# Wideband Active Small Magnetic Loop Antenna

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There are now extremely wideband software defined radios (**SDR**) where the wideband antenna is a natural choice. Wideband small magnetic loops (**WSM loop**) are used already 3-4 decades and I was curious to see what can be reached with them and to evaluate their usefulness as a wideband SDR input. The WSM loop should work in short circuit mode in order to reach flat frequency response in wideband frequency range. The antenna should be used with an amplifier since the loop current is very small. This amplifier must be with very low input impedance. [1, 2, 4, 6, 12].

## Schematics and Construction

A circuit diagram of active WSM loop antenna is shown on **Fig.1**. The antenna specification is given for 1m diameter circular loop with aluminum conductor with diameter 3.4 mm.

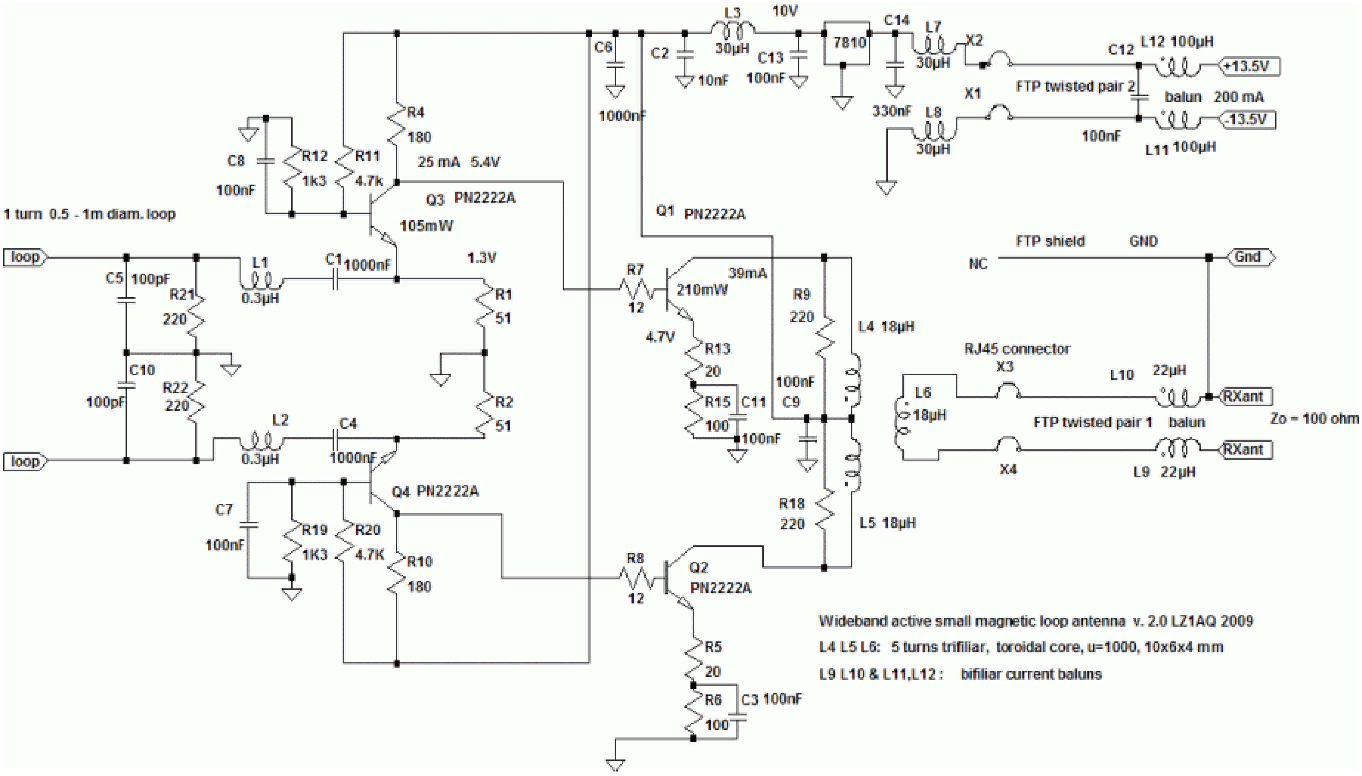

**Fig. 1** *Schematics diagram of wideband active small loop amplifier. Common base circuit. DC operating point voltages and currents are given.*

### Specification

Diameter: 1 m, 1 turn
Material: aluminum conductor with 3.4 mm diameter
Loop inductance: 4 uH
Antenna Factor $K_a$: 6 dB meters$^{-1}$ @ 10 MHz (computed from the spice model)
(1 uV/m input signal will give 0.5 uV output voltage)
Flatness: Within 3 dBmeters$^{-1}$ 0.5 – 30 MHz; (computed from the spice model)
Noise floor: >= 0.7 uV/m (computed from the spice model)
Power supply: Remote, 13.5 V >150 mA
Dynamic range: TBS; 1 dB Compression point >= 130 dBuV/m ( 5.6 V/m p-p output voltage, from the spice model)

### Construction

An experimental amplifier and antenna construction are shown in **Fig. 2 ,3,4** .

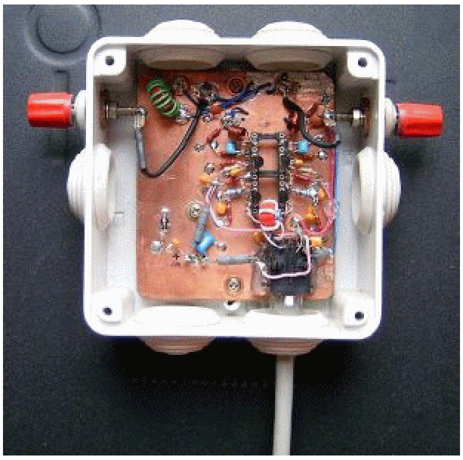

**Fig.2**

**Fig.3**

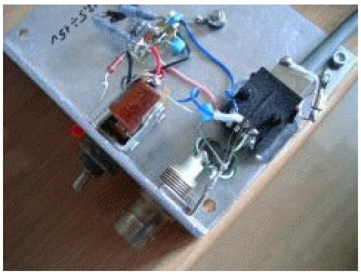

**Fig.4**

The construction of the loop should be considered with the following rule: the ratio of loop area to loop inductance should be maximized (see the Appendix) . That automatically means that circular shape with 1 turn is the best choice. The practical diameter is around 1 m with the conductor as fat as possible. The material might be copper or aluminum – actually the loop Q-factor is not important. The important factor is the low loop inductance. 1m diam. loop made from aluminum wire 3.4 mm gives inductance around 4 uH. I have used also 0.9 m diam. loop made from double foil FR-4 PCB material (**Fig.3**) with 1.5mm thickness and 20 mm width which reduces the loop inductance to 3 uH. The best results can be obtained with “parallel” and “crossed parallel ” loops (CP loop, see **Fig. 5 , 13,14** , Appendix I,II). For urban locations where the noise level is much higher smaller loops can be used.

**Fig.5** *The author at the experimental green field.*
*4 $m^2$ 4-squares crossed parallel loop is mounted on a wooden frame..*

This antenna will be used outdoors and the amplifier is placed in a small, IP55 secured, plastic box (**Fig.2**). These boxes are widely available on the market - any similar one can be used. The connecting cable between the antenna and receiver (**RX**) is shielded LAN cable FTP type with 4 twisted pairs. The signal and power use separate pairs. RJ45 standard connectors are used. These connectors are very cheap and reliable but the RJ connector should to be placed inside the box since it is not waterproof. There is no need for the box to be shielded – it is supposed that the antenna will be mounted at least several meters away from electrical equipment and direct near field influence to amplifier board will be reduced. The FTP shield must be connected to RX ground (chassis), but at the far (antenna) end should be left floating. The power supply (**PS**) ground also is floating if independent DC supply is used. Do not use switching PS - it will be very difficult to remove its noise. The control box **Fig.4** contains RJ and BNC connectors, PS chokes and L9, L10 balun. The box should be shielded since it is placed in the shack and interferences are possible. The LAN cable has 100 ohms impedance and it can be connected directly to 75 or 50 ohms input of the RX without any noticeable adverse effects. For the purists a 2:1 wideband impedance matching transformer can be used for precise matching.

There are 4 unused wires in the cable. The unused wires should be grounded in the RX part. They can be used for remote control of additional relays or rotator. I have used 1 relay to switch 2 identical loops rotated 90 deg. to each other.

## Some comments on the amplifier schematic

The amplifier is a standard common base differential amplifier. The differential input resistance of the amplifier is around 3 ohms at 1 MHz (rises with frequency, module =7 ohms @ 30MHz, spice modeling) and this assures flatness of the antenna factor in wide band. This very low input impedance reduces also the electric field sensitivity to minimal levels. The gain of the amplifier with 1 $m^2$ loop is set to give approximately between 0 to +6 dBmeters$^{-1}$ antenna factor (depends from the loop size, shape and inductance, see the Appendix). In this case the level of output internal noise at the active WSM loop is about 10-15 dB above the internal noise level of RX with -130dBm @500Hz MDS (this sensitivity is very common between commercial transceivers). Increasing the amplifier gain will increase only the non-linear distortions level.

The differential amplifier has two advantages for the non-linear distortions reduction: reduces with 6 dB the signal level of each arm and reduces the output level of 2nd (and all even) order distortions with 20 – 30 dB. The reduction depends from the symmetry of the transistor pairs and output wideband transformer. The second order distortions are the main source of spurious signals in this wideband antenna.

The transistors are the popular PN2222A which have quite linear response [7] noise figure of 4 dB and acceptable power dissipation. Using lower noise transistors do not improve substantially the noise floor (Appendix I). To improve the 2nd order distortions a matched transistor pairs should be used (at least $h_{FE}$). The collector currents of the first and second pair are 25 mA and 40 mA correspondingly. The power dissipation of PN2222A (TO92 case) is 0.5 w at 50 deg. C ambient temperature and these transistors work without radiators. In the case where the loop will be used for frequencies up to 50 MHz the output transistor pair should be with $F_T$ > 1 GHz e.g. BFR96 or something similar.

There is no classical matching of the antenna to the amplifier input since the antenna actually is working in short circuited mode. I have modeled several solutions with input wideband transformers. Slight reduction in the noise floor at some frequencies can be obtained but not significant, so I leave the simplest solution without any transformer. There is an input LP filter (C5, L1, R21, C10, L2, R22) to reduce the signals from the FM broadcasting band. This filter also raises the frequency response in the higher frequencies. The filter Q-factor is controlled by R21,R22 resistors. In authors city location there are very strong nearby FM stations and without this filter the nonlinear distortions occur. This filter can be omitted if there are no FM transmitters in the vicinity or the antenna will be used up to 50 MHz.

This amplifier can withstand very high filed intensities without additional protection. For example the loop was mounted 20 m from a full sized antenna feed with 1.5 Kw PA and works flawlessly during 48 hours ham radio SW contest. Static leakage resistor with 100 K value can be connected between antenna amplifier common point and ground.

The possible common mode currents are reduced by using separating transformers, chokes and baluns between amplifier and RX and PS parts.

## Results

All experiments are performed with vertical loop plane with loop center height approximately 2 m above the ground. Horizontal loop plane is possible but then the polarization is horizontal. The horizontal loop should be placed at least wavelenth/4 height to have omni directional low angle pattern and acceptable signal levels.

### Noise floor

The active WSM loop noise floor is a figure which measures the ability of this antenna to receive weak signals. This is the magnitude of the internal noise voltage (effective values) at the output of the amplifier $V_{nout}$ [uV] but multiplied by the antenna factor $K_a$ [1/meter] (antenna factor $K_a$ is reciprocal of effective height $h$ ). The measurement must be performed in predefined bandwidth which in our case is 1 KHz. This is convenient way to compare the external and internal noise in the active antenna expressed in [uV/m] as if the internal noise is coming from the space.

$$N_{floor} = V_{nout} * K_a \qquad \text{in } [\,uV/m] \qquad (1)$$

If we have antenna factor $K_a$ =1 m$^{-1}$ that means that field with 1 uV/m will give output voltage of 1 uV. If the active antenna output noise voltage measured in the screened chamber is 1 uV at $B_W$=1KHz the noise floor of this antenna is 1 uV/m. In this case the power of the antenna noise and external signal are equal.

Measuring the antenna noise in screened chamber needs special equipment. More simple way is to replace the loop with equivalent inductance with lump parameters with the same value. Measuring the noise on the band with small magnetic (**SM**) loop, and then the noise with equivalent inductance will clearly show the relative noise floor of the active antenna compared with the current band noise. The equivalent inductance should to be wound on the ferrite toroidal core to minimize the external field influence.

The results of such experiment are shown on **Fig.6** . N/N is the ratio of the power of current band noise + internal noise to the power of the internal noise of the antenna. The band noise was measured directly from the spectrum display of the SDR at frequencies where there are no transmitting stations (**Fig.6a**). As it can be seen, in city location, the band noise is much higher and is the limiting factor for antenna sensitivity. For rural locations however this is not the case. N/N ratio should be above 10 dB if we want that the real sensitivity of the active antenna is not degraded noticeably by its internal noise.

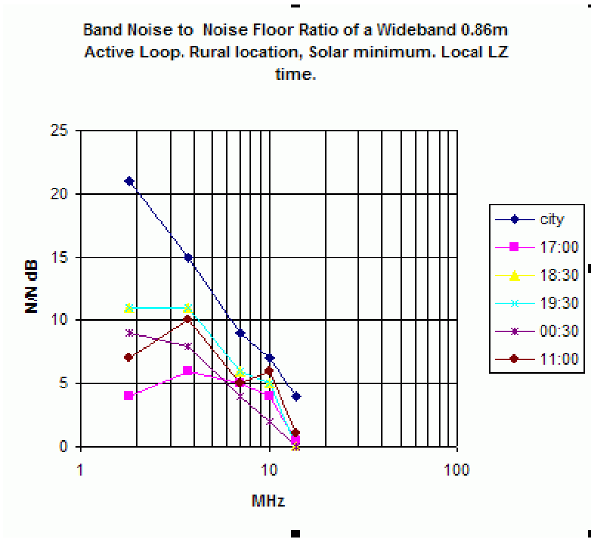

**Fig.6** *An experimental measurement of band noise to noise floor ratio of active circular WSM loop 0.86m diam., aluminum conductor 3.4 mm.*

*This ratio is measured at different times of the day in rural place.*

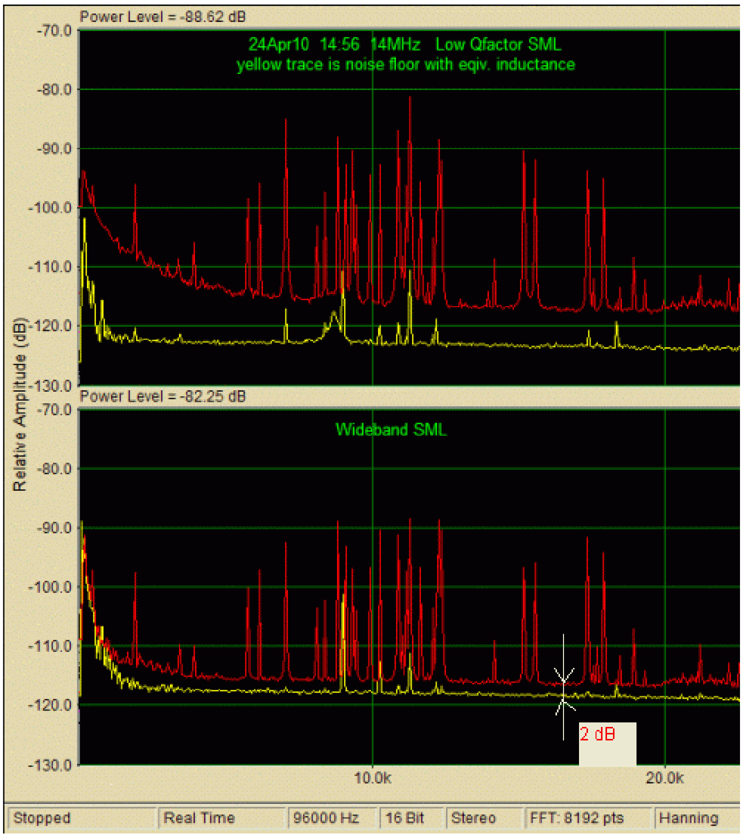

**Fig.6a** *Comparing two different magnetic loops with 2-channel synchronized RX. Quiet rural location.*
*The spectrum is result of 10 sec 2-channel averaging of the signals on 14 MHz CW portion of the band.*
*The upper channel is signal from tuned low Q-factor (Q=25) loop. The lower is from the wideband loop.*
*Both loops have 0.86 m diam. and are placed 5 m from each other.*
*Notice that S/N ratio in tuned loop is 6 – 10 dB better than that in the wideband loop.*
*The yellow traces are the output signal when the loops are substituted with toroidal coils with same equivalent inductance as the corresponding loop. These traces present the internal noise level of the active antenna – its noise floor. .*
*For the tuned loop the external noise is 8 dB higher than the noise floor. For the wideband loop this value is only 2 dB.*

**Non-linear distortions**

This is a very wideband antenna and total MW and HF spectrum is applied at its input. I measured the wideband power at the amplifier output (1m diam., 4 uH loop) with thermocouple power meter (HP432A). In urban environment Pout = -22 to -29 dBm depending from the time of the day ( night time is higher). In rural places Pout is from -24 to bellow -30dBm. (An active GSM handy induces -15 dBm when 1 meter from the loop.) These are averaged values and the peaks can be much higher.

I do not have an access to good measuring equipment to obtain reliable figures for the 2$^{nd}$ and 3d order distortions. What I have done is to check carefully whether there are any signs of such distortions on the band. I checked the 2$^{nd}$ order products (F1+F2 and 2F ) which might exist as a spurious signals in 14.400 – 15.200 MHz band as result of action of the strong broadcasting stations on 41 m band with frequencies 7.200-7.600 MHz. The important condition is that there must be no propagation on 14-15 MHz band to be sure that all existing signals are spurious. Night winter time is most suitable for this experiment. This test was performed several times at night time with SDR (Winrad) which is very convenient for this purpose. The SDR RX has input narrow band pass filter (200 KHz BW at 14.7 MHz with attenuation > 35dB for 7 MHz) to avoid direct second harmonic mixing. **Fig.7** shows the results of this experiment. All candidate spurious frequencies should be multiples of 5 KHz since this is the distance between broadcasting frequencies. I used a 60m long wire (LW) antenna connected through the antenna tuner directly to the SDR input for reference. At start the LW antenna was switched on (upper part of the waterfall display). Then the active loop was switched which is well seen on the picture. (lower part of the display). There are probable very weak spurious traces at 14660, 14720 and 14740. 14730 exist in both cases so it is real signal. If the band is open these spurious signals will be buried in the band noise. A slight noise probably from pulse PS is seen very well on the LW antenna. Seemingly there is a “reduction” of this noise when the loop is activated. But it should be considered that the noise floor of the loop in this case is at least 10 -15 dB above the noise floor of the LW antenna.

3-d order distortions (2F1-F2) can also be found in this way but they are buried in the same 41 m band. There are chances to find such spurious products in the vicinity of the BC band . I tried to identify light carriers that exist on the amateur 40 m band and are multiples of 5 KHz but do not find an obvious candidate for such case in this natural experiment.

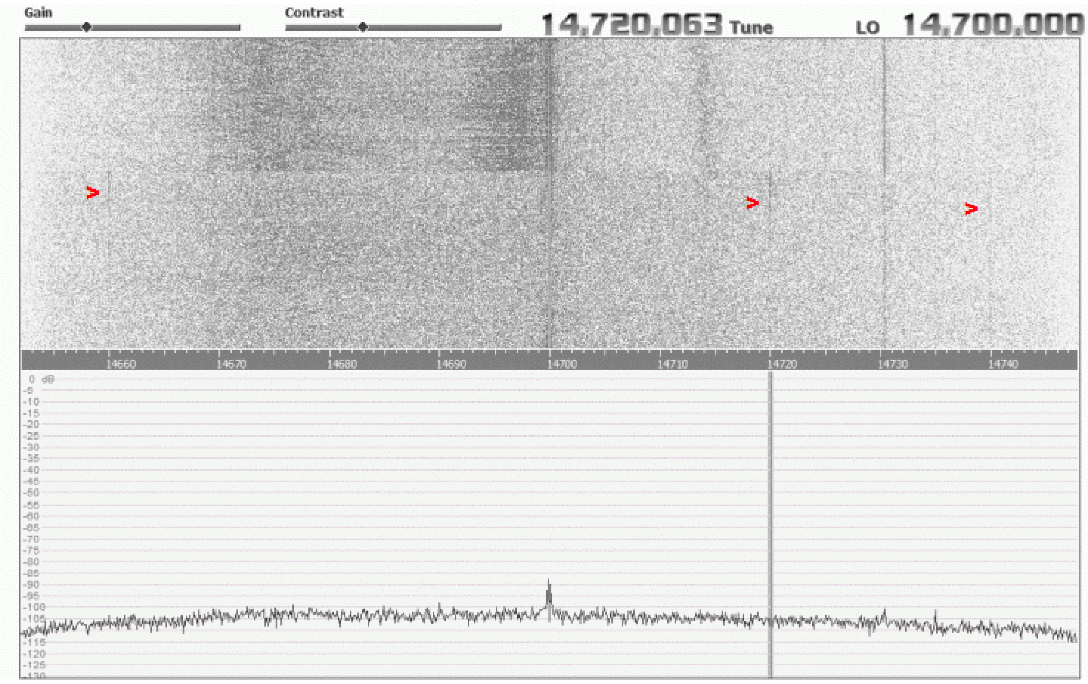

**Fig.7** *A 96 KHz SDR display to check the existence of $2^{nd}$ order spurious products from 41 m BC band.*

### Comparison with full sized antenna

The results of precise comparison of the 1 m diam. thin loop with full sized antenna - Long wire (LW 60 m length, 15 m above the ground) are shown in *WSML_eval.pdf* in real environment, at the same time. The comparison is performed with synchronized 2-channel direct conversion receiver. Active SML and LW are fed into each channel input and the signal from the each channel output is fed to the two sound card inputs. A dual channel spectrum-analyzer is used (Spectralab, Sound Technolgy Inc.). The spectrograms are made in amateur bands with averaging of 10 seconds (see more detailed description of the method in previous article [23]). The place is quiet rural with low level of man made noise. The noise floor is acceptable on 1.8 and 3.5 MHz bands but on 14 MHz at least additional 6 -10 dB reduction of the WSM loop noise floor is needed. Do not pay attention to the absolute level of the signals - just the S/N ratio is important.

The most striking lack of sensitivity is at day time on 14 MHz band. The S/N ratio of a full size LW antenna is 5 to 15 dB better than the WSML. Some of this inefficiency is due to the location of the loop - only 1.5 m above the ground (the lower part of the loop) but in the same conditions a tuned loop gives 4 - 6 dB lower noise floor (**Fig.6a**). At the twilight time when the band noise increases, the wideband and tuned loop antennas become almost equal.

## Conclusions

This antenna acts almost as a pure magnetic transducer. The input impedance of the amplifier is so low that any currents induced by electric field become very small compared to the currents induced by magnetic filed. This antenna does not need shield or any type of grounding. For vertically polarized low elevation angle signals the antenna has very sharp null. The directivity for the sky wave signals is not determined since their polarization is stochastic. The influence of nearby non-resonant conductive object is negligible. The differential circuit also reduces the influence of common mode currents. It works from height almost zero above the ground (there is almost no change in signal levels when the loop side is placed several centimeters above the ground in field environment). The wideband properties are excellent - from LW to upper HF even 50 MHz band can be included. The dynamic range obtained from on the air tests on the bands is good and no apparent non-linear distortions are found. The circuit is very simple, stable and cheap and there is nothing critical for adjustment. The antenna can be mounted outdoor and connected with FTP cable to RX and PS parts. The FTP cable is widely available and the associated connectors are very reliable and cheap. This is my favorite antenna for my city office where nothing else can survive the EMC pollution. The only drawback of this active antenna is its relatively higher noise floor specially for frequencies above 10 MHz which is several dB above the atmospheric noise levels for quiet rural locations at some frequencies and times of the day (for single loop 1m diam.) . The antenna noise floor is acceptable and suitable for all locations where the man made noise is moderate and above. The noise floor limit of these types of WSM loops is essential - see the Appendix section for more details. The noise floor can be reduced by using “fat” , parallel or parallel crossed loops especially for places where the electromagnetic noise is very low.

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## Appendix I Analysis of the Active Wideband SM Loop Performance

### Tuned Loop

In previous article [23] it was pointed out that the sensitivity of narrow band high Q-factor SM loop antenna is limited by the thermal noise of its loss resistance. The noise floor of such antenna with modest size (1 turn loop 0.5 to 1m diam.) which can be reached in the range between 1 – 30 MHz can be bellow the atmospheric noise level in quiet rural location. The “signal- to- thermal noise ratio” is described by simple equation:

$$E/U_n = 164{,}7 \frac{A\ f}{(B_w\ R_L)^{1/2}}\ e \qquad (2)$$

where $E$ is the e.m.f. induced in tuned loop form external filed with intensity $e$ (uV/m). $f$ is frequency in MHz, $A$ is the loop equivalent area in $m^2$, $B_w$ is the measurement noise bandwidth in Hz, $R_L$ is loss resistance in ohms, $U_n$ (uV) is the loop thermal noise voltage at specified $B_w$.

*Remarks:*

*1. For magnetic transducer it is more natural to use* $H$ *(the intensity of the magnetic field component) expressed in uA/m instead of* $e$*. In electromagnetic wave in free space (vacuum and in far zone) the ratio between* $e$ *and* $H$ *is always the same – the so called free space impedance = 377 ohms. Intensity of* $e$ *= 1 uV/m is always equal to* $H$ *= 0.00266 uA/m. Further on* $e$ *values will be used since the intensity of the electromagnetic field is given usually in V/m.*

*2. In previous article [23, Eq.3] I have used the term “effective area”* $A$ *as parameter which is: geometric loop area times number of turns times permeability. This term is used in different sense in the antenna terminology. There , antenna effective area is a measure how much power of the incoming wave front can absorb and fed to its optimal load any antenna. To avoid misinterpretations I will use the term “equivalent area”.*

A useful graphic is presented on **Fig.8** which can give a rough estimation of the loop size and Q-factor in order to reach 10 dB S/N ratio for signal with field intensity $e$ of 0.2 uV/m at 1 KHz bandwidth. The level of 0.2 uV/m was somewhat arbitrary chosen by me as an average lower boundary of atmospheric noise in rural locations according to ITU reports.

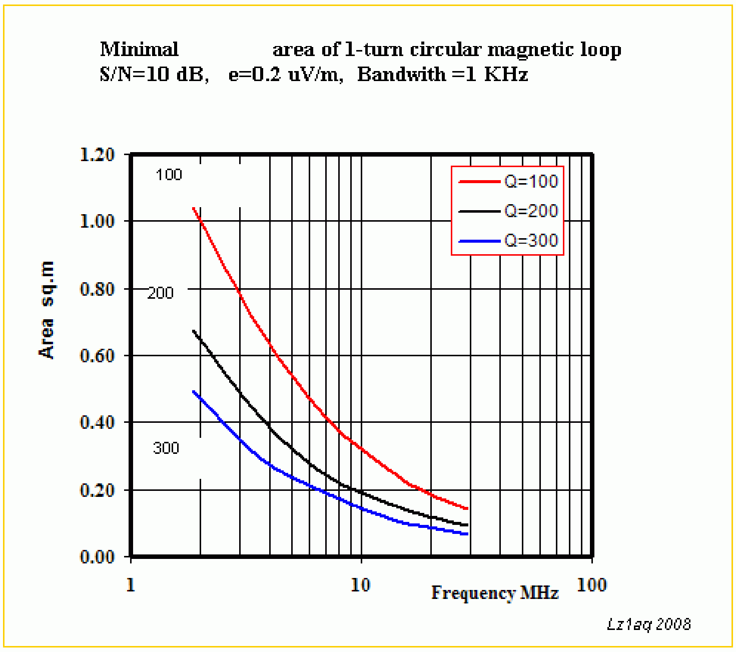

**Fig. 8** *Minimal area of 1-turn circular magnetic loop in order to reach 10 dB S+N/N ratio for signal with field intensity* $e$ *of 0.2 uV/m. N is the thermal noise voltage of loop loss resistance measured in 1 KHz bandwidth. Q is Q-factor of the tuned loop.*

The drawback of such SM loop is that it is very narrow band and continuous tuning is needed even in narrow ham radio bands. The placement of this type of loop outdoors is not very convenient since its needs some kind of remote tuning.

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## Computer modeling of active WSM Loop

The absolute measurements to obtain the active WSM loop parameters need sophisticated equipment which was not available. Here I will present the results of computer modeling of this active antenna as well as some experimental results. 3 programs are used for this purpose. All three sources are freeware.

- Excel spreadsheet [24] where the well known analytic formulas to compute the SM loop parameters are realized. Especially the current that flows into SML induced by incident electromagnetic wave with known intensity can be computed with good accuracy.
- Antenna modeling program MMANA (v.1.7) which is implemented with MININEC core. The analysis of simple antennas in free space is accurate.
- Spice program LTSpiceIV from Linear Technology Inc. The spice programs are quite accurate in their small signal and noise analysis.

### Equivalent circuit of the loop and loop bandwidth

The equivalent circuit of the antenna in the spice model is shown on **Fig. 9**. This is Norton equivalent circuit which is more convenient for analysis in the frequency range where:

$$X_{L1} >> R2. \qquad (3)$$

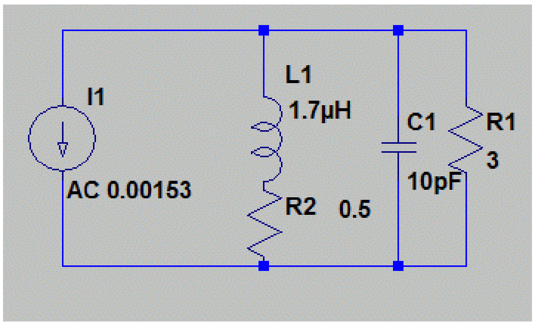


**Fig.9** *Norton equivalent spice model. The current source is in uA and is frequency independent.*

***R2*** is the loop loss resistance, ***L1*** is the loop inductance, ***C1*** is the loop capacitance and ***R1*** is the load resistance which is actually the input resistance of the wideband common base amplifier. The value of the current source if *(3)* is fulfilled is equal to:

$$I_1 = E / X_{L1} \qquad (4)$$

where $E$ is the e.m.f induced by the incident field, $X_{L1}$ is the impedance of $L1$. $E$ and $X_{L1}$ are functions of the physical shape and size and can be computed from the *RX_Mag_Loop.xls* for simple single turn loops. This model is adequate for frequencies above the lower bandwidth limit of the loop $f_C$.

$$f_C = R2/(2*pi*L1) \qquad (5)$$

Above let say 3* $f_C$ the value of the current source does not depend from the frequency . $I_1$ and can be computed by the same *RX_Mag_Loop.xls* spreadsheet. The current $I_1$ can be calculated at arbitrary frequency above *3** $f_C$ and for field intensity of 1 [uV/m]. It should be expressed as LTSpice current source in [uA]. Then all voltages in the model will be in [uV] and the gain will be obtained directly as equivalent effective height $h$. Then the antenna factor $K_a$ can be plot as 1/ $h$ .

The loss resistance is deliberately left serial to inductance. This is more realistic physical model since its value depends from physical factors (skin effect and radiation resistance) and not from serial-to-parallel transformation formula. Above frequencies 3* $f_C$, ***R2*** can be neglected and a fixed value in the model can be used – let say 1 ohm. Bellow $f_C$ the current source is no more frequency independent and more suitable model is the Thevenin (serial) equivalent circuit. In our case $f_C$ is rather low. For the SM loops sizes and inductances of interest it is well bellow 100 KHz.

There is another low cutoff frequency $f_L$ which is more important for the wideband loop response:

$$f_L = R1/(2*pi*L1) \qquad (6)$$

$f_L$ determines where the flat frequency response of the output voltage begins. Above $f_L$ (where $X_{L1} >> R1$) the loop has flat antenna factor.

**Results from the spice modeling**

The results from modeling with LTSpice IV are presented on **Fig 10** and **Fig.11**. The amplifier is the same as shown on **Fig.1**. Two main parameters are shown.

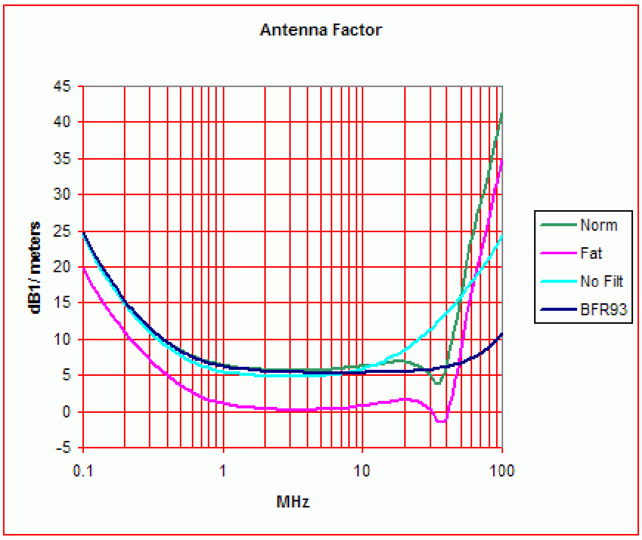


**Fig. 10** *Antenna Factor for 1 turn 1 m diam. circular loops.*
*Norm: L1=3.6uH and* $I_1$ *= 0.00073 uA*
*Fat: L1=1.7uH and* $I_1$ *= 0.00153 uA*
*NoFilter: Norm. without input LP filter.*
*BFR93: Nofilter with BFR93 transistors as second pair.*

The antenna factor ***Ka*** is expressed in dB (20log*Ka*). Two different loops – normal and “fat” are modeled. The “fat” loop is with conductor diameter of 40 mm and the normal - with 3.4 mm aluminum. Fat loop has almost 6 dB higher gain. High frequency response (**Fig.10**) is limited by the $F_T$ of the second transistor pair and the parasitic stray inductance of the output wideband transformer. The input “anti FM” low-pass filter flattens the response at higher frequencies which is not bad. The differential input resistance of the amplifier is around 3 ohms at 1 MHz and rises with frequency. The module of Rin becomes around 7 ohms at 30MHz and this assures flatness of the antenna factor in wide band.

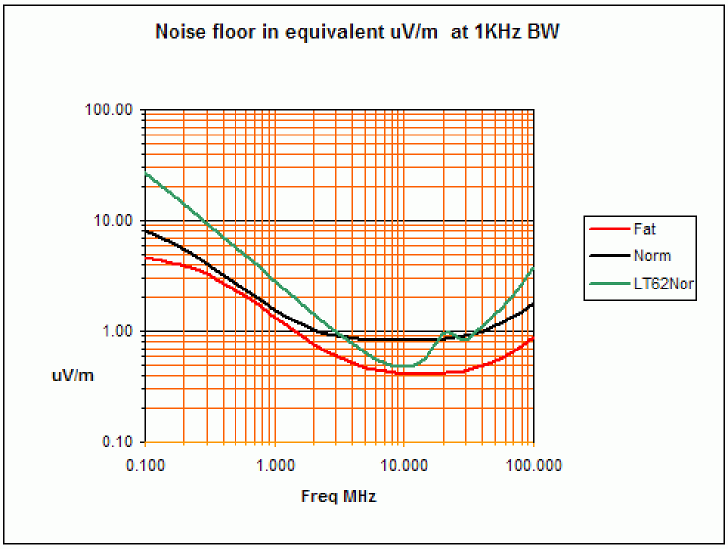


**Fig.11** *Noise floor of 1 turn 1 m diam. circular loop at 1 KHz bandwidth*
*Norm: L1=3.6uH and* $I_1$*= 0.00073 uA, with LP filter*
*Fat: L1=1.7uH and* $I_1$*= 0.00153 uA, with LP filter*
*LT62Nor: 2 op.amp differential amplifier LT6230-10, with input LP filter.*

Noise analysis was performed for CB amplifier with the same two loops and also for differntial current-to-voltage convertor with LT6230-10 op. amplifiers (with normal loop). As it can be seen the noise floors for all cases of the WSM loop are above the 0.2 uV/m line and that means that the antenna sensitivity is limited by the internal noise rather by the external atmospheric noise.

**Limitation of the models**

This model is reliable at about frequencies 15 MHz with the used single turn loop. Above this frequency the loop can not be presented by simple fixed inductance since the wave and resonance effects can not be neglected. The loop becomes longer than 0,1 wavelength and its equivalent inductance, losses and radiation pattern becomes different. For example, the loop Q-factor drops dramatically above these frequencies. For CP loops the model is adequate up to 30-40 MHz. For frequency bellow the $f_C$ the loop model should be changed to serial (Thevenin) with frequency dependant source but this is beyond of the scope of this paper.

**Wideband loop noise floor**

The current that flows in the wideband loop is very small. In 1 $m^2$ loop with inductance of 4 uH, the induced short circuit current from 1uV/m external field in the flat frequency response region will be 0.7 nA. The voltage drop across 3 ohms load resistor will be 2.1 nV. From the other hand the thermal noise voltage at 290 deg. **K** of 3 ohm resistor at BW of 1 KHz is **7** nV. In this case we have 3.3 uV/m equivalent noise floor of the loop which is terminated with 3 ohms load resistor. Actually speaking this is the main factor that limits the noise floor of a WSML.

It is good to increase the load resistance since the thermal noise is proportional to square root of the resistance. If we increase 2 times the load resistance we should increase the loop inductance 2 times to preserve the loop lower bandwidth limit. If the loop area is preserved that will reduce 2 times the loop current! Obviously this limitation is fundamental. The antenna large bandwidth and low noise floor of small antenna are antagonist factors. High Q-factor tuned loop has very low noise floor but very narrow bandwidth.

## How to reduce the noise floor of wideband SML

In the flat frequency response region the current in the loop with fixed area is determined only by the loop inductance. The loop works in short circuited mode with very small load resistance. The loop loss resistance is not important since it is much smaller that the inductive resistance of the loop. The obvious solution is to maximize the loop short circuited current.

**Loop size**

MMANA modeling gives the following results: L of 1 $m^2$ quad loop = 4.5 uH, L of 2 $m^2$ = 6.8 uH , the induced voltage is doubled but the current through the load resistor is *increased only 1.33 times*. From the other hand increasing the loop size will lower the upper frequency response (0.1 wavelength rule).

**Loop turns**

Doubling the loop turns increases 2 times the induced voltage and 4 times the inductance and the short circuit current is *reduced 2 times*.

**Loop inductance**

One of the methods to reduce the inductance when the physical size is fixed is to make a “fat loop”. The conductor diameter can be increased and the inductance can be lowered significantly. For example 1 m diam. loop with conductor diameter 3.4 mm has inductance of 4 uH. (MMANA simulation) The same loop with conductor diameter 40 mm will have already 2.1 uH. The current through the pickup load resistor will be increased almost 2 times and the noise floor will be reduced.

**Fig. 12** *"Hermes" loop*

**Parallel loops**

On **Fig. 12** is given the commercial loop construction (named Hermes). [18, 3]. Probably these are two parallel connected loops with 1 m diameter. The inductance is declared to be equal to 1.4 uH. It is not clear whether the axial connections on the picture are electrical or just mechanical.

I have modeled two parallel square loops with MMANA. A single loop with 1m side conductor diameter 3.6 mm has inductance of 4.5 uH. Two parallel loops at distance 8 cm with conductor with the same diameter has 3 uH inductance. Axial electrical connections at additional 3 points as in the **Fig.12** does not change the inductance and the radiation pattern. The mechanical construction of the parallel loops is much more convenient than using a fat conductor.

**Parallel crossed loops**

In his very interesting page PA0SIM [1] used wideband loop antenna which he called Alford loop (K6STI has described loop with the same pattern in QST article [8] ). I will call these loops 'crossed parallel loops' (CP loop), (Appendix II).

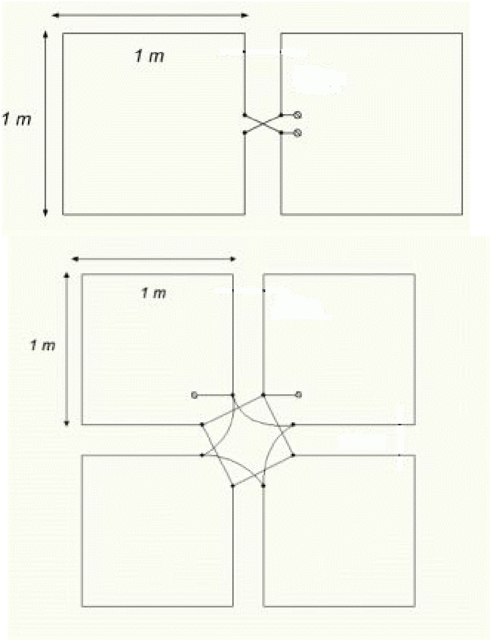


**Fig.13, 14**, *Crossed parallel loops (square shapes).*
*The drawing is not scaled to show better the connections between loops.*
*The conductor was PVC insulated copper wire 1.8 mm diam. The distances between inner sides of quad wires are 3 cm.*

On **Fig,.13** and **14** are shown two type of crossed loops tested by me. These are big loops consisting of 2 or 4 parallel loops in one plane (area is 2 and 4 $m^2$). These loops have very weak mutual coupling compared to the normal parallel loops. Their terminals should be cross connected as shown in the **Fig.13,14** so that currents induced by the incident field are added. The main properties of these crossed loops are that they have much lower equivalent inductance and increased short circuit current, preserving at the same time the small loop radiation pattern (compared to single turn loop with same area).

These two loops have 2.2 and 12.5 times lower inductance correspondingly compared to a single square loop with the same area. (MMANA model, see Appendix II). The short circuit current is increased which leads to lower noise floor. With these loops two decades of bandwidth with flat frequency response can be reached.

Preliminary experiments with these CP loops were performed and they were compared to 1 $m^2$ simple loop. The predicted reduction of the noise floor with 2-4 dB (2 squares) and 6 – 10 dB (4 squares) was observed in the 14MHz band since there the atmospheric noise is bellow the WSM loop noise floor. Further more precise experiments should be performed to prove the effectiveness of the crossed loops.

**The Amplifier**

The noise floor of WSML is actually due to the very low level of the antenna loop current which becomes in order of the thermal noise current of the load resistor. Using better, lower noise preamplifiers will not change drastically the loop noise floor (**Fig.11**). Better lower noise transistors with higher $F_T$ were simulated: BFR93(NF=1.9) , BFR96(NF=3.3) and newer ones BFR520 (NF=1.6) and BFR540 (NF=1.5) all with $F_T$ higher than 5 GHz. The resulting noise floor is almost the same just the bandwidth of the amplifier is increases when higher $F_T$ transistors are used in the output pair.

Then I simulated also a differential amplifier with 2 operational amplifiers as a current to voltage converter [1, 2, 12] Unfortunately I do not have ready spice models of suitable op. amp. (e.g. OPA687, AD8099 etc.) the only suitable amplifier which was available in the LTSpice library was LT6230-10 which is limited to 600MHz with noise density of $1nV/Hz^{1/2}$ . This amplifier is low current one and is not suitable for wideband high dynamic range antenna amplifier. But its noise parameters are very good and can be used to evaluate the noise behavior. The results in the noise floor are similar to PN2222A amplifier except for frequency region 4 to 16 MHz where the OP amp amplifier has lower noise floor. At frequency bellow 3 MHz the noise floor is higher (up to 6 dB). The explanation is that the input resistance of the op. amp amplifier is very low at low frequencies but increases with frequency. The increased input resistance improves the signal-to-thermal noise ratio. The common base transistor amplifier has much more stable input resistance and at higher frequencies it is much lower. I speculate that the ideal amplifier for a wideband loop will be an amplifier with input resistance always equal to let say 1/10 of $X_L$ i.e. amplifier which increases its input resistance with 6 dB/oct.

**Noise floor in other active loops published in the Net**

I analyzed data from several amateur publications and commercial products to which I have access [ 1,2,4,5,15,16,17,18,19]. It must be pointed out that very often, the important figure of noise floor expressed in uV/m is not given and there is no direct information about this most important active WSM loop parameter. Some authors present the noise figure of the amplifier which is of no use if other data are not given. The several available noise floor figures are <1dBuV/m @ 200Hz BW in [17] and -42dBuA/m (named sensitivity?) in [16] . Some of the authors have expressed the noise floor as " accdeptable" [1,2,4] but in [5] the author definitely declares that WSM loop noise floor is above the atmospheric noise .

The antenna factor usually is given and its value is between 0 and 30 dB(meters$^{-1}$). This is equivalent to effective height ***h*** of 0 to -30 dBmeters. In most of publication the non-linear distortions figures again are expressed in dBm. The non-linear parameters should also be expressed in dBuV/m to have some meaningful figures.

## Conclusions

The main problem in the active WSM loops is the increased noise floor compared to other antennas. The origin of the problem lies in the very small loop current and very small load resistance which is needed to obtain wideband flat frequency response. Thermal noise of the load resistance (which is the input resistance of the amplifier) is the main limitation factor. This limitation is fundamental. The large bandwidth and low noise floor in this small antenna are antagonist factors.

Using very low noise input transistors will change almost nothing. The modeling shows that increasing the signal pickup resistor reduces the noise floor but we loose the frequency flat antenna factor. Increasing the pickup resistor above certain limits reduces the loop current and degrades noise floor. High pickup resistance also increases the influence of the electric part of the field which is manifested as deviation from the ideal small loop diagram.

The main rules are:

1. Only single turn loop s must be used.
3. The loop loss resistance is not important so the material can be aluminum instead of copper.
2. A circular form of the loop – the ratio L / Area should be minmized.
2. A "fat" conductor loop with low inductance or parallel loops should be constructed to reduce the inductance.
5. Parallel crossed loops are promising. With this technique loops with much bigger area, low inductance and high upper frequency can be constructed. At the same time they exhibit the radiation pattern of a very small loop. In this way the wideband loop noise floor can be reduced to acceptable level for the shortwave frequencies.

# Appendix II Parallel Crossed Loops

## The name and history

I have found very few publications in the Net for this theme. PA0SIM [1] use for his wideband active antenna a loop which he called Alford loop (K6STI has described a loop with the same shape but with much larger size in QST article [8]). I found in the Net the following definition of Alford loop in IEC publication **Antennas / Specific terms for antennas consisting of radiating conductors**:

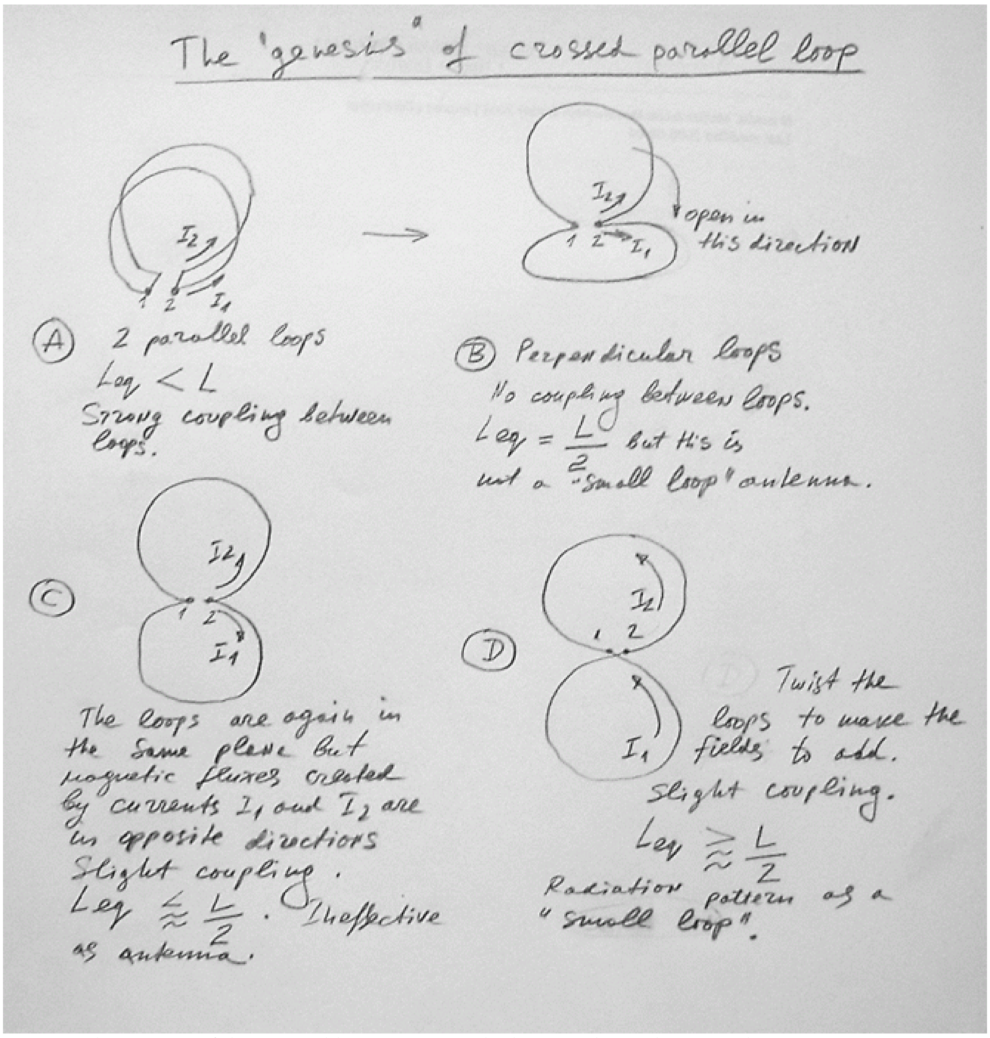
*" an essentially omni-directional antenna consisting of four insulated conductors, each approximately one-half wavelength long, positioned in the form of a square in a horizontal plane and symmetrically fed by balanced lines at two diagonally opposite corners of the square"*

So I do not think that the term "Alford loop" is suitable for this type of loop. I will call them crossed parallel loops (**CP loop**). (English is not my native language and I do not know whether the term is very appropriate).

Jan, PA0SIM pointed to the fact that his crossed loop has almost perfect radiation pattern of a small loop instead of its larger size. C. Baum [11], used CP loops for different goals but the basic idea is the same. Similar CP loop called "Figure 8 magnetic loop antenna" [6] is suggested by PA0FRI for transmitting loop.

## Simple theory

The genesis of a crossed loop from a simple two parallel loops is shown on **Fig. 15**.



The 'genesis' of crossed parallel loop

Ⓐ 2 parallel loops
$L_{eq} < L$
Strong coupling between loops.

Ⓑ Perpendicular loops
No coupling between loops.
$L_{eq} = \frac{L}{2}$ but this is not a "small loop" antenna.

Ⓒ The loops are again in the same plane but magnetic fluxes created by currents $I_1$ and $I_2$ are in opposite directions
Slight coupling.
$L_{eq} \lessapprox \frac{L}{2}$. Ineffective as antenna.

Ⓓ Twist the loops to make the fields to add.
Slight coupling.
$L_{eq} \gtrapprox \frac{L}{2}$
Radiation pattern as a "small loop".

**Fig.15** *The genesis of the crossed loop. Opening the loops reduces the equivalent inductance and increases 2 times the area. They must be twisted so that the currents induced by the incident field are added.*

This principle of crossed parallel loops can be generalized – the single loop can be divided into several smaller loops with the same total area. They should be cross connected as shown in the **Fig. 16** so that currents induced by the incident field are added. The main properties of these crossed loops are that they have much lower equivalent inductance and increased short circuit current, for the same area of a single loop. The radiation pattern of these loops is the same as the pattern of a "small loop"(**Fig.18 – 20**)

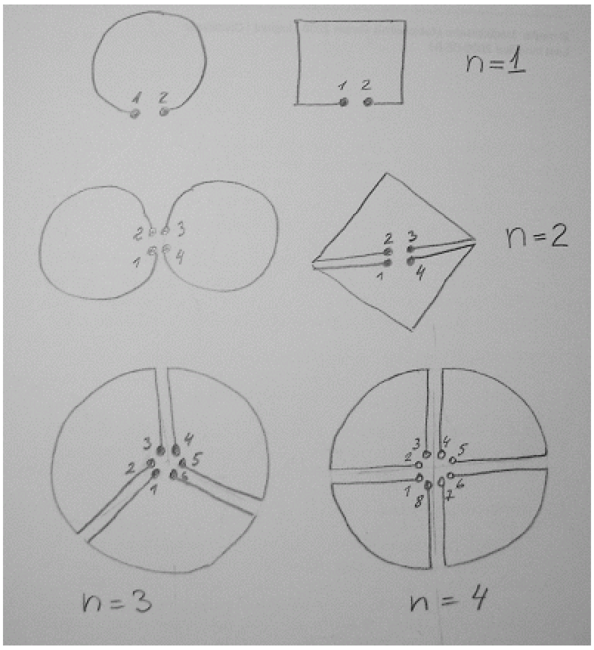


**Fig.16** *Different CP loops. All odd points and all even points must be connected together. The load is between odd and even points.*

If we have ***n*** smaller loops with the same total area as the single big loop with inductance ***L*** and induced e.m.f ***E***, then the equivalent circuit is shown on **Fig17**.

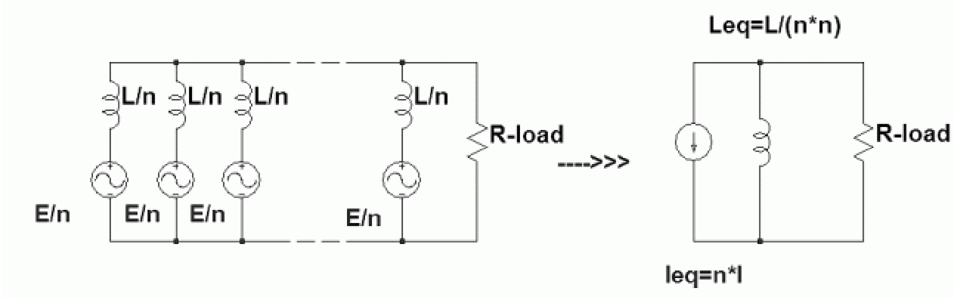


**Fig.17** *CP loop simplified equivalent circuit*

For each small loop the inductance is $L/n$ ($n$ times smaller than the inductance of a big loop). The induced e.m.f is $E/n$ (n times smaller area). Obviously the short circuit current in small loop is equal to that of the big loop $I$ (see Eq.4). Then the total equivalent current is :

$$I_{eq} = n * I \qquad (7)$$

and equivalent inductance is :

$$L_{eq} = L / n^2 \qquad (8)$$

and we should expect n times decrease of the noise floor. Of course these formulas are very approximate. There is always some mutual coupling between loops and the inductance of a loop with half area is not exactly L/2, but these simple equations present the nature of the problem.

## Numerical Simulation

More detailed analysis of the receiving currents in the crossed loop was performed with MMANA program. This program is convenient to analyze the transmitting antennas but here I will present a method to analyze these loops in receive mode. Most of the loops are with quad shape since it was easier for me to draw them with the wire editor. The idea is to calculate the load resistor currents in different loops excited by a small dipole radiator placed in a fixed distance in the far field zone.

With the wire editor I placed in the far field at 80 m distance a simple vertical dipole radiator with length 1 m with the source at the dipole center. The dipole is in the direction of maximal loop sensitivity (they are in the same plane). The source in the loop was replaced with load resistor of 3 ohms (the input resistance of CB amplifier). To increase the accuracy the number of segments was set to be high (automatic tapering, DM1 = 3000, DM2= 800, SC=2,EC=1). After the computation the currents in the loop induced by dipole radiation are very small and they are not displayed on the graphical screen. But these currents can be taken from "Table currents" menu in MMANA. The program creates *csv file which contains the values of currents in all segments and can be exported in Excel for easier processing. The currents are given in relative units. ( in *csv file "Magnitude" colon).

The procedure is as follows: first we run the program with vertical dipole as radiator with referent 1 $m^2$ single quad loop. The resulting *csv file must be saved. Then we run the new loop of interest with vertical dipole as radiator keeping the program settings the same as in the previous case ( the distance, the number of segments, frequency etc.). The new *.csv file with currents of the new antenna is saved and we can compare the currents that flow in the referent loop and in the new loop. These currents are induced by the same vertical radiator with the same current and at the same distance. We should compare only the currents in the wires where the load is connected.

I think that this numerical experiment is quite accurate: the dipole radiator is with small size and the distance is sufficient so the receiving loop is almost certainly placed in the far field zone (see [14] for determination of the near field zone for 1.7 m diam. loop) . The polarization of both antennas is vertical and the calculation is performed in the free space. The currents table gives currents in every segment of each wire.

MMANA modeling of different loops gives the following figures presented in **Table 1**:

| Freq. = 3.5 MHz | MMANA model | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Antenna | Side m | Area sq.m | Wire diam. mm | X ohm @ 3.5MHz | L uH | R loss | Ga dBi | fc MHz | $X/R_{load}$ @ 3.5 MHz | $L/L_{ref}$ | $I/I_{ref}$ | $I/I_{ref}$ dB | I*L |
| Single turn loop | | | | | | | | | | | | | |
| 1 Quad | 1 | 1 | 3.4 | 98.8 | 4.5 | 0.24 | -24 | 0.11 | 32.9 | 1.0 | 1.0 | 0.0 | 1 |
| 1 Quad Fat 40mm | 1 | 1 | 40 | 56.4 | 2.6 | 0.02 | -14 | 0.19 | 18.8 | 0.6 | 1.8 | 4.9 | 1 |
| Pararlel loops | | | | | | | | | | | | | |
| 2parallel Quads 4cm dist. | 1 | 1 | 3.4 | 71.1 | 3.2 | 0.13 | -21 | 0.15 | 23.7 | 0.7 | | | |
| 2parallel Quads 8cm dist. | 1 | 1 | 3.4 | 65.4 | 3.0 | 0.13 | -21 | 0.16 | 21.8 | 0.7 | 1.5 | 3.6 | 1 |
| 2parallel Quads 8cm dist.Fat | 1 | 1 | 20 | 50.1 | 2.3 | 0.02 | -14 | 0.21 | 16.7 | 0.5 | 2.0 | 5.9 | 1 |
| 2parallel Quads 14cm dist. | 1 | 1 | 3.4 | 61.6 | 2.8 | 0.13 | -22 | 0.17 | 20.5 | 0.6 | | | |
| Crossed loops | | | | | | | | | | | | | |
| 2 triangles (PA0SIM) | 1 | 1 | 3.4 | 38 | 1.7 | 0.12 | -25 | 0.28 | 12.7 | 0.4 | 1.5 | 3.8 | 0.59 |
| 2 Quads | 0.71 | 1 | 3.4 | 29.6 | 1.3 | 0.09 | -26 | 0.35 | 9.9 | 0.3 | 1.6 | 4.2 | 0.49 |
| 4 Quads | 0.5 | 1 | 3.4 | 7.9 | 0.4 | 0.04 | -28 | 1.33 | 2.6 | 0.1 | 2.5 | 7.8 | 0.2 |
| 2 Quads | 1 | 2 | 3.4 | 45.3 | 2.1 | 0.12 | -22 | 0.23 | 15.1 | 0.5 | 2.1 | 6.4 | |
| 4 Quads | 1 | 4 | 3.4 | 23 | 1.0 | 0.07 | -19 | 0.46 | 7.7 | 0.2 | 4.3 | 12.6 | |

**Table 1** *Results from MMANA simulations. The referent antenna is single quad loop with 1* $m^2$ *area.*
*I is the current in 3 ohms load resistor* $R_{load}$. *I*L is ( I/Iref * L/Lref) and is a quantity which esimates the relative eqivalent area compared to the referent loop.*

The following conclusions can be drawn looking at the Table 1:

1. Notice that the current increase is not proportional to reduction of L for the crossed loops (the colon "I*L"). As it can be seen the current increase is not as big as predicted by the simplified Eq.7. That means that the equivalent area of crossed loops is smaller than their geometric area. For other shapes and number of crossed loops the reduction might be different. Further experiments and theory are needed in this direction.
2. Notice that there is 4 dB gain reduction of 4 crossed loops compared to single loop which might be interpreted as slight increase of Rloss/Rradiation ratio of the crossed loop. Advantages in using cross loops for transmitting is questionable.
3. Increasing the distance between 2 parallel loops decreases the inductance but at the same time the radiation pattern changes and is not equivalent to a single small loop pattern. The optimal distance for the 1 $m^2$ parallel loops is somewhere between 4 – 12 cm.

5. All these parallel loops have radiation pattern equivalent to a single very small loop. (see also PA0SIM article). They preserve this radiation pattern to much higher frequencies than the simple single turn loop. The numerical experiments show that approximately 0.1 wavelength rule must be applied to the partial loop length, not to the sum of the lengths of the conductors of all loops. More over, above this 0.1 wavelength limit these loops still have small loop radiation pattern (see **Fig.20**). Their parallel resonance frequency is moved substantially upward. This directly means that we can build loops with much larger area with radiation diagram properties of a very small loop.

As an example I will give 4-quads crossed loop with 4 $m^2$ total area. (2 x 2 m size, **Fig. 13**) This large loop has “small loop pattern” up to 50 MHz . The lower frequency response (Eq.6) is 0.46 MHz. It has almost 13 dB larger current at 3.5MHz compared to “conventional” 1 $m^2$ single quad loop.

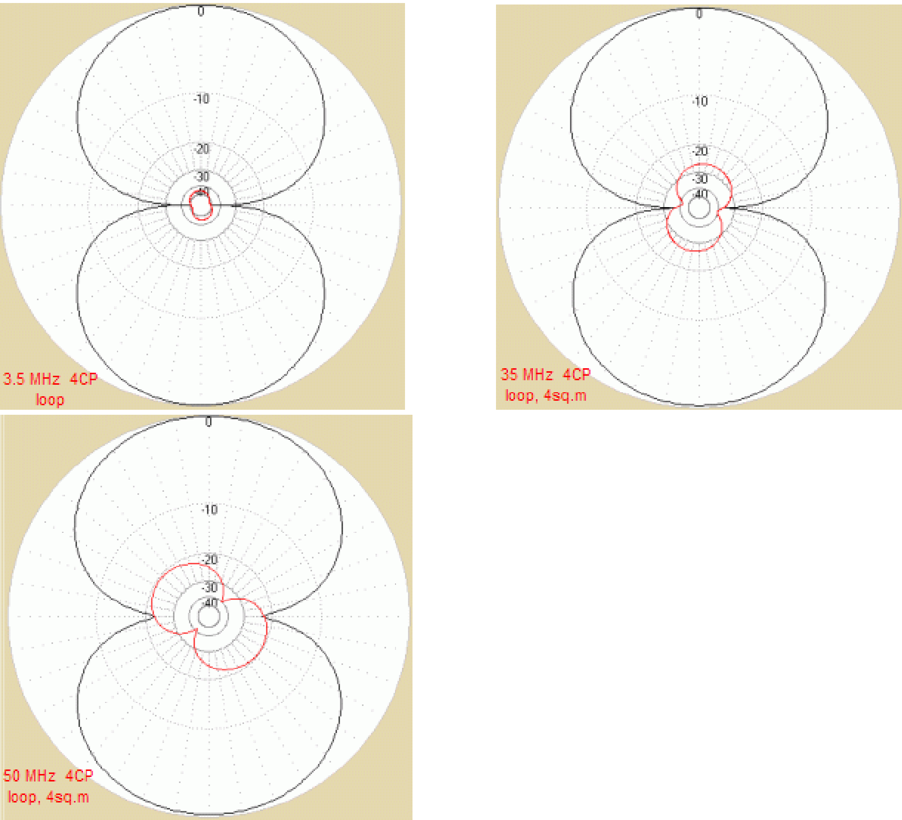


**Fig. 18, 19,20** *The radiation patterns of 4* $m^2$ *quad shape CP loop for elevation of 0 degrees. The asymmetry in horizontal component (red) is due to small imperfections in wire drawings especially around the feed points*

At the same time a single quad loop with the same area of 4 $m^2$ (quad side = 2 m) at 3.5 MHz has a pattern which is marginal - the loop perimeter is already 0.1 wavelength. The short circuit current is almost 3 times lower than the current in 4-quads CP loop and at 14MHz the radiation pattern is quite different to that of “small loop pattern”.

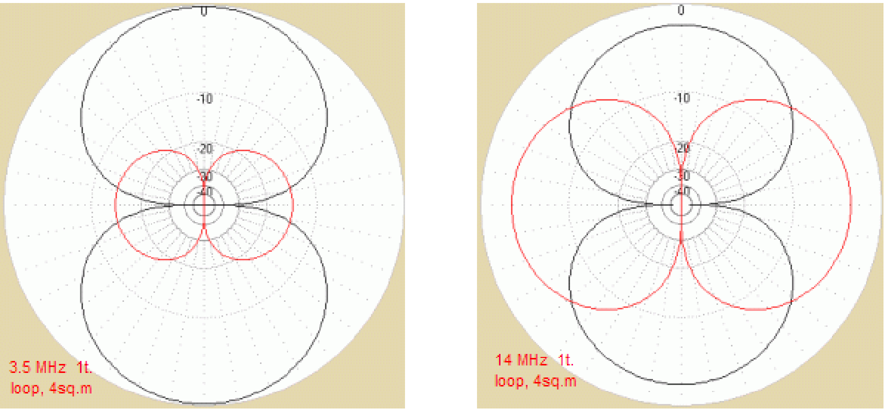


**Fig. 21,22** *The radiation patterns of 4* $m^2$ *quad shape single loop for elevation of 0 degrees.*

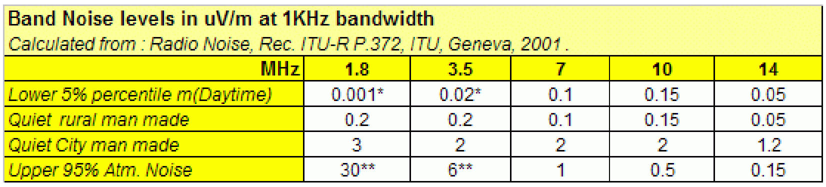
## Conclusions

The most important properties of CP loops are the ability to built loops with large area and low inductance which still preserve the small loop radiation pattern. Their short circuit current is higher compared to a single turn loop with the same area. Their equivalent area is smaller than their geometric area. I could not find any analytic equations to obtain the ralationship between filed inensity and induced voltage for the given geometry of these loops. There is a place for further experimental and theoretical investigations .

The wideband properties of such loops are almost 2 decades in frequency. These loops are very suitable for design of active wideband SM loops.

## Appendix III Band noise levels

**Table 2**



**Band Noise levels in uV/m at 1KHz bandwidth**

*Calculated from : Radio Noise, Rec. ITU-R P.372, ITU, Geneva, 2001 .*

| MHz | 1.8 | 3.5 | 7 | 10 | 14 |
|---|---|---|---|---|---|
| *Lower 5% percentile m(Daytime)* | 0.001* | 0.02* | 0.1 | 0.15 | 0.05 |
| *Quiet rural man made* | 0.2 | 0.2 | 0.1 | 0.15 | 0.05 |
| *Quiet City man made* | 3 | 2 | 2 | 2 | 1.2 |
| *Upper 95% Atm. Noise* | 30** | 6** | 1 | 0.5 | 0.15 |

* *Day-time values or when the band is closed*

** *Night-time values or when the band is opened*

For reference, the half-wave dipole at 14 MHz will produce 50 uV voltage (S9) at 75 ohms load when field intensity is 16 uV/m.

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*Sofia, Bulgaria, May 2010* Chavdar, LZ1AQ

*Revision 1.1 13 June 2011: Minor changes in the text for better clarification. On Fig.13,14 measurements lines are removed to avoid confusions that they are wires.*

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