

Experimental Comparison of Small Wideband Magnetic Loops.

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In previous article “Wideband Active Small Magnetic Loop Antenna” [1] it was pointed out that the wideband loop sensitivity can be increased if the short circuit current of the loop is increased, since the wideband loop is loaded with amplifier with low input resistance R_{in} where $\omega L \gg R_{in}$. Further analysis show that this current depends only from the loop factor $M = A/L$ (see Appendix I and II) where A is the loop equivalent area and L is the loop inductance. The quantity M in some sense is an equivalent to what is the effective height quantity h for dipole antennas. In order to decrease the loop inductance and to increase the loop area, parallel loop connection was considered. It can be achieved in 2 ways - with parallel loops e.g. forming a rectangular prism as shown on **Fig.2 & 3** and coplanar crossed¹ (CC) loops (**Fig.1 & 5**) connected in way to add the loop currents into the load (cross connection [1,2]). There might be also mixed approach –coplanar and parallel as shown in **Fig. 4**.

The goal of the next experiment is to measure the current in several types of loops and compare it to the computed M factor and experimentally estimate the benefit of using parallel and CC loops.

1. Experimental setup

An experimental verification is performed with three different loops each with the same total geometric area $A = 1\text{m}^2$.

Loop 1 Simple quad loop with $A = 1\text{m}^2$ (1 m side). The conductor is PVC insulated Cu wire 1 mm diam. This is the reference loop and all measurements from other loops were compared with it. The loop inductance L is 5.9 uH.

Loop 2 Two quad CC loops (**Fig. 1**) with 1m^2 total geometric area (0.71m side of each loop) with the same 1 mm diam. Cu wire. The inductance of the small constituting loop is 4 uH and of CC loop is 2 uH.

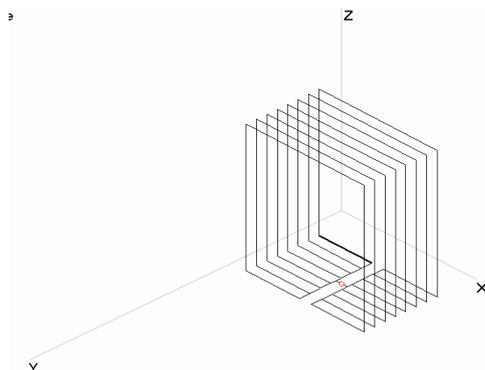
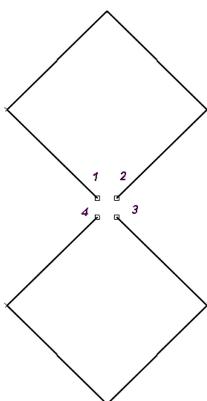


Fig.1 CC loop.

Even and odd points are connected together

Fig. 2 Parallel loops

Fig. 3

Loop 3 Eight parallel loops (**Fig. 2 & 3**) each with 1 m side with the same conductor. The distance between parallel loops is 4 cm. All loops are electrically connected at the lower side. The measured inductance is 2.15 uH.

Another two CC loops were measured (**Fig.4 & 5**) to compare them with the reference loop since these loops are interesting for practical reasons. These loops do not have the same area as the reference one. They are described in details in [3] (items 3.2 and 3.3).

A small transmitter (TX) is located at some distance (270 m) from the loop under test. The TX transmits continuous signals simultaneously at 4 frequencies as follows: 1.755 , 3.510, 7.022 and 10.01 MHz. All TX antennas are vertical aluminum rods with 1.2 m length, the exception is 1.755 MHz where the length is 4 m vertical wire. The common counterpoise is a 30 cm copper rod inserted into ground. The wave polarization is supposed to be vertical. The loop under test is active and AAA-1 amplifier is used [2] with input impedance R_{in} approximately 6 - 7 ohms which means that the loops are almost in short circuit mode.

The voltage at the output of the amplifier is proportional to the loop current. Perseus (<http://microtelecom.it/index.html>) direct sampling receiver is used as a measuring device. It has very good measurement properties - its power measurements were compared with calibrated HP432A power meter and the deviations were within 1 dB on all frequencies. All measurements are performed in 100 Hz bandwidth, dither on, filter off, 125 KS/sec, attenuator off. All the equipment is battery powered in field environment.

¹ In [1] abbreviation CP (crossed parallel) was used but I think that a better term is crossed coplanar (CC) to avoid confusions with parallel loops.

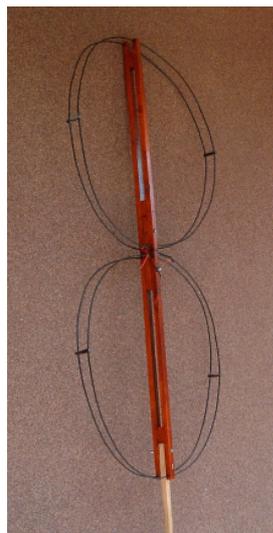


Fig.4 Loop 4: 2 x CC/parallel loops with 0.7m diam. Each loop consisted of two parallel wires.



Fig.5 Loop 5: 2 x CC loops with 0.96m diam. Loops are from PE covered 15mm diam. alum. tubes.

Loop directivity test was performed before each measurement. The single loop directivity to vertically polarized signals has figure 8 pattern. The ratio between maximal and minimal signal was measured and also the direction of the minimum. This experiment was performed on all 4 test frequencies. The min/max ratio should be at least 20 dB and there should be no greater than several degrees difference of direction of the minima and the pattern must be symmetric. Any deviations from these figures show that there are some external non-controllable factors. It might be common mode receiving path or influence from conducting objects etc.

The results of the measurements are presented on **Table 1**. All loops were directed to the source TX at maximal level of the receiver S-meter. The height of single loops above the ground is 2.2 m (the lowest loop point of single or the middle point for the case of CC loops). The $\omega L \gg R_{in}$ requirement was fulfilled for all frequencies. The received signal level was measured for all loops at these 4 frequencies. All measurements are related to the reference values of a single quad loop (I_0, M_0) with 1 m² area. A_{tot} is the total area of the antenna and L_{cc} is the equivalent inductance in the case of CC loops. For each loop M factor was calculated according to Eq. (6 & 9).

	A [m ²]	A_{tot} [m ²]	L [uH]	L_{cc} [uH]	M [uA/pT]	Measured relative signal level I/I_0 dB				I/I_0			
						1.8 [MHz]	3.5	7.0	10.0	1.8	3.5	7.0	10.0
Loop 1, 1 Quad	1	1	5.9	5.85	0.17	0	0	0	0	1	1	1	1
Loop 2, 2 x CC Quad	0.5	1	4.0	2.03	0.25	2.6	2.9	2.5	3.1	1.35	1.40	1.33	1.43
Loop 4, 2 x CC Circular	0.38	0.76	2.0	1.0	0.38	4.6	6.1	5.3	4.8	1.70	2.02	1.84	1.74
Loop 3, 8 parallel Quads	1	1	5.9	2.15	0.47	7.8	8.7	7.7	7.2	2.45	2.72	2.43	2.29
Loop 5, 2 x CC Circular	0.72	1.44	2.7	1.35	0.53	8.1	9.1	8.2	7.6	2.54	2.85	2.57	2.40

Table 1 Measurement data are referred to the reference Loop 1. All loops are measured at 4 different frequencies. The loops are ordered by M factor which is a measure of loop sensitivity.

The measurement data are presented also on **Fig.6** as a relationship between measured loop current and calculated M factor. The relation is approximated with regression line.

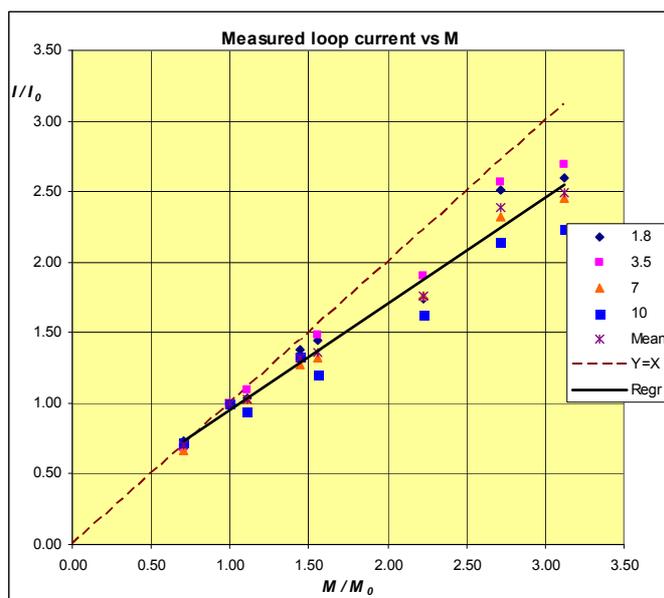


Fig.6 Experimental results: Relationship between measured loop current and M factor. All measurements are related to the reference values from the single quad loop (I_0, M_0) with 1 m^2 area. The relationship is approximated with regression line. Data points are from all 5 loops and for 4 frequencies (in MHz). The dashed line is $Y=X$. The deviation from $Y=X$ line shows an influence from some unrecognized factors most probably transmission line effects (the deviations at 7 and 10MHz are most suggestive).

2. Numerical experiments

The loop currents in the load excited from external electromagnetic field was computed with MMANA (see Appendix III). 15 different loop models were tested - single, CC and parallel loops and combinations of them. Also the shape was changed – quad, rectangular, triangle and octagon. All loops are with total area A_{tot} of 1 m^2 . For each loop M factor was calculated according to (6) or (9). The loop inductance L was calculated from the value of the reactive part of the impedance given from the MMANA program. The frequency of the test was 3.5 MHz. All currents I and M factors are referred to the reference loop (single square, with I_0, M_0) and the relationship is shown on **Fig.7**.

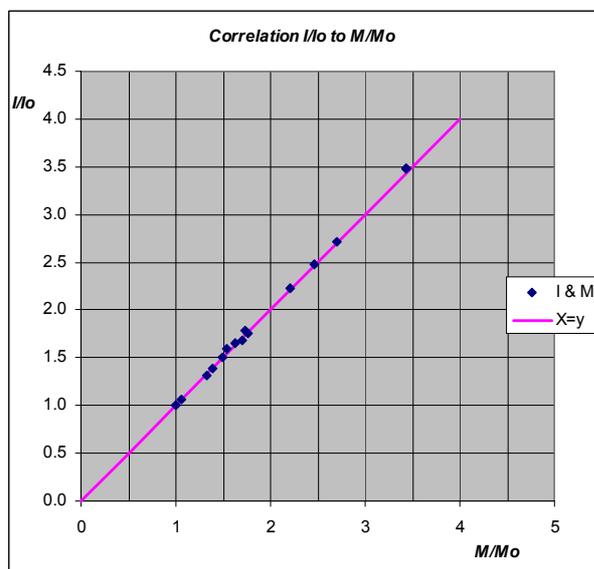


Fig.7 Numerical experiment in MMANA CAD program. Correlations between loop current and M factor for 15 different loops at 3.5 MHz are given. All currents and M factors are referred to the reference loop (single quad, I_0, M_0). The correlation is almost perfect which means that M is a reliable measure of loop sensitivity.

2. Conclusions

A. Obviously M is a good predictor of loop sensitivity. The deviation from $Y=X$ line (**Fig.6**) is probably due to transmission lines effects which are most evident for bigger loops (with higher M) and at higher frequencies.

B. By using CC loops we can increase the loop sensitivity linearly with the total loop area e.g. two CC loops each with 1 m^2 will have exactly two times better sensitivity (or M factor) than a single loop with the area of 1 m^2 . A single loop with 2 m^2 area will have less sensitivity than these two CC loops. The effect of splitting a loop to smaller CC loops is clearly seen on **Fig.8**.

C. Doubling the total loop area (preserving the loop shape and type) increases current with approximately 2.5 dB for all loops.

D. The current of CC loops (2 and 4 loops) is approximately 3.5 dB and 7.5 dB respectively higher compared to the single loop with the same area.

E. The wideband loop sensitivity can now be predicted by calculating the loop factor M - Eq. (6), (9),(11). M factor is a measure of loop sensitivity to electromagnetic field when loaded with low impedance (or a measure of the loop short circuit current). M can be calculated also for the case of coplanar crossed (CC) loops.

F. Two simple measurements are needed to predict the wideband loop sensitivity – the loop area A and loop inductance L .

4. Some practical comments about loop choice

For peoples living in quiet rural area a loop with higher M must be used since the loop noise floor must be below the atmospheric noise. From my experiments I will suggest to use loops with $M > 0.5 \text{ uA/pT}$ when an amplifier of the type described in [1, 2] is used. In the spreadsheet [WLoop_calc.xls](#) [4] (which can be loaded from the www.lz1aq.signacor.com) the calculated M factor for several loops with different shapes and sizes are given. The user can select a proper loop configuration according to his needs. For example the parallel loop is the best choice when we need minimal volume of the loop. From the other side CC loops can give the best sensitivity for given limit of the loop area. Low frequency response should also be considered when LF bands are used. Also the mechanical reasons must be taken into account. For example 4 CC loops can be made as 4 quads or 4 triangles or rectangles (See [WLoop_calc.xls](#). **Fig. 14, 15, 16**). **Fig.15,16** versions will have more stable mechanic construction irrespective of the slightly smaller M factor for these loop shapes.

Calculation example

We can use the spreadsheet [WLoop_calc.xls](#) [4]. Let us have the following goal: a loop with $M=0.8$ (this is quite sensitive loop) and $f_{low}=0.3 \text{ MHz}$. The antenna amplifier input resistance $R_{in}=6 \text{ ohms}$. Then the minimal loop equivalent inductance is:

$$L_e = R_{in} / 2\pi f_{low} = 3.18 \text{ uH}$$

Let us try with a single loop. With the help of the square loop calculator we find the quad loop with side 4 m (16 m^2) and conductor 7 mm diam. will have $M=0.8$, the $f_{low}=0.05 \text{ MHz}$ and this antenna will have small loop behavior up to 1.87 MHz. This is impractical loop – quite big and the wire diam. of 7 mm actually must be a tube. Also the high frequency flatness is very limited.

Let us try with two CC quad loops. We now can find that a single loop of 2.1 m side with wire $d=2.8 \text{ mm}$ have $L=5.5 \text{ uH}$ and $M=0.4$. With 2 CC loops (8.8 m^2) we have $2.75 \text{ uH } L_{eq}$ and $M=0.8$ and $f_{low}=0.34 \text{ MHz}$. This CC loop has small loop type radiation pattern up to 20 MHz.

Appendix I Loop factor M

The wideband small loop is working almost in short circuit mode (**Fig.7a**) since it is loaded with the input resistance of an amplifier with low input impedance (several ohms) [1]. So it is interesting to calculate the short circuit current which flows in the loop and is induced by the external electromagnetic field.

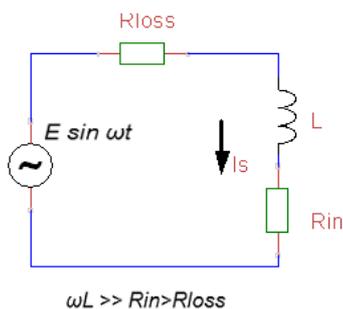


Fig. 7a Wideband loop equivalent circuit

The well known equation of the amplitude of the induced voltage E in a small loop (Faraday law) when the loop plane is perpendicular to magnetic field vector is :

$$E = \omega w A_l B \quad (1)$$

where ω is angular frequency of the sine wave, w is the number of turns of the loop, A_l is the loop geometric area, and B is the amplitude of magnetic induction component of the field vector. We are assuming sine voltages and currents. The short circuit current I_s is equal to:

$$I_s = E / \omega L \quad (2)$$

where L is the loop inductance. We ignore the loss resistance of the loop i.e. $\omega L \gg R_{loss}$ and there is no need to use complex number values. Taking into account (1) and (2)

$$I_s = (w A_l B) / L \quad (3)$$

We can introduce a transducer coefficient M which we can call “loop factor”. For magnetic loop:

$$M = I_s / B \quad (4)$$

Then

$$M = w A_l / L \quad (5)$$

We can use loop equivalent area $A = w A_l$ and (5) becomes:

$$M = A / L \quad (6)$$

M is a measure of loop sensitivity to electromagnetic field when loaded with low impedance R_L i.e. $\omega L \gg R_L$. The M factor of single turn loop depends only from the equivalent area of the loop and its inductance. It does not depend from the frequency. M is magnetic equivalent of the effective height factor h in dipole antennas.

The dimension of M is $[A/T]$ “amperes per teslas”. More convenient is to use as dimension $[uA/pT]$ “micro-amperes per pico-teslas”:

$$M [uA/pT] = A[m^2] / L[uH]$$

Here are calculated values for single turns loop without magnetic core with 1 mm diam. conductor:

$$1 \text{ m}^2 \text{ circular loop: } M = 0.199 [uA/pT]$$

$$1 \text{ m}^2 \text{ quad loop: } M = 0.183 [uA/pT]$$

The inductances of the loops are calculated with [5]. Another transducer coefficient can be defined

$$M_e = I_s / e \quad (7)$$

where e is the electric field amplitude. It can be deduced in the similar way as (5) :

$$M_e = (1/c)(A / L) \quad (8)$$

where c is the speed of light. We assume that the loop is without magnetic core. The dimension of M_e is $[A / (V/m)]$ “amperes times meter per volt”. In some cases it might be more convenient to use M_e because the intensity of electromagnetic field is given usually in terms of e in V/m. The following practical equation can be used:

$$M_e [nA/(uV/m)] = 3.33 (A[m^2] / L [uH])$$

If a loop with area 1 m² has 1 uH inductance and the field is 1 uV/m then the loop current will be 3.33 nA.

For the case of parallel loops L is the equivalent inductance of all loops connected in parallel (assumed as a single flat turn) and A is the area of the single constituting loop.

For crossed coplanar (CC) loop consisting of n small equal loops each with area A and inductance L

$$M = n A / L \tag{9}$$

The explanation of (2) is very simple - all small loops are connected to common resistor of very low value so they can be considered as current sources and their currents are added. Here we ignore the mutual coupling between CC loops which is small. The constituting n loops might be not equal, then

$$M = A_1 / L_1 + A_2 / L_2 + \dots + A_n / L_n \tag{10}$$

If we assume that the equivalent inductance L_{cc} of n equal CC loops is almost L/n then (2) becomes

$$M = A / L_{cc} \tag{11}$$

Note that here A is the area of the single constituting loop.

Appendix II Loop current versus loop area for CC loops

Increasing the loop area does not increase the loop sensitivity linearly since the loop inductance is increased also. The loop current as a function of total loop area is given on **Fig.8**. For CC loops, this total area is the sum of areas of all small loops. Currents of three loops are plotted – single quad loop, 2 CC quad loops and 4 CC quad loops. The currents are normalized to the current of single loop with .0625 m² area. The results are from MMANA modeling (see *Appendix III*). All models are with fixed wire diameter of 1.7 mm. The empiric conclusions are that:

A - doubling the total area increases current with approximately 2.5 dB for all loops.

B - the current of CC loops (2 and 4 loops) is approximately 3.5 dB and 7.5 dB higher compared to the single loop with the same area.

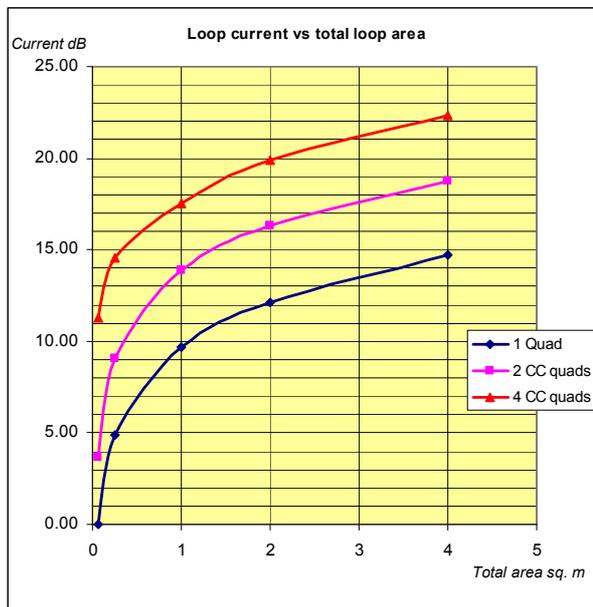


Fig.8 Loop current versus total loop area. The values are referred to the current of a single quad loop with 0.0625 m² area. MMANA model.

Fixed improvement of the current gain should be expected when single loop is converted into CC loops with the same total area. The exact value probably depends to some extent to the shape of the constituting loops but the above figures can be used as a working estimation of the expected current gain improvement.

Increasing the number of constituting CC loops can not be infinite since the loop inductance becomes low and the lower wideband cutoff frequency f_{low} of the wideband loop rises (see also [1]).

$$f_{low} = R_{in} / (2\pi L_e) \tag{12}$$

where L_e is the equivalent inductance at the loop terminals.

For example for CC loops according to **Fig.4** with 0.7 m diam. the equivalent inductance is 1 uH and for $R_{in} = 6$ ohms (as is AAA-1 amplifier) $f_{low} = 0.95$ MHz. Below this frequency the loop current will be determined mainly from R_{in} rather than from the loop inductance L and the frequency response of this wideband loop is no more flat. This does not mean that the loop will not work, only the frequency response will be with decay with 6dB/octave which is due to the physics of the loop (Faraday law).

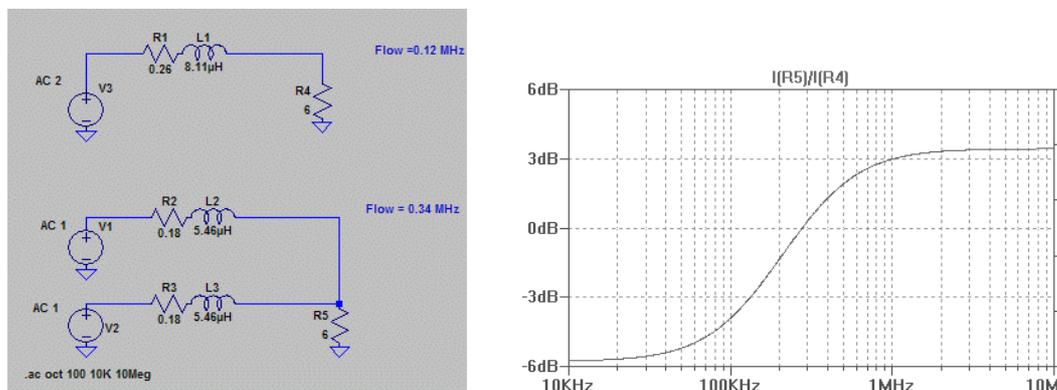


Fig.9 Spice model of the low frequency response of a single (quad 1.41 m side) and 2 CC (two quads with 1m side) loops with equal total area and wire conductor (Cu, d=1mm). Current ratio at 6 ohms load is shown. At 0.28 MHz the loops have equal currents. Below this frequency single loop has higher current which is almost 6 dB higher at very low frequencies. At high frequencies CC loop is 3.5 dB better as predicted by the theory.

More detailed analysis of single loop and CC loop at frequencies below f_{low} is shown on **Fig.9**. The results of spice modeling of two quad (single and 2 CC) loops with same total geometric area are given. $f_{low} = 0.12$ MHz and $f_{low} = 0.34$ MHz for single and 2 CC loops respectively. Loss resistances and inductances are calculated with spread sheet [4].

Appendix III How to use MMANA to model receiving antennas

More detailed analysis of the receiving currents in the crossed coplanar and parallel loops 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. The idea is to calculate the currents in load resistor in different loops excited by a small dipole radiator placed at 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 several ohms (6 ohms is the input resistance of wideband AAA-1 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 loop currents 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 m² single quad loop. The resulting *.csv file must be saved. Then we run the new loop of interest with the same vertical dipole as a 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 exciting current and at the same distance. This file gives currents in every segment of each wire but we should compare only the currents in the segments 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. The polarization of both antennas is vertical and the calculation is performed in the free space.

The inductance of arbitrary shaped loop can be computed quite accurately with MMANA. By feeding the loop in normal way as a transmitting antenna the input impedance is calculated. The inductance is calculated from the reactive part of the impedance as $L = X / 2\pi F$.

Appendix IV Wideband loop amplifier gain

The amplifier used for wideband loops is a current to voltage converter - so called trans-impedance amplifier. It is convenient to express its gain as a ratio of output voltage to input current.

$$\text{Gain} = U_{out} / I_{inp} \text{ [ohms]} \quad (13)$$

The dimension is in ohms. The AAA-1 amplifier gain is 850 ohms. That means that 1 uA input loop current will give 850 uV output voltage. It is now easy to compare different loop amplifiers irrespective of their input resistance. For example if we have two trans-impedance amplifiers with the same gain and different input resistances e.g. 6 ohms and 9 ohms their voltage gain differs substantially (with 30%) but their gain as a wideband loop amplifiers will be almost the same.

Links

[1] <http://www.lz1aq.signacor.com/docs/wsm1/wideband-active-sm-loop-antenna.htm>

[2] <http://www.active-antenna.eu>

[3] http://www.active-antenna.eu/tech-docs/3_ActiveAA_Antena_11.pdf

[4] Spreadsheet *WLoop_calc.xls*

Sofia, August 2013