An Overview of the Underestimated Magnetic Loop HF Antenna

It seems one of the best kept secrets in the amateur radio community is how well a small diminutive magnetic loop antenna can really perform in practice compared with large traditional HF antennas. The objective of this article is to disseminate some practical information about successful homebrew loop construction and to enumerate the loop's key distinguishing characteristics and unique features. A magnetic loop antenna can very conveniently be accommodated on a table top, hidden in an attic / roof loft, an outdoor porch, patio balcony of a high-rise apartment, rooftop, or any other space constrained site.

A small but efficacious HF antenna for restricted space sites is the highly sort after Holy Grail of many an amateur radio enthusiast. This quest and interest is particularly strong from amateurs having to face the prospect of giving up their much loved hobby as they move from suburban residential lots into smaller restricted space retirement villages and other communities that have strict rules against erecting elevated antenna structures. In spite of these imposed restrictions amateurs do have a practical and viable alternative means to actively continue the hobby using a covert in-door or portable outdoor and sympathetically placed small magnetic loop. This paper discusses how such diminutive antennas can provide an entirely workable compromise that enable keen amateurs to keep operating their HF station without any need for their previous tall towers and favourite beam antennas or unwieldy G5RV or long wire. The practical difference in station signal strength at worst will be only an S-point or so if good design and construction is adopted.

Anyone making a cursory investigation into the subject of magnetic loop antennas using the Google internet search engine will readily find an overwhelming and perplexing abundance of material. This article will assist readers in making sense of the wide diversity of often times conflicting information with a view to facilitate the assimilation of the important essence of practical knowledge required to make an electrically-small loop work to its full potential and yield very good on-air performance with a capable account of itself.

A few (sobering) facts:

A properly designed, constructed, and sited small loop of nominal 1m diameter will equal and oftentimes outperform any antenna type except a tri-band beam on the 10m/15m/20m bands, and will at worst be within an S-point (6 dB) or so of an optimised mono-band 3 element beam that's mounted at an appropriate height in wavelengths above ground.

Magnetic loops really come into their own on the higher HF bands from say 40m through to 10m; frequently with absolutely stunning performance rivalling the best conventional antennas. Easily field deployable and fixed site tuned loops have been the routine antenna of choice for many years in professional defence, military, diplomatic, and shipboard HF communication links where robust and reliable general coverage radio communication is deemed mandatory. On 80m and 160m top-band the performance of a small loop antenna generally exceeds that achievable from a horizontal dipole, particularly one deployed at sub-optimal height above ground. This is a common site limitation for any HF antenna.

The real practical advantage of the small loop compared to say a short vertical whip tuned against earth or a full sized vertical antenna is the loop's freedom from dependence on a ground plane and earth for achieving efficient operation; this unique characteristic has particular profound significance for small restricted space antennas operating on the 80m and 160m HF bands.

So where's the catch; if the small loop is such a good antenna why doesn't everyone have one and dispense with their tall towers and traditional antennas? The laws of nature and electromagnetics cannot be violated and the only unavoidable price one pays for operating with an electrically-small antenna is narrow bandwidth. Narrow instantaneous bandwidth rather than poor efficiency is the fundamental limiting factor trade-off with small loops.

Any small and compact (in terms of a wavelength) antenna will inherently be narrow band and require tuning to the chosen operating frequency within a given HF band. Users of magnetic loops must be content with bandwidths of say 10 or 20 kHz at 7 MHz or a little more than 0.2%. They are content as long as the antenna can be easily tuned to cover the range of spot frequencies that they wish to use. For a remotely sited or rooftop mounted antenna implementing this tuning agility to QSY across the band requires just a modicum of that ingenuity and improvisation radio hams are renowned for, e.g. Figures 15 and 16.

Comparing the efficiency of a small vertical with a small loop antenna one trades ground dependency and earth losses for much easier controllable conductor losses in both the loop radiating element and ohmic loss in the associated tuning capacitance and interconnections.

A small transmitting loop (STL) antenna is defined as having a circumference of more than one-eighth wavelength but somewhat less than one-third wavelength which results in an approximately uniform current distribution throughout the loop and the structure behaves as a lumped inductance. Unlike a short vertical or dipole antenna, the loop presents an inductive reactance at its terminals so tuning and matching is conveniently accomplished with a single capacitor. The loop self-inductance can be resonated with capacitance to form a high-Q parallel tuned circuit. The antenna Q is very high because the radiation resistance is small compared to the reactance of the loop and the VSWR bandwidth is very narrow. The attainment of a high-Q tells us that the loop antenna is not lossy and inefficient. When power is applied to the loop at its resonant frequency *all* of that power will be radiated except that portion absorbed in the lumped I^2R conductor and capacitor losses manifesting as wasteful heat. With proper design and careful construction these series equivalent circuit losses can be made negligible or at least sufficiently small compared to the loop's radiation resistance such that a resultantly high *intrinsic* radiation efficiency and good antenna performance can be achieved from a relatively small HF antenna structure. Splendid!

The vertically oriented STL antenna's figure-of-8 doughnut shaped radiation pattern maximum is in the plane of the loop with nulls at right angles to the plane of the loop. Vertical oriented loops function perfectly well close to ground level. When horizontally mounted, the antenna pattern is omnidirectional with nulls straight up and straight down. Horizontally oriented loops should be elevated a significant fraction of a wavelength above ground to prevent significant ground losses; consequentially this orientation is uncommon.

Current flow through the loop's radiation resistance results in RF power being converted to electromagnetic radiation. A propagating radio wave must comprise both magnetic and electric field components in order for it to exist. In the case of an STL, a strong magnetic field is generated by passing a substantial RF current through the loop conductor and this magnetic field in turn generates a corresponding electric field in space thus providing the two essential E and H elements. This is where the term "magnetic loop" antenna originates.

However, since the small loop's radiation resistance is very small compared to that of a full sized resonant ½ λ dipole, getting a favourable ratio of loss to radiation resistance is the only "tricky" and challenging part of practical loop design and homebrew construction.

The current flowing through an antenna's radiation resistance when squared and multiplied by that resistance determines the amount of power that's actually radiated. Due to the relatively low value (few hundred milli-Ohms) of a small loop's radiation resistance, high currents (tens of Amperes) are necessary to enable even moderate powers to be radiated; so it is essential that all contributing sources of loss must be kept low in comparison with the radiation resistance in order to achieve high efficiency with the majority of the antenna input power transmuted into the radiation field, rather than being dissipated as heat energy in all of the contributing sources of deleterious loss resistance.

Through utilizing a large sized split-stator (see Figure 1) or a similar butterfly style air variable capacitor construction, or preferably a vacuum variable capacitor, low loss can be achieved in the tuning capacitor. Conductor loss can then be controlled by optimal choice of the diameter of copper tubing used to form the loop element and paying very careful attention to low ohmic interconnections to the capacitor such as welded or silver soldered joints, wide copper straps, etc. With 100 Watts of Tx drive power there are many tens of Amperes of RF circulating current and Volt-Amps-Reactive (VAR) energy flowing in the loop conductor and tuning capacitor; particularly with small loops on the lower HF bands.

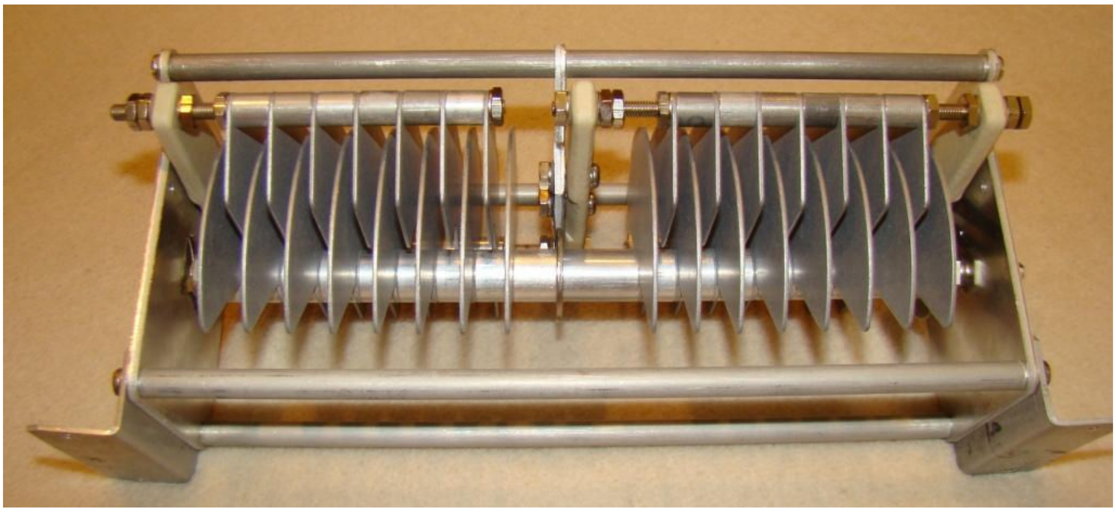

Figure 1 Large wide spaced split-stator style air variable capacitor

In the case of an air variable, capacitor losses are further minimised by welding the rotor and stator plates to the stacked spacers to eliminate any residual cumulative contact resistance. When connected across the loop terminals the butterfly construction technique inherently eliminates any lossy rotating contacts in the RF current path. The configuration permits one to use the rotor plates to perform the variable coupling between the two split stator sections and thus circumvent the need for any lossy rotor wiper contacts to carry the substantial RF current. Since the fixed stator plate sections are effectively in series, one also doubles the RF breakdown voltage rating of the composite capacitor. In view of the fact the loop antenna is a high-Q resonant circuit, many kilovolts of RF voltage can be present across the tuning capacitor and appropriate safety precautions must be taken. Small transmitting loop antennas capable of handling a full 400 Watts PEP or greater are readily achievable when appropriate construction and tuning components are carefully selected.

With air variables the older mil-style silver plated brass stator and rotor plate construction have lower losses than does aluminium construction. These can also be homebrewed.

Figure 2 Vacuum variable style low-loss capacitors

Figures 2 and 3 pictorially illustrate low loss vacuum variable capacitors for yielding very low conductor and dielectric losses in the loop tuning element with vernier control of capacitance with typically 36 or more shaft rotation turns to traverse the capacitance range.

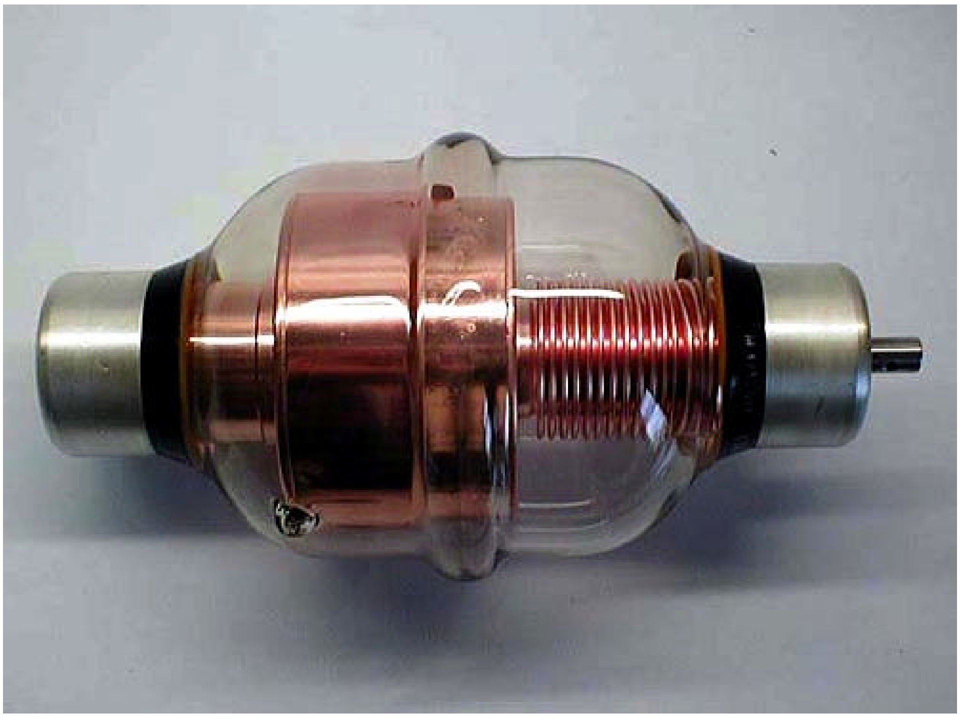

Figure 3 Large kVA rated vacuum variable capacitor

Feeding and matching:

Although loop antennas have deceptively simple appearance, they are complex structures with radiation patterns and polarisation characteristics dependent on whether they're fed in a balanced or unbalanced fashion. The method of feeding and matching the loop resonator, ground plane configuration, as well as the geometric form factor and physical proportions of the loop element itself are all fertile ground for experimentation. Various matching methods include series capacitor, transformer coupled subsidiary shielded-Faraday loop, simple unshielded coupling loop, gamma-match, and toroidal current transformer (CT); each with their respective merits.

The choice really boils down to personal preference as both the gamma and Faraday feed techniques work well. However, the Faraday shielded auxiliary loop or a CT located at the bottom central symmetry plane (located directly opposite the tuning capacitor) yields better loop electrical symmetry and balance that can in turn provide sometimes beneficial deeper front-to-side ratio and pattern nulls. In addition to imparting slight pattern asymmetry the Gamma match method can also result in some deleterious common-mode current flow on the outer braid of the feed coax that might need choking-off and isolating with a ferrite decoupling balun to prevent spurious feeder radiation and extraneous noise pick-up on Rx. Much also depends on the site installation set up in respect of conductive objects in the loop's near field that can disturb the antenna's symmetry and balance.

With the elegantly simple transformer-coupled Faraday loop feed method the 50Ω signal source merely feeds the auxiliary loop; there's no other coupling / matching components required as there are no reflected reactive components to deal with (the main loop appears purely resistive at resonance with just the core R_{rad} and R_{loss} components in series). The main loop conductor serves as one winding of a large RF air core transformer while a small one-turn auxiliary feed loop, fed by a coaxial cable, serves as the other winding.

The impedance seen looking into this auxiliary feed loop is determined solely by its diameter with respect to that of the primary tuned resonator loop. A loop diameter ratio of 5:1 typically yields a perfect match over a 10:1 or greater frequency range of main loop tuning. Simple transformer action occurs between the primary loop and the feed loop coupled circuit due to the highly reactive field near the resonant primary loop which serves to greatly concentrate magnetic flux lines which cut the small untuned feed loop. The degree of magnetic flux concentration is a function of the Q of the tuned primary which varies with frequency, i.e. the highest Q occurring at the lowest frequency of operation and the lowest Q exhibited at the highest frequency. This variation in Q factor results from the variation in the sum of the loss resistance and the complex mode radiation resistances of the primary radiator loop as a function of frequency. The effective feed impedance of the secondary loop is controlled by its diameter / ratio of area and by the number of flux lines cutting it; thus the impedance seen looking into the secondary loop will be essentially independent of frequency. One can intuitively see this because when the feed loop is extremely small in relation to a wavelength at the lowest frequency of operation, the number of magnetic flux lines cutting it is large because of the very high Q, whereas when the feed loop becomes a larger fraction of an operating wavelength as the frequency of resonance is increased, the concentration of flux lines is reduced due to the lower Q.

The above description can be helpful in visualizing what is happening from a conceptual point of view and in providing an understanding what is going on with this feed method.

If one seeks loop mode purity and figure-8 pattern symmetry with deep side nulls, the fully balanced Faraday transformer coupled subsidiary broadband impedance matching loop with its 5:1 diameter ratio would be the preferred choice of feed structure. Figure 4 below illustrates the construction of the Faraday feed loop. Mounting rigidity is achieved with the use of either RG-213 or LDF4-50 heliax for constructing the feed loop.

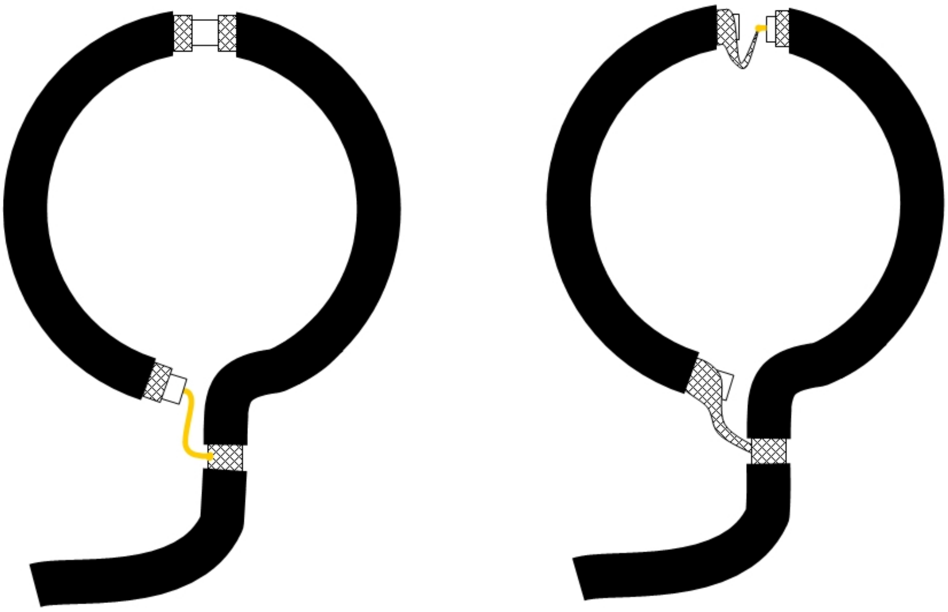

Figure 4   Alternative constructions for shielded Faraday loop

A variation of the shielded / Faraday feed loop is the simpler unshielded loop illustrated below in Figure 5. The loop is placed at the bottom centre directly opposite the top side tuning capacitor with the coax outer braid optionally connected to the main loop at its central neutral point. The diameter is again 1/5 that of the main radiating loop element.

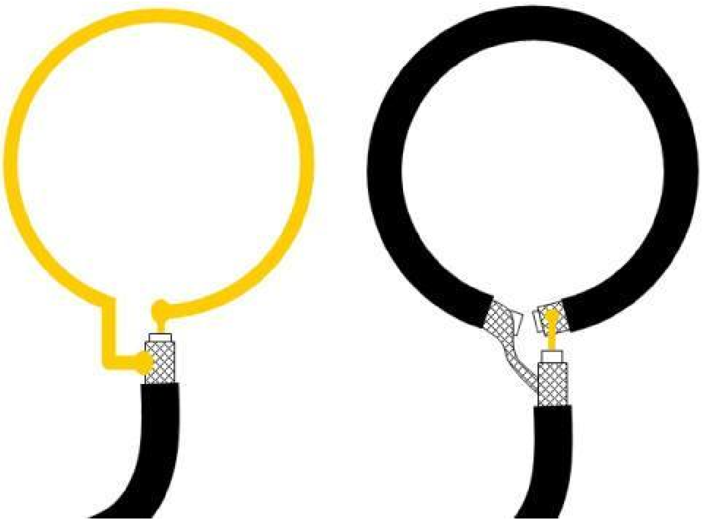

Figure 5   Unshielded coupling loop

Loop balance is important for rejecting local electric E-field conveyed noise; whereas the small loop is predominantly H-field responsive, any electrical imbalance results in unwanted common-mode currents flowing on the feeder that can skew the radiation pattern and impart deleterious E-field sensitivity which may contribute to additional local noise pickup. These extraneous feeder currents can be readily choked-off and eliminated with a ferrite core balun common-mode choke as conceptually illustrated in Figure 6.

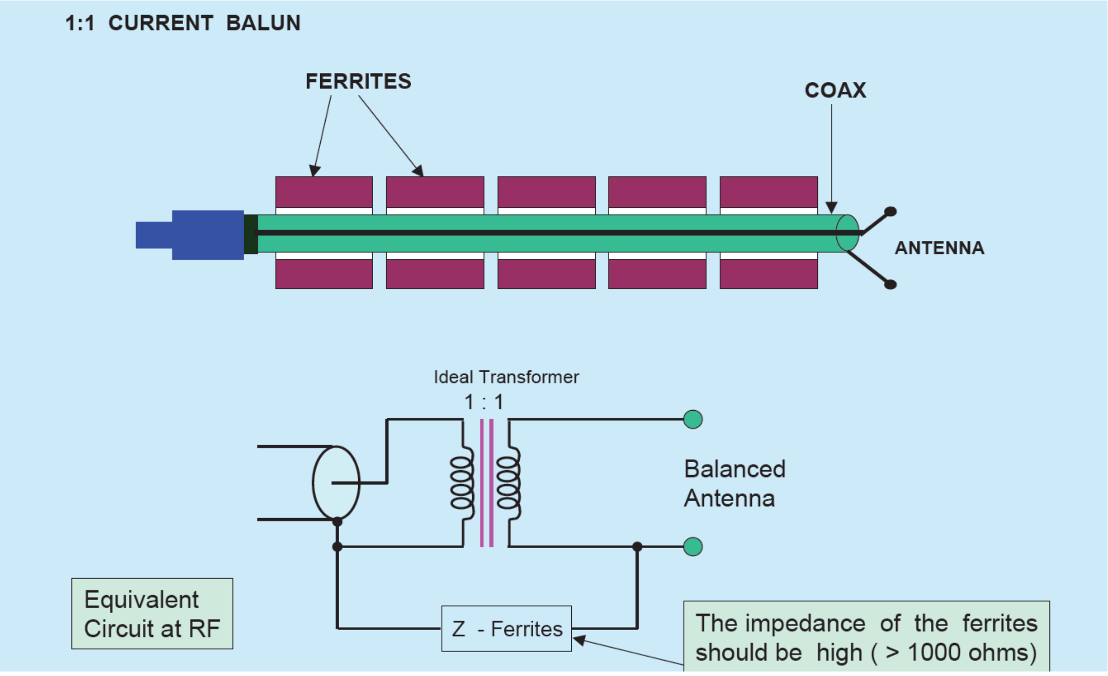

Figure 6 Common-mode current choke / balun

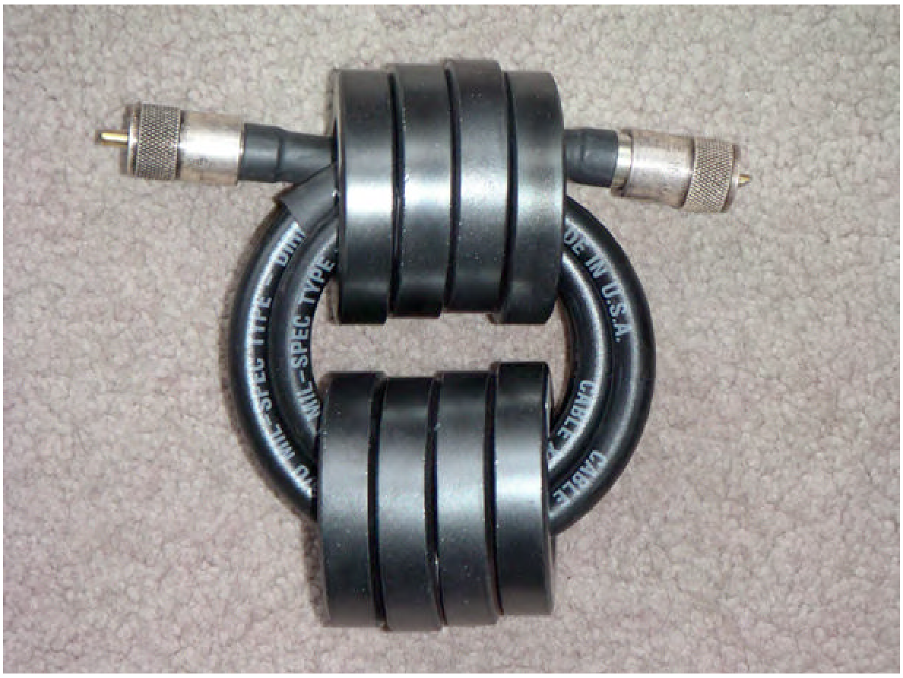

Figure 7 Multi-turn high power common-mode choke balun

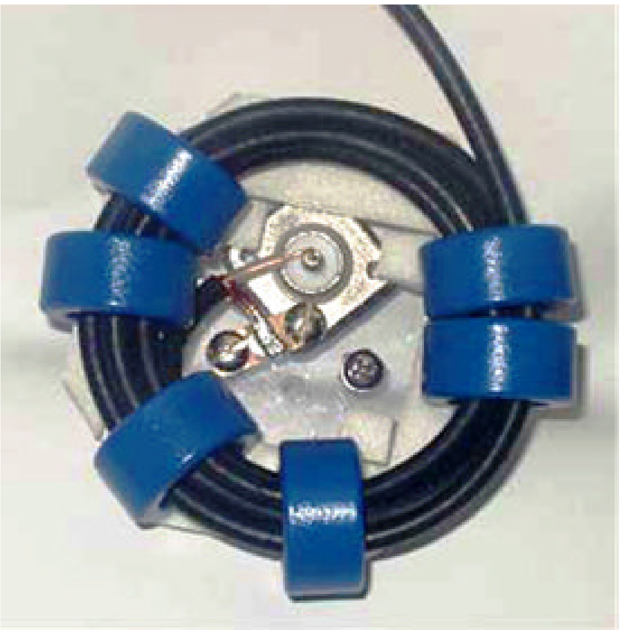

Figure 8 Simple common-mode choke construction

The various coaxial balun choke configurations depicted here use Amidon or equivalent ferrite mix 43 (μ = 850) or mix 61 for the toroid core stack and are placed in the coax feedline nearby where the coax interfaces to the loop.

Figure 9 Alternative common-mode choke construction

The Gamma match method is illustrated below in Figure 10. It is basically a tapped auto-transformer with the coax feed braid connected to the loop's central neutral point and the centre conductor connected via the concentric adjustable Gamma tube to the point on the loop conductor where the voltage to current ratio matches 50 Ohm. There is some inherent loop imbalance and asymmetry imparted with this arrangement and slight radiation pattern skewing is one of the consequential trade-offs associated with a Gamma feed compared to that obtained with an auxiliary Faraday loop matching or current transformer feed.

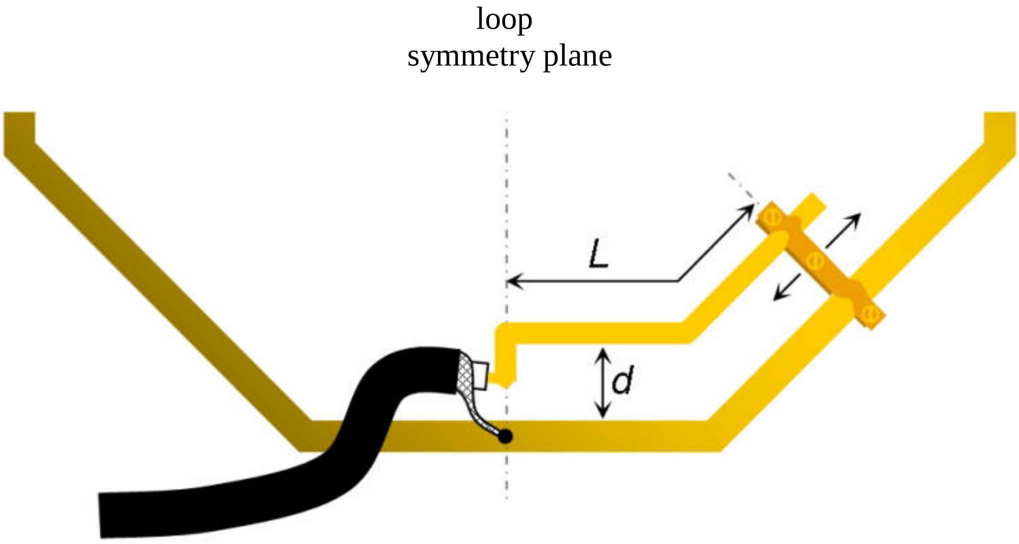

Figure 10 Asymmetric Gamma match

The above geometric parameters and the sliding shorting strap are juggled empirically to achieve a perfect 1:1 VSWR at loop resonance.

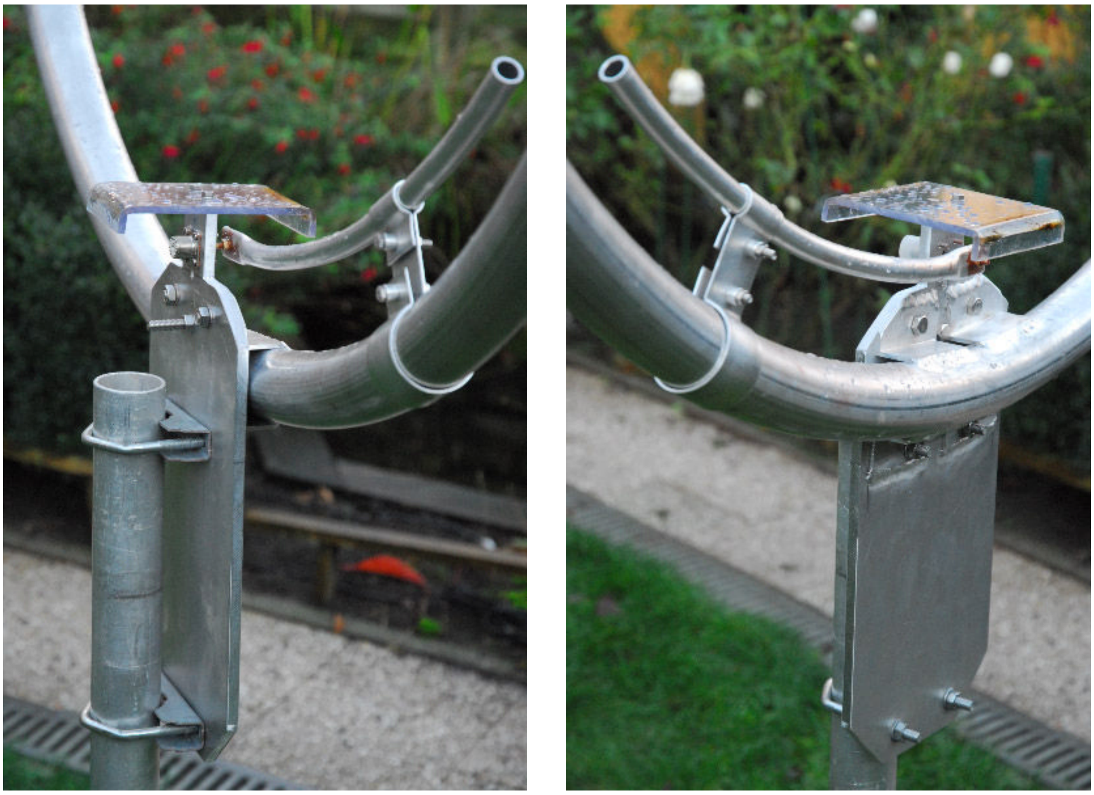

Figure 11 Gamma feed implementation technique

When a current transformer feed method is deployed one must of course endeavour to match the sum of the loop's radiation resistance and *total* loss resistance to the 50 Ohm feed coax. Depending on the loop's size and operating band, the loop feed impedance may be as low as 50 to 100 milli-Ohm, thus requiring an impedance transformation ratio of circa 1000 to 500, or a turns ratio N of 30:1 to 22:1. The "one" in this ratio is simply the loop tubing conductor passing through the centre window of the toroid core.

A ferrite toroid such as Amidon FT-140-43 (ID = 23 mm) FT-240-43 (ID = 35 mm) is fitted over the loop conductor directly opposite the tuning capacitor as illustrated in Figure 12 below. The multi-turn primary winding has the appropriate number of turns to match the loop to the 50 Ohm feeder. The loop conductor is effectively its own single-turn secondary winding. For proper operation one must ensure the core permeability μ is high enough to yield a primary reactance of greater than twice the feedline impedance while the core material must have a low hysteresis loss at the operating frequency. Ferrite mix 43 with a mu of 850 satisfies this requirement. This simple feed method works very well at the 100 to 200 Watt drive level when the evenly distributed primary turns are wound with 1.5mm^2 PVC insulated copper wire.


1: N ratio CT

1:1 feed

Figure 12 Conceptual and practical realisation of transformer coupling

An interesting variation depicted in the top right hand side of Figure 12 is the 1:1 transformer comprising a one-turn loop of the feeder coax threaded through the toroid core. This arrangement effectively places the 50 Ω impedance of the coax feed line in *series* with the very low fractional-Ohm impedance of the loop and can result in some mismatch losses. However the more precise multiple N winding CT technique yields the better result.

Loop radiation characteristics:

Small loop antennas have at least two simultaneously excited radiation modes; a magnetic and an electric folded dipole mode. When the ratio proportions of loop mode and dipole mode radiation are juggled to achieve equal strengths some radiation pattern asymmetry results and a useful degree of uni-directionality can be achieved with a typical front to back ratio of about 6 dB or so.

The small loop with its doughnut shaped pattern exhibits a typical gain of 1.5 dBi over average ground and a gain of 5 dBi when deployed with either short radials (the length of each radial need only be twice the loop diameter) or mounted over a conductive ground plane surface. By comparison a large ½ λ horizontal dipole mounted ¼ λ above average ground has a gain of 5.12 dBi and a ¼ λ Vertical with 120 radials each ¼ λ long has a gain of 2 dBi over average ground. The front to side ratio of a well balanced loop is typically 20 to 25 dB when care is taken to suppress spurious feeder radiation due to common-mode currents flowing on the coax braid.

However the small loop has one very significant advantage over any other antenna due to its unique radiation pattern. If the vertically oriented loop's figure-8 doughnut pattern radiation lobe is visualised standing on the ground the maximum gain occurs at *both* low and high angles, radiating equally well at all elevation angles in the plane of the loop, i.e. radiation occurs at all vertical angles from the horizon to the zenith. Because the loop radiates at both low and high angles, a single loop can replace both a horizontal dipole and a Vertical. This is particularly beneficial on 160, 80 and 40m where the loop will provide outstanding local / regional coverage and easily match and often outperform a tall ¼ λ Vertical for long haul DX contacts, i.e. an exceptionally good general purpose antenna.

Energy radiated by the small loop is vertically polarised on the horizon and horizontally polarised overhead at the zenith. It will be quickly realised that a loop has the distinctive property of providing radiation for transmission and response for reception over both long distances and over short to medium distances. This is achieved by virtue of low angle vertically polarised propagation in the former case and by means of horizontally polarised oblique incidence propagation in the latter case. In contrast, a Vertical monopole is useful only for low angle vertically polarised propagation since it exhibits a null overhead and poor response and radiation at angles in excess of about 45 degrees. Such antennas are of course very useful for long distance communication by means of low angle sky wave skip propagation, or for short range communication via the ground wave propagation mode.

In further contrast, a horizontal ½ λ dipole (or beam arrays comprising dipole elements) at a height above ground of a just a fraction of a wavelength (as opposed to idealised free space or mounted very high) exhibits maximum polar response directly overhead (good for NVIS) with almost zero radiation down near the horizon. Such popular "cloud warmer" antennas in residential situations as the surreptitiously hung ubiquitous G5RV, End-feds, dipoles, inverted-V, etc. are thus most useful for short to medium range communication in that portion of the HF radio spectrum where oblique incidence propagation is possible.

Importantly it should be noted when comparing small loops with conventional antennas that a 20m Yagi beam for example must ideally be deployed at a height above ground of at least one wavelength (20m) in order to work well and achieve a low take-off angle tending towards the horizon for realising optimal no compromise long-haul DX operation.

Unfortunately such a tower height is impractical in most residential zoning rule situations imposed by municipal councils and town planners. If the Yagi beam is deployed at a lower 10m height then a diminutive loop will nearly always outperform the beam antenna. This writer never fails to be amused by folks who acquire a potentially high performance Yagi HF beam and sacrilegiously deploy it in suboptimal installations in respect of height above ground or proximity to a metal roof. The problem worsens on the lower bands below 20m where the resultant high angle lobe pattern direction due to low antenna height is not at all very conducive to facilitating good DX communication.

In comparison to a vertically mounted / oriented loop, the bottom of the loop does not need to more than a loop diameter above ground making it very easy to site in a restricted space location. There is no significant improvement in performance when a small loop is raised to great heights; all that matters is the loop is substantially clear of objects in the immediate surrounds and the desired direction of radiation! Mounting the loop on a short mast above an elevated roof ground-plane yields excellent results.

A good HF antenna for long haul DX propagation paths requires launching the majority of the Tx power at a low angle of radiation; things a good, efficient and properly installed vertical, a properly sited small magnetic loop, and a big multi-element beam atop a very tall tower do very well. Of course the latter beam antenna has a forward gain advantage over the loop that may be helpful on some weak signal paths.

Receiving properties:

In a typical high noise urban environment a loop will nearly always hear more than a big beam on the HF bands. The small magnetic loop antenna (a balanced one) responds predominately to the magnetic component of the incident EM wave, while being nearly insensitive to the electric field component; which is the basic reason why loops are so impressively quiet on receive; often times dramatically so. They will pull in the weak signals out of the ambient noise and you will very likely receive stations that you'd never hear when switching across to a vertical, dipole or beam antenna deployed in suburbia.

In a propagating radio wave the magnitude of the electric vector is 120π or 26 dB greater than the magnitude of the magnetic vector, the difference being due to the intrinsic impedance of free space (377 Ohms). On the other hand the induction fields associated with man-made noise have electric E-field components many times greater than a normal radiation field (radio wave). While a dipole or vertical antenna is sensitive to both the electric and magnetic components of a wave, the small loop is responsive only to the magnetic H-field component and it will be substantially "blind" and offer a high degree of rejection to pickup of undesired man made noise and propagated atmospheric disturbances.

Hence the widely used term "magnetic loop" antenna to signify this field discrimination to the components of the incoming incident EM wave. Antenna theory treats the loop as the electrical conjugate of the dipole, i.e. the loop is a "magnetic dipole" while an ordinary dipole is an "electric dipole".

Significantly, a small loop antenna will typically produce a signal-to-noise ratio / SNR that is some 10 to 20 dB greater than a horizontal dipole in a noisy urban environment and an even greater improvement in SNR when compared to a vertical antenna as a result of the man-made noise comprising a strong electric field component and being largely vertically polarised. The SNR determines readability, not the received signal strength per se. The missing strength can be returned noiselessly by the receiver’s AGC system.

The most important criterion for reception is the signal to noise ratio and *not* antenna gain or efficiency. In the HF band, particularly at the low-mid frequency portion, external man-made, seasonally and solar cycle variable galactic / atmospheric noise is dominant.

The magnetic loop antenna has one other important practical advantage in receive mode. The aforementioned high-Q resonator imparts a very narrow band frequency selective bandpass filter ahead of the Rx front-end stages. Such an incidental preselector comprising the antenna itself imparts greatly improved receiver performance on the congested lower HF bands with high power broadcast stations and particularly when lightning strikes and atmospheric electrical discharges are present in the regional area. Unwanted overload causing and adjacent-channel QRM interference signals are rejected or heavily attenuated.

As well as eliminating strong-signal overload and intermodulation effects, the filtering dramatically reduces the amount of lightning induced broadband impulse energy fed to the Rx front-end and weak signals can still be heard when reception under such adverse conditions was previously impossible with other antenna types.

It is these collective characteristics of small loop antennas that enable them to often very significantly outperform their large dipole, Yagi or Quad beam counterparts during direct A/B comparative testing. Conversely in Tx mode the antenna’s inherent filter action selectivity causes any transmitter harmonics to be greatly attenuated and not radiated. This can help with eliminating some forms of TVI and BCI.

Some words about efficiency and losses:

As with most antenna systems departure from perfect electrical symmetry will result in currents flowing in parts of the system and surrounds where no currents should flow. Such extrinsic factors can add to the total system loss. Losses attributed to the environment are the most difficult to deal with as isolating the loop from ground and its electrical environment is virtually impossible at the low HF bands. This includes common mode currents flowing on the outer braid of the coax feed cable and adjacent conductor objects such as pipes and electrical cables in nearby proximity to the loop antenna.

When the loop conductor length approached 0.25 λ the STL achieves maximum efficiency. This corresponds to the largest VSWR bandwidth and the lowest voltage across the tuning capacitor due to the higher radiation resistance and associated lower Q.

Efficiency is influenced by some radiated RF energy being captured or absorbed by objects in the proximity of the loop, e.g. energy absorbed by ferrous materials like iron and steel contribute significant Eddy current and hysteresis losses.

Efficiency is also a function of the earth's soil conductivity. Even though an STL antenna does not require radials or a ground plane, once the RF energy is radiated it is still subject to the same laws of radio physics that all other types of RF radiators experience.

Better earth conductivity usually results in more of the vertically polarized signal being reflected (in the far field, not in the near field), thus combining with and reinforcing the direct-path signal at the desired lower elevation angles of radiation.

Vertical orientated small loops may provide up to twice the signal strength under certain conditions when operated near a highly reflective surface or earth surface, such as salt water. This is why a vertical loop is very special, and, as a bonus, it does not have the disadvantage of overhead nulls in the antenna pattern like verticals and short whip antennas have.

Effects of ground on loop antenna performance:

When a dipole antenna is placed horizontally above ground, its electrical “image” in the ground is of the opposite phase. As a consequence, if the height above ground of a horizontal dipole is reduced to less than ¼ wavelength, fairly high system losses develop due to a rapid decrease in radiation resistance concurrent with a rapid rise in loss resistance resulting from dissipation of power within a less than perfect ground. This represents a classic double-whammy scenario and deleterious performance for dipoles deployed at insufficient height above ground (a widespread limitation for many ham radio antennas).

By way of contrast, the oscillatory RF currents associated with the image of a small vertical oriented loop antenna above ground are “in-phase” with those of the loop. Therefore the effect of ground on the performance of a vertically oriented loop is relatively small. In fact, because the magnetic component of an electromagnetic wave is maximum at the boundary between the ground and the space above, loop performance is usually best when the loop is located near the ground at a distance outside of the loop’s close-in induction field (just a loop diameter or two). However, if nearby conductive objects such as power lines or buildings exist in the direction of transmission / reception; it is normally preferable to choose a height above ground which will provide the loop with a clear and unobstructed view of the intended signal path.

In comparing the performance of a vertical whip and a small vertical loop located atop of a building, it may be said that the loop will generally be the clear winner with respect to vertical and horizontal radiation patterns. This is because the pattern of a whip antenna driven against the top of a building is usually not predictable with any accuracy at all because vertical currents will flow all the way up and down the several conductive paths between the antenna and the earth; each path contributing to the total radiation pattern in the form of multiple lobes and nulls.

A balanced loop antenna, however, is inherently immune to such problems because the ground below the antennas does not form the missing half of the antenna circuit in respect of supporting ground-return currents as it does with a vertical whip / monopole antenna. Therefore the multiple current paths to ground (earth) are eliminated with the loop. Of course both the loop and the whip are subject to the well-known wave interference effects in elevation due to height above the ground (or water).

Reflective metal objects having a size greater than about 1/3 of a wavelength and at a distance of less than about 2 wavelengths from the loop antenna can produce standing wave “nulls” in a given direction at various frequencies. If the antenna is to be mounted atop a metal roof, diffraction interference from the edge of the building roof should be considered if undesirable nulls in certain directions at some frequencies are to be avoided.

Usually the best antenna siting location is near the edge of such a conductive roof, in the direction of the desired signal or signals.

Whereas vertically oriented loop operation over good ground is more efficient than over poor (lossy) earth, this is far less critical than with verticals and small whips tuned and fed against earth or artificial ground plane. In the latter vertical case the attainable antenna efficiency is wholly dependent on the quality of the ground plane system and radial mat.

Loop Directivity:

It is commonly believed that a vertically oriented loop antenna exhibits a bi-directional pattern with maximum reception occurring in the plane of the loop. Although this is true for vertically polarised sky-wave signals arriving at very low elevation angles (less than about 10 degrees) and for ground-wave signals, it is certainly not true for reception of high angle sky-waves (greater than about 30 degrees) whose polarisation usually rotates from vertical to horizontal at a fairly random rate due to “Faraday Rotation” of free-electrons within the ionosphere.

At angles exceeding 45 degrees, the loop response shifts to a preference for horizontal polarisation arriving at an azimuth angle of 90 degrees with respect to the plane of the loop. Thus, for short-range communication links, i.e. less than about 500 km, best reception will usually occur with the loop rotated 90 degrees, that is, the plane of the loop perpendicular to the azimuthal arrival angle.

It is not easy to predict which azimuthal bearing will provide the best night-time reception with a loop over paths of less than about 500 km at frequencies of less than about 7 MHz. This is due to the prevalence of both sky-wave and ground-wave signals which randomly combine to produce rather serious fading. Usually, trial and error is the best solution for determining which antenna orientation will produce the most favourable compromise between the highest average signal-strength and the least troublesome fading. Generally for distances exceeding 500 to 1000 km, the best orientation is with the plane of the loop in the direction of the arriving signal.

Further, the side nulls exhibited by the loop at low elevation angles may be used to “null-out” the ground-wave signal to reduce fading when sky-wave propagation exists simultaneously. In comparison a vertical whip has a null overhead and thus is ineffective for short and medium distances.

A vertical loop antenna located less than about 0.15 λ above ground exhibits excellent coverage from the zenith down to almost zero degrees in the elevation plane making the loop useful over almost any distance range. At elevation angles higher than about 20 degrees, a loop is almost omnidirectional in azimuth when receiving sky-wave signals.

For a loop above average ground, as opposed to ground having perfect conductivity, the response at very low vertical angles e.g. less than about 5 degrees, is typically 10 dB or more below the achievable response above perfect ground. It is perhaps worthy to note that the ground immediately below the loop principally affects the response at high vertical angles while the properties of the ground at a large radius distance from the antenna tends to characterise the performance of the loop at low vertical angles in the plane of the loop.

Construction and siting issues:

Without a good quality low-loss split stator or butterfly or vacuum variable capacitor of adequate RF voltage and current rating, it is quite futile building a magnetic loop antenna and expecting it to yield the impressive results it’s potentially capable of. The minimisation of all sources of ohmic loss is particularly important in Tx mode. TIG welded vanes and fillets of weld on the spacer stack on an aluminium split-stator air variable lowers the capacitor’s ohmic loss resistance by a significant amount.

By virtue of the shorter rotor, the butterfly style capacitor has slightly lower rotor loss than the split-stator construction style. In either case the two stators are connected to each end of the loop conductor via wide copper straps. The tuning capacitor is undoubtedly the single most critical component in a successful homebrew loop project. TIG weld fillets on all of the mating metal-to-metal surfaces of fixed parallel-plate or variable capacitors will ensure the lowest possible ohmic loss accumulation especially over time in the presence of moisture and surface oxidation.

Although more expensive and harder to find, vacuum variable capacitors have a large capacitance range in respect of their min/max ratio and allow a loop to be tuned over a considerably wider frequency range than that achievable with an air variable capacitor. Vacuum capacitors also have lower intrinsic losses than most air variables. High quality Jennings vacuum variable capacitors (Figure 2) and numerous Russian made equivalents (Figures 13 and 14) can be readily found on the surplus radio parts market and eBay, as can their associated silver-plated mounting and clamp hardware to ensure a low contact resistance connection to the loop antenna conductor. A low contact resistance interface is absolutely essential between the capacitor terminals and the copper loop conductor. Eliminating every stray milli-Ohm counts towards achieving highest efficiency!

Figure 13 Homebrew capacitor clamps with silver-soldered copper fittings

Figure 14 Russian Mil-style vacuum variable with integral clamps

Other creative means can also be used to fashion a high VAR rated low-loss capacitor such as trombone, piston, or interdigitated meshing plate configurations. Fixed value homebrew parallel plate capacitors can be constructed from scrap sheet copper and silver-soldered spacers and augmented by a smaller value variable for bandspreading in a mono-band loop. Air is always the preferred dielectric as most other materials have high loss tangents and dissipation factors. Whether a vacuum or air variable or homebrew capacitor is chosen, their mechanical shafts can be readily interfaced to a reduction gearbox and motor drive to facilitate easy remote tuning of a roof top or covert loft mounted loop. Figure 15 illustrates an innovative homebrew fixed air dielectric capacitor stack + variable combo capacitor constructed by VK5JST using readily available low-cost materials, incorporating vernier bandspread tuning using an adjustable vane on a servomotor driven threaded lead screw arrangement. The dielectric material is a thick slab of polyethylene breadboard sourced from the local supermarket or the XYL’s kitchen. The antenna tuning can be manual or automatic based on VSWR sensing and a self-tuning servo system to control the stepper motor drive. Peaking the loop tuning capacitor for strongest band noise on Rx will get the loop antenna tuning in the right ballpark for achieving a low VSWR when the Tx is subsequently keyed up.

Tuning motor control cables should be routed symmetrically with respect to the two halves of the loop and be decoupled and chocked-off immediately outside of the loop area. Routing the cabling up though the inside of the loop tubing and out a small hole drilled in the bottom electrical neutral point of the loop directly opposite the top tuning capacitor is a benign way to keep the control cables shielded and electrically cold with respect to RF.

Failure to pay very careful strict attention to construction details in relation to eliminating all sources of stray losses and making bad siting choices such as close proximity to ferrous materials are the two main reasons why small magnetic loop antennas sometimes fail to live up to their performance potential; instead behaving as a proverbial “wet noodle” with associated poor signal reports. Conversely a well built / sited loop is an absolute delight.

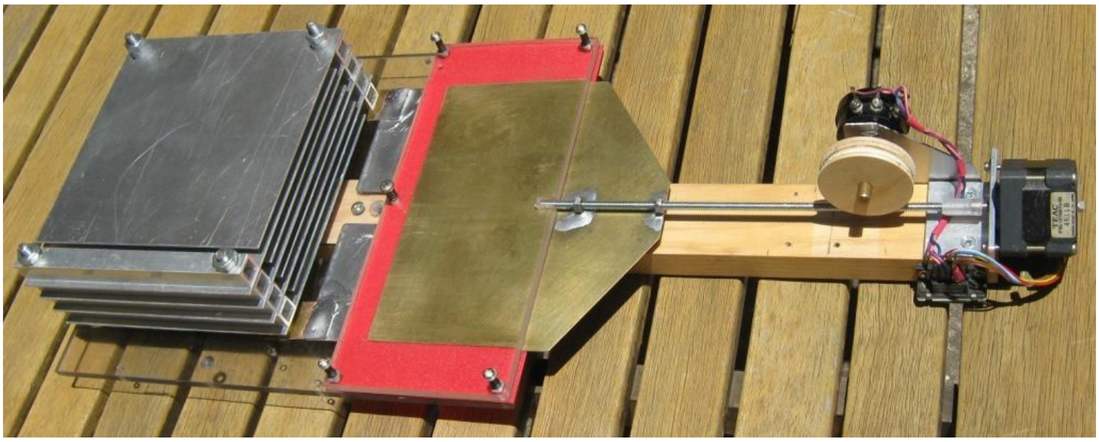

Figure 15 Combo fixed plate + sliding vane vernier bandspreading

Another homebrew capacitor construction method is illustrated in Figure 16 comprising a parallel-plate air variable for tuning a mono-band 20m copper tube loop of nominal 1m diameter. Breakdown voltage and hence power handling level is determined by the air gap spacing of the parallel-plate flap vane capacitor and / or any intervening dielectric material.

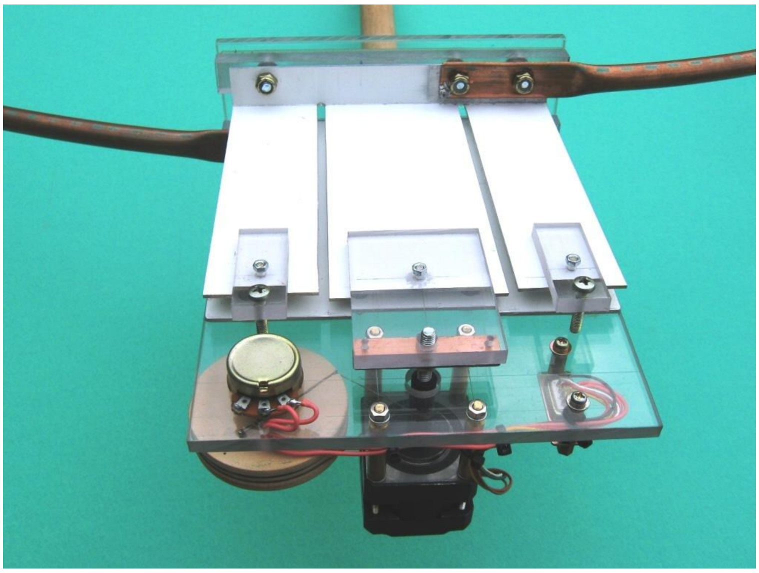

Figure 16 Stepper motor and lead screw driven moving vane air variable

Transmitting loop antennas intended for optimal coverage of the most popular portion of the HF spectrum ranging from 3.5 MHz to 30 MHz are best segregated into at least 2 distinct loop sizes. If top-band 160m is also required then 3 loop sizes are best.

A nominal 0.9m diameter loop for covering all the upper HF bands from 20m through to 10m (and perhaps also tunable down to 30m depending on capacitor min/max ratio), and a 2m diameter loop for covering the lower bands 80m through to 30m. For best operation down at 160m and improved 80m performance increased loop diameters of 3.4 m to 4 m should be considered. The small loop's radiation resistance and hence attainable efficiency / radiation effectiveness is proportional to the fourth power of its circumferential length.

An important thing to note about vacuum capacitors is they don’t have a uniform RF amperage current rating over their entire capacitance range, but it is less at small plate mesh / their low capacitance end. So one needs to factor this characteristic into design calculations and make sure you operate the capacitor within its ratings over the desired loop tuning range. Manufacturers like ITT Jennings provide nomographs of this data. This is another good reason for restricting the loop tuning / operating range over a nominal 2 to 3:1 range so the vacuum capacitor always works in its optimal VAR / RF current “sweet-spot” region. The saving grace with the current ratings of vacuum capacitors is they are continuous RMS Amps, i.e. key-down CW operation; and can be considerably safely exceeded when running relatively low duty cycle SSB voice modes / PEP transmissions. All is OK with vacuum capacitors as long as the rated glass / metal seal temperature is not exceeded. This is unlikely to occur in practice as the silver plated copper mounting clamps efficiently heatsink and remove heat into the thermal mass of the copper loop conductor.

Mono-band loop operation generally yields the best result as the optimum loop inductance to capacitance ratio can be chosen and the majority of the tuning capacitance can be provided with a fixed-value vacuum capacitor. A much smaller vacuum variable capacitor can then be deployed in parallel to achieve fine vernier “bandspread” tuning across the whole band of interest, e.g. 40m or 80m, etc.

Top-band operation at 1.8 MHz is always the hardest challenge for any antenna type, small loops (typical dimensions of 0.02λ) included; but their on-air performance can nevertheless be authoritative with a commanding signal presence. There are no "free lunches" (and few cheap ones) when shrinking the size of antennas as the free space wavelength has not yet been miniaturized by nature redefining the laws of physics! Consequently antennas of such diminutive size must always be placed into proper perspective when compared with the performance attainable from a full-sized λ/2 horizontal dipole for 160m. However, most amateurs haven’t got sufficient residential block size and/or mast height in a fraction of wavelength to accommodate a 160m dipole that works properly with a decent radiation efficiency and ability to put its radiated power in a useful direction. Similarly, reasonably efficient and efficacious Verticals for 160m operation unfortunately exceed the allowed height by a great margin that’s permitted by local council and residential building code regulations. Then a huge amount of real estate is required to accommodate the extensive radial system.

The practical on-air performance of a loop on the 160/80m bands will be highly dependent on what antenna you use as a reference comparison, e.g. a centre-loaded mobile whip or full size resonant dipole/monopole, etc. and what path is used, NVIS, ground wave, sky wave, etc. The loop conductor diameter is determined by the desired loss resistance due to skin-effect, and choices can range from modest 6mm copper tubing to large bore 100mm copper or aluminium tube. Commonly used conductor diameters used to construct a magnetic loop are 20mm and 32mm soft copper tube. Heavy wall thickness tubing is not required as the RF current flow is confined to the conductor surface due to the skin-effect. Note that the radiation efficiency is *not* related to the loop size. Loop antenna efficiency is determined by the conductor tube diameter and its electrical conductivity.

This conceptual notion is counterintuitive for many folks. A small loop will also be efficient and radiate power very effectively on 80m and 160m but the resultant L–C ratio and stored energy will often be such that the loop’s Q factor will be so high as to yield an impractically small instantaneous bandwidth that’s not useful for SSB communication purposes where a VSWR bandwidth of circa 2 to 3 kHz is the desirable minimum.

Achievable bandwidth is roughly proportional to loop size / diameter and Q is inversely proportional to the loop diameter. Depending on its construction a small loop of nominal 1m diameter can exhibit an *intrinsic* radiation efficiency of 90% over the 1.8 to 30 MHz frequency range.

This “intrinsic” efficiency does not take into account the external / extrinsic ground and environmental losses that can suck up power from the localised fields. This quite obvious point can be observed empirically because you can pump in hundreds of Watts of CW power and the loop conductor and tuning capacitor remain cool. If the STL was ostensibly inefficient it would rapidly heat up and melt the silver solder joints with such input power.

Copper tubing is the preferred material to fabricate the loop as it has a higher conductivity and lower resistance per unit length than aluminium. RF losses are dominated by skin effect and concentration of RF current flow along the conductor surface. This is mitigated through use of large surface area (fat diameter) tubing to form the loop conductor.

Larger size semi-rigid Heliax coax such as LDF550 / LDF650 / LDF750 will conveniently make excellent loop construction material for the smaller diameter 20m to 10m HF band loops when run at the 100 to 400 Watt power level. The whole of the heliax cable should be used with the inner and outer conductors connected together at their ends.

The optimum loop form factor shape is a circle as it will yield the best enclosed area to perimeter ratio. Radiation resistance is proportional to loop area, whereas ohmic loss resistance is proportional to the loop circumference / perimeter. A square loop is the worst form factor while an octagonal loop (constructed with tube straights and elbows) encloses beneficially 20% more area than a square of the same circumference and ohmic resistance.

An important point to note is the small loop’s radiation resistance and hence radiation effectiveness is proportional to the fourth power of its circumferential length.

The larger bore 2-inch LDF750 can be used on the lower bands to beyond 1 kW. In relation to resistance and conductivity, small loop antennas inherently exhibit very low radiation resistances, which compete with the ohmic resistances of the loop conductor and the resistances from connections and welds, including the tuning capacitor connection. Magnetic loop antennas will typically have a radiation resistance in the order of 100 to 200 milli-Ohms. This means that every additional milli-Ohm caused by a poor contact will cost you one percent efficiency. That is why professional magnetic loop antennas designed for transmitting purposes will never have mechanical contacts and *everything* including the capacitor plates should be welded or silver soldered. It is not uncommon to experience 60 Amperes or more of RF circulating current in the loop and capacitor when fed with several hundred Watts of power.

In the practical deployment and siting of a loop antenna there are extrinsic factors of both a beneficial and deleterious kind affecting the radiation and loss resistances when the loop is not strictly deployed in an idealised free space scenario.

When the loop is mounted over a perfectly conducting ground plane reflector or copper radial wire mat an electrical image is created that increases the effective loop area. This increase in turn beneficially increases the loop’s radiation resistance by a substantial factor. Such a favourable situation is easy to facilitate.

Conversely if the loop is placed over average ground (a reasonable reflector) the radiation resistance increases but a reflected loss resistance is also introduced due to transformer effect coupling of reactive near-field energy into the lossy ground. Mounting the loop a certain minimum distance above ground (a loop diameter or so) is therefore important as the increase in antenna efficiency gained from minimising intrinsic loop conductor loss can be quickly negated by this deleterious earth proximity resistance (extrinsic factor).

Similarly when ferrous / iron material is too close, the magnetic near-field of the loop will induce by transformer action a voltage across the RF resistance of the material causing a current flow and associated I^2R power loss. This situation might for example arise when the loop is mounted on an apartment balcony with nearby iron railing or concrete rebar etc; the deleterious influence can be minimised by simply orienting the loop to sit at right angles to the offending iron or steel material. Another loss contributing component is due to current flowing in the soil via capacitance between the loop and the soil surface. This capacitive coupling effect is again minimised by keeping the loop at least half a loop diameter or more above the nearby ground.

Ground loss comprises two components; that due to the current induced in a mirror image of the loop below the earth surface with resistance of the image loop being proportional to the soil resistance plus that due to current flowing in the soil via capacitance between the loop and the soil surface. Total systemic loss varies in a complex manner as a function of frequency, loop height, soil resistance and permittivity, and RF skin depth of the soil.

The transformer analogy for the loop antenna is a good one. The HF communication link may be visualised as a reciprocal “space transformer” with the loop acting as a secondary “winding” very loosely coupled to the distant transmitting antenna. The magnetic field component of the incident electromagnetic wave induces a small RF current to flow in the loop conductor by means of induction that in turn gets magnified by the loop resonator’s high Q that’s appropriately impedance matched to the coax transmission line.

A freestanding transmitting loop is best supported on a short non-metallic mast such as a section of 100mm diameter PVC pipe and pedestal foot fashioned from plastic plumbing fittings. The loop can also be placed on a rotator drive plate and turned for best signal strength or it can be oriented in angle to null-out particularly bad QRM.

Care must be taken not to touch the loop when transmitting and to keep a safe distance away from the loop antenna’s magnetic near-field to ensure conservative compliance with electromagnetic radiation / EMR standards for human exposure to EM fields. A distance equal to or greater than one or two loop diameters away is generally considered a safe field strength region. RF burns to the skin from touching the loop while transmitting are very unpleasant and take a long time to heal.

Concluding remarks:

The proof of the pudding is always in the eating so experimentally inclined amateurs are encouraged to gain some first hand practical experience by getting into the shack workshop and constructing some homebrew loop antennas. Such empirical validation of efficacy is always very gratifying, particularly when a VK station can have a solid 5 and 9 QSO on 40m or 20m with a distant USA or Canadian station from an elegant looking Lilliputian loop sitting on a table fed with a modest 50 Watts! What we ultimately seek from any antenna is reliable HF communication at all times when a band is open for DX and, simply put, that means efficiently radiating most of the RF that’s applied to the antenna in a useable direction and take-off angle. The underestimated magnetic loop antenna satisfies that basic criteria very well.

A well designed and constructed small magnetic loop antenna is perhaps one of the rare few instances where a proverbial gallon of performance can be extracted from a pint bottle!

It is hoped the reader of these notes will gain a good appreciation of magnetic loop antenna characteristics and be better guided in assimilating those factors that really matter and need to be taken into account when contemplating and building an STL antenna project (or two).

7 July 2009 / updated 28 November 2010