Electrically Small Resonant Loop Antenna for Mediumwave Reception

By Bob Colegrove

Abstract

Herein the author describes how on exploring the musty stacks of a large engineering library some years ago he uncovered a trove of peer-reviewed journal articles and ancient texts related to the theory, design, and operation of loop antennas, as well as their attendant components of inductors, capacitors, resonant circuits, and direction-finding apparatus. This material still has much to say to us today. Considering the author's own untutored background, and not being one to question the validity of these electronic pioneers, he has documented the salient points, and attempted to reconstruct their principles in the form of a suitable resonant loop antenna for the reception of mediumwave, amplitude-modulated signals. By following vicariously in their footsteps, the theory, design, construction, and operation have been described in Electrically Small Resonant Loop Antenna for Mediumwave Reception.pdf.

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1. Introduction

I began listening to radio in 1958 – that is, seriously listening to radio. I discovered magnetic-field antennas in the early '80s, continue to tinker with them to this day, and use them to the exclusion of most every other type of antenna. A loop antenna is a delight for those of us from the pre-phase-locked-loop vacuum tube days. It gives you the sense that you are really tuning your radio and not just pressing buttons. At the time, I had access to a large engineering library and availed myself of its wealth of electronic information, particularly regarding loop antennas. Much of the early research and theory was available, some of it quite intelligible to an English major. My primary interest was mediumwave, although I subsequently constructed resonant loops operating at longwaves and shortwaves.

1.1. Properties of Resonant Loops

There are a few properties of loop antennas which make them attractive.

- Properly constructed, they will produce a signal+noise-to-noise ratio comparable to or better than random-wire, electric-field antennas. Initially, you may be discouraged that the volume and signal strength indication is not as high. However, careful tuning will uncover signals that are not otherwise detectable.
- Resonant loops are highly *selective*. They are not wide-band antennas. They must be tuned as you move up or down the band. At mediumwave frequencies, a change of 5 or 10 kHz will produce a noticeable increase in signal strength when the antenna is retuned. Thus, loops of the type described here are passive preselectors. With a limited bandpass, they mitigate interference which might otherwise be processed by the receiver downstream, reducing the susceptibility to overloading and intermodulation.
- Loop antennas are *directional*. The signal will peak over a broad directional pattern and completely disappear or 'null' within a range of very few degrees [Solt, 1932, pp228-260]. This makes possible separate reception of two or more stations on the same frequency. Directional response also works in favor of local noise reduction. Since noise and interference are often in opposing directions to that of the signal, it may be possible to greatly reduce these annoyances. These features give the loop a distinct advantage over random wire antennas.

1.2. Specific Characteristics

The design presented here offers no new insights into the subject of loop antennas. It is rather a distillation of numerous documents covering a period during which time radio navigation was born and developed into a highly sophisticated science having indispensable marine and aviation applications. There is no single, perfect loop design. Materials and dimensions may be selected to optimize anyone of several characteristics. These are the characteristics of the antenna described herein:

- ***Receiving*** – Despite their inherent low radiation resistance, loop antennas are sometimes adapted to transmitting. This, however, is a strictly receiving antenna.
- ***Electrically Small*** – The dimensions of the primary coil are much shorter than the wavelength being tuned, defined as less than or equal to $\lambda/10$, where λ is the wavelength of the incoming signal.
- ***Resonant*** – The primary loop consists of a coil and variable capacitor which resonate over a band of frequencies to produce an alternating magnetic field having a high figure of merit or Q. This article focuses on an antenna which operates over the mediumwave (AM) broadcast band, that is, between 530 kHz and 1700 kHz. The same concept can be applied to longwave, or

shortwave. They are all similar in design and operating principle. They differ primarily in the size of the primary coil winding. The longer the wavelength, that is, the lower the frequency, the larger the coil.

- ***Passive*** – There is no active amplification outside the receiver. Preamplifiers can be used to some advantage with loops. Their purpose should be as a coupling device, converting the high-impedance of the primary circuit to a low-impedance for the transmission line to the receiver. It must be remembered that the system is only as good as the coil, and a preamplifier is not the place to start improving a basically unresponsive winding. Instead, this antenna relies on its proximity to the radio and a good impedance match to provide optimum signal input.
- ***Air Core*** – The space between turns of the coil, notwithstanding the wire insulation, is air. It relies on the number and the area of turns for its effective height, or ability to generate a voltage across its terminals. This differs from a ferrite core coil, which due to its high magnetic permeability can focus or concentrate a larger area of magnetic field through the center of the coil, thus greatly minimizing the size of the coil.
- ***Spiral*** – This is sometimes referred to as a flat or ‘pancake’ loop; that is, the coil is wound in a single plane. It differs from a solenoid loop which is wound cylindrically along the coil’s center axis; that is, a solenoid is three dimensional. For a given value of inductance, a spiral loop will have less distributed capacitance than a solenoid [Welsby, 1960]. Distributed capacitance acts with the coil to produce a self-resonant frequency; however, its fixed value prevents it from being useful to manually tune the circuit.
- ***Local*** – The antenna is intended to operate near the radio. This may be either indoors or outdoors. Remote operation was not considered for a couple practical reasons.
    - Some experimenters have used variable capacitance diodes, or, as they are variously known as a varicap diodes, varactor diodes, variable reactance diodes or tuning diodes. These devices permit a remote resonant antenna to be tuned. The associate circuitry to precisely adjust the voltage on the diode was regarded as unnecessarily complex and providing very little functional value for this application.
    - Assuming the antenna is located outdoors, it may be exposed to periods of excessive moisture. This has a negative effect on the figure of merit or Q of the tuned circuit seriously compromising its performance [Sandretto, 1942, p 121; Levy, 1943, p 56].
- ***Transformer-Coupled*** – There are two coils, which operate on the principle of a transformer. The primary coil is the main receiving antenna, which, in resonance with the variable capacitor, produces an alternating magnetic field. The secondary coil, which is shielded to normalize directional response, operates by mutual inductance, and, along with a twisted pair transmission line, provides low-impedance input to the radio.

Figure 1-1 shows the basic concept for this antenna. The primary resonant circuit is formed by C1 and L1. L2 is a low-impedance, shielded coil having just three turns, which feeds the low-impedance input of the receiver through a twisted pair. The shield is grounded to the receiver through one side of the twisted pair, and has an all-important gap, which interrupts it from making a complete circle, in which case it would prevent penetration of the magnetic field.

C2 in series with C1 lowers the circuit capacitance, thereby extending the band coverage somewhat higher and enabling a higher inductance/capacitance (L/C) ratio. S1 is a ‘band switch’ which can be used to short C2, thereby restoring variable capacitance to the value of C1; thus, a high band with the switch open, and a low band with the switch closed. Typically for mediumwave, there is a band overlap between ~1200 kHz and ~1400 kHz. C_d represents the inherent *distributed*- or *self*-capacitance of the coil, L1. This contributes to the circuit resonance but cannot be used to manually change frequency. I will have more to say about the importance of distributed capacitance and its effect on the L/C ratio of the circuit in Section 1.4, below.

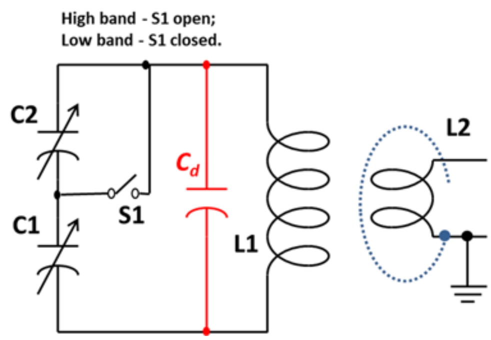

Figure 1-1. Schematic of Loop Antenna

1.3. A Little Bit of Theory

The performance of a loop is directly related to the product of its effective height, h_e and figure of merit, Q [Swinyard, 1941, p 385],

$$h_e \times Q \text{ or } \frac{2\pi AN}{\lambda} \times \frac{X_l or\ X_c}{R}$$

Effective height is a relative figure, which allows comparison among two or more antennas. It increases with coil size, or, more specifically the product of coil area, *A*, and number of turns, *N* [Martin, 1937; Sandretto, 1942, pp 32, 120; Browder and Young, 1947, p 520]. *Q* is maximized by reducing high-frequency circuit resistance at resonance, the most significant components of which are skin effect of the wire and loading by the pick-up coil and receiver [Sandretto, 1942, p35; Levy, 1943, p 58; Terman, 1943, p 77].

Since loop antennas are directional, a complete consideration of effective height must also consider the orientation of the antenna with the incoming electromagnetic field. The complete function for effective height is $h_e = \frac{2\pi AN \cos\theta}{\lambda}$. Response of the antenna is greatest when the axis of the primary coil is normal to the incoming signal. Since we are dealing with flat spiral or 'pancake' coils, this means the plane of the coil is pointing toward the station's ground wave. When θ is zero degrees, that is, the plane of the coil is aligned with the incoming signal, cos θ = 1, and the signal is peaked. When cos θ = 0, a sharp null occurs [Martin, 1937]. See also Ideal Nulls on Page 6 and Section 9, Operation, beginning on Page 24.

1.4. Inductance/Capacitance (L/C) Ratio and Sensitivity

Assuming a high-impedance circuit, that is, a tuned resonant circuit, it is desirable to have the highest possible L/C ratio to obtain the largest possible effective height. This requires special consideration in coil design. The distributed capacitance, which exists in every coil, acts in parallel with the inductance. It represents wasted capacitance in the circuit; that is, it cannot be varied and used in the tuning range of the antenna. In other words, if we could minimize distributed capacitance, we could increase the size of the coil (i.e., greater effective height) to resonate the same frequency. It has been found that, for a given size inductor, distributed capacitance is least when the winding is a flat spiral, in a single plane [Welsby, 1960]. Antennas using this geometry are sometimes called 'pancake' loops. A 24" square pancake loop designed to tune the upper end of the broadcast band will have ¼ to ½ the distributed capacitance of a 24" solenoid winding used to cover the same band. Because of this, it can have higher inductance resulting in nearly twice the effective height.

As a corollary to this principle, one of the serious deficiencies of most loop antenna designs is that they try to cover too much of the rf spectrum. Parallel capacitors are often switched in to extend the range to lower frequencies. There is an inherent drop-off in sensitivity as the L/C radio is decreased. On an analog radio for example, the stations at the lower end of the AM broadcast band will not be as strong as those at the higher end. Coils used to cover the entire broadcast band, have 1/3 the effective height at 540 kHz as at 1600 kHz. This represents a 10-db loss. In the days of analog shortwave radios, better radios had six bands instead of the usual four bands on lower priced models. In this way the spectrum was divided into smaller segments, and not as much capacitance was required to tune to the lower end of each band. Also, where possible, the high end of the band occurred just above an amateur or broadcast band to provide coverage of popular tuned bands in the region of best sensitivity.

1.5. Ideal Nulls

The ideal loop response pattern and maximum nulls are produced when the loop is either electrostatically balanced to ground or shielded. Three-dimensionally, the pattern is in the shape of a doughnut with an infinitely small hole in the center. A cross section is customarily shown as a 'figure 8.' The lobes of the pattern are the antenna's response directions; whereas the 'hole' represents points 180 degrees apart where there is no response or null direction. In the three-dimensional representation, the null is a vector having both azimuth and vertical components. The response pattern is illustrated and described more fully in Section 9, Operation, Page 24.

To achieve this response pattern, the loop must be balanced electrically with respect to ground. If this is not done, the current flowing between each side of the loop and ground will not be equal, and the greater current flowing through one side of the loop will produce greater voltage than the other side. This will then cause an irregular pattern in space instead of the regular figure 8. [Sandretto, 1942, p 36].

Shielding provides the necessary capacitance equalization between each side of the coil and ground, but this is done at a sizeable increase in distributed capacitance. This results in a lower L/C ratio and lower effective height than that which is otherwise possible given the same amount of coil inductance. For that reason, shielding a high-impedance coil is not practical. Instead, either a secondary, low-impedance coil may be shielded (Figure 1-1) or the primary coil may be balanced with a ground near its center [Schelkunoff and Friis, 1952, p 328].

1.6. Coupling to the Receiver

Overcoupling to the receiver will cause serious degradation in primary circuit *Q*, just as very loose coupling will result in inadequate signal transfer. With this antenna, a small secondary coil wound in the same plane as the primary has proven to be the most effective method of coupling. There are two parameters at work here: impedance match and coefficient of coupling.

a) ***Impedance Match*** between the two windings***:*** The goal for the coupling (secondary) coil is to have output impedance roughly equal to that of the transmission line and ultimately the receiver – 50 ohms for example. The primary circuit at resonance produces a reactance which is a function of the frequency and coil inductance. As the frequency goes up, so does the inductive reactance. Although within the primary circuit the inductive and capacitive reactances cancel one another, each is still present, otherwise there would be no resonance. It is this impedance which has to be transformed by the secondary.

Thus, the secondary must have the correct reactance ratio with the primary in order for optimum signal transfer to occur. As the tuned frequency of the resonant circuit becomes higher, this ratio must also be higher. Since the inductance of the primary coil is constant, the inductance of the secondary (coupling) coil must be decreased in order to increase the ratio. At LW and MW frequencies, the tuning range is not that great, and a single value of inductance will normally produce acceptable results. At SW frequencies however, the tuning range of the antenna may be several MHz and the change in reactance of the primary coil can be significant.[1]

b) ***Coefficient of Coupling*** between primary and secondary***:*** This deals with the actual physical size and orientation of the coupling coil in relation to the primary coil, regardless of its inductance; that is, how much of the alternating magnetic field generated by the primary circuit is captured by the coupling coil? A widely accepted rule of thumb is a 5:1 ratio between the diameters of the primary and secondary coil. There are likely many factors which enter into the precise size of the secondary coil, but the 1/5 rule for a secondary coil is a good starting point.

1.7. The Balanced Primary Coil

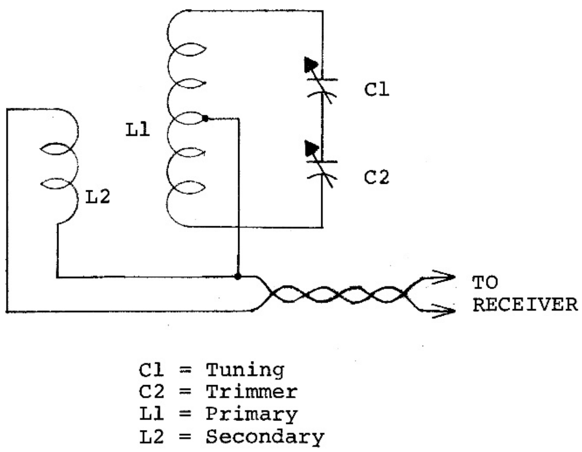

Figure 1-2. Schematic of Loop Antenna (balanced primary configuration)

Figure 1-2 shows the schematic for an antenna having a balanced primary coil. L1 C1, and C2 form the primary, high-impedance resonant circuit. L2 is the unshielded secondary coil, which functions as a low-impedance coupling loop.

L1 and L2 are both flat coils constructed in the same plane with L2 occupying the center area. L2 is coupled to the receiver with a twisted pair. C2 is added to the primary circuit to tailor the main tuning capacitor to the required frequency range. Since it is in series, it also lowers the minimum value of added capacitance permitting a slightly higher L/C ratio than if the variable capacitor alone were used. For applications where a single antenna is going to be used to tune the entire broadcast band, a dual-section variable capacitor is used with each section connected in series. A range switch is added to short out one section, raising the capacitance and allowing the antenna to tune to 530 kHz. Selection of appropriate capacitors is described in Section 6.2, Page 18.

The flat spiral or 'pancake' primary coil is somewhat difficult to balance electrically. This is because the capacitive center of the coil is not the center turn or geometric center of the coil. Each turn is a different size and has a different capacitance to ground. The actual balance point is located toward the outer turn of a pancake coil and is found experimentally as is described in Section 7.2, Page 21.

1.8. Shielded Secondary Coil

As indicated above, another means of balancing the antenna is to shield the secondary coil. This does not affect the performance of the loop in terms of sensitivity or selectivity and produces the same fine null characteristics of the balanced primary [Levy, 1943, pp 57-58]. In this arrangement, the primary coil and tuning capacitor are allowed to 'freewheel' in space generating a large magnetic field in the presence of the secondary loop.

The shielded or secondary pickup coil functions as a low-impedance, non-resonant loop. The shield ensures that all parts of the loop will always have the same capacity to ground regardless of the loop

[1] While fabricating loop antennas for shortwave, which generally cover a much larger range of frequencies, it was found that the inductance of the secondary coil had to be adjusted to better match the impedance at various frequencies throughout the tuning range. Consequently, these secondary coils, which are unshielded, are tapped and switched to provide optimum impedance match throughout the range of the antenna.

orientation or the presence of nearby objects [Terman, 1943, p 877]. In this way, the balancing effect of the shield provides the correct null response.

This shield does not complete a closed turn; there is a small gap where the terminals of the inner coil protrude. Consequently, the magnetic field will produce a voltage across the shield's open ends, but no current can flow. On the other hand, the magnetic field will penetrate the shield and act on the conductors, inducing a voltage. When connected to a load, that is, the impedance of the receiver, a current will flow [Sandretto, 1942, p 119]. Distributed capacitance of the secondary coil may be neglected. Fabrication of a shielded secondary coil is described in Section 15, Page 15.

1.9. Mechanical Considerations

Mechanical construction is no less a consideration than electronic theory. A loop must rotate 360 degrees to respond to any vertically polarized ground wave. In addition, a minimum of 90 degrees of vertical pitch are required to compensate for sky wave reception or electromagnetic field anomalies caused by nearby magnetic objects. Thus, the antenna assembly should be rotated to any position over a hemispheric dome. Since nulls are often obtained within a two- to three-degree arc, the coil must be mounted on a reasonably stable platform and easily adjusted to the proper position with minimal backlash. The tuning capacitor must be mounted so that it requires a short wire lead from the coil and can be adjusted without body capacitance affecting the resonant frequency. The higher the L/C ratio, the more important this becomes, as two or three picofarads of body capacitance will seriously detune the antenna.

2. As You Begin

This article describes a 2'-square antenna (Figure 3-1) covering the entire mediumwave AM broadcast band from 530 kHz to 1700 kHz. There are included a couple of notable options which represent a departure from the as-built configuration. My own experience is that, as built, this antenna will be entirely adequate for most hobbyists. It represents the evolution of what I have managed to learn and my subsequent tinkering over a period of a couple years, and has remained virtually unchanged for about 40 years. Though frail in appearance, the coil assembly was fabricated with light-weight material to facilitate mechanical balancing. Having survived the vicissitudes of handling and storage over that time with negligible maintenance, its reasonable ruggedness is attested.

This antenna, as described features a shielded secondary coil for electrical balance. For the sake of completeness, I have also described the alternate process of electrically balancing the primary coil.

I highly recommend the purchase of an LCR meter to measure inductances and capacitances. They are inexpensive and relatively accurate these days, but such was not the case when this antenna was designed and fabricated. Also, it will be helpful to put the variant formulas for resonant frequency, inductance, and capacitance into a spreadsheet, to give yourself a target value for each component. These tools are primarily responsible for the resulting Measurements Section beginning on Page 29.

$$f = \frac{1}{2\pi\sqrt{LC}}; \quad L = \frac{\left(\frac{1}{2\pi f}\right)^2}{C}; \quad C = \frac{\left(\frac{1}{2\pi f}\right)^2}{L};$$

for two capacitors in series, $C_{Tot} = \frac{C_1 C_2}{C_1 + C_2}$

The electronic and mechanical requirements listed here were the guidelines for the antenna described in following sections. Within limits, most dimensions are not too critical. Finally, the reader will eventually conclude my personal penchant leans toward function over form. Elegant finish and application of accoutrements are left to the discretion of the builder.

3. General Description, Tripod, and Universal Fork

Figure 3-1 shows the major parts of the antenna and its tripod. Note that the secondary coil is shielded. The tuning capacitor is mounted near the bottom of the vertical diagonal. The handle, besides being used to position the antenna, provides a counterbalance to maintain the pitch angle – more on this later. In practice, the knob on the capacitor is often more convenient than the handle to aim the antenna. The wooden tripod minimizes any metal interference or shielding.

3.1. Tripod

The tripod serves as the platform on which the coil assembly is mounted. The entire tripod and coil assembly are intended to be located near the receiver and adjusted as each station is tuned. The tripod should be constructed first, as it is required for trimming and calibration of the coil. The tripod consists of three legs, a platform, and a center post. Dimensions are not critical. Those given here are nominal and will serve for use with any antenna you choose to build, including a much larger longwave loop or smaller shortwave loops. The important characteristic for the tripod is that it be stable.

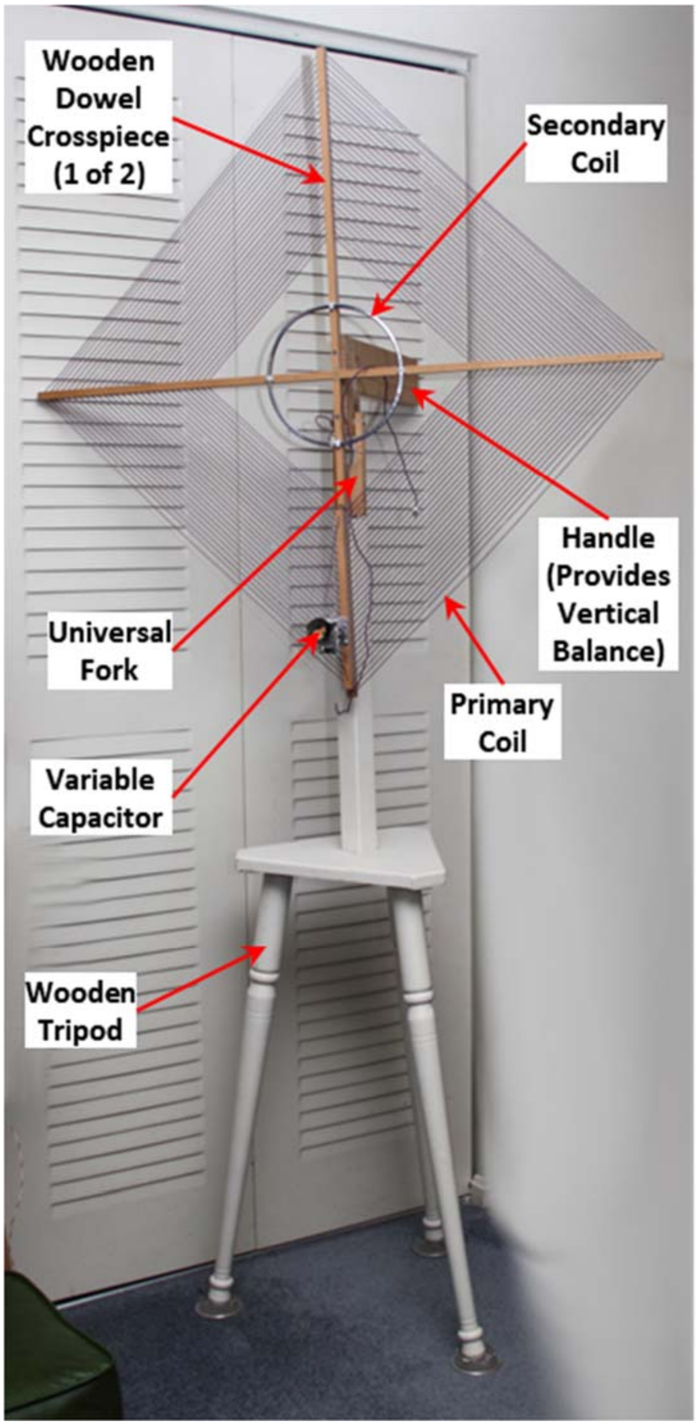

Figure 3-1. Two-foot MW Loop Antenna

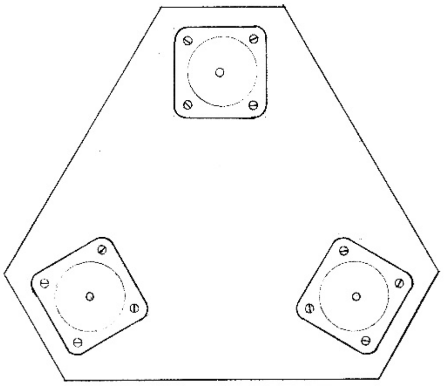

Figure 3-3. Platform, Bottom Side

The platform serves as a connection point for the legs and center post. A set of 30-inch, wooden, bolt-on legs, available at hardware stores will minimize construction time. If possible, obtain beveled mounting plates for the legs so that, when assembled, the legs will cant outward in tripod fashion. If straight mounting plates are used, shims can be installed under the plates at the inner screws to provide an outward cant to the legs. Figure 3-3 shows the bottom side of a platform for the tripod with the leg mounting plates installed. The mounting plates should be fastened at 120-degree intervals from the center point of the platform. The legs should either come with self-leveling feet or these should be added. If the antenna is to be operated on a carpeted floor, it is recommended that the large furniture cups be purchased and glued on the self-leveling feet. This will ensure a more stable foundation.

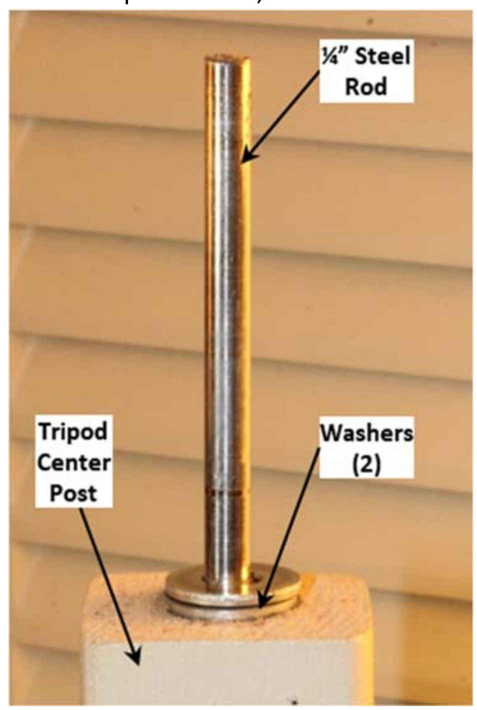

Figure 3-2. Steel Rod for Azimuth Rotation

The center post can be a 2' section of wood, nominally 1 $^1/_2$" × 1 $^1/_2$" square. It is fastened to the center of the platform with four wood screws. Care should be taken to fit the center post as squarely on the platform as possible. A $^1/_4$" diameter, 3" deep hole is drilled in the top end of the center post and a ¼" diameter, 6" long steel rod is inserted into this hole. This rod forms the mounting and azimuth pivot point for the coil assembly. Steel rod stock can be purchased at a hardware store. Figure 3-2 shows the steel rod with the coil assembly removed. It extends about 4" out of the tripod column to provide a stable grip on the universal fork.

3.2. Universal Fork

The key to the mechanical construction and operation of this antenna is the universal fork and handle arrangement shown in detail in Figure 3-4 and Figure 3-5. Note that the handle is described separately in Section 8, Page 22. Figure 3-4 shows the basic operation of the universal fork. This is fitted over the ¼" steel pin which extends vertically from the top of the tripod center post. Rotation of the universal fork on the pin provides 360-degree rotation of the loop in the azimuth. Both pitch and azimuth may be adjusted with the handle in a joystick fashion. Smooth, accurate pitch adjustment depends on proper mechanical balance of the coil assembly. A procedure for balancing the coil is presented in Mechanical Balancing, Page 23.

Figure 3-5 shows a side view of the universal fork with the plane of the coil oriented in the vertical (left) and horizontal (right) positions. The coil end of the handle is wider than the far end, and the pivot hole located in the lower portion of the handle. This permits the handle to be rotated through the prongs of the fork into a completely vertical position. A slight downward pitch is also permitted. Some tension on pitch rotation is provided by tightening a wing nut on the pivot bolt. This is necessary to minimize any backlash or drifting and to balance the azimuth tension, so that the handle can be moved in any direction with minimal change in mechanical resistance.

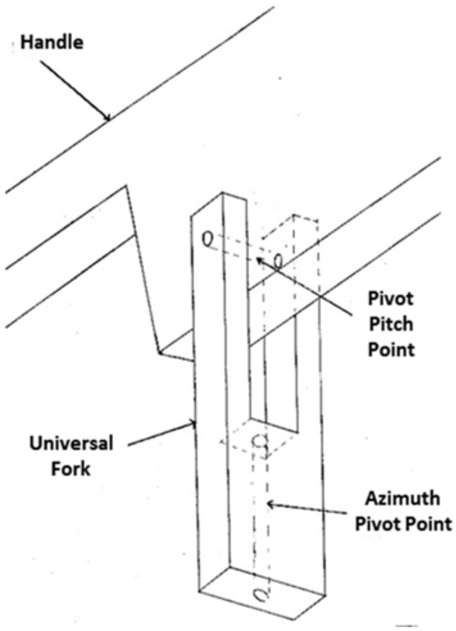

Figure 3-4. Arrangement of Universal Fork and Handle

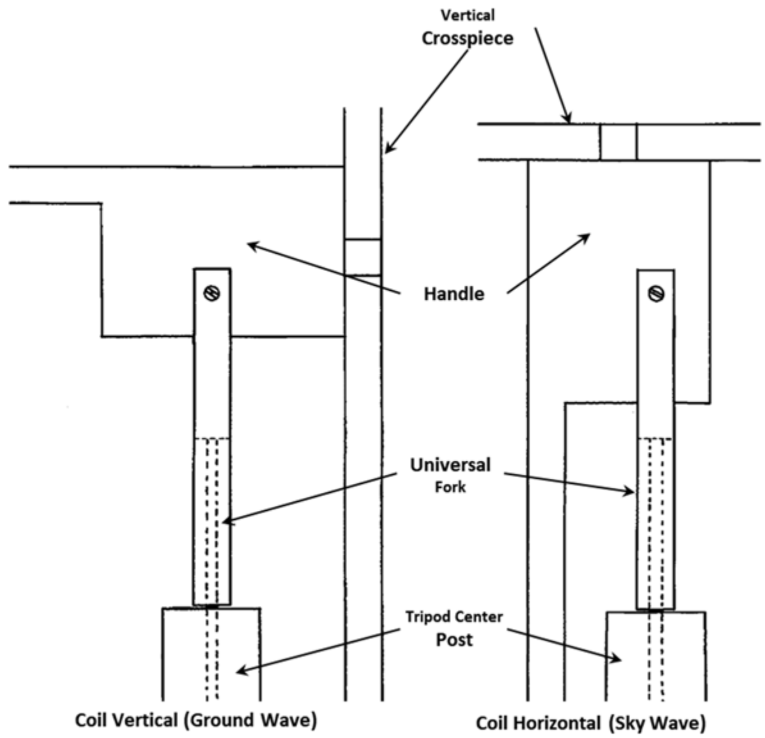

Figure 3-5. Operation of Universal Fork, Vertical and Horizontal

Dimensions of the fork are shown in Figure 3-6; some variance is alright. The fork must provide a stable link between the coil assembly and the tripod. It is made from a piece of wood approximately $^3/_4$" × 1 $^3/_4$" × 6" (nominal 1"-thick board). One end of the board is channeled forming a two-prong fork which receives the $^3/_4$"-thick handle. The channel in the universal fork should be cut slightly wider than the handle to accommodate flat washers on either side of the handle. A stove bolt through the fork and handle provides the pivot point for 90-degree variation in pitch.

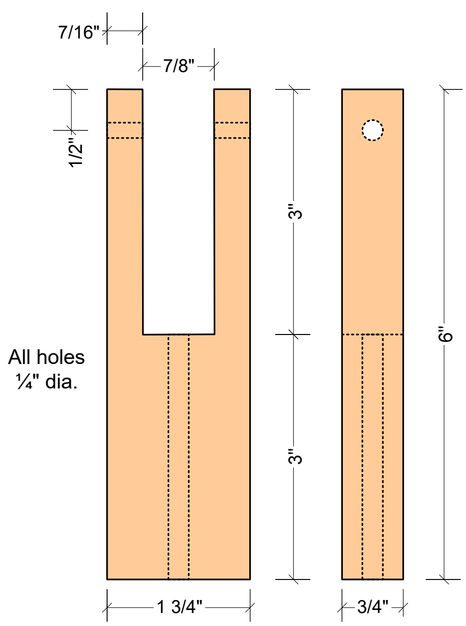

Figure 3-6. Dimensions of Universal Fork

A ¼" hole is drilled through the other end of the fork, extending from the end to the prongs. The fork should be fabricated so that the ¼" pin extends into it by at least 3 inches. This minimizes any play in the fork which would otherwise result in backlash in the pitch adjustment. When drilling, it is recommended that a bit less than ¼" be used at first to provide a pilot hole and ensure good alignment. The hole can then be reamed with a ¼" bit. The pin can be lubricated with paraffin to eliminate any initial sticking in the azimuth direction.

Figure 3-7 shows the universal fork on the steel pin on the tripod column. Two ¼" inside-diameter flat washers between the tripod column and fork provide a bearing surface for horizontal rotation. The vertical pivot bolt passes through each prong of the fork and the handle. Flat washers are used on either side of each prong.

Figure 3-7. Universal Fork Installed

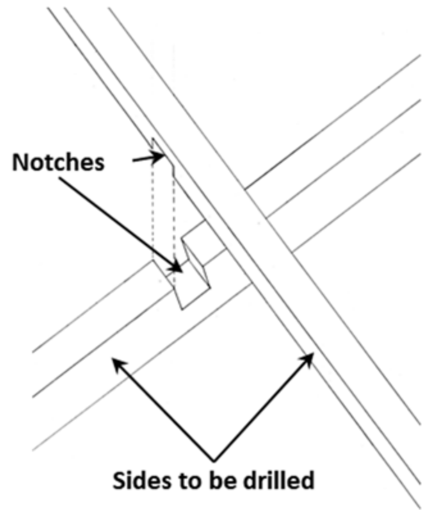

Figure 3-8. Notch Cut in Center of Crosspieces

Aside from the requirements listed in the paragraph above, dimensions of the parts described so far are not critical, and you are left to your own resourcefulness. Dimensions for the coil frame and handle depend on the frequency range and size of the coil to be constructed. More will be said about these later.

4. Coil Frame Construction

4.1. Basic Frame

The frame consists of two crosspieces, notched in the center to fit flush together. The recommended crosspieces for this antenna are ½" × ½" square dowel 36" long. These can be found in most hardware stores or ordered online. The ½" × ½" dimensions are not too critical, the parameters being light enough to permit easier mechanical balancing, while robust enough to sustain a taut coil.

Drill the holes for the wire before you cut the notches. The holes should be centered ¼" from each edge. Each dowel should be predrilled to accept AWG 22 stranded wire using a drill press with a $^{5}/_{64}$" bit. Mark each hole location along the sides of the dowels. Holes are drilled $^{3}/_{8}$" apart beginning $^{3}/_{8}$" from each crosspiece end. There are 28 turns in the primary coil, resulting in the last turn being located approximately 10.5" from the end of each crosspiece. It is advisable to add 3 to 5 extra holes toward the center of each crosspiece for the primary coil. When the antenna is trimmed (Section 7), it may be possible to increase the coil size.

When all of the holes are drilled, cut the $^{3}/_{8}$"-wide notches in the center of each dowel (Figure 3-8). Note that the notches are $^{3}/_{16}$" deep on the undrilled sides of the dowels. Do not glue the crosspieces together yet.

The wire will eventually be laced through the holes in the crosspieces. Figure 4-1 shows an end of the horizontal crosspiece with the turns of the primary coil laced through the holes in the dowel. Note that these dowels are ½" × ¾", which may prove difficult to find.

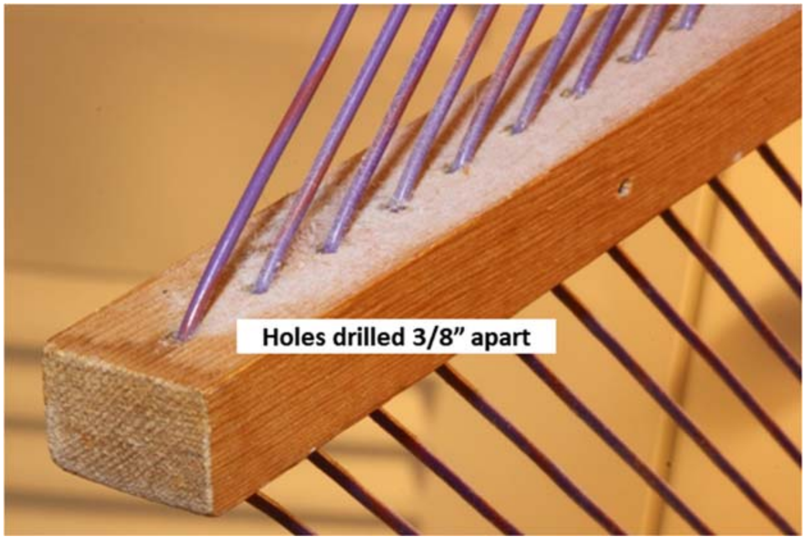

Figure 4-1. Detail of Primary Coil Winding

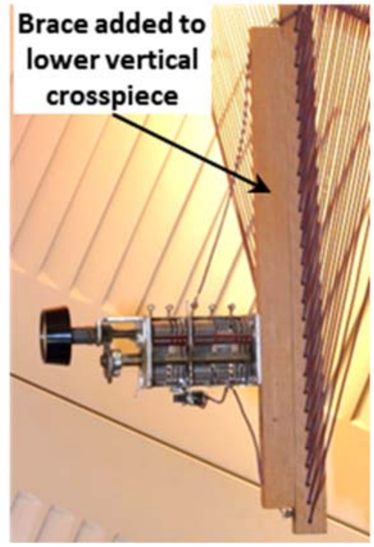

Figure 4-2. Tuning Capacitor Mounting Brace

An ***unshielded secondary coil*** can be wound the same as the primary coil, that is, through holes in the crosspiece. These holes should be drilled at the same time as those for the primary coil. There will be 3 to 5 turns required for the secondary coil. The inner holes should be located approximately 3" from the notches on the crosspieces and extend outward at ¼" intervals. Since the secondary coil is relatively small and not resonated, distributed capacitance is not an issue.

With all the holes drilled, you can attach the two cross pieces at the notches with wood glue.[2] Figure 4-2 shows a side view of the lower vertical crosspiece. A piece of dowel has been glued to reinforce the crosspiece in this area. This brace should be about 10.5" long extending along what will be the primary coil winding. The tuning capacitor will be mounted on this brace in Section 6, Page 17.

4.2. Alternate Frame

It may have occurred to some that slotting the crosspieces could be an alternate way of lacing the coils (Figure 4-3). This is a much easier method for fabrication, as the lead end of the wire does not have to be progressively threaded through each hole in the crosspieces. There, however, ends the single advantage of this approach: a) It may be difficult to cut the slots evenly; or b) the stress of the wire on just one side of the two crosspieces may warp or possibly crack them. Otherwise, a less than ideal shape will merely be a cosmetic issue. Perhaps alternating the slots front and back on each adjacent crosspiece would solve this problem, but that will add to the lacing difficulty. More importantly than the first objections, if not properly tensioned, the wire may slip out of the slots. While gluing will help secure the wire to the slots the wire may not be free in case it ever needs to be tightened. A better

[2] Initially, some consideration was given to adding four braces around the perimeter of the frame. These would hold the two crosspieces normal to one another and provide some protection to the outer turns of the coil but would have added considerable weight making mechanical balancing more difficult. In retrospect, these would not have proved necessary. Temporarily clamping the crosspieces during coil winding and reasonable care in handling the antenna have resulted in a serviceable antenna for many years.

solution might be to cant the slots inward slightly toward the center of each crosspiece, or cover the slotted side with a laminate tape or wood. In any case, the size of the crosspiece dowels should be somewhat larger than for drilled dowels. In Figure 4-3, they are ¾" square.

5. Winding the Coils

5.1. Wire Selection

When this antenna was designed, an investigation of ac wire resistance was conducted to determine the impact of skin effect at frequencies of 1600 kHz and below. It was found that the point of diminishing returns was reached with AWG 16 wire. Beyond this point, increasing wire size produced very little decrease in ac resistance. Unfortunately, with the increased wire size, the problems of weight and coil fabrication increase. In addition, there might be some slight effect on distributed capacitance. These problems become significant at low frequencies where the number of turns in the coil is high and the winding pitch is small.

Figure 4-3. Alternate Slotted Crosspiece

For the design described here, the use of AWG 22 solid or stranded wire has proven to be an adequate compromise. Resistance will be low enough to maintain an impressive circuit Q, and the final assembly will be light enough to be mechanically balanced with minimal problems.

Bare or insulated wire? Uninsulated wire or magnet wire will result in less weight, but from an electronic standpoint, insulation will not be a performance inhibitor. However, if you want to electrically balance the primary coil, consider that insulation must be removed at several places in what is an iterative testing process as explained later. The enamel on magnet wire can be removed more easily than plastic insulation.

Litz wire has often been used for loop antennas and will to some extent make up for small-diameter wire. Its cost and availability are not in its favor. If Litz wire is used, electrical balancing will be difficult. Connections to Litz wire require care to ensure all the strands are soldered.

5.2. Primary Coil

If the frame is to be painted, it should be done at this time before the coil is wound. Ensure there is no buildup of paint in any of the wire holes. Allow 24 hours for all the paint and glue to dry before attempting to wind the coil.

While winding the primary coil, it is important for appearances that both crosspieces remain at right angles with one another, although a distorted coil form will not affect performance. Before winding the coils, use C clamps to temporarily secure the crosspieces to some reasonably stable object such as a piece of plywood or stiff cardboard. The winding is accomplished most easily with the frame on the floor or low table.

Each end of the coil is terminated on the brace at the bottom portion of the vertical crosspiece. Locate a small finishing nail near each end of the brace (Figure 4-2). These will serve as the coil terminals. One nail should be opposite the outermost hole where the winding is to start. The other nail should be next to the innermost hole.

Lacing the primary coil can be tedious and frustrating. The following process can be used with either insulated or bare wire. Using the dimensions provided for the frame construction above, 28 turns in the primary coil will require approximately 170 ft. of wire. Starting with the outside turn, all of the wire must be pulled through each hole in turn around the frame. To minimize the feeding process, there is no reason why the wire can't be cut into sections, then ends soldered together as each section is laced. Bare ends of each wire forming a joint should be lapped across one another, twisted together and soldered. The joints should be small in diameter so they can pass through the crosspiece holes when the turns are finally tightened. Solder one end of the wire to the outer nail on the crosspiece brace and proceed to wind it through the holes in the crosspieces. Care should be taken on the first few outer turns that the crosspieces remain orthogonal, although, again this is a cosmetic issue.

When winding the coil, the idea is to keep the wire as straight as possible without putting undue stress on it. Too much stress can cause fatigue which could raise the wire resistance or possibly cause it to break. On the other hand, loose wire will cause some turns to sag close together, increasing the distributed capacitance gradient and limiting the amount of inductance which can be used in the circuit. Generally, a gentle tug as you lace each notch is quite sufficient to maintain the proper amount of wire tension. The wire tends to bend at each crosspiece, which will help hold it in place. Use a pair of cloth work gloves when making the winding. This will be easier on the hands and help to smooth out the kinks or sharp bends in the wire. The last turn is terminated on the inner finishing nail on the lower vertical crosspiece.

With all the turns laced, it is a good idea to progressively give each turn a tug working from the inner turn outward. It might be necessary to remove any slack and resolder the outer terminal. If you have trouble getting the last turn or two of the coil to remain taut, here is an easy trick. Ensure the entire coil is reasonably taut with each turn spaced uniformly from adjacent turns. Then, jam a round toothpick in the last laced hole on the crosspiece. Do this from the terminal side of the crosspiece (end of coil). This will lock the wire preventing it from becoming loose. The exposed end of the toothpick can be cut flush with the crosspiece.

5.3. Secondary Coil

There are some acceptable choices for a secondary coil. The main decision is whether you want an unshielded secondary coil with a balanced primary coil or a shielded secondary. In either case, the result is intended to provide optimum signal response pattern when the antenna is rotated. If you choose to have an ***unshielded secondary coil***, it may be wound on the crosspieces at this time. Use the same technique used for the primary coil. Secondary coils should be 3 to 5 turns. A twisted pair lead-in will be attached later, as will a procedure for balancing the primary coil.

The concept of a ***shielded secondary coil*** is shown in Figure 5-1[Martin, 1937; Levy, 1943, pp 57-58]; again, you have some choices. For example, the shield could be made from a piece of ¼" inside-diameter copper tubing, and three turns of AWG 22 insulated, stranded hookup wire threaded through the ends of the tube which form the gap. This gap is important. If the circuit of the shield were complete, it would act as a shorted turn, and there would be very little magnetic field induced in the coil. Bending the tubing will present a problem, as it must be prevented from collapsing. One trick is to temporarily fill the tube with sand and seal it at the ends while making the bend. The bend could be made around a rigid form of the same diameter. Threading three turns of wire through the shield will also require some patience. Ensure there are no gaps in the wire insulation.

My own approach for a secondary coil is shown in Figure 5-2. It consists of three turns of AWG 14 wire wound approximately 7 ½" in diameter. The coil is wrapped with $^{3}/_{8}$" wide lead foil. There is a small gap in the foil shield where the 'hot' lead is brought out. The remaining lead is the ground and is soldered to the lead foil. The figure also shows the shielded loop mounted to the crosspieces with four electrical staples, and two flat-head wood screws used to attach the coil assembly to the wooden handle.

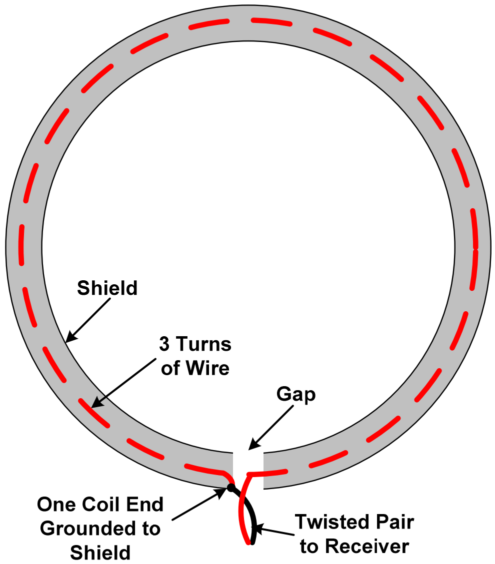

Figure 5-1. Shielded Secondary Concept

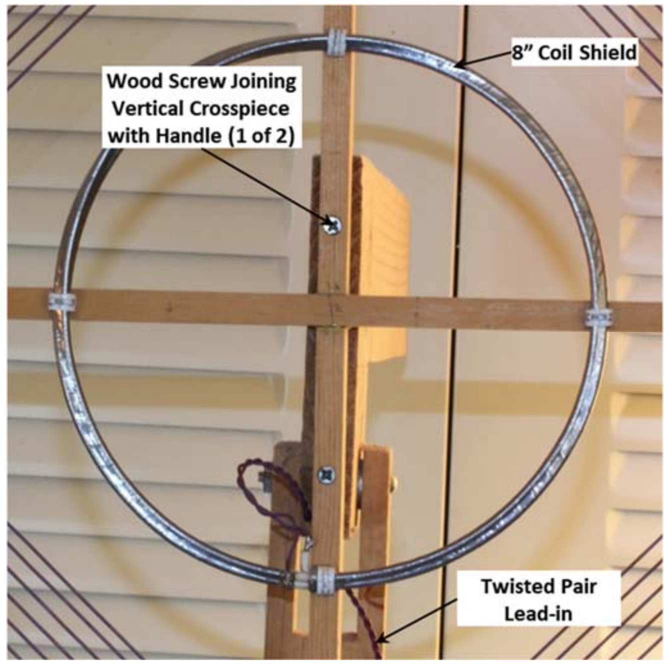

Figure 5-2. Shielded Secondary as Fabricated

AWG 14 solid copper wire is used for the coil. This provides a rigid flat shape and low resistance. A six-foot section of wire will be necessary. The wire can be salvaged from a length of Romex cable. The outer cover should be stripped off and either the black or white insulated wire used to form the coil. The wire should be straight with no significant kinks or bends; roll it smooth on a flat surface pressing it with a wide board. The coil should be preshaped on a cylinder having a slightly smaller diameter than the final coil size. The turns do not have to be positioned in the same plane as in the case of the primary coil. Since there are three turns, they should be interleaved (wound) so that a cross-sectional view would show them bedded down in a triangular form. In this way the turns will have maximum strength as a coil. Temporarily tape the turns together with several small pieces of electrical or masking tape. Ensure each turn is the same diameter with no slack or air gaps between the turns. Bend one terminal end inward and tape it close to the three-turn bundle. The remaining end can be stripped back about ¼", and will be soldered to the shield for the ground connection.

The material recommended for ***shielding*** is $^{3}/_{8}$" lead foil tape with adhesive backing. The tape is commonly used on window glass for security systems, and can be purchased in a variety of stores or through Internet outlets. This will hold the coil in a rigid form. Also, with care, it can be soldered.

Begin wrapping the coil near what will be the gap at the ends of the coil. Keep the coil windings and tape as tight as possible, being careful not to break it. Each turn should overlap the previous turn about $^{1}/_{16}$". Remove each piece of electrical or masking tape from the coil as it is reached in the wrapping process. Continue wrapping all the way around the coil until you come to the leads. Cut off the unused portion of the lead foil.

The gap in the shield should be just large enough for the terminal ends to pass through, about ¼". To keep the ends of the lead foil from unraveling or shorting, bonding wires will be soldered to the foil on each side of the gap. Tin two pieces of AWG 22 or 24 bare wire approximately 3 inches long with solder and wrap two or three turns around each end of the foil shield as close to the terminal leads as possible. Solder each bonding wire to its corresponding end of the lead foil shield. Use a low-power soldering iron. Apply the iron to the bonding wire and not the foil. Allow the solder to flow on the foil. Too much heat will melt the foil causing it to separate from the wire. Some practice using a small piece of the unused foil is advisable prior to soldering the actual shield before trimming the excess wire from one of the bonding wires, wrap two turns of the excess around one of the coil leads. This will be the ground connection for the shield, one side of the secondary coil, and the receiver. Use a knife to trim away any excess foil in the gap between the bonding wires.

Figure 5-3 is a detail of the shielded loop terminal. The gap in the shield is located here. The end of the twisted pair lead-in is connected to the shielded coil at this point. Only one coil lead is visible. The remaining lead is soldered inside the shield, that is, the ground. Care must be taken to ensure the polarity is observed through the twisted pair into the receiver. One of the electrical staples connecting the shielded loop to the crosspieces is shown.

Three more bonding wires should be soldered to the shield at 90-degree intervals around the coil (Figure 5-4). As an alternative to electrical staples, grounding lugs can be soldered to the 90-degree bonding wires and wood screws used to attach the coil to the crosspieces. The shielded secondary coil can be installed on the frame at this time. The gap should be on the lower vertical crosspiece.

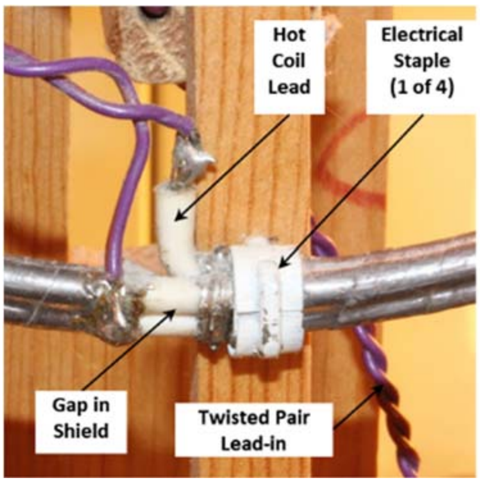

Figure 5-3. Detail of Shielded Loop

Figure 5-4. Bonding Strap and Mounting Lug

6. Lead-in and Tuning Capacitor

By now you should have completed the coil assembly windings, including the high-impedance primary and a non-resonating secondary coil. In this section, we will construct the lead-in cable, offer some advice on capacitor selection, and make some preliminary tuning adjustments.

6.1. Lead-in

A twisted pair is used to connect the secondary coil to the receiver low-impedance input. This is lighter and more flexible than coaxial cable. Used in moderate lengths, it will not contribute any significant loss or pick up any stray signals. Figure 6-1 shows a twisted pair fabricated from two pieces of insulated AWG 22 stranded wire approximately six feet long. This lead-in is terminated with a $^{1}/_{8}$” phone plug.

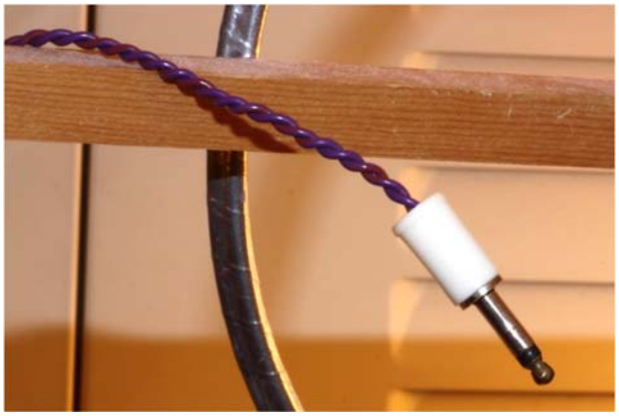

Figure 6-1. Lead-in

To twist the wires, attach one end of each wire to a vice or other secure clamp. Attach the two remaining ends to a drill chuck. With the two pieces of wire stretched out, operate the drill until there are 4 to 6 twists per inch in the wires. The twist should be applied in the same direction as the inherent twist in the strands. Disconnect the wire and strip the ends. Attach whatever connectors are required by your receiver to one end of the twisted pair. Using an ohm or continuity meter, determine which wire in the pair will be the ground and mark it as such.

- For an ***unshielded secondary***, solder the ends of the lead-in to the ends of the secondary coil. Identify which lead-in wire will ultimately be connected to receiver ground and mark it. The primary balance wire will be connected at this point when the primary coil is balanced.
- For a ***shielded secondary*** coil, the ground from the lead-in twisted pair should be soldered to one of the bonding straps on the shield gap. One end of the secondary coil, that is, the ground, should have been soldered to the same point when the coil was fabricated. The 'hot' lead-in should be soldered to the remaining, exposed end of the secondary coil.

6.2. Tuning Capacitor

The size of the variable capacitor used to resonate the primary coil is important because it determines the range over which the antenna will operate. For this application we want a capacitor arrangement, which, in parallel with the primary coil, will tune a range from 530 kH through 1700 kHz. A slight extension at each end will ensure the channels at the end of the band will be covered.

Choice of a variable capacitor will depend on what you have available or what you may be able to buy. It will be almost impossible to locate a single-section capacitor which will neatly complement the primary coil inductance and cover the entire broadcast band. The coil described has relatively high inductance, 515 µH, and its distributed capacitance is estimated at 12 pF (See Section 11, Measurements on Page 29). The maximum amount of additional capacitance to resonate at the lower end of the mediumwave band will about 200 pF.

For lack of a variable capacitor having the precise range, there are some easy ways to tailor surplus or salvaged multi-gang capacitors.

- A ***trimmer*** capacitor is in *series* with the main tuning capacitor. Variation in trimmer value has more effect at the low end of the tuning range. However, as its effect is to lower the capacity, across the entire tuning range, we use it here to decrease the minimum capacitance, thereby allowing more inductance, slightly raising the L/C ratio, and tune higher frequencies.
- A ***padder*** capacitor is in *parallel* with the main tuning capacitor. Its value is added to that of the variable capacitor setting to yield a higher total capacitance and tune lower frequencies across the range. In this loop antenna application, a padder should not be necessary.

Although trimmers and padders are customarily thought of as variable capacitors, once the necessary value is determined, a fixed capacitor may be substituted. Even with the use of trimmers, the variable capacitor may still not be able to tune the entire mediumwave band, and it will be necessary to insert a "band switch" to short out the trimmer to increase capacitance and extend the range to 530 kHz.

We shall use the 515 µH primary coil described above as an example. Table 6-1 gives the capacitance required to resonate this coil at the lower and upper end of the mediumwave band. Possibly the best way to describe the capacitor arrangement is to look at a few examples. Figure 6-2 shows diagrams for three different primary circuits. Each of these makes use of a trimmer capacitor to lower the minimum capacitance and extend the tuning range to a slightly higher frequency. Operating the band switch to short out the trimmer increases the total capacitance and lowers the tuning range.

Table 6-1. Examples of Suitable Capacitor Arrangements

	Frequency (kHz)	pF	Figure 6-2a Example A	Figure 6-2b Example B	Figure 6-2c Example C
Total necessary capacitance	520	182			
	1710	17			
Capacitor value allowing for 12 pF distributed capacitance	520	170	330 in series with 365 =**173 pF**	365 in series with 365 = **183 pF**	**194 pF**
	1710	5	8 in series with 15 = **5 pF**	365 in series with 365 and 5 = **5 pF**	11 in series with 8 = **5 pF**

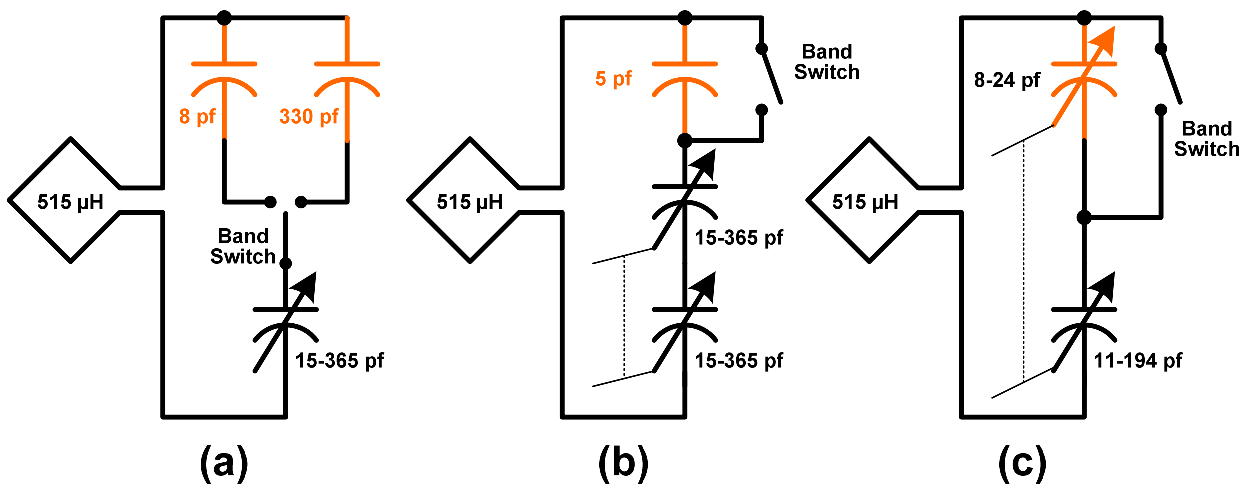

Figure 6-2. Example Capacitor Arrangements

Figure 6-2(a) uses a single-gang, 15-to-365-pF variable capacitor for tuning. These capacitors are perhaps among the last classic-style, metal-frame, air-dielectric, variable capacitors still available in new condition. It will be necessary to use two trimmers in this arrangement, one for the upper frequency range and another for the lower frequency range. Table 6-1 shows the capacitor linkages and total values for each example.

Figure 6-2(b) uses a two-gang, 15-to-365 pF variable capacitor for tuning. These are also metal-frame, air-dielectric, variable capacitors. There are still new ones available for a price, but they were also commonly used throughout the classic era of radio. Note that both gangs operate in tandem and when connected in series will produce ½ of the capacitance of a single gang at any position throughout the range. For example, fully open, the capacitor will produce approximately ½ × 15 = 7.5 pF. The 5 pF capacitor in series with the band switch open will lower the total capacitance to slightly less than 5 pF. Note that the metal frame of the variable capacitor 'floats,' that is, it forms the connection between each gang joining the two rotor sections. The connections to the coil on one end and the trimmer on the other end are made through the respective insulated stator section terminals.

Figure 6-2(c) is an example of a two-gang variable capacitor of unequal gang values. These were also quite common in the classic era, the oscillator gang having a lower value than the antenna gang. In this example the smaller gang acts as a trimmer. Again, the metal frame is floating and the band switch is connected across the trimmer with one end connected to the metal frame.

Finally, what about miniature, plastic-cased variable capacitors? Properly fitted, they may be acceptable, particularly in small ferrite coil applications. However, I consider their inferior mechanical robustness, use of plastic film dielectric, and difficulty in fitting a large knob to render them less attractive. In addition, the minimum tuning capacitance may not be in the desirable 5 pf to 10 pf range.

Figure 6-3 shows the tuning capacitor installation. This item happens to be a surplus five-gang capacitor probably intended for an AM-FM radio. It was selected due to the included reduction gears which make tuning easier.

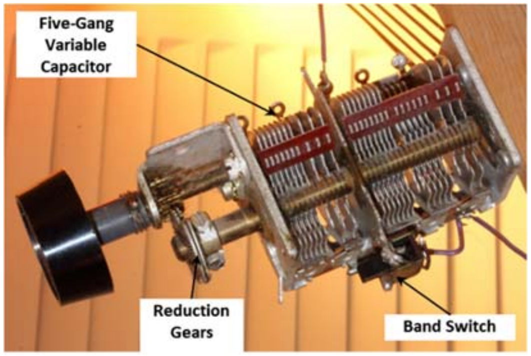

Figure 6-3. Tuning Capacitor

The tuning capacitor is located on the dowel brace near the bottom of the vertical crosspiece using two flat-head wood screws (Figure 4-2). It is mounted outward in the opposite direction from the handle. When selecting screws, care must be taken that they do not interfere with rotation of the capacitor rotor plates. Alternatively, the metal frame can be glued to the wooden brace using contact cement. Attach the leads between the capacitor and each end of the primary coil. Dress each lead along the brace away from the coil. If the leads are positioned too close to the coil, an appreciable amount of distributed capacitance will develop.

7. Final Tuning Range and Electrical Balancing

In this section the tuning capacitor and primary coil will be adjusted to produce a nominal tuning range of 530 kHz to 1700 kHz. Then, for antennas having a balanced primary in lieu of a shielded secondary, the primary coil will be balanced to ground in a trial-and-error procedure.

7.1. Final Tuning Range Adjustment

The information in Section 6.2 contains examples for selection and configuration of various tuning capacitor arrangements. Others may be possible. The objectives are to cover the entire range of the mediumwave band with the variable capacitor while keeping the L/C ratio as high as possible.

- Using your chosen capacitor arrangement, it may be necessary to add or remove one or two turns to get the coil to resonate at the high end of the band. If you must remove more turns, you will be lowering the effective height of the antenna and you should consider selecting another variable capacitor or examine the coil winding to ensure all the turns are tight and evenly spaced.
- Use the formulas in Section 2 to calculate values, and, if possible, an LCR meter to measure the values of your capacitors.
- Remember to allow for distributed capacitance; this will be approximately 12 pF for the primary coil described here. When calculating resonant frequencies, distributed capacitance must be

added to the capacitor values at both the lower and higher ends. It will tend to lower the minimum and maximum tuned frequencies, particularly at the high end. Distributed capacitance is in parallel with the variable capacitor and has the effect of a padder.

7.2. Electrical Balancing (with Unshielded Secondary)

Electrical balancing of the loop antenna provides optimum null operation of the circuit. If a shielded secondary is being used, the shield described above fills this purpose, and this procedure can be skipped. Ideally, a null from a ground wave should occur in two azimuth positions 180 degrees apart. In practice, most structures have a significant amount of magnetic material to cause anomalies in the electromagnetic field. This can produce erroneous heading errors, even in a perfectly balanced antenna. Since you are concerned more with obtaining the most complete nulls without regard to direction-finding accuracy, we will not consider the complex techniques required for null error compensation.

If the balance point is not correct, distributed capacitance of the coil will increase. Consequently, the variable capacitor will have to be opened slightly (less capacitance) to compensate. At the correct balance point, no distributed capacitance is added.[3] A trial-and-error technique based on this principle is used to find the electrical center or balance point of the primary coil. If the antenna were a solenoid instead of a flat spiral, we could simply rely on the symmetry of the coil winding, locate the balance point on the center turn of the coil, and expect to be close to the perfect balance. The case of the spiral loop is not that simple. Each succeeding turn moving outward is larger and presents more capacitance to ground. Therefore, the balance point is not on the center turn, but rather on a turn located toward the outside of the coil.

a. For this operation the variable capacitor should be fitted with a temporary dial or pointer so differences in its capacitance (just more or less) can be noted. This does not have to be a calibrated dial, just a large disk with a single mark so you can determine whether capacitance is being added or deleted in each step.

b. Select a station near (not at) the high end of the antenna range. This is the portion of the band where very little capacitance is required, and any change caused by relocation of the balance wire will have the most effect.

c. Note the position of the capacitor with the balance wire disconnected from the primary coil. This will be your target setting for balance.

d. Connect the balance wire between the ground side of the secondary coil and a point on the primary coil near its center (For a 28-turn coil, this will be ~14^{th} turn from the outside). An alligator clip temporarily attached to the coil end of the balance wire will help.

e. Repeak the capacitor. The peak position will likely be higher on the dial indicating some distributed capacitance has been added to the circuit and less variable capacitance is needed to resonate the same frequency. If there was no change in the setting of the variable capacitor, stop. You are at the balance point.

f. More likely, the balance point is outboard of this connection. Begin attaching the balance wire to each succeeding outboard turn, repeak the variable capacitor each time, and note its setting. If variable capacitor setting is more capacitance than the previous turn, you are headed in the right direction. When the antenna is balanced, the variable capacitor will be at or near the same

[3] During design of this antenna an effort was made to find the linear center of the wire and to locate the balance point there. This did not always work.

position it was with the balance wire disconnected. Moving the balance wire further outward from this turn will cause distributed capacitance to increase again.

It might be possible to note differences in distributed capacitance as the balance wire is moved around the same turn. The balance wire should be tested in several different positions until the maximum value of the variable capacitor is reached. The balance wire should be dressed about 1" away from the coil turns, cut to minimum length, and soldered to the coil at the nearest crosspiece. This completes electrical assembly and testing of the coils.[4]

8. Handle Construction, Final Assembly, and Mechanical Balancing

In addition to a tripod, you have now completed all of the electrical work on the antenna, and should have a coil assembly which is tuned to cover the entire mediumwave broadcast band. Final construction is described in this section.

8.1. Handle Fabrication

Besides pointing the antenna in the desired direction, the handle is used as a counterbalance for the coil so the entire assembly will retain whatever pitch is required. Figure 8-1 shows the general plan. Dimensions are those for the loop described in this article. Depending on materials and dimensions, your handle may be different. Due to variations in assembly and construction techniques, it is recognized that your coil assembly may require slightly more or slightly less weight in the handle. The handle can always be cut down or weight added near the end during the balance procedure which follows.

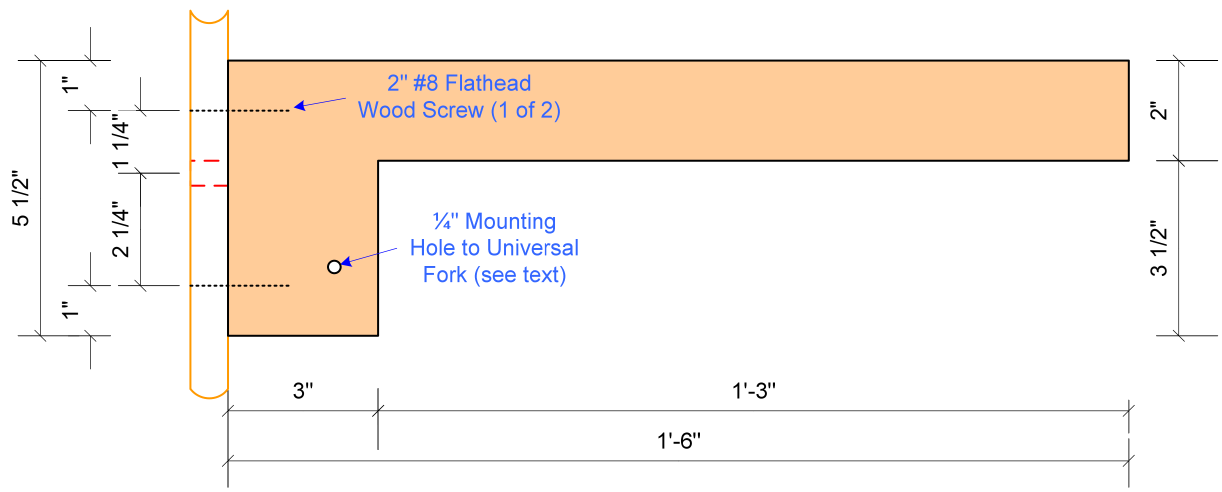

Figure 8-1. Handle Dimensions

This handle is fabricated from 1 inch (nominal 3/4 inch) lumber. The handle can be cut from a single piece of wood or assembled from a few smaller pieces. Do not drill the hole for the universal fork yet. Its exact position will be determined during Mechanical Balancing, Section 8.2, Page 23.

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[4] One interesting note on electrical balancing is that slight variations from perfect balancing cause one response lobe of the antenna to become larger than the other one. This results in increased sensitivity and sharper peak in one direction. Also, the nulls are no longer precisely 180 degrees apart in the ideal pattern - the angle formed by the nulls on either side of the larger lobe being greater than 180 degrees. This phenomenon could prove useful in tuning different pairs of stations on the same frequency, where the null positions are now at different headings than they were with the ideal response pattern.

The orange outline in Figure 8-1 represents a portion of the vertical crosspiece. The red outline is the cross-section of the horizontal crosspiece. The dotted shapes represent two 2" #8 flathead wood screws used to mount the handle to the coil assembly. Again, the precise positioning will depend on the materials and dimensions of your antenna, and should only be used as an initial guide.

Figure 8-2 shows how the handle is mounted to the vertical crosspiece using two wood screws. Ensure the handle forms a right angle with the coil frame. Do not use any glue on this joint. It may be necessary to raise or lower the position of the handle to balance the assembly; also, this joint serves as a logical disassembly point for transport or storage of the antenna.

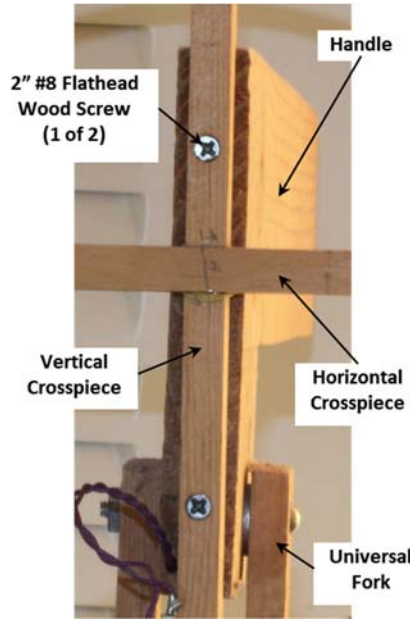

Figure 8-2. Detail of Coil Assembly-Handle Mount

8.2. Mechanical Balancing

a. To mechanically balance the antenna, install the universal fork, previously constructed, on top of the tripod.

b. Locate thin finishing nails in opposite sides of the lower portion of the handle in the approximate position shown in Figure 8-3. This will be the first trial point for location of the vertical pivot hole.

c. Place the fully assembled coil assembly on top of the universal fork so that each finishing nail rests on the end of its corresponding prong on the universal fork. Proper balance is achieved when you can reposition the coil to any pitch position and have it remain in place without tilting upward, downward, or settling somewhere in between. This requires alternately locating the finishing nails and retesting the balance.

d. Allow the assembly to seek its natural position of unbalance. If the handle angle is approximately 45 degrees, the balance point should be directly below the current nail position.

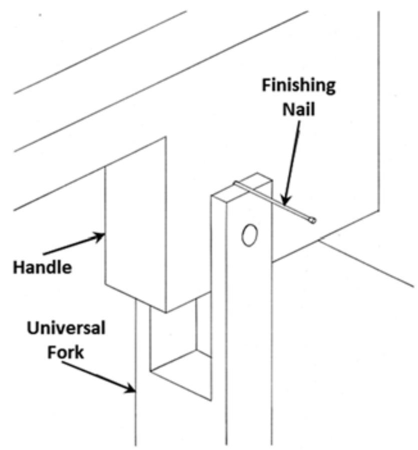

Figure 8-3. Arrangement for Balancing the Coil Assembly

e. Ensure that the back corner of the lower portion of the handle will pass between the prongs in the fork when the coil is rotated to its horizontal position (handle vertical). See Figure 3-5, where the coil is adjusted for reception of a 90-degree sky wave. Allow for the fact that the nails are resting on top of the fork and not in the bolt holes which will be about ½" lower.
If the lower corner of the handle will not clear the center of the fork; that is, the coil cannot be adjusted through a complete 90-degree arc from vertical to horizontal, it will be necessary to remount the coil assembly higher or lower on the handle. This will have a corresponding effect on the location of the balance point, and a new balance point will have to be located as described above.

f. When you are certain that the balance point is correct and the antenna will remain at any set position throughout its pitch range, mark the last position of the finishing nails, remove the nails, and drill a small pilot hole squarely through the handle at this point. Enlarge the hole to ¼" diameter. Obtain a suitable ¼" stove bolt, four matching flat washers, one lock washer, and a wing nut. Assemble the universal fork with this hardware, bracketing each prong of the fork with a flat washer, then the lock washer and wing nut.

Mount the completed coil assembly on the tripod. The coil assembly should operate smoothly throughout a 360-degree azimuth and a minimum 90-degree pitch. The pitch tension can be controlled with the wing nut. This should be adjusted so that the amount of force required to change the pitch is about the same as that used to adjust the azimuth.

This completes the description of the loop antenna construction. I have tried to stress the important factors without being too restrictive in what materials you use or what process to follow. In some cases, precise dimensions depended on your unique requirements, as in the case of the loop handle where final mechanical balancing procedures could not consider all the possible construction variations which could have occurred. You are ready to connect your antenna to your radio and operate.

9. Operation

9.1. Basic Tuning

Two adjustments must be made to the loop antenna each time a different frequency is tuned. The capacitor must be tuned to resonance, and the coil must be directed to either the peak or point of null signal. This sounds simple enough; however, just like playing a musical instrument, some developed skill is involved in 'playing' the loop. This includes some basic knowledge of linear polarization of radio waves, the corresponding response of the loop, and some practice.

First , slight changes in the variable capacitor will affect the tuned resonant frequency. A change of a single picofarad at the high end of the band will detune the loop away from the intended signal. For this reason, the capacitor should be adjusted back and forth, and the results noted on the receiver S-meter.

Second, aiming or orienting the loop will affect the strength of the signal induced in primary coil. The loop can be used to peak the signal strength of the desired station, or null a source of interference. Local noise can also be eliminated or significantly reduced by orienting the loop counter to the direction of the noise field.

What follows is a greatly simplified description of the linear polarization of radio waves. Figure 9-1 shows the graphic response of the antenna at three different angles. Visualize the response being in the shape of a doughnut with an infinitely small hole in the center as shown by the blue circles. The figure shows antenna viewed from above. Focus on the dark blue circles which represent a horizontal slice across the doughnut and indicate the relative strength of the antenna's response as a function of its angle with the incoming signal. The red lines represent the plane of a spiral loop antenna, and the green lines are the null axis through the doughnut hole. In each case, the yellow dots are the response of the antenna to the incoming signal. Figure 9-1(a) shows the plane of spiral antenna aligned for peak response to the incoming signal,[5] Figure 9-1(b) the antenna rotated 45 degrees, and Figure 9-1(c) null response. It can be seen that the antenna produces a significant signal through a very wide arc. At 45 degrees, the response is 70 percent of peak. The null direction is extremely sharp.

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[5] A solenoid coil will produce the same pattern with the plane of each turn aligned with the incoming signal.

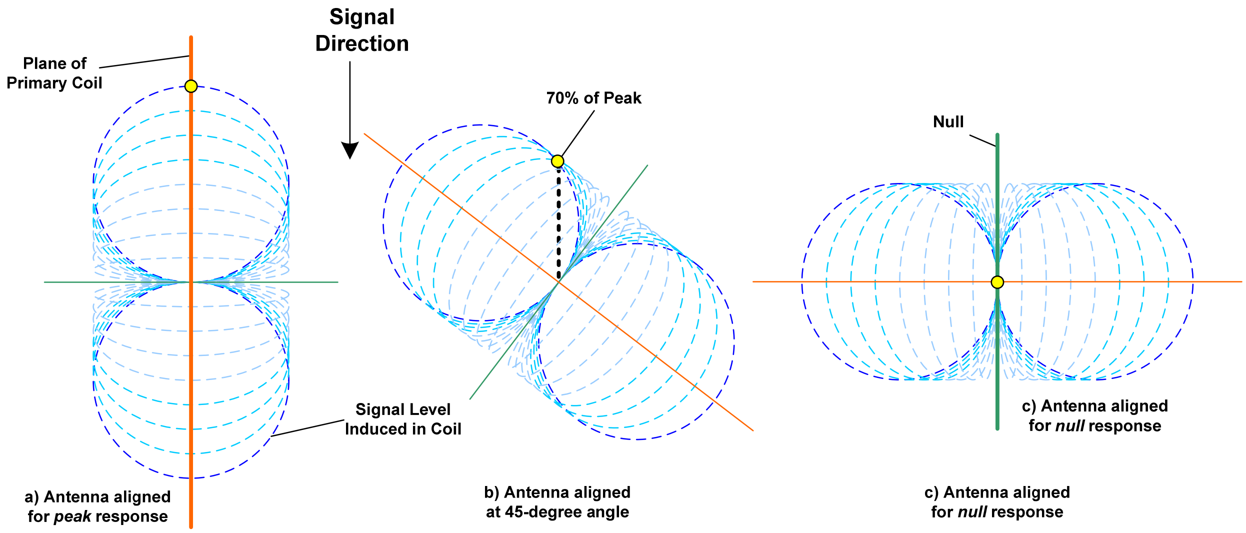

Figure 9-1. Bird's Eye View of Antenna Reception

9.2. Nulls

The purposes in adjusting for a null signal are:

a. to tune a station on the same frequency as another which is dominant,

b. to eliminate interference from a station on the same frequency or an adjacent frequency, or

c. to eliminate noise.

The ability to tune two signals on the same frequency with little or no mutual interference is a prime goal for having a loop antenna. It potentially doubles the number of stations audible at any given time. Generally, one station will be dominant on each frequency. For an ideal loop response pattern there will be two nulls at 180-degree intervals. With most broadcast stations having continuously changing modulation, it is generally difficult to tune to a null by ear alone. Observe the indication on the S-meter and watch for a significant dip in the carrier. Since the peak response is so broad, the precise peak is often found by first locating a null direction, then rotating the coil one way or the other 90 degrees.

As an example, Figure 9-2 shows how the null feature of the loop can be used to receive a weak signal on the same frequency as a strong signal. Assume that the dominant signal lies due north of the receiver. A signal approximately half as strong is situated toward the northwest. The antenna is adjusted so that one of the null positions is aligned to the north. The plane of the coils is aligned in an east-west direction and peak response of the antenna is towards either the east or west. The larger circles represent the ideal polar response pattern of the loop for the dominant signal and the smaller circles represent the pattern for the weaker signal. In the north direction, there is no response. The strong signal is not received. In the northwest direction response is not at peak but is significant. The response is equal to E cos 9, where E is the peak voltage. In this case the station is 45 degrees from response, so cos 45 degrees 0.707. For the dominant signal, cos 90 degrees equals zero [Glasgow, 1936].

With the dominant signal completely nulled, the weaker signal will be attenuated 3 db from its peak. It can be seen from Figure 9-2 that the antenna can be operated quite close to the null position before there is significant reduction in signal level. For example, at 6 degrees from null, there is only a 20-db drop in signal level. Figure 9-3 shows signal response as a function of antenna angle.

9.3. Adjacent Signal Interference

Adjacent signal interference from local stations may be eliminated by first adjusting the loop to the null position for the interfering local station, retuning receiver to the desired adjacent frequency, and repeaking the loop capacitor to the desired frequency. It should be noted that even though receiver selectivity or sideband selection may permit elimination of carrier interference, only a loop can suppress sideband interference which may extend up to or even past the carrier frequency of the desired signal. In the case of extremely powerful or close interfering signals, the loop may mean the difference between receiving an adjacent signal and not receiving one. A slight reorientation of the antenna may result in significant interference, so that it may only be possible to receive one signal on the adjacent frequency; whereas, the strong local can be completely nulled and another signal received on its frequency.

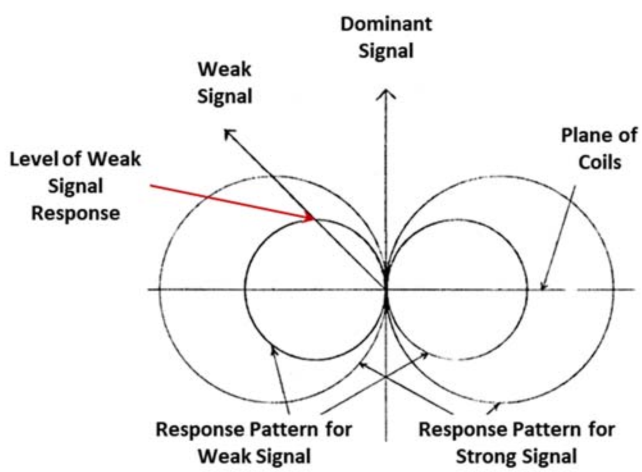

Figure 9-2. Polar Response Pattern Used to Null a Signal

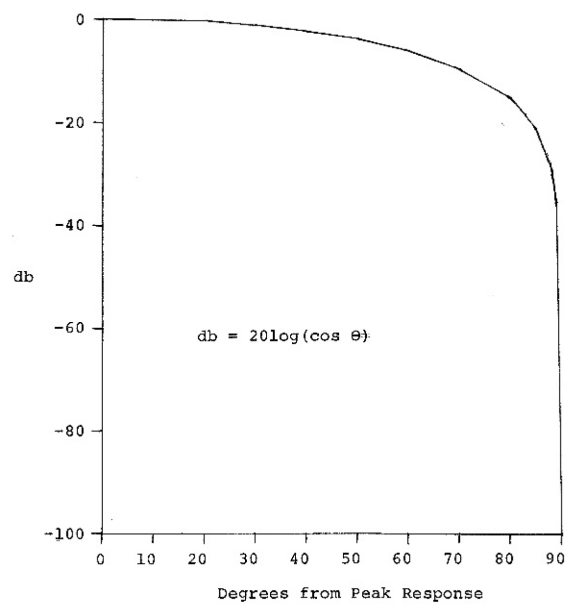

Figure 9-3. Normal Loop Response as a Function of Angle

9.4. Null Anomalies

The existence of any large magnetic object in the vicinity of the coil will cause signals to be reflected or the electromagnetic field to become distorted. This will often result in the electric field not being perfectly vertical. The same effect occurs at night when the signal arriving at the antenna has been reflected off the ionosphere. In either case, the null points are no longer tuned with the plane of the coil oriented vertically. The pitch of the coil must be changed, sometimes by nearly 90 degrees to achieve a null. Nulls are located by rotation of the coil in the azimuth until a dip is indicated on the S-meter. The pitch of the loop is then adjusted until further reduction in the signal strength is indicated. If the reduction comes because of a downward pitch (mechanically limited movement), the azimuth should be adjusted 180 degrees to the other null position and the pitch adjusted upward until the null is found. It may be necessary to alternately adjust the pitch and azimuth until the precise null is located.

9.5. Inability to Produce a Null

The inability of the loop to completely null a station may be caused by any one of several conditions. Stations at intermediate distances can have both sky wave and ground wave signals arriving at the reception site at the same time. This creates the same effect as two separate signals arriving at the antenna. It will be possible to null one or the other, but not both.

The angle of rotation through which the complete null may be observed is a function of the signal-to-noise ratio. The angle becomes smaller as the signal/noise ratio increases. Even a slight rotation of 1 degree or less from null can result in a significant signal level. An antenna which produces easily defined complete nulls on 50 kW stations 5 miles away is more insensitive than directive. It will take significant signal strength to receive a second station on the same frequency.

The polar diagram of Figure 9-4 illustrates how the null response of a loop antenna depends on the signal-to-noise ratio of the system [Martin, 1937, p 79; Sandretto, 1942, p 121]. The two larger circles tangent to the 0/180-degree line represent the ideal response pattern of the loop. Peak response is along the 90/270-degree line and nulls along the 0/180-degree line. The center circle represents the non-directional response pattern of background field noise and receiver noise. The angle AOB represents the amount of antenna rotation in which the noise level exceeds that of the signal. As the signal-to-noise ratio is improved, this angle becomes smaller. Ideally, a sensitive antenna will have an infinitesimally small angle in which a complete null is observed.

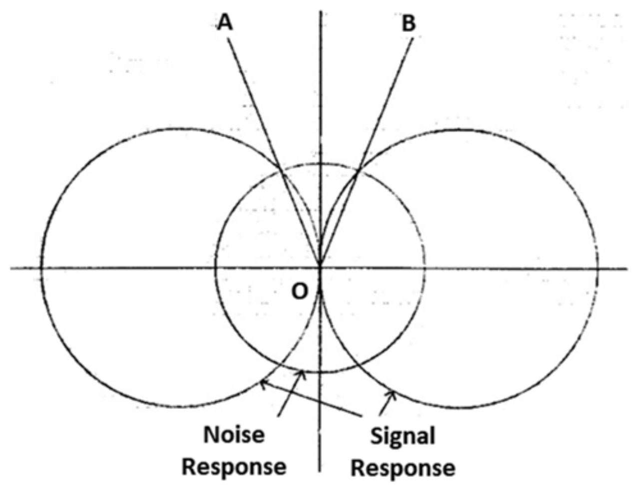

Figure 9-4. Null Response as a Function of System Sensitivity

Perhaps the most common problem is the inability to null strong local signals. Sometimes, when the precise null point is reached on a strong local station, the carrier will all but disappear, but strong, distorted modulation will remain. This has been attributed to a wave scattering effect caused by nearby reflecting surfaces and structures.

In extreme cases the near-field effects of the transmitter antenna may defeat any attempt to null its signal. In this writer's memory is the case of a 50-kW transmitter on a hill about a mile away from the listening post. The modulation was often audible over the telephone lines.

Adding to the difficulty in finding a null position is that of maintaining it. The direction of the incoming wave changes with variations in propagation conditions, particularly with sky waves. Deviations of 20 or 30 degrees can occur within a few seconds during turbulent evenings.

9.6. Local Noise

In the case of local noise, which is polarized, the loop is simply adjusted for minimum noise response. With multiple noise sources, it may be impossible to completely eradicate the problem. Whatever signals lie within the antenna's response lobes in any given direction will be received with reduced or eliminated noise.

10. Some Tips on Using Your Loop

10.1. Precautions

The primary coil of your loop is made from AWG 22 stranded copper wire. This will stretch and become loose if subjected to moderate and repeated contact with hands, furniture, etc. This will cause the turns to sag and probably come in proximity with each other. The result will be poor performance and could cause the tuning of high frequency stations to become impeded. The coil can be pulled tight, but this is something of a delicate operation. By avoiding any unnecessary contact with the coil, it will retain its shape indefinitely. To tighten a loose coil, refer to the toothpick trick described on Page 15.

10.2. Body Capacitance

When operating the loop at high frequencies, you may notice that bringing your hand near the coil or capacitor will tend to detune the loop. This is the one disadvantage of the high L/C ratio. The circuit is very susceptible to small changes in capacitance. When tuning the antenna, you should turn the capacitor toward you and adjust the capacitor for peak response, then turn the coil assembly in the direction of peak or null. If you must reach around the coil, chances are your arm will tend to detune the coil, and you will notice some falloff in the signal strength. Avoid contact with the metal capacitor frame. This will also detune the circuit. The capacitor should be fitted with a plastic or wooden tuning knob, and operate smoothly enough to peak the circuit without having to brace your hand against anything else.

10.3. Use of the Antenna on Inexpensive Receivers

Using your antenna on an inexpensive receiver will on one hand turn it into a very sensitive system. On the other hand, you may notice that, as you attempt to peak the antenna, in addition to the tuned frequency of the radio, the antenna will tune through adjacent frequencies. This creates the effect of ‘pulling’ the radio off its tuned frequency. This happens because the bandpass of the antenna is actually narrower than that of the radio’s intermediate frequency. As you adjust the antenna, this narrow bandpass with very high gain will sweep across the wider bandpass of the radio and alternately peak signals lying within the skirts of the radio’s bandpass.[6] To ensure the antenna is centered on the radio’s bandpass, leave the antenna somewhat off frequency while first tuning the radio. Then peak the antenna on the radio’s tuned frequency. For better radios having double conversion and tighter bandpasses this will not be a problem.

10.4. Silence Is Golden

What you don’t hear with this antenna is just as important as what you do hear.

- While the overall volume may be lower than with a long wire antenna, the signal+noise-to-noise ratio will be higher with the loop.
- It is highly selective, allowing only those signals close to its point of resonance to pass on to the receiver. This virtually eliminates harmonics and images which would normally be produced by the receiver if it were connected to a long wire. For this reason, you should keep the loop close in tune with the receiver whenever you are ‘scanning’ the band, particularly during daylight hours when the power on any particular frequency is minimal.

[6] This is true even though the bandpass of the antenna is based on a tuned frequency as high as 1700 kHz. The high Q of the antenna may still allow reception of signals within the skirts of the receiver’s 455 kHz intermediate frequency.

11. Measurements

11.1. Coil

A Proster Model BM4070 LCR meter was used to measure the values of inductance and capacitance in the resonant primary circuit. The measurement across the leads of the 28-turn coil indicated 515 µH with an accuracy of ±3%. By way of comparison, three loop antennas molded on the back panel of old table radios were measured and found to have 150 µH, 180 µH, and 255 µH, respectively. In addition, the turns × area product (*NA*) of these antennas, which is used to determine the effective height was $^{1}/_{12}$ or less than that of the fabricated coil described here.

11.2. Capacitor

Each gang of the variable capacitor was measured with an accuracy of ±2.5%. The larger section had a range of 10.6 pF (rotor open) to 194 pF (rotor closed). The smaller section had a range of 8 pF to 23.8 pF. As described earlier, these two sections were connected in series through the rotors and metal frame of the capacitor. Using the formula, $C_T = C_1C_2/(C_1+C_2)$, this provided a high-band capacity range of 4.6 pF to 21.2 pF. For the low band, the smaller gang was shorted with a band switch leaving the larger gang to provide its range of 10.6 pF to 194 pF. The bands have a calculated overlap between 1217 kHz and 1475 kHz.

11.3. Tuning Range and Distributed Capacitance

The upper resonant frequency was then calculated using the formula $f = 1/(2\pi\sqrt{LC})$ and found to be 3270 kH and the lower frequency 504 kHz. The antenna was then connected to the radio and actual upper and lower frequencies measured as 1710 kHz and 490 kHz, respectively. Assuming the self-inductance of the capacitor to be negligible, this results in the actual capacitances at the upper and lower end being 17 pF and 205 pF. This indicates an estimated increase in capacitance at each end of the band of about 12 pF, which is attributed to the distributed capacitance of the primary coil.

12. A Loop for Longwave

The advantages and practicality of resonant loop antennas become highly attractive at mediumwave frequencies. Below 500 kHz they are even moreso. I have extrapolated the basic design described above to cover a band from 150 kHz to 450 kHz. The frame is 3' square and uses ¼" × 1 ¼" lattice stock for crosspieces, but the primary coil remains AWG 22 stranded wire, only this time 80 turns of it (approximately 580') with holes in the crosspieces spaced at ¼" intervals. In hindsight, the crosspieces, though strong enough, should have been thicker to prevent distortion as the coil was threaded. Again, this is a matter of aesthetics. The secondary coil is identical to the shielded one described above. If there is any question as to the resistance at resonance, consider that the resulting Q and bandwidth obtained throughout the tuning range of this antenna requires that it be retuned every 1 kHz. Directional properties remain excellent.

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