Small Transmitting Loop Project

Compact and Efficient Antennas for HF Radio

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Introduction

Of the many different antenna projects I have built for HF, the most interesting and rewarding project was the small transmitting loop. After consulting many of the available Internet sources, and by combining ideas, I was able to assemble an antenna that performed well, even under poor band conditions. The experience was so much fun that I built several different ones, all described below.

Thinking About Loops

Having previously spent many years as an apartment-dweller, I have a keen sense of how difficult it is to do effective HF communications from restricted spaces. Even though I now have a small yard in which to experiment with antennas, the idea of a high-performance, small HF antenna still holds my interest.

There are a number of amateurs who have suggested that small loop efficiency and effectiveness can actually be far better than conventional wisdom might suggest. Some have even challenged traditional round loop designs altogether, using different shapes and materials to squeeze more performance out of their antennas. Despite the challenges associated with confronting long-held traditions in design, these amateurs continue to perform some impressive experiments with their creations.

For me, the process of building loops started small, mainly as an experiment driven by idle curiosity. Over the past few years, however, I have slowly developed my loop antennas into fully automated, remotely controlled, high power (500W) antennas for the 80m through 6m bands, becoming a major part of my radio hobby. In fact, my experience with low-band (40m and 80m) loops has convinced me to use this type of antenna as a main contesting antenna, even when other larger antennas are available.

Even for those of us who live on property without antenna restrictions, the ever-shrinking lot size for new development is combining with all manner of consumer electronic devices to make our HF bands noisier than ever. Because of these and other factors, the need for smaller and quieter HF antennas is growing. One of our challenges in the future is to design and build small antennas that still have good performance characteristics, both for DX and domestic contacts.

On that note, the project has inspired a couple of related receive-only antenna projects. These share many traits with the small transmitting loops, but they also have some important differences for those seeking to optimize receiver performance. A dedicated installation of independent transmitting and receiving loops could be the ultimate small-lot, high-performance HF antenna system, especially for the longer wavelengths.

What follows is a walk-through of my experiences building transmitting loops. I'm not going to include the spreadsheets, calculations, theoretical formulae, etc. I will include links to the more interesting ones at the bottom of the article. What I want to capture here are the more practical experiences, and some of the "Ah ha!" moments of the project.

This document continues to grow, so it's time to add a **Table of Contents**, to help organize it:

Step 1 — Just the Essentials

Starting out, I wanted to avoid investing any significant amount of money in an experimental antenna until I was convinced that the principles were sound, and that I could make them work for me. People who use small loops often make impressive claims about their performance, but then again, even a light bulb can work the occasional DX station, right? I wanted to prove the concept before committing a lot of resources to the project.

Finding a quality tuning capacitor is the most difficult step in procuring materials, so I started with that. I had quite a bit of success using open-wire feed line for feeding and matching a dipole for QRO operation, and I knew that the voltage handling capacity of such line is quite high. This line is also rather inexpensive, with a 100' roll of 300-ohm window line at around $20.

I decided on a basic and minimal small loop, 3' in diameter, using a stub made from quality window line as the tuning capacitor. Such an antenna would, in theory, readily resonate in the 20m band. This design would also allow me to simply discard the antenna if it didn't work well, without losing a lot of money.

This first loop was tuned for a single frequency, 14,070kHz. I thought digital modes would be a good way to test the antenna, especially since so much digital activity is clustered tightly around a single PSK-31 frequency on each band. That would allow me to find the highest number of stations in close proximity to each other.

In keeping with my cost-saving approach to my experimental antenna, the first mast was made from PVC plumbing pipe. It is non-conductive, and the large-bore PVC pipe is very rigid at short lengths. I keep a surveyor's tripod handy for doing antenna experiments, so between that and the PVC, I had the materials to build the support. The tripod will accept a schedule 40 PVC pipe of nominal 1-1/4" size, so that was the type chosen for the mast. 5' lengths are commonly available, and threaded connectors were used to to join the loop's 5' section with a second 5' section that would slide into the tripod. This allowed a 10' overall height, that could be easily assembled and disassembled.

Some things I learned about using PVC as a mast:

- Conveniently, 1" PVC pipe fits very nicely within 1-1/4" PVC pipe. If you cement the two together, one inside the other, the strength and rigidity of the mast increases substantially. Most of the loops shown here use this arrangement in at least some part of the support structure.
- When using the threaded connectors, it is very wise to apply a small amount (or not-so-small amount) of dielectric (silicone) grease to the threads before trying to mate them. Remember, this is plumbing pipe, and the various connectors are not meant to be disassembled repeatedly. They are meant to glue together and stay glued <u>for decades</u>. The threaded connectors I used had a slight taper, which means they were also meant to thread together tightly, and stay that way. Without some kind of lubricant to prevent this, I would eventually need some large wrenches to twist them back apart.
- Using a high-quality cement to join the pipe to the connectors is a must. Few things will ruin your day faster than watching your beautiful antenna creation come crashing to the ground because a joint worked loose. Cement is cheap. Rebuilding an antenna is not.
- The tripod is a great way to support the antenna, but loop antennas can get very top-heavy. The tripod will easily support the bottom mast by itself. Before threading the loop itself onto the bottom mast section, I made sure to guy the bottom mast section just above the tripod. This is absolutely mandatory. More than once, I had to catch a falling loop because the wind had caught it just right, and caused it to tip over. The tripod wasn't enough to resist the leaning tendencies of the loops under wind load, even though the entire thing was only 10' above ground.
- The green guy lines in the pictures are relatively thick nylon rope. Nylon is not typically UV-resistant, so using it as a long-term guy line for a permanent installation is probably not a good idea. There <u>are</u> inexpensive ropes available that are meant to be used as guy lines for permanent antenna installations, and these ropes are UV-resistant. If you use nylon outside for long periods of time, the sun will eventually make it brittle to the point of failure.
- Speaking of guys, I used cheap aluminum tent stakes from the camping section of a local store. These were were more than adequate to hold the long guys in place. However, there is also a stake in the ground that you cannot see in the photographs. It is directly inside the bottom support PVC pipe segment. This keeps the bottom of the mast from sliding around on the ground. This is also mandatory, because of the top-heavy nature of the loop. Without it, the bottom mast segment could shift, and send the antenna falling.

For the loop itself, I chose **5/8" soft copper tubing**. This is the type you might use to feed refrigerant to an air conditioner. It is often sold as "refrigeration tubing." The small-loop theory says that larger bore tubing makes the antenna more efficient, but 5/8" seems to be a nice compromise size, and is still in the "cheaper" grade of tubing. Price starts to climb rapidly as you increase the tubing size, and again, I was just trying to prove the theory.

Soft copper tubing also lends itself to being easily formed into a circular loop. Unlike loops built from copper pipe, the tubing doesn't have to be cut and joined with elbows. Having a long continuous piece of copper seemed ideal for keeping losses low. After all, solder joints increase losses. I have seen some very clever jigs for doing circular bends of piping. I did mine by hand, and the result was almost as good. The trick is to bend the tubing a little at a time, working your way around the length of tubing several times, making very small bends every few inches during each pass. Out of the box, the tubing is already coiled up in a nice circular shape. All you have to do is increase the radius of curvature to get it to the diameter that you want.

For the inner (driven) loop, I chose 1/4" soft copper tubing. An SO-239 connector was carefully soldered to the ends of the inner loop.

Both types of tubing can be purchased by the foot from local hardware shops for reasonable amounts. I was able to secure both from Lowe's for just over $1/foot.

Some notes about working with copper tubing:

1. Handling copper with your bare hands will very quickly cause it to tarnish. The copper content of pipe and tubing is extremely high, and copper loves to react to the natural oils and salts from your skin. If you will wear thin latex gloves while handling the tubing, and especially while bending it, the copper will retain its shiny appearance and you will minimize contaminants on the surface of the inductor.
2. On the subject of contaminants, remember that the thickness of the copper is irrelevant for an antenna. The skin effect of RF flowing on any conductor will force all of the current into the top few micrometers of the copper tubing. I have not seen any literature that describes how tarnish, oxidation, and other surface contaminants effect the RF resistance of a conductor, but the cleaner you can keep the surface, the better.
3. It is easy to polish the copper loops with a wire wheel, available at any store that sells drills and bits. The coarseness is up to you, but mechanically polishing the imperfections out of the loop is easy and well-advised. If you use a drill or Dremel to work on any part of your loop, make **sure** to wear eye protection.

3' Loop with Window Line Capacitor

Now it was time to tune it.

To figure out how long to make the capacitor stub, I used some existing 300-ohm stubs cut for the dipole project. These were in lengths ranging from 6" to 8', in binary increments. I can combine these into any length of stub, to a resolution of 6". To interconnect them, I soldered PowerPole connectors to the ends. In a very handy coincidence, the spacing between PowerPole contacts is almost exactly the same as the spacing between the wires of 300-ohm window line. This way the stubs could be connected in series quite easily. At the top of the loop, where the copper tubing is split, I soldered in a 2" stub with a PowerPole connector, for attaching to the stub of the stub.

Some thoughts about capacitive stubs:

- Using feedline stubs for matching isn't a new idea. People have used open-wire and coaxial feeder stubs for impedance matching purposes for some time. The dipole matching project used both series and shunt stubs between the coax and a 600-ohm feedline to match the two, and was inspired by W5DXP's work on that very subject. His project used series transformer sections exclusively. I just extended the idea by adding a second piece of feedline, open-ended, as a shunt section on the high-impedance side, to further refine the match. That piece served (mostly) as a matching capacitor of very small value. That is the idea here, with the loop. The stub is open-ended, and serves only as a capacitor.
- From an efficiency standpoint, the stub isn't a good permanent solution, because it adds more than capacitance. It serves as a delay line that also contains a non-negligible amount of inductance, that actually adds to the effective length of the large copper loop. For use as a first experimental capacitor it was a wonderful and cheap way to do tests. In the long run, a good design will probably use some kind of lumped-C capacitor, such as a vacuum-variable or an air-variable.
- I have seen some really nice designs for homebrew trombone-style capacitors made out of copper pipe (not tubing). I opted to avoid these as a final solution for two reasons.
    1. I wanted to operate high-power levels. This means that the dielectric of the capacitor needed to be high-quality and low-loss. A vacuum is hard to beat for this purpose.
    2. I'm not yet convinced either way with respect to how much additional inductance is introduced by the trombone arms. It may be negligible, but as with the window-line stub, it certainly "looks" substantial, due to the lengths involved.

After some experimentation, I found the length closest to 14,070kHz for the loop. Using a Palstar analyzer, I mixed stubs until I found a length that was close. I then took a spare stub that only had one connector, and started cutting it from one end about 1/8" at a time, until I slowly resonated the antenna at 14,070kHz.

For the feed loop, I used a single turn of 1/4" tubing, fed directly in a balanced fashion from the coaxial cable. I used an MFJ-915 choke close to the feed point, to ensure that no common mode current flowed on the cable. During later experiments, I found that this is usually not needed, but I didn't want to pollute my test with common mode radiation or reception. I wanted all the power to go into the large loop, whether that mean radiation or loss.

Even before making any contacts, I noticed that the loop Q was quite high. Drifting in frequency more than 15kHz from the center frequency would raise the SWR quickly to 2:1 and beyond. Another 15kHz would take the SWR beyond 10:1, which is the measurement limit of the Palstar device.

Since the high Q is critical to maintaining loop efficiency, I knew I was on the right track. Efficiency and Q are very tightly coupled, and for an electrically small (dare I say, tiny?) antenna, efficiency and Q are directly proportional. Higher Q tends to indicate higher efficiency for a small radiator. If the antenna had a lot of resistive loss, the Q would fall, and the 2:1 bandwidth of the antenna would be wider.

The band conditions on 20m the day of my first tests were terrible, but I still had no problem making coast-to-coast domestic contacts on PSK-31, even in the presence of heavy fade. After spending an afternoon making contacts on the loop, and watching several DX stations come in quite clearly, it was obviously working well enough to justify getting more serious about the loop project.

Step 2 — Vacuum-Variable Capacitor

The next step in improving the loop was to add a variable capacitor, to allow the antenna's frequency to be changed. I wanted to use the loop on at least a couple of different bands, to see how the performance changed as the loop wavelength was changed. A 3' loop is just under 9.5 feet in length. That's about 1/8 wavelength on 20m, almost 1/4 wavelength on 15m, and well over a quarter wavelength on 10m.

Alan at MaxGain was able to provide me with a couple of used vacuum variable capacitors, 10-60pF, 10kV, for around $100 each, shipped. Vacuum variable capacitor prices only go up from there, so I thought that would be a good starting place. According to the calculators available online, those capacitors would allow me to tune across the frequencies that I cared about, at a peak power level of 500W, which is the limit of my station, anyway.

The capacitor replaced the stub, and I added a shaft made of PVC, to allow for turning the capacitor shaft from the ground. At left is an image of a drive shaft added to a 5' loop, constructed later. At right is a close-up of the capacitor mounting.

Vacuum-Variable Capacitor

You will note that I used wires to connect the ends of the inductor to the capacitor. Although this wasn't optimal from the standpoint of keeping resistance low, the Q of the loop remained quite high after this change. More importantly, I could tune the loop to any frequency from 20m through the CW/data portion of 10m.

The wires were soldered to the tubing using standard PC-board solder. I tried silver solder, but my first attempts didn't work out well. Later, I'll describe how I was able to successfully resolder with silver-bearing solder.

As a side note, most capacitors are rated for maximum *voltage*, and they are typically marketed that way. While the voltage rating is important applications like this, I found that an equally important capacitor rating is its maximum steady state *current* rating. The voltage rating only matters once you get close to the limit; anything less than that, and the capacitor's voltage handling is just as good whether you run 100V or 10kV. This contrasts with the current rating, which is the point where the capacitor is no longer able to keep itself properly cool, and heating effects occur. I have seen more than once where the limiting factor for a loop antenna was the capacitor, and it was the *current* rating that was the limit. As the power level caused the circulating current to approach this value, the capacitor would start to heat, causing thermal drift of the resonant frequency.

Unfortunately, the AA5TB spreadsheet doesn't capture the circulating current value of the loop you are modeling, but it is not difficult to do calculate, since it is included with the ARRL loop formulas. I modified the spreadsheet to include circulating current, which has been very helpful in selecting proper capacitors to use for a given design. I won't publish the updated spreadsheet here, but if anyone would like a copy, please send me an email. I noticed that the MaxGain folks are usually good about documenting the current capacity of their products, so it would be a good idea to compare these ratings with the anticipated value from the ARRL model before selecting a specific capacitor model.

While working with this loop, I noticed some other interesting things that the standard literature didn't seem to mention. I have no explanation for why any of these were true, but my experience was consistent across all of the loops built:

1. Adjusting the inner loop for 50-ohm resonance was much easier if I moved it vertically, within the loop plane, rather than rotating it about the mast. All of the literature I read suggested the latter.
2. The proper location of the inner loop for a 50-ohm match was extremely dependent on the loop's surroundings; e.g., its height above ground, whether it was indoors or out, proximity to other objects, etc.
3. The *range* of resonant impedances attainable by moving the inner loop along the mast could also be changed by deforming the inner loop to be oblong, rather than circular. This was another technique suggested by some texts, and it was necessary to get 50-ohm resonant matches when the loop was sited in difficult locations, e.g., indoors.
4. The overall loop was also easier to match to 50-ohms if the inner loop was fed at its top, as shown in the picture at right.

The first point was very helpful, because simply rotating the inner loop didn't always work. By raising or lowering it on the mast, so that the two loops remained coplanar, I could easily reach a 50-ohm point at resonance, regardless of the location details. When mounted outdoors in the clear, the 50-ohm position of the inner loop was several inches up the mast. When used indoors, the 50-ohm position of the inner loop was near the bottom edge of the outer loop. At right, you see what the 3' loop looked like adjusted for use outside.

A few QSOs later, it was time to add a motor drive to the capacitor, so that I could remotely tune the loop.

Step 3 — Motor Driven Capacitor

Robotics is a fairly common hobby today, so finding a motor to move the capacitor shaft was easy. I bought a gearhead motor from a robotics wholesale outlet. The gearhead reduced the RPM of the motor from several hundred RPM, to about 3 RPM. Both the motor and the capacitor had 1/4" shafts, so connecting them required only adapting the PVC drive shaft to them. I found a couple of knobs at Radio Shack that did the trick. They were replacement knobs for audio equipment volume controls. The knobs fit tightly inside the 1/2" pipe, and to the shafts.

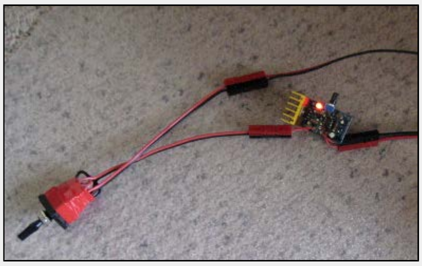
High-current antennas such as this are capable of generating huge magnetic fields close to the antenna, so I adopted a rule to help keep my test results as trustworthy as possible. I decided not to run any conductors near the outer loop, where the high loop currents exist. That way, the mutual coupling between the outer loop and other conductors was kept to a minimum. The intent was to keep the antenna's radiation pattern as pure and undistorted as possible. To accomplish this, I did a couple of things that also were not mentioned in any of the small loop literature that I found:

1. The coaxial feedline was mounted in such a way to keep several inches between it and the outer loop. This was done by making a large arc from the feed point, over the main loop, then back to the mast.
2. The motor drive for the capacitor was not mounted close to the capacitor. Instead, a long "drive shaft" was formed with PVC pipe, and used to connect the motor to the capacitor. The drive shaft was long enough to allow the motor to be placed well outside the outer loop.

I added a couple of protection items to the motor before using it. First, I placed a 0.05µF capacitor across the motor's DC terminals. This keeps the RF out of the motor windings. Second, I choked the power leads with a common mode snap-on bead, to keep RF from flowing into the motor from the long leads, or back to the power supply from the motor. The motors also had a vinyl cover added, to weatherproof them.

Another handy tool I borrowed from the robotics hobby was the PWM motor controller. These devices generate pulses of DC to drive the motor. Using voltage to control a motor's speed can also be done, but it has some disadvantages:

1. A motor running at a lower voltage develops less torque than one running at full voltage.
2. A motor running at a lower voltage can generate more internal heat, especially since it stalls more easily under load.
3. A motor running at a lower voltage is less efficient than when it runs at its design voltage.



The PWM mostly solves these problems. By pulsing the power, rather than lowering the voltage, the PWM allows the motor to run at full voltage while moving. The PWM generator takes advantage of the rotational inertia of the rotor to provide a natural slow-down of its motion, which allows much more fine-grained control over the motor speed.

Adding the PWM to the motor circuit allowed me to more easily find and adjust the resonant frequency of the antenna. I added a DPDT, momentary, center-off switch to the PWM circuit *output*. This allows me to send normal or inverted voltage pulses to the motor, to rotate it in both directions. Many DC motors are reversible in this way, and the specifications of the motor will tell you for sure. At right is the PWM controller, with the DPDT switch on the output.

The loop was really taking shape, and I was happy with the performance I was getting, but there were still a couple of things I wanted to do to try to squeeze out the last bit of efficiency.

First, I replaced the wire jumpers between the capacitor and the main inductor. Georgia Copper sells nice, polished copper strap in various lengths. I used 1/2-inch strap to make the connections. I also used silver solder the second time. It turns out that my previous attempt failed because I did not properly flux the conductor before applying the solder. Tractor Supply sold me a roll of silver-bearing solder that contained its own flux, and that worked much better.

Note that the copper and solder around the joints was polished after assembly. This removed the discoloration and oxidation that naturally occurs when using a torch for soldering. Again, the skin effect of RF flowing on the surface of a conductor adds enough resistance on its own. I hoped the polish would make sure that the current wasn't flowing through any additional impurities.

Radials

Several loop builders also mentioned potential improvements in performance by adding a fan of short radials underneath the loop on the ground. I added a set of 15 to 18 radials under the loop, each of which was around 6' long, and made from THHN-insulated copper wire.

After several attempts at using loops both with and without radials underneath, I have concluded that the loop doesn't benefit substantially from the addition of radials over our local (relatively conductive) soil. The computer models agree with this conclusion — in fact, the number and length of radials required for the computer model to show any substantial improvement is almost prohibitively high — far more than needed to cause a similar improvement in a simple λ / 4 vertical antenna. Some authors have commented on the loop antenna's weak dependence on ground (as opposed to a typical vertical antenna which is strongly dependent upon the ground underneath). This would seem to be supported by the experiments and models based on our local ground. The performance of the loop appears to be far more influenced by its *proximity* to the ground, which I will discuss later.

Radiation Pattern Observations

The overall loop pattern was nearly omnidirectional. The nulls that I did find were rather sharp. They were, however, enough to null out some RFI from a local neighbor, when the loop was properly rotated. DX contacts were readily made at angles 60-80 degrees azimuth from the loop plane, and sometimes, directly above the null. The theory seems to indicate that this is typical for a small-loop pattern.

Installation Height

After looking at several EZNEC+ models of small transmitting loops, I have concluded that the optimal installation height for a vertically-oriented loop is approximately 0.90 * λ / 4, measured from the *top* of the loop to the ground. At this height, the peak gain of the main lobes is the highest, and the angle of peak radiation is the lowest. Some people recommend one to two loop diameter elevation, which usually results in a very usable antenna, but not always optimal, and certainly not optimal across several bands. An approach that is more consistent with the computer models, is to raise the antenna to somewhere just below a quarter of one wavelength above the ground for the band most often used for the loop.

There are obviously a couple of exceptions to this rule of thumb, both having to do with low-band loops.

First, a loop for 40m or 80m is going to be difficult to raise to near λ / 4, and doing so defeats one of the advantages of using a small loop -- compactness. What I discovered with the 40m and 80m loops described below, is that lower installation heights can be used effectively, with minimal adverse effect to the DX capability of the antenna. The trick is to be reasonable with the trade-offs, and computer modeling of the desired installation height can help visualize the effect on its pattern.

Second, if NVIS response is desired, raising the antenna to near λ / 4 will remove much of its high-angle response. Much like lowering a dipole to increase high-angle response, installing a 40m or 80m loop at below its ideal height increases its NVIS capabilities. The models suggest that a good height for a NVIS loop is indeed between one and two loop diameters, measured from the ground to the *bottom* of the loop, and my experiments with NVIS loops confirms that this is a good working estimate. If NVIS operation is desired, it is also best to place the capacitor at the *bottom* of the loop, rather than at the top. Doing so places the current maximum at the top of the loop, which helps maximize the overhead antenna gain.

Bandwidth Observations

The three-foot loop has a 2:1 SWR bandwidth of **22kHz** on 15m, as measured at the end of a 45' length of RG-213/U. As I later discovered, the coaxial cable tends to correct impedance mismatch along its length, so the actual 2:1 bandwidth measured at the antenna would be somewhat less than that measured at the end of a long cable. All of the loop antennas described below were measured with similar cables, unless otherwise noted, so it may be useful to go back at some point and repeat the measurements of some of these antennas, to see how close each of them is to the theoretical values.

Others have contacted me to point out that the bandwidth predicted by the Antenna Book formulas is measured at its -3dB points, not a 2:1 SWR. That means that the bandwidth numbers I provide here are not directly comparable with the results from these formulas. Others still have pointed out that a -3dB point is often correlated as a rule of thumb with a 2.61 SWR. However, I am not convinced that a 2.61 SWR reading correlates to the -3dB points, because this rule of thumb has some other assumptions built into it. In any event, the reader should be aware that the bandwidth measurements I present here are based on measured 2:1 SWR points, and *not* -3dB points.

Regardless of the convention used for measuring bandwidth, there are some general principles that apply to all of them. The foremost idea is that bandwidth and Q are inversely proportional, regardless of the units used. That means, for example, that comparing the efficiency of one capacitor to another should yield a narrower bandwidth with the more efficient part, since it increases the Q value of the circuit. So performing meaningful comparisons is still a practical exercise, even for those of us who may not have the ability to measure the true -3dB bandwidth of the antenna.

More Loops

So far, I have built several different loop antennas, some of which have had two or three rounds of modifications done to them. These antennas ranged in size from 9 feet down to 17 inches diameter. Each of the new loops was built to emphasize a particular band. The loop described above was approximately 3' in diameter, and is a good choice for multiband operation from 20m through 10m (strongest on 15m) with the capacitor chosen.

20m Loop

One of the loops was a 5' model specifically built for 20m performance. It was a larger diameter, making the overall circumference about a foot less than one quarter wavelength at 14,350 kHz. This maximized the efficiency for that band, but still kept it electrically small. Its measured 2:1 SWR bandwidth on 20m is **18kHz**. This antenna used the second of the two 10-60pF variable capacitors I originally picked up from MGS. This allowed it to tune well outside the 20m band, even with the relatively narrow range of the capacitor.

This antenna served as a first draft for the Mark-7, which I have installed semi-permanently at my house. That antenna also tunes across several bands, and is used regularly and successfully for contesting. This antenna is also of similar size to the 40m loop described below. In fact, this loop, the 40m loop, and the Mark-7 loop are nearly identical electrically. The main difference between the three designs was in the range of the tuning capacitor attached to each one.

6m Loop

Back in my college years, 6m FM had some fantastic propagation, and I remember some very nice band openings. I have been wanting to get back into 6m, but didn't have an antenna that fit well anywhere at the house. So as an experiment, I also tried a 6m loop. This loop has a diameter of about 17 inches. It used a single 3-30pF capacitor for tuning, which was sized to be usable into the 100W range. This loop has made several domestic CW contacts, but has not seen a lot of use beyond that.

The computer model suggests that the optimal installation height is a few inches shy of five feet, measured from the ground to the top of the main loop. This places the top of the loop at just over λ / 4. This raises some interesting issues not seen with most of these loop designs. First, a 5' installation height is easy to achieve either outdoors or from inside a single-story building, but it is too short for an attic installation. If this antenna is used in an attic, it should be installed as low as possible within that space to achieve the best possible pattern. Second, like any other ground-mounted antenna, care must be taken to prevent others from touching the antenna during transmission. Given the elevated voltage *and* current present on the loop conductor, even at low power levels, RF safety is particularly important with an antenna that is easily reached by humans of any age.

40m Loop

Loops that are extremely small electrically are able to maximize other aspects of their operation. For example, lower noise pick-up and deeper nulls. I built a 40m loop to experiment with these properties.

The loop size was chosen to be approximately 4.5 feet in diameter. This makes the circumference of the antenna about 11% of the wavelength at 7,000kHz, and the diameter about 3% of the wavelength. Electrically speaking, that is the definition of "small".

The measured 2:1 SWR bandwidth of the 40m loop is **5.4kHz**. At this bandwidth, the antenna is still capable of SSB transmission. However, it reminds me that loops of this size will only be usable for narrow modes (e.g., CW or PSK-31) on longer wavelengths. Antennas large enough for SSB on the lower bands will likely not be easily portable. This antenna's Q is high enough that it needs frequent retuning while moving up and down the band, even on CW. Adding an automatic controller eased operation considerably.

This loop was a little different than the others, in that I didn't try to use a single capacitor to tune it. Instead, it used two capacitors arranged in parallel. The first was a vacuum-fixed capacitor, 100pF, to provide most of the 120pF required to bring the resonant frequency down to around 7,500kHz. The second capacitor was a smaller 3-30pF vacuum-variable, used to provide the tuning adjustment to pull the frequency down further into the 40m band.

The maximum current rating for the 100pF vacuum-fixed cap was considerably higher than that of the vacuum-variable. The reason for this is that the current flowing into and out of each capacitor in a parallel arrangement is directly proportional to its value. When the vacuum-variable is adjusted to 20pF, it shoulders roughly 1/6 of the total circulating current within the loop antenna. So the current ratings for the two capacitors were chosen accordingly. This was very helpful, because high-capacity fixed capacitors are far cheaper than high-capacity variables, mostly due to the simplicity of the construction. By using two caps in parallel, I minimized the cost of the overall capacitor bank considerably.

The initial tests of the 40m loop were very promising. During a CW contest, the 40m loop made numerous DX contacts in Europe. When running at 500W, the capacitors showed no signs of heating (SWR drift, physical warmth, etc.).

I ran several computer models of this antenna, to determine the effect of differing installation heights. Unsurprisingly, the *ideal* installation height for a low-angle pattern is somewhat less than λ / 4, in the neighborhood of 30' to 31'. That height isn't very practical for a loop antenna, and people who can install a 40m antenna at that kind of height will probably use a vertical, instead. That said, I was still impressed by the DX performance of the antenna, so I looked at several models at lower installation heights.

What I found was that the difference in low-angle performance between the antenna at its "ideal" height and more practical heights isn't much. When installed at a height of 31', the elevation angle of peak gain (the so-called "take off" angle) is around 18°. When the antenna is installed at 12', the gain at that elevation angle is within 0.2dB of the 18° gain for the same antenna installed at 31'. As a result, the antenna is quite usable for DX, even when installed at less than half its ideal height. Further, the antenna's high-angle response is much better at the lower installation height. So installing the antenna at 12' allows it to work both NVIS and DX contacts. This kind of versatility is difficult to find in any other type of antenna.

10m Loop

A few years back, while 10m conditions were somewhat better, a dedicated 10m loop seemed to be a good idea. Its construction was very similar to the others, with a 6' circumference and a measured 2:1 SWR bandwidth of **27kHz**. As with the other antennas, the computer models suggest that the optimal height for installation is just under λ / 4, or somewhere around 98" (just over 8'), measured from the ground to the top of the loop. As with the 6m loop, such a height places the loop conductor within reach of an average adult, so RF safety precautions should be taken with placement of the antenna.

During one 10m Contest, I did several A/B tests between the 10m loop at 8', and a KIO hexbeam at 23' — reasonably close to optimal for 10m. The received signal strength on the loop was about one S-unit less than that of the beam. Given that the difference in expected gain between the two antennas is around 8dB, the signal levels received on the loop were more than satisfactory. The noise level on the loop was also down about one S-unit (6dB). When transmitting, this loop was just as capable of European and domestic contacts as the beam: I found *no* stations that could be worked on the beam but not on the loop. I verified this by attempting to work all stations first with the loop.

As you can see in the photo, this loop has been painted with a coat of white enamel. This protects the copper from tarnishing from handling, but it does not seem to have effected the performance in any measurable way. The copper was finely sanded prior to painting, to make the copper surface as conductive as possible. The other HF loops have been similarly painted, with no adverse effects to performance, or even a measurable change in operating parameters such as Q or resonant frequency.

The antenna performed as expected for 10m, the band for which it was designed to be optimal. However, with a capacitor of appropriate range, this antenna can be resonated across *all* of the higher HF bands from 20m through 10m, despite its small size. The predicted ideal efficiency between those extremes varies from around 35% on 20m to nearly 90% at the top of 10m. The range of capacitor required to cover those bands is approximately 125pF to 25pF. On 20m, the loop is about 9% of 1·λ, a size that makes it a textbook "small loop" for that band.

For an installation where space is truly limited, this antenna could provide effective coverage across the higher HF bands with reasonable efficiency, and it can fit literally *anywhere*. If such extended operation is desired, it would be advisable to pay particular attention to efficient construction, including generous conductors sizes, limiting the number of joints, and low-loss capacitor selection.

80m Loop

The yard in which I build my "antenna farm" is roughly 64ft square. Even a loaded 80m antenna would take up a lot of room. I modeled a few 80m antennas, and decided to try a loop for this band, as well.

This antenna's construction differed from the others in some significant ways. First, it used flat copper strap, rather than tubing. The 3" strap width was selected so as to give an equivalent surface area to that of tubing roughly 1.9" in diameter. The strap does not have any structural strength of its own, so a "plus"-shaped PVC structure was built from 1.25" schedule-40 PVC. This turned out to be sufficient, but it is still quite flexible under the weight and wind load. A larger-bore pipe would be a better selection.

The antenna is rather large, as compared to the others. The arms of the support structure were each 4.5' long, and each of the four sides are over 6' long, for a total conductor circumference of 26', with about a foot curled up near the tuning capacitor. This means it is *possible* for the loop to fit through a door, but not *easy*. So this antenna was built to have some basic protection for the motor and capacitor, so that it could be left outdoors for extended periods of time. The housing around the moving parts is 4" PVC nominal I.D.

This antenna is fed with the capacitor at the *bottom* of the loop, and the smaller driven loop at the *top*. This is an inverted configuration from my other loops. I spent some time in EZNEC+, modeling these antennas, and found that for the higher band antennas, the normal (cap-at-the-top) configuration gave the best overall pattern for these bands. However, for a low-band loop, I found that the pattern was slightly better (between 1dB and 2dB) if I inverted the antenna in its resonant state. I can't explain why the models worked out that way, but I suspect it might have something to do with the distance of the antenna from the ground, as measured in wavelengths. Since they are all roughly the same height (5 to 8 feet) from the ground, this is the main difference between them.

Because of the inverted configuration and large size, I moved the location of the motor, as well. While I could have placed the motor below the main loop on a short drive shaft, this would have increased the size of the overall antenna significantly, and it would have placed the motor very close to areas of high RF energy. So this time, I placed the motor near the center of the loop, which should be a near-null area for RF. While the motor is in the center of the area of high flux density, it does not appear to pick up any significant levels of RF on the control lines.

Further, the 4kHz square-wave PWM signals that drive the motor during rotation produce only faint RFI to the antenna if the motor is moved while the radio is receiving. Given the coincidence of two areas of high magnetic flux, that of the antenna and that of the motor, I was pleasantly surprised by the effectiveness of placing the motor inside the antenna's null zone at the center of the large loop.

The capacitor selected was a 500pF Jennings, with some impressive power handling specifications. The copper strap was attached directly to the capacitor body, to eliminate any unnecessary mechanical joints in the high-current part of the loop. The ends of the strap were cut to form several "fingers" that fit under the silver clamps on the ends of the cap. The antenna shows no signs of drift due to RF heating, even under 100W continuous key-down. The model suggests that it should be fine through 500W for CW operation, and perhaps higher for SSB duty cycles.

The feed point was made from #16 solid wire, rather than from tubing. This made it easy to shape, and to attach to the weatherproof enclosure housing the coax connector. This was the first antenna that does *not* have a choke on the coax feed — and as it turns out, it wasn't needed. The loop balance was quite good, and the broadside nulls were very pronounced. A local neighborhood noise was S-9 end-fire to the loop, but when the loop was turned so that the noise was broadside to loop, it could no longer be heard at all.

This antenna was easily managed with the AutoCap software, using a 400-step/rev stepper motor attached to the capacitor through a 4' PVC drive shaft.

Outdoors, the bandwidth was quite narrow, and it showed a measured 2:1 bandwidth of approximately **3kHz** on 80m. The antenna's circumference is less than 1/4 wavelength on 40m, so it is also very usable there, and with higher efficiency. On 40m, the bandwidth was also considerably higher.

80m STL

My first QSO with this antenna was broadside, to an MFSK-16 station in Missouri. My transmit power was 25W, and we chatted for about an hour. The distance was ~340 miles, and the skip angle was approximately 55 degrees. Later testing over the next few days showed it to be quite capable of domestic contacts at all distances, from coast to coast, as well as within the skip zone at high angles (NVIS). I made contacts on both 40m and 75m SSB, running 500W without any signs of heating or temperature-related drift. Received signal reports are always subjective, but the SSB contacts all gave me feedback along the lines of, "wow that really is a big signal."

During the 2015 IARU contest, I used this loop as a dual-band antenna, for 40m and 80m, doing CW contacts at 500W+. The loop was oriented with the main lobes pointed NE/SW, and the feedpoint was adjusted for lowest SWR (1:1) on 40m. On both bands, the antenna made numerous contacts at all elevation angles. Once each band's propagation was fully formed, DX stations, NVIS stations, and everything in between arrived with similar signal levels. Working Europe and South America was done with amazing ease, even on 80m. The reception on both bands was exceptional, with generous signal levels.

The nulls appear to be limited to near-zero elevation angles. While the loop can greatly attenuate noise from nearby buildings when turned broadside to the source, it is still able to send and receive skywave signals along the same bearing. If the EZNEC model is anywhere near accurate, the loop should be able to do NVIS and other domestic contacts broadside, although DX signals perpendicular to the loop are probably getting close to the null's elevation angle.

On that subject, it was surprising to me how far off-axis from the main lobes a station could still be worked. NE/SW contacts were not that big of a surprise, but some distant stations were worked with ease at angles exceeding 60 degrees from the main lobes. While the loop is certainly not a gain antenna, on the low bands, the ionosphere is doing most of the heavy-lifting for propagation, so gain doesn't seem to be an issue.

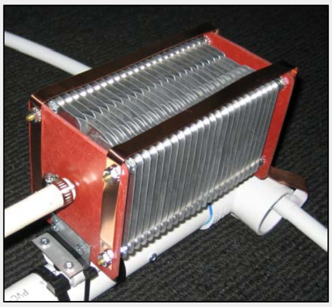
About that feedpoint adjustment... One issue with using an inductively-fed loop for multiple bands is that the 50-ohm feedpoint position for one band is not necessarily the 50-ohm feedpoint position for the others. This effect was more pronounced with the 80m loop than the others, as adjusting for 1:1 on one band meant almost 2:1 SWR on the other. For 2015 IARU, I decided to optimize, and run 1:1 on 40m, and 2:1 on 80m, so I would not have to readjust during the contest. This allowed me to switch back and forth quickly between bands, and it put the 2:1 SWR where it would cause the least coaxial feedline loss.

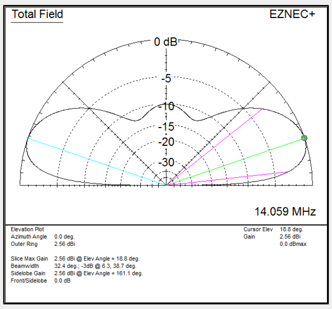
This brings up a slightly controversial point with respect to loops. It is often said that a loop cannot be used with a tuner. While it is true that a tuner should not be used to *adjust* a loop antenna, there is no reason why an otherwise resonant loop cannot have its impedance transformed to 50 ohms by a normal "L" or "pi" tuner, if the loop's *resonant* point is not 50 ohms. As with any other antenna, the tuner and feedline loss will be proportional to the feedline SWR, but at moderate levels, the losses can be kept negligible. See the Notes on Multiband Operation below for more details on how I do this with my own loops.

Because of the sharp bandwidth on 80m, large movements in frequency would require me to preadjust the tuning point using the controls in the AutoCap software. This wasn't a particular challenge, since it is easy to estimate the correct adjustment by tuning for maximum noise level. A panadapter view makes this procedure even easier, since you can move the noise peak visually, and with more precision. After that, the AutoCap software can do the fine-tuning on its own. The software can do large adjustments, too, but SWR above 2.0 will cause my amplifier to fault before the software can get the antenna tuned. One way to avoid this is to simply avoid large movements, and just work stations in frequency-order. Otherwise, it is only necessary to preadjust as needed to keep the gear happy for the second or two while the software gets the antenna centered up on the new frequency.

With these minor adjustments in the operation of the loop for 80m, it was easily used as a dual-band low-band loop for contesting. Considering that the next step up in antennas for these bands are 1/4-wavelength verticals (with 33' and 67' mast and radials, for 40m and 80m, respectively), a loop antenna with its base 5' above the ground, and its top at 15' is a good option for limited space, and has the benefit of working equally well for DX and domestic contests.

The Mark-7 — An Optimized 20m STL — Extended to Cover 20m through 80m





The seventh STL project — which I have dubbed the "Mark-7" — has been the most used and updated of all of them. This antenna started as a 20m-only replacement for my hexbeam, which was large, heavy, and of limited utility in low-sunspot years. The Mark-7 has been modified and reinstalled several times, and seems to be just the right size for a number of different uses beyond just 20m.

After taking down the hexbeam, I modeled a number of antennas to use for 20m DXing and contesting, and realized that a slightly larger version of my other 20m loop, with an improved mounting structure, would be the best option for my location for a long-term installation. When built properly, it would have better low-angle gain than a vertical, with an efficiency of nearly 95%. In fact, the gain on 20m at elevation angles of less than 10° would even be better than a hexbeam installed at anything less than 33'. In contrast, the optimum installation height of the loop would be with the top of the loop at around 15', which is much less of a mechanical project than a hexbeam at over 30 feet!

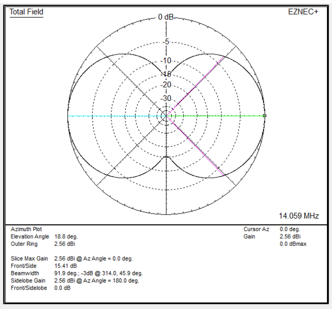
So I built a new 20m loop to replace the hexbeam until the next solar peak.

The initial version incorporated some design changes that I thought would be worth sharing. Some worked, and *some didn't*.

The first change I made for this loop was the support. In order to control the wind-induced torque of the "wings" of the antenna, I used a cross-shaped or plus-shaped PVC frame that supports the copper at four points. I replaced the threaded break-down coupling at the bottom of the loop with an O-ring-bearing union joint. This joint has two nice improvements over a simple threaded joint. First, the strength of the joint isn't on the threads, making it much stronger and resistant to breakage. Second, it is much wider, which forms a nice flange that can be used to hold guy ropes in place. The overall structure is 1.25" schedule 40 PVC, with a 1" piece of schedule 40 PVC telescoped into the vertical portion of the structure for added rigidity and strength.

Eventually, the union joint would no longer be needed, but it's still handy for test-standing. The "plus"-shaped structure was a real improvement for stability.

The next change I made was to use an air-variable capacitor instead of a vacuum cap. This new capacitor wasn't a butterfly capacitor, but rather a differential capacitor from Palstar, with two stator halves, which



were connected to the main ring. Although still a split-stator like a butterfly, this cap has two advantages over a butterfly. First, it allows a larger range of C values for a given size of capacitor, while retaining the butterfly's advantage of not flowing current through wiper connections. Second, the differential cap does not have a uniform rate of change of the C value as the rotor turns. The value changes faster at low C values, and slower at high C values. This is an advantage because at high frequencies (low C), the bandwidth of the antenna is larger, so tuning rate isn't nearly as critical. At lower frequencies (high C values) the bandwidth of the antenna is lower, requiring a slower rate of C change to avoid overshooting the target value. The air-variable cap is just aluminum plates, which should make it more durable than a vacuum cap. Since the air-variable is shaped like a large heatsink, any heating that occurs should be easier to manage.

The third change was to use a CT-style feed, instead of a simple air-loop wire. I used a few turns of wire on a large 43-material toroid core from Fair-Rite. The **µ** values for #43 at 20m were nearly identical to those of #31 and #44 material, so I chose #43, as it also tends to be the most available of the material types. With the loop at its optimal 15' height (10' mast underneath it), a 6:1 turns ratio provides 50 ohms at the feedpoint on 20m. When the antenna is on its 4' test stand mast, the best turns ratio is 4:1 on 20m, so the siting of the loop does have substantial effect on the feedpoint impedance.

Initial testing of the loop suggested that it would have performance on par with that predicted using AA5TB's spreadsheet. The measured -3dB bandwidth was 50kHz at the end of 45' of RG-213, while the 2:1 SWR bandwidth was 35kHz. As an added benefit, the capacitor was large enough to allow operation on 30m and 40m.

I initially used the antenna in the NAQP CW contest, where it performed as expected on 20m. The azimuth and elevation patterns achieved in practice seemed to match that predicted by the model (see EZNEC+ plots at right), with peaks and nulls where they were expected. Even with long CQ runs at 100W, the #43 split-bead showed no signs of heating or stress-related SWR drift. Later QRO testing showed a *very* different result (discussed later on).

To minimize resistance related losses, the capacitor was connected in a series split-stator configuration, with the rotor connection left floating. Copper strap was used to connect opposite ends of each stator bank. This way, current wouldn't need to flow along the full length of the stators.

One point of consideration with the joints between the vanes of the air variable capacitor is that of water intrusion. Weatherproofing for an outdoor antenna will be a must, to prevent water from seeping into the joints between the vanes if they are not welded together. Alternatively, the careful application of a silicone-based grease to seal these joints would seem to be a good idea. Otherwise, oxidation and/or corrosion may eventually compromise the joints slowly over time, increasing the losses between the plates.

After the first couple of contests, I set up the antenna in a good location for higher power testing with an 800W amplifier. What I found was rather interesting.

The AT2KD capacitor worked fine at 100W, but at higher power levels, it can't withstand the elevated voltages, even on 20m. Judging by the measured bandwidth, the air cap doesn't have excessive losses, even when compared to a vacuum equivalent, but when running anything over 150W CW on 20m, the capacitor arcs. Both the NEC model and the ARRL formulas predicted a peak voltage *far* below the 5kV rating of this capacitor at that power level, and further, this capacitor should have been able to handle double that rating, as the two stator halves were connected *in series*. But the cap just can't take the stress. For the $150 price tag of this unit, I could have gotten a nice NOS vacuum capacitor with a 25kV rating, so the AT2KD is not a good value for this purpose.

On the bright side, the AT2KD still has some nice advantages, if one is willing to live with the modest power limitations:

First, the AT2KD has some amazing long-term temperature stability. After weatherproofing the capacitor, and leaving the antenna outside across several months, from springtime to well into winter, the resonant point stayed right in place. Its stability rivals any of the vacuum variable capacitors I used.

Also, the AT2KD has plenty of efficiency on this loop, with a tight, narrow bandwidth, high Q, and yielding an overall antenna that earns consistently excellent signal reports from other stations, even at considerable distances.

Not least of all, attaching the AT2KD to an STL of this size gives a large usable frequency range, fully handling 100W at 100% duty cycle, from 20m to 40m. That covers at least three very popular DX bands at the 100W level. So even this modest capacitor is very DX-capable.

Nevertheless, my desire for higher power levels on 20m led to the next experiment with this loop, which was to replace the AT2KD with a 25kV, 50pF vacuum variable capacitor. This capacitor easily handled power levels up to 750W CW, which was the safe limit of my amplifier. It is actually a very nice device, and I wish I had bought two or three of these instead of just one. The 50pF range allowed the antenna to cover both 20m and 30m, and kept the amplifier happy.

When running at these elevated power levels, however, the #43 core I used to couple at the feedpoint gets rather warm. It would probably be fine for a CW or even a RTTY contest, as the thermal drift is quite slow. Nonetheless, heat dissipated in the ferrite is power that doesn't get radiated, so my next step was to replace the ferrite transformer feed with a more familiar single-turn inductive feed. For what it's worth, AD5X ran into similar issues with ferrite-core QRO transformers while he was developing his now-famous base-loading matchbox for 43' vertical antennas. In the end, he also switched to a large air-core inductor instead of the compact ferrite-core design. Other than the relative size of the two strategies, there really is no advantage to using the ferrite feed over the air-core coupling.

The vacuum-variable capacitor modestly increased the loop Q, to the point that measured bandwidth is slightly *lower* than predicted by the ARRL formulas, when mounted in the clear, and outdoors. This implies that the losses in the antenna are lower than predicted by the classical loop models. Even when adjusting the formulas to account for both the outside *and inside* conductor surfaces of the tubing, the measured Q is still higher than the formulas predict.

November 2019 Update - Extended Operation from 20m through 80m - More recently, while tinkering with models and formulas for the Mark-7, I realized that a 500pF variable capacitor would increase the range of the loop to cover all bands from 20m through 80m. That seemed like a lot to ask of a loop that was just over 5' in diameter, but it was an irresistable challenge.

So I updated the loop with a very large Jennings vacuum variable, and reinstalled it. During the first month of testing, the loop made ~2,500 contacts on the 20m, 30m, 40m, and 80m bands, using just 50W. The big surprise was the 80m performance. Over several hundred contacts' worth of FT8/FT4 SNR reports, the averge signal reports received from others differed by only 4dB between 20m and 80m. While I am skeptical of WSJT-X SNR estimates in general, the consistency of reported performance is difficult to ignore. The STL had very comparable performance across 40m and 80m (both in terms of QSO rate and average signal reports) to the HF2V, which it replaced. During the first month of operation, I picked up several new 80m countries using the Mark-7.

Another nice surprise was that the antenna performend well for both NVIS and DX contacts. This could be a nice feature for a limited-space installation, because one antenna can cover all distances, from DX to down the street, without having to make any adjustments.

The very respectable 40m and 80m performance of this very small antenna (which has a diameter of roughly 0.02λ on 80m) leads me to another efficiency-related observation—when comparing an STL design to other antennas, one needs to consider more than just raw intrinsic efficiency predictions of computer models and generalized formulas. While it is wise to consider conductor losses, it is more important to consider the overall antenna and its surroundings, as well as the characteristics of the bands being sought. That includes considering near-field ground losses and counterpoise losses, among others. Many perfectly-capable vertical antennas for longer wavelenths have very low intrinsic efficiencies, especially if they are heavily loaded to make them shorter. This means that even a *small* STL antenna may be able to compete favorably with much larger antennas, if an honest comparison is done that includes all of the losses that can be quantified. *Remember*—it's the *ionosphere* that does the heavy-lifting for us. If the signal gets to the receiver with the desired SNR, the antennas involved have done their job.

I installed the updated Mark-7 loop semi-permanently just above the roof line of my house. The installation height is roughly the same that one would get from an attic installation in a single-story home, or when set up in a second-story loft or work room. I installed mine outdoors, because the best performance (and least RFI potential) comes from getting the antenna clear of the clutter in the house. But if an indoor installation is one's only option, the antenna has excellent performance from such modest installation height.

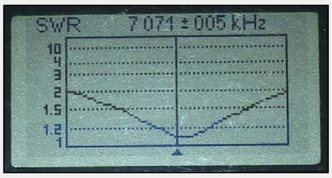
To protect the capacitor from the weather, I cut some slots in a plastic storage bin, and used it to enclose the capacitor and its drive motor. The plastic wasn't particularly UV-friendly, so I coated it with an enamel paint to keep it from deteriorating. This installation also uses a Balun Designs 1115 coaxial choke.

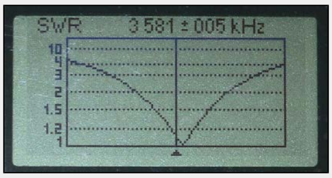
The Zebra — A Helical STL for 40m & 80m

The copper-strap 80m STL described earlier worked very well, but it needed to be improved. For one thing, the copper strap acts like a wing during windy conditions, which causes it to twist and torque. That causes the resonant frequency to drift up and down as the conductor is continually warped by the wind. With a usable 80m bandwidth of only a few kHz, the antenna can't really afford a lot of drift. Thicker copper strap would be one way to stabilize the "vanes" formed by the loop, but thicker strap is both more expensive, and *heavier*.

Further, the diamond loop was a simple enough shape, but it seemed like there should be some way to better exploit the area enclosed by the loop without making it heavier. The simple 25' perimeter loop has a predicted efficiency of around 38%. While this is competitive with many vertical antenna installations for 80m, I wanted to find a way to improve this, if possible, without making the antenna significantly larger.

I have often looked at K8NDS's helical loop designs, and wondered if such a design could be made to work efficiently on 80m, using helical windings to increase the length of the loop without increasing the enclosed area. I also wondered if the helical design might provide a more stable mechanical shape, without adding excessive weight to the antnena.





The Zebra antenna, shown at right, is just such an antenna. It uses the same 6.25' diamond support shape as the previous 80m loop, but it uses foam tubing along the perimeter to provide a cylindrical form for wrapping thin copper strap into a helix. The foam uses a piece of thin-walled PVC tubing inside, to hold it into a linear shape, and to keep the foam from collapsing due to the inner void. The copper strap is actually a very thin copper foil tape, typically used for forming shields inside plastic project enclosures.

The copper tape wrapped around black foam tubes reminded me of a zebra, so I named it the "zebra loop."

Unlike the previous copper strap, this tape is only 3 mils thick. That's roughly the thickness of a glossy magazine cover — thin enough to be easily cut with a pair of scissors. This makes it rather light for its size. Unlike the previous loop, where the copper had to hold its own form and support itself for significant spans, all of the mechanical support for the Zebra's main loop is done by the foam.

The skin depth at 80m is approximately 35µm, or ~1.5 mils. Since the copper tape is 3 mils thick, it is near the optimum thickness which still allows both sides of the tape to support independent current flows. This allows the 2"-wide copper tape to approximate a closed, round copper conductor of ~1.27" in outer diameter. The $15 USD that I spent for 52' of copper tape is *nothing* compared to what I would have spent for 52' of 1" copper tubing or pipe. So the tape is about as cost-effective as STL conductor materials can get, at least for copper.

The perimeter of the loop form is approximately 26', with four sides of 6.25' each. With a conductor length of 52', the helical winding of the conductor yields a size reduction ratio of just over 2:1, in both diameter and perimeter. The foam "noodles" that I used are 1" ID, and ~2.125" OD, which was large enough to allow the 2" tape to have a spacing between turns of ~1".

The first test-stand of the Zebra yielded an antenna that could be made to resonate anywhere between 80m and 40m. The tuning is *very* sharp, as one might expect, with the 40m 2:1 bandwidth being around **10kHz**, and the 80m 2:1 bandwidth being approximately **4.5kHz**, as measured at the end of approximately 50' of RG-213 cable. The SWR sweeps for 40m and 80m are also shown at right.

According to the ARRL formulae, a circular loop of 50' circumference, when mated with a 500pF capacitor, should be able to resonate over the entirety of the 160m band as well. However, winding the inductor into a helix changed the properties enough that I was only able to tune down to about 2350kHz with 500pF. So the 160m band is definitely possible with this loop, but it will require a bigger cap than what I have handy.

Resonance near the bottom of 80m was accomplished with less than 250pF of the 500pF capacitor. Since vacuum variable capacitors have the best voltage handling characteristics when they are fully enmeshed, a 250pF or 300pF capacitor *might* be a better choice for this design.

Unsurprisingly, the 80m SWR bandwidth, even when measured at the end of a piece of coaxial cable, is *lower* than that predicted by the ARRL models for a full-sized loop made from strap of the same length, measured at its feedpoint. It is possible that winding the single turn inductor into a rough toroidal form is hiding additional losses by narrowing the bandwidth through normal "loading" mechanisms seen in other antenna types. That said, if there were any substantial losses introduced by the shape of the antenna, I would expect to see more change in the bandwidth than what I observed.

The first on-air testing of this antenna was during ARRL Field Day 2018. I put the antenna up about one loop diagonal high, measured from the ground to the bottom corner, and proceeded to work 80m in the event. I used an 0.5 RPM DC motor for simplicity, which was about the right speed to enable easy and manual adjustment with a simple toggle switch.   As expected, the antenna worked stations coast-to-coast (and all distances in between) on 80m, despite poor conditions (elevated A-index) and lots of local thunderstorms. I worked stations until the storms closed in on my location, then lowered the antenna around 00:45 local time. Since 80m was still in the process of "going long," more testing under quieter conditions is definitely on the calendar.

The good news about this antenna design is that the helical shape wrapped around a foam and PVC support did indeed stabilize the conductor physically, providing a far more consistent match than the previous design when operating in windy conditions. The thunderstorms during Field Day provided excellent test conditions for physical stability.

The helix pitch is completely at the control of the designer, so even if a helix isn't an explicit goal of an antenna project, the tubular support shape could be used to wind a very loose helical form for a copper strap/foil antenna. So even if the helix doesn't contribute to the "loading" of the antenna, the general shape could be used for purposes that are related solely to mechanical stability. I previously thought of the helical designs as just a way to get more copper length on a fixed-size form, but the helix shape is a general tool with several advantages, each of which is valid independently of the others.

Notes on Multiband Operation

I tend to use my loops on single bands, but I have used a few on more than one band. It is easy enough, given sufficient funds, to buy or build a tuning capacitor that has a large enough range that it can resonate a given loop on any frequency across several HF bands. However, the radiation resistance will vary widely as you move from band to band, because the loop circumference is a very different fraction of a wavelength on one band than it is on another. This makes feeding the loop a challenge.

My experience has been that feeding a loop on one band for a 1:1, 50-ohm match, will result in around 1.5:1 match on the two adjacent bands, and a 2:1 match on the two adjacent bands beyond that. For example, if I adjust the Mark-7 loop so that it has a 1:1 match on 20m, the 30m match will show about 1.5:1, and the 40m match will show 2:1. Similarly, the 80m loop can be matched for 1:1 on either 40m or 80m, but once adjusted, the other band will be 2:1, with 60m showing about 1.5:1. I have often used my original 3' loop for both 20m and 15m, but when I move the feed loop to achieve 1:1 on either band, the other band will show about 1.5:1.

So what can a multiband loop user do?

You can adjust the feed loop (or change the number of turns on a CT-style feed) when you change bands, but this isn't terribly convenient. There are probably all kinds of clever ways to motorize the position of the feed loop, or use relays to adjust the number of primary taps on a CT, or to selectively switch in a hairpin matching inductor. And there is nothing wrong with any of these approaches.

There is also nothing wrong with using a common desktop tuner on an otherwise resonant loop. As long as the loop capacitor has been adjusted to cancel the reactive component of the feedpoint impedance, the loop is resonant. If the SWR presented at that point is still reasonable, perhaps 1.5:1 or 2:1, corresponding to a resonant impedance between 25+j0 and 100+j0, using a desktop tuner to pull the real portion of the impedance closer to 50 ohms is perfectly acceptable. The trick is to avoid using the tuner to trim a loop that is off-frequency, even by a small amount. A proper sequence should be something like this:

1. Bypass the tuner, removing its reactive components from the feedline
2. Adjust the loop antenna to be resonant on the current frequency; this means that the reactive part of the impedance is **zero** or as close as possible to zero. This might not be the point of minimum SWR for a 50-ohm system; the target impedance is the point where the loop reactance is zero.
3. Put the tuner back in-line, so that the reactive components are connected to the feedline
4. Adjust the tuner, or run its automatic tuning sequence, to bring the impedance presented to the transmitter to 50 ohms
5. Operate as normal, by adjusting only the loop capacitor as operating frequency changes
6. DO NOT ADJUST the desktop tuner until a band change; use the loop capacitor to do all the tuning within a band. If the tuner has an automatic mode, switch the tuner to manual mode. Do not allow the tuner to make automatic adjustments within the current band.
7. When changing bands, repeat the entire sequence from the top

I have used this sequence for multiband operation of small loops, up to a 2:1 SWR reading at the desktop tuner, and it works very well, even at power levels in excess of 500W. Again, the main idea is that I only use the desktop tuner to do real-valued impedance transformation, with the loop capacitor performing all of the adjustment needed to change frequency within a single band. It is the loop capacitor that does all the work of presenting a real, resonant impedance to the feedline.

Next Steps

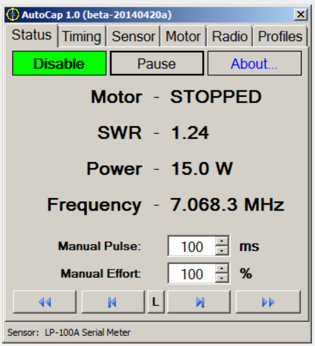
Beyond the extensive tinkering described above, any loop will need some additional work before use in a permanent outdoor installation:

1. **Security** — Copper theft is all the rage these days. A yard full of copper loops sticking up in the air might be too much temptation for a thief to resist. Finding a way to prevent this may be tough, since the tubing would be easy to cut from the mast. Height is one tool, getting the loop up high enough in the air to make it difficult to reach. Another option is to paint the copper with a flat enamel that is a dull gray or green color. That would make the antenna harder to see, as well as making it appear to be just another piece of plastic yard junk. A nice side-effect of painting the antennas with an appropriate paint is that it prevents the copper from tarnishing or oxidizing over time, which is particularly helpful with portable antennas like these, that are handled regularly for set-up and tear-down.

2. **Weatherproofing** — The capacitor needs to be covered and protected from rain, ice, dirt, debris, birds, insects, etc. Some kind of sealed plastic enclosure be ideal, especially if the plastic is resistant to UV from the sun. The main challenge is the number of protrusions that need accommodation. The enclosure needs holes for the mast, the shaft, and the two inductor ends, at a minimum. The 80m strap loop used a PVC tube as a jacket around the motor and capacitor, and this seemed to be a good first draft. The plastic shell around the Mark-7 is also holding up well after several months outdoors.
3. **Mast Alternatives** — The PVC mast was cheap, simple and effective. However, not all PVC is made to endure the elements. PVC can deteriorate under UV exposure, and it can even deform when heated. Further, PVC does have limits on how much voltage it can withstand. When high voltage is presented across short lengths of PVC, the PVC can absorb substantial amounts of power due to heating. Rebuilding the loops on a fiberglass mast would be better, since fiberglass is also non-conductive, but is also tougher and more rigid.
4. **Motor Stops** — For some capacitors, there needs to be a way to prevent the motor from running the capacitor shaft all the way to either of its physical limits. If the capacitor adjustment range is limited, this could do some damage to the capacitor or the attached motor. For now, I'm just careful, and I use an antenna analyzer to make sure the position of the capacitor is still well within its limits while tuning. I discussed this topic at somewhat more length in the AutoCap article.

An Improved Control System

I have also done some work on an automated control system for these antennas, and that project is described on the AutoCap Software Page. That article is a continuation of this one, describing control system changes. The software-based controller allowed me to convert the loops to use stepper motors to move the capacitor shafts, and achieve some truly impressive tuning speeds.



That said, the simple DC motors described above are more than adequate for loop control, and are easy to run remotely with very simple wiring. The AutoCap software supports many types of motors, and can even be interfaced to some types of self-contained motor controllers. For the casual operator who likes to rag-chew, a simple gearhead motor with a DPDT switch at the control point makes the loop antenna easier to use than a typical tube amplifier.

Some Conclusions

Over the course of several years, I constructed and tested loops for all of the major HF bands, and for some bands, more than one. In hindsight, if I were to start from scratch setting up a limited-space set of permanent outdoor loops, my goal would be to have *two*:

- The first would be a smaller loop, such as the ~3ft diameter loop like the one described at the top of this article, for the shorter HF wavelengths.
- The second would be a larger loop, such as the extended Mark-7, which would include the 80m and 40m bands in its coverage.

Even though I have described several purpose-built loops for single bands, the combination of two such loops would cover all of the HF bands, and would consume a very small installation area. In fact, such a setup could easily fit in the attic space of nearly any medium-sized house. An attic installation has the nice feature of eliminating the need for weatherproofing the capacitor and feedline connections. Such an arrangement could also work for apartment dwellers, consuming only a tiny bit of floor space.

Closing Thoughts — Possibly Controversial Ones

There are two aspects to loop performance that interest me. The first is receive rejection of certain kinds of interference, and the other is efficiency during transmit.

<u>Noise Reduction</u>

People who study EM theory point out that a loop antenna's pattern isn't all that "magnetic" in a large portion of the near field. They also point out that in the far field, the propagated EM wave has a fixed ratio of E/H components, with the ratio being fixed by the impedance of free space. The latter argument is solid, but the former argument needs some context.

For transmission, the ratio of E/H is variable within the near field, with the ratio being a function of distance from the antenna. As the wave travels away from the antenna, the ratio approaches the fixed ratio that it will hold as it propagates through free space. The small loop antenna does have a mostly magnetic response, very close to the antenna during transmission. However, during transmission, the antenna is *driving* this field variation. As the current oscillates within the antenna conductor, it forms a strong magnetic field, and a very weak electric field, which generates a wave that transitions to a normal free-space E/H ratio in the far field.

However, during reception, the antenna isn't actively driving the E and H fields in the antenna's near field. EM waves that approach the antenna don't magically start to change their E/H ratio when they cross the imaginary two-wavelength surface surrounding the antenna's near field. These waves maintain their E/H ratio at a natural value, defined by the impedance of free space, until these waves actually *strike* the antenna, and start to generate a response. Since the loop conductor is essentially a large current probe suspended in free space, the response of the antenna is driven by the magnetic field crossing the conductor, which induces a small current in the loop. So during reception, it is entirely possible that the antenna really does respond mostly to the magnetic component of an arriving wave.

More important still is the nature of the arriving wave. Remember that a small loop antenna is a high-Q resonant circuit. If an arriving signal is self-similar (i.e., the signal has a high autocorrelation value), wave after wave of energy strikes the antenna, each one adding to the circulating current building up in the loop, producing a signal at the receiver. If the signal isn't self-similar at RF, the amount of circulating current allowed to build within the antenna is limited, which limits the signal level at the receiver. Most ham transmissions (CW, SSB, RTTY, PSK, etc.) are highly autocorrelated, otherwise their spectral purity would be poor. Many pulse-like QRM sources (engine ignition noise, arcing power line hardware), have poor autocorrelation because they are generated by individual sparks at a rate far less than the receiver's RF frequency. This may be another reason why loop builders report significant S/N ratio improvement from their loops, even when the offending noise source is well within the main lobe of the antenna, and not located in a null. The loop may indeed be less sensitive to some kinds of noise than other antenna types, depending on the autocorrelation value of the noise signal, and the Q of the loop used for reception. If the loop is particularly lossy, this might improve the situation even more, because the required amount of autocorrelation in an arriving signal would be even higher in order to produce a significant signal at the receiver. This "lossy improvement" is likely present even though the loss resistance tends to lower the Q of the antenna.

<u>Efficiency</u>

Many people are quick to dismiss the STL as a practical antenna due to efficiency concerns. They design an STL using the AA5TB spreadsheet or other equations from the Antenna Book, and they see that their preferred design has a less-than-stellar predicted efficiency. For example, according to those formulae, the 40m, 5' antenna described above should have an efficiency on the order of 30%, or -5.2dB. That sounds fairly poor on first glance, but even if the predicted efficiency is correct, it requires some perspective. AD5X did considerable work on antenna efficiency, and he points out that even a quality installation of many popular multiband verticals can easily have an efficiency on the order of 30% or less. For multiband verticals that use a wide-range indoor tuner, the extra feedline losses can make the -5.2dB efficiency of an STL particularly competitive — while fitting in a *much* smaller space, even indoors. A loop that is close to λ / 4 in circumference (approximately λ / 13 in diameter), can easily have an intrinsic efficiency of 90%, while achieving this with even the best vertical antenna is a nontrivial challenge. As both the loop and the vertical are reduced in size, the STL remains very competitive, and can even have a *better* performance than the vertical if all losses are accounted for, including coaxial SWR losses, ground losses, and the reduced resonant impedance of a shortened or loaded vertical element.

All of these considerations are well-known for people who are willing to research and understand them. However, there are some other possible reasons why the efficiency of an STL, of the type and design typically used by amateurs, might be more efficient than suggested by the normal design tools.

There is some well-accepted classic theory that describes the efficiency of a small transmitting loop. That theory is documented in the ARRL Antenna Book, among other places. However, people like G3LHZ have done some interesting work trying to account for the losses claimed by the classic theory. Strangely, there are real-world thermodynamic experiments that do not seem to support the traditional loss calculations. For example, if a magnetic loop for 2MHz is constructed so that the classic calculation shows a 5% efficiency, and if we feed that antenna with a 100W carrier, we should be able to find 95W of energy (or something close to it) being dissipated as heat somewhere in the loop. Mr. Underhill's experiments using thermal cameras show this may not be the case. When he accounts for the detectable heat generated by the loop, his experiments suggest typical small-loop efficiencies to be on par with other classic antennas, such as dipoles and verticals. At the very least, they may be no worse than the loaded versions of these antenna types.

I have spent some time thinking about this discrepancy, and how to account for it within the typical ham home-made loop. This is not to say that I am asserting this as correct, but I suspect there are straightforward reasons why the efficiency of a small loop of typical construction <u>could</u> be better than the classic formulae predict.

One simple possibility has to do with construction. Many loop designs, mine included, use open-ended copper tubing for the radiating element. Mechanically, this means that the loop itself actually has <u>two</u> conductors, wired in parallel. One is the outside of the loop conductor, and one is the *inside* of the loop conductor. The reason for this is skin effect. Anybody who has run high power RF into a coaxial cable that is poorly matched to a balanced antenna is familiar with the "feedline radiation" effect, where the shield of the coaxial cable forms *two* conductors, with current flowing on both. In the loop case, The outer and inner surfaces of the loop conductor are connected together at the ends, so the two conductor shells carry current in parallel. Depending on the difference in diameter of the two surfaces, the effective increase in surface area can be almost 100%, roughly doubling the surface area of the main element. *"But the inner conductor is shielded from the environment by the outer conductor,"* someone might object. This is true for the electrical field, but *not* the magnetic field, which just happens to be the largest component of the EM near-field created by this type of antenna. A small loop is driven almost completely by the magnetic field generated by the driven element, and the lines of magnetic flux cut both the inner and outer surfaces of the main (large) loop, inducing current flow into each one, independently, and the two are able to create a combined magnetic field around the antenna.

Many loop builders unknowingly *depend* on this two-surface behavior, because their designs utilize trombone-style capacitors. These capacitors are often fed current on their outside surface, but the outer "plate" of such a capacitor is actually the *inside* surface of the outer trombone tube.

If the tubular loop's effective surface area is nearly double that used in the calculations, because it has both an inner and outer surface, the current flowing in *each* surface is roughly *half* what is predicted for the loop conductor using the standard formulae. Since power lost in the resistance is proportional to the square of the current passing through the resistance ($P = I^2R$), the heating loss in each surface of a tubular loop could be closer to 25% of that predicted by the model. The two surfaces together, then, have a combined heating effect that is 50% that predicted by the model for a wire of equivalent outer diameter. Put another way, the two surfaces in parallel form a net resistance that is half that for a solid wire with an outer diameter equal to that of the tube. This results in a power loss of one half the amount of a wire of the same outer diameter. This dual-surface feature alone is enough to explain a 3dB discrepancy between the model (which assumes a solid conductor) and an open-ended tubular loop antenna.

Another possibility that applies to loops of *any* construction has to do with the pattern of current flow on a loop antenna's main conductor. At its core, such a device is a capacitor and an inductor, connected back-to-back. You can think of it as a resonant circuit, where the capacitor and inductor are in series with the abstract "radiation resistance", which is the "load" presented to any antenna, allowing the RF current in the antenna to be transferred into free space.

We want the "radiation resistance" of any antenna to be much larger than the sum of all other losses. This is the heart of antenna efficiency calculations.

Power transferred into the antenna is going to be dissipated in one of two ways — radiation into space, or heating of the antenna or its immediate surroundings. The copper loops and the metals in the capacitor contain the real resistive components of the antenna. If heating of the antenna is to occur, it must happen here. In addition to the intrinsic real resistance of the copper itself, we must again consider the skin effect, which effectively "thins" the copper conductors for the purposes of conducting RF current.

Copper conductors in a magnetic loop antenna are not simple conductors, however. Even when you factor in skin effect, there is still a component missing. All of the copper conductors in a small transmitting loop are part of one of two inductors. The small loop is a primary winding of a two-winding air-core transformer. The large loop is the secondary. The current flowing through these conductors are operating at varying amounts of phase angle from the voltage at any given point. Inductors delay current changes, capacitors delay voltage changes. Since all of the metal in the antenna is part of a reactive component, the power flowing in the entire loop is subject to voltage-current phase angle shift.

There are two points in the antenna where the phase angle between voltage and current will be zero. These points would be very difficult to locate physically, but they must exist. The large copper loop is an inductor along its entire length. The capacitor is a lumped reactive component, and its leads are, for all practical purposes, part of the inductor. As current circulates in the loop, the current will experience the highest inductive VAR (volts-amps-reactive, or "reactive" power) value at the bottom of the loop, furthest from the capacitor. The highest capacitive VAR value will be within the capacitor itself. Somewhere along the conductive path between each capacitor plate and the bottom of the loop, the capacitive phase angle will cancel the inductive phase angle, and all of the power at that point will be real (i.e., the impedance is completely real, and has no complex components). Remember these points for the moment.

Heat in a circuit is generated as current passes through real resistance. The reactive components of a resistor do not add to the heat generated. Put another way, current cannot do work (including generating heat) unless a voltage potential is also present. The amount of work that can be done is inversely proportional to the phase angle between the voltage and current. This is the whole idea behind power factor — the voltage and current must overlap to some level to do work. Power companies rely on this principle, and enforce it vigorously in their customer contracts. So heating of any AC circuit component is directly related to the phase angle of the voltage and current within that component.

Now back to the loop. Remember that there are two "loads" within our antenna. The first is the radiation resistance of the antenna, which is its ability to transfer RF current into radio waves in free space. The second load is the loss inherent within the antenna. Remember also that there are two points in the antenna where voltage and current are in-phase. These are the points where the RF energy is able to do real work and heat the antenna conductors. As we move away from these points, there is some amount of phase angle between voltage and current. This angle diminishes the ability of the RF energy to heat the conductors where the angle is not zero. The closer the angle is to 90°, the less heating can occur. By restricting the zero-VAR area of the antenna to two points, and to a lesser extent, the regions immediately around those points, the resistive losses of the antenna are concentrated around those two points. Despite the fact that RF current flows at high levels throughout the antenna, these two points and their immediate surroundings become the focus for resistive losses.

However, remember that there is a second load in the circuit: the radiation resistance. We can't pin a location on this load, but its value is still part of the efficiency equation. If we rethink the loop, and realize that the heating losses don't occur throughout the entire conductor length, but are instead centered at two points in the loop, that realization leads us to the conclusion that the current theory for small transmitting loops is grossly overestimating the contribution of I^2R losses contributing to the efficiency calculation. This would go a long way to explain Mr. Underhill's experimental results. The ratio of RF energy being dissipated by the radiation resistance to that of the RF energy being dissipated by the resistive losses of the conductors is likely much higher than predicted by the classic theory. I am increasingly convinced that this is due to the reactive nature of the antenna components, as described above.

If we assume that this is correct, then how might this influence the design and construction of loop antennas? How could we squeeze the highest efficiency out of an antenna if we are correct?

A key improvement would be to focus on the two points of minimum phase angle, and minimize the real resistance of the conductor found there. To do this would require being able to calculate these locations. Given a value for the capacitor, and a length of the attached inductor (that included the leads and plates inside the capacitor itself), it should be possible to estimate their location. Given that the capacitor is a lumped value, and the inductor's reactance is distributed over a relatively large length, it is entirely possible that most real heating occurs close to the capacitor body, possibly within the jumpers between the capacitor leads and the main inductor body. This may explain why heating in G3LHZ's loops appeared to be rather uniform within the inductor body. The maximum heating may have been taking place at spot locations on the capacitor jumpers. Since we tend to expect these connections to be "weak spots" anyway, the extra heating there and its cause may have been overlooked.

It is also possible that the heating effect of loop antennas is just not sufficient to make it necessary to find the two main heating points. Even at these two points, the radiation resistance may sufficiently trump the real losses that the real losses are insignificant. This idea is also supported by the experimentally determined efficiencies of Mr. Underhill's loops.

Devising experiments that would support or discredit these ideas is difficult. However, the current experimental evidence has made me curious, and will continue to encourage me to experiment with these antennas.

Links

AutoCap Version 1.0 — An autotuner project specifically for small transmitting loops.
An Overview of the Underestimated Magnetic Loop HF Antenna by Leigh Turner, VK5KLT
AA5TB Small Loop Site — includes an excellent Excel calculator for sizing loop components.
ARRL Antenna Book — Source for the formulas used by AA5TB's design spreadsheet.
Georgia Copper — Source for all sorts of copper products.
ServoCity — Source for all sorts of DC motors.
MaxGain Systems — Source for surplus vacuum capacitors and other hard-to-find components.
Balun Designs — Source for customized coaxial chokes.