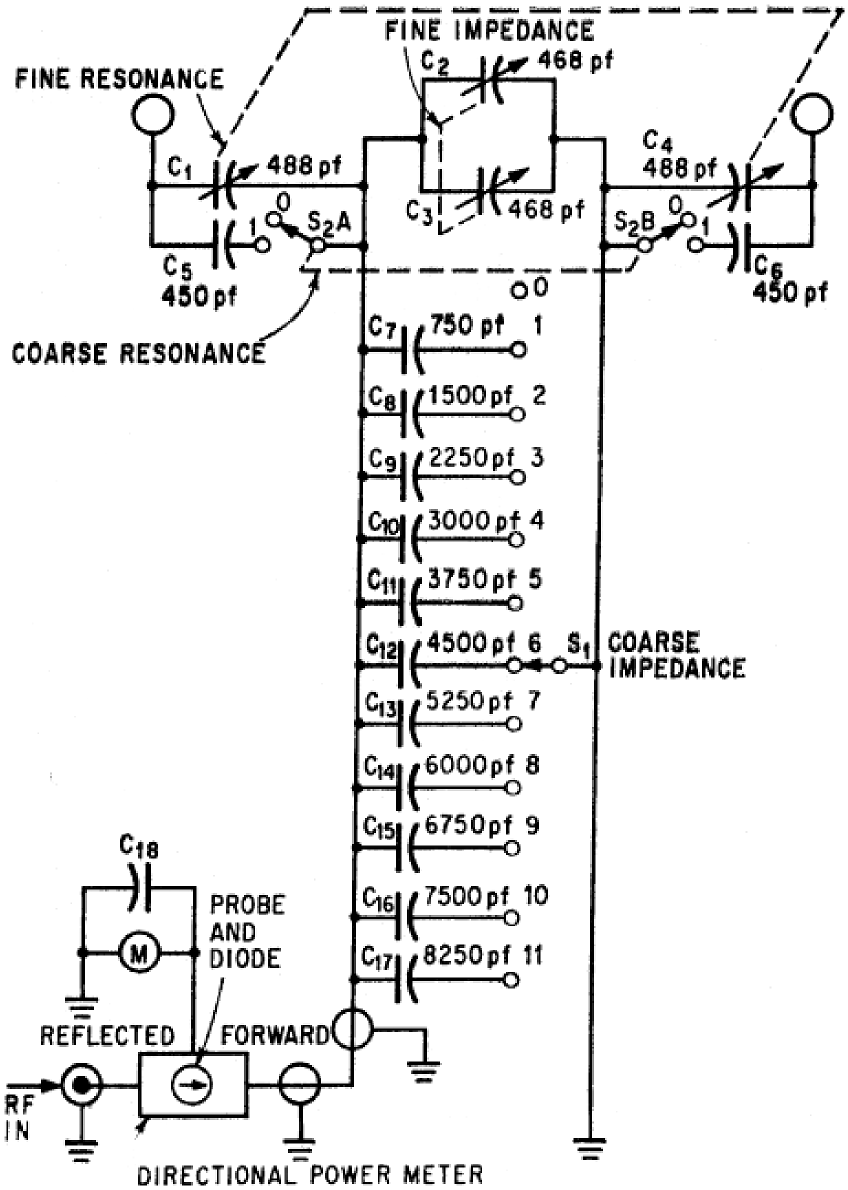


Figure 29: The tuning & matching unit of the "Patterson" Loop
(note that tuning is done based on maximizing the antenna current, not minimizing SWR)

MAGNETIC TRANSFORMER COUPLING (FERRITE RING)

A simple transformer coupling can be made, by passing the antenna loop through a ferrite ring (toroidal core). The secondary side of the transformer is then formed by one or more turns of insulated wire. The coax cable is connected across the secondary winding. There are no adjustments or other manipulations required.

This coupling method only has a few simple variables:

- The type of ferrite material.
- The size of the ferrite cores.
- The number of stacked cores.
- the number of secondary turns.

There are many different ferrite material mixes. Most commonly used in STL transformers are Amidon / Fair-Rite / Micro Metals mixes nr. 31, 43, and 61 (or equivalents from another manufacturer). Important parameters from the data sheets (ref. 7) are "Initial Permeability and Loss Factor vs. Frequency" and "Core Loss vs. AC Flux Density" curves. Note that the permeability of ferrites varies with the magnetic flux level. Hence inductance of a coil or transformer made of such material will change with the power level. Power handling of a loop with transformer coupling is often limited by core losses, rather than the voltage rating of the tuning capacitor. These core losses (primarily hysteresis loss and eddy-current loss) roughly increase with the square of the flux density in the core, at any frequency. Some recommendations:

- Mix 43 becomes quite lossy above about 7 MHz. Use this material mix for 80-40 mtrs, possibly 80-30.
- Below 5 MHz, Mix 31 (a manganese-zinc mix) is probably a better choice than type 43 (nickel-zinc mix).
- To cover 20 mtrs and above, use material Mix 61 (nickel-zinc-iron mix).

Note that properties of ferrite cores may vary as much as 30% from the nominal values in the data sheets! Also, there are not homogeneity specs for ferrite material, and hot-spots may occur at power levels below the maximum.

Obviously, the ferrite core must be large enough for the ring to be slid over the loop tubing and accommodate the required number of secondary turns. More importantly, ferrite RF transformers must be operated at a core flux-density level that is commensurate with the volume and cross-sectional area of the ferrite ring. Conversely, the core dimensions should be adequate for the power level and frequency. The maximum allowed flux level is driven by the loss-tangent (= dissipation hysteresis loss factor) of the ferrite mix. If that flux density limit is exceeded, then a runaway effect causes the core temperature to rise very quickly and ultimately (and possibly violently) destroy the core! Note that mix "61" has a Curie temperature (above which the ferrite properties are permanently destroyed) that is much higher than that of type "43": 350 °C (660 °F) vs. 150 °C (300 °F). Two or more cores can be stacked to increase power handling capability. However, stacking cores also increases the total inductance of the transformer. Furthermore, a *larger core* also results in larger inductance, compared to a smaller core of the *same* material. E.g., a T-240-43 toroid (2.4 inch outer diameter, material type 43) has a higher A_L value (inductance in μH per 1000 turns) than an FT-140-43 (1.4 inch OD): 1075 vs. 885. Experiment! Very small cores such as T-82 or T-130 are basically limited to QRP operation.

As it is a 1:*N* transformer for voltage and current, *N* (the number of secondary turns) has to be chosen such that $50 / N^2$ = impedance of the loop at the point where the transformer is installed on the loop. *N* is typically determined empirically, by trial-and-error: start with a number that is too high, measure SWR at resonance, then reduce by one or two turns at a time. In a small transmitting loop, the current is basically constant around the loop circumference. This is illustrated in the introduction section at the top of this page. So it does not make much of a difference where the transformer is placed around the loop. However, if the loop size is increased to, say 0.2 - 0.25 λ, the loop is no longer "small", and the current through the capacitor is significantly smaller than the current at the point opposite the capacitor. This means that the coupling with a ferrite core transformer then *does* depend on where the transformer is placed along the loop. The turns of the secondary winding should be spread out evenly around the ferrite ring, to minimize parasitic capacitance.

One of my first experiments with the transformer coupling was with an 1:1 transformer comprising an T-140-43 ferrite core and a single-turn coax loop. See the figure below. This configuration puts the 50 ohm impedance of the coax feed line in series with the very small loop impedance. This results in significant mismatch. I tried this, and found a low SWR over the entire frequency range of interest, but a bandwidth that was at least an order of magnitude larger than when using multiple wire windings. Still to be explained...

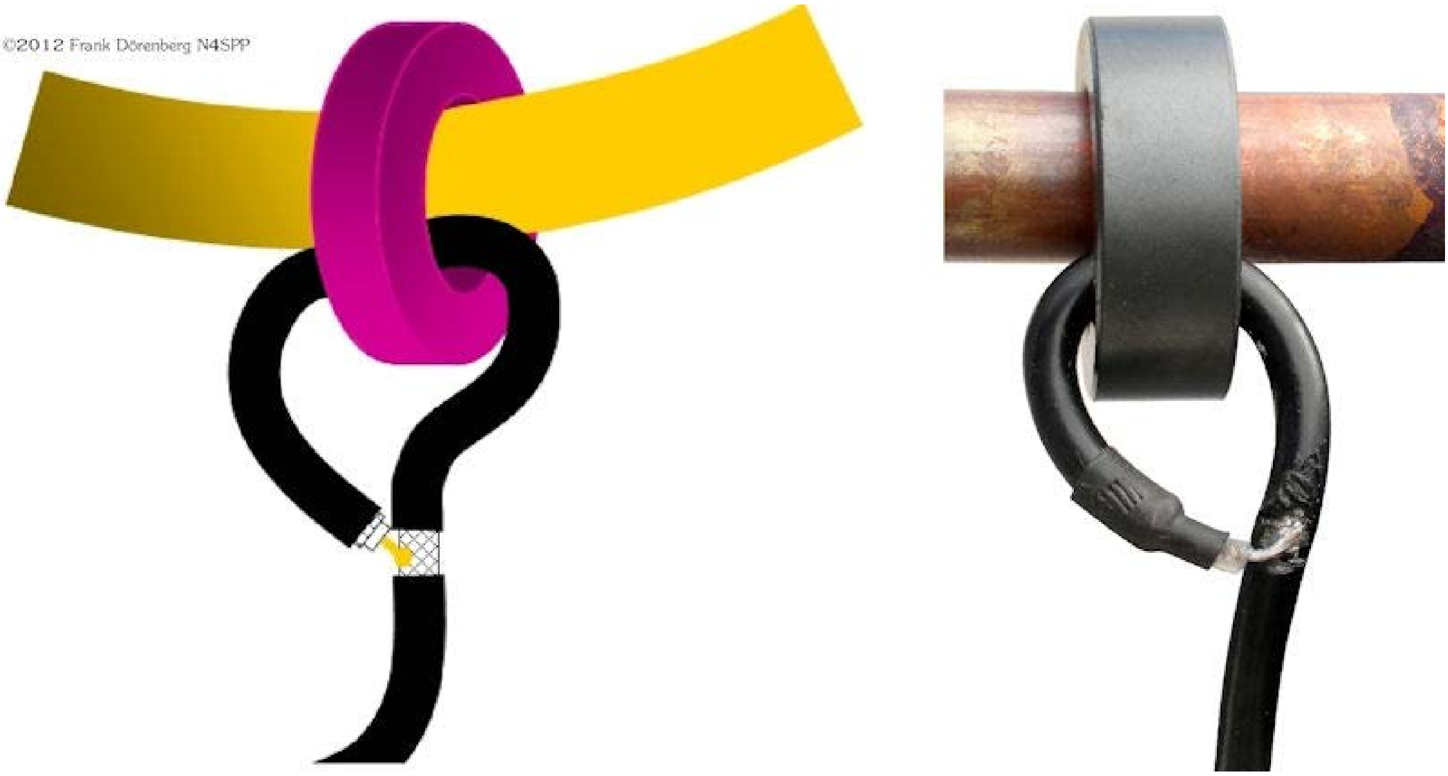


Figure 30: A 1:1 ferrite transformer-coupling with coax loop as secondary winding

Figure 31: A 1:N transformer coupling with a ferrite core

The two graphs below show my measurements for two of my STLs, with ferrite material mix nr. 43 and 31 transformer cores:

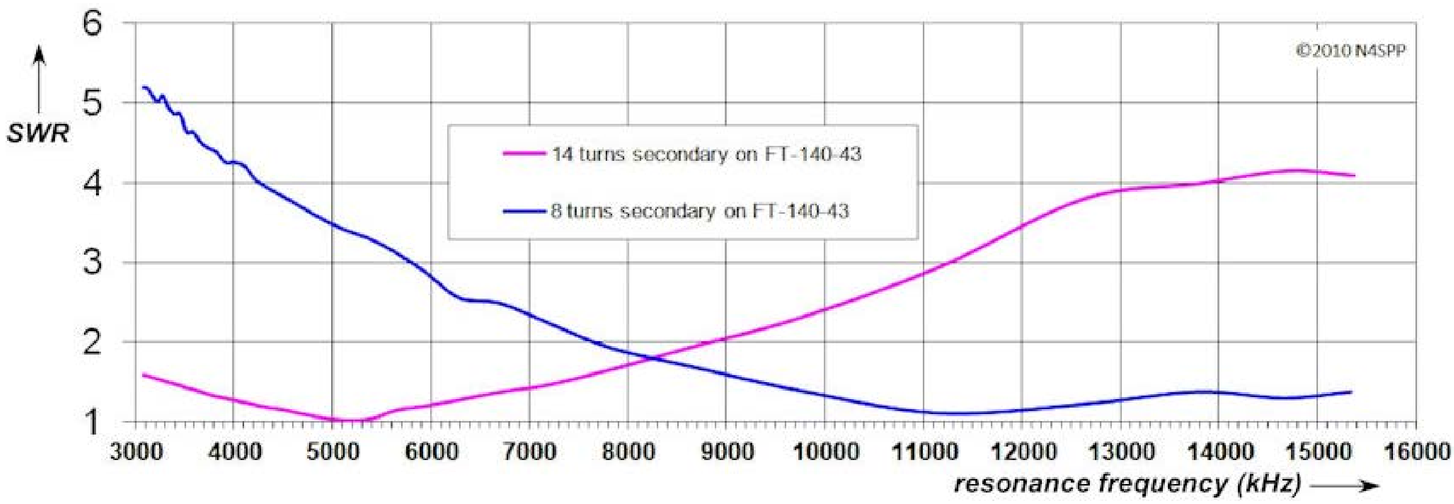


Figure 32: SWR plot of [my first STL antenna (80-20)](), with a ferrite transformer core FT-140-43

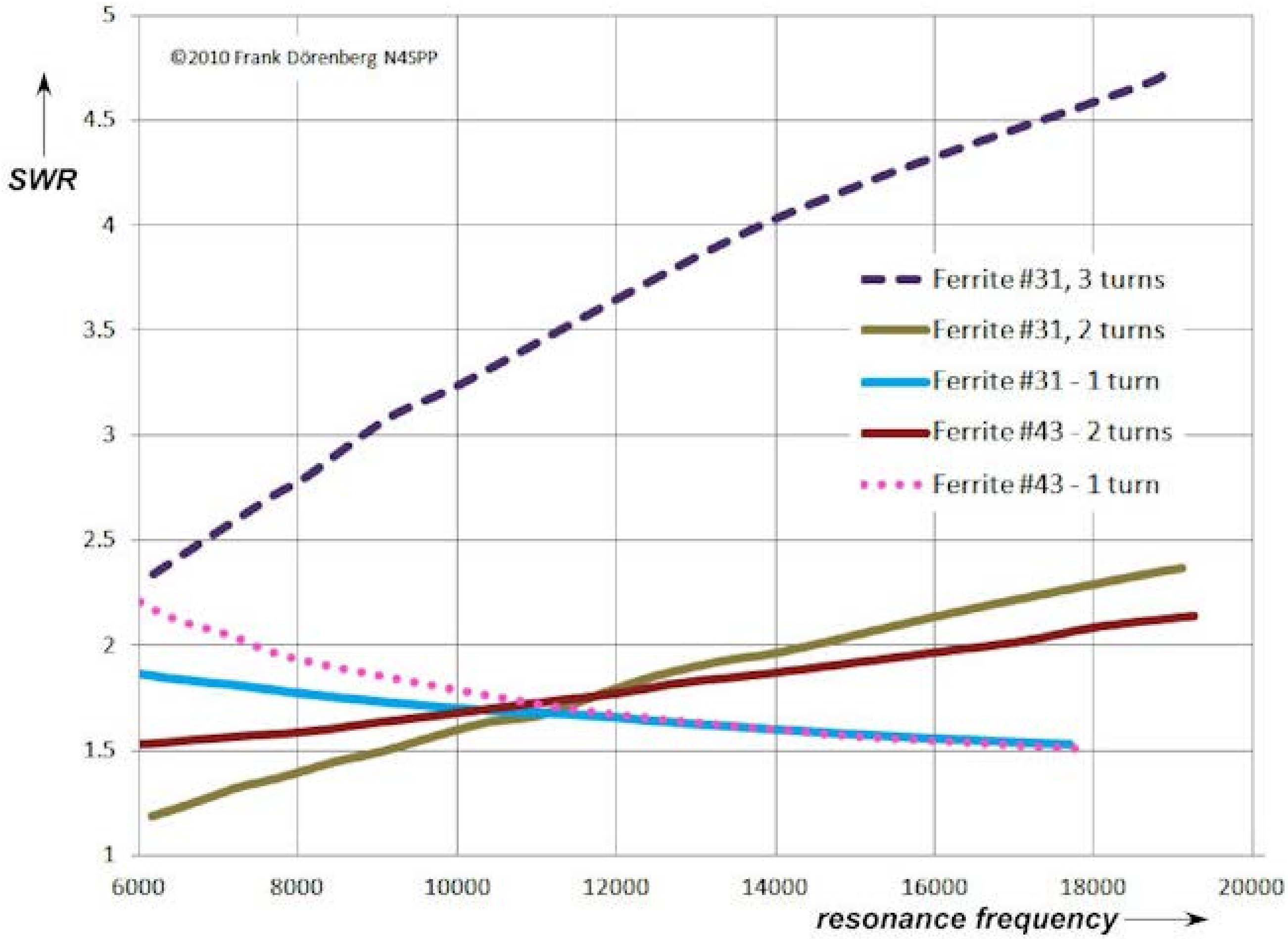


Figure 33: SWR plot of [my third STL antenna (40-10)](), with ferrite cores FT-140-43 and FT-240-31

Lásló Rusvai (DL2JTE/HA7HN) has done extensive testing with the transformer coupling (ref. 6C/D). One of his initial loops has a diameter of 1.2 m (4 ft) and is made of 20 mm (3/4") OD copper tubing. Using a T200-2 iron powder core and 2 secondary turns, he obtained SWR = 1.01 over a frequency range of 3.5 - 10.1 MHz. He also confirmed that with an STL antenna, the position of the transformer along the loop circumference makes absolutely no difference. An other 80-and-up loop that he tested, has a diameter of nearly 3 m (10 ft) and is made of thin copper wire (0.4 mm Ø, AWG #26). With a single ferrite core, he could not get SWR below 1.2. He obtained wide-band coupling (SWR < 1.1) with a stack of 9 ferrite cores of type T-240-61 cores (size FT-140 OK when not QRO). Eight of the cores are tightly stacked on the loop, the 9th core is only on the two secondary turns. See the diagram below. Note that he furthermore attaches a dipole across the tuning capacitor.

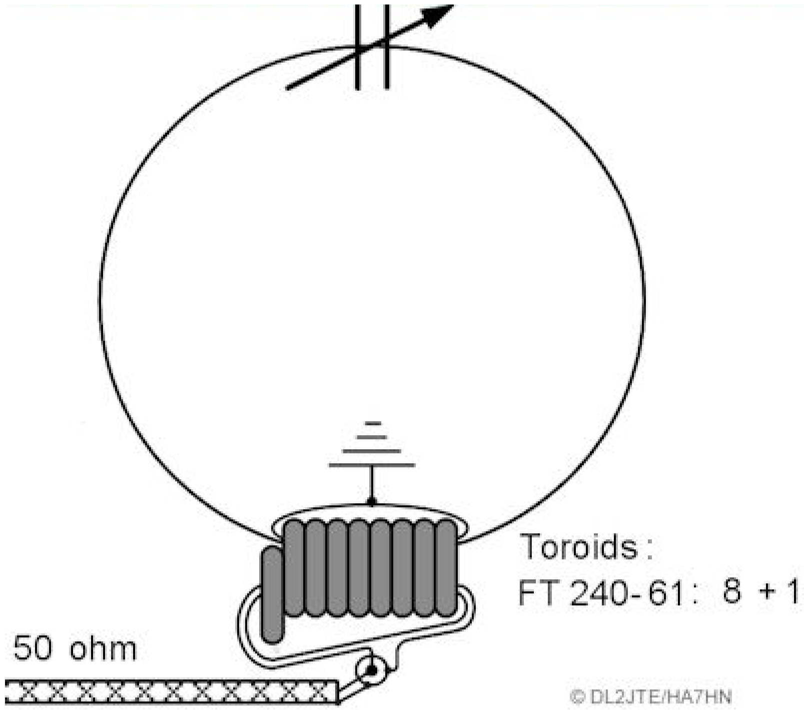


Figure 34: Transformer-coupling per Lásló (DL2JT/HA7HN)
(source: ref. 6C/D)

Another variation on the toroidal transformer coupling is using a small number of primary windings, instead of just a single one. I.e., an N:M transformer. This requires the loop to be opened and the primary windings to be connected across the gap. For a loop made of copper tubing, the transition to wiring may not be great. But I have no experience with this, nor references regarding its performance. Joe (W9SCXH) used 2 primary and 5 secondary turns on a small (= QRP) T-50-2 (iron powder) core in his 30-15 mtrs square wire loop (ref. 6F).

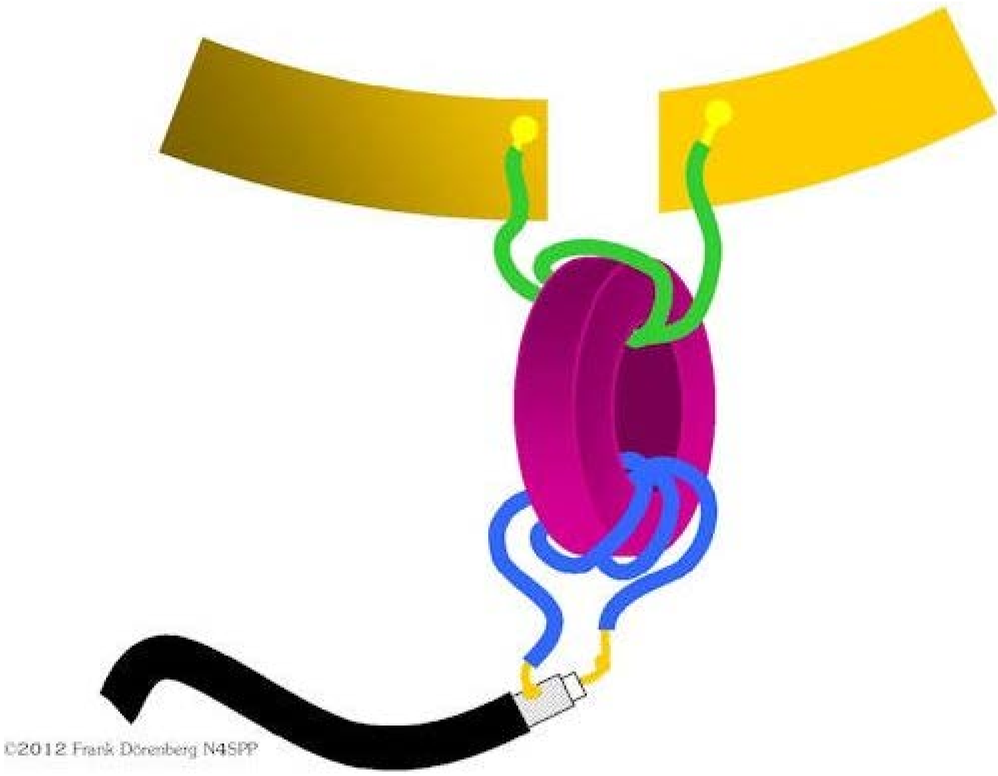


Figure 35: N:M transformer coupling with a ferrite core

WARNING: if you are experimenting with various forms of coupling, do **NOT** leave a ferrite ring on the loop and transmit via another coupling (e.g., a coupling loop, Gamma rod, or ferrite transformer). Any unused ferrite ring will act like a current choke, and will get fried if you transmit with more than QRP (you will see the SWR increase when that begins to happen). Another clear symptom is that the SWR=2 bandwidth will be much larger.

AUTO-TRANSFORMER COUPLING (GAMMA MATCH, ETC.)

Recall the voltage and current distribution of an STL antenna, as discussed at the top of this page:

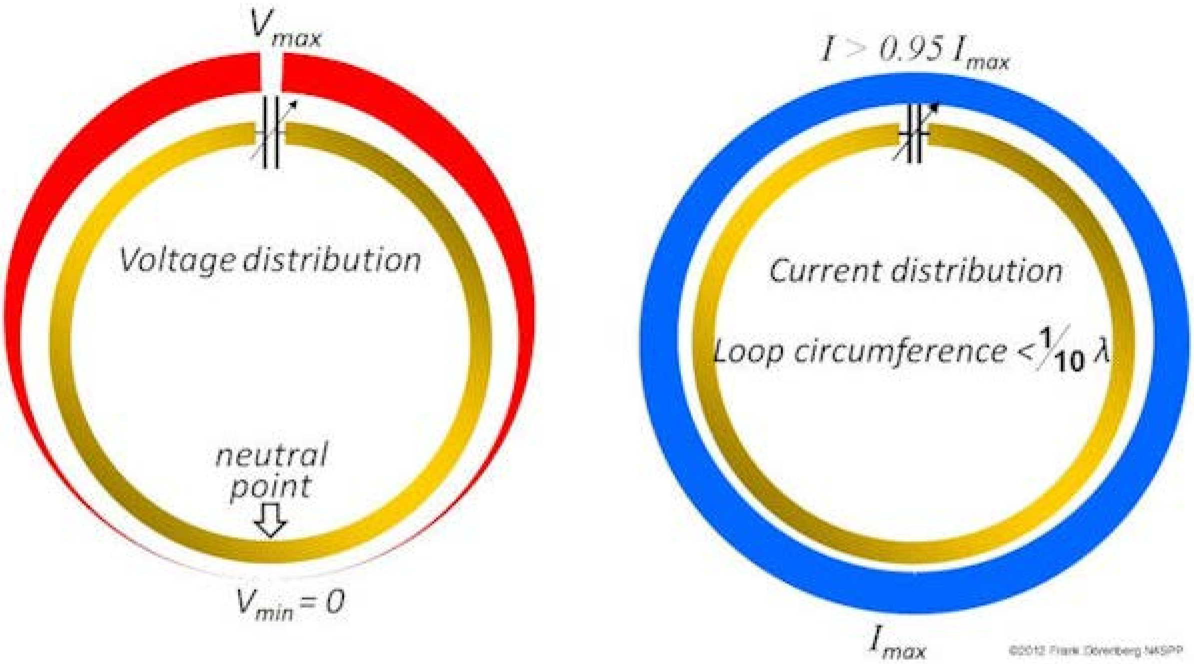


Figure 36: Voltage and current distribution of an STL antenna

Clearly, the voltage distribution is symmetrical with respect to the neutral point (V = 0) that is located opposite the tuning capacitor. In an STL antenna, the current distribution is basically constant. Resistance (impedance) is voltage divided by current. Hence, an STL has a resistance "distribution" that looks like the voltage distribution. The neutral point is a convenient reference point. If we move along the loop circumference, away from that reference point, we will find a point at which the resistance is 25 Ω with respect to the reference point. There is a similar 25 Ω point on the opposite side of the reference point, at the same distance from that point. Moving further away, we will find a symmetrical pair of 50 Ω points. This (admittedly simplistic) description suggests some simple methods for coupling the loop to an asymmetrical/unbalanced feedline (i.e., coax) or to a symmetrical/balanced feedline (twin-lead, ladder line).

When using a coax cable as feedline, we need an asymmetrical tap on the loop. The shield of the coax is connected to the neutral point of the loop. The conductor of the coax is connected to a so-called **Gamma Rod**. The rod is installed parallel to the loop. At some distance from the neutral point, the rod is connected to the loop. The tap is typically made adjustable, to be able to tune the effective length of the rod. This method also does not have the operating power limitations that are typically inherent to components of the transformer and capacitive coupling methods. This coupling method is wide-band: reportedly as much as 10:1, if the antenna installed sufficiently clear (15-20 ft, 5-6 m) from any objects and at least 1/2 loop diameter above ground). but the exact location of the tap point does depend on the frequency. In my own experiments, I have not obtained acceptable SWR (less than 1.5) over more than a 2:1 frequency range.

Some notes:

-

- The Gamma Rod adds inductance to the coupling. In a Gamma **Match** coupling, there normally is a variable capacitor in series with the rod, to cancel out that inductance. Ref. 6G, GH, 6J. In "magetic loop" applications, this compensation capacitor is typically omitted. However, a small series capacitor (several pF) may significantly increase the frequency range over which low SWR is obtained.
- As the Gamma Rod configuration is asymmetrical, the radiation pattern is slightly skewed, causing a front-to-back ratio that slightly favors the direction of the Gamma Rod mount.
- Contrary to the inductive coupling and transformer coupling methods discussed above, this coupling is galvanically connected to the antenna loop.

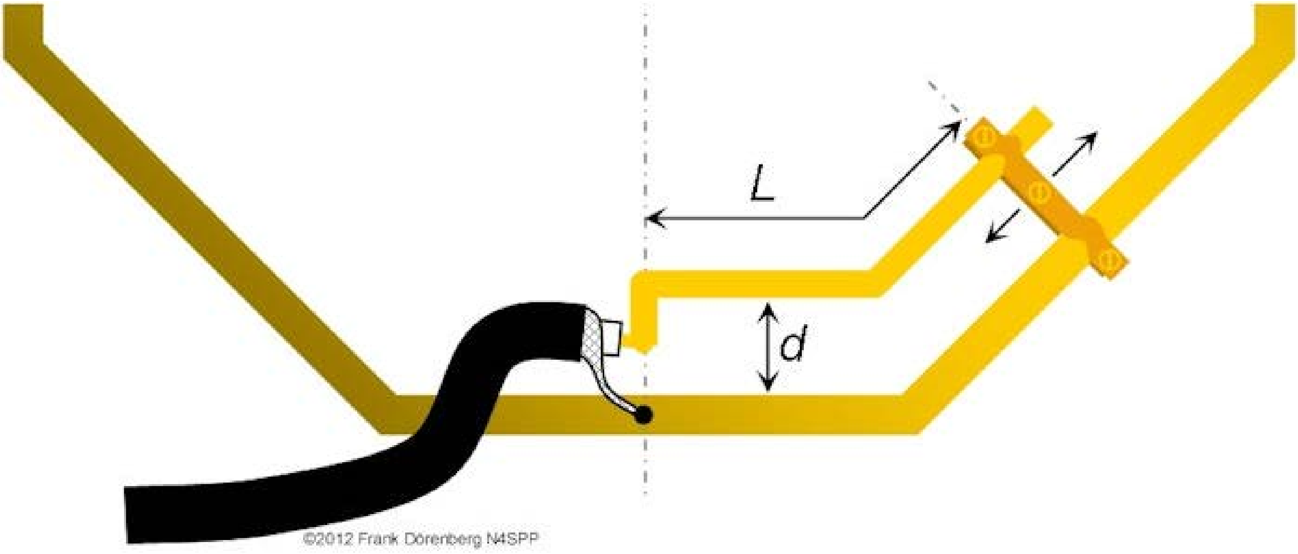


Figure 37: Gamma Rod coupling

In my first loop, I decided to insert a copper T-piece at the neutral point, just in case I ever wanted to play with a Gamma Rod. The T-piece is for 16 mm OD copper tubing (my loop), whereas the side connection is for 10 mm OD copper tubing. The latter is perfect for a female BNC chassis-mount jack. I drilled a hole opposite the BNC connector. A 1 m (3ft) section of heavy, insulated household installation wire is soldered to the BNC connector and passed through the hole that I drilled. That serves as Gamma Rod. A hose clamp (*UK*: "jubilee clip") can be used to fix the end of the wire in place at the tap point.

Figure 38: Copper T-piece - inserted into the main loop at the neutral point - with BNC connector

Ref. 6N provides following nominal dimensions for the rod and the tap point:

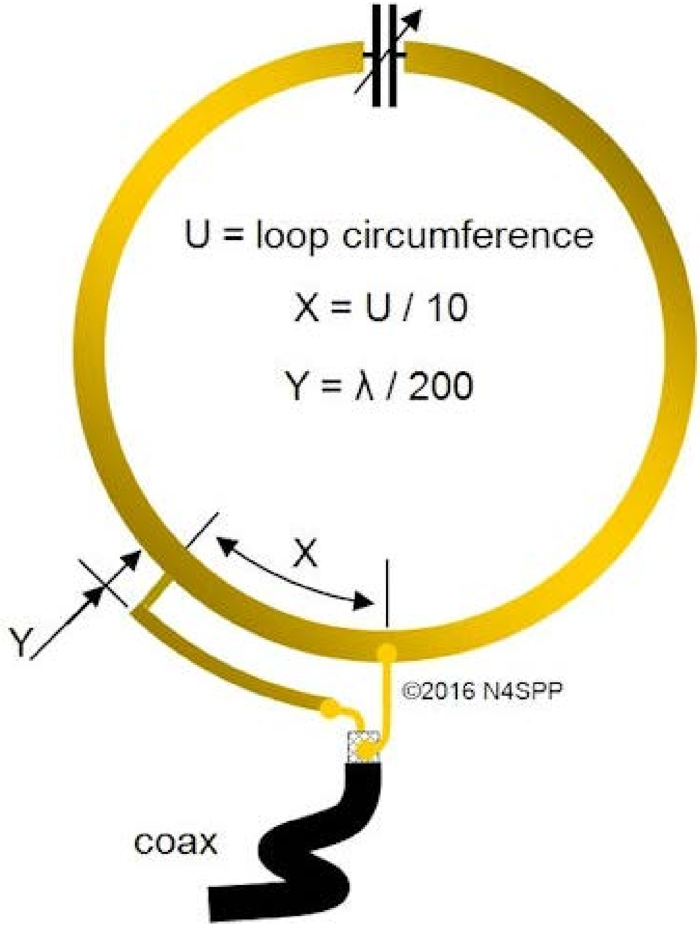


Figure 39: Nominal dimensions for the Gamma Rod coupling
(source: adapted from ref. 6N)

Instructions for adjusting/tuning a Gamma Rod/Match are deceivingly simple:

"Change the size, shape, material, position with respect to the loop, and the tap point of the Gamma Rod along the loop, until the desired impedance matching is obtained"

This is not all that surprising, as the position tap point depends on characteristics of the Rod: length of the bar/wire/tubing, diameter of the rod, shape of the loop formed by the rod and the loop, center-to-center spacing between the Rod and the loop, etc. See ref. 6H and 6J, considering the main loop as a circular folded dipole that is terminated with the tuning capacitor. The position of the tap point also depends on the loop and its construction. In general, the lower the Q of the loop is (e.g., due to losses in solder joints), the farther away from the neutral point the tap point will be. Converesely, the higher the Q, the closer the tap point will be to the neutral point, and the more sensitive the position of the tap point will be: moving the tap just a couple of mm (≈ 1/8 inch) may make a difference!

This basically means that finding the "sweet spot" for the tap point is pretty much 100% empirical. This is why there appear to be as many settings as there are antenna builders, and settings vary widely. Here are some examples that I have collected from designs posted on the internet (only very few indicate sufficient details to reconstruct the actual design):

- Some literature suggests the tap point at "main loop circumference / 10" from the center point, and the rod at a distance of "main loop circumference / 200".
- Tap point at "loop circumference divided by 15.8" from center point; rod is 1/4" diam. copper tube, 2⅜" (6 cm) distance from the loop(diam. 3½ ft); started half-way up the loop (i.e., 1/4 circumference from the neutral point), final tap at 8.375" (≈ 21 cm).
- Tap point at "loop circumference divided by 10" from the neutral point; rod at distance of 0.5%

λ from the loop.

- Tap point at "loop circumference divided by 10" from the neutral point; rod at distance of 20 cm (8") from the loop. Loop circumference 2.4m (8 ft), rod length 23 cm (10"); 20m loop.
- Tap point at "loop circumference divided by 8" from the neutral point.
- Tap point at "loop circumference divided by 11.4" from the neutral point ; rod at distance of 7.6 cm (3") from the loop with 20 ft (6 m) circumference..
- Tap point at "loop circumference divided by 7" from the neutral point; rod is 12" of 1/8" wire, spaced 1" (2.5 cm) from the loop made of 5/16" (8 mm) copper tubing.
- Tap point at "loop circumference divided by 4.3" from the neutral point.
- Tap point at "loop circumference divided by 10" from the neutral point; rod is 12" log, parallel to main loop at 1" distance
- Tap point at "loop circumference divided by 4" from the neutral point; rod is 9"
- Loop diameter 1 meter, rod length 31 cm, rod spacing 11 cm
- Tap point at "loop circumference divided by 10" from the neutral point. Loop circumference 4m (13 ft), rod of 8 mm Ø copper tubing, parallel to main loop at 8 cm (3.25") distance.

The Gamma Rod construction itself can also be considered as a kind of loop. If the end of tap point is chosen relatively close to center point (where the coax braid is attached) but we retain the size (area) of the loop, we end up with the Hairpin (stub) Match (a.k.a. Beta Match).

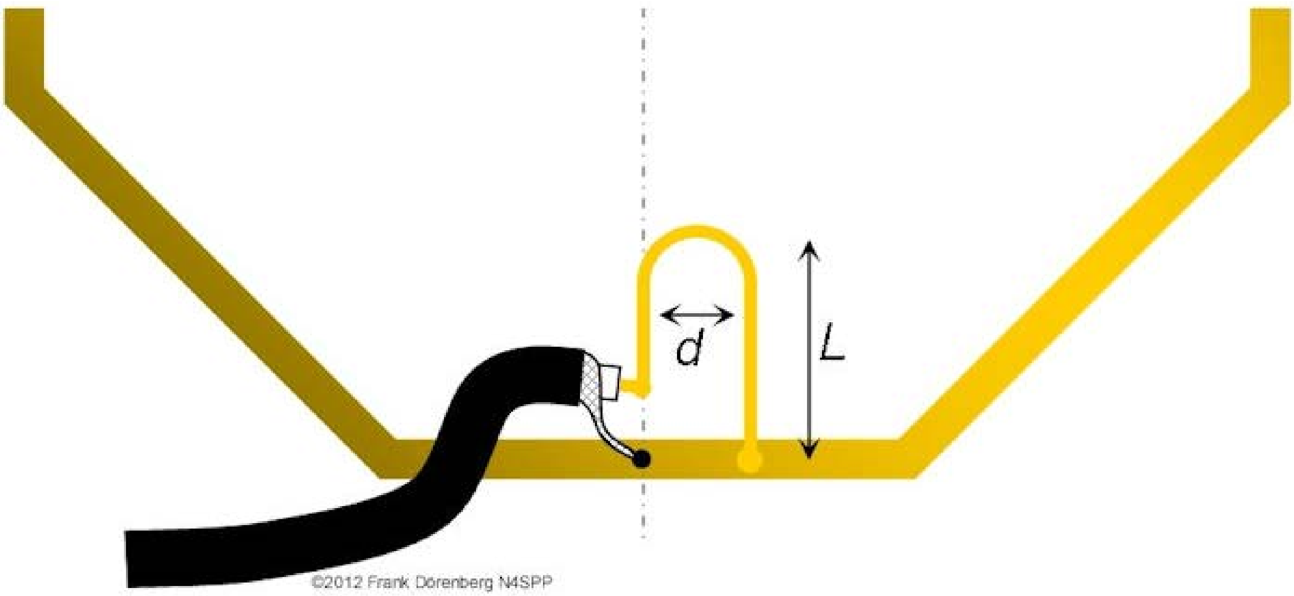


Figure 40: Hairpin coupling

Yet an other variation is the "Twisted" Gamma Match (a.k.a. "Mu-Gamma" or "G3LHZ-Gamma", ref. 3B (pp. 12, 13, 20) and 6K). I have no suggestions regarding the total length of the wire and the number of turns.

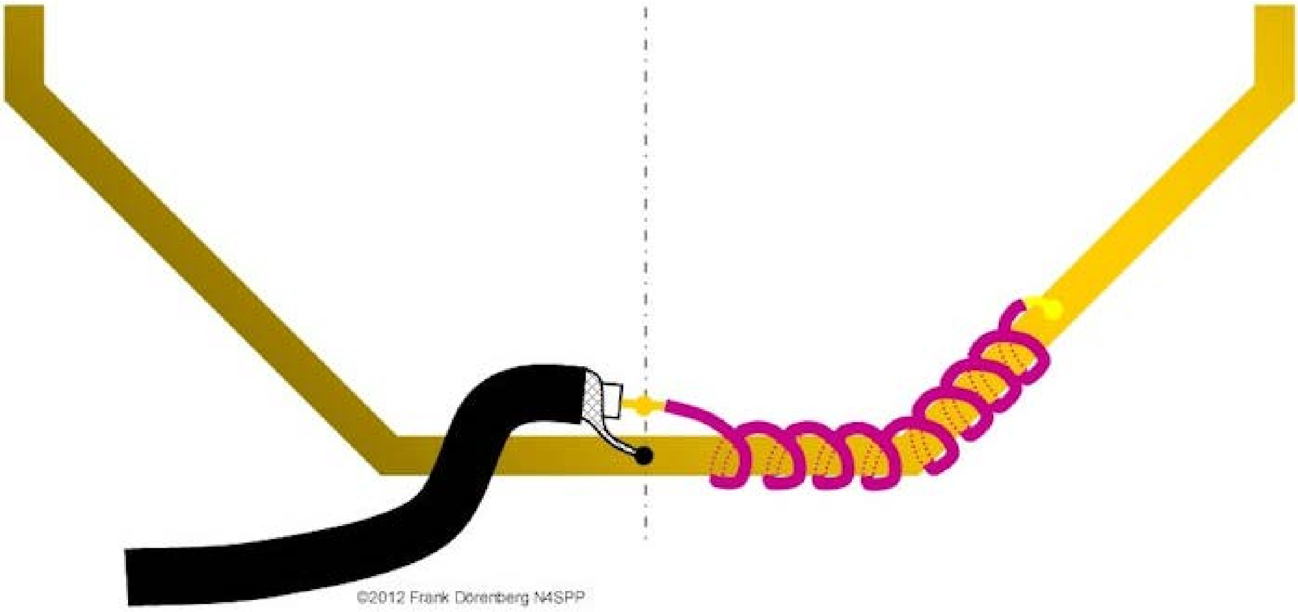


Figure 41: Twisted-Gamma coupling

If a Gamma Rod is installed on both sides of the neutral point, we have a **T-Match** It can be used with a 2-wire feedline.

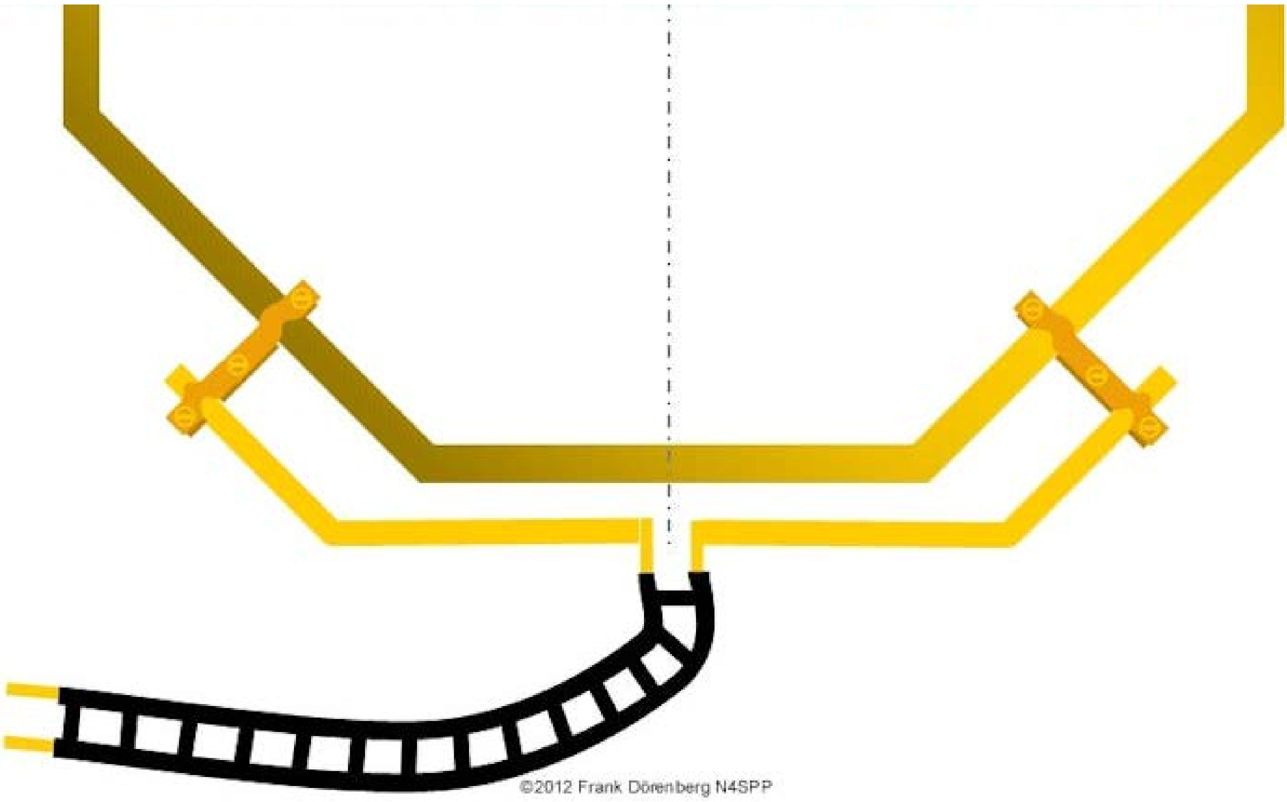


Figure 42: T-match coupling

The T-match can also be used in combination with an N:M transformer, to connect to a coax cable. But this should actually not be necessary, if the T-Match dimensions are adjusted correctly...

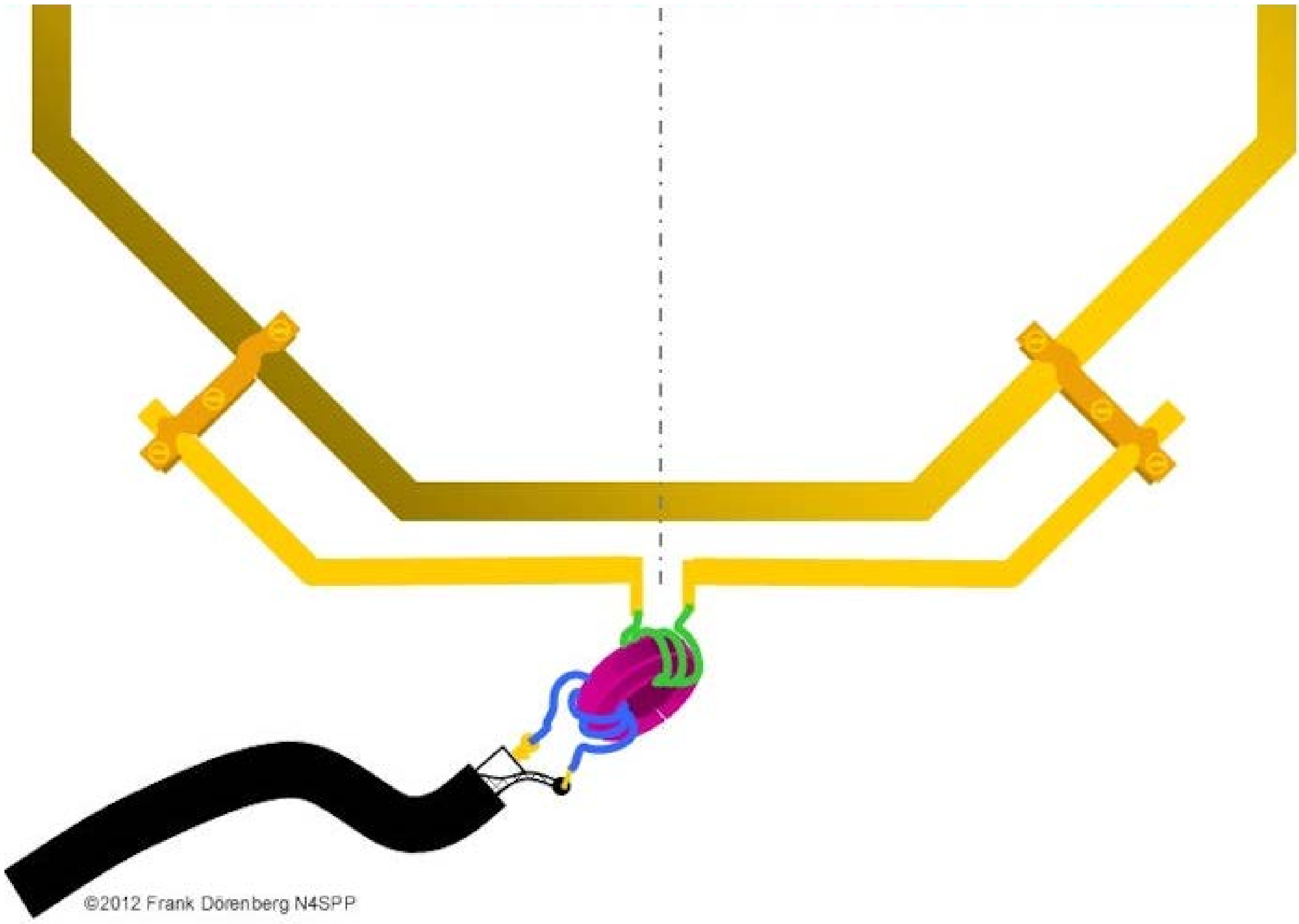


Figure 43: T-Match coupling combined with N:M transformer

MY FIRST SMALL TRANSMITTING LOOP

As with all antennas, the efficiency depends on the radiation resistance. For an STL, the radiation resistance at a given frequency is proportional to the square of the surface area. So, bigger *is* better. For a given circumference (= total length of copper tubing), a circular loop has the largest surface area of all shapes. However, I have no access to a tube/pipe bender, and annealed (heat treated) copper tubing is quite hard and stiff. So I decided to build an octagonal loop instead of a circular loop. But as derived below, a circular loop has a surface area that is only about 5% larger than an octagonal loop with the same circumference.

For a **circle** with radius *R* and diameter *D*:

$$Area = \pi \cdot R^2 = \frac{\pi}{4} \cdot D^2$$

$$Circumference = 2\pi \cdot R = \pi \cdot D$$

$$\Rightarrow Area = \pi \cdot R^2 = \frac{\pi}{4} \cdot D^2 = \frac{1}{4\pi} \cdot Circumference$$

For an **octagon** with side *L*:

$$Circumference = 8 \cdot L$$

$$Area = \left(2 + \sqrt{2}\right) \cdot L^2$$

After some basic manipulations, we can derive that for equal circumferences (= total length of the copper tubing), the circular and octagonal loops basically have the same surface area:

$$Area_{circle} = \frac{16}{\pi \cdot \left(2 + \sqrt{2}\right)} \cdot Area_{octagon} \approx 1.055 \cdot Area_{octagon} \qquad \text{q.e.d.}$$

Note that the radiation resistance of an STL increases with the square of the loop area surface. For the same circumference, a round loop has a radiation resistance that is 1.055^2 = 11% larger (= better) than the octagon!

However, that is not the entire story. Clearly, maximizing the surface area is rather important. Typically, we have room for a "loop" with a certain width and height. Let's take the simple case where "maximum width" and "maximum height" are the same. In this case, a square loop will have the largest possible surface area. Obviously this is not the shape with the smallest circumference - that would be a round loop. However, a square with a standard construction has soldered, braised or welded elbow-joints at the four corners, which *may* introduce loss resistance that a single-piece round loop does not have. For a given width = height = *D*, and all else remaining equal, we obtain the following surface areas and *relative* radiation resistances.

$$Area_{circle} = \frac{\pi}{4} \cdot D^2 \approx 0.78\, D^2 \longrightarrow R_{rel-rad,circle} \propto 1$$

$$Area_{octagon} = \frac{2}{\left(1 + \sqrt{2}\right)} \cdot D^2 \approx 0.82\, D^2 \longrightarrow R_{rel-rad,octagon} \propto \frac{1}{\left(0.82^2\right)} \approx 1.5$$

$$Area_{square} = D^2 \longrightarrow R_{rel-rad,square} \propto \frac{1}{\left(0.78^2\right)} \approx 1.6$$

Based on that, the square loop would have the largest radiation resistance (but the loss resistance mentioned above does factor into effciency...). Just to keep in mind.

Anyway, I decided to make a loop with a circumference of about 5 mtrs (16 ft). The resulting octagon is then 1.5 mtrs tall and wide (5 ft). This size is quite manageable, but the circumference is sub-optimal for 80 mtrs: only about 0.06 λ. Note that the connections between the loop and the capacitor increases the circumference, but hardly the loop's surface area. The cross-shaped support is made of standard PVC tubing. The "mast" fits in my heavy cast-iron umbrella stand.

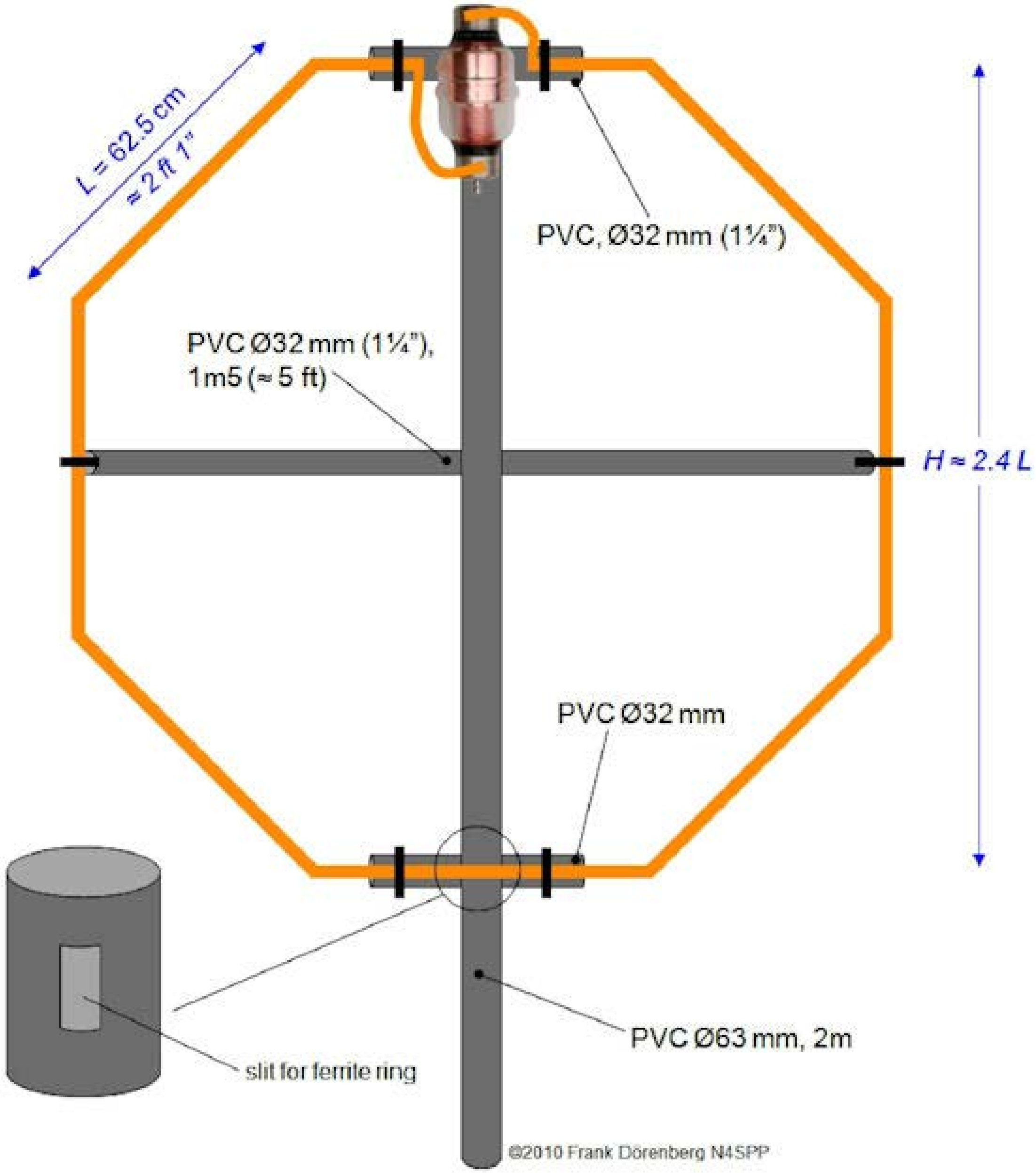


Figure 44: The construction concept of my first STL antenna - 1.5 m (5 ft) high & wide

An octagonal loop requires nine sections of straight copper tubing. They are connected with copper elbow-pieces - *no bending required*. Note: industry standard is to refer to the *outer* diameter when talking about tubing, and the *inner* diameter when referring to a pipe. Just so you know, hihi.

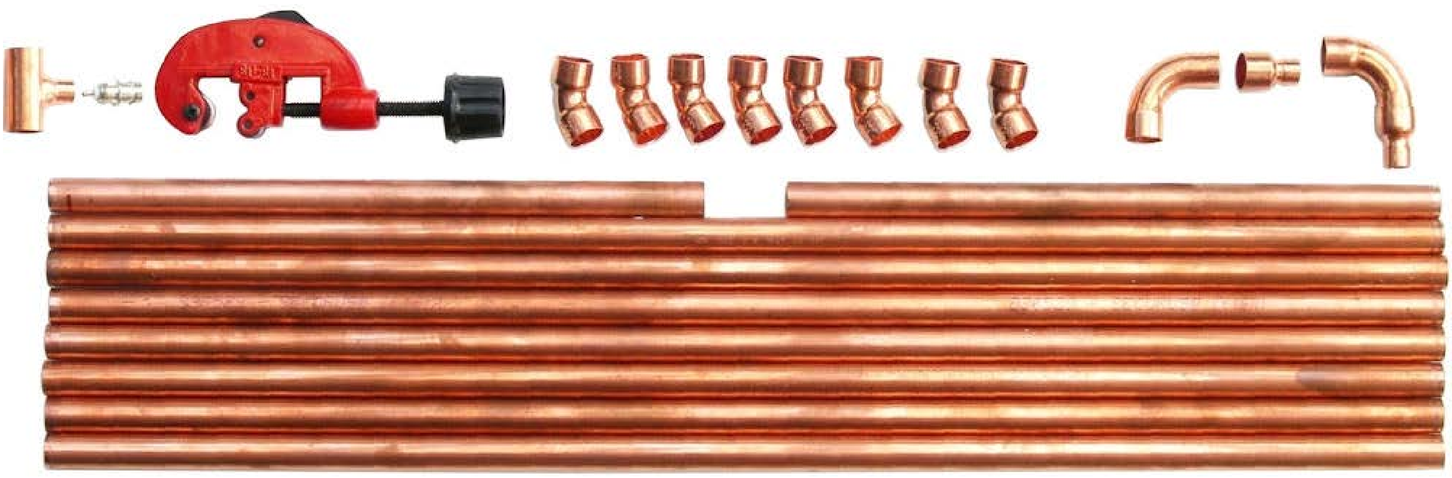


Figure 45: The "plumbing" parts of my STL antenna (tubing, elbow pieces, T-piece) and a cutting tool

Here are the copper components of this loop (all European standard 16 mm outer diameter (OD), ≈ 5/8 ich):

- 7 sections of copper tubing, each 62.5 cm (24.6") in length
- 2 sections of tubing, each 29 cm (11.4") in length
- 8 elbow pieces, 45º, female-to-female, for 16 mm OD tubing
- 2 elbow pieces, 90º, female-to-male, for 16 mm OD tubing
- 2 reduction pieces, from 16 mm to 10 mm OD (to connect tube to braid to capacitor)
- 1 copper T-piece,2 x 16 mm ID, 1x 10 mm ID (for Gamma Rod coupling as described above)

Figure 46: Terminating of the ends of the loop, for connection to the capacitor
("spark" gap between the elbow pieces above must have at least the same voltage rating as the capacitor: here: 10 kV)

Components for connecting the tuning capacitor to the loop:

- 2 stainless steel hose clamps (*UK*: jubilee clips), large enough for the end-caps of my vacuum capacitor (6 cm OD, 2.4")
- 2 x 25 cm (10") thick & wide copper braid (also available from automotive supply store, as ground strap for car batteries). Alternatives: silver-plated 2-layer braid from large-diameter coax, or heavy multi-strand copper wire (e.g., AWG #4)

Figure 47: Heavy multi-strand wire and hose clamps for connecting the loop to the capacitor

Components for the mounting plate of the capacitor:

- 10x12 cm (4x5")polyethylene cutting board, 8 mm (5/16") thick - from the kitchen.
- 2 bolts, M6, stainless (long enough to pass through the board + 2mm thickness of the 63 mm OD PVC + lock nut).
- 2 washer,6 mm ID.
- 2 self-locking nuts, M6, stainless.
- 4 large tie-wraps (cable ties). For some reason, black ones (tie-wraps that is), generally hold up better in sunlight than white ones...

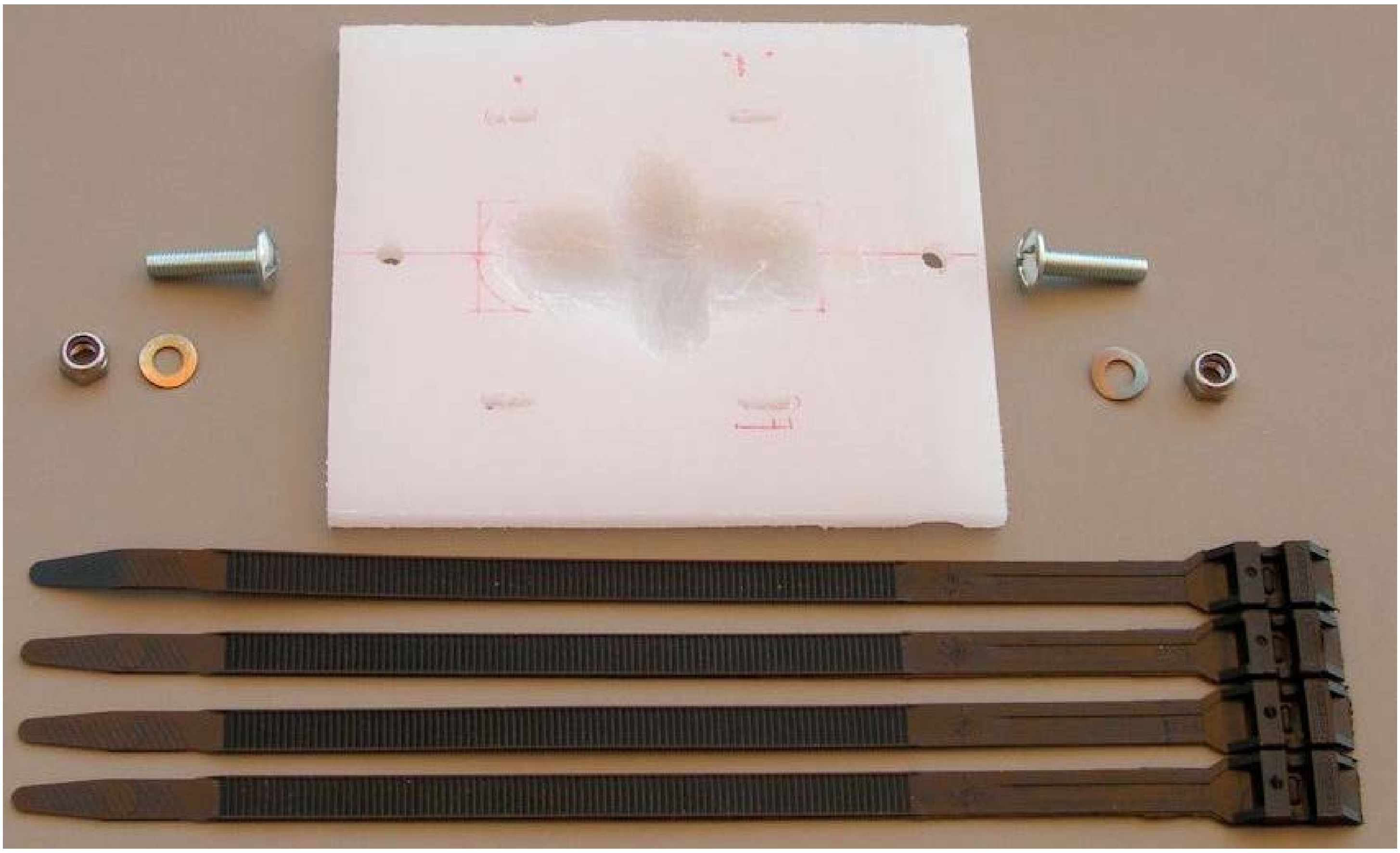


Figure 48: The components of the mounting plate for the vacuum capacitor

The vacuum capacitor "bottle" is not a cylinder. I used a grinding bit to carve out recesses in the cutting board, for the shape of the "bottle". I also cut 2 x 2 slits in the board, to pass the tie-wraps through the board. Well, I actually drilled a series small holes for each slit. Each pair is spaced less than the width of the capacitor (10 cm), to be able to get the tie-wraps to pull the bottle tighter onto the board.

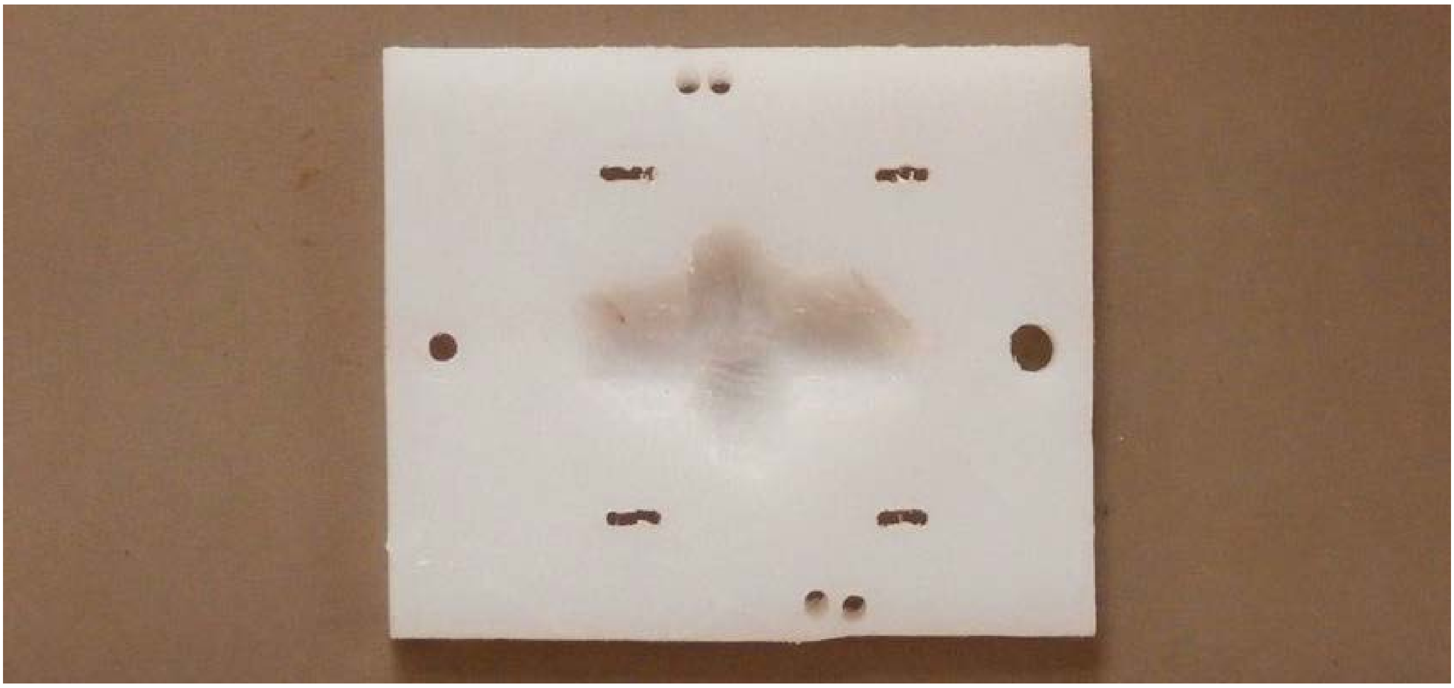


Figure 49: The components of the mounting plate for the vacuum capacitor

Components for the mast and the cross-braces:

- 2 mtr (6.6 ft) PVC tubing, 63 mm OD (2.5") - mast
- 1.75 mtr (5.7 ft) PVC tubing, 32 mm diameter OD (1.25") - main cross-brace
- 2 sections of 40 cm (16") PVC tubing, 32 mm diameter OD (1.25") - top & bottom supports
- 6 snap-in clamps for 14 mm OD tubing (yes, tighter than the 16 mm OD of the copper)
- 6 M6x45 bolts for the clamps (long enough to pass through the 32 mm OD PVC tubing and into the nut of the clamp)

Figure 50: One of the six tube clamps

Initially, I tried to braze the copper elbow pieces to the straight copper tubing with a household propane/butane blowtorch and plumber's silver solder. Such a blowtorch just doesn't generate enough concentrated heat. So I took my pieces to a friendly neighborhood plumber, who used his oxy-acetylene blowtorch. Much better! I did do some pre-planning, and put the roof rack on the car, to bring the assembled loop back home!

Figure 51: Propane blowtorch

Obviously, an acetylene + oxygen blowtorch will do a much better job than a propane blowtorch: you can weld with it, instead of just solder. However, they are very expensive and you typically cannot rent them. But you pay a local welding shop to do it, or ask a friendly plumber (which I ended up doing).

Figure 52: The back side of the capacitor mounting

(the hole in the mast is for inserting a socket wrench for tightening the nut on the bottom bolt of the capacitor mounting board)

Fig. 53: Close-up of the capacitor connection wire, brazed to a copper reduction piece on the loop-ends

Figure 54: Close-up of the hose-clamp with the heavy wire brazed onto it

Figure 55: Commercially produced mounting clamps for a vacuum capacitor

Figure 56: The vacuum capacitor mounted at the top of the mast

Figure 57: My first STL, erected on my terrace. Beautiful at any time of day or night, hihi

Figure 58: Another picture of this STL.
(it's the umbrella stand that is tilted, not my STL. I finally took the grinder and fixed that late 2015)

Fig. 59: My miniVNA - a tiny antenna analyzer for 0.1-180 MHz, with USB connection to a PC

As I had several FT-140-43 ferrite cores in stock, that is what I used. These cores have an outer diameter (OD) of 1.40" and an inner diameter of 0.9" (≈ 23 mm). This is large enough to slide over a tube with 16 mm (5/8") OD, and still have room for about 16 windings of insulated heavy installation wire of 1.5 mm^2 (AWG 14-16). The G4FGQ calculator (ref. 2D) predicts that my loop would require 24 secondary windings at 3.5 MHz, and 8 at 14.230 MHz - *for a ferrite core of "suitable grade"*. K3JLS (ref. 6E) uses 3 turns of 14 AWG enameled wire on an FT-240-43 core for his 40-20m loop. AA5TB (ref. 8A) used 2 turns on his 30 m loop.

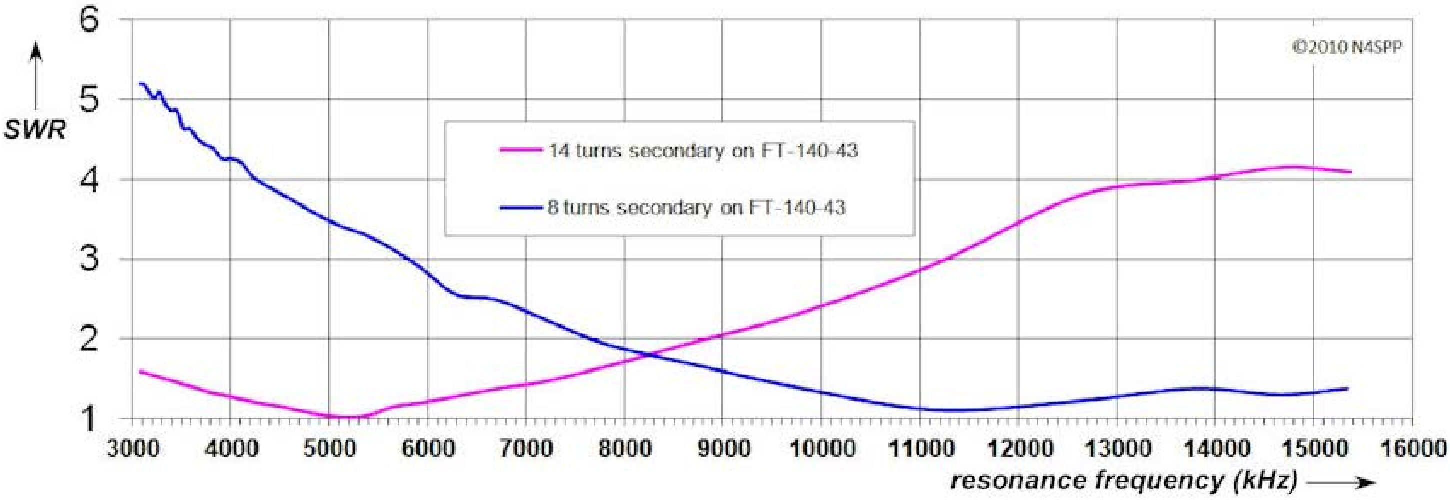


Figure 60: Coupling transformer: FT-140-43 ferrite core with 8 & 14 secondary turns
(bottom of the antenna loop is placed 80 cm (2.5 ft) above ground)

The above plots suggest that workable SWR (< 1.5) can be obtained over a 2^+:1 frequency range. However, I'd like to have 4:1, to cover 80 - 20 mtrs...

The curve below shows that for maximum capacitance (500 pF), the resonance frequency is 3064 kHz; with minimum capacitance (15 pF) it is around 15.8 MHz. This range covers 80-20 mtrs and is larger than what the various calculators estimated - suits me fine! Note that the connections between the loop and the tuning capacitor do add to the size of the loop.

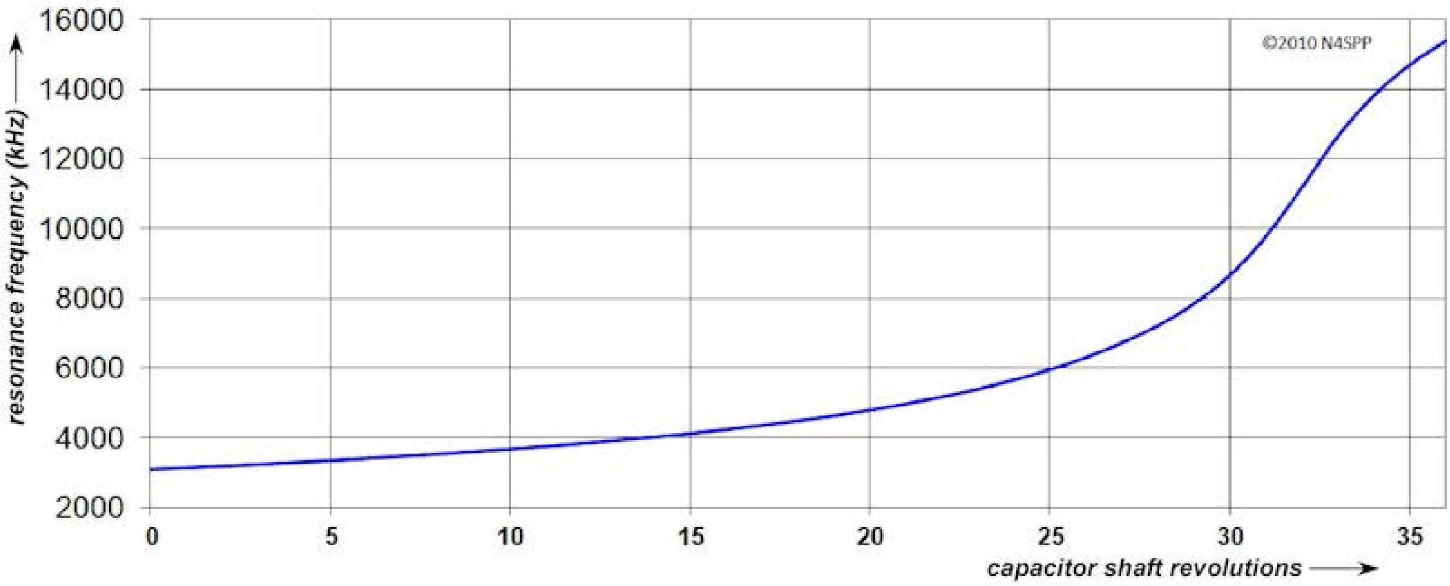


Fig. 61: Coupling transformer: FT-140-43 ferrite core - same curve for 8 & 14 secondary turns

As the resonant loop is an LC-circuit, the resonance frequency varies with the square-root of the tuning capacitor's value. My capacitor has a 15-510 pF = 1:34 capacitance range. As shown above, I measured a corresponding resonance frequency range of about 3-15.8 MHz = 1:5.2, whereas the expected resonance frequency range would be 1:√34 = 1:5.8; the difference is explained by the accuracy of the capacitance measurement and the loop's parasitic capacitance. Loop calculators (such as ref. 2A-2E) estimate that this parasitic capacitance is often of the same order of magnitude as the minimum value of a tuning capacitor. Note: read ref. 2F for caveats about mag loop calculators.

The plot below shows that towards minimum capacitance, the capacitance does not vary linearly with the capacitor's shaft position: the frequency-vs-capacitance curve is no longer quadratic. This is caused by edge effects in the vacuum capacitor, when its concentric plates have little or no overlap.

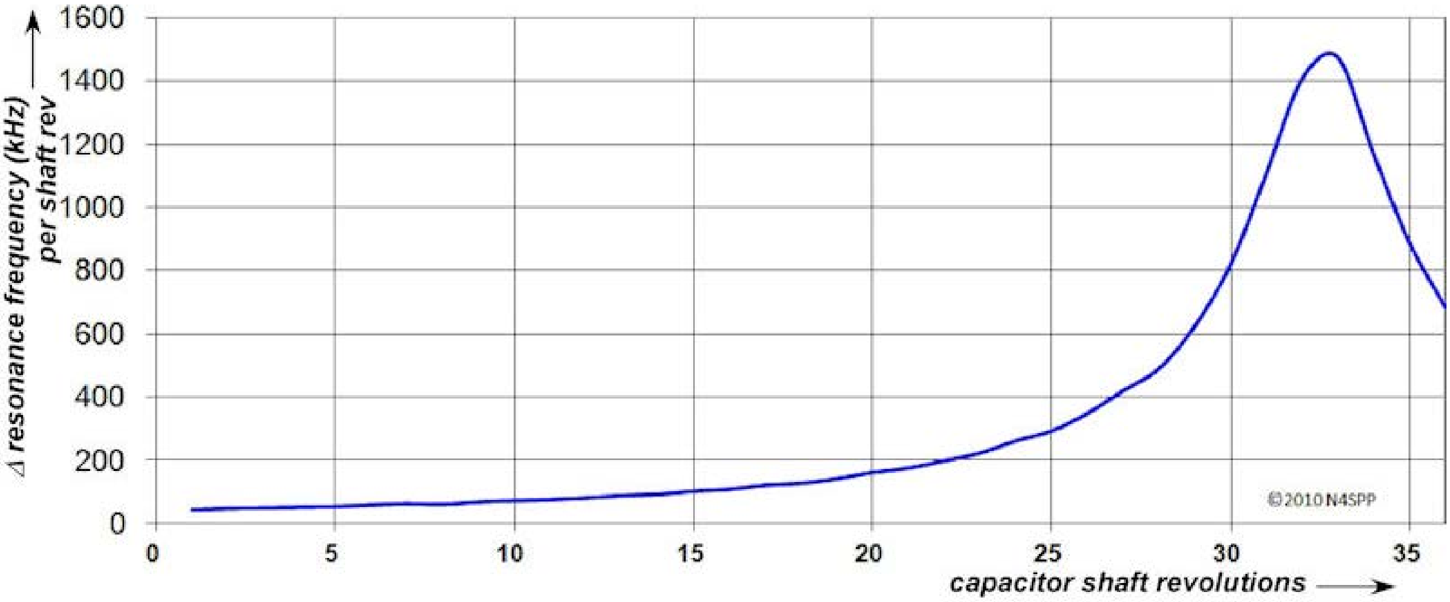


Fig. 62: Non-linear change in resonance frequency vs. varco shaft position
(coupling with FT-140-43 ferrite core)

The "Q" (Quality) factor depends inversely on the bandwidth. It is a measure for how lossy the resonant circuit is: peak energy stored in the circuit, divided by the average energy that is dissipated per cycle, in the circuit at resonance. This can be expressed as:

$$Q = \frac{1}{BW} \cdot \frac{SWR-1}{\sqrt{SWR}} = \frac{f_{res}}{\Delta f_{SWR}} \cdot \frac{SWR-1}{\sqrt{SWR}}$$

where *BW* is the normalized bandwidth for a given SWR (referenced to SWR=1 at f_{res}). E.g., the bandwidth between the "half power" frequencies (= the -3 dB frequencies) is the bandwidth between the SWR = 2.62 frequencies. The plot below shows both bandwidth and Q for the ferrite transformer coupling with 14 secondary windings. The bandwidth varies from 6.8 kHz around 3 MHz, to 50 kHz around 15 MHz. The associated Q varies from 450 to 300, with a maximum of 600 around 5 MHz.

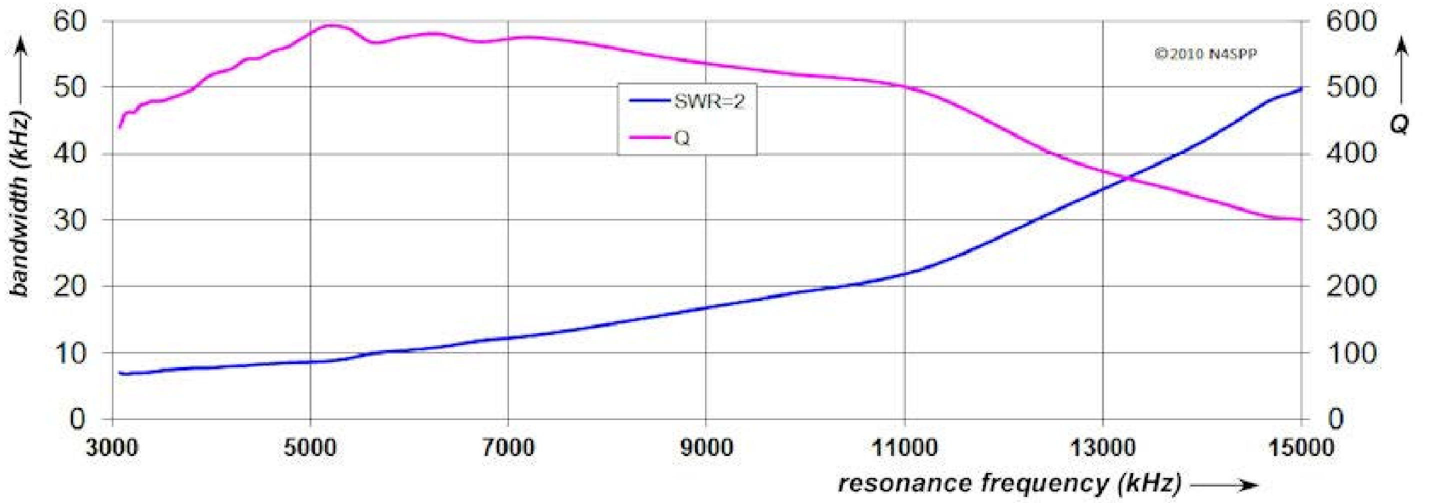


Fig. 63: Bandwidth & Q - transformer coupling with FT-140-43 core and 14 secondary turns

I built this STL primarily for DX on 80 mtrs. To test antennas by myself, I typically use remote receivers on the internet: Web-SDRs. The screenshots of the waterfall display of a Web-SDR in The Netherlands (my QTH is in the south of France) clearly showed my signal:

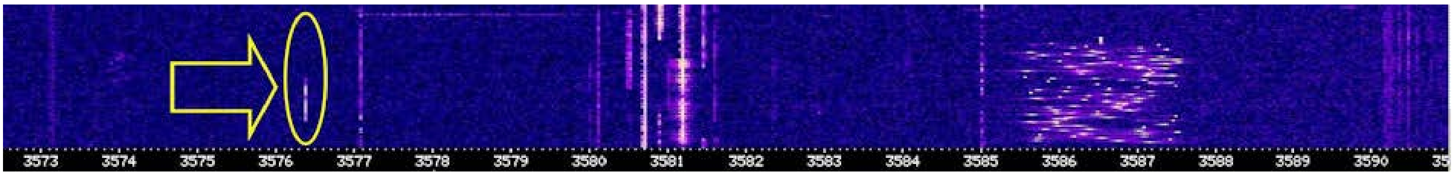


Fig. 64: My carrier, visible (with some fading) in the waterfall display of a Web-SDR 80 at a distance of 1000 km (600 miles)

(19-Oct-2010 ,19:00 local time,80 watt)

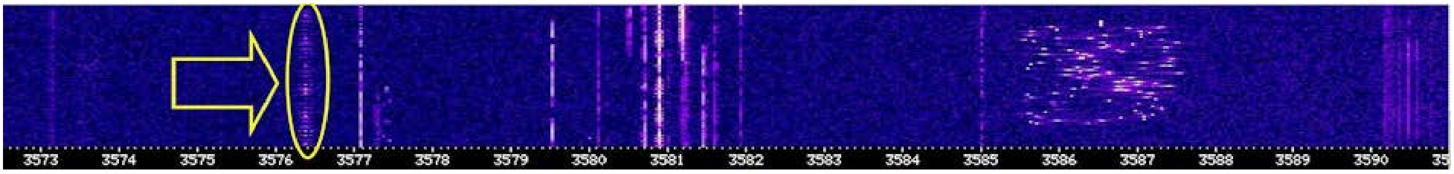


Fig. 65: Same conditions as above, but now sending a series of "E" characters in Hellschreiber mode

The Web-SDRs have audio. So, when operating in a digital mode, you can print your own signals:

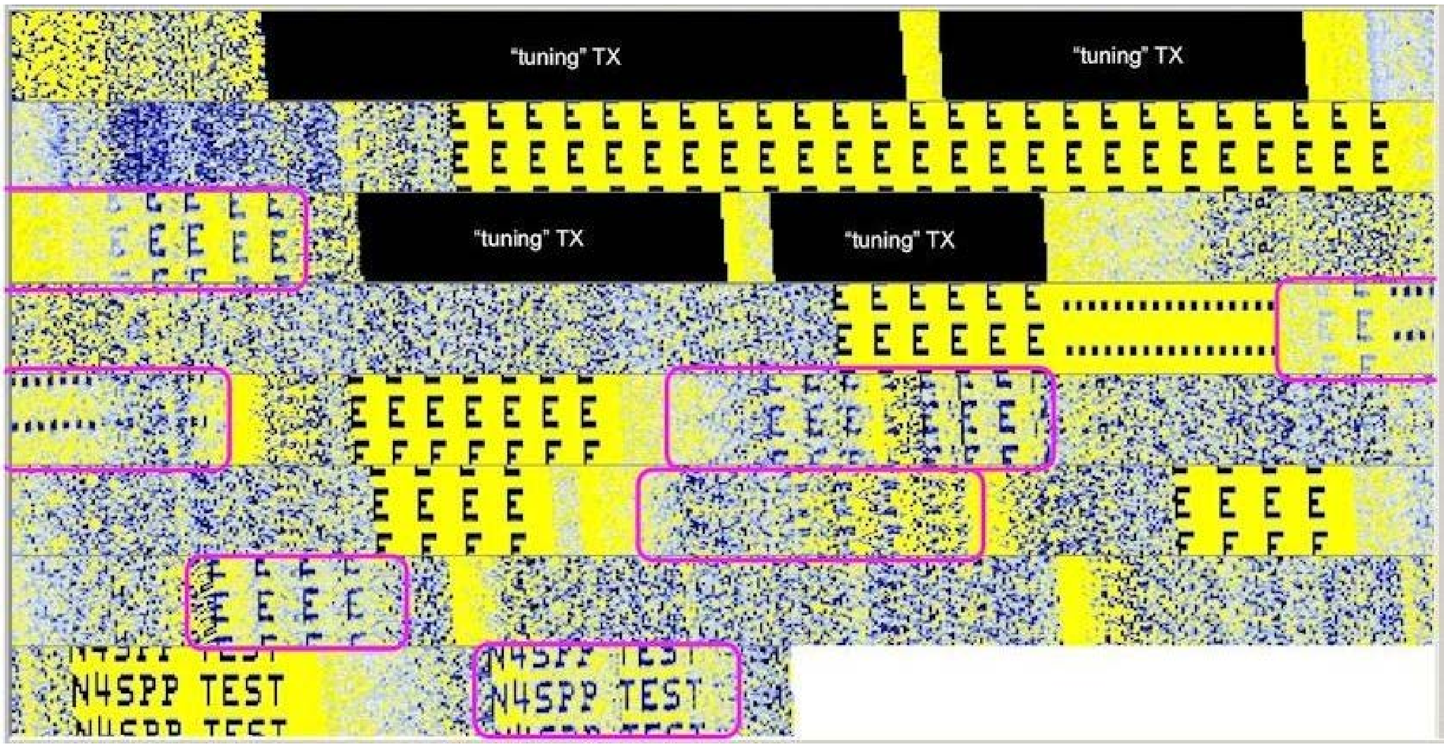


Fig. 66: My Hellschreiber signal, received on 80 mtrs by a Web-SDR receiver at a distance of 1000 km (600 miles)

(31-Oct-2010 ,17:00 local time, 80 watts; my signal received at the SDR-RX is in the magenta boxes)

In the above tests, the plane of the loop (not the opening of the loop!) was pointing at the remote receiver. When I turned the antenna 90 degrees, the S-meter of that receiver went down by roughly 2 points (12 dB). In November of 2010, I did some comparative receive tests with the loop and my short "Cobra" dipole (2x7 m). A coax relay allowed quick A-B switching. The loop was noticeably quieter than that dipole, and a couple of S-point stronger. I also ran some tests on 40 mtrs with my dear friend Rolf, DF7XH, at a distance of 750 km (465 miles). With all my other antennas (short dipoles and short verticals), we only have marginal communication at best. This time it was FB and 59+ in both directions.

I also did a quick experiment by installing the loop horizontally. It appeared rather "deaf" on 80 mtrs, since it is installed at only 2 mtrs (= 0.025 λ) above ground, and the ground is "poor" (concrete). As I am not interested in local QSOs, I did not pursue this.

Figure 67: My STL, installed horizontally

The mast of my STL is installed on top of another PVC mast with a PVC T-piece. I cut a slit into the T-piece, so it can be clipped onto the STL mast and still hold tightly, without needing to glue anything.

Figure 68: The modified PVC T-piece

MY SECOND SMALL TRANSMITTING LOOP

Some "lessons learnt" from my first loop:

- Reduce the losses in the loop by reducing the number of joints: bend long copper tubing into a circular or octagonal.
- Use a different method to connect the ends of the loop to the vacuum capacitor:
  - After about a year and half after construction, the total DC-resistance of the copper part of the loop has not changed: still at 3.2 milliohm (measured with an HP4328A professional milliohm meter). I realize that this says nothing about RF losses. However, the resistance between the copper wire and the stainless steel hose clamps had increased to a little over 4 milliohms - per clamp! This kills the efficiency of the antenna. All loop calculators (ref. 2) will quickly show this, and I had already noticed a decline in performance over time. Note: read ref. 2F for caveats about mag loop calculators.
- As I am primarily interested in using this antenna for DX on 80 m, or 80-40:
  - Increase the loop circumference from 5 to about 7 m (16 to 23 ft). I.e., from 0.06 λ to almost 0.09 λ on 80 mtrs. This is still well below the optimum 0.15 λ, but on 80 mtrs that optimum implies a diameter of 4 m (13 ft)! The increased size will double the area of the loop, and should more than double the efficiency of the antenna on 80 m!
  - Try a Gamma Rod coupling, or change over to ferrite rings made of material type 31. This should be better than type 43 material for frequencies below 10 MHz.
- Simplify the attachment of the vacuum capacitor to the mast.

Obviously, I had to make an new loop and mast - which is what I did late 2012. This time, I used a 20 ft (6.1 meter) roll of soft copper tubing with an OD of 5/8 inch.

Don't make the mistake to assemble a loop of this size inside the house: it probably will not fit through a regular door. Don't paint yourself into a corner, hihi.

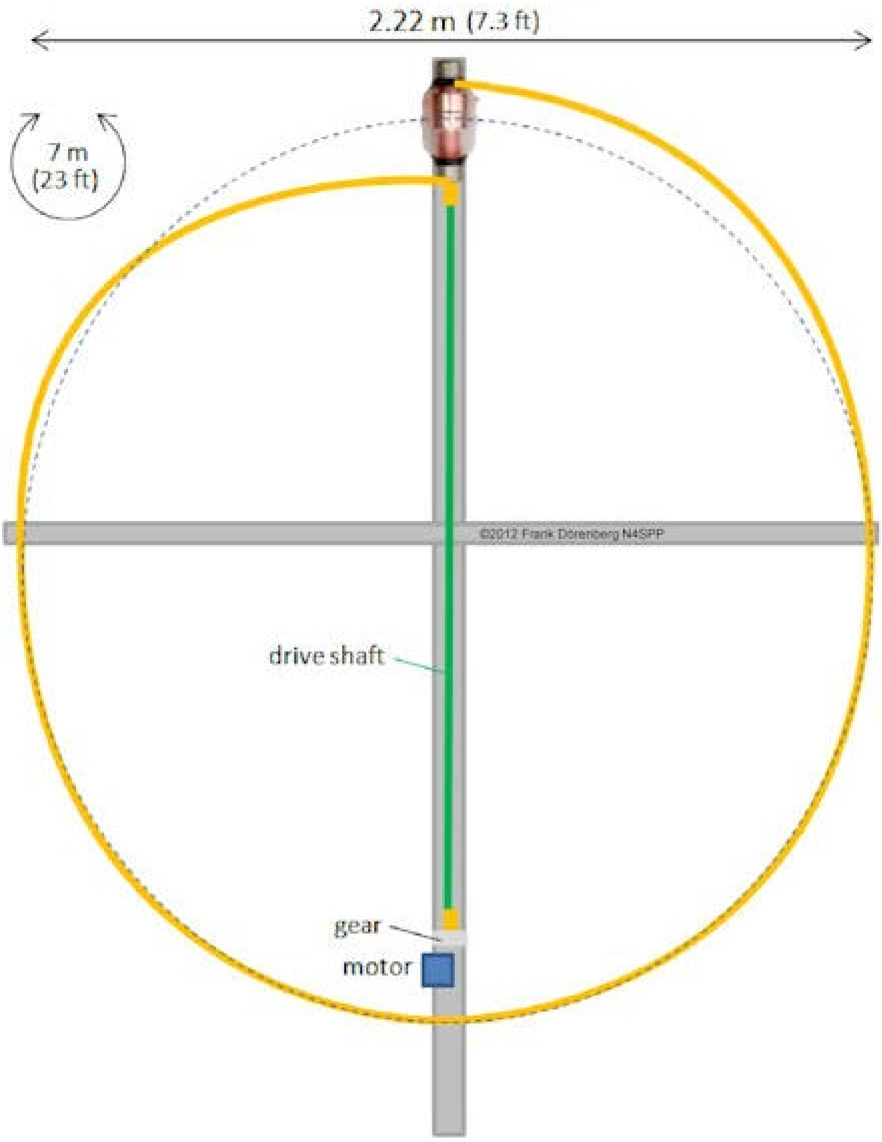
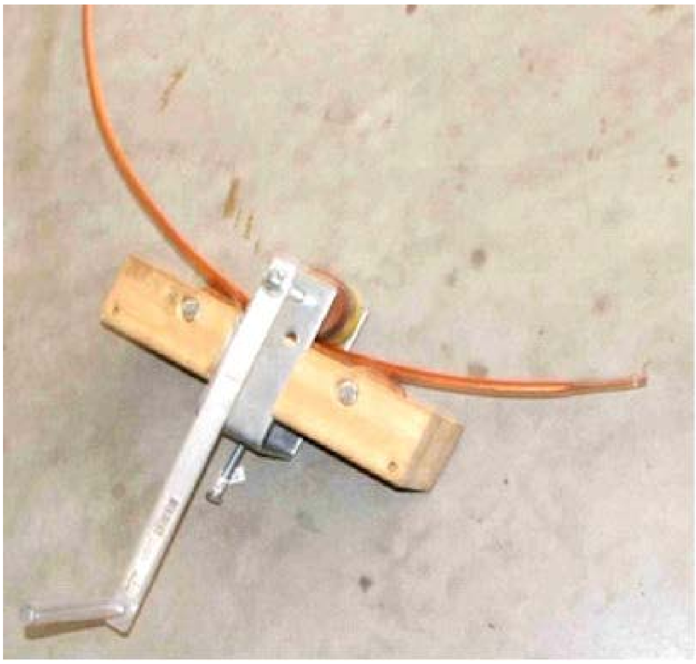


Figure 69: Diagram of my second STL

My second loop is (nearly) circular. I had my copper tubing bent by local company that makes railings for staircases and balconies. However, one can home-build a tube bender - but it will only work work *soft* tubing, not *hardened* (heat treated) tubing, which is typically sold as straight tubing, not coiled.



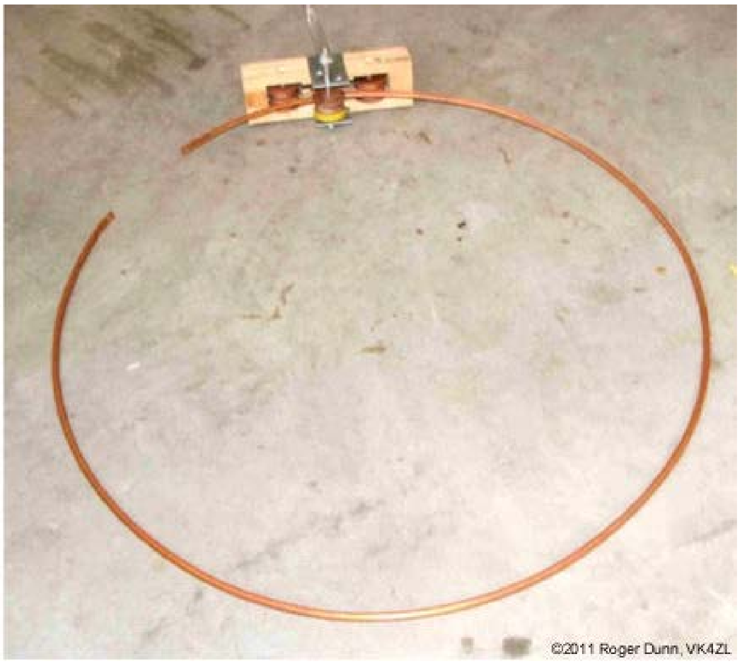
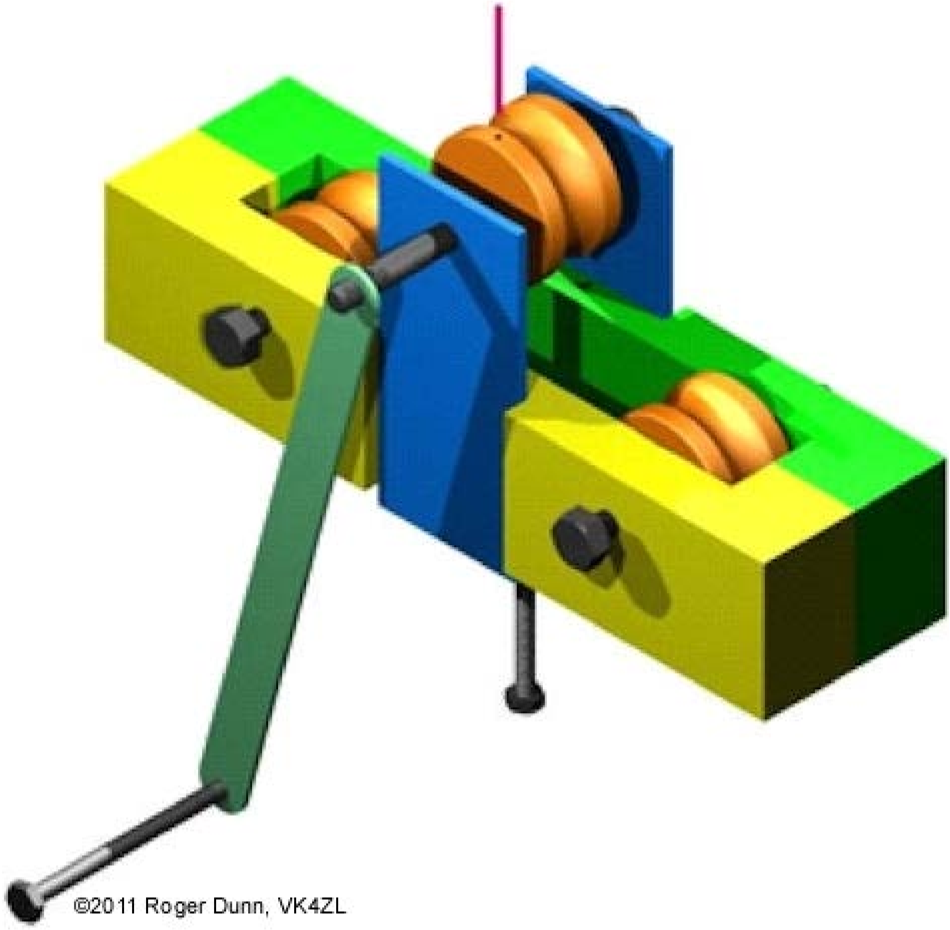


Figure 70: A tube bender built by Roger Dunn (VK4ZL)
(description: ref. 10; photos and image used with permission)



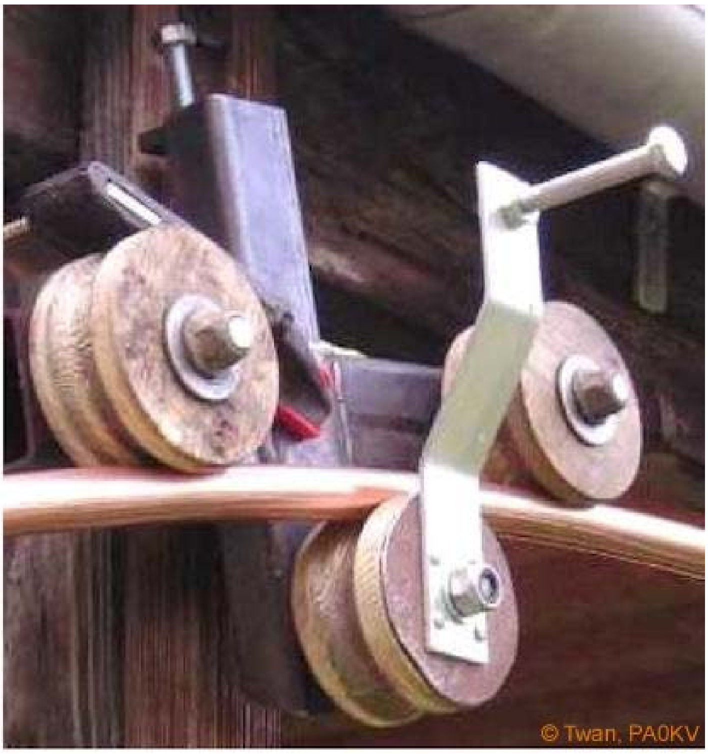


Figure 71: A sturdy tube bender made by Twan van Gestel (PA0KV)
(photos used with permission; his large loop with motorized vacuum capacitor is described on [his website](#) [[pdf]](#))

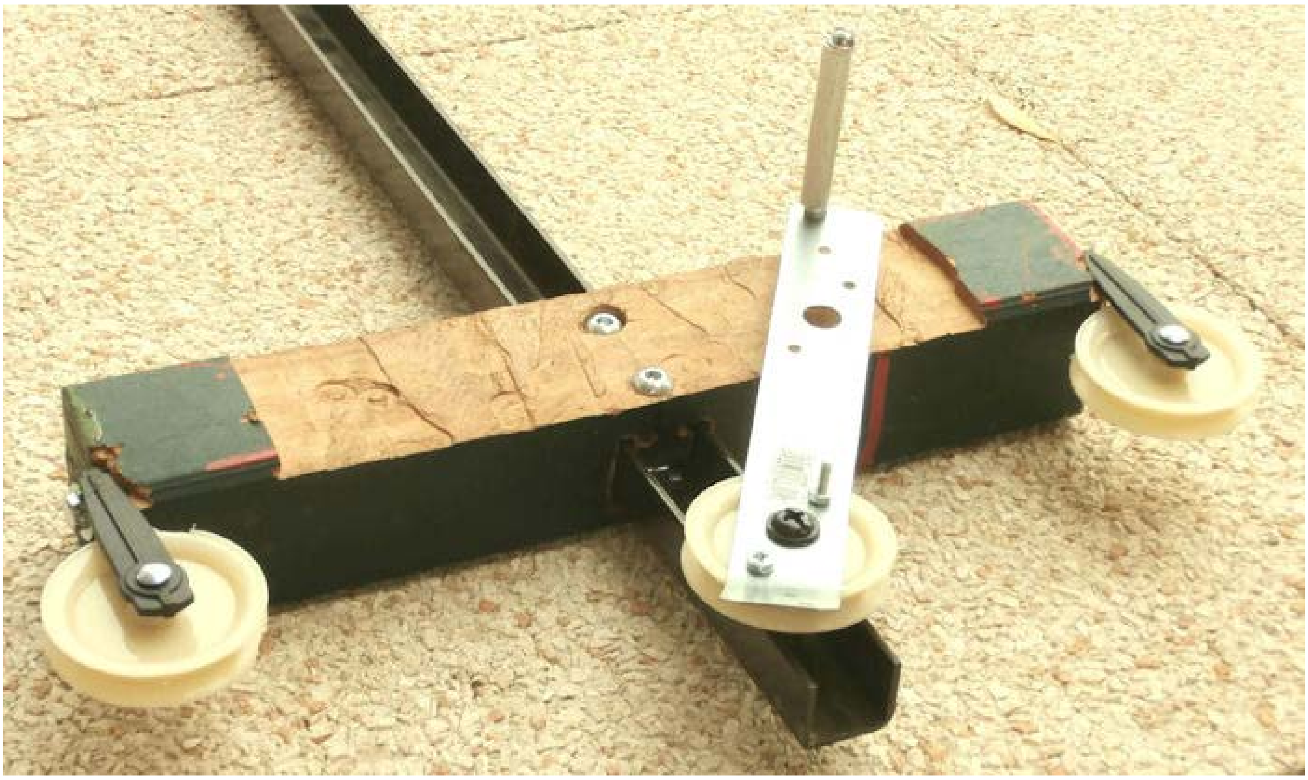


Figure 72: An adjustable tube bender that I made for my [third (smaller) STL](#)
(my third STL is made of 12 mm (0.5") soft copper tubing)

I made clamps for the vacuum capacitor out of soft copper strip, about 2-3 cm wide (≈1") and 2-3 mm thick (≈0.1"). I have toyed with the idea of silver plating the copper loop and clamps to further reduce RF loss resistance (ref. 9A), but that may not be worth the effort (see half way down the page of ref. 9B). The clamps are dimensioned such that the inner circumference is just about 1-2 mm too small for the end-caps of the capacitor. This way, when I tighten the bolt of the clamp, it is nice and tight. I used stainless steel bolts and a heavy stainless washer on both side of the clamp. I squared the washers to make them fit better, and also to make them touch the full width of the circular part of the clamp. I (carefully) pinched the ends of the copper loop with a pair of vise-grip™ (locking) pliers.

Figure 73: Copper connecting clamp for my vacuum capacitor

The "bottle" of the vacuum capacitor is now attached directly to the mast, with two large tie-wraps.

With my first STL, the tie-wraps were passed through slits in the mounting board. Here, they are passed through slits in the PVC mast. The tie-wraps do not full immobilize the capacitor. However, once the ends of the copper loop are attached to the clamps, the installation is quite stable.

Figure 74: My vacuum capacitor, attached to the mast and connected to the loop

I finished building the loop in January of 2013, and took some measurements with my miniVNA analyzer. I used an FT-240-31 ferrite ring for coupling. The first measurement, with a single secondary winding (just a wire stuck once through the ferrite ring), showed an impedance of about 10-12 ohms. So, I needed a 4:1 transformation ratio to get close to 50 ohms. I.e., a 2:1 current transformer. So I doubled the number of secondary turns to 2. I also added a 1:1 current choke right at the coupling transformer. The plots confirm the suitability of type 31 ferrite material for the lower frequencies.

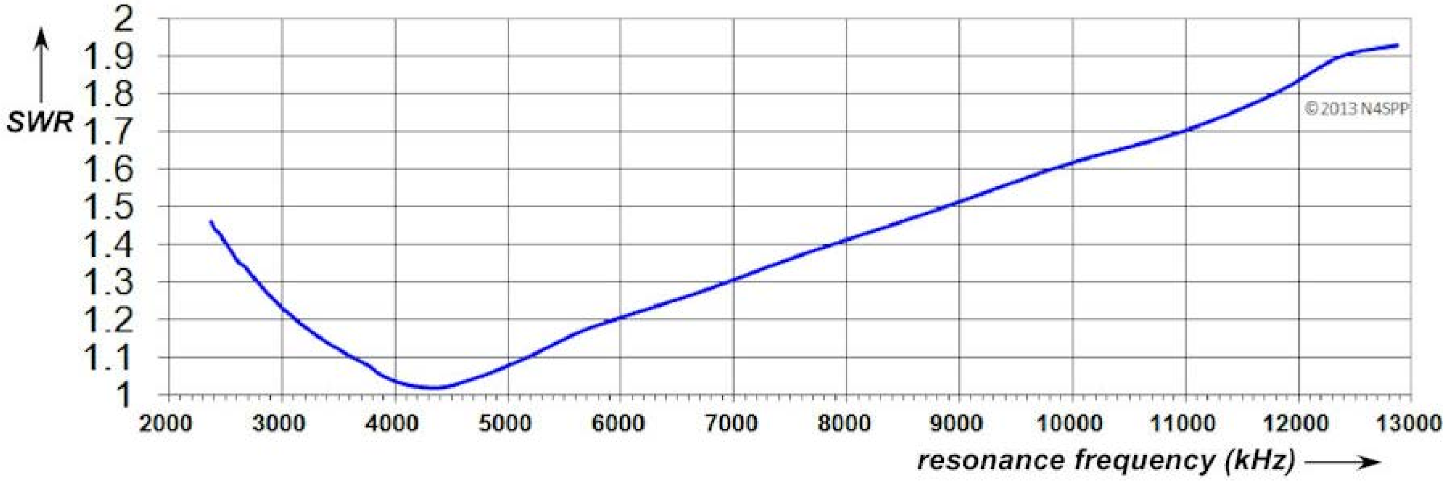


Fig. 75: Coupling transformer: FT240-31 ferrite core with 2 secondary turns, 1:1 current choke at feedpoint

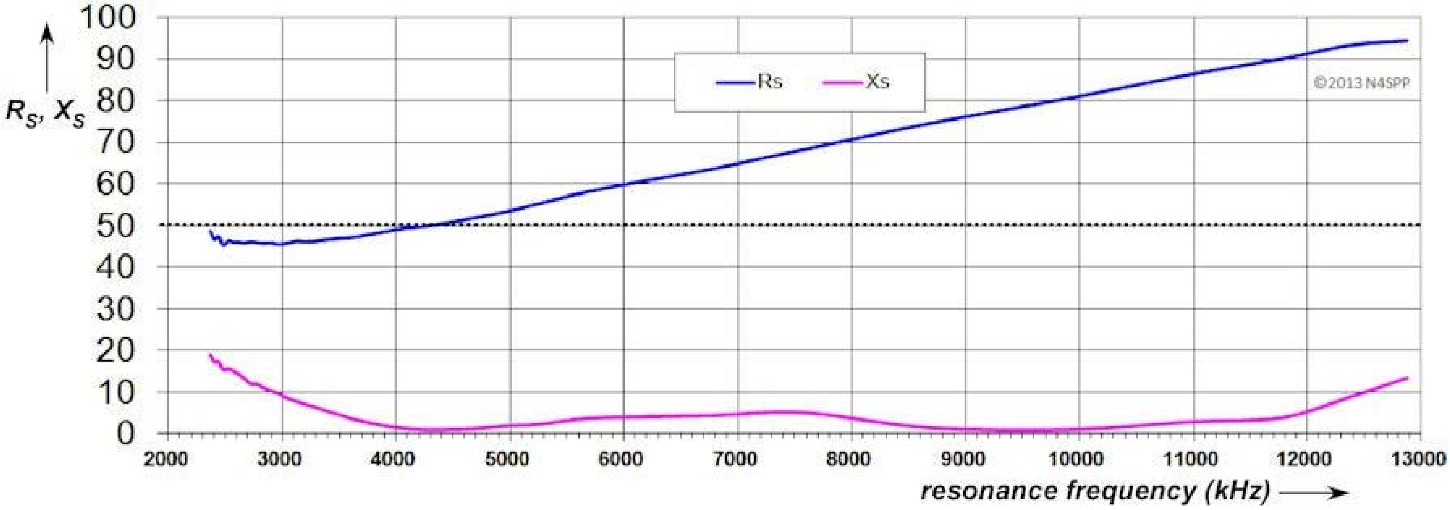


Fig. 76: Coupling transformer: FT240-31 ferrite core with 2 secondary turns, 1:1 current choke at feedpoint

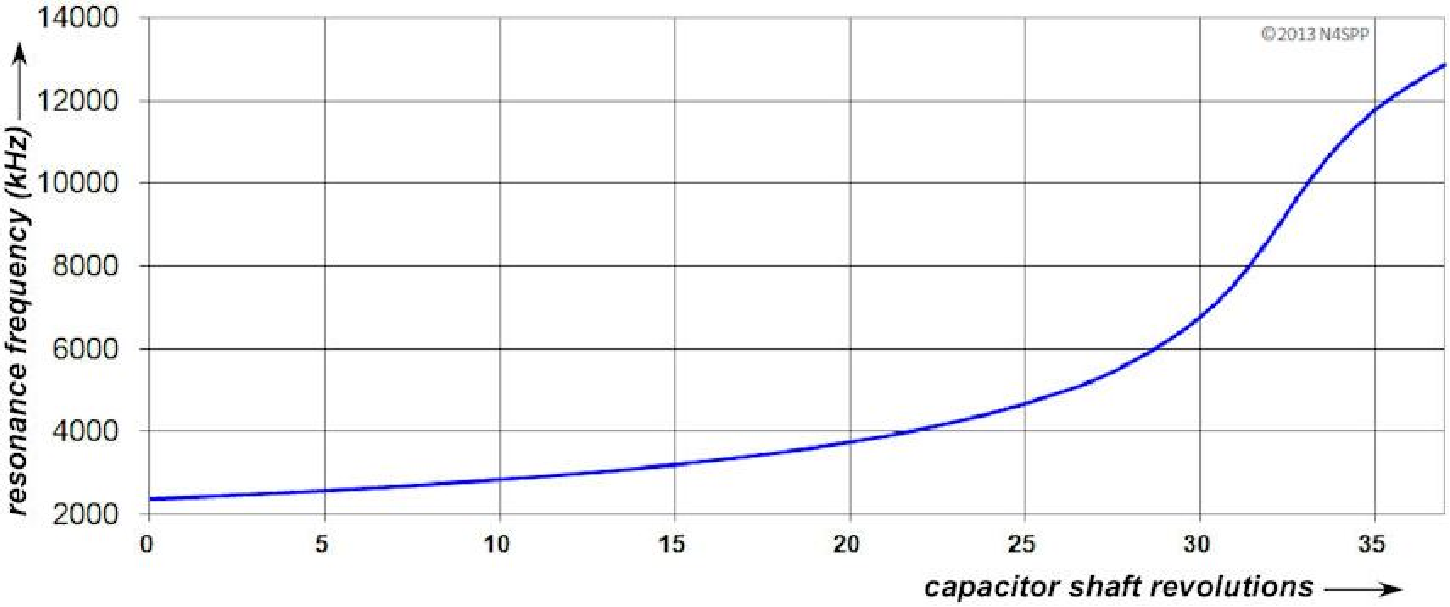


Fig. 77: Coupling transformer: FT240-31 ferrite core with 2 secondary turns,1:1 current choke at feedpoint

I measured the following SWR values for various placements of the ferrite transformer around the main loop:

Ferrite position	SWR	R_S	X_S
0° = at capacitor	1.1	47.5	3.9
45°	1.1	48.8	4.7
90°	1.1	48	4.4
125°	1.07	48.9	3.3
180° = opposite capacitor	1.04	50	1.8

Fig. 78: SWR for several positions of the ferrite transformer around the circumference of my STL

(transformer: 2 secondary turns on FT-240-31 core, 3600 kHz,)

I also tried a standard 1:5 size coupling loop, made of standard 1/4 inch (6.3 mm) <u>soft</u> copper tubing. I mounted the coupling loop onto the 63 mm PVC mast with PVC clamps, so its position is easy to adjust up & down, and rotate around the mast. Initially, I had mounted the coupling loop with the BNC connector at the *bottom*, i.e., near the main loop. As I had the BNC connector on the *outside* of the coupling loop, the gap between the coupling loop and the main loop is rather large. SWR was good, but I wanted to get the most out of it. Instead of making a coupling loop with the BNC connector on the *inside*, I just turned the coupling loop upside down. Now the coupling loop could be placed very close to the main loop. Also see the coupling discussion around Fig. 25-27 above.

Figure 79: The two configurations of my coupling loop

(the BNC connector is mounted on a small aluminium L-bracket)

Note that in both photos above, the plane of the coupling loop is not aligned with the plane of the main loop: the coupling loop is rotated about the mast until lowest SWR is obtained. So, it sticks out both sides of the plane of the main loop. However, for minimum SWR, the angle between the two loops is larger in the photo on the right. This is to be expected, as the coupling is tighter. Had the coupling loop been slightly smaller, the required angle would also have been smaller.

I prefer this type of coupling loop to the ferrite ring transformer coupling methds. Reasons: easily adjusted, no power limits, larger frequency range.

With both configurations, SWR is quite good over a frequency range of at least 1 : 3 (in my case, 80-30m). The second configuration is basically perfect over that range. The small bandwidth confirms the very high "Q".

Coupling loop with BNC at bottom

Frequency (MHz)	SWR
3.584	1.1
7.085	1.2
10.140	1.3
14.075	2.5

Coupling loop with BNC at top

Frequency (MHz)	SWR	Bandwidth (kHz) SWR=2	Bandwidth (kHz) SWR=1.5
3.583	1.03	3.2	1.9
7.090	1.05	10.2	5.8
10.120	1.15	16	8
14.110	1.92	13	-

Fig. 80: SWR vs. frequency for the two coupling loop configurations - tuning capacitor at the top of the main loop

(position of the coupling loop was optimized for 80m; "BNC at bottom" vs. "BNC at top" only impacts distance between the coupling loop and main loop)

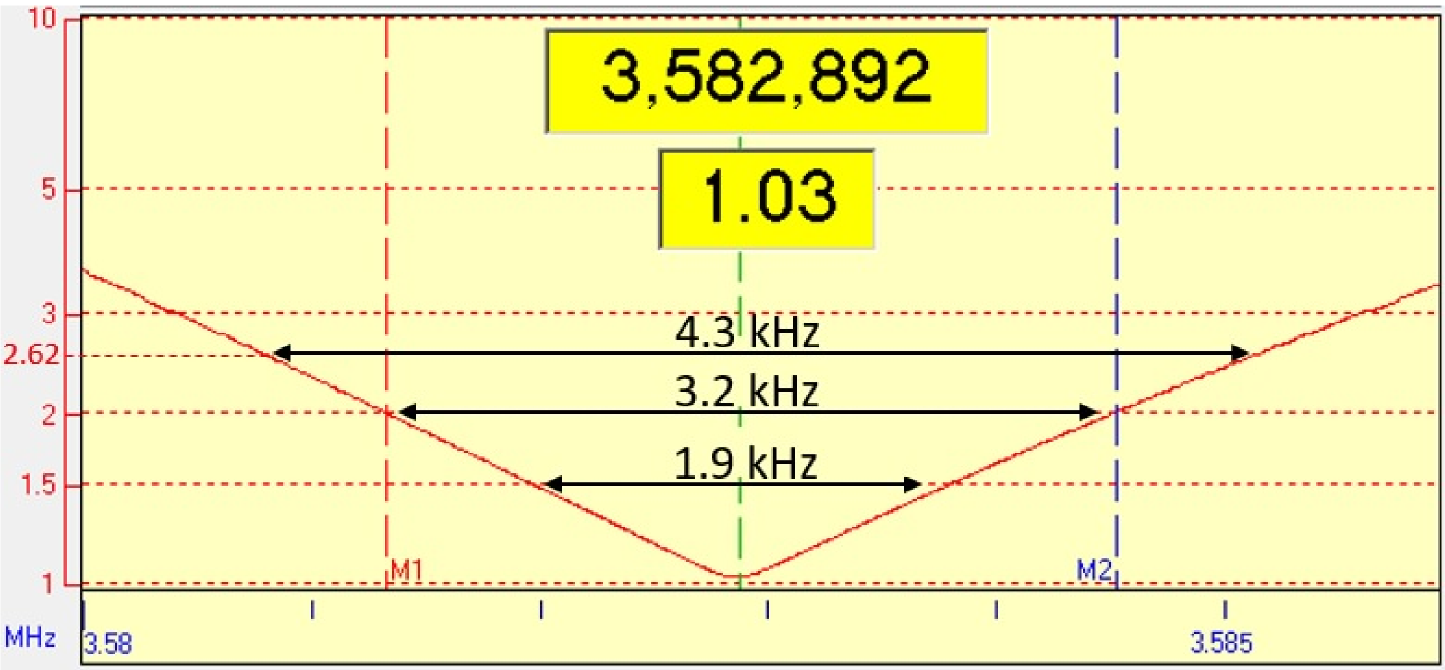


Figure 81: SWR vs. frequency in the 80m band

The table below shows the efficiency and "Q" of my loop, calculated with an on-line calculator (ref. 2G) for the measured SWR bandwidth shown in Fig. 81:

Inputs:			Results:	
N4SPP Mag Loop Antenna			Perimeter (λ)	0.0729
Frequency for min VSWR (<1.5) (MHz)	3.583		-3dB BW (kHz)	4.24
Loop type	Circle		Q	845
Loop perimeter (m)	6.1		Loop inductance (µH)	6.18
Conductor diameter (mm)	13.3		X (Ω)	139
Min VSWR	R<R0	1.03	Cs (pF)	7.81
VSWR	2.618		Rtotal (Ω)	0.165
Bandwidth @ VSWR (kHz)	4.3		Rradiation (Ω)	0.00557
Rr/Rrfs (pu)	1.000		Efficiency (%)	3.387
Directivity (dB)	1.761		Efficiency (dB)	-14.7
Calculate			Gain (dBi)	-12.9

Figure 82A: Calculations based on measurements in Fig. 81
(calculator: ref. 2G)

With this particualr calculator, the resulting "Q" is 845 and efficiency is around 3.4%. Note that this calculator assumes that the antenna is placed in free space. I.e., far away from ground and objects. The calculator's default settings for the parameters "Rr/Rrfs" and "directivity" were used, rather than adjusting them for ground effects.

Based on the loop inductance (6.18 µH) and "Q" (845) as calculated above, and assuming 100 W transmit power, the peak voltage across the capacitor at the 3.583 MHz resonance frequency can be estimated with the following formula (ref. 2H):

$$V_{peak} = \sqrt{2 \times P_{transmit} \times Q_{loop} \times X_{loop}} = \sqrt{2 \times P_{transmit} \times Q_{loop} \times 2\pi \times f_{res} \times L_{loop}}$$

$$= \sqrt{2 \times 100 \times 845 \times 2\pi \times 3.583 \times 10^{6} \times 6.18 \times 10^{-6}} \approx 4850$$

For the same measured half-power bandwidth, the formulas in ref. 3E yield a "Q" of 833 and an efficiency of 7%, also for free space:

			= data input cell					
Center freq	3583	kHz	-->	83.73	meter λ	-->	0.075042	wave nmbr ***k***
SWR 2.62 upper limit	3585.15	kHz						
SWR 2.62 lower limit	3580.85	kHz						
SWR 2.62 BW	4.3	kHz		**Note:** 1/2-power bandwidth = -3dB = SWR 2.62				
Qtot =	833							
Loop radius ***b***	1.0	m	-->	6.09	meter circumference		1.94	meter diameter
Conductor radius	12.5	mm	-->	0.013	meter radius ***a***			
Qrad =	11443							
Efficiency =	7	%						

$$Q = \frac{\sqrt{F_U F_L}}{F_U - F_L} = \frac{Frequency}{Bandwidth}$$

$$Q_{RAD} = \frac{3\left[\ln\left(\frac{8b}{a}\right) - 2 + \frac{2}{3}(kb)^2\right]}{\pi(kb)^3\left(1+8(kb)^2\right)\left[1-\left(\frac{a}{b}\right)^2\right]}$$

Here k = 2π/λ is the wave number, where λ is wavelength, b is the loop radius, and a is the loop conductor cross-sectional radius. Use the same units for all dimensions.

Spreadsheet by Frank, N4SPP, based on formulas in "How Efficient is Your QRP Small Loop Antenna?", Amir Findling (K9CHP), Kazimir Siwiak (KE4PT), in "The QRP Quarterly", Summer 2012, pp. 22-23

Figure 82B: Calculations based on measurements in Fig. 81
(source formulas: ref. 3E; MS Excel spreadsheet calculator: ref. 3F)

I implemented the formulas of ref. 3E in an MS Excel spreadsheet (ref. 3F). To put the effciency into perspective: compared to 100% efficiency, the 3.4% implies 15 dB down, or 2.5 S-points. Likewise, 7% implies 12 dB down, or 2 S-points.

PLACEMENT OF THE ANTENNA

There are operators who claim that an STL antenna works just as well (or poorly, as the case may be) indoors as outdoors. I believe this to be nonsense, or pure coincidence at a particular indoor and outdoor placement (and I don't believe in coincidence). For simplicity, let's define "antenna performance" as the resulting signal strength (field strength) at the receiving station, and vice versa for reception. All objects near the antenna influence the antenna's radiation pattern, as some radiation will reflect from them, or refract around them. Furthermore, *conductive* objects (metals, plants, trees, people and other animals, soil) couple with the antenna, and put a load on it. Note that antenna radiation pattern diagrams are typically for onobstructed free space, and change drastically when ground is introduced, or other objects.

Antenna performance not only changes significantly when going from indoors to outdoors. When moving the antenna around outdoors, the antenna performance also depends on the location with respect to other objects. Example: the standard placement of my STLs is at the center of my terrace (see ppoint "X" in the photo below). At this position, my STL is half way between two parallel reinforced concrete walls: the outside wall of my apartment, and the wall between my terrace and my neighbor's terrace. These walls are spaced by 6 m (20 ft). The floor of the terrace is also reinforced concrete.

Figure 83: The STL placement situation on my terrace

At one end of the terrace, there is a reinforced concrete overhang and a grounded, heavy steel I-beam pergola to the wall with the neighbor's terrace. On top of the overhang, there is a free view in all directions, and the antenna is about 25 m (80 ft) above street level. When I put my antenna here, pointing in the same direction, two things happen. First of all, SWR changes from 1.1 to 1.3. Not as good (power is reduced by a percent or 2), but I did not bother to adjust my coupling loop. Despite this deterioration, my signals at a DX receiving station on 80 mtrs increased by 1/2 to 1 S-point, i.e., 3 to 6 dB. This is equivalent to doubling to quadroupling the power!

EFFECTS OF CORROSION

I sometimes get emails from fellow amateur radio operators, who claim that the surface oxidation of the copper loop causes a significant increase in loss resistance. This would cause a significant decrease in performance. These operators claim that the loop should be polished until all oxidation is removed, and the copper is nice and shining. The same opinion can be found in forums. However, none of these people are able to provide *any* references from refereed/scientific literature, or from credible experiments, that support their opinion. And if you search around, you will quickly find out that there is little or nothing published on this topic. Which is why this misconception perpetuates...

For HF frequencies, there simply is no credible theory or evidence that surface oxidation causes significant loss resistance!

You have to get up to higher VHF before the effect of surface oxidation becomes noticeable!

But be careful! Corrosion at connections WILL cause loss resistance! In my loop, I very carefully remove all corrosion before I tighten the connection beteen the ends of the loop and the capacitor brackets. If I loosen the connection a year or two later, they are still perfectly clean, with no visible corrosion. The loop itself, however, is fully covered with black copper oxide (CuO, "cupric oxide", tenorite). Note that this oxide is a p-type semiconductor. Fully oxidize connections make cause strange rectification effects on small signals.

MOTOR DRIVE FOR THE VACUUM CAPACITOR

My loops are installed on the terrace of my penthouse apartment, so they are quite accessible. Even so, it is entirely impractical having to go outside several times to manually adjust the capacitor position when changing operating frequency, or when the resonance frequency drifts away for whatever reason. Standing next to the loop also de-tunes it a bit. The loop has a very narrow bandwidth, esp. on 80 m. A remote-controlled motor-drive for the capacitor is a must! The basic motor options are a stepper motor (*D*: Schrittmotor, *F*: moteur à pas), and a DC motor. Especially with a DC motor, down-gearing will be required.

[Stepper motor] [DC motor]

STEPPER-MOTOR DRIVE

When I built my first STL, I could not figure out an easy way to motorize the vacuum capacitor with a DC-motor, while providing end-stop protection at both ends of the motion range of the shaft (36 revs). So, why not make a little science project out of it?

Primary parameters for the motor-drive are:

- required minimum torque at the capacitor shaft,
- required minimum angular resolution, and
- drive speed.

Note that "precision" and "accuracy" are not on this list. I am not particularly interested in the ability of the drive-system to move *exactly* to some (pre-)selected position, or exactly follow some predefined acceleration and speed profile. Depending on the outside temperature, the alignment of the moon, planets and the stars, etc., the exact capacitor shaft position for a given resonance frequency will vary. So, one will have to search around a bit anyway, for fine-tuning. It is important, however, to change the position just a tad.

The first design parameter for the motor-drive is the **torque required** to overcome the stiction (static friction), and turn the shaft of the variable capacitor. This drives the size of the motor and reduction gear (if required). Variable vacuum capacitors have a torque value that depends on the position of the capacitor (mid-range vs. close to the end-stops), and the direction (towards or away from an end-stop). I do not have the data sheet of my Russian capacitor. To get an order-of-magnitude idea, I checked the values for a comparable capacitor (25-500 pF, 10 kV test, 9 inch length) manufactured by Jennings: 6 inch-pound (in.lb) or 6 x 0.113 ≈ 0.68 Nm = 68 Ncm.

I then decided to measure it myself ("trust, but verify!"). This is actually quite easy to do! I clamped a standard 30 cm (1 ft) ruler onto the shaft of the capacitor with a small C-clamp. Pushing slowly down onto a kitchen scale until the shaft barely turns, and read the "weight". *Voilà*. See photo below. The force was applied to the shaft with half of the ruler, i.e., an arm of 15 cm.

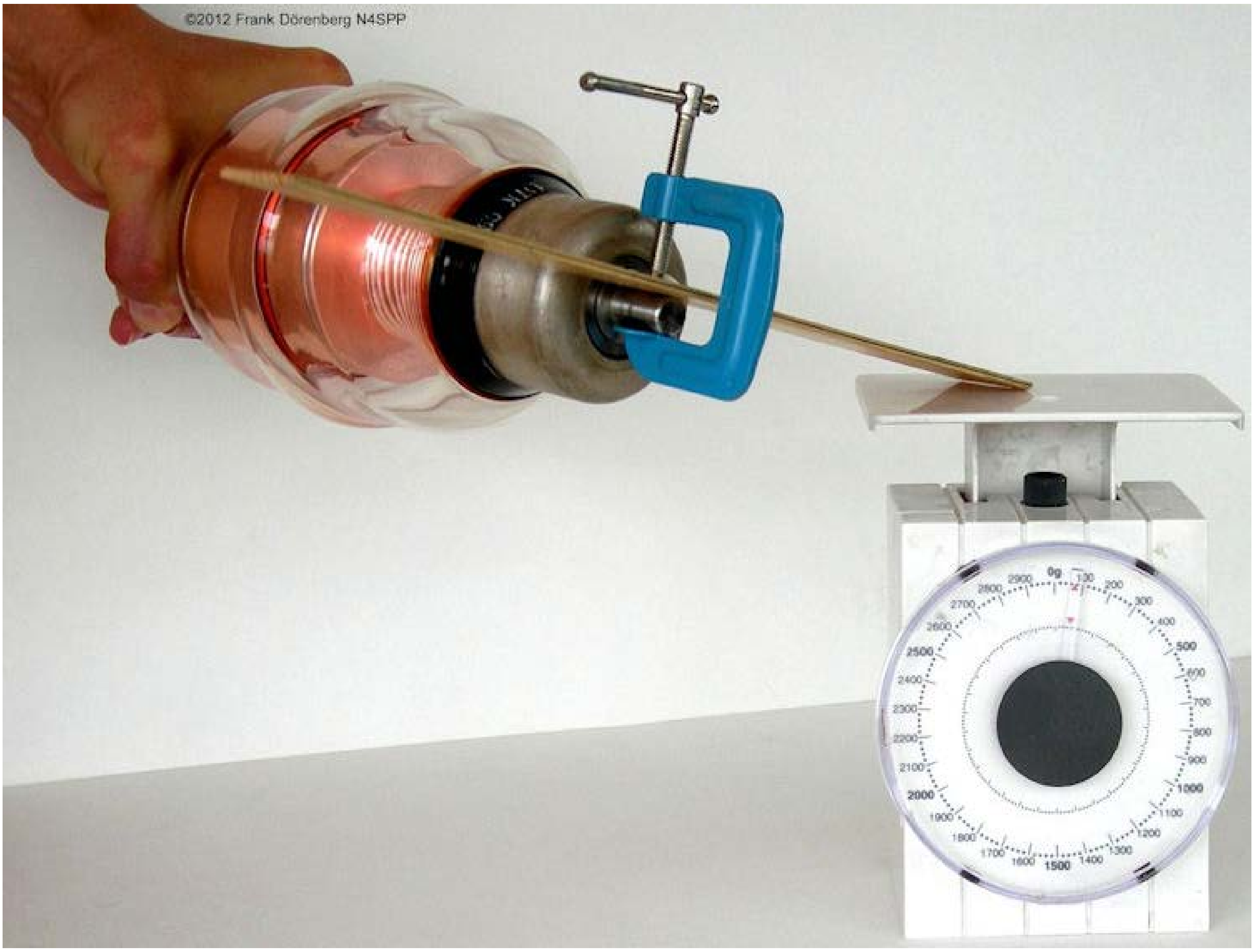


Figure 84: Determining the torque values of my capacitor

Here are the measurement results:

- Depending on the turn-direction, I measured about 80 to 100 grams at positions up to mid-range (starting at minimum capacitance). So, the applied torque was (0.1 kg x 9.8) x 0.15 m ≈ 0.15 N.m = 15 N.cm (≈ 21 oz.in).
- Somewhere mid-range, it became harder to turn the shaft, and I needed to apply about 140 gram, i.e., 20.6 N.cm (≈ 29 oz.in).
- I needed about 300 gr to get completely to the opposite end (maximum capacitance), i.e., 44.1 N.cm (≈ 63 oz.in).
- I cranked it up to 1000 gr without breaking anything, i.e., 150 N.cm (≈ 208 oz.in). If the motor-drive (motor + gearing) delivers less than this, I do not have to worry about not having end-stop protection. I decided to not measure the torque required to go beyond the end-stop of the capacitor, hihi.

The second important design parameter is the **angular resolution of the motor-drive**. The loop antenna has a large Q, or - equivalently - a very narrow bandwidth. The motor-drive must be able to make angular displacements that are small enough, such that the associated capacitance change does not change the resonance frequency more than a fraction of the bandwidth. Otherwise it will be next to impossible to tune the resonance frequency close enough to the desired operating frequency.

Let's simply assume that the capacitance changes linearly with rotation of the capacitor's shaft (which is actually only true for about 2/3 of the motion range). Then we get 500 pF / (36 rev x 360º per rev) ≈ 0.04 pF / degree. For my first STL, one of the loop calculators (ref. 2B) suggest the following:

In the middle of the 80 m band:

- Calculated bandwidth is about 3.5 kHz. I actually measured 4.6 kHz for my loop. The difference is probably because I did not enter a value for additional loss resistance in the calculator...
- A capacitance change of 1 pF results in a calculated change in resonance frequency of 4.2 kHz. I.e., 0.24 pF per kHz.

At the high end of the 20 m band:

- Calculated bandwidth is about 52 kHz. I actually measured 61 kHz.
- A capacitance change of 1 pF results in a calculated change in resonance frequency of 275 kHz. I.e., only 0.004 pF per kHz.

Clearly, variation around the minimum capacitance (highest frequency) is the critical case!

Let's assume that practical tuning requires changing the resonance frequency with a resolution that is better than 20% of the bandwidth. The above data implies a required resolution of better than 20% x 52 kHz = 10.4 kHz. That is: 10.4 / 275 kHz/pF = 0.038 pF! Based on the 0.04 pF / degree change in capacitance as estimated (assumed) above, I need an angular positioning resolution of better than 0.038 pF / 0.04 pF/deg = 0.95 degree.

Note that an air variable capacitor goes through its capacitance range in a single revolution of the capacitor shaft. For multi-band tuning (large capacitor value), this implies a positioning resolution that is at least an order of magnitude better than what is needed for a multi-turn (10-40 turns) vacuum variable capacitor!

A secondary design parameter is the **minimum drive speed**. We don't want to wait an hour for the capacitor position to move from min to max value, or vice versa. My capacitor requires 36 turns for this min-max range, which should cover the 80-20 m bands. If I could live with 1 minute, that would be 36 rpm at the capacitor shaft = 0.6 rev/sec.

Now we can choose a motor and associated drive electronics. Gearing must be added, as necessary for torque, speed, and/or position resolution. There are two basic options:

- Stepper-motor,
- DC-motor with gearing + position feedback (unless you just want to move the motor while observing the SWR or antenna impedance and don't care about the motor position). If the DC motor is not a brushless type, then (as a minimum) a noise suppression capacitor must be installed across the motor wires. Otherwise the brushes will generate electrical noise when tuning the antenna in receiver mode.

Open-loop control of a DC motor is simple. Apply DC power with the correct polarity, and turn of that power when at the target position. Speed can be controlled (again: open-loop control without position feedback, no speed regulator) with a cheap and simple Pulse Width Modulator (PWM) circuit, such as I used for my third STL. Small DC-motors with large down-gearing are relatively inexpensive.

Stepper motors do not have built-in position feedback, but their movement *is* deterministic, as long as the motor does not stall or lose sync. Their control/driver electronics are more complicated than what is needed for DC-motors. Positioning accuracy and torque requirements are easily met with a stepper-motor: they have a specified torque and step size. Stepper control electronics often have half-stepping capability (though this typically reduces available torque by about 30%). Common step sizes are 1.2, 1.8, 3.6, 7.5, and 15 degrees. I.e., 300, 200, 100, 48, and 24 steps per revolution, respectively. Smaller step sizes do exist, e.g., 0.9 and even 0.36 deg, but at a cost...

When one of my colleagues donated a stepper-motor (thank you Helmut!), I decided to throw all caution to the wind, and go with that. It is an old Slo-Syn SS25-1001. This is a 5-wire brushless permanent magnet inductor motor that can be operated as a constant-speed AC synchronous motor, and as a 1.8º uni-polar DC stepper motor. As I needed better than 0.95 deg positioning resolution, at least 2:1 gearing is required.

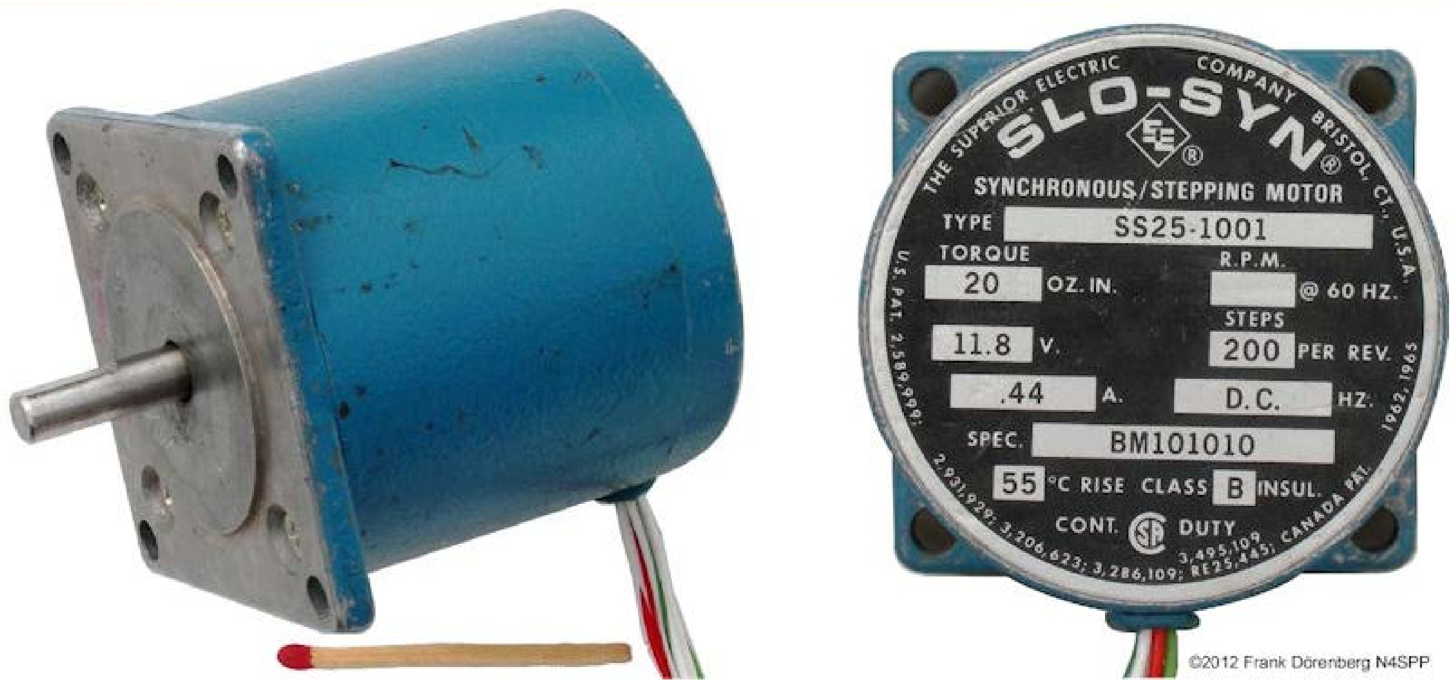


Figure 85: An old Slo-Syn SS25-1001 motor

"SS25" stands for "Standard Slo-Syn" with 25 oz.in (17.7 N.cm) torque at 72 rpm (120 Vac, 60 Hz). However, as a stepper motor, it has different torque ratings:

MOTOR TYPE	MINIMUM HOLDING TORQUE				TYPICAL RESIDUAL TORQUE OZ-IN (Ncm)	MAX. RADIAL FORCE LB (N)	MAX. AXIAL FORCE LB (N)	NEMA FRAME SIZE	NET WEIGHT	
	ONE WINDING ON OZ-IN (Ncm)	TWO WINDINGS ON OZ-IN (Ncm)	CURRENT PER WINDING (AMPERES)	DC VOLTS PER WINDING					LB	kg
SS25	30 (21.2)	40 (28.2)	0.07	80	1 (0.7)	15 (67)	25 (111)	23D	1.3	0.6

Figure 86: Specification of the Slo-Syn SS25 stepper motor

There are several kinds of stepper-motor torque to consider:

- **holding torque** (a.k.a. **break-away** torque): the amount of torque required to break the shaft away from its holding position, with motor at standstill and coil(s) energized with rated current & voltage.
- **pull-in torque**: max torque at a given speed, for stopping/reversing without losing sync.
- **pull-out torque**: max torque at a given speed, without losing sync or stalling.
- **residual torque** (a.k.a. **detent** torque): torque produced by the motor's permanent magnets, when no coils are energized.

The holding torque and residual torque are not interesting for my application, as the motor will not be holding a load. Of interest are the pull-in and pull-out torque, typically provided as a torque vs. speed curve. The curves are highly dependent on the type of motor-driver that is used.

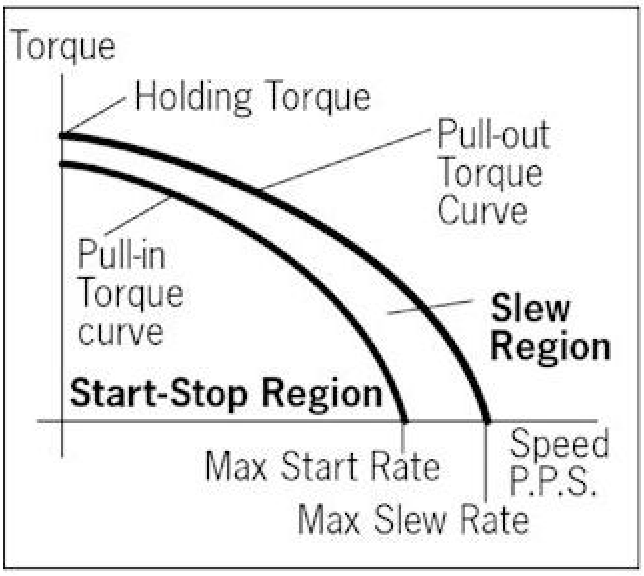


Figure 87: Typical shape of the torque curves

I do not have the torque curves for this motor, but typically it appears to be about a factor three smaller than the holding torque. That would imply a torque of about 10 oz.in (7 N.cm). Less than half of what I need! But why not determine the actually required torque, the same way I measured the required torque. With the motor energized, just make the "arm" push down on the scale until the motor turns.

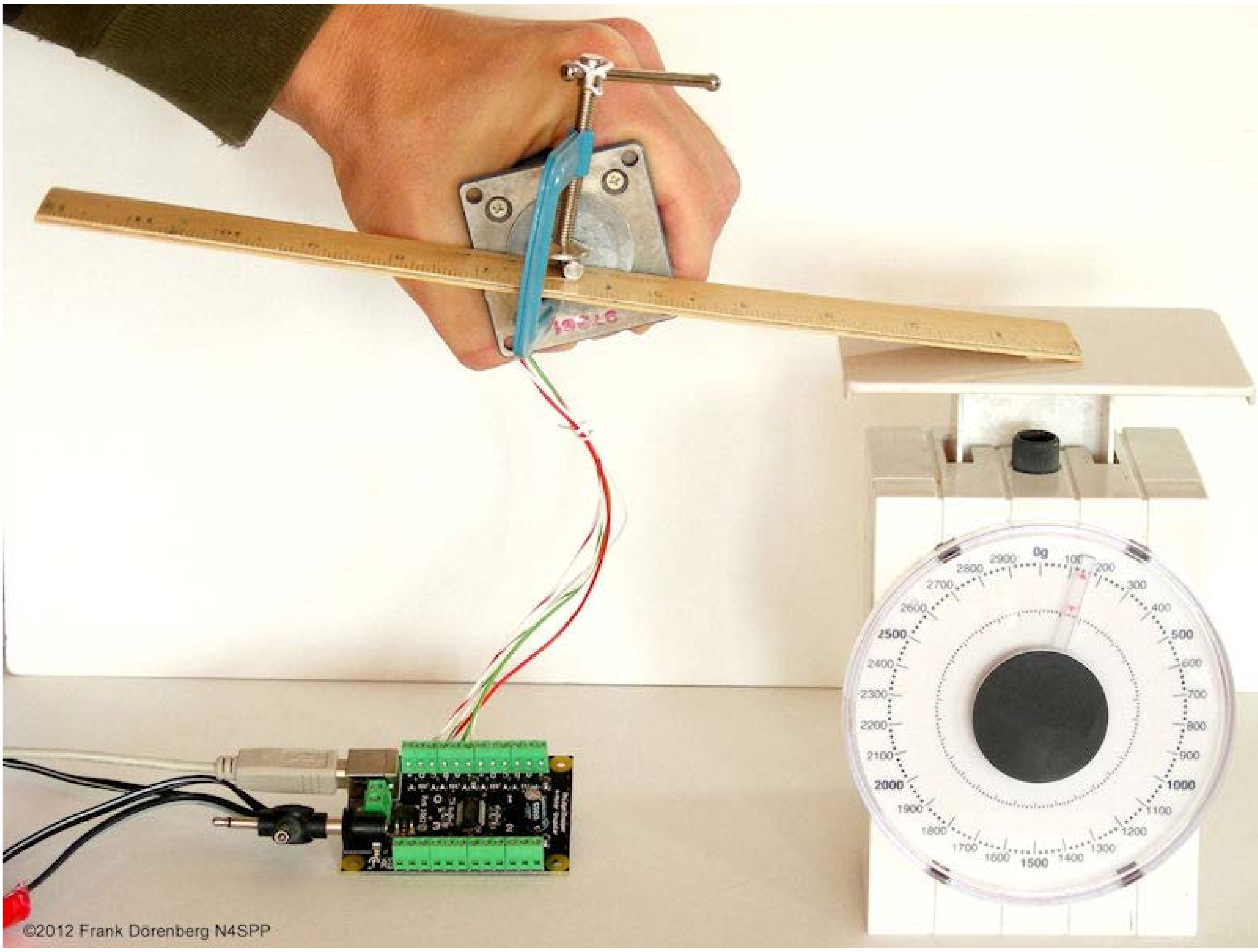


Figure 88: Determining the break-away torque value of my SS25 motor

With my simplistic kitchen scale method, I measured a break-away torque of approximately 140 grams x 15 cm = 2100 g.cm = 20.6 N.cm = 29.2 oz.in. Almost exactly as specified! The same value is obtained by fixing the motor in place, and commanding it to turn, one step (or 1/2-step) at a time until it "pops". This very easy to do with the controller software I wrote (see further below).

Keep in mind that I need at least 44 N.cm (≈65 oz.in). So I have to add down-gearing of at least 3:1.

The SS25 is a 5-wire device. It has a common wire (white) and four coil wires (green, green/white, red, red/white, for coil 1-4). This corresponds to the connections "+", and A-B-C-D on the Phidgets motor controller card that I use.

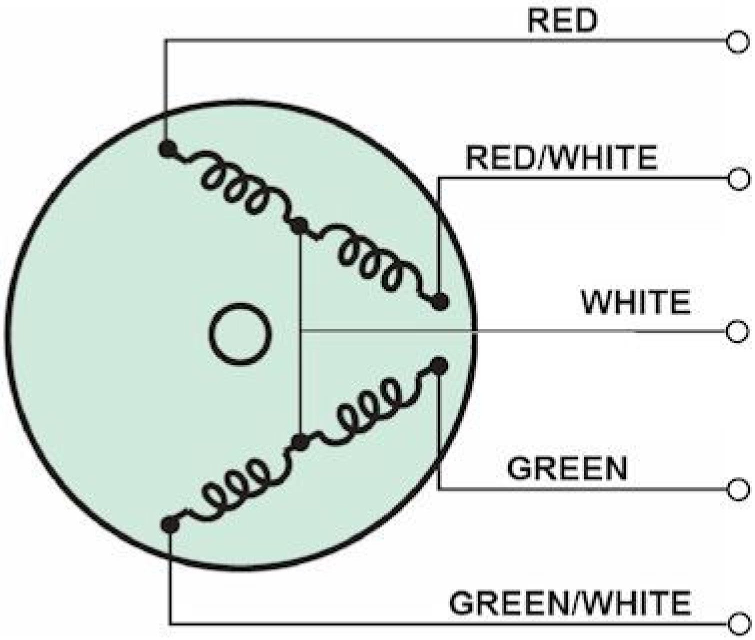


Figure 89: Wiring of the SS25

We have a motor, so now we need to control it. I wanted to control the motor from my PC, rather than having a separate control box. This means that the controller hardware must have an interface to the PC. Standard options are an RS232 interface via a COM port, or - more modern - a USB interface. My PC only has one COM port, and that one is already used for the PTT-interface from the PC to my transceiver. Yes, I could add a USB-serial interface. But if I go USB, I might as well skip the RS232.

The main choice to make now, is "make" vs. "buy". Yes, there are many stepper-motor controller hardware designs floating around in cyberspace. Few have a USB interface. I determined that piecing a design together, building and debugging it, was too much of a hassle. Instead, I searched for a relatively inexpensive off-the-shelf USB solution. I decided to go with a Phidgets 1062 controller card. It handles up to 4 **unipolar** stepper motors simultaneously (e.g., an antenna rotor as well). It is almost "plug-and-play", via USB. This controller card is really tiny: 5 x 6.3 cm (2 x 2½ ")! And: it is rated for 1 amp per winding, without a heatsink! It does come with some rudimentary software, to check out the card and the motor.

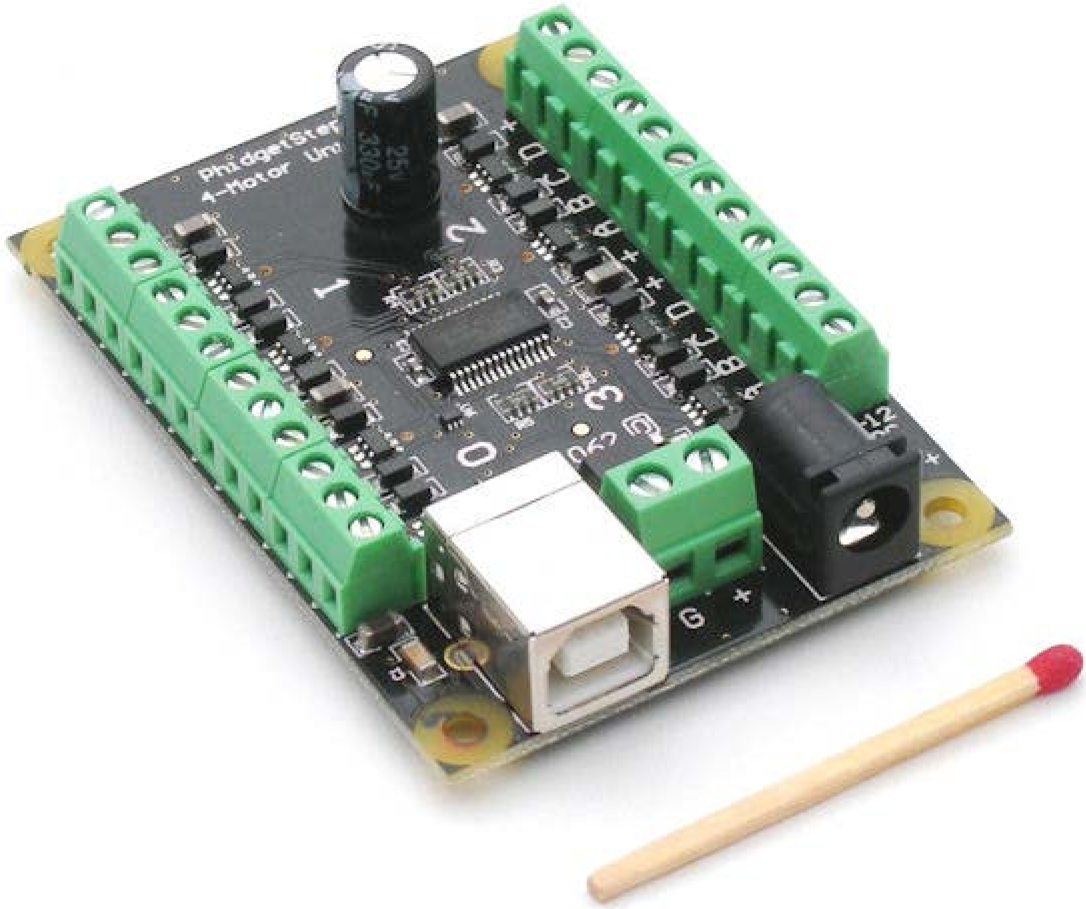


Figure 90: The small USB controller board for four uni-polar stepper-motors

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The unipolar Phidgets card (model 106**2**) does not support speeds above 383 half-steps per sec! That is almost 1 rps with a 1.8 deg stepper motor (200 full steps/rev).

This Phidgets card uses half-stepping: the drive alternates between "two phases energized" and "single phase energized". This provides smoother motion and doubles the angular resolution from 1.8º to 0.9º. However, when half-stepping, the motor also typically produces about 30% less torque (at the 1/2 step positions between full step positions). Maybe I will only get about 7 oz.in (5 N.cm) out of my SS25 motor! This means I will probably need a 4:1 gear ratio between the motor and the shaft of the variable capacitor...

Phidgets also sells a controller card (model 1063) for a single bipolar motor. As the name suggest, control of bipolar stepper motors involves changing the polarity of the applied voltage across the motor windings. This makes bipolar controller hardware inherently more complicated (typically H-bridges instead of simple transistor switches). Yes, unipolar motors are very old-fashioned and generally produce less torque then bipolar/hybrid steppers. The latter can also be micro-stepped, whereas half-stepping appears to be the limit for unipolar motors. The bipolar controller card supports much higher speeds, and also has 4 discrete/digital inputs.

The instruction set of the Phidgets 106**3** card is a super-set of the 1062's instruction set. I.e., the 1063 has all functionality of the 1052 - and some additional functions. E.g., limiting the motor current (= torque). This means that the control software that I developed for the 1062 will also work with the 1063. Leslie, EI5GJB, has confirmed this (November 2011) and is quite pleased!

Some other controller hardware options are:

- The "Stepper-Bee" card.
- The "Motor Hawk" card. Twan van Gestel (PA0KV) has made a big loop (160-40) with a Gamma match, and used one of these cards for a stepper motor in his 2015 design. He made nice controller software in Visual Basic. See here.

Both come with more useful demo software than the Phidgets.

External links last checked: January 2016

The next step is choosing a mechanical coupling of the motor to the shaft of the variable capacitor, including the necessary down-gearing.

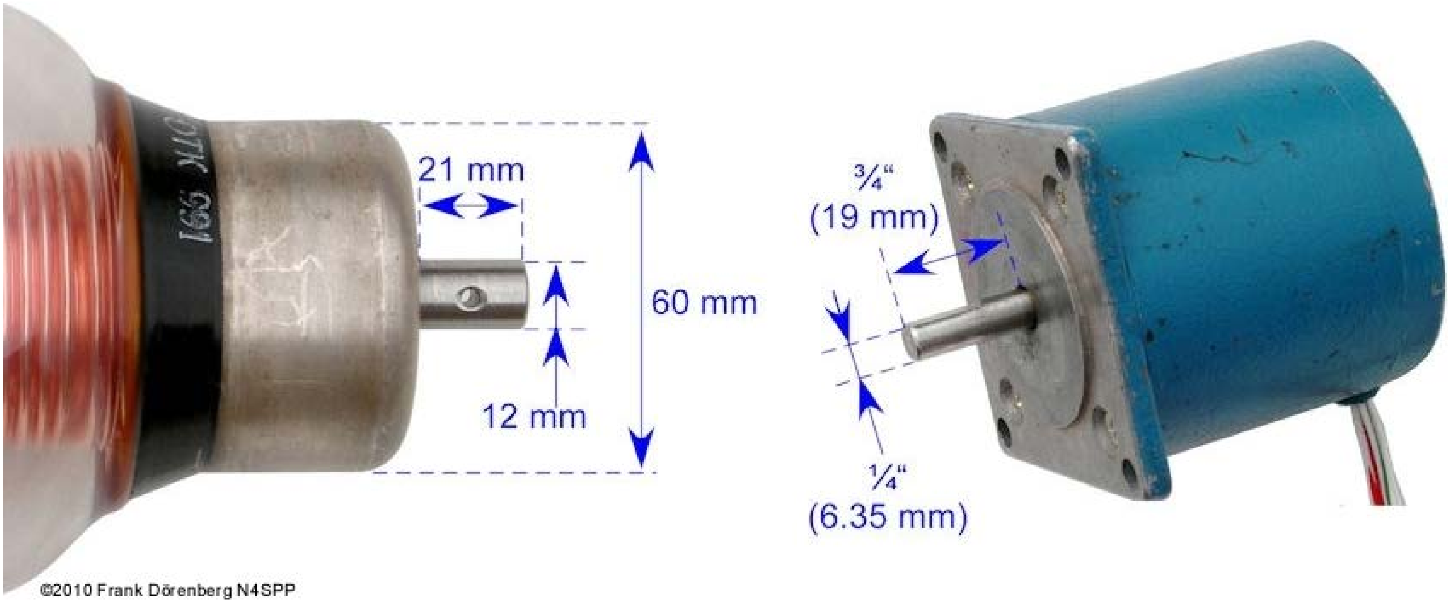

Figure 91: Shaft dimensions of my capacitor and motor

IMPORTANT: you need non-conductive material or rod to couple the motor to the capacitor. The capacitor shaft is not insulated from the capacitor itself. Hence, it is at the same potential as the capacitor (up to several kV at resonance). You don not want the capacitor voltage on the motor (or its wiring)! Standard options are using a non-conductive (plastic, ceramic) driveshaft or a belt drive. The shaft and housing of the motor, and any metal gear wheels attached to it, must remain at a safe distance (at least 1 cm (1/2") from the shaft and connections of the capacitor.

I would have preferred a straight, rigid shaft-to-shaft coupling. But as as determined above, my motor doesn't generate enough torque for 1:1 coupling: I need down-gearing of at least 3:1. The easiest way to do this, is with pulleys (cog wheels) and a timing belt.

A timing belt (a.k.a. toothed, notch, cog, synchronous belt; *D:* Zahnriemen, *F*: courroie dentée) has teeth that fit into a matching toothed pulley. When correctly tensioned, there is have no slippage: motor and load remain "synchronized". Timing belts need the least tension of all belts, and are among the most efficient (though no issue at very low speeds of a few RPM). Standard belts are fiberglass reinforced neoprene or polyester-urethane (PU). There are several standard belt profiles, but this is not critical in our low speed, low torque application. The basic choice was between a simple T (trapezoidal) profile with 2.5 mm pitch and 6 mm width, vs. 5 mm pitch and 10 mm width.

Figure 92: Standard metric belt profiles (left to right: T, AT, HDT)
(similar British/Imperial profiles are L, H, XL, MXL)

There is a finite choice of standard pulleys. The standard number of "teeth" is typically 10-20, 22, 25, 28, 36, 40, 48, 60, 72, or 84. The diameter of the pulley is determined by this number, and the pitch of the belt (i.e., the distance between the centers of adjacent teeth). It is recommended that at least one of the two pulleys has flanges, to avoid the belt from running off the pulleys when the input and output shaft of the gear are not properly aligned. Standard materials are aluminium and plastic (typ. acetal resin). Pulleys for a T5 belt are significantly larger than for a T2.5 belt. Pulleys have standard bore sizes.

Figure 93: Plastic flanged pulley

Some considerations:

- I did not want the pulley on the capacitor shaft to be larger than the end-connector of the capacitor (60 mm diameter).
- I want to be able to create a 3:1, 4:1 or 5:1 gear ratio.
- The diameter of the hub of the pulleys has to be large enough to increase the bore (with a drill press!) to the respective shaft size, and still have at least 2 mm hub thickness left.
- The height of the hub has to be enough to allow drilling a radial hole, thread it, and use a set-screw (grub screw) to fix the pulley onto (or through) the shaft.

I settled on a T2.5 x 6mm belt, a 60 teeth pulley (48 mm diam.) for the capacitor shaft, and a 15 teeth pulley for the motor. I.e., a 4:1 ratio (I also got a 10 teeth pulley, just in case I needed 5:1 gearing, but did not need it).

Now we need to figure out the length of the belt with the formula below (it is a very close approximation, as it neglects the fact that the belt does not touch the pulley over only half its circumference, unless the pulleys have the same size):

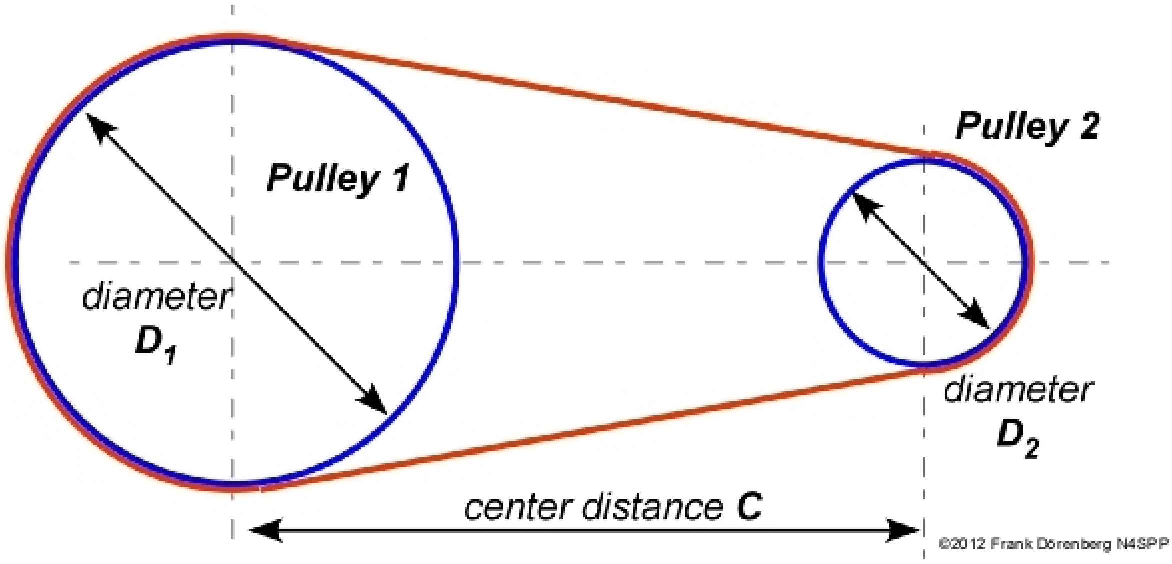

Figure 94: Pulley configuration parameters

$$L = (\tfrac{1}{2}\times\text{circumference of pulley 1}) + (\tfrac{1}{2}\times\text{circumference of pulley 2}) + 2\times\sqrt{\left(\frac{D_1 - D_2}{2}\right)^2 + C^2}$$

$$= \frac{\pi}{2}\times(D_1 + D_2) + 2\times\sqrt{\left(\frac{D_1 - D_2}{2}\right)^2 + C^2}$$

$$\approx \frac{\pi}{2}\times(D_1 + D_2) + 2\times C$$

For the diameter of the selected pulleys, and a minimum of 2 cm spacing between the pulleys, I ended up with a standard belt with a 200 mm (8") overall length (80 teeth). I.e., a standard T2.5 x 6 x 200 belt.

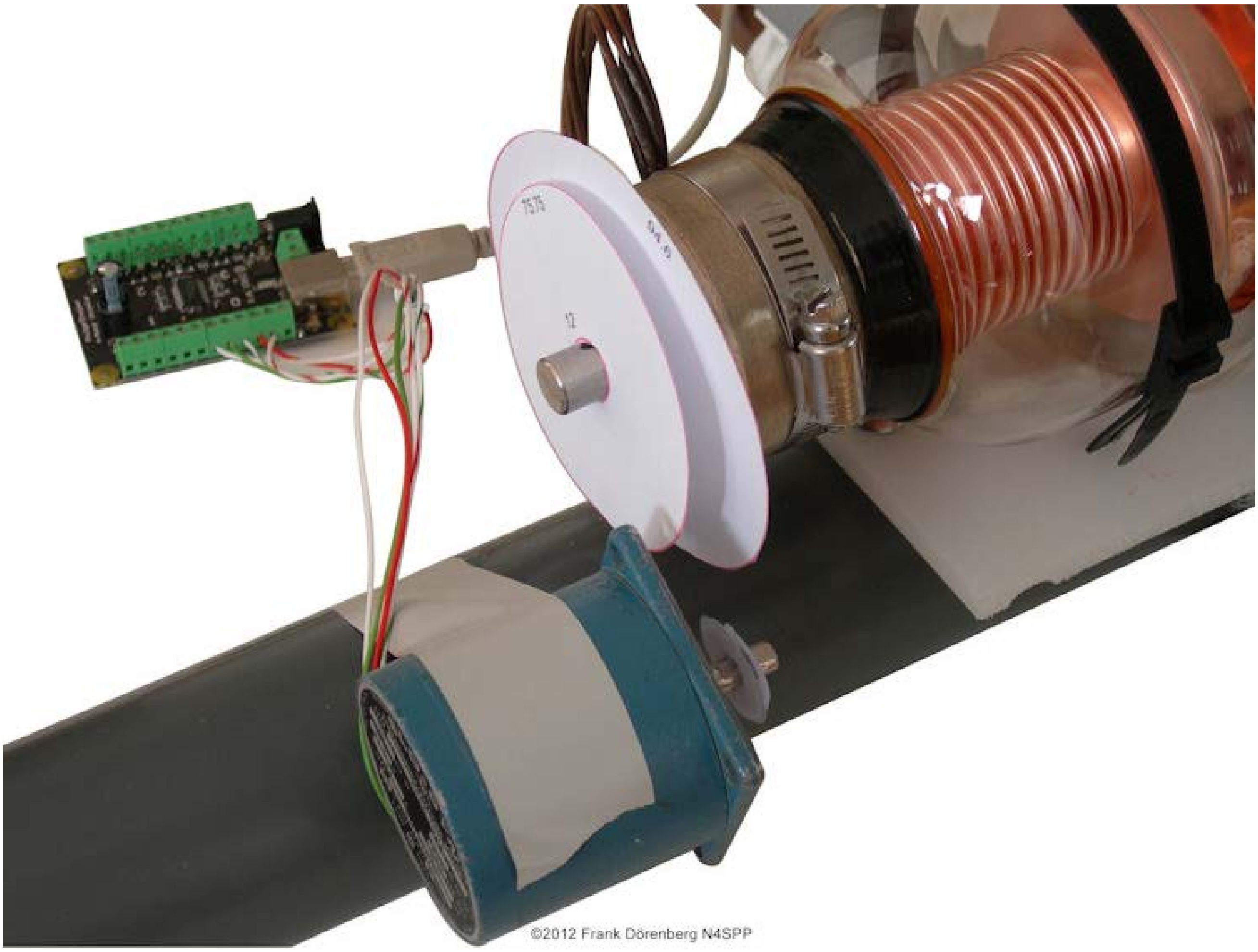

Fig. 95: paper disk "pulleys" on the motor and capacitor shaft to check dimensions and clearances

I installed the motor onto the antenna mast with two "worm drive" hose clamps (a.k.a. radiator clamps; *UK*: "jubilee® clips").

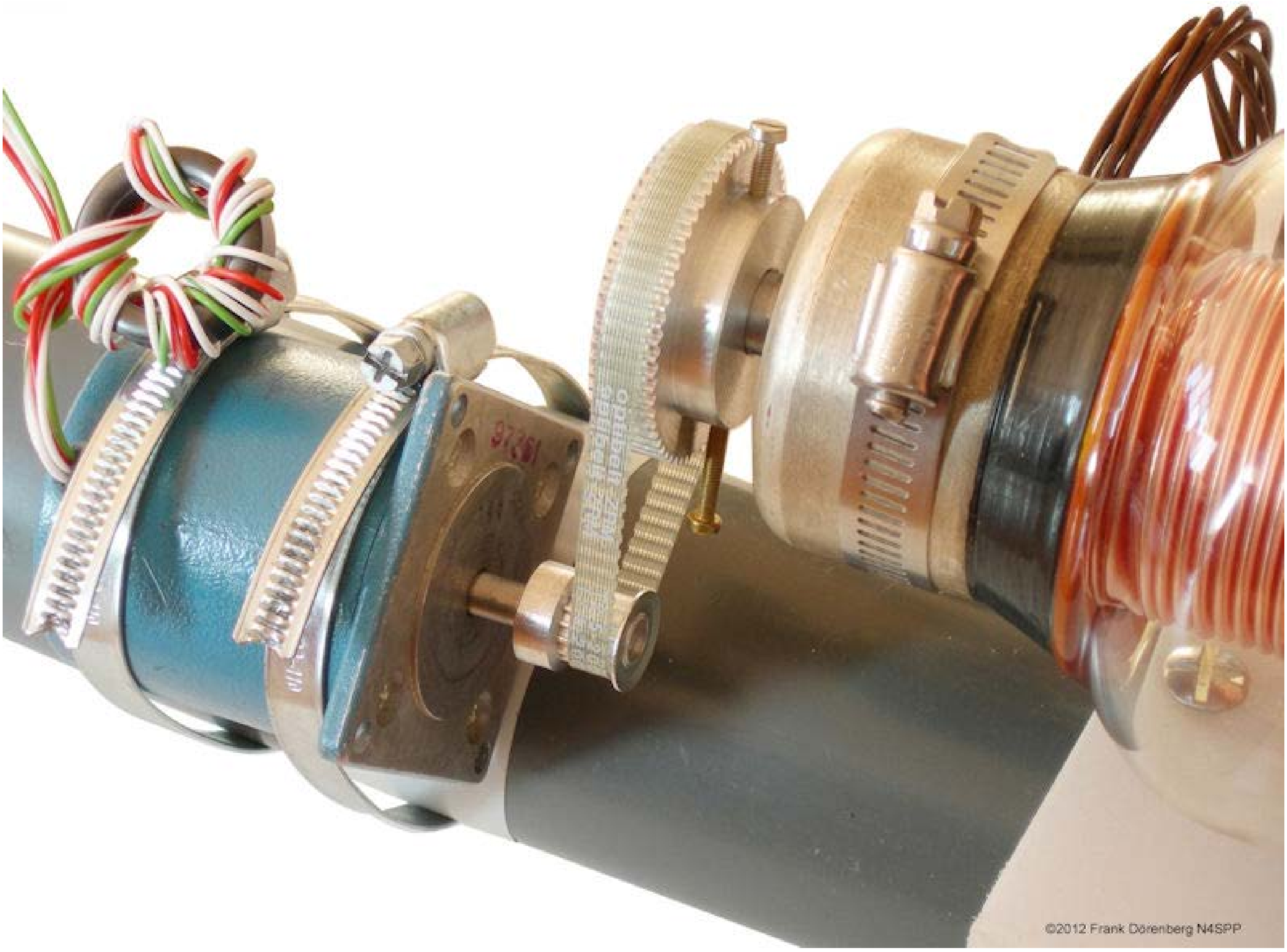

Figure 96: The pulleys and belt installed on the motor and capacitor
(note the 5-turn ferrite toroid "choke" on the motor wiring)

NOTE: I had to revise my choice of belt material! The original belt was reinforced with embedded steel tension cords. As you can see in the photos below, this caused arcing between the belt and the pulley of the motor. Luckily, no damage was done to the controller card, PC, or my transceiver. Clearly, one must use polyurethane or neoprene belts that are reinforced with fiberglass, polyester, or polyurethane cords!

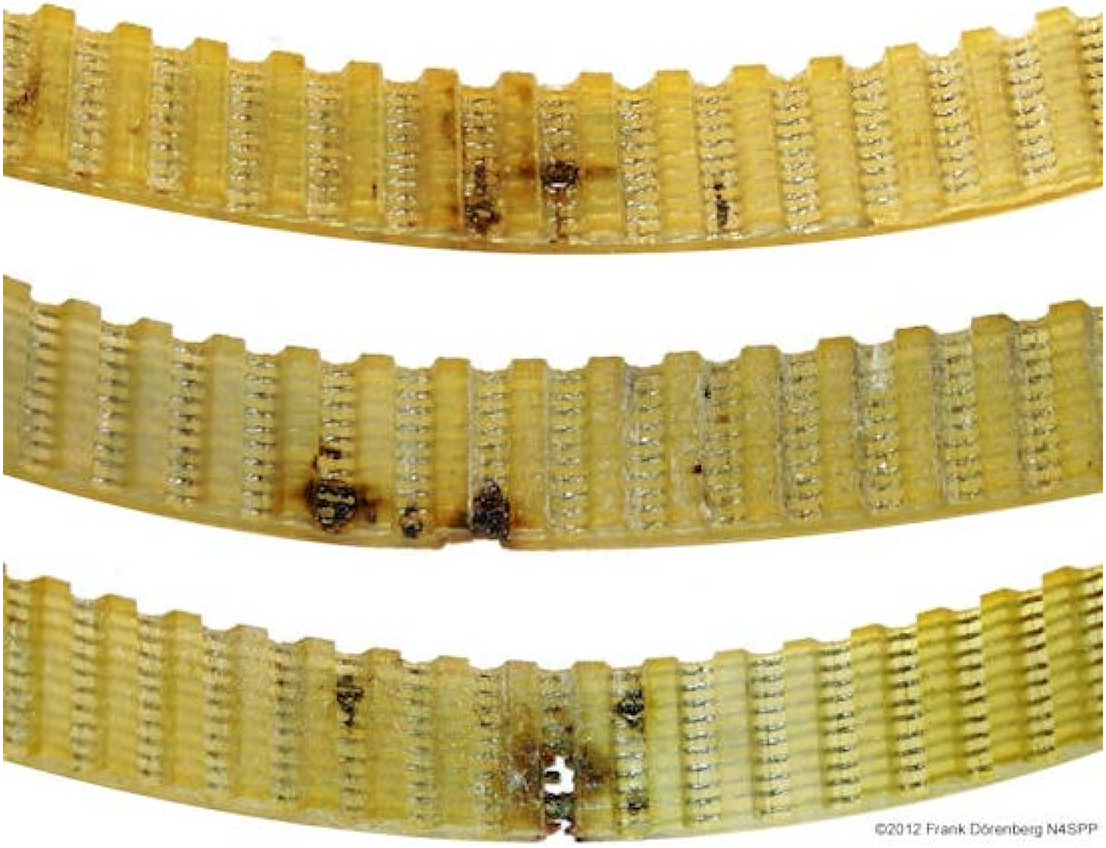

Figure 97: Arcing damage to the steel-reinforced belt

Figure 98: Arcing damage to the pulley of the stepper-motor

The Phidgets cards needs to be connected to the PC via a standard USB printer cable (supplied with the card). My motor happens to be a 5-wire motor (some unipolar stepper motors have more wires), so I need to run a cable with at least 5 conductors from the card to the motor. Some options are:

- Standard Cat 5 (category 5) cable; this is for 10/100 Mbs Ethernet communication - no need to go for Cat5e or Cat6 cable (100/1000). This is an 8-conductor cable, usually 4 twisted-pairs. There are UTP (unshielded twisted pairs) and STP (shielded) cables. STP is recommended for the application at hand.

- 5 conductor thermostat cable,
- 5 or 7 conductor antenna rotor cable,
- 6 or 8-wire phone cable.

The advantage of an 8-conductor cable is that this leaves 3 conductors to accommodate a sensor at the motor drive, e.g., a potentiometer or end-stop switch. Of course, it can also accommodate an 8-wire stepper motor. As I had several long Cat5 cables laying around, I settled for one of 15 mtrs (50 ft). With two mating RJ45 chassis connectors (8P8C modular jacks), I'm in business.

The controller card takes its power from the USB port, but only for the control electronics - not to power the motor! The latter power must be supplied separately to the card: either via a standard barrel connector, or hardwired to a terminal block. My motor uses 12 volt DC. I use the barrel connector and a 12 V / 750 mA "wall wart" power supply, or a sealed 12 V / 4 Ah motor cycle battery.

IMPORTANT: As noted in the warning section above, the antenna generates strong a RF field when at resonance - enough to light up a fluorescent light tube, with just a couple of watts transmit power. You do not want to get this RF into the controller card and damage it, or into the PC connected to it.

As for most of my HF-chokes, I use FT140-43 ferrite rings. One is placed at the controller card, between the RJ45 connector and the card. I use a short section of Cat 5 cable between the connector and the card. This cable is wound 5 times through the ferrite ring. This has been adequate so far (I use 100 W max).

Fig. 99: Toroidal current choke on the CAT5 cable between controller card and stepper-motor

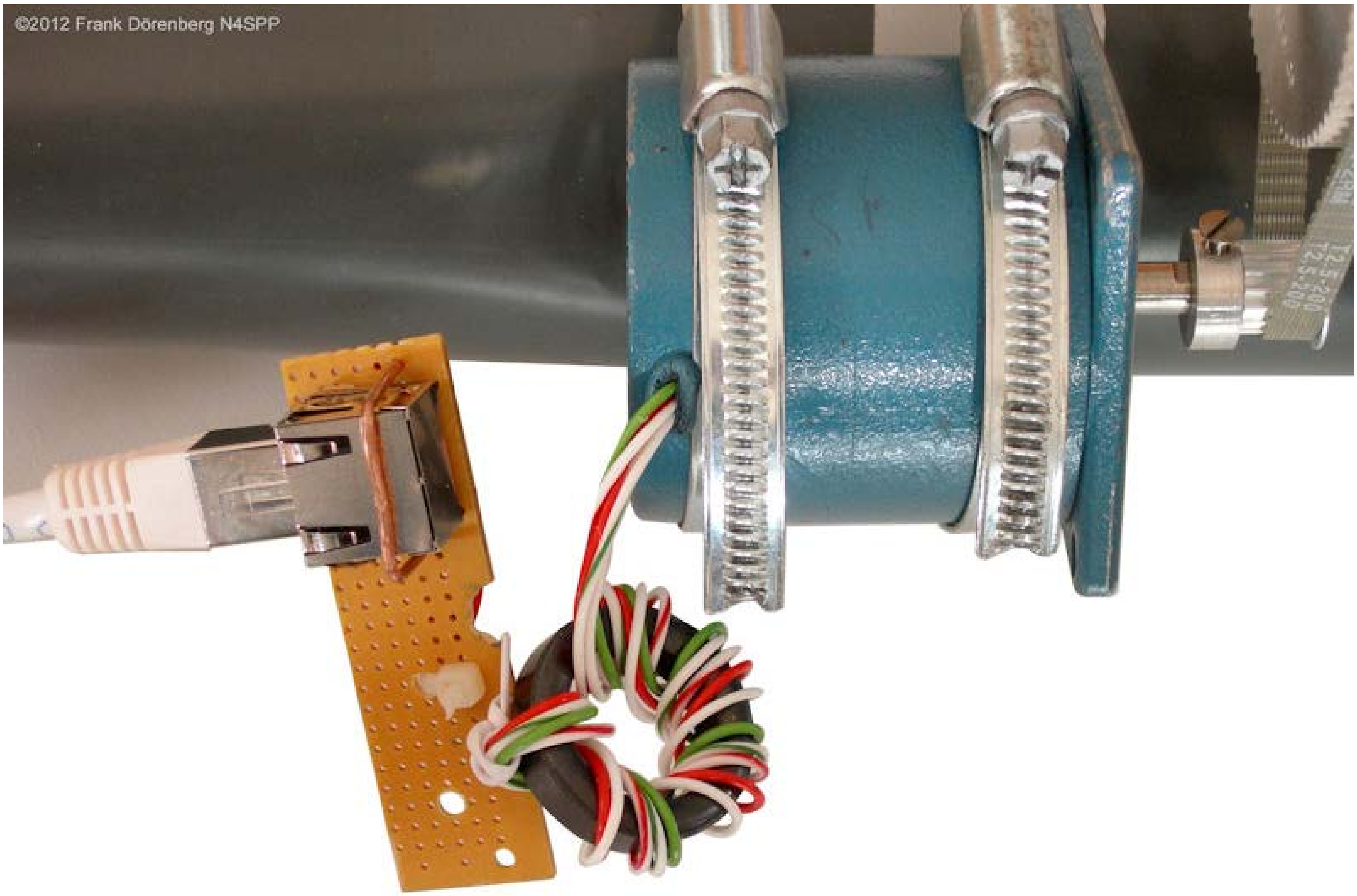

Figure 100: A second ferrite ring current choke is placed at the motor

According to various loop antenna calculators, the highest capacitor voltage for my size antenna, occurs for a resonance frequency around 7 MHz. Running 100 W into the antenna - with the controller card operational - did not cause any damage or abnormal behavior.

I may move the motor away from the capacitor, to the "neutral" point opposite the capacitor. This requires a long, torsionally-stiff drive shaft. I found very stiff green plastic rods of 1.8 m (6 ft) length and 16mm diameter in the gardening section of the local do-it-yourself store (thanks for the idea Mark, KF7KIN). Be careful: some of these green garden rods are just plastic-coated metal tubes or rods. It is not easy to tell! I ended up with a 1.8 m section of regular 16 mm PVC electrical conduit. It is flexible, but torsionally stiff.

The bore of my large gearwheel is 12 mm, as is the diameter of the capacitor-shaft. Adapting the 16 mm rod to the 12 mm bore (inner diameter) is easy, with a 16-to-10 mm copper adapter piece. It has 1 wall-thickness of 1mm, so 10+1+1= 12 mm outer diameter. I pressed it in with the bench vise. Adapting the 16 mm rod to the 12 mm outer-diameter of the capacitor shaft is equally simple, with a 16-to-12 mm adapter piece. The store didn't have that one in stock, so I used a 3 adapters: 16-to-10, 10-10 (female-female), and 10-to-12 mm. I will install a ball bearing with 16mm bore on the rod, close to the motor.

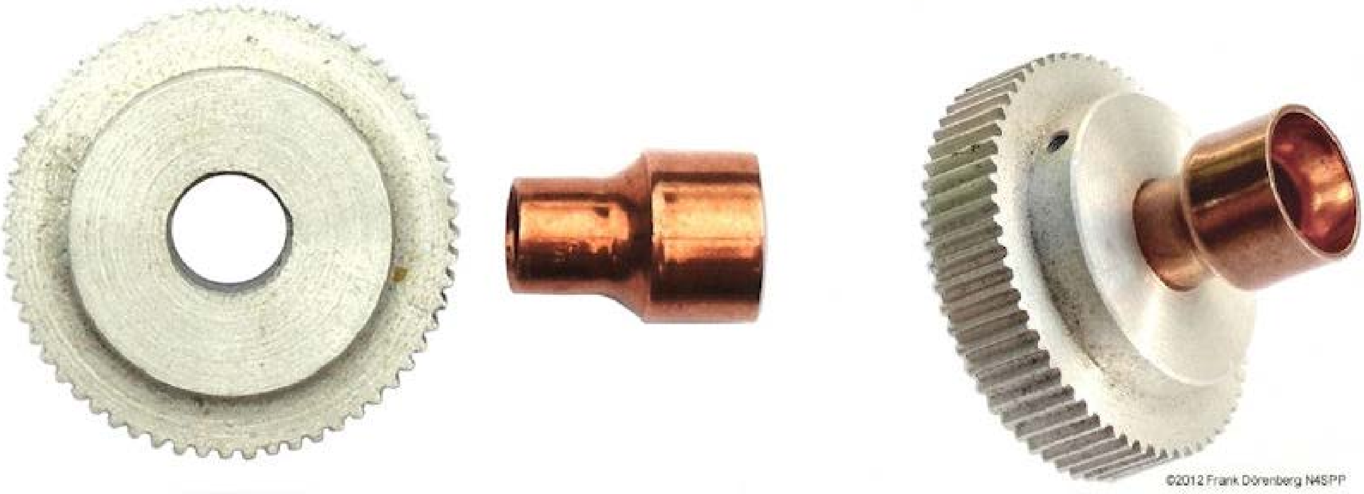

Figure 101: Gear wheel and copper adapter piece

Figure 102: Plastic drive-shaft with gear wheel installed

STEPPER-MOTOR CONTROLLER SOFTWARE

Obviously, the Phidgets motor controller card needs to be controlled from my PC. This requires the user (me) to somehow create software. The Phidgets website provides a library of dll and API files, and some simplistic code samples and low level suggestions on how to control the card via Visual Basic, C/C++, LabView, MatLab, Java, etc.

I decided to go with LabView, because I have access to it, and it is graphically oriented (both design and the controller). It has taken me over a week of spare time to learn "LabView 8 Pro" well enough to make a quite decent controller with a nice Graphical User Interface (GUI). My GUI has three tabs: "Control", "Cal", and "Config".

Next time around, I may have a go at Visual Basic, though it is limited to "Windows". The development tools are basically free, whereas LabView is prohibitively expensive for private use. And unlike LabView, no enormous Real Time Operating System needs to be installed.

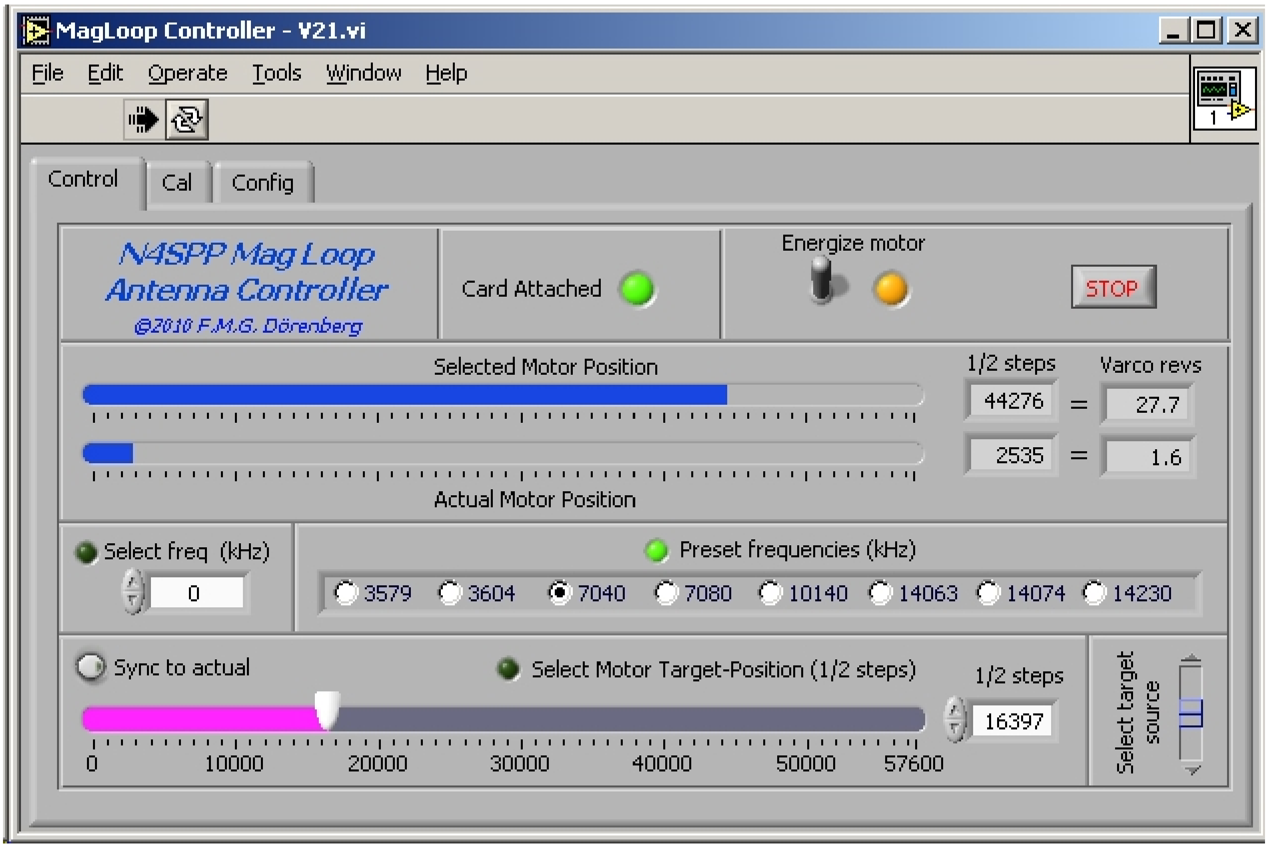

Figure 103: The "Control" tab of the GUI of my varco motor-drive control software

The "**Control**" tab provides the GUI for the following functionality:

- Indication of whether the software has established contact with the Phidgets card.
- A toggle switch for commanding the Phidgets card to energize the motor. Default is de-energized. A LED indicates energization status feedback from the card. Note that the card does not know whether a motor is actually attached or electrical power is available, so this (and of other parameters such as speed and position) is only a feedback of the *commanded* state.
- Three ways to enter the desired motor position. A 3-position slide switch (lower right-hand corner) is used to select one of them (a small LED lights up next to the selected source):
  - Type-in the desired antenna frequency (followed by "enter" on your keyboard), with incremental up/down buttons (+/- 1 KHz).
  - Radio-buttons for eight preset (and configurable) frequencies.
  - A magenta slider (with incremental up/down buttons, +/- ½-step) to command motor position, rather than frequency. There is a push button next to this slider. When pushed, the slider position is synchronized to the actual motor position. This is useful when using a pre-set frequency, and needing to tune around this position.
- Two blue sliders that indicate the selected motor position and the actual motor position. The associated numerical positions are expressed in both motor ½-steps, and revolutions of the tuning capacitor. The upper limit of all three control & indicator sliders is initialized based on the gear ratio and the number of 1/2 steps per motor rev. Note that the actual motor position is not measured - the controller card just keeps track of how many steps it commanded with respect to the initialization position.
- A "stop" button, that halts execution of the control software and commands the controller card to de-energize the motor.

If a desired frequency is selected (numerical entry or preset), then the software interpolates the antenna's calibration data to calculate the corresponding motor position. This interpolation scheme, and assigning the labels of the radio buttons based values read from a file, was the trickiest part of the software design! Note that the calibration data is only valid at a certain temperature and position or the antenna. E.g., if the data was obtained with a cold antenna, and the sun (or QRO operation) heats it up, then the actual resonance frequency will drift.

When turning a vacuum capacitor, there is no need to apply holding torque when not moving (unlike other applications. Hence, there is no need to keep motor energized while at rest. However, no harm is done when the motor is kept energized, and turning the energization on & off for each movement makes the controller software more complex. Also, when the motor is re-energized, it may jump a step. So: my controller software keeps the motor energized (with manual override).

Upon start-up, the controller reads-in three tiny text files:

- Initialization settings for the Phidgets card and the controller: acceleration limit, velocity limit (½-steps/sec), the number of ½-steps per revolution of the motor, gear ratio between the motor and the tuning capacitor, offset (½-steps), number of capacitor revs for end-to-end travel.
- Preset frequencies of the operator's choice.
- Calibration data (resonance frequency of the antenna, measured for each full revolution of the capacitor shaft). Obviously, the calibration data from my antenna will not be correct for someone else's antenna (or my own antenna at a different location).

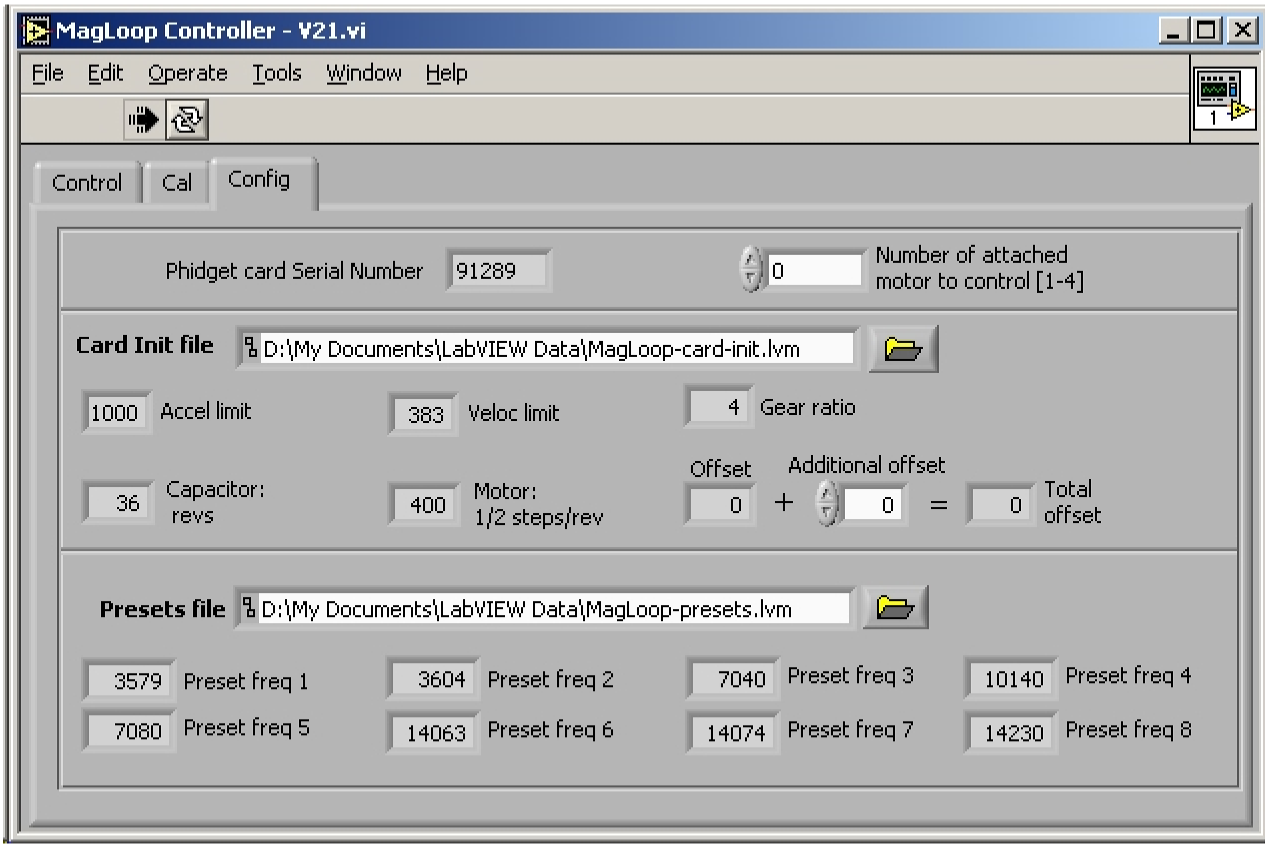

Figure 104: The "Config" tab of the GUI of my varco motor-drive control software

The "**Config**" tab provides the GUI for the following functionality:

- Indication of the serial number read from the Phidgets card.
- Setting of which motor to command (the Phidgets 1062 card handles four motors; default is 0). Note: this not the number of motors that are attached to the card.
- Location of the initialization data for the card and the controller. The file location has a default, but a browser button can be used to locate the file.
- A numerical entry (with incremental up/down buttons) for modifying the offset. I added this feature, to be able to adjust the applied offset (from the init file) when (re)starting the software, without having to modify the initialization data file. This allows to adjust for imprecise positioning at the reference position.

- Indication of the eight preset frequencies red from the presets data file. The file location has a default, but a browser button can be used to locate the file.

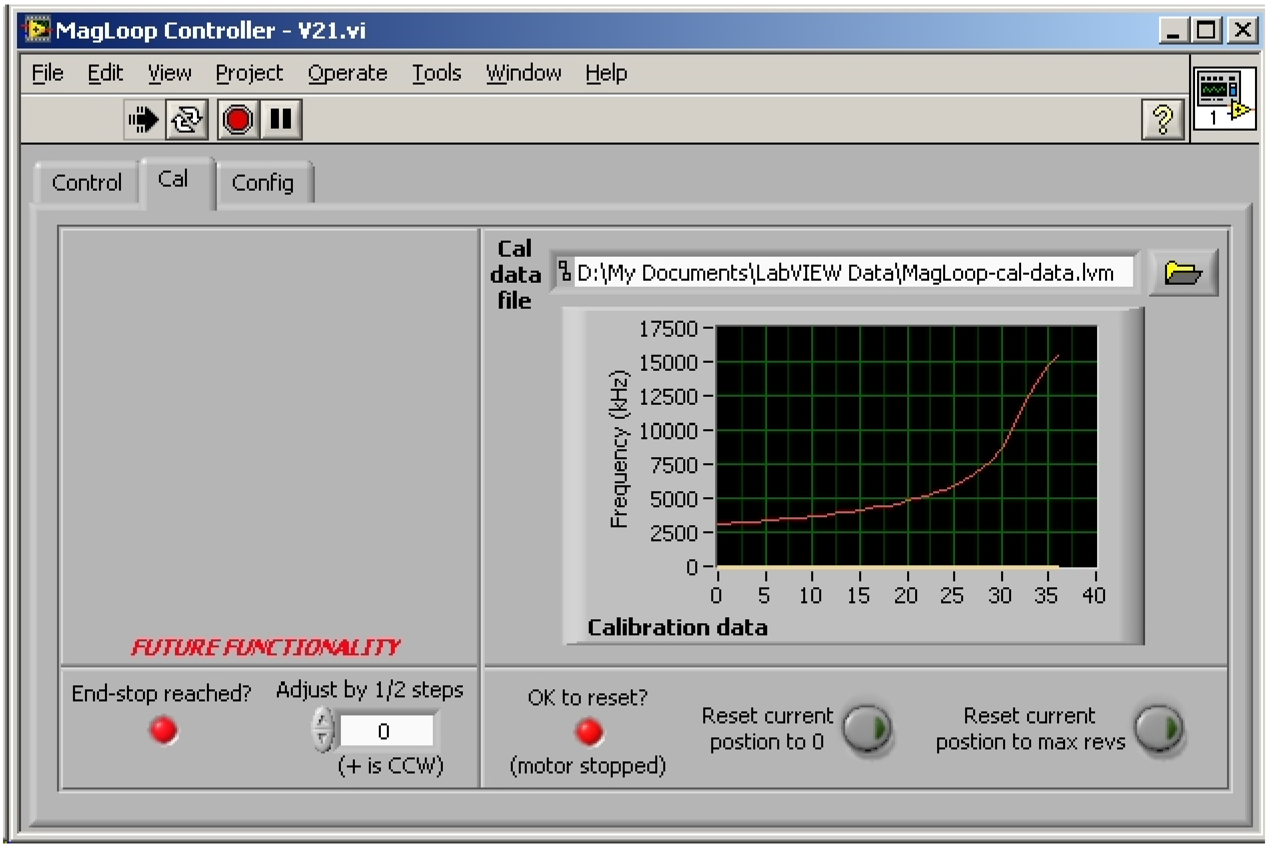

Figure 105: The "Cal" tab of the GUI of my varco motor-drive control software

The "**Cal**" tab provides the GUI for the following functionality:

- A plot of the calibration data. The file location has a default, but a browser button can be used to locate the file.
- Two push-buttons, for resetting the card's internal "current position" either to zero or to max position (the motor's ½-steps per rev, times the number of revs of the capacitor). This feature is used when the motor is positioned at the known reference position ("end stop"). The LED next to the button indicates whether it is OK to push the button (OK = when the motor is not moving).
- A block for future functionality.

IMPORTANT: I have made the entire design and software package of my controller application available below. It comes without guarantees. Please note that I do not have the time to provide support for its installation or operation. Sorry!

- The graphical design (detailed block diagram) of V21 of my controller is here (the image has enough resolution for fully zooming-in on the details).
- The actual LabView "virtual instrument" design file (.vi) of my controller is here.
- LabView "Pro" supports creating a LabView-independent .exe file. The zipped executable package of my controller is here.
  - This .exe application can run without the LabView development environment (i.e., you don't need the costly LabView suite), but is *does* require the LabView Run-Time Engine (RTE) Version 8.0. This is available for free - for all standard operating systems - from

the National Instruments website. It appears that using RTE version higher than 8.0 causes problems with my software.

  - Of course you must install the drivers that came with the Phidgets card (or download from phidgets.com). I used this executable drivers package.

- The zipped package of the three data files that I use (initialization, presets, calibration data) is here. Changes to these files must be made with an ASCII-editor such as Notepad or Wordpad - do not use a word-processor such as Microsoft Word!
- As noted further above, my control software can also be used with the Phidgets 106**3** controller for a single bipolar stepper motor. The 1063 is based on 1/16 steps, whereas the 1062 is based on 1/2 steps. When using my software with a 1063 card, the MagLoop-card-init.lvm file must be edited accordingly (again, only with a simple ASCII text editor, not MS Word or similar).
  - This means that I do **not** know if my software can work at all with Phidgets cards other than 1062 and 1063! You can try it at your own risk. Sorry: I can not provide support for your experiments.
- In 2016, Patrick Nobecourt (F5TJZ) adapted my design in LabView2015, to make it work with a Phidgets 106**7** card for his NEMA17 motor. He included current monitoring/protection and increased the velocity limit. Patrick actually uses two cards and two motors in the remote matching unit for his vertical antenna: one for a vacuum variable capacitor, the other for a variable inductor. His .vi design file is here, the two executable are here, and the associated initialization data files are here.

DC-MOTOR DRIVE

Before I get into all the details of the DC motor-drive that I developed for my vacuum capacitor, here is a simple-yet-effective way to motorize such a capacitor - ***if the shaft of the capacitor moves in & out of the capacitor as the shaft is turned***. Unfortunately, this is not the case with my capacitor.

If the shaft *does* move out when the shaft is unscrewed, then an inexpensive small DC-motor with down-gearing can be used. If mounted on a thin, flexible L-bracket, the motor (and the bracket) will be pushed away from the capacitor when the shaft unscrews. This can be used to actuate a micro-switch when the shaft is approaching its maximum position. With some simple circuitry, the motor will then only be allowed to reverse direction. The geared-down motor can produce a certain maximum torque. It should be small enough, such that it cannot damage the capacitor when the shaft is completely screwed in. The motor will simply stall at that point. This is easily detected with a simple motor-current monitor, consisting of an LED across a current-sensing resistor in series with the supply voltage. Ref. 11A.

Figure 106: Motor-drive with end-stop protection by Rich Fusinski (K8NDS)
(source: ref. 11A)

This concept can actually be expanded to a provide end-stop protection for a capacitor shaft that does *not* move in & out. The rotational movement of the motor-capacitor shaft has to be converted to linear motion. This can be done with a threaded rod (lead screw, feed screw) and a screw nut that is installed on the rod. It has to be prevented from turning with the shaft, and only be allowed to slide along the rod. The nut can then actuate a micro switch (or two such switches, to obtain end-stop protection at both ends of the motion range). An implementation of this by Dominique, F1FRV, is illustrated below (ref. 12F). The design includes a remote control unit and a 10-turn potentiometer (down-geared) for position feedback.

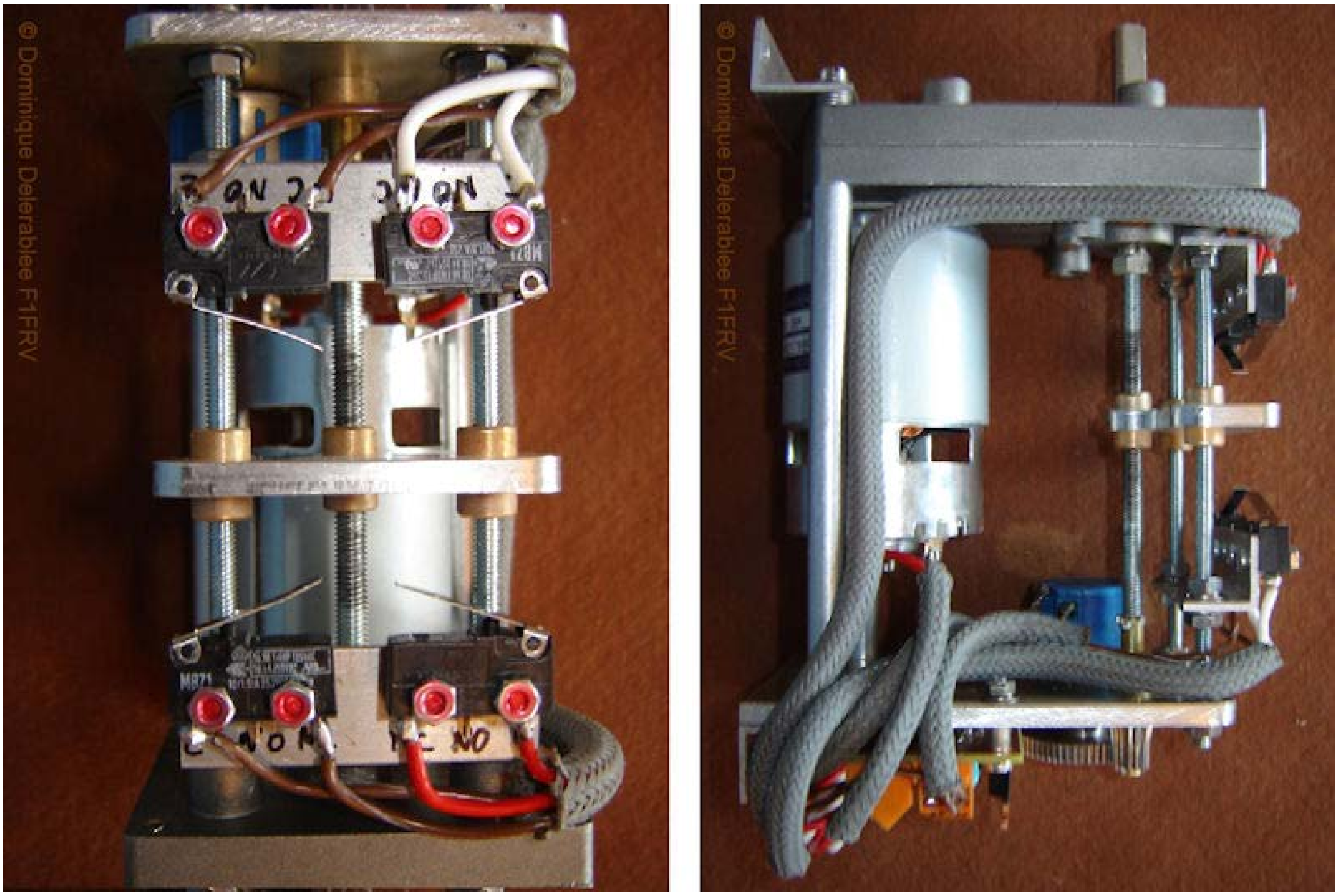

Figure 107: Top view & side view of a motor-drive by Dominique Delerablee (F1FRV)
(source: ref. 12F)

I liked Dominique's implementation: it is compact, and the shafts are inherently properly aligned. However, the important parts of his design are not readily available. So I decided to roll my own - not very compact, but basically all parts available via eBay:

MY DC-MOTOR DRIVE

At the heart of my drive system is a small 12 volt DC motor:

- The shaft of my vacuum capacitor makes 36 turns, end-to-end. I would like the motor to turn the required 36 revs in about 1 minute. I.e., a speed of about 36 rpm.
- I selected a motor with a gearbox that has 2 output shafts. This way, I can add a multi-turn potentiometer for position feedback in the shack. If you do not want this feedback, you can use a motor with a single output shaft. However, I recommend that you do add the feedback, or at least get a 2-shaft motor, so you can easily add the feedback when you finally find out that you really need or want it.
- I purchased the motor via eBay ("worldwide" search on "DC 12V 35RPM Double Shaft Worm Geared Motor GW31ZY"). It delivers a nominal torque of 147 N.cm (15 kg.cm). This is plenty! The output shafts have a diameter of 8 mm.
- I made the motor mount out of pieces of 8 mm thick poly kitchen cutting board, and threaded holes for the bottom mounting screws. When I completed the construction, I found that a matching metal mounting bracket was also available via eBay ("worldwide" search for "worm gear motor mounting bracket")...

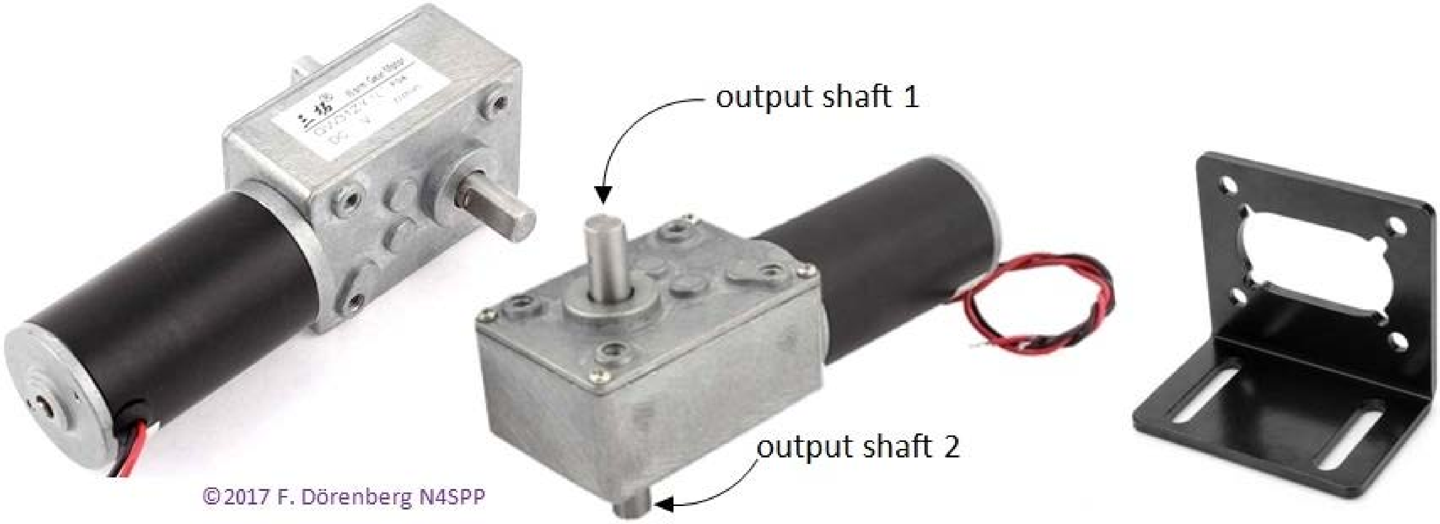

Figure 108: The 35 rpm / 12 VDC motor and a matching mounting bracket

The motor must turn the shaft of the capacitor, so we need a drive shaft system. Its purpose is threefold:

- Connect one motor shaft to the capacitor shaft.
- Convert the shaft rotation to linear motion, with actuation of an end-stop switch at both ends of the linear travel.
- Connect the other motor shaft to a multi-turn potentiometer for position feedback.

I selected a lead screw (feed screw, threaded rod, *D*: "Spindel, Leitspindel", *F*: "vis-mère") with a length of 200 mm (20 cm, 8 inch) and a pitch of 2 mm. I.e., the thread makes 200/2 = 100 turns. A nut can spin on the lead screw. For 36 revs, this nut will travel 36 revs x 2 mm/rev = 72 mm = 7.2 cm. The nut must be prevented from turning. It shall only translate along the lead screw. To do this, I used an 8 mm guide shaft. It is installed parallel to the lead screw. A slider block can move freely on the guide shaft. The lead screw nut is fixed in a groove of a piece of poly cutting board that is mounted onto the slider block.

I mounted the lead screw just above the guide shaft. The two pillow block bearings of the lead screw are raised with standard M6x30 mm standoffs (I also needed washers between the standoffs and the bearings, to raise the bearings another 3 mm). Sets of a lead screw with one or two guide shafts and mounting material are easily available via eBay (do "worldwide" search for "Lead Rod Linear Shaft Rail Support Slide Block Couplings").

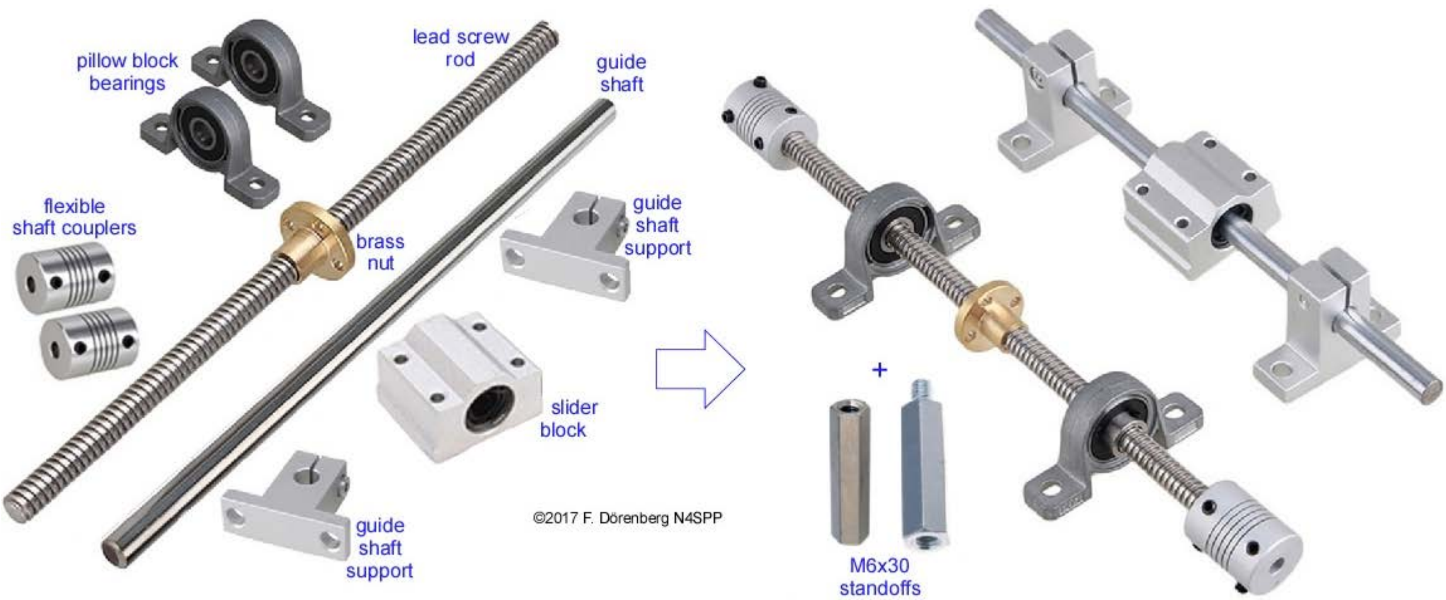

Fig. 109: The assembly for converting shaft rotation to linear motion - for actuating the end-

stop switches

One end of the lead screw is connected to one of the motor shafts. This is done with a flexible shaft coupler (8 mm to 8 mm). The other end of the lead screw must be connected to the capacitor shaft. This must be done via an insulating shaft, to avoid the capacitor voltage from ever reaching the drive system and remote control. I used a 10 cm (4 inch) section of acetal copolymer (polyoxymethylene-C, POM-C). This is acetal resin, a thermoplastic that was discovered in the 1920s by the German scientist Hermann Staudinger. POM trade names incl. delrin® (= acetal homopolymer = POM-H). This insulating material has high strength and stiffness, good dimensional stability, is abrasion resistant, easy to machine (lathe, mill, drill, laser cut,…), and is generally unaffected by solvents, fuels, other chemicals. Its mechanical properties are somewhere between metal and plastic. Two flexible shaft couplers are required: 8-to-8 mm between the lead screw and the insulating shaft, and an 8-to-12 mm coupler between the insulating shaft and the capacitor shaft (12 mm diameter).

The motor is probably strong enough to destroy the capacitor when continuing to drive when the end of the capacitor's shaft is reached. In the opposite direction, the capacitor shaft becomes unscrewed and can fall out of the capacitor. So, we need end-stop protection at both ends of the 36 rev travel! This is why we convert shaft rotation to linear motion, and use micro-switches to detect reaching the end of the travel. The micro-switches must be "single pole, double throw" (SPDT) types. I.e., with three contacts: common, "normally open" (NO), and "normally closed" (NC). The switches are not only used to interrupt power to the motor, but also to enable changing the motor direction away from the end-stop.

The capacitor shaft makes 36 revs, and a standard multi-turn potmeter makes 10 turns. So we need 4:1 down-gearing. I decided to do this with two gears (note: "gear wheel" is a misnomer) and a small timing belt (toothed belt, synchronous belt). The pulley on the second motor shaft has a width of 10 mm and 15 teeth. This is a flanged pulley, so the belt will stay on. The pulley on the potmeter shaft has a width of 10 mm and 60 teeth. The belt is an 8T2.5x150, i.e., 8 mm wide, with a "tooth" pitch of 2.5 mm, and length of 150 mm (= 60 teeth).

The capacitor and the entire drive system are mounted on a 10x60x1.1 cm plate of acetal copolymer (polyoxymethylene-C, POM-C), bought via eBay. All holes are countersunk on the back side of the plate, and used with countersunk ("undercut") M4, M5, and M6 screws. See the photos below.

IMPORTANT: even though flexible shaft coupler are used, alignment of the capacitor shaft, the leads screw rod, and motor shaft must be done very accurately! This means that the various holes in the POM plate must be located accurately: <u>much better</u> than 0.5 mm = 0.02 inch = 20 thou. So, you must use a caliper when marking the drill holes, and use a drill stand to drill straight and at the marked location!

IMPORTANT: as stated, the capacitor shaft shall not be driven all the way to its physical limits. To avoid destroying the capacitor, the end-stops are carefully adjusted such that only 35 of the 36 capacitor shaft revs are used, with 1/2 rev margin at each end. I mounted the micro-switches on a small piece of poly kitchen cutting board. It has a slot in it, so its position can be adjusted parallel to the lead screw and guide shaft over a distance of about 1 cm (see Fig. 112 and 116 below). Make sure that the micro-switches are wired correctly: before fixing the flexible shaft coupler to the capacitor shaft, drive the motor so as to center the lead screw nut about half way between the mirco-switches. Then drive in one direction and manually actuate the associated micros-switch. Then repeat in the other direction. As stated before, the lead screw nut will move over 70 mm for 35 revs. So the micro-switches must have a nominal spacing of 70 mm, plus the length of the slider block on the guide shaft. Adjust the position of the second micro-switch, such that it switches after moving <u>exactly</u> 35 revs away from the opposite switch. Then drive until the micro-switch corresponding to the capacitor's hard mechanical limit is actuated (CW rotation for my capacitor). Then <u>manually</u> rotate the capacitor shaft to that stop, and back off 1/2 rev. At this point, the capacitor "bottle" is fixed in place. I used two long cable ties that go through the mounting plate. Note that the plate has a hole for the nub of the capacitor bottle. See the far left side in Figure 113. Now the shaft coupler on the capacitor shaft is fixed. Likewise, the 10-turn potentiometer has physical limits. The 4:1 down gearing of the second motor shaft results in 35 / 4 = 8.75 revs of the potmeter shaft. This leaves a margin of (10 - 8.75) / 2 ≈ 0.6 revs on each side of the travel of the potmeter shaft. Once the micro-switches are adjusted, the system is driven until one of the micro-switches is engaged. Make sure (!!!) you know the turn direction of the second motor shaft during this system movement. If you get the direction wrong, you will immediately destroy the potmeter! Turn the potmeter shaft all the way to limit that corresponds to the actuated micro-switch. Then back off 1/2 rev and do not rotate that shaft any more, until the timing belt is installed.

Figure 110: Top view of the DC motor drive assembly with vacuum capacitor

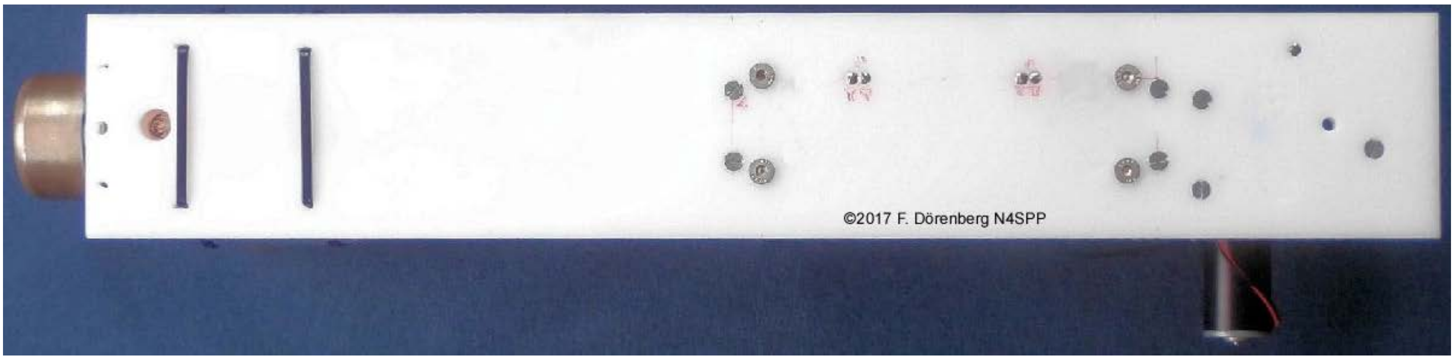

Figure 111: Bottom view of the DC motor drive assembly

Figure 112: Right hand view of the DC motor drive assembly

Figure 113: Left hand view of the DC motor drive assembly

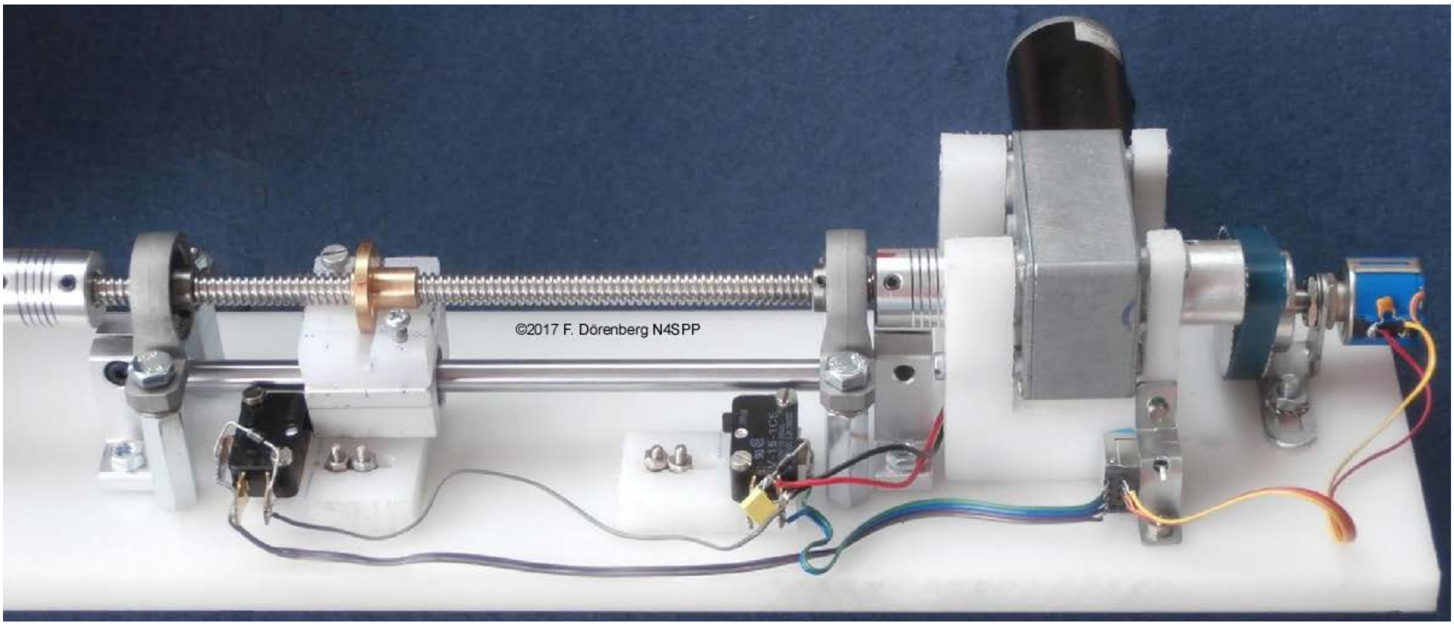

Figure 114: Close-up view of the drive shaft, end-stop slide, motor, and position feedback potmeter

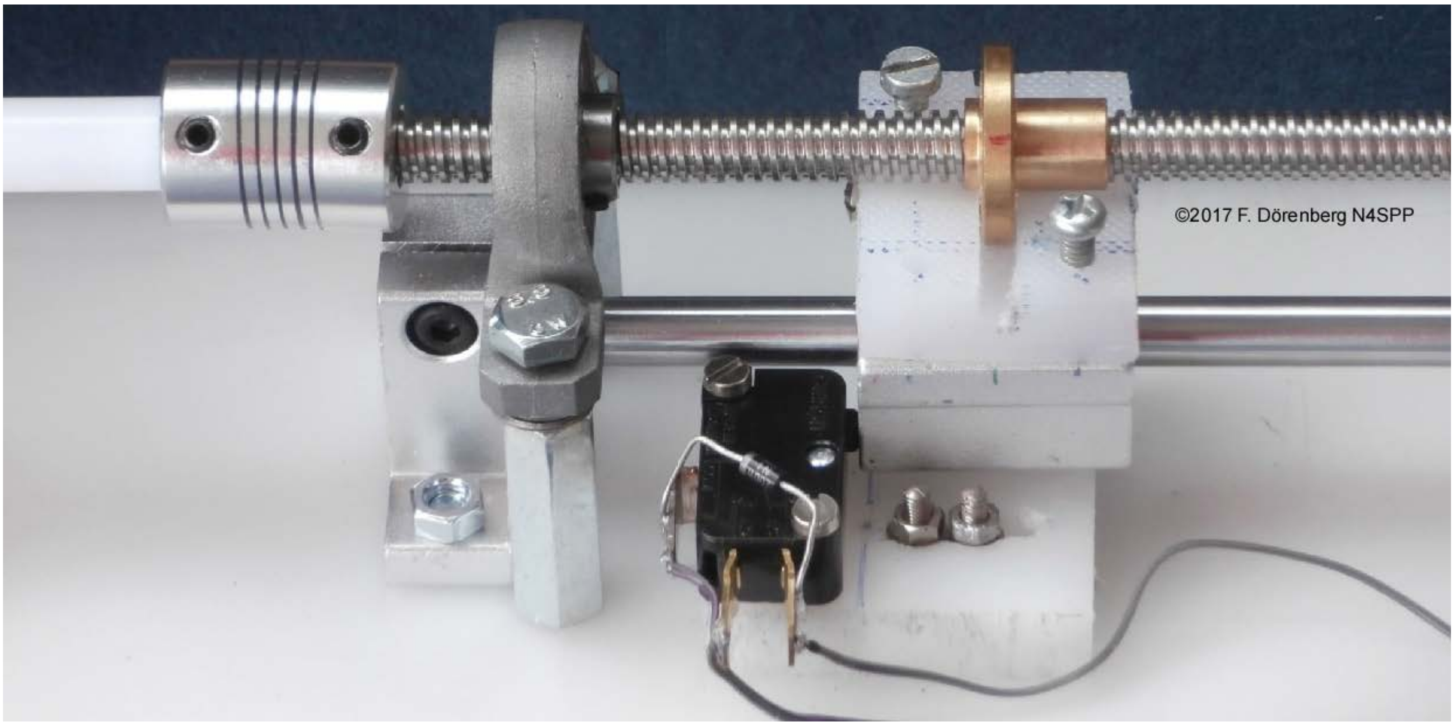

Figure 115: Close-up view of one end-stop with micro-switch, actuated by the sliding block

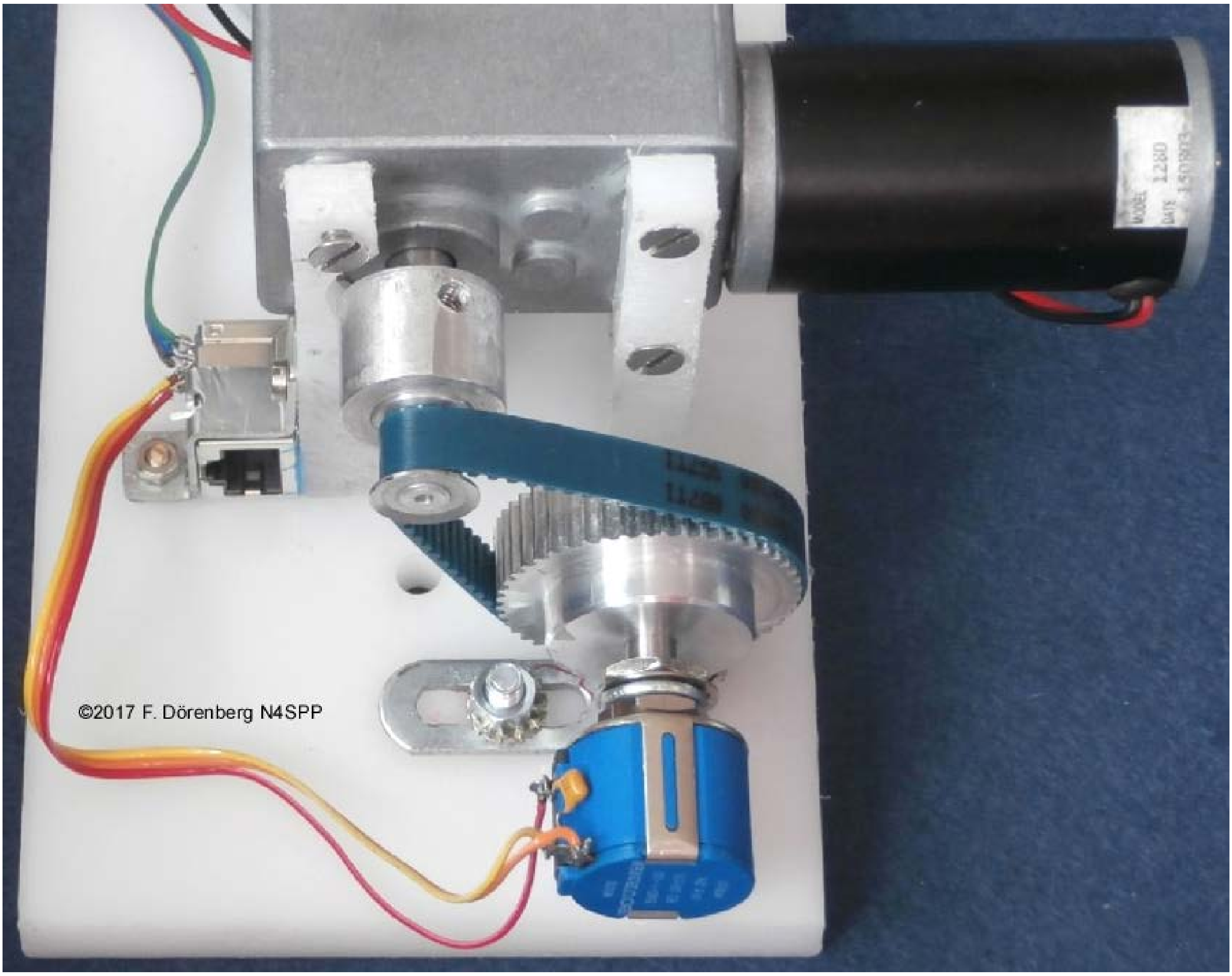

Fig. 116: RJ45 connector and second output shaft of the motor's gear box with 4:1 belt drive to the 10-turn potmeter

The complete drive (capacitor + plate + motor drive) weighs a hefty 4.2 kg (9.3 lbs), about twice the weight of the capacitor by itself. The drive is mounted at the top of the PVC mast (63 mm diam.) with two M6 bolts. Clearly, this configuration makes the antenna quite top-heavy. My antenna is not installed permanently on my terrace. On a windy day, I attach guy wires to the upper half of the mast, in three or four directions.

Figure 117: Motor drive installed on the PVC-tube antenna mast

For weatherproofing, I made a hood by combining two inexpensive plastic storage boxes that measure 35x20x15 cm (LxWxH, ≈13.8x8x6 inch). I cut one end of both boxes and of both lids. I combined the two boxes with industrial 1-sided sticky "duckt" tape (sometimes referred to as "duck" tape; I actually used Gorilla® tape), both on the outside and on the inside of the seam, and combined the two lids with industrial 2-sided sticky tape. **NOTE**: these clear plastic storage boxes are made for *indoor* use, so they have no UV protection. Outdoors, they will become brittle and opaque fairly quickly, depending on how sunny your QTH is!

Figure 118: Protective hood made of two clear plastic boxes and their lids

The merged lids are installed between the plate of the motor drive and the PVC mast. I drilled two 20 mm holes in the hood at the appropriate place for the ends of the 12 mm diameter copper tubing of the main loop. With a thin blade saw, I then very carefully cut a slit between each hole and the open side of the hood. This makes it easy to install and remove the hood. An other hole was made for the cable between the motor drive and the remote control box. I closed the ventilation holes at the top, but left the ones at the bottom open.

Figure 119: Weather protection installed

We need a remote control box, with the following controls, indicators, and interfaces:

- Power on/off switch.
- Selection of motor rotation direction: clockwise (CW), off, counterclockwise (CCW). This will correspond to "increase frequency" and "reduce frequency" (or vise versa).
- Indication of the drive shaft position (some representation of 0-36 revs).
- Indication of "end-stop reached", separately for the CW and the CCW direction.
- Motor stall current warning (not mandatory, but nice to have and easy to implement).
- Standard 12-13.8 VDC input (13.8 is the normal supply voltage for transceivers and for charging 12 volt batteries).
- Multi-wire cable to the motor drive: 2 wires to the motor, 2 wires for the "NO" contact of the CW and CCW end-stop switches, 3 wires for the position feedback potentiometer. So, at least 7 wires. I decided to use a standard Ethernet cable (8 wires).

I originally intended to install one or more ferrite rings on these cable, as common mode chokes. However, with 100 watt transmit power, I did not notice any interference in any equipment in the house. So I did not install such rings. Not good! As you can see in Fig. 126 and 128 below, the 12 VDC powerplug on my remote control box is a little too long. The common/ground barrel is exposed. It became "RF hot", which is a rather unpleasant experience! I have added a ferrite choke on the power cord between the control box and the power supply (near the power supply). I placed another one on the control cable to the motor drive (at the control box end). This took care of my problem. I did not give the placement of the the ferrites much thought. Note, however, that a ferrite choke is most effective at the point along the cable where the common mode current wave is at its maximum, per the standing wave pattern. Depending on the length of the cable, there may be severeal such points - and they move with the operating frequency (frequency band).

Fig. 124 below shows the simple schematic for a remote control box. It includes high/low speed selection, by switching in a series-resistance of a couple of ohms. The shaft position feedback indication is done with the 10-turn potmeter. I use a separately regulated; supply voltage of 9 VDC for the potmeter, to make the feedback voltage independent of voltage drops in the motor drive circuitry (e.g., across the current-sensing resistor of the motor stall detection). The voltage of the potmeter wiper is measured with a simple and cheap 4-digit digital voltmeter (via eBay; search for "0.36" 4-Digit Digital Voltmeter Range 0-33V").

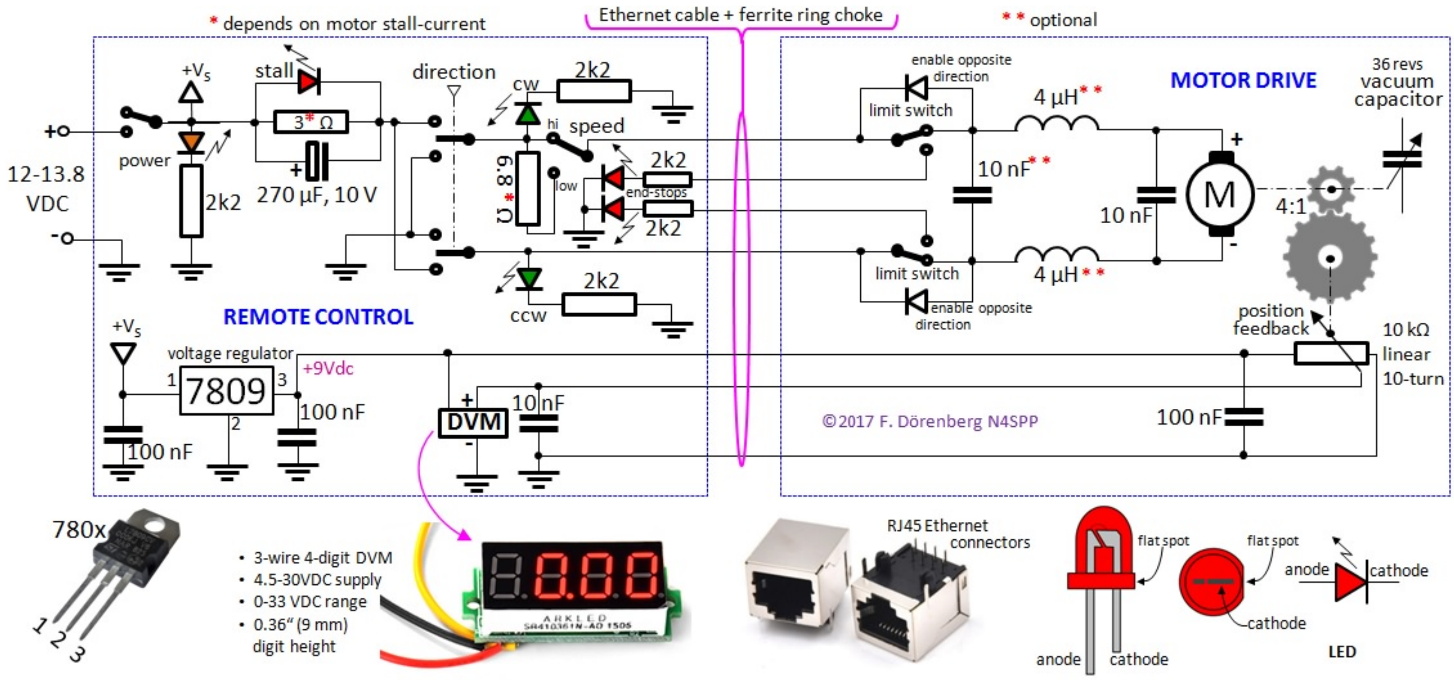

Figure 120: Remote control schematic - with simple high/low speed selection

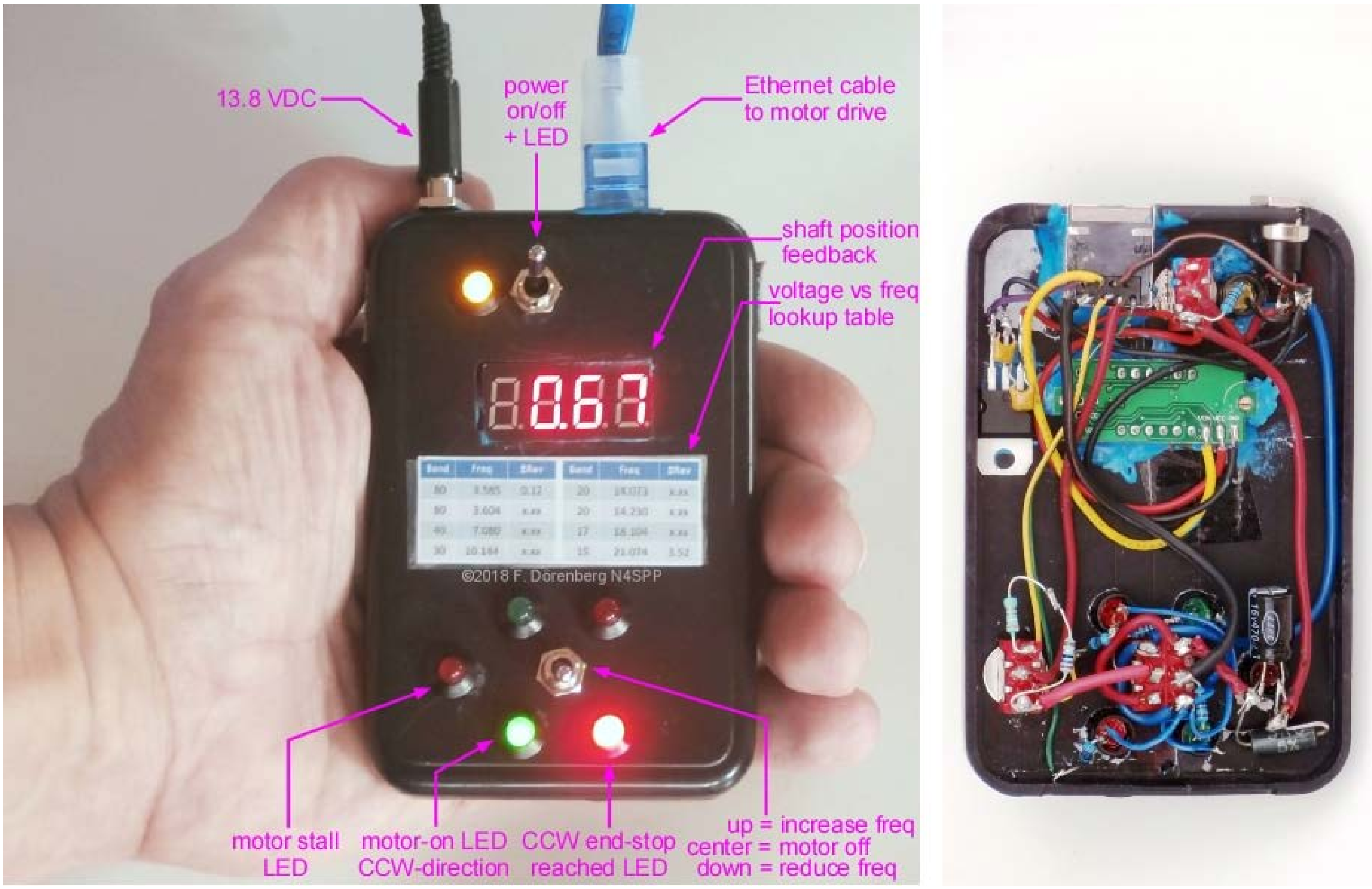

Figure 121: The prototype remote control box, and the "ugly style" wiring
(the project box measures 7x10.5x2 cm; high-low speed switch and the associated resistor is not shown in the left-hand photo)

Reducing speed with a series resistor (= voltage drop) also reduces motor torque. For fine-tuning the antenna, this is very undesirable! So, I decided to modify my remote control, and re-use the simple

Pulse Width Modulator (PWM) controller of [my small STL project](). My PWM is a 6-24 VDC, 3A type (inexpensive purchase via eBay; search for "DC motor speed control PWM"). It measures only 3x5 cm (≈1.2x2 inch):

Figure 122: The small PWM speed controller card

The PWM circuit must be placed before the "direction" toggle switch. This means that the brightness of the green motor direction LEDs and the red end-stop LEDs now depends on the duty cycle of the PWM (= speed setting)... To me, that is a small price to pay for being able to smoothly (and continuously) vary the motor speed between zero and max - with full torque! **It just works beautifully!**

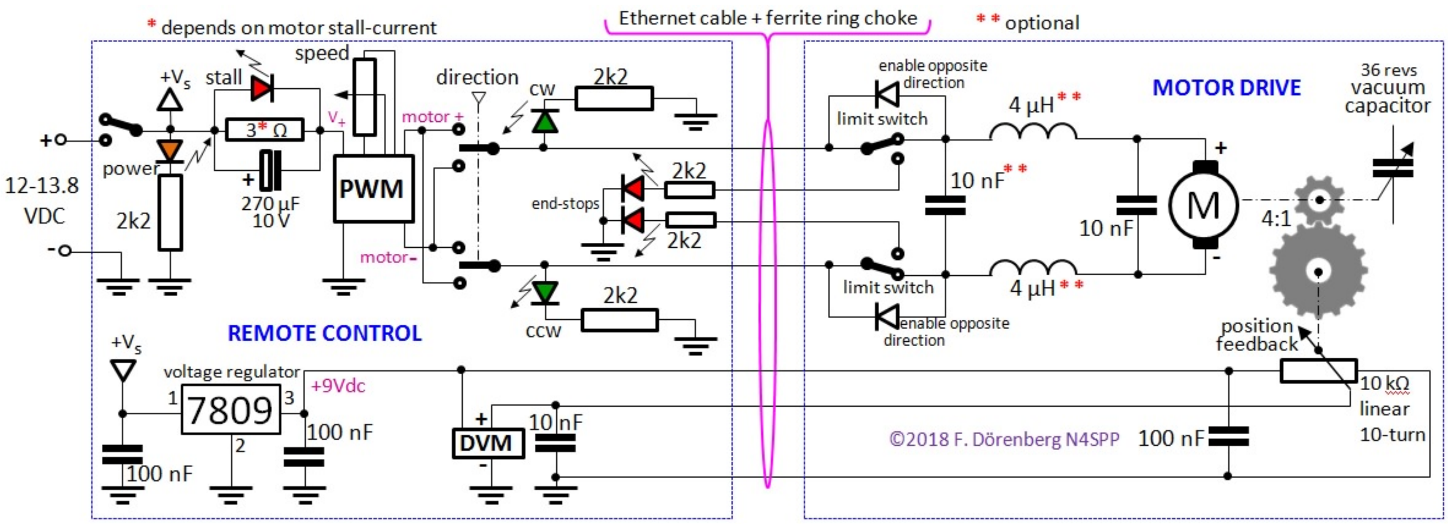

Figure 123: Remote control schematic - with PWM variable speed adjustment

Figure 124: The prototype remote control box - now with variable speed adjustment
(red contrast filter added to the 4-digit DVM display)

MOTOR DRIVE FOR THE COUPLING LOOP

One of the standard coupling methods is the Coupling Loop, see the "Inductive coupling" section above. This is basically an air-core transformer. Normally, the configuration is as follows:

- The size of the coupling loop is fixed. Standard recipe is 1/5 the size of the main loop, but I normally use a slightly larger coupling loop.
- The position of the coupling loop is fixed, after adjusting it once for lowest SWR on the frequency (or frequency range) of interest. Sometimes the shape of the coupling loop is also adjusted.

This way, SWR can be good (= SWR < 1.2) over a frequency range of about 1:3. Beyond that, the SWR quickly becomes worse than 1.5. Also, if you change the installation height of the antenna, the SWR will change. In 2018, I acquired a 6 m (20$^+$ ft) telescopic mast. I decided that I needed a remote control for adjusting the coupling between the coupling loop and the main loop. One of the ways to do this, is to rotate the coupling loop about its vertical axis, such that it no longer lies in the same plane as the main loop:

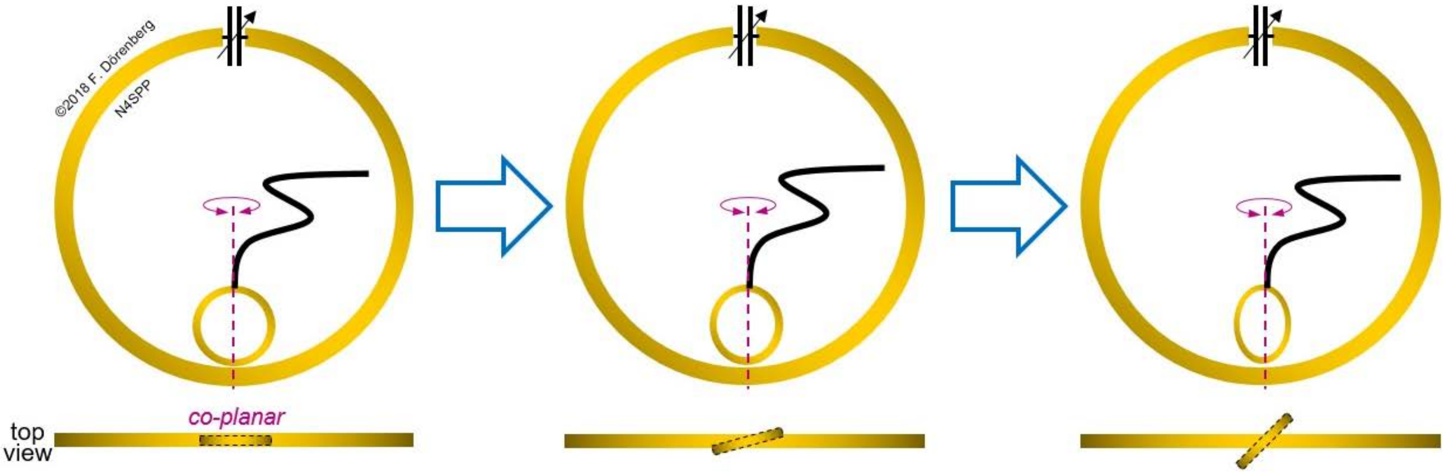

Fig. 125: turning the coupling loop about its vertical axis to change the coupling with the main loop

The rotation has to be motorized. If the orientation of the two loops is close to perpendicular (90°), then the coupling factor is basically zero. I decided to use a maximum swing of 45°. My coupling loop is already mounted onto the PVC mast with two standard PVC tube clamps. By loosening the clamps a little bit, they can rotate around the mast without too much resistance. I use the same approach during manual adjustment. I decided to motorize the clamp that is farthest from the main loop. Somehow, this clamp must be rotated around the mast with a small electric motor. I do not need position feedback for this motor, and I don't want to add end-stops. The motor control should simply be on/off. The standard way to convert 360° motor shaft rotation to a limited rotation angle (>0° - <180°) of the load is to use a double-eccentric (= "off center") drive. This is also known as "crank-and-rocker" and "4 bar linkage":

Motion of a double-eccentric / crank-and-rocker / 4-bar-linkage arrangement
source: YouTube

In the video clip above, it looks like the linkage only has 3 bars. However, it is generically called a 4-bar linkage. The fourth bar is the "vertical" offset between the axis of rotation of the motor and of the load. I.e., if the motor is moved up or down along the gray vertical line in the image.

A crank-and-rocker mechanism has several parameters that must be chosen to obtain the desired angular swing range:

- The length of the crank on the motor shaft (= distance between shaft axis and swivel point at the end of the motor crank).
- The length of the crank on the load (= distance between axis of rotation of the load, and swivel point at the end of this crank).
- The length of the push-pull bar between the two cranks (= distance between the two swivel points).
- The distance between the two axes of rotation.

For installation on the antenna mast, these parameter must be chosen such that the crancks, and the bar between them, do not touch the mast. Otherwise, the drive mechanism will self-destruct. This can all be calculated with trigonometry. Have fun with it! Or, you can model it with a CAD tool - which I don't have. I simply took a large sheet of paper, drew the cross section of the PVC mast tube on it (scale 1:1), added the rotation radius of the coupling loop, and assumed a simple mount for the small 12 Vdc / 3 rpm motor that I happended to have. I placed the motor 135° away (= behind the mast) with respect to the plane of the main loop. Then I started to play with crank lengths and the push-pull bar length:

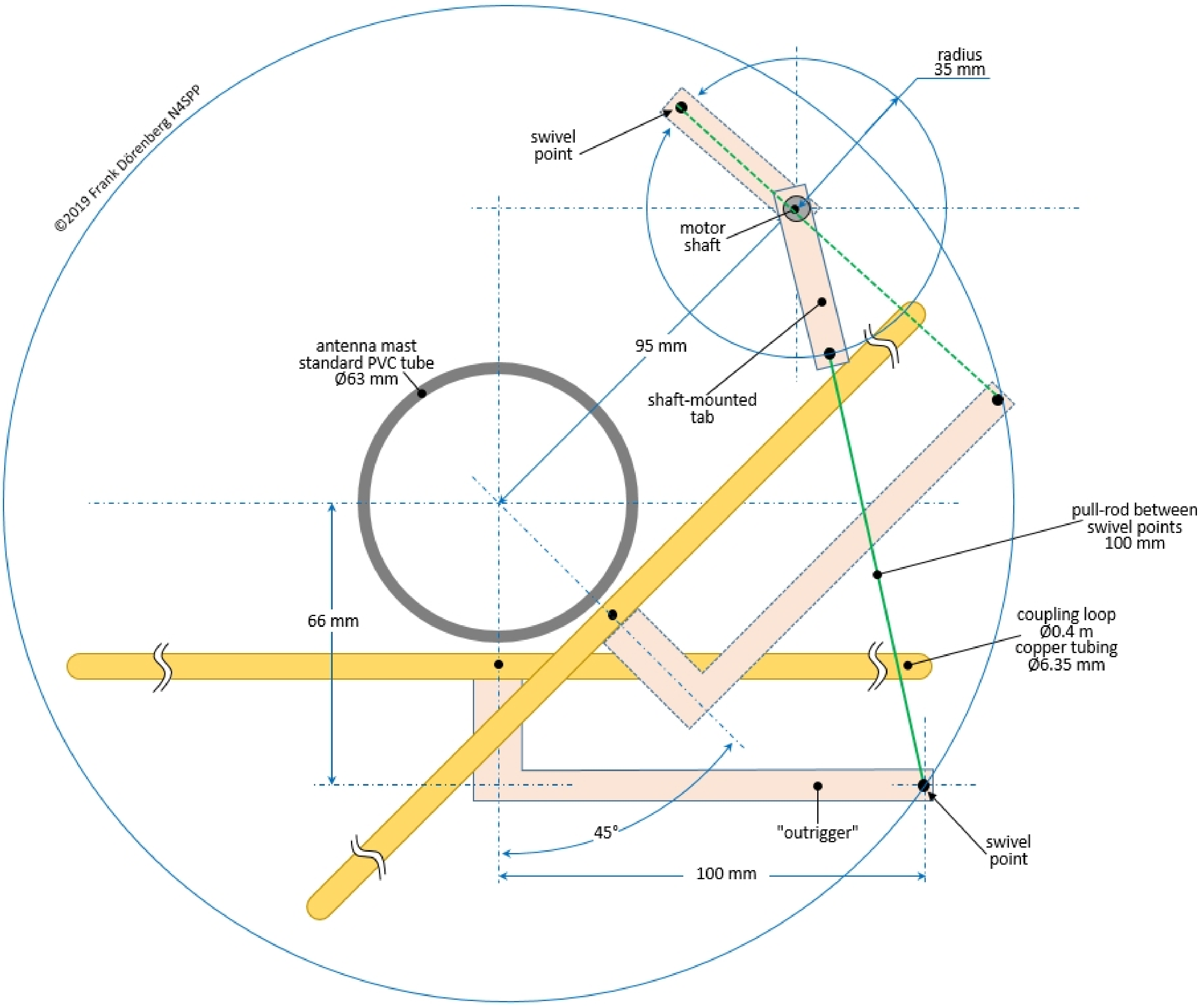

Figure 126: design drawing of my double-eccentric drive

The drawing above shows the dimensions that I finally selected. The motor mount, the two "arms", and the push-pull bar are all made of 11 mm thick polyethylene (= kitchen cutting board). This material is light, strong, and easy to machine (drill, saw, grind,...). I fixed the motor mount to the PVC tube mast with a standard "munson" type tube/pipe clamp and a heavy angle bracket. The swivels are made of 6 mm bolts, with washers and lock nuts (= nut with a nylon insert).

Figure 127: side view of the double-eccentric drive for the coupling loop

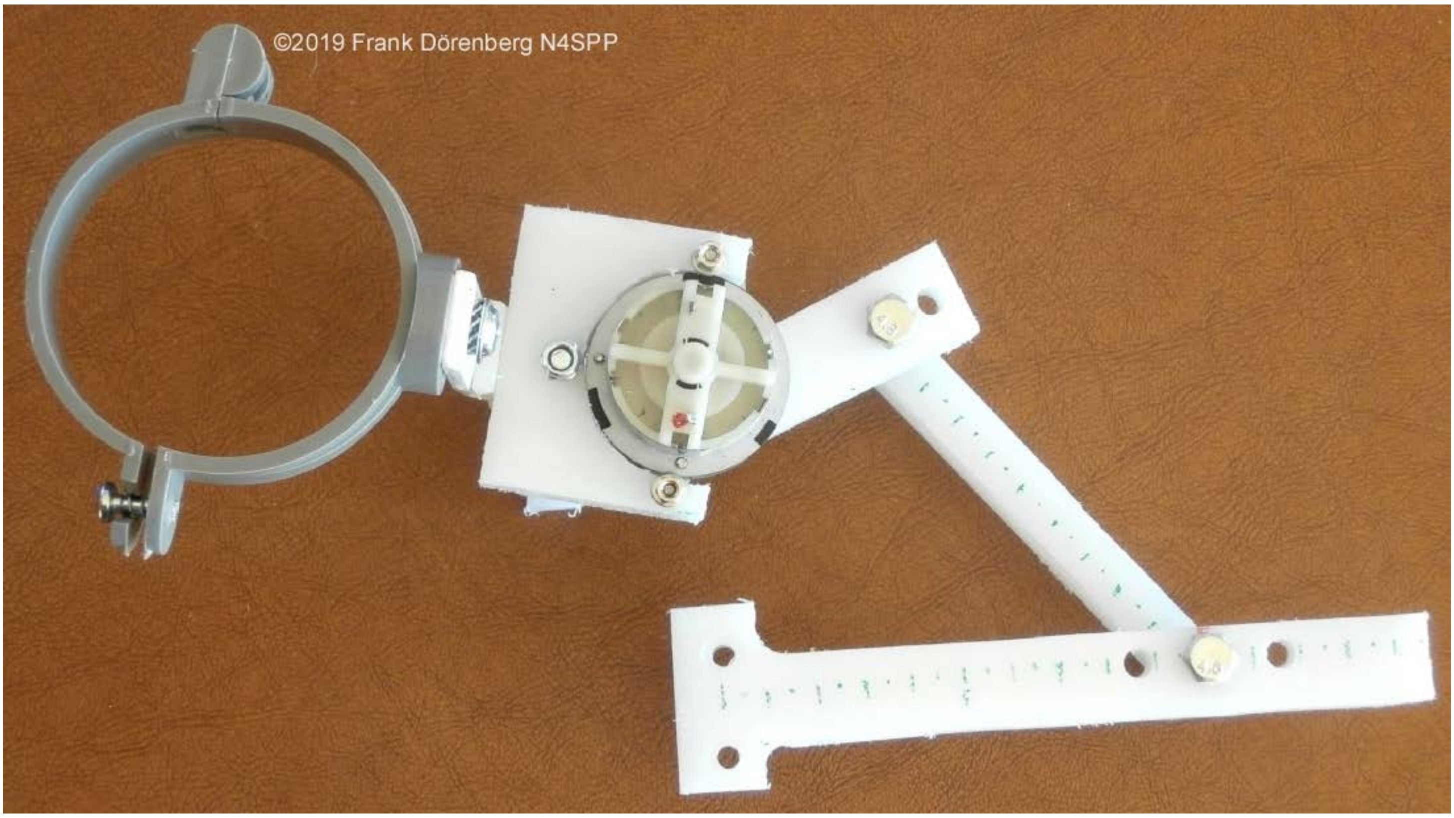

Figure 128: top view of the double-eccentric drive for the coupling loop

Note that the crank bars on the motor shaft and on the coupling loop have some extra length and holes. This was done, just in case I needed to make some adjustments to the swing range. Actually, my original design was very close to "perfect".

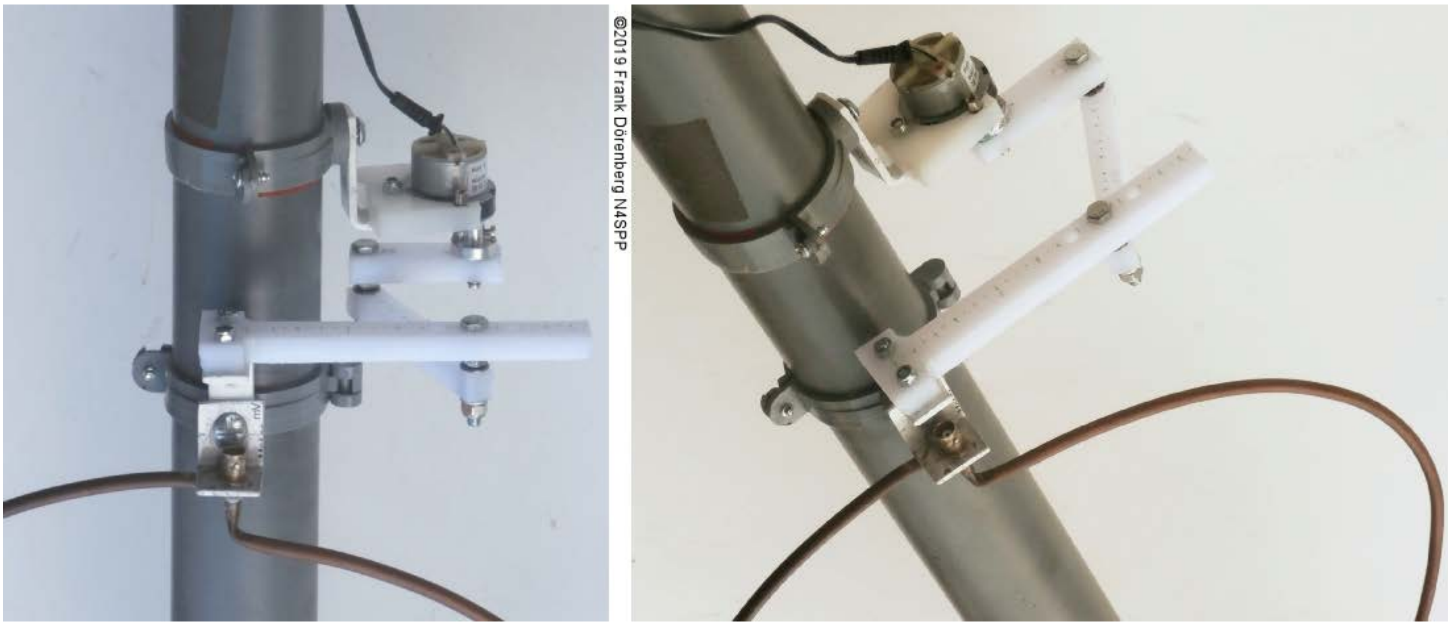

Figure 129: the double-eccentric drive for the coupling loop - installed

Full motion cycle of the motorized coupling loop (max speed)
©2019 Frank Dörenberg (N4SPP)

I am using the same remote control method as for [motorizing the tuning capacitor](), see Fig. 124. I use a standard 8-conductor ethernet cable between motor drive(s) on the antenna and the remote control box in the shack. With only the capacitor tuning motor (and position feedback), only 7 conductors of the cable are used. I use the 8th conductor to actuate a small relay at the antenna. It switches the power between the two motors. Other options are to run a separate cable with a separate control box. Or: run a separate cable and switch the control box between the two cables at the shack end. I clearly prefer my solution with the relay. I did not have a small 12 volt **D**PDT relay in my junk box, so I used two very small 5 volt **S**PDT relays (type DR-5V) that I happened to have, and connected their solenoids in series:

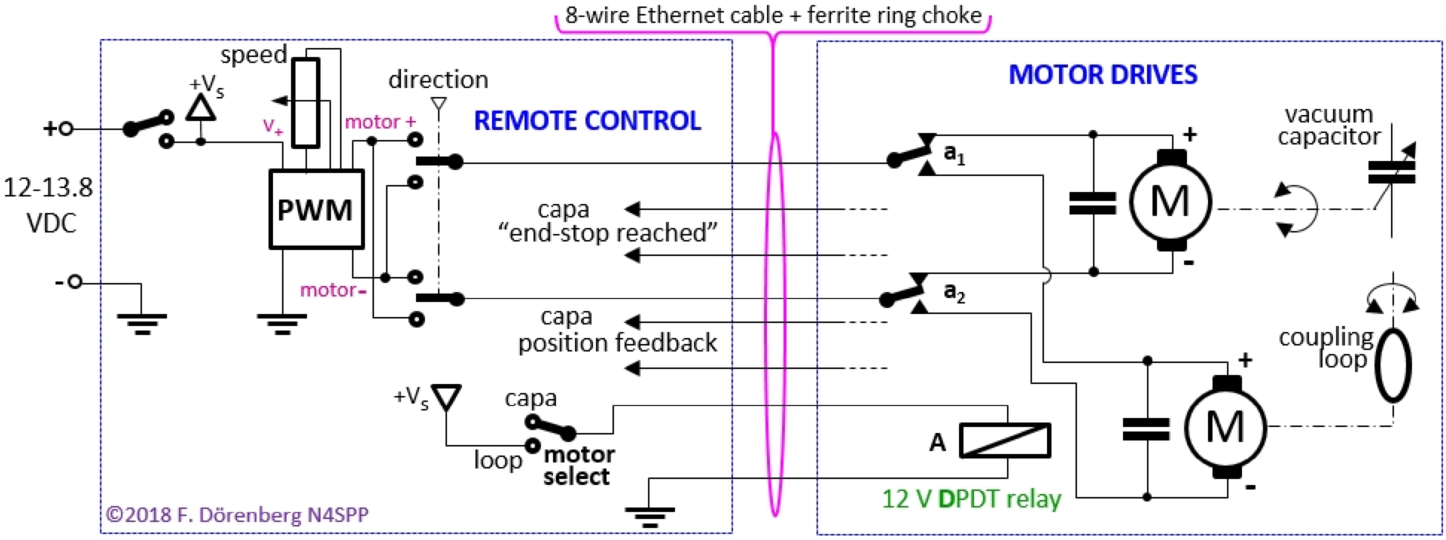

Fig. 130: Simplified remote control schematic - with toggle switch for motor-selection and one DPDT relay

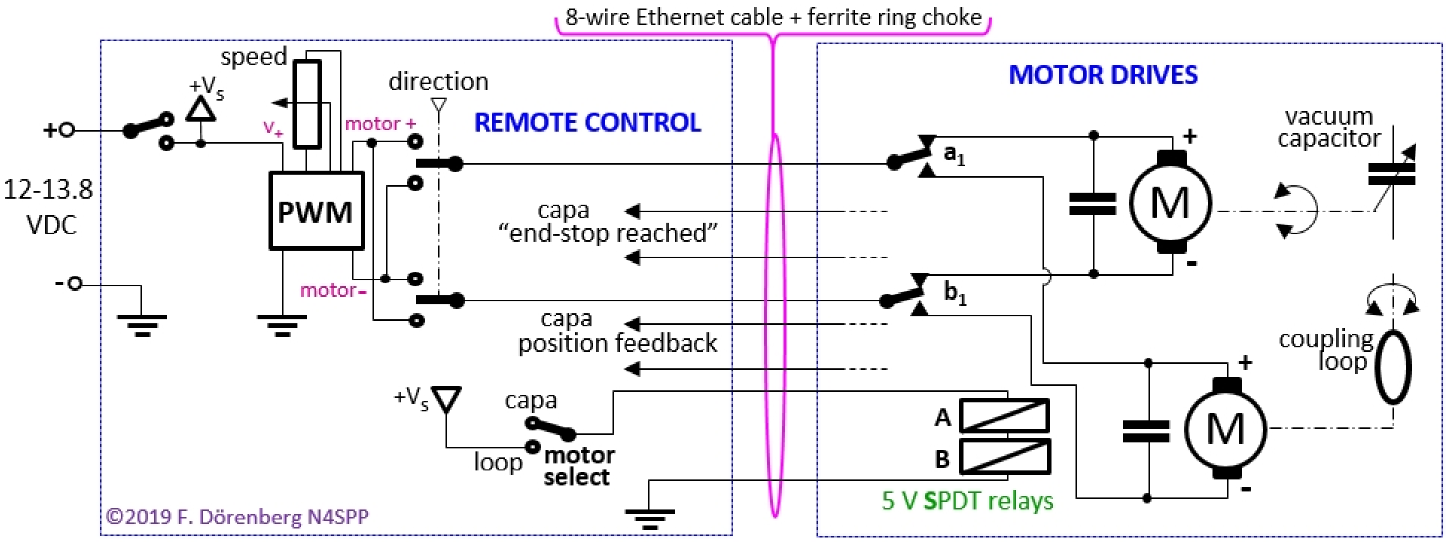

Figure 131: The remote control box - with toggle switch for motor-selection and two SPDT relays

Figure 132: The remote control box - now with a toggle switch for motor selection

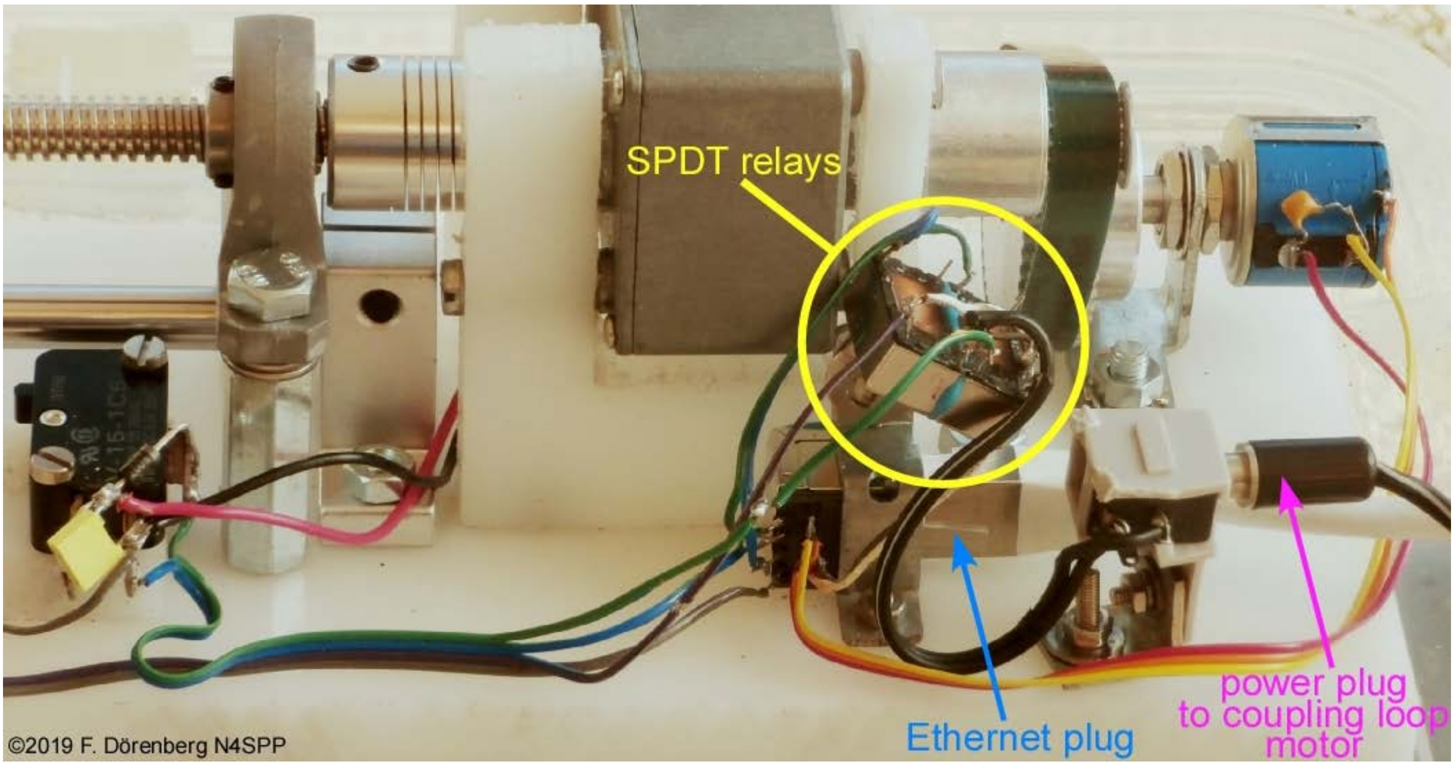

Fig. 133: The SPDT relays (glued together with blue Loctite) near the Ethernet cable connector at the antenna

(compare to Fig. 118)

I completed this motor drive mid-January 2019. Now I have to run some tests, and see if I can increase the frequency range and/or installation height for which I can get good SWR (better than 1.3).

Just like the motorization of the tuning capacitor can be automated, so can the coupling loop drive. Work on this has been done by the (primarily) Japanese "MLA 48" group, in particular Hajime Nakajima (JR1OAO). His automatic antenna coupler measures the RF voltage and current at a point along the coax to the antenna. The position of the coupling loop position is adjusted based on the ratio of these two parameters (effectively an impedance value), to minimize the SWR. The measured phase angle between the current and voltage is used to adjust the motorized tuning capacitor until the resonance frequency matches the operating frequency. Note: the phase angle to be adjusted/calibrated is measured at the antenna feedpoint (or a point along the transmission-line that is at an electrical distance of a whole multiple of 1/2 λ away from the feedpoint).

REFERENCES

- **Ref. 1:** "Magnetic Loop Antenna" with video clips about radiation direction and voltage/current distribution of STLs, Ben Edginton (G0CWT)
- **Ref. 2:** Loop calculators and formulas:
  - **Ref. 2A:** KI6GD calculator
  - **Ref. 2B:** AA5TB calculator (Microsoft Excel file - if you don't have MS Excel on your PC, you can download a freeware viewer from Microsoft here)
  - **Ref. 2C:** "66pacific" on-line loop calculator (based on ARRL Antenna Handbook)
  - **Ref. 2D:** RJELOOP1 calculator for performance of single-turn magloop antennas of various regular shapes and MAGLOOP4 calculator for performance versus height and type of ground, by Reg Edwards (G4FGQ, SK)
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