Receiving Phased Array with Small Electric or Magnetic Active Wideband Elements. Experimental Performance Evaluation.

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The phased directional antennas have been used for years for transmitting and receiving. Active receiving phased arrays have been used in large arrays projects for scientific [25, 26] and military purposes. There are numerous scientific, commercial and amateur publications on these topics [6 to 25]. The demand in the amateur community for small sized directive antennas on lower frequencies is obvious.

Here I am trying to answer several questions whose answer I could not find in the papers or in commercial documentation to which I have access. What are the practical limitations for very small sized phased arrays with active elements and can we predict and calculate their parameters ? I am not a professional in this field and instead of trying to find the proper paper, book or document which might exist somewhere in the information space I tried, with the help of some fundamental books [1, 2], simple reasoning and simple experiments to answer quantitatively some of these questions.

It is possible to build a multi-element receiving directive array with small active antennas as elements and there are published papers and commercial products on this subject. In this article the simplest possible 2-element receiving phased array is considered and an attempt is made to answer the following practical questions:
- What is the bandwidth of an array with fixed delay line between elements?
- What are the restrictions to the distance between elements in order to build an array with small dimensions?
- What are the restrictions of the size of the elements ?
- Is front to back (F/B) ratio degraded when the elements are very closely spaced?
- What is the effective height (EH) of the array compared to a single element of the array?
- What are the limitations in sensitivity when building a closely spaced array?
- What are the differences between a small vertical dipole and a small vertical loop array?
- What kind of delay line (phasing) circuit can be used.
- What is the sensitivity of the radiation pattern to deviations of the delay from the optimal one ?
- How are the parameters of these arrays influenced when located nearby conducting objects, imperfect surroundings etc.?

In order to answer some of these questions an experimental setup was developed to measure certain array parameters that can be compared to the theoretical ones – mainly the forward effective height (EH) and F/B (front to back) ratio.

1. Simplified theory of the 2-element closely spaced wideband receiving array with small active elements

A 2-element phased array with two short vertical dipoles is shown on ***Fig.1***. This is the simplest configuration for directional antennas. It is the basic element for building larger arrays with more elements and much better directivity.

Here some useful equations are deduced which then will be used to compare the experimental results with this theory. The idea is to use relative measurements since the absolute measurements of the field strength are difficult to perform and they need expensive equipment. We will compare the behavior of a 2-element array with a single element antenna of the same type and size as individual element of the array. Since the behavior of a single element is well known any quantitative results compared to a single element will be useful and informative as to what to expect from an array of elements.

Let us have 2 receiving antennas (***Fig.1)***. For simplicity we will use short dipoles. Short means that their length is smaller than wavelength/10. The dipoles are vertical and in free space – very far away from the ground. The distance between the dipoles is *D*. We will consider only closely spaced array where this *D* is smaller than 0.5 wavelength (λ). The incident plain electromagnetic wave is propagating along the *X* axis and is vertically polarized - the electric filed vector is parallel to the dipoles in the *Z* direction. The sinusoidal wave source is far away from the dipoles and we will assume that the field intensity *is the same* at both dipole sites. We will assume also that there is almost no influence between two antennas i.e. the current flowing in one antenna is so small that there is no change of the current flowing in the other antenna as compared to the case where the antenna is alone. This is the most important assumption which simplifies the analysis substantially. This condition is fulfilled because the both antennas are not at resonance, are small sized (length < 0.1 wavelength) and are loaded with high input impedance active amplifiers so that they are working almost in open circuit mode[1].

[1] One of the limitations in this model is when the distance *D* is comparable to the size of the elements. Here probably we should expect some deviations from the next theory mainly due to the direct influence of the element reactive (near) field.

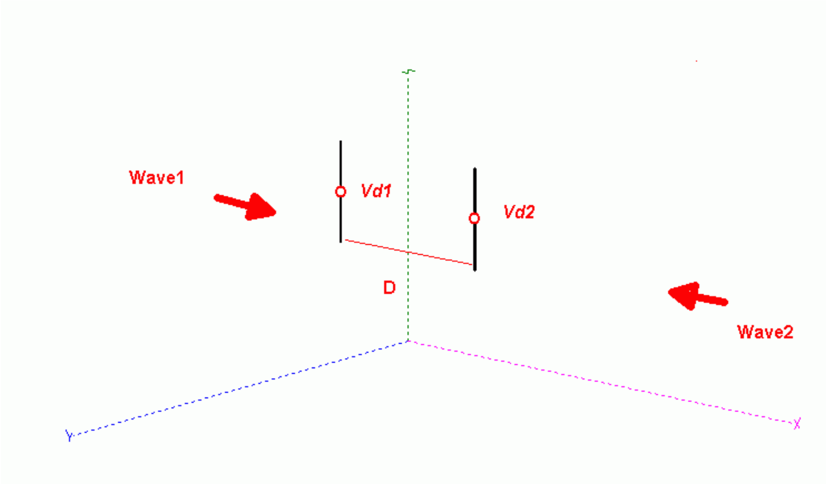


Fig.1 *Basic 2-element array*

Two cases will be analyzed: the first where the wave is coming from the left side (-X) and the second where the wave is coming from the right side (+X). Voltages V_{d1} and V_{d2} are induced in terminals of each dipole. They are with equal amplitudes but with different phase due to the time delay needed for the incoming wave to reach the other dipole. For the wave propagating from left to right we get:

$$V_{d1} = V_0 \cos\omega t \qquad (1)$$

$$V_{d2} = V_0 \cos\omega(t-\tau) \qquad (2)$$

where τ is the time delay for the wave to reach the dipole #2 and is equal to:

$$\tau = D/c \qquad (3)$$

where c is the speed of light and D is the distance between the elements.
ω is the angular frequency :

$$\omega = 2\pi c/\lambda = 2\pi f \qquad (4)$$

where λ is the wavelength and f is frequency.

1.1 Subtractive array[1]

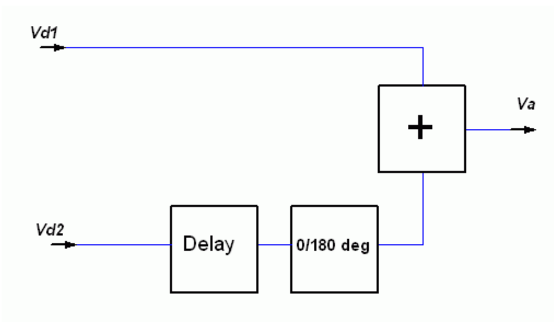


Fig.2 *Basic processing circuit*

Fig.2 shows the basic signal processing circuit. There is a delay line in the chain of dipole #2 and also a phase switch which can give inverted or non-inverted signal at its output. Then the signals are added (e.g. in combiner).

Let us subtract the voltages from the two elements by setting the switch to 180 deg. Let the time delay of the delay line τ_d be *the same as is the physical time delay:*

[1] "Endfire array" term is used elsewhere [*1, 4, 15*] but I have used the term "subtractive" deliberately to emphasize the way of processing. Moxon [*3*] also has used this term.

$\tau_d = D/c \qquad \tau_d[ns] = 3.34 * D[m] \qquad (5)$

The voltage at the output of the adder will be:

$V_a = V_0 \cos\omega t - V_0 \cos\omega(t-2\tau) \qquad (6)$ For wave 1 coming left to right

$V_a = V_0 \cos\omega(t-\tau) - V_0 \cos[\omega(t-\tau)] = 0 \qquad (7)$ For wave 2 coming right to left

It is evident that this system has unidirectional properties - for the wave coming form the right it has always a null. *It must be noted that the null does not depend on the frequency* - *Eq. (7)* is true for any ω and this is a wideband unidirectional antenna.

If the wave is coming from a different direction this perfect cancellation at the back side is not true and there will be some voltage at the output. For the different polarization of the wave, the induced voltages will be lower but the same directivity will be preserved. The radiation pattern of this array resembles cardioid curve - it is well known and can be found elsewhere [*1, 4*] . (see ***Fig.5***). (we will use the radiation pattern term and plots since there is a well known reciprocity between the receiving and the transmitting cases). The specific radiation pattern of the array depends on the distance between elements *D*, τ_d of the delay line and working frequency. The things can be simplified if we use D/λ as a parameter and also fix the delay to $\tau_d = D/c$ which will be called *optimal delay*.

Remark.: The delay can be expressed also in angles $\varphi = 2\pi D/\lambda$ for a given wavelength but we will use mostly delays, not angles, since the delays represent the real physical process and the results are simple and understandable when it comes to wideband relations.

The output voltage from the adder is sinusoidal with some phase shift ψ and can be written in the form :

$V_a(t) = V_A \cos(\omega t - \psi) \qquad (8)$

To calculate the output amplitude V_A we can represent $\cos\omega(t-\tau)$ as $\cos(2\pi ct/\lambda - 2\pi D/\lambda)$ assuming *Eq. (3,4)* and then use the well known trigonometric identity for sum of cosines. The final equation for the amplitude V_A for the subtractive case is:

$V_A = 1.41 V_0[1 - \cos(4\pi D/\lambda)]^{1/2} \qquad (9)$

Here V_0 is the amplitude of the induced voltage in a single element taken alone. Obviously the maximal value will be when $D/\lambda = 0.25$ then $V_A = 2$. There will be a null at $D/\lambda = 0.5$. We are not interested in ψ so we will ignore it in our further discussion.

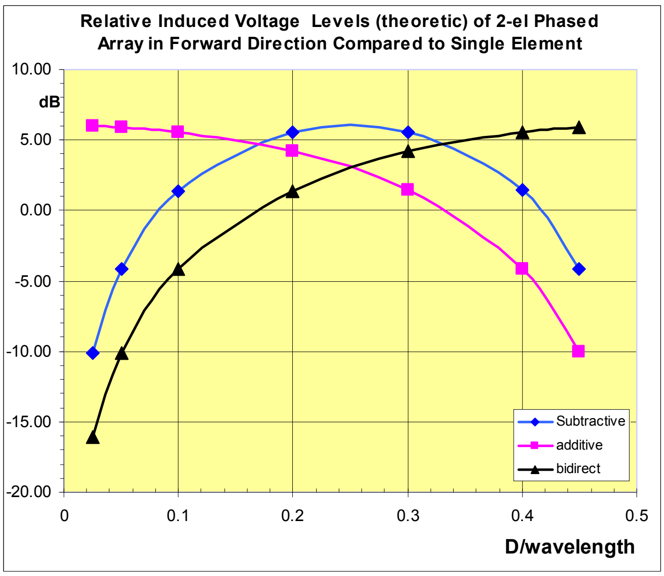


Fig.3 *Output voltages (in forward direction) of 2-el. phased array compared to output voltage of a single element for 3 different modes of operation – subtractive, additive and bi-directional. The curves are derived from Eq. (9), (11) & (13)*

1.2 Additive array

The voltages from the elements can also be added by setting the phase switch to 0 deg. and the delay $\tau_d = 0$ ***(Fig.2)***. The resultant radiation pattern is almost circular ***Fig.7.*** The induced voltage V_a for the right and the left waves is the same:

$$V_a = V_0 \cos(\omega t) + V_0 \cos\omega(t-\tau) \qquad (10)$$

so the radiation pattern is symmetric without a null. The output amplitude V_A for this case will be:

$$V_A = 1.41 V_0[1+ \cos(2\pi D/\lambda)]^{1/2} \qquad (11)$$

The maximal value will be when $D/\lambda = 0.5$ then $V_A = 2$. There will be a null at $D/\lambda = 1$ .We can set a certain time delay in dipole #2 chain, as it is done in the subtractive case, but for the closely spaced arrays this will not give useful directivity and we will not consider this case.

1.3 Bidirectional array

We can again subtract the voltages from the elements but without any delay $\tau_d = 0$.

$$V_a = V_0 \cos\omega t - V_0 \cos\omega(t-\tau) \qquad (12)$$

the amplitude Va for this case will be:

$$V_A = 1.41 V_0[1 - \cos(2\pi D/\lambda)]^{1/2} \qquad (13)$$

The voltage V_A is the same for both directions (forward and backward) so the radiation pattern is symmetric but now there will be a null in *Y* axis direction since the *Y* direction wave will induce equal voltages with the same phase in both dipoles which will be subtracted. (***Fig.7)***

1.4 Effective height

All these equations are valid also in terms of the antenna effective height (EH) h – for example for subtractive array taking into account *Eq. (9)* :

$$h_A = 1.41 h_0[1 – \cos(4\pi D/\lambda)]^{1/2} \qquad (14)$$

where h_0 is the effective height (EH) of the single element of the array. *Eq. (14)* and is obtained by a simple substitution of *V* with *h* since the induced voltage *V* is always proportional to *h*..

1.5 Comparison with experimental data

Plottings of the *Eq. (9), (11) & (13)* as a function of *D/λ and fixed optimal time delay* are shown on ***Fig.3***. They describe the output voltage of the array with a processing circuit as in ***Fig.2*** induced from a plain wave propagating along the X axis in three modes of operation: subtractive directional mode with fixed time delay τ_d, additive omni directional mode and bi-directional subtractive mode. In the experiment we will measure these voltages and compare them with voltages obtained from a single element of the array which is V_0. We will compare the experimental results with these theoretical equations.

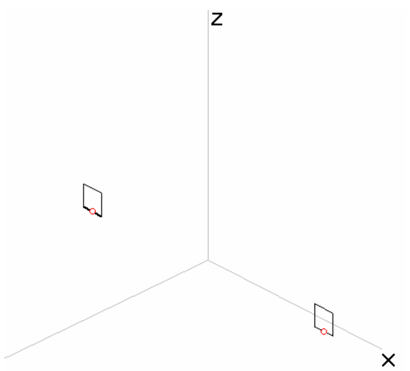


Fig.4 *2-el. array with coplanar small loops. It has similar directional properties along the X axis as the dipole array.*

It does not matter whether the elements are small loops or short dipoles since all the preliminary assumptions can be applied also to small loop antennas. The only requirement is that the loops must be coplanar and placed in one plane XZ. (***Fig.4***)

In the case of real ground these equations should work since the only requirement for the field is to have a uniform intensity in the space surrounding the array. There might be also a tilt in the polarization but the field intensity is not expected to be non-uniform. However the existence of closely spaced conductive objects might change the necessary time delay requirements due to refractions so for this case a different behavior might be expected.

2. Numerical models

2.1 Radiation Patterns

The results of modeling (in real ground) are presented here for arrays of two small vertical dipoles (V. dipole) and two small vertical quad loops (V. Loop). MMANA program (with MININEC 3 core) was used for this purpose. The variable parameter is the wave-distance between elements D/λ with fixed time delay $\tau_d = D/c$. These plottings can be considered as the behavior of the array with fixed distance and fixed time delay τ_d for different wavelengths. The radiation patterns(***Fig.5 Fig.6***) are calculated for transmission mode but they are the same in receive mode. The azimuth plot is at section at 20^{O} elevation angle. The dipole length and the loop perimeter are < $0.1\ \lambda$. . The time delay of the delay line *is fixed* for all cases and is equal to optimal value $\tau_d = D/c$. All these plots are given for reference and are deliberately placed side by side in order to compare the patterns of dipole and loop arrays visually.

The radiation patterns for the cases where the array is in additive and subtractive modes without time delay ($\tau_d = 0$) are given on ***Fig.7*** *and* ***Fig.8***.

Fig.9 shows the sensitivity of the radiation pattern to time delay deviations. The time delay is changed +-20% from the optimal.

2.2 Determining the minimal distance between the signal source and the array in experimental measurements

A true plane wave can be generated only from a very distant source. It is interesting to obtain some quantitative data how far must be the signal source to fulfill the requirements of equal field strength and consequently equal voltage or current amplitudes in each element. A model was built in MMANA with two small vertical loops (quads, 1m side, 14.5 m distance) and a small vertical dipole (1m length) as the source of a field. The dipole is located in the same plane as the loops and at certain distance r from the loops (given in the first column of ***Table 1)***. Both loops are terminated with 6 ohms resistor which is approximately the input impedance of the active loop amplifier. The currents in both loops are computed and the results are given in the following ***Table 1***.

Distance to source r [m]	*I Ampl. Difference*	*I Phase diff. Degrees*
300	**4.7%**	**35.95**
1000	**1.4%**	**36.14**
5000	**0.3%**	**36.16**

Table 1

MMANA simulation. The amplitude and phase difference of induced currents between the small loops in 2-element array. $D=14.5$ m, $D/\lambda = 0.1$. *The wave source is a small vertical dipole located at some distance. The theoretical phase difference* $\varphi = 2\pi D/\lambda$ *is 36.2 in degrees.*

As it can be seen the numerical model gives almost the same value of phase difference as predicted by the simple model. There are differences in amplitudes which are the main source of errors and are due to the field gradient $1/r$ along the X axis since the source is in finite distance. The minimal distance to the source r can be determined by the requirements of the experiment accuracy.

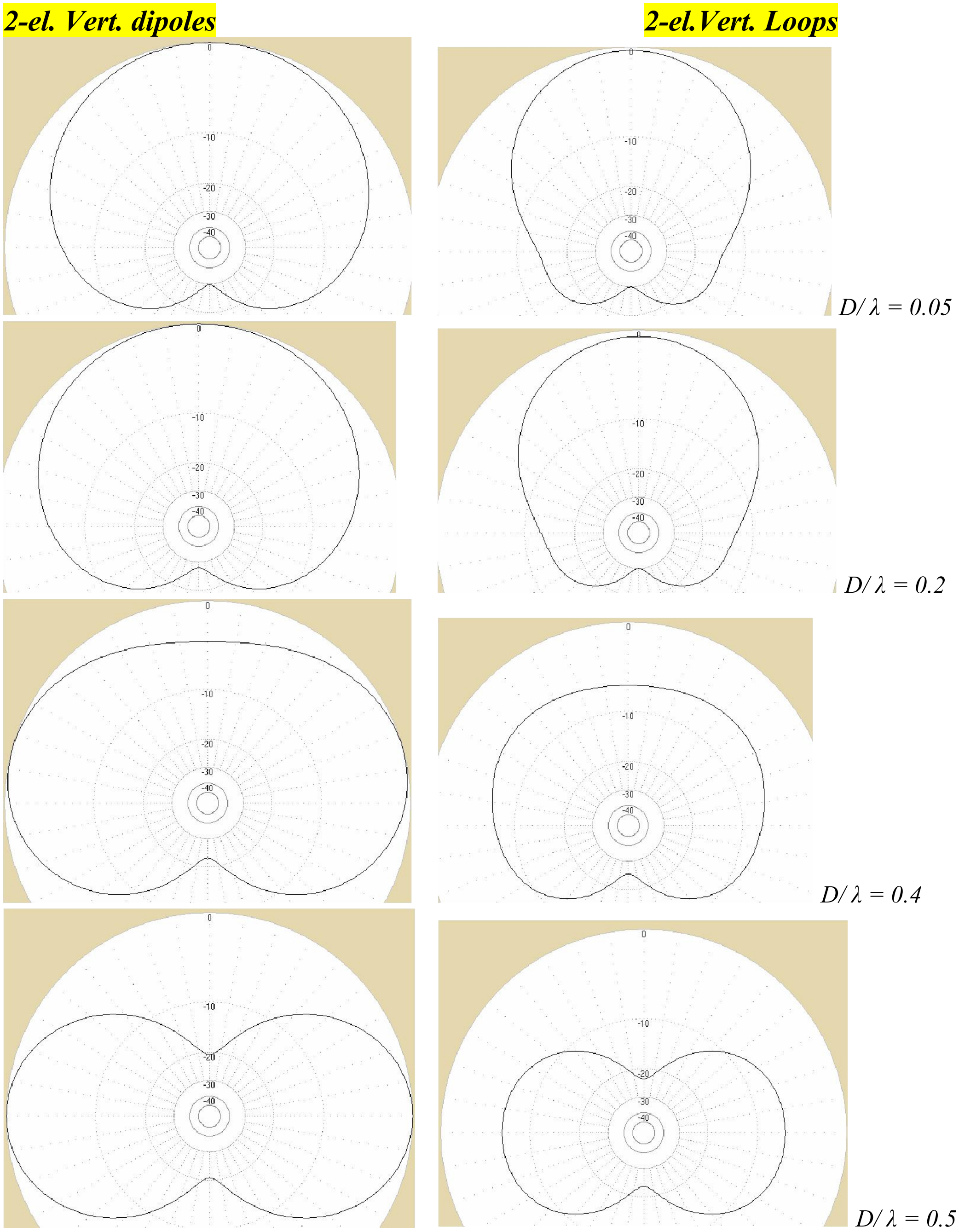


Fig.5 *Radiation patterns of 2-el. V. dipole and V. loop arrays in horizontal plane at section at* 20^{O} *elevation angle. Real ground setup* ε*=13, S=5. MININEC core. The time delay is fixed and is equal to optimal* $\tau = D/c$ **.** *These figures can be viewed as the behavior of the array with fixed distance D and fixed time delay* τ *of the delay line for different wavelengths. The gain for each case is normalized to maximal gain so gain comparisons must not be made.*

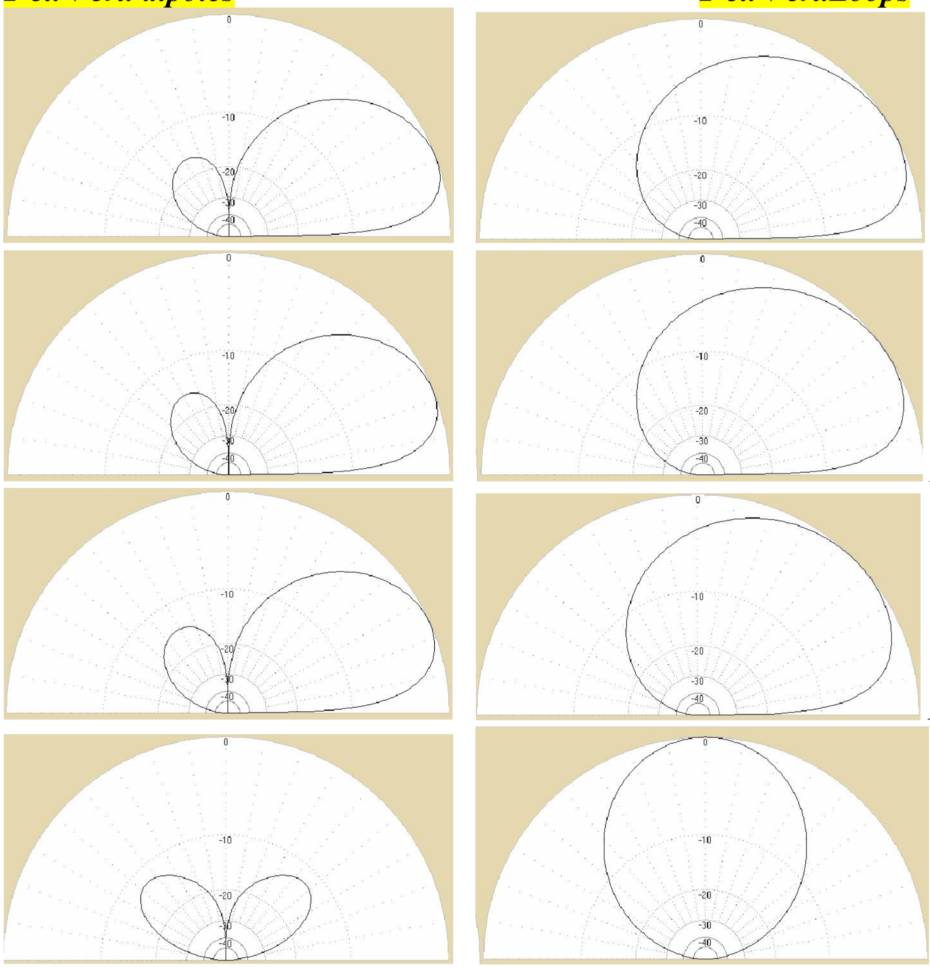


Fig.6 *Radiation patterns of 2-el. V. dipole and V. loop arrays in vertical plane. Real ground setup. The time delay is fixed and is equal to optimal* $\tau = D/c$ **.** *These figures can be viewed as the behavior of the array with fixed distance D and fixed time delay* τ *for different wavelengths. The gain for each case is normalized to maximal gain so gain comparisons must not be made.*

3. Experimental setup

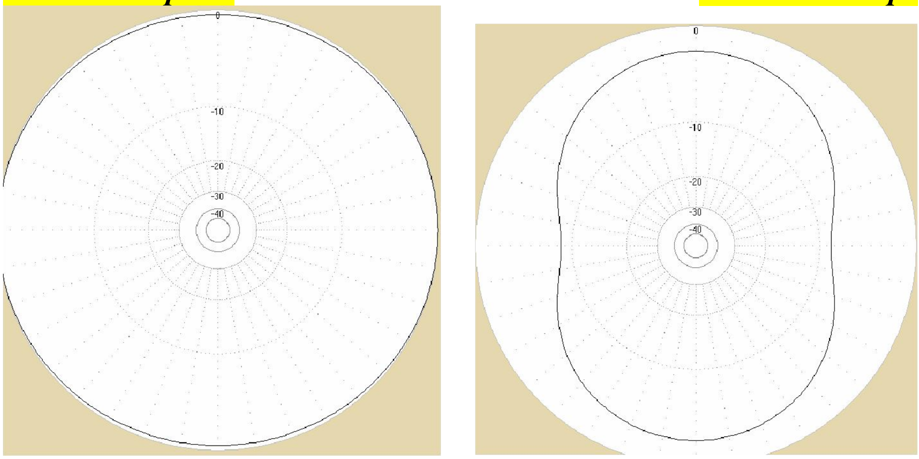
A block diagram of the experimental setup is shown on ***Fig.9***

3.1 Transmitter

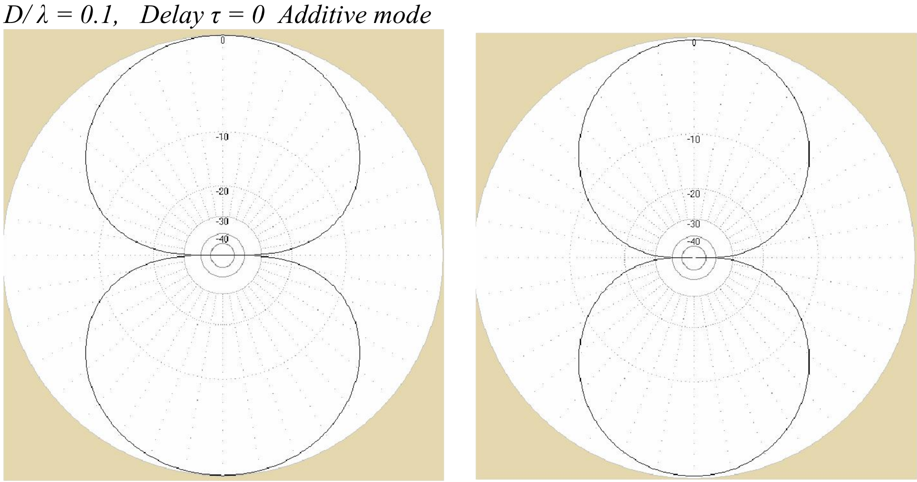
A small transmitter (TX) is located at some distance from the array. It transmits continuous signals simultaneously at 4 frequencies as follows: 1.755 , 3.510, 7.022 and 10.01 MHz. It has two X-tal oscillators and frequency dividers fed to 4 independent outputs, each output with separate LC antenna matching circuit. Each output consists of 4 parallel connected outputs of 74HC273 line driver gates (***Fig.10***).

All antennas are vertical aluminum rods with 1.2 m length, the exception is 1.755 MHz where the length is a 4 m vertical wire. The common counterpoise is a 30 cm rod inserted into the ground. The measured peak voltage at resonance is between 50 and 75 volts. The measured signal level at 800 m distance is between -90 to -70 dBm with single 1 m diam. receiving loop, AAA-1 amplifier and Pereseus RX [*23*]. A “waterproof” solution is used as shown on ***Fig.11*** The polarization of the generated wave is supposed to be vertical.

2-el. Vert. dipoles **2-el. Vert. Loops**



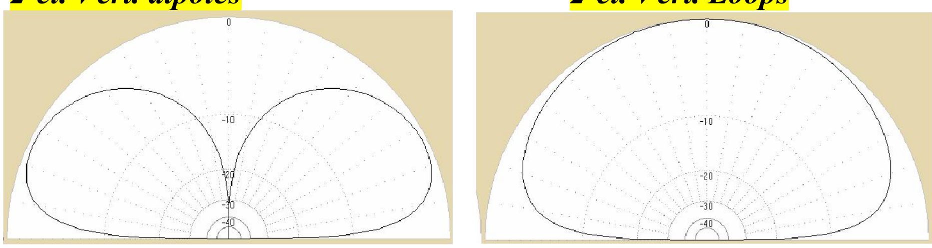
D/ λ = 0.1, Delay τ = 0 Additive mode



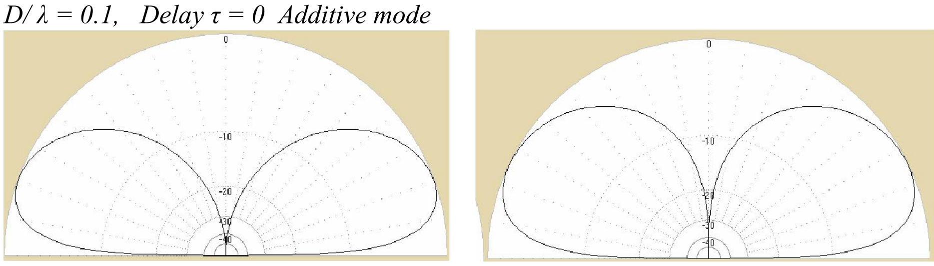
D/ λ = 0.1, Delay τ = 0 Bi-directional mode

Fig.7 *Radiation patterns of 2-el. V. dipole and V. loop arrays in horizontal plane at section at 20^{O} elevation angle for additive and bi-directional modes. Real ground setup. There is no time delay between elements but voltages from the elements are added or subtracted**.** The pattern remains almost the same for other values of D/ λ .*

2-el. Vert. dipoles **2-el. Vert. Loops**

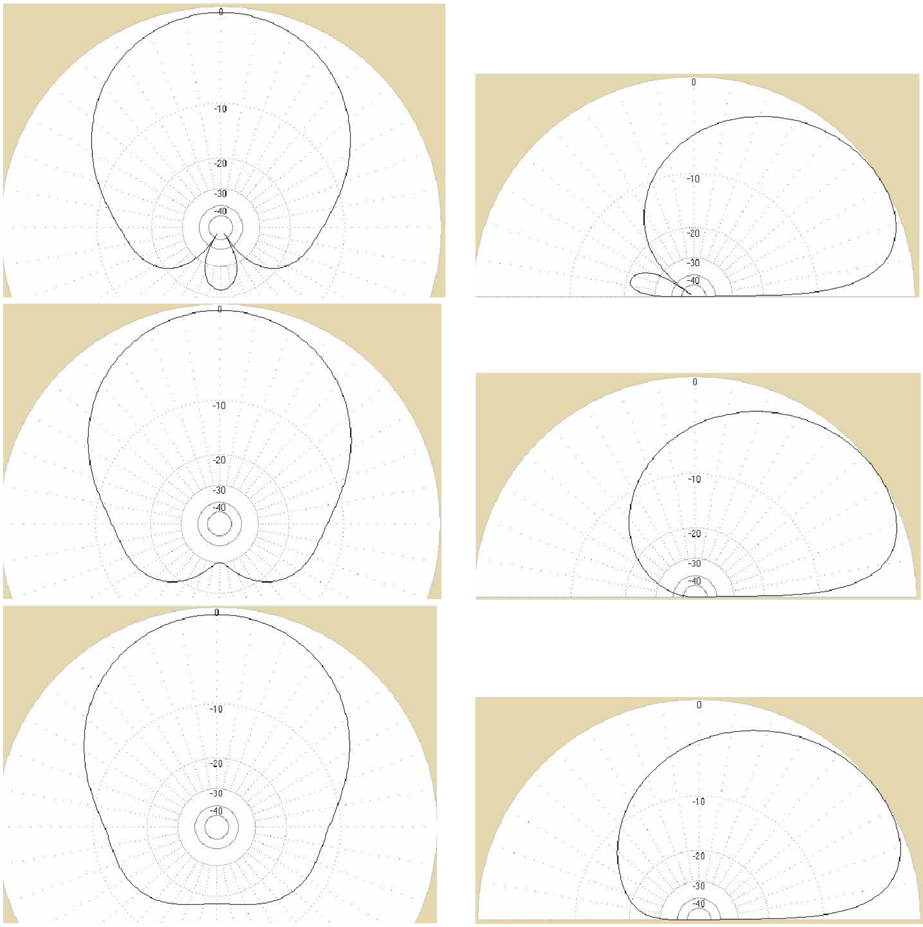


D/ λ = 0.1, Delay τ = 0 Additive mode



D/ λ = 0.1, Delay τ = 0 Bi-directional mode

Fig.8 *Radiation patterns of 2-el. V. dipole and V. loop arrays in vertical plane for additive and bi-directional modes. Real ground setup. There is no time delay between elements but voltages from the elements are added or subtracted**.** The pattern remains almost the same for other values of D/ λ .*



$\tau_1 = 0.8\,\tau$

τ

$\tau_1 = 1.2\tau$

Fig.8 *Radiation patterns of 2-el. V.loop array when the time delay τ is changed +- 20%. from the optimal. D/ λ = 0.1. The pattern changes have almost the same characteristics for other values of D/ λ which means that they are frequency independent. Similar changes are observed in the case of V. dipole array. Note that for the case of 0.8 τ the radiation pattern has somewhat lower elevation angle.*

3.2 Amplifiers

AAA-1B amplifiers are used [*24*] (www.active-antenna.eu) . The measured gain difference between them is no more than 0.3 dB and negligible phase difference. They can be set remotely in dipole or loop mode. The output of the amplifiers is symmetric with Z=100 ohms and CAT5E FTP (shielded) cable is used to carry the RF and control signals to the delay line module.

3.3 FTP cables

FTP cables are 15 m long and are cut with the same length from a single longer piece. The same color pair is used for the RF path in each cable. The measured delay difference between the cables was less than 1 ns without any trimming.

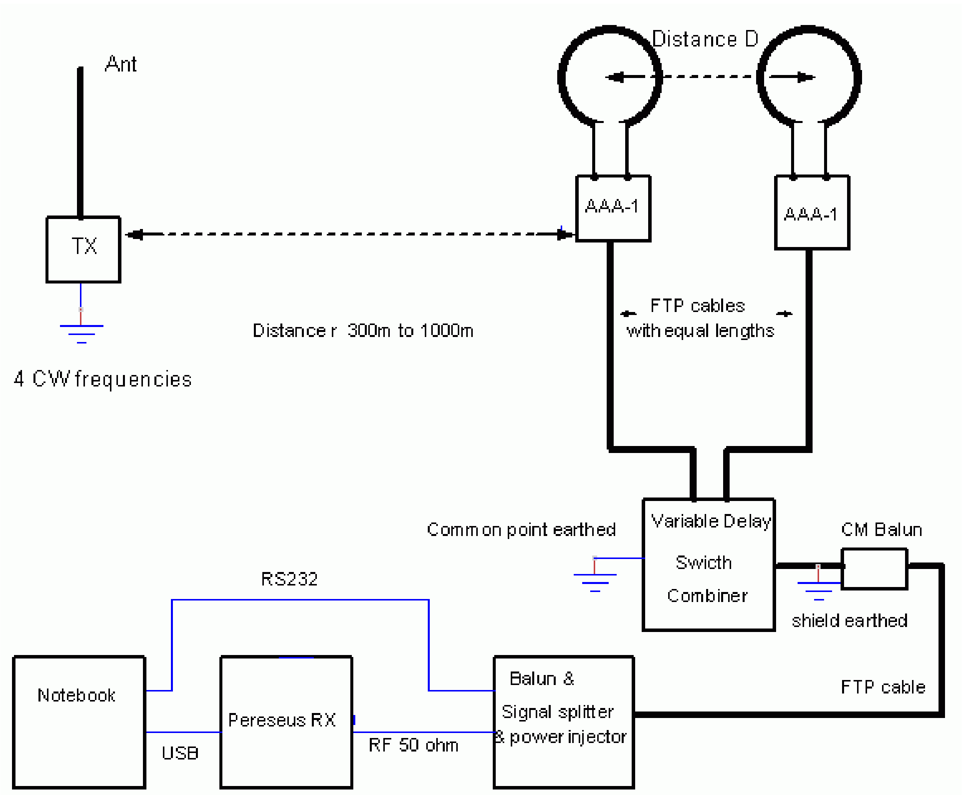


Fig.9 *A block diagram of the experimental setup. For "clean" experiment TX and the array must be located in a field without any obstacles between them and without near conducting objects. Reflections from distant objects should also be avoided (hills, large buildings, high voltage lines etc..). Common mode chokes are used to minimize common mode currents which might distort the measurements.*

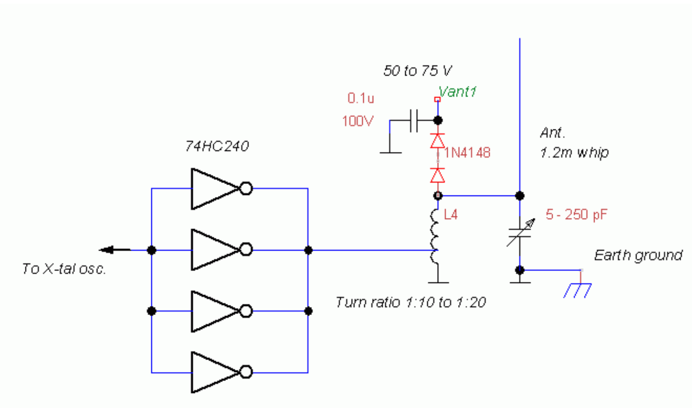


Fig.10 *Output stage and antenna matching circuit of the TX unit. There is a peak detector to track the resonance. The peak output voltage is between 50 to 75 V depending on the band, the antenna and the Q-factor of the matching circuit.*

Fig.11 *The TX LC matching circuit is inserted in a glass jar and is waterproof. All antennas and the TX unit are placed not more than 1 m apart from each other. There is no harmful interaction between them. The peak detector output is accessible from the cover of the jar in order to check the resonance and antenna voltage in field environment.*

3.4 Antennas

A single loop with 0.97 m diam. made from PE heating tube (16mm external diam. of the PE coating) was used for the loop array (see also http://www.active-antenna.eu/tech-docs/3_ActiveAA_Antena_11.pdf *Fig.3.5.1*). For dipole mode the upper arm of the dipole is the loop antenna with +A and –A points short circuited. The lower arm is 1.5 m vertical wire (***Fig.12***). The lowest loop pont in all experiments was 2 m above the ground level.

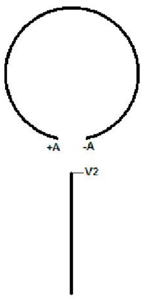


Fig.12 *The loop and the vertical dipole antenna*

3.5 Variable Delay line, switches and combiner

The schematic of the delay line is shown on ***Fig.14 .*** The line is non symmetric and input baluns T1,T2 are used. The signal from one of the antenna elements can be inverted with relay K10. The signal from one of the elements is fed directly to a T combiner – the other signal passes through the delay line. There is another switch which can exchange the element, so forward and backward direction can be switched. The characteristic delay line impedance is 100 ohms because CAT5E cables are used. The delay τ_d can be set at any value between 0.3 and 76.5 ns (256 values with 0.3 ns resolution). The LC line is made form single value commercial chokes of 1 uH to reduce the possible value dispersions. With these values the maximal usable frequency for delays (larger than 10ns) is 11 MHz. The smallest delays are made with microstrip lines on the PC board (***Fig.13***) . Single element mode is switched with relay k12 in order to compare the array signal with single element signal. All three modes discussed in sect. ***1*** can be used - subtractive with delay, additive and subtractive without delay and single element. The relays are controlled by a microcontroller located on another board. There is serial RS232 line which is optically insulated and connected to the notebook COM port. There is appropriate software to control the switches and delays. The RF output signal, the power lines and serial line are fed to another FTP cable with 20m length to the DDC receiver (Perseus) and notebook. There is a common mode filter on the FTP cable [*18a*]. The delay line common point is also earthed with small 30 cm rod inserted into the soil.

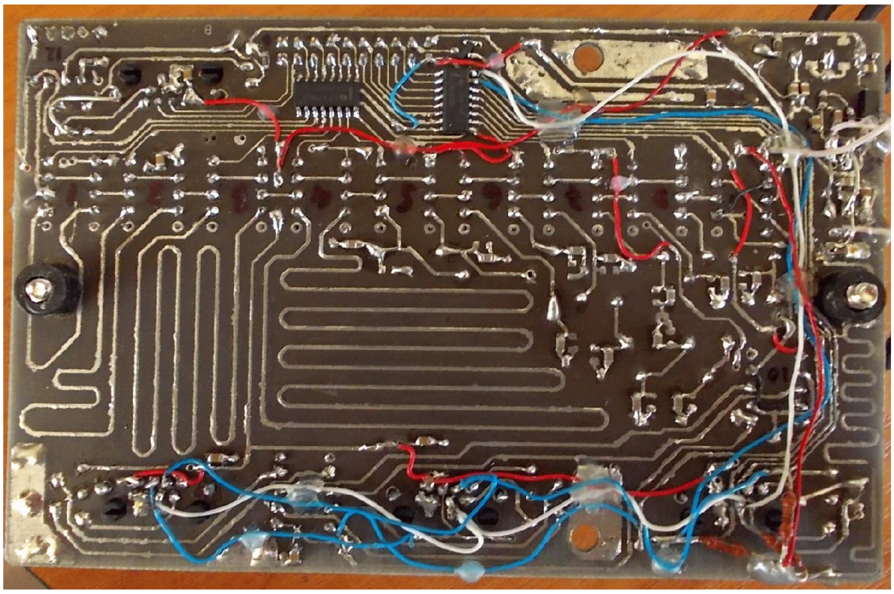


Fig.13 *Variable delay line PCB with micro-strip lines for short delays from 0.3 to 2.5 ns. The other side of the board is a ground plane layer. The PCB is handmade (laser printer & flat iron technology).*

3.6 Receiver and power supply

Perseus direct sampling receiver [*23*] was used as a measuring device. It has very good measurement properties - its power measurements were compared with HP 432A power meter and the deviations were within 1 dB on all frequencies. All measurements were performed in 100 Hz bandwidth, dither on, filter off, 125 KS/sec, attenuator off. All the equipment was battery powered in field environment.

4. Experimental results

Since the AAA-1 amplifier can be switched in loop or dipole modes, each experiment was performed for both modes at the same place and time.

Before each experiment 2 important measurements must be performed to be sure that the experiment is clean.

A. Single loop directivity. 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.

B. Signal level difference between elements of the array. The induced signal level was measured separately for each element. This was performed for both V.dipole and V.loop arrays. In ideal conditions they should be equal.

Three experiments were performed in different places and times. The experimental conditions were as follows:

Experiment #1 *Distance r to TX 280 m; Distance between elements D= 7.5 and D=15 m with N/S X axis direction. Terrain between TX and array is a green field free from any electrical cables. The location is a valley, the nearest small hill is at 500 m at Y direction.*

Experiment #2 *Distance **r** to TX 750 m; Distance between elements D= 14 m. Terrain between TX and array is semi-urban. See the **Fig.15.** The location is a valley, the nearest hill is at 150 m at west direction.*

Experiment #3 *Distance **r** to TX 580 m; 3 measurements were performed with a distance between elements D= 17 m, 12 m and 6 m. careful measures were taken to avoid any influences from reflections and conductive objects. Terrain between the TX and the array is a green field free from any electrical cables. The location is a plain, the nearest hills are at 10 Km distance.*

The results of these 3 experiments are presented side by side in graphical form on the following figures. Hopefully they are quite clear and do not need much discussion.

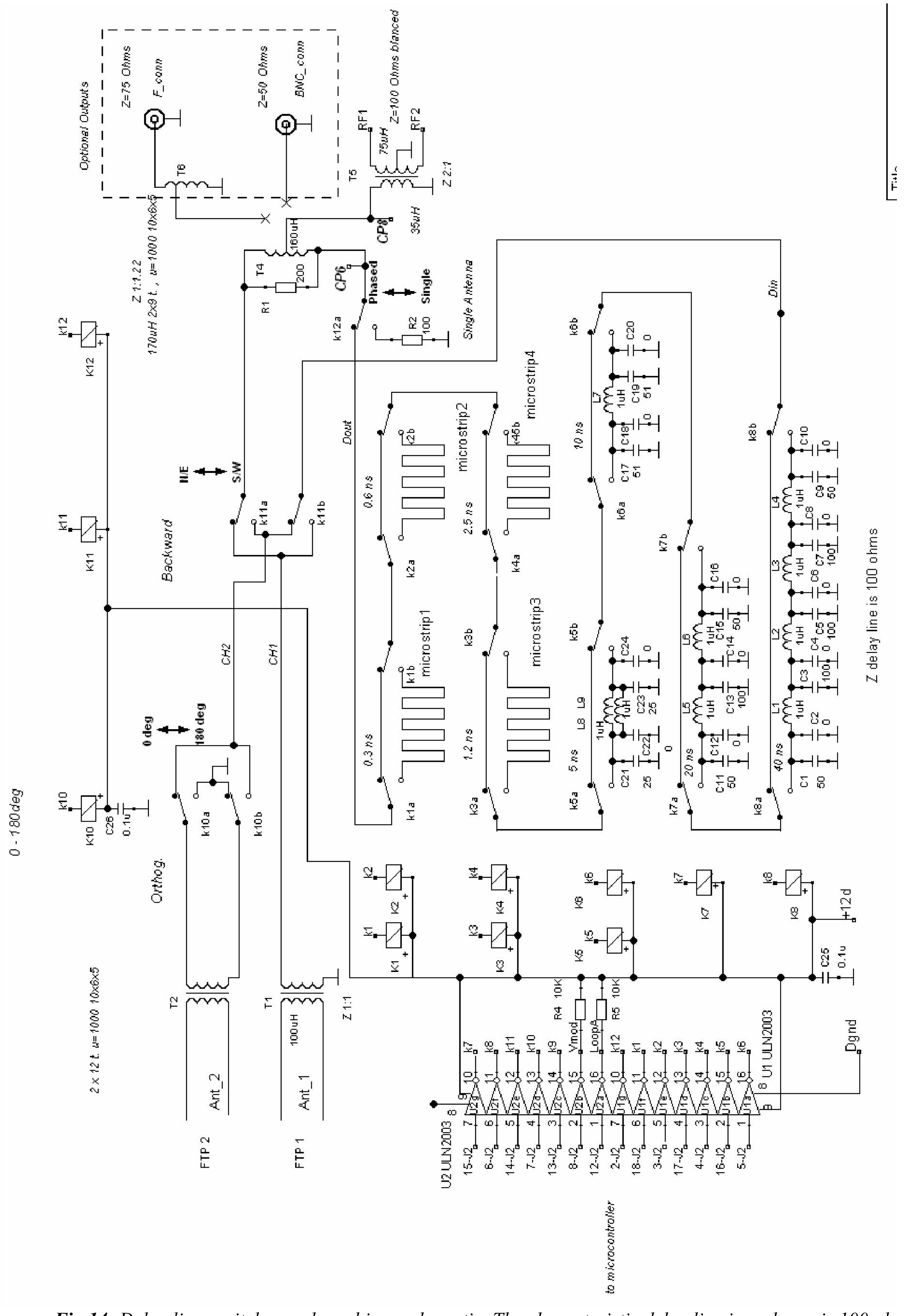
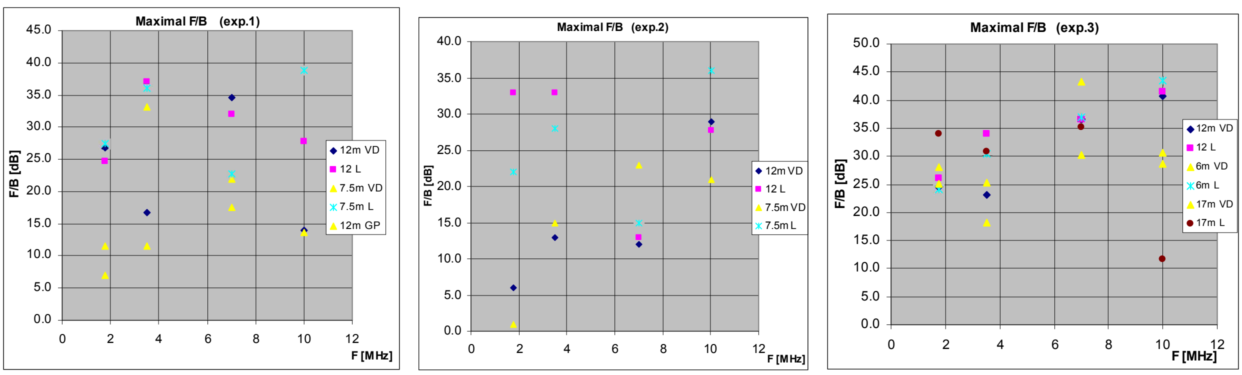


Fig.14 *Delay line, switches and combiner schematic. The characteristic delay line impedance is 100 ohms. For smaller delays micro-strip lines are used.*

Fig.15 *Terrain of the Experiment #2. TX is located in the green field at 750 m from the receiving array. The yellow line shows the path between TX and array. There is a high voltage line 20 KV (red dashed line) passing at 250m form the array. The array is in a small yard surrounded by 4 houses (right picture). There is a light metal grid fence between yards with 1.5 m height. There is an elevated radial (from inverted L antenna), 20 m long which passes at 5 meters to one of the elements of the array. There is also 220V mains installation on 7 m high poles along the street at 15 -20 m distance from the array. This is a typical environment in most suburban areas in Bulgaria.*

4.1 Front to back ratio

For each frequency, in backward direction, a minimal signal level was found by switching the delay line to different delays (***Fig.16***) . Then the array was switched to forward direction and the ratio of these two signals was calculated.

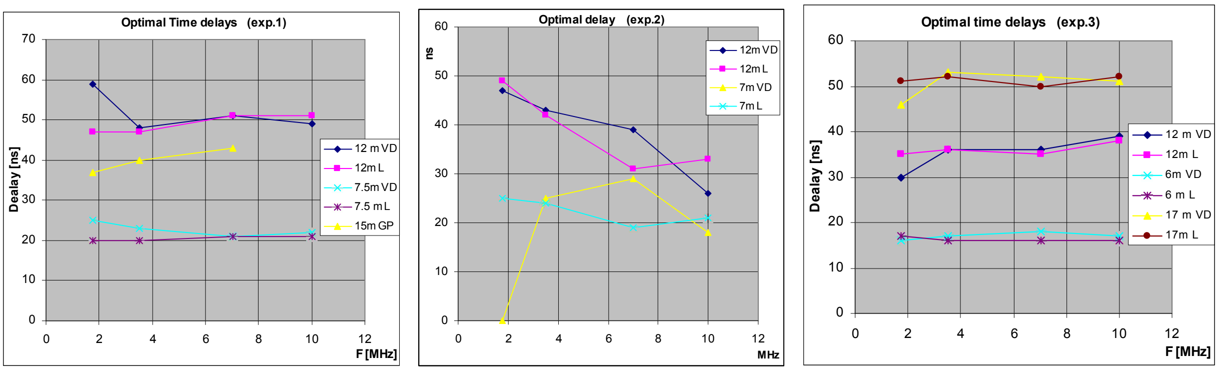


Experiment #1 *Experiment #2* *Experiment #3*

Fig.16 *Maximal F/B ratio*
Exp.#1 : V. Loops (L) and V. dipoles (VD) with 15m and 7.5 m distance between elements –green field..
Exp.#2 : V. Loops (L) and V. dipoles (VD) with 12m and 7.5 m distance between elements in small yard location.
Exp.#3 : V. Loops (L) and V. dipoles (VD) with 17m, 12m and 6 m distance between elements –green field.
Points for D = 17 m in Exp. #3 must be omitted since the 0.5 D/λ limit is passed.

4.2 Time delays

The corresponding time delays at maximal F/B points are plotted (***Fig.17***) .



Exp.#1 *Optimal delays are 25ns and 50 ns* ***Exp.#2*** *Optimal delays are 25ns and 40 ns* ***Exp.#3*** *Optimal delays are 20ns, 40ns and 57 ns*

Fig.17 *Measured time delays with the maximal F/B ratio. Note the dispersion at 7 MHz in Experiment #2. Theoretic optimal delays are given below each figure.*

4.3 Deviations in time delay

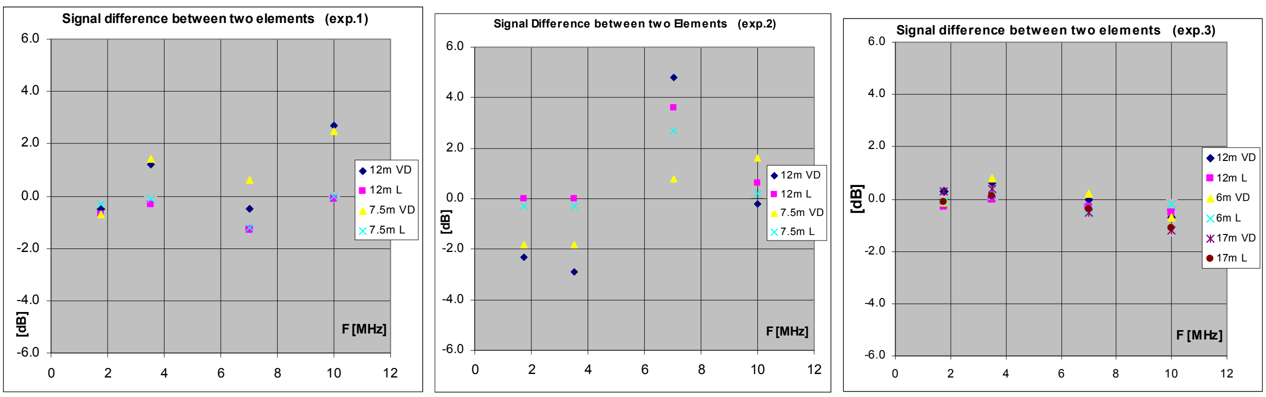
*On **Table 2*** the results of the measurements of F/B are shown when the delay is +5 ns and -5 ns from the experimentally obtained optimal time delay. The measurements are performed in Experiment #1 with *D*= 15m. The optimal theoretical τ_d *=50 ns* so the deviation is approximately +-10%.

Table 2

F	F/B [db] V. Dipole			F/B [dB] Loop		
MHz	**+5ns**	**Opt**	**-5ns**	**+5ns**	**Opt**	**-5ns**
1.76	20	27	26	21	25	24
3.51	15	22	15	24	37	23
7.02	18	35	21	12	32	11

4.4 Signal difference

The signal level from each element alone was measured and the differences between two elements are plotted on ***Fig.18***. The theoretical presumption is that the signal amplitudes in both elements should be equal.



Experiment #1 *Experiment #2* *Experiment #3*

Fig.18 *Differences in signal level between the elements of the array. Note the wide dispersion of levels at 7 MHz in Experiment #2. In Experiment #3 the difference is less than 1dB on all frequencies.*

4.5 Forward EH in subtractive mode compared to a single element

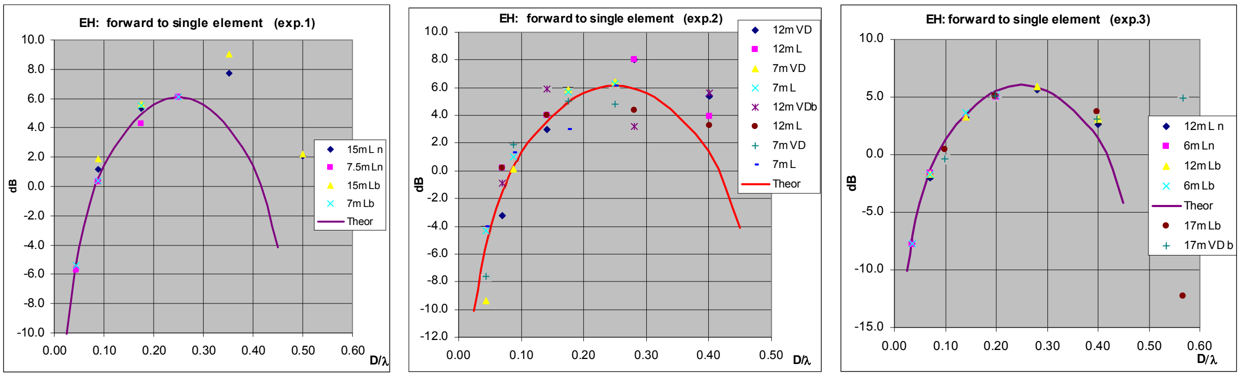
These are plots (***Fig.19***) from the experimental measurements of the effective height difference between forward mode and a single element. The theoretical curves according to *Eq.9* are plotted.

4.6 Additive mode EH compared to a single element

These are plots (***Fig.20***) from the experimental measurements of the effective height difference between additive mode with zero delay and a single element. The theoretical curves according to *Eq.11* are plotted.

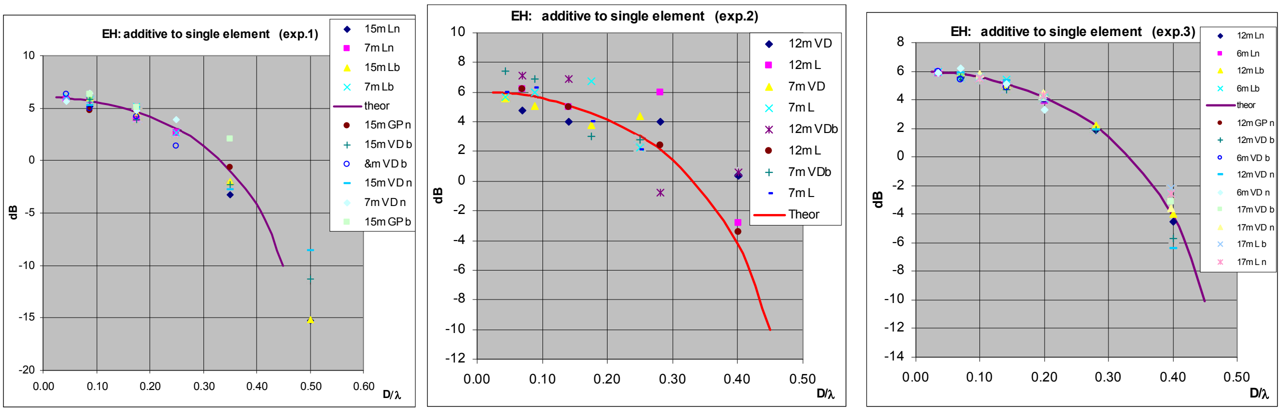
4.7 Bi-directional subtractive mode EH compared to a single element

These are plots (***Fig.21***) from the experimental measurements of the effective height difference between subtractive mode with zero delay (bi-directional) and single element. The theoretical curves according to *Eq.13* are plotted.



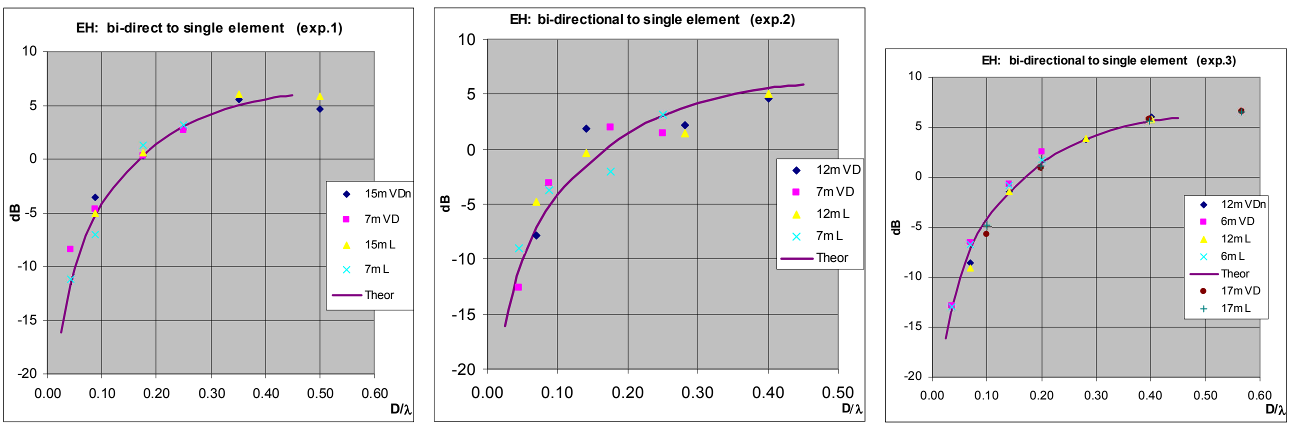
Experiment #1 *Experiment #2* *Experiment #3*

Fig.19 *Forward direction EH of subtractive mode compared to EH of a single element. The theoretical curves are plotted for comparison.*



Experiment #1 *Experiment #2* *Experiment #3*

Fig.20 *Additive mode EH compared to EH of a single element. The theoretical curves are plotted for comparison.*



Experiment #1 *Experiment #2* *Experiment #3*

Fig.21 *Bi-directional mode EH compared to EH of a single element. The theoretical curves are plotted for comparison.*

5. Discussion and Conclusions

The analysis and discussions of the experiments are given in a form of Q&A since it is difficult to systemize them in logical order and probably this form will be more convenient for the reader.

5.1 What is the bandwidth of an array with a fixed delay line between elements?

If the goal is a unidirectional array then the upper limit is somewhere around 0.4 D/λ. Above this frequency the diagram degenerates and at 0.5 λ it becomes bidirectional and moreover rotated at 90 deg to the main directional lobe ***Fig.5***. Of course this might be useful directivity.

The lower limit depends very much on the sensitivity of the array. The conclusion from the theory (*Eq. 9*) and experiments (***Fig.19***) show that the forward EH of the array drops very rapidly when D/λ is lowered. With the AAA-1 amplifiers and 1 m diam. 2.5 uH single loop the practical limit is somewhere in 0.04 D/λ . The dipole array loses the directional properties below 1 MHz for unknown reasons (probably from common mode signal infiltration). From ***Fig.3*** for 0.05 D/λ the EH is -4 dB compared to that of a single element. Another 3 dB attenuation must be added if T-combiners are used for adders (***Fig.28***) . The author's experience with array with D = 14 m shows directional properties down to 0.3 MHz (D/λ = 0.014) with the loop array. Irrespective of the low EH for the MW , at night times when the external noise and signals are quite strong it is possible to listen to stations which are masked when using only a single element. When very closely spaced elements are used, they must be made of larger size in order to compensate the reduction of the EH and increased noise floor. Practically, a useful frequency range of 1:10 is quite possible.

5.2 What is the effective height (EH) of the array compared to a single element of the array?

Fig.19 shows that the theoretical curve describes quite accurately the forward EH of the array. The EH drops down rapidly when the distance becomes very short.

5.3 What are the main limitations in a closely spaced array?

The main limitation is that the sensitivity (or effective height) drops rapidly with the reduction of the distance D. The wideband active antennas are usually very small sized and the induced voltages or currents are also very small so the noise properties and the matching of the amplifier become important irrespective of the higher level of the external noise in HF bands. The main goal in the active antenna design is to have a noise floor which is limited by external noise not by the internal noise factors. So the first requirement is to have low noise floor in the active individual elements.

The second requirement is to have sufficient gain from the amplifiers in order to compensate the reduction of the EH in the case of very closely spaced elements. With a passive delay line it must be taken into account that each combiner has also additional 3 dB attenuation (***Fig.14***). Also, the attenuation of the cables must be included. The final requirement is that the composite noise at the input of the receiver must be higher at least with 6 to 10 dB from the input noise floor of the main receiver. In order to compensate these losses the elements of the array must have higher EH – e.g. vertical dipoles or monopoles with length 4-5 m and crossed loops with M-factor >0.5 [*18*] must be used.

5.4 Is the radiation pattern degraded when the elements are very closely spaced and is it possible to achieve a very high F/B ratio ?

Modeling shows that the radiation pattern becomes even more directive when D/λ decreases. Theoretically very high F/B ratios can be achieved with any distance between elements in ideal conditions. Looking at the experimental results for F/B ratio (***Fig.16***) it can be seen that the dispersions of F/B values are significant– from 6 to 45 dB. Some of the experimental points are probably measurement errors.

The most accurate Experiment #3 gives values between 16 and 45 dB. It must be pointed out that if we change the delay in very small steps (less than 0.3ns) the F/B value in this case will be probably above 30 dB but practically this perfect tuning will not change at all the real performance of the array compared to the case where we have tuned the delay to more practical 15-20 dB values.

The results in Exp.#2 are influenced by imperfect environment. There, the induced voltages in the elements of the array are not equal anymore (***Fig.18***) and the high F/B ratio cannot be achieved at all. There are also other limitations which degrade the F/B ratio in very closely spaced arrays – mainly common mode infiltration since the common mode signal levels become in the order of differential signal levels.

5.5 What is the noise floor of the phased array compared to a single active element?

It depends on the mode of the array and on the type of the noise. We should distinguish that at the output of the amplifiers of each element the noise has correlated and uncorrelated part. The correlated noise means that we have the same random signal in both outputs shifted by phase. This is the noise coming from external sources and can be assumed as a signal. The uncorrelated part is the internally generated noise – thermal and from active components (transistors). Let us take the case of a very closely spaced subtractive array with D/λ = 0.05 and the source signal in optimal beam direction. We have 2 cases:

A. For additive mode (forward direction), at the output of the adder, there will be an increase with 6 dB of the signal and 3 db increase of the uncorrelated noise. There will be improvement of S/N with 3 dB compared to a single element.

B. For the case of subtractive array things are quite different. At the output of the adder the correlated signal and noise level from forward direction will be 4 dB less (***Fig.16***). But the uncorrelated noise will be again higher with 3 dB since it does not matter whether we add or subtract uncorrelated noise sources. If we have a case where the noise floor of each active element is determined by the internal noise there is a problem. The output noises of amplifiers from each element are uncorrelated and we will have reduction of S/N with 7 dB: 4 db from the reduction of the signal level and 3 dB increase of the noise level! That is why for the case of very closely spaced subtractive arrays the noise floor of each active element should be well below the level of the external noise!

5.6 What are the differences between a small vertical dipole and a small vertical loop array?

- The vertical dipole array has a lower take-off angle (***Fig.6).***
- The vertical loop array has better directivity – the main lobe is narrower ***(Fig.5).***
- In additive mode the patterns are quite different (***Fig.7)***
- The loop array is not so sensitive to environment.

For people living in urban and semi urban environment I will suggest using loop array. For those who have a large open area and quiet rural place the vertical dipole array will give excellent results. Using both antennas for the array is the best solution since we practically have also somewhat elevation angle choice.

5.7 How deviations from the optimal delay in delay line affect the pattern of the array?

Fig.8 from modeling shows that the deviations of the delay line parameters are not critical. The experimental results given n ***Table 2*** also suggest that the time delay settings are not critical. Even deviations from optimal delay of +-20% still preserve the unidirectional pattern with acceptable back lobes. Note that for the case of 0.8 τ_d (***Fig.8***) the radiation pattern has somewhat lower elevation angle. The same is true for the vertical dipole array.

5.7a Can you suggest practical distances D and element sizes for serious DX-ing ?

For 1.8, 3.5 and 7 MHz : D = 12.9 m. This is corresponds to D/λ 0.075, 0.15 and 0.30. The optimal delay τ_d is 43 ns. The corresponding radiation patterns can be found on ***Fig. 5, 6.*** The forward EH will be -3.8 dB, +1.5 dB, +2.6 dB compared to a single element (the 3 dB attenuation of the T-combiner is included).

For MW band, 1.8 and 3.5 MHz : D = 24 m , τ_d = 80 ns, where D/λ is 0.15 and 0.3 and the EH is +1dB and +2 dB. This distance will have forward EH – 8 dB at 500 KHz which is quite acceptable bearing in mind the high level of the noise and signals on these frequencies when the band is open (night time).

For loop antennas I will suggest for each element 2 crossed coplanar loops [*17, 18*] with 1 m diameter made from PE aluminum coated tubes with 14 mm diameter. For vertical dipoles two arms with 2 – 3 m length each will be sufficient. 3 – 4 m vertical GP with simple radial system will do the job also. The time delay might be reduced with 5 - 10 % from the optimal to lower the take-off angle.

5.8 Can I use other types of active antenna for element of an array?

Any kind of small apperiodic active antennas can be used for elements in array. (I will not suggest to mix the array elements with different antenna type – e.g. to use vertical dipole element and loop element at the same time). The only requirement is to match the output of the element amplifiers to the Z of the delay line. Short active ground plane (GP) verticals (monopoles) can be used which are the usual choice in such designs [*12, 14, 15, 15a, 19*]. The GP will give several dB higher signal level compared to vertical dipole with the same length but I have found out that in semi urban environment the GP is noisier. Medium sized directional loops such as K9AY, flags etc. [*6, 7, 8, 11, 13a, 16, 21*] can also be used but they must be active (with preamplifier) and the output impedance of the preamplifier must match the delay line impedance. The resulting radiation diagram will be even more directive according to “multiplication principle” [*1*].

Resonance antennas, even small, need quite different approach in order to reach the desired phase correlations which can be found elsewhere [*4*].

5.9 What kind of delay line can be used?

The variable delay line described here was built for experimental purposes. The resolution is too high (0.3ns) which is not needed if we limit the upper frequency range to 10 MHz. Probably 2 or 3 ns resolution is more adequate. The maximal time delay of 85 ns will be adequate for these frequencies (1- 10 MHz) which corresponds to distances *D* up to 30 m. 6-7 bit delay line will be sufficient. The delay lines made from cable pieces are not needed since this is receiving array and there are no requirements for power. The LC line has upper cut-off frequency which must be taken into consideration when designing the individual elements of the line.

For fixed arrays a single fixed delay line can be used with success. The commercial inductors (chokes) can be used with Q > 20 at working frequencies. The attenuation of the line is negligible. Measured attenuation for the line shown on

Fig.14 varies from 0 to 1.2 dB for the case of maximal delay. A small Excel spreadsheet *DelayL.xls* is given [*18b*] where all parameters of the delay line can be calculated. See also *[19b]*.

5.10 How to cover 360 deg direction circle?

The 2-el. array has relatively wide front lobe in the pattern so practically direction switching with 90 deg steps is sufficient. This means that all directions can be covered with only 3 active antennas. (***Fig.22***) This is an L-shaped set of two separate 2-el. arrays at 90 deg. directions. For the loop array, the central element must have two orthogonal loops each coplanar with the corresponding second element of the array and the central active amplifier must have a switch to choose between these loops. Each array can be switched at opposite direction by changing the element which is connected to the delay line. Three active antennas can be arranged also as an equilateral triangle but the commutation is more complicated (especially for loop case) and the possibility to switch in 60 deg steps is not actually needed.

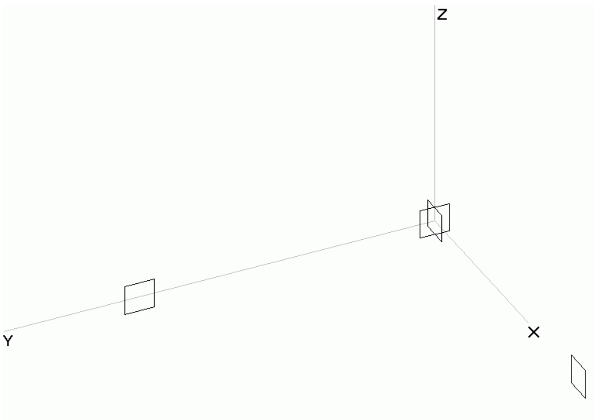


Fig.22 *4-directional array with loops*

5.11 How can I adjust the 2-el array?

For those who want to adjust and test precisely the behavior of the array, a remote TX must be placed somewhere and the described measurements to be performed – mainly F/B ratio. But it is possible to set the delay line to optimal delay according to *Eq. 5* and if the wiring and cable lengths are in order, to expect that the array will work as supposed. Local medium wave BC station can be used for tests during daytime. The most important test is to measure the signal levels from each element alone and to be sure that the difference between them is not greater then 1 -2 dB. The less is the difference the better F/B should be expected. The switching scheme must be designed in a way to allow the measurements of the level of each element alone. The simplest way is to load one arm of the combiner with its characteristic impedance as shown on ***Fig.14***.

5.12 How are the parameters of these arrays influenced when located near conducting objects etc. ?

To answer this question the results of the *Experiment 2* must be analyzed:

Fig.16 *F/B ratio.* F/B = 0 at 1.8 MHz for the case of V. dipole array with *D*=7.5 m by uknown reasons. It was not possible to find any difference between forward and backward directions. Note also the low F/B values for 7 MHz.

Fig.17 *Optimal time delays.* Again for the case V. dipole 7.5 m at 1.8 MHz there is no optimum. For 7 MHz there is substantial dispersion of the delay values both for V. dipole and V. loop arrays. Note that in the cases of *experiments #1 and #3* the optimal time delays are almost with fixed values for all frequencies and also are very close to the theoretical optimum.

Fig.18 *Signal difference between elements.* Here again there is substantial difference up to 5 dB on 7 MHz of signal levels measured for each element alone. There is clear relation between difference in signal amplitudes from each element and F/B. But the reduction of F/B might come also from phase difference (even with similar amplitudes) which probably is the case for V. dipole 7.5 m array at 1.8 MHz.

Fig.19, Fig.20, Fig.21. *Forward EH for subtractive, additive and bidirectional modes.* These figures show that the experimental results follow the prediction of the theory irrespective that the dispersion of data points is higher compared to the other two experiments.

Analysis of the environment show that one of the reasons for bad 7 MHz results is the resonance of the 20 m long elevated radial passing at 5 m distance from one of the element of the array. There is no definite explanation as to why at 1.8 MHz the V. dipole array with 7.5 m *D* has such a strange behavior (probably common mode signal leakage). Another conclusion which can be made is that the loop array is much less influenced by the environment compared to the V. dipole array. Obviously if the optimal experimental delay is substantially different from the theoretical delay there is some problem in the system and most probably there are external influences by the environment. Irrespective of the "bad" electromagnetic environment a useful array can be built even at this far from the optimal location.

5.13 Can I use phasing devices that are on the market?

There are phasers (often named noise cancellers) on the market which can change the mutual phase and gain between their two channels. The problem is that they are frequency dependant and for each new frequency the optimal phase and gain must be set again. I will suggest to set the gain of both channels to be equal and then to seek for optimal phase only with phase control. But usually the gain and phase settings are not independent and the procedure is time consuming and not very practical. These devises are usually active and some IMD problems might occur also. The advantage of the active devices is that the reduction of EH can be compensated in very closely spaced arrays. There is obviously no sense to have wideband active antennas and using frequency dependant phasing system. For phase-gain independent phaser look at [*13*]

5.14 What are the results from the "on air" tests?

Do not expect from a 2-el. array a behavior as that of a several element Yagi antenna. The on-the air F/B ratio is usually between 6 to 30 dB and floats with the fading. The high figures of F/B obtained in the experiments are only for vertically polarized signals in a strictly controlled environment. In reality the polarization of the ionosphere signals are random, there are also different reflections from close and distant objects so the F/B ratio will be lower. Higher F/B will be observed on MW and LW bands where the signals might be vertically polarized most of the time. But in any case the direction to the transmitter can be obtained easily on any frequency with a 4-directional array.

For reception of AM signals even a small difference in amplitude of the carriers is important and will boost the stronger station. The author has built an array in N or S direction with D=10m. On MW, switching to South suddenly changes the band dramatically – numerous African and Mediterranean stations appear which are normally not heard. (on MW on the same frequency there are usually several stations working simultaneously from different regions of the world).

The array is very effective to reject local noise. A noise form a high voltage line located to south direction from my house totally disappears when the array points to the North.

For the DX-ers the array is most effective in the cases where the DX station is at the noise level. Even a small improvement of S/N with 1-2 dB will make the difference between successive and failed contact.

I have tested combined loop/dipole array with 4 directions in the last CQWW SSB DX Contest (oct. 2013). The distance was D = 13 m and the same loops and dipoles setups (as described in experiments part) were used. The 4 directions were N, S, E and W. The QTH was semi urban (that described in ***Fig.15***), relatively quiet electromagnetically. During the contest I compared the array sensitivity with a long wire (L.wire) aerial, 50 m long and 15 m above the ground. Other pole of the L.wire was a counterpoise 20 m long. The L. wire was tuned to resonance by an antenna tuner.

For 160m band, the loop and dipole arrays were noise limited by the internal noise. In some cases the weakest stations received with LW were not heard with the array. But there are also weak signal cases where the station was not readable on LW antenna and quite readable in array when set to proper direction. For this very closely spaced (0.08 D/λ) array, parallel or crossed coplanar loops must be used with M factor > 0.5 [*18*] e.g. 2 crossed coplanar loops with the same diameter as the tested one will decrease the noise floor with 6 dB. The dipole array has lower noise floor but still above the atmospheric noise. The actual length of the dipole arm was only 1.5 m so obviously longer dipole arms in the array elements must be used.

For 80 and 40 m bands the noise floor was low and below the band noise. There were almost no cases where the LW was better. For weak signals the differences between dipole and loop array depend very much from the time of the day and propagation but having both modes definitely is an advantage. Probably the dipole array will be better for weak DX stations but the location was in a valley where the low elevation angles were closed by the nearby hills.

The real benefit in the contest was the attenuation of strong stations coming from the back side of the array. The improvement compared to LW was substantial. Here the loop array was very efficient to attenuate the European QRM. Quite often even strong DX stations were unreadable on L.wire due to QRM and perfectly readable with the array. The same holds true of the weak europian stations which were pushed down by the "big guns" . The loop array has 3- 4 dB better attenuation from the sides compared to the dipole array and was more useful. The F/B of the dipole array was not as good due to influence of other conducting objects as described earlier.

As a conclusion, for the stations which do not have possibility to build large directional antennas, this small spaced array will improve the reception substantially.

Sofia, November 2013

Appendix I 4-square Phased Array

Here is an example of synthesis of the popular 4-square array [4] (***Fig.23***) by means of the three basic 2-element structures –subtractive, additive and bidirectional. For simplicity we will consider an array of short active dipoles. The side of the square is *d* and the diagonal is *1.41d*. There are 2 basic directions – along the diagonal and along the quad side.

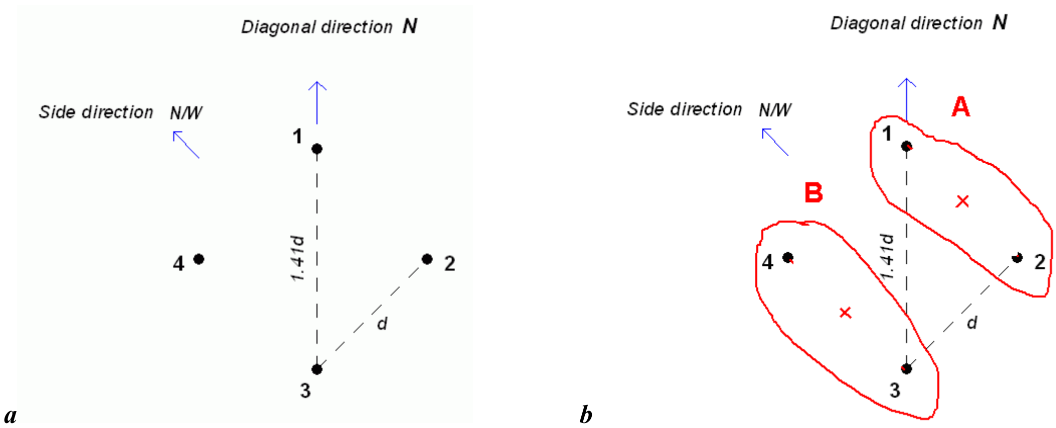


Fig.23 *4-square array*

A1. Diagonal direction mode

Let the wave come from the north (denoted as *N* on ***Fig.23***). We can form two virtual antennas named A and B as shown on ***Fig.23b.*** The wave distance between elements 1 and 2 (and 4 and 3) is $D = 0.707d$. The north wave must travel this additional distance D to reach the second element of the virtual antenna. It does not matter that the elements are shifted – for the incoming wave the time delay will be exactly half of the diagonal. Virtual antenna A will be formed as 2-elelement subtractive array with optimal delay of $\tau_d = 0.707d / c$. The same must be done with B antenna. The block diagram of the processing circuit is shown on ***Fig.24***

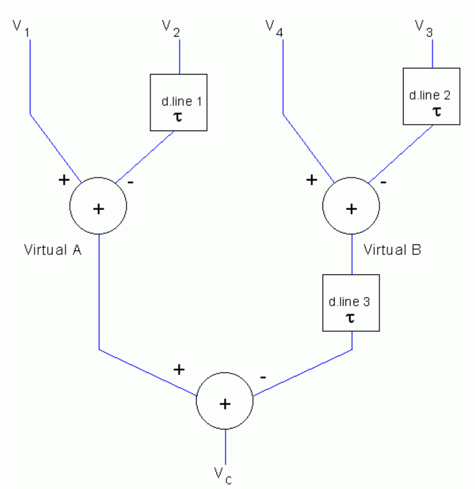


Fig.24 *Diagonal mode processing circuit for north direction. Signs in adder's inputs determine the sign of the input signal. In practical circuit if the sign is – (minus), a phase inverter must be included.*

From these two arrays we can form a third 2-element virtual array C whose two elements are A and B. For symmetry considerations the virtual centers of A and B are exactly at the middle point between their physical elements (denoted by X on ***Fig.23b***) . The time distance between these virtual elements is again $\tau_d = 0.707d / c$. The new subtractive array must be with the same optimal delay τ_d. The basic processing equation becomes :

$$V_c(t) = V_1(t) - V_2(t - \tau_d) - V_4(t - \tau_d) + V_3(t - 2\tau_d) \qquad (15)$$

where $V_i(t)$ are the voltages from the respective physical elements of the array. This equation is derived from the processing circuit by calculation of all delays in the path from each element to the output and taking into account the sign changes in the adders.

Let us calculate the forward output voltage $V_c(t)$ of this array expressed by the output voltage $V_0(t)$ of a single element of the array. The contributions of the voltages from each physical element to the output voltage $V_c(t)$ are:

$V_1 = V_0 \cos(\omega t)$ (16) *no delay*

$V_2 = -V_0 \cos\omega(t-2\tau_d)$ (17) *2 delays - from distance 0.707d and delay line 1*

$V_4 = -V_0 \cos\omega(t-2\tau_d)$ (18) *2 delays - from distance 0.707d and delay line 3*

$V_3 = V_0 \cos\omega(t-4\tau_d)$ (19) *4 delays - from distance 1.41d and delay lines 2 and 3*

And the final equation is:

$$V_c(t) = V_0 \cos(\omega t) - V_0 \cos\omega(t-2\tau_d) - V_0 \cos\omega(t-2\tau_d) + V_0 \cos\omega(t-4\tau_d) = V_C \cos(\omega t - \psi) \quad (20)$$

In order to calculate the output amplitude V_C we have to calculate the module of the *Eq.20* in a similar way as in *Eq. 9* . We can also substitute everywhere *V* with effective height *h* as in *Eq. 14* . The final result is shown graphically on ***Fig.28*** as a function of D/λ.

Similary we can calculate the backward output voltage for the wave coming from the south which is:

$V_1 = V_0 \cos\omega(t-2\tau_d)$ (21) *2 delays - from distance 1.41d*

$V_2 = -V_0 \cos\omega(t-2\tau_d)$ (22) *2 delays - from distance 0.707d and delay line 1*

$V_4 = -V_0 \cos\omega(t-2\tau_d)$ (23) *2 delays - from distance 0.707d and delay line 3*

$V_3 = V_0 \cos\omega(t-2\tau_d)$ (24) *2 delays - from delay lines 2 and 3*

$$V_c(t) = V_0 \cos\omega(t-2\tau_d) - V_0 \cos\omega(t-2\tau_d) - V_0 \cos\omega(t-2\tau_d) + V_0 \cos\omega(t-2\tau_d) = 0 \quad (25)$$

$V_c(t) = 0$ and does not depend on the frequency.

A.2 Side direction mode

Let the wave come from the north-west (denoted as *N/W* on ***Fig.23***). We can form again the same virtual antennas A and B. The wave distance between elements 1 and 2 and respectively 4 and 3 is now $D = d$. Virtual antenna A will be formed as 2-elelement subtractive array with optimal delay of $\tau_d = d / c$. The same procedure is for B antenna. From these two arrays we can form a third 2-element virtual array C whose two elements are A and B, but this time the only thing we can do is to add them using the additive mode. There is no time delay between virtual elements A and B for the wave coming from the NW direction so it is not possible to use the subtractive mode. The block diagram of the processing circuit is shown on ***Fig.25.*** The basic processing equation is:

$$V_c(t) = V_1(t) + V_4(t) - V_2(t-\tau_d) - V_3(t-\tau_d) \quad (26)$$

The forward output voltage is:

$$V_c(t) = 2V_0 \cos(\omega t) - 2V_0 \cos\omega(t-2\tau_d) = V_C \cos(\omega t - \psi) \quad (27)$$

The final result is shown graphically on ***Fig.28*** again as a function of D/λ. We can calculate in a similar way the backward output voltage for the wave coming from south-east an it will be 0 for all frequencies.

The radiation patterns of the 4-square array in all modes are given on the next figures (***Fig .26, 27***)

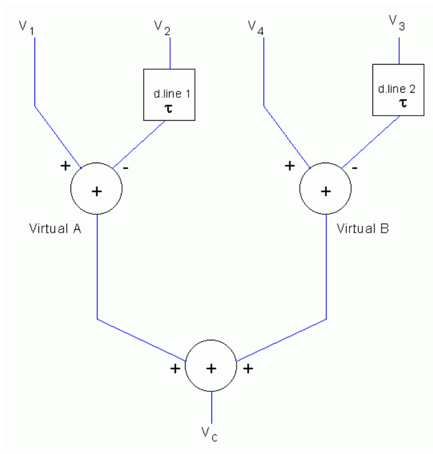
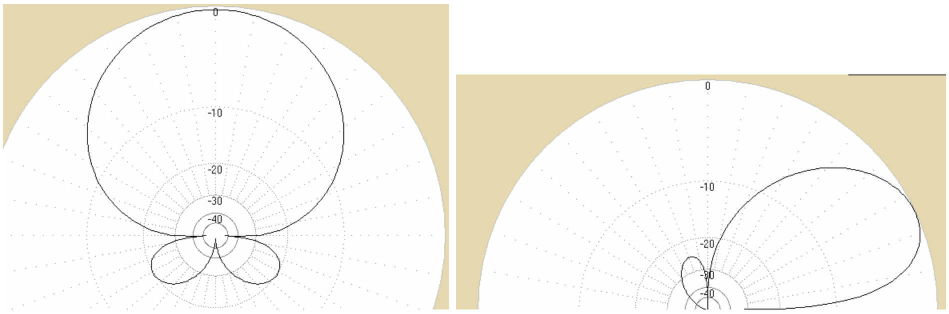
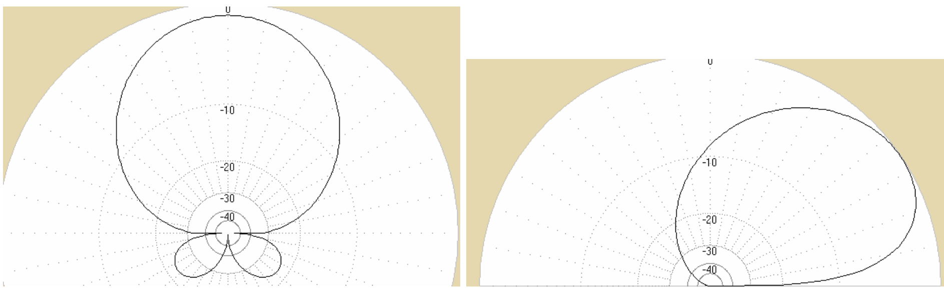


Fig.25 *Side mode processing circuit for the north-west direction. Signs in adder inputs determine the sign of the input signal. In the practical circuit if the sign is – (minus), a phase inverter must be included.*

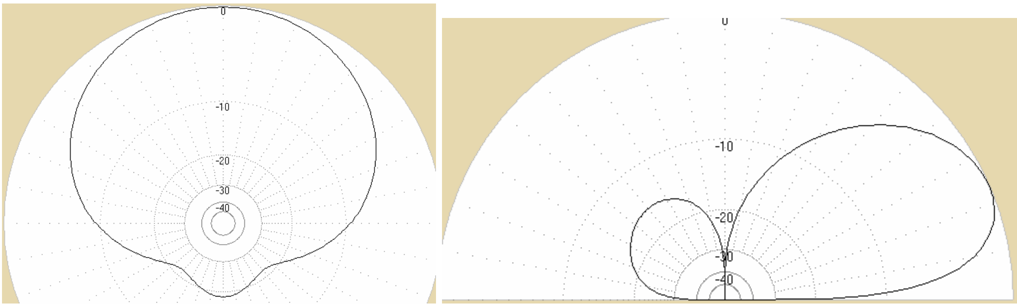


Dipole array

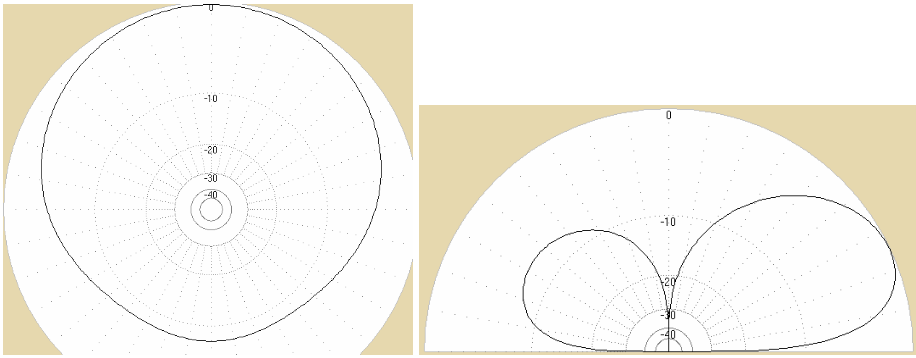


Loop array

Fig.26 *Radiation patterns of a 4-square array in diagonal direction mode. The horizontal plane is at section at* 20^{O} *elevation angle. Real ground setup ε=13, S=5. MININEC core. D/ λ = 0.1*



D/λ = 0.3



D/λ = 0.4

Fig. 26a *Degradation of the 4-square (dipoles case) pattern when D/λ increases. D is equal to the half of the square diagonal.* τ_d *= D/c and processing equation is Eq. (15). The horizontal plane is at section at 20*^{O} *elevation angle. Real ground setup ε=13, S=5. MININEC core.*

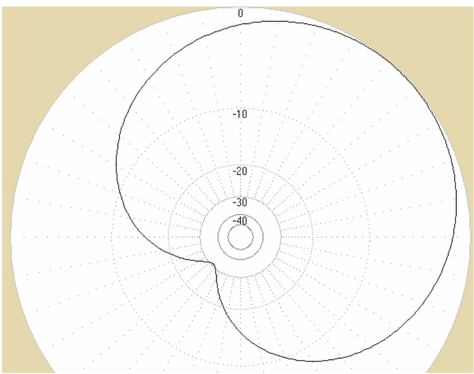


Fig.27 *Dipole array. Radiation patterns of a 4-square array in side direction mode. The horizontal plane is at section at 20*^{O} *elevation angle. Real ground setup ε=13, S=5. MININEC core. D/λ = 0.1*

The radiation pattern of a diagonal mode is quite narrow and what is more, there are nulls at 90^{o} from the main lobe. The loop pattern compared to the dipole is sharper due to the radiation pattern of the single loop. This follows from the so called "multiplication principle" [*1*] which roughly states that the final pattern of an array is equal to the multiplied patterns of the virtual isotropic elements into which it can be divided.

For the dipole array (diagonal mode) we have:

*circular diagram of vertical dipole * 2-el. subtractive array * 2-el. subtractive array*

For the loop array (diagonal mode):

*figure 8 diagram of vertical loop * 2-el. subtractive array * 2-el. subtractive array*

For the dipole array (side mode)

*circular diagram of vertical dipole * 2-el. subtractive array * 2-el. additive array*

The additive array has an almost circular pattern (***Fig.7***). This is the reason for the broader radiation pattern in side direction mode ; the pattern shape is nearly the same as that of a 2-element subtractive array.

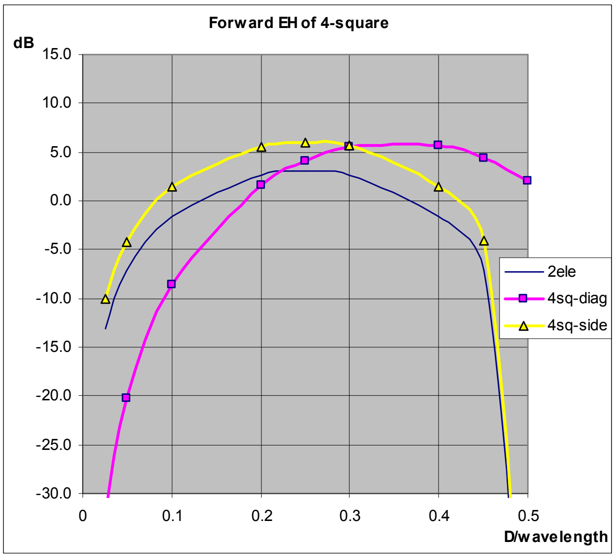


Fig.28 *Forward EH of 4-square array compared to EH of a single element. The EH of 2-element subtractive array is included for comparison. The attenuation of the processing circuit with T-combiners is included (-3dB for 2-element array and -6 dB for 4-square array). D is the side of the square (for 4-square, both modes) or the distance between elements in 2-el. array.*

A.3 Practical processing circuits

Looking at *Eq.15* we can simplify the processing circuit taking into account that the voltages from elements #2 and #4 are delayed with the same delay τ_d and we can add them before the delay line thus using only one delay line. (It does not matter whether we add and delay or delay and add.) The *Eq.15* might be rewritten as:

$$V_c = (V_1(t) + V_3(t-2\tau_d)) - (V_2(t-\tau_d) + V_4(t-\tau_d)) \qquad (28)$$

The corresponding processing circuit is shown on ***Fig.29*** along with direction switching. Now only 2 delay lines must be used with delays τ_d and $2\tau_d$. There must be an input matrix with several relays which can control all 4 directions. This circuit is known – refer to *[19a]*.

A practical processing circuit for the side mode is shown on ***Fig.30***. It is derived in the same way as the previous one and uses only one delay line.

T-combiners can be used as adders but it must be clear that each combiner has 3 dB attenuation so the output voltage from the processing circuit will be less than that given by *Eq.(20, 27)*. The total attenuation of this processing circuit is 6 dB since the signal from each antenna passes through two combiners. This is power attenuation since the input and output impedances of the processing circuit are different.

In order to have 8 directions these two processing circuits must be combined. This is possible but the switching scheme becomes more complicated and we will need 3 delay lines (τ_d in diagonal mode is different form τ_d in side mode!). It is simpler to switch the diagonal mode as a 2-el. array . This will broaden the pattern and side directions will be heard almost without attenuation.

As can be seen from ***Fig.28*** the EH of 4-square drops much more rapidly compared to 2-el. array. In order to build a very closely spaced 4-square array we must use individual elements with higher EH in order to avoid limitation of the noise floor by the internal noise of the active elements.

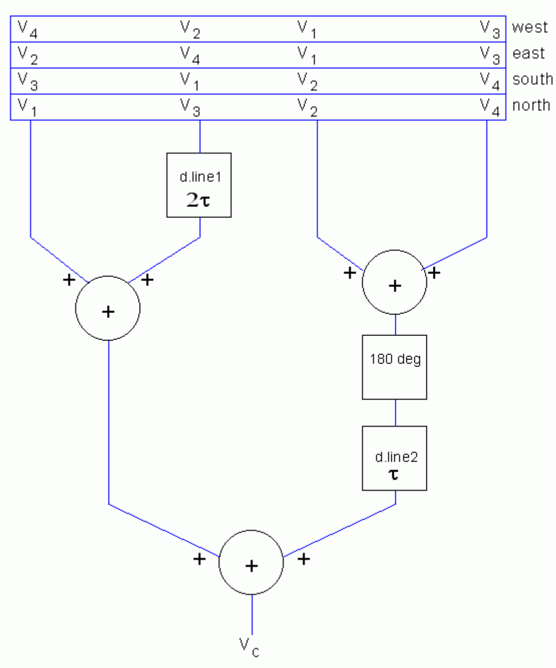


Fig.29 *Diagonal mode. Practical processing circuit with 2 delay lines. The directions switching is performed by changing the input signals as shown in the upper table. The directions and element enumeration correspond to those given on **Fig.23**. All adders are with + sign and simple T-combiners can be used . Note that after each combiner the characteristic impedance is halved and the delay line must be calculated according to the new impedance.*

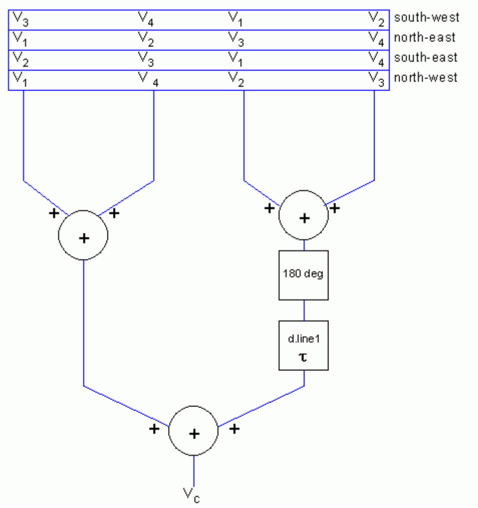


Fig.30 *Side mode. Practical processing circuit with one delay line and direction switching. All adders are with + sign and simple T-combiners can be used . Note that* τ_d *in diagonal mode is different form* τ_d *in side mode.*

Links

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[2] Feynman R, Leighton R, and Sands M. The Feynman Lectures on Physics . 3 volumes, Ch. 28, 1964, 1966.
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[11] Mark Connelly, WA1ION, Phased Spaced Active Whips and Broadband Loops,– 30 JUL 2002
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[17] Chavdar Levkov LZ1AQ, Wideband Active Small Magnetic Loop Antenna, 2011,
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[18b] Chavdar Levkov LZ1AQ, Excel spreadsheet DelayL.xls, in Download part of www.lz1aq.signacor.com
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[19b] Rick Karlquist N6RK, How to Design LC Lumped Eelement Delay Networks,
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v.1.1 20.11.2013 Initial submission
v. 1.2, 1.3 4.12.2013 Minor corrections and typos.
v. 1.4 20.12.2013 Added additional links [19a, 19b].