Antenna simulations with 4NEC2 including an application example for 2300MHz

Presentation made by Gunthard Kraus, DG8GB, at The Radio Amateur Meeting at Munich 10/3/2018

1. Simulation of wire antennas with NEC

NEC (Numerical Electric Code) is a simulation method for wire antennas developed by the Lawrence Livermore Laboratory in 1981 for the Navy. The antenna is split up into very short pieces called "segments" where the current and the voltage change linearly (almost). Then the behaviour of each segment is calculated and at the end everything is summed up (integrated). This makes amazingly accurate simulations possible. The standard is NEC2 - there are many software applications, even free ones. Of course, development has continued and the weaknesses of NEC2 (e.g. wrong calculation of structures that are very close, closely spaced parallel wires or buried wires) were ironed out first with NEC4, but:

NEC4 was blocked from export for a long time and was considered secret. Today, it is available outside the USA but quite expensive ($500).

NEC2 could be downloaded from The Internet, but that's not enough. It is the pure "calculator" that was originally written in Fortran that is also available as a compiled engine program. As a result, many people have designed extensive user interfaces and marketed them as Windows programs - partly for free, partly for reasonable prices. The best by a big margin is "4NEC2" because it is supplied with so many additional programs that give possibilities that you can only dream about. Plus it's free. Therefore praise and thanks to the author Arie Voors!

2. Proper use of 4NEC2

It is important to follow the rules of the game for a successful simulation. Namely, NEC works according to the "moments method" where the antenna structure consists of wires and each wire is subdivided into segments. You must not violate the following rules:

The length of each segment must be between 5% and 10% of the wavelength.

You must carefully consider the wire gauge otherwise it will cause problems. The decisive factor is the ratio of segment length to wire radius:

If this **ratio is greater than 8** then the normal computer program called **"Thin Wire Kernel"** is sufficient. It simulates the current flow in the wire as a very thin current thread.

If the **ratio is between 2 and 8** the **"Extended Thin Wire Kernel"** must be called up using the **"EK"** card in the NEC file. The current is evenly distributed on the circumference of the wire and this considerably increases the accuracy of the result.

For a **ratio below 2** the computational accuracy drops very quickly but still remains tolerable using EK down to a value of 0.5.

4NEC2 can be downloaded from The Internet then unpacked and installed. **Always download NEC-2/MP.** The suffix "MP" means **"Multiprocessing"**, the revised "exe" files that this version contains give significantly higher computing speed and thus a reduced waiting time for the result. The download comes from:

http://www.ok1rr.com/files/NEC2MP.ZIP

The "MP" files are included in the 4NEC2 package and are automatically included during installation.

2.1. Creating an NEC file for a 2375MHz dipole

There are several possibilities and they hide behind "Settings" in the 4NEC2 Menu. They are one after the other:

Notepad Editor / NEC Editor / Geometry Edit / NEC Editor (new)

Nothing beats the **Notepad editor under Windows,** because it allows the fastest possible introduction and testing of changes and enhancements. However, never forget to set the finished file type to **"All Files"** and then add the file extension **"* .NEC"** .....

The principle used by NEC for its input files is: they are a sequence of instructions called **"Cards"**. This is because the data was originally held on IBM punched cards using their storage system (rows and columns), this is still used today.

CM	(Comment)
'	use an apostrophe to enter a comment line if necessary
CE	(Comment End)
SY	(Symbols, to be followed by declarations for variables defining the different factors used, physical quantities or calculation equations)
GW	(Geometry of wire, the definition of wires with all the necessary details)
GM	(Geometry Move, used to rotate, move or copy the generated structure or parts from that structure)
GE	(Geometry End, end of the structure input). Additional input of the ground type is possible)
LD	(Load , used to build in additional components such as R, L, C for certain segments)
FR	(Frequency, definition of the frequency or the sweep range)
EK	(Extended kernel, used to call the additional program for the correct simulation of thin wires)
EX	(Excitation, excitation of the structure by supplying drive)
EN	(End, file of end)

We now want to take a closer look at the details of the NEC file for a half wave dipole.

Please note:

All length or diameter data are ALWAYS in the unit "metre"! The real NEC file is shown below. The red text is for explanations - they are only allowed here in the lecture!

As a precaution empty commentary lines (using an apostrophe) should be used between the individual cards.

CM Half Wave Dipole	Comment
CE	Comment end
'	
SY freq=2375	It should work at the frequency f = 2375MHz
SY dipolarm=300/freq/4	Each dipole arm has the length "quarter wavelength" at 2375MHz. You can easily go to a different frequency!
SY dr=0.002/2	The radius of the antenna wire is 1mm
GW 1 9 0 -dipolar 0 0 dipolar 0 dr	Now we have to use the dipole as wire define. It works like this:

1 = The wire represents "tag 1" (object 1)

9 = It is divided into 9 segments

0 -dipolarm 0 = xyz coordinates of the wire start

0 dipolar = 0 = xyz coordinates of the wire end

dr = Finally, the wire radius

'

GE	Geometry End = End of structure definition
FR 0 1 0 0 freq 0	programming the sweep frequency range

Note:

0 = linear sweep

1 = number of frequency steps (only one frequency here)

0 = both following places on the map must be empty

0

freq = start frequency

0 = step size, i.e. the width of the frequency step

'

EK	Extended kernel, the additional program for thin wires is activated
'	
EX 0 1 5 0 1 0	Excitation or supply drive.

Note:

0 = excitation by voltage source (current source would be "6")

1 = excite tag 1 …

5 = ... in segment 5

0 = empty space on the map

1 = excitation by a real voltage of 1 volt

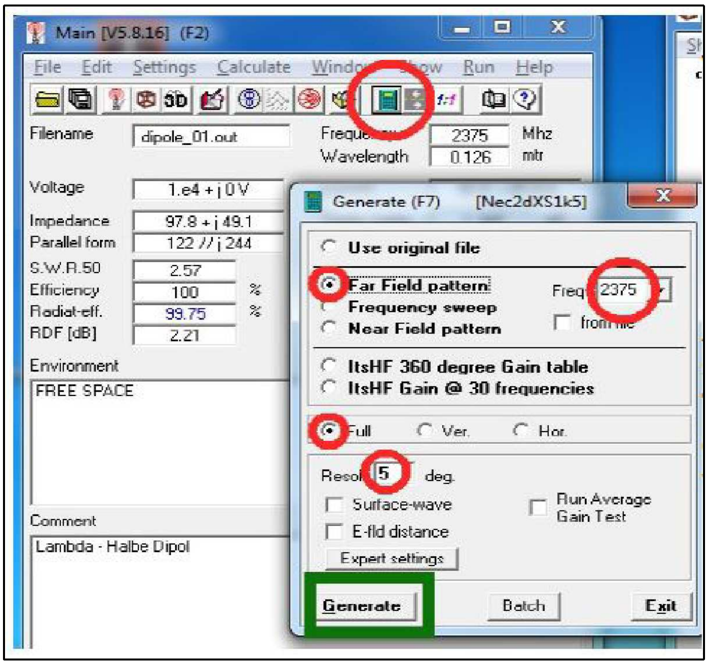
0 = no imaginary voltage component

'

EN	End of the NEC file

Once this NEC file has been completed and saved all you need to do is start the 4NEC2 software and start the "File" then "Open 4NEC2 in/out file" to call up the created file.

2.2. Simulation and optimisation of dipole properties



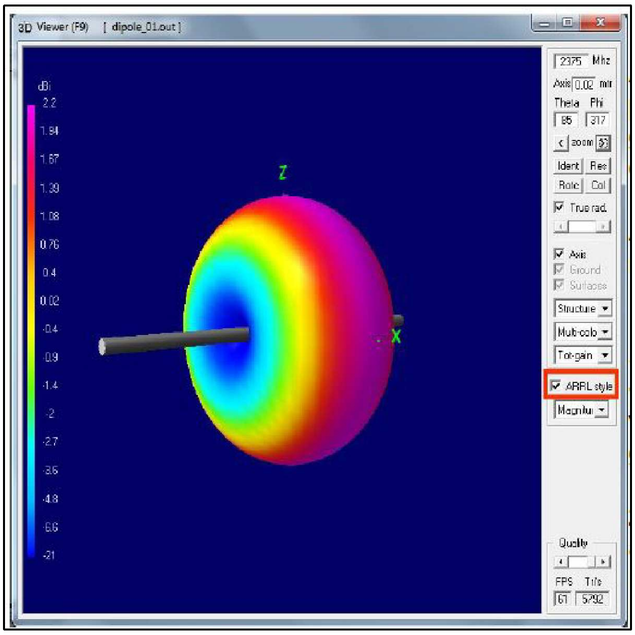
To do this, click on the symbol of the calculator, select "Farfield" and check the settings:

Frequency = 2375MHz

Full

Resolution = 5 degrees

Clicking on **"Generate"** starts the calculation and output of the directional diagrams required. But you should give yourself a treat and press the **F9 key.** A 3D representation of the antenna structure appears (assuming that "DirectX" is installed on the computer and the computer hardware can handle it ... my own bitter experience with an older notebook). The result is a nice 3D representation of the dipole. It can be rotated and swung around by "dragging with the mouse", its size can be changed via the zoom buttons. In the submenu under "hide pattern" there is an option **"multi-color"**, clicking this shows this picture on the screen.



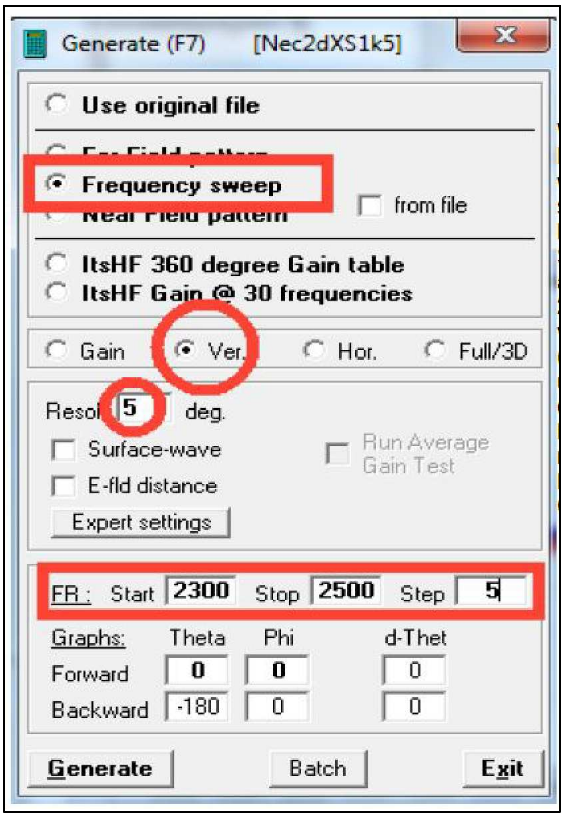
The size of the radiation pattern can be adjusted with the zoom buttons and the gain values in **"dBi"** are shown by the coloured scale on the left.

However, there is a very important remark necessary:

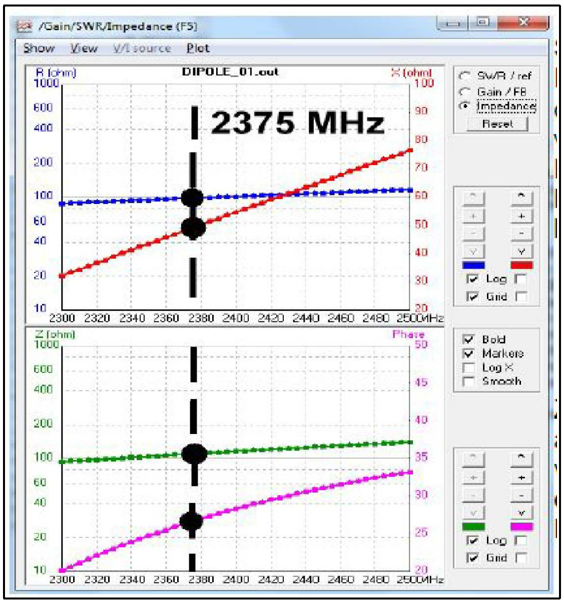
At the bottom right there is a check box named **"ARRL"**. This works with a completely different logarithmic scale where the **range from +2.15dBi to -4.7dBi is shown greatly stretched,** while it goes down from -4.7dBi with a step equal to -21dBi.

This has its advantages if one still wants to recognise the absolute minimum, but places the greater value on a good resolution, if it goes in the direction of maximum.

You only need to remove the checkmark at "ARRL" to see the difference. This shows a correct (dB-linear) coloured dBi scale and the stretching near the maximum disappears. You have to try and then decide for yourself what is more practical ....

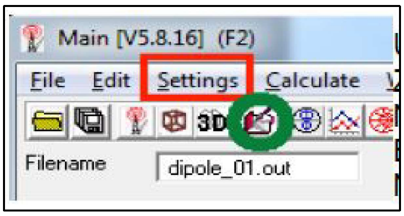


Anyone interested in the input impedance characteristics should choose the "calculator button" and then switch to **"Frequency sweep".** Do not forget to specify the sweep range and the step size. A range from **2300 to 2500MHz** was selected with a **step size of 5MHz.** The other basic settings (e.g. angle resolution = 5 degrees) remain unchanged, but **the program automatically switches to "vertical".** The calculation now takes less time than it takes to select the result under the **representation of SWR, reflection factor, gain or impedance.**



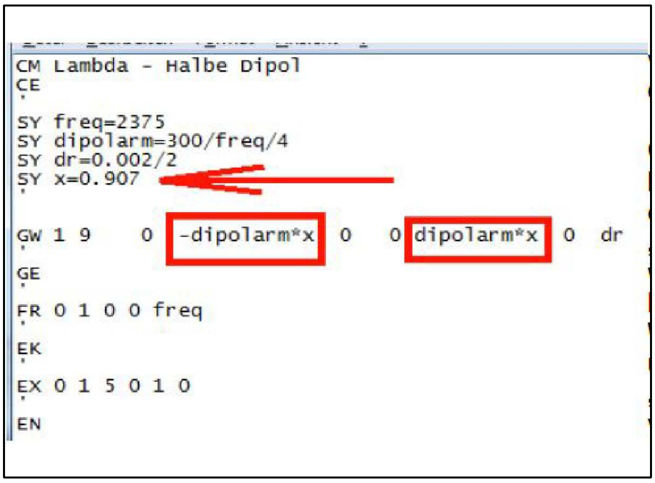
Let's take a closer look at the input impedance curve. That's when we realise that the antenna has a proper "Open End Extension" like the open end of a microstrip line. **A repetition of the sweep for 2100 to 2200MHz shows us that the resonance frequency has dropped to 2160MHz!**

A **shortening factor "x"** for correction is provided as a new symbol for the dipole arm lengths in the NEC file to adjust the value. With x = 0.907 you get **exactly the desired resonance frequency of 2375MHz.**



It works like this:

First, we call up the settings (red frame) and select the Notepad editor (first option). A click on the editor button (green circle) then opens the NEC input file used. The correction factor is inserted as an additional symbol "x". The y-coordinates of the two wires are then multiplied by this factor.



VERY IMPORTANT:

After opening the file menu in the upper left corner of the editor, select "save". This closes the menu again. But we open it again and click on "Exit".

Those who do not do this are unlikely to be in trouble because without "quitting" the results of the previous action will not be erased but only the simulation results of our change will be written. This gives incredibly confusing results (from my own experiences causing several hours of troubleshooting)!

Note:

There are three more editor options under **"Settings"**. You should check these out occasionally. In some cases, it is advantageous to use the **second option under "Settings"**, namely "NEC Editor ". It presents the NEC file in the same form as Notepad but provides all the details of a selected line (card / tag / segment / coordinates, etc.) in the form of an additional overview. Now you no longer have to look in the NEC manual to find out what a particular value means and the part in question will be highlighted in extra green in the geometry display.

Also the fourth editorial version **"NEC Editor (new)"** is often very helpful. Here everything is shown in tabular form, the entered values can be changed easily and new tags added.

The **third possibility ("Geometry Editor", keys <Ctrl> + <F3>)** opens a graphical representation of the object being examined and when a wire of the antenna is clicked an incredible amount of details is shown. It's almost too much and it's much better to **just press <F3>.** This opens the presentation "Geometry" that shows the same representation, you can then **show the wire or tag numbers or the individual segments** under "Show". This is sufficient in most cases and is much clearer

3. Simulation of a transmission path

3.1. A second antenna is needed

NEC can also perform simulations in the far field and that can be used to examine the exact characteristics of other simulated antennas. **Simply arrange a "measuring dipole" at a sufficient distance and turn it to taste and determine the current flowing in its 50Ω termination resistor.**

So in our NEC file "dipole_01.nec" we add an identical dipole (by copying the original antenna) at a distance of **x = 2 metres.** This corresponds to 16 wavelengths and thus safe operation in the far field. In addition we add a 50Ω resistor in the middle of this receiving dipole. Then the new NEC file will take the following form.

CM Half Wave Dipole

CE

'

SY freq = 2375

SY dipolarm = 300/freq /4

SY dr = 0.002/2

SY x = 0.907

'

GW 1 9 0-dipole arm * x 0 0 dipole arm * x 0 dr

GM 10 1 0 0 0 2 0 0 1

'

GE

'

LD 0 11 5 5 50

FR 0 1 0 0 freq

'

EK

'

EX 0 1 5 0 1 0

'

EN

Let's take a closer look at the first red line, because that gives the second antenna:

GM	**Geometry move,** this creates a copy
10	Tag increment. Thus this antenna is managed as **"tag 10 + 1 = tag 11"**
1	we just want to make **a copy**
0 0 0	do not provide rotation about any axis
2 0 0	move the copy **2 metres in the X direction**
1	start the copying process from **tag 1** (original antenna)

And with the second red line we add a 50Ω load resistor in the middle of the new receiving antenna:

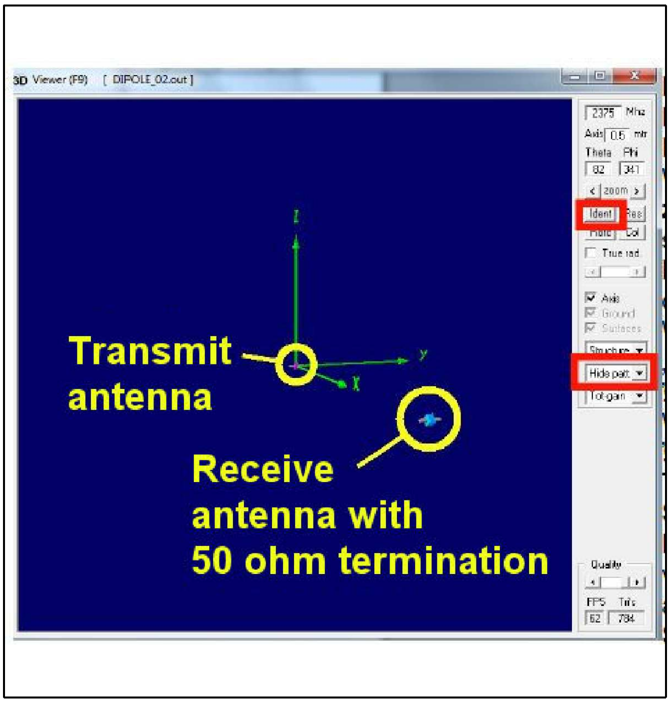
LD	**Load card.** So we can add components
0	we want to insert an RLC array
11	insert in the wire of the new antenna, the **tag 11** (10 +1) is called
5 5	insert between start and end of **segment 5** (wire centre)
50	is inserted a 50Ω resistor .. L and C would follow but both have the value zero

Finally, we go to "Settings" in the main menu and open **"Input Power".** There we enter a transmission power of **1 Megawatt** (1000000 = 1e6), so that even for larger distances something happens and we are therefore ready for further action.

Please enter the changes in the NEC file and finish again with the "two-step procedure".

(Order: Change / Save / Close / Open again / Click "Finish")

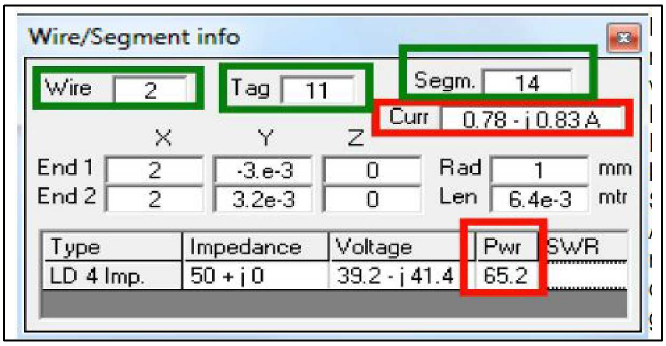
3.2. The result of the far field simulation



The simulation is done using exactly the same procedure as in chapter 2.2 but the 3D representation via the F9 key is very helpful here.

If **"hide pattern"** is active and we zoom carefully then we have this picture in front of us. In it we see the transmitter antenna with a purple band that marks the feed. The receiving antenna has a light blue cube in the middle segment which represents the "load", i.e. the 50Ω load resistor.

We are interested in the reception performance in the 50Ω resistor and therefore double click on the **"Ident"** button. We can enter the desired segment, which is **number "14".** This is easy to understand because all the segments are listed in order and each antenna consists of 9 segments. So we find the centre of the receiving antenna at "9 + 5 = 14".



Here we see the result and we find in addition to all other data a receive power of 65 watts and a current of 0.78 -j0.83 A. Now we can check whether we are really in the Far Field and whether 4NEC2 calculated the conditions correctly. To do this, repeat the simulation several times and double the distance between the two antennas (enter 4m / 8m / 16m, etc. at X). This is very easy because we only need to change one line in the NEC file with the editor. Change the value of X marked in red then save, restart, click on "Finish" and then simulate. Now you can see the current in segment 14:

GM 10 1 0 0 0 2 0 0 1

The results are:

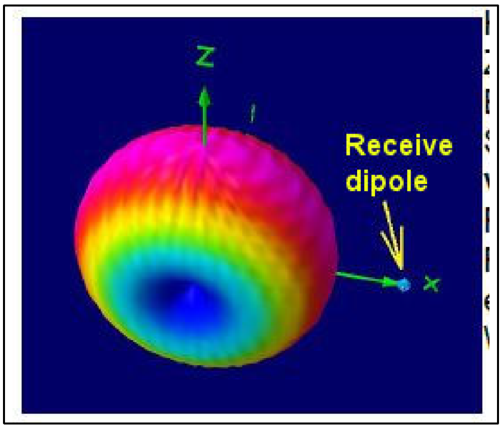
for 2m:	**I = 0.78 - j0.83**	**(P = 65.2 W)**
for 4m:	**I = 0.4 + j0.1**	**(P = 16.3 W)**
for 8m:	**I = -0.2 + j0.24**	**(P = 4.03 W)**
for 16m:	**I = 0.14 -j0.03**	**(P = 1.02W)**

It can be seen that the field strengths and the real current components decrease approximately linearly with increasing distance and thus the power drops quadratically. This is exactly the theory and strengthens the confidence in the program but .....

Another test is interesting: if you make a rotation of 90 degrees around the X axis (=its polarisation changes from horizontal to vertical) The received power should decrease to zero. So you go back to the NEC file and provide a corresponding rotation around the X axis on the GM card (with the saving procedure described):

GM 10 1 90 0 0 2 0 0 1

The simulation confirms that very nicely.

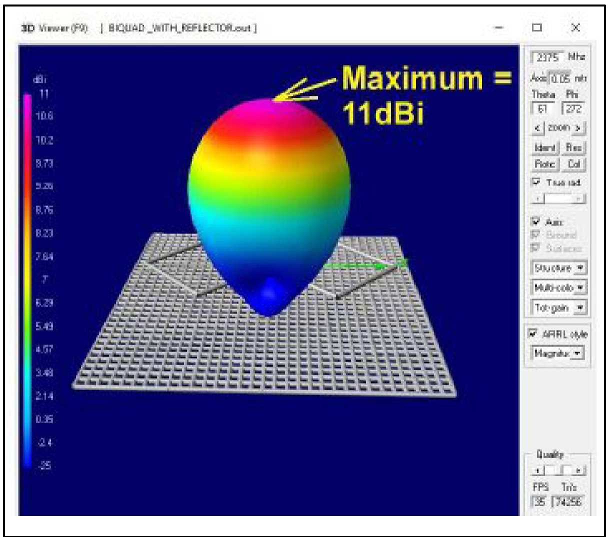


Note:

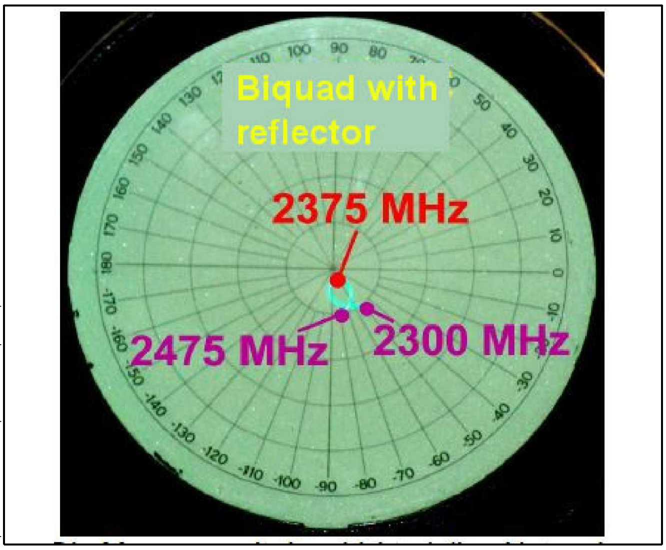
To the rule "Measurement only in the far field" you should also look at this picture. For this purpose, the distance betw-een the receiving antenna and the transmitting antenna has been reduced from **2m (16 wavelengths) to 1m (8 wavelen-gths)** and it can be seen that the second antenna causes distinct repercussions. This results is a clear "ripple" of the directional diagram of the transmitting antenna. At 2m dista-nce that is tolerable but it gets really good only at much larger distances. Who would have thought that....?

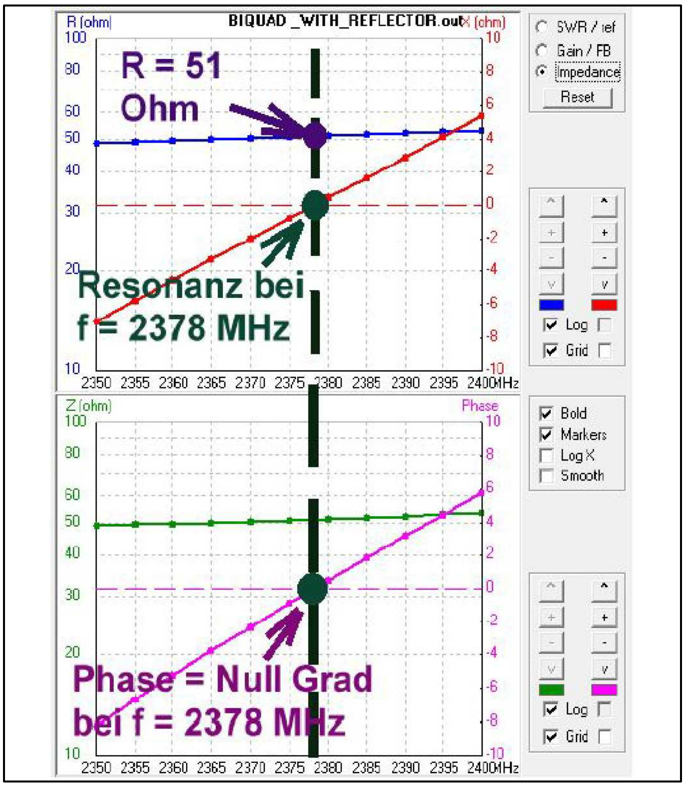
4. An example for the advanced: A biquad antenna for 2375MHz

This is what the radiation pattern for 2375MHz looks like ...



a n d t h e i n



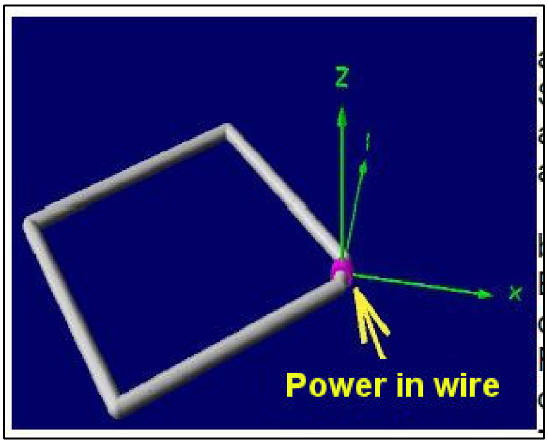


and the input impedance ...

The measurement with a Vector Network Analyser confirms that these are correct.

4.1. The antenna design

We start with a simple quad antenna and put it together from 5 wires:



a) A 4mm long piece of 2mm diameter wire for feeding the antenna (feed). It is arranged in the direction of the y-axis, starts at "-2mm" and ends at "+2mm". It consists of only one segment.

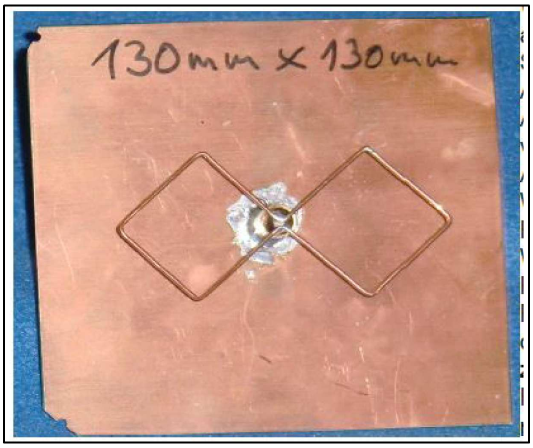
b) Add 4 wires (length = $\lambda/4$ and 8 segments each) to form the square. By default we connect one wire end to the beginning of the next wire and start at "+2mm", i.e. at the end of the feed. The wires form a square ending at "-2mm" i.e. at the beginning of the feed. The picture shows the arrangement and the associated NEC file is now easy to understand:

```
CM Quad 2375 MHz
CE
SY FREQ = 2375
SY dr = 0.002/2                'Radius of the copper wire = 1mm
SY x = 300/freq /4*sin (45)
'Spotlight
GW 1 1 0 -0.002 0 0 0.002 0 dr        Feed
GW 2 8 0 0.002 –x x 0 dr              Four wire pieces form a square
GW 3 8 –x x 0 -2*x 0 0 dr             ...
GW 4 8 -2*x 0 0 –x –x 0 de            ...
GW 5 8 –x –x 0 0 -0.002 0 dr                    ...
GE 0                                  “Zero” means “Free Space”
EK
EX 0 1 1 0 1 0
FR 0 1 0 0 FREQ
EN
```

Then we simply copy this quad structure, rotating it by 180 degrees around the Y axis. This is done by the red line added after the "GW" cards:

```
'Spotlight
GW 1 1 0 -0.002 0 0 0.002 0 dr
GW 2 8 0 0.002 –x x 0 dr
GW 3 8 –x x 0 -2*x 0 0 dr
GW 4 8 -2*x 0 0 –x –x 0 de
GW 5 8 –x –x 0 0 -0.002 0 dr
GM 4 1 0 180 0 0 0 0 2
GE 0
```

We have finished our Biquad, it is just missing the reflector.



We assume a symmetrical operation of the antenna and in practice the balancing is done by a $\lambda/4$ balun. It consists of a 10mm outside diameter brass tube with an 8.3mm inner diameter from the hardware store. The inner conductor is the copper sheath of the 3.55mm outside diameter semi-rigid cable used as the balun. So you get a line with a characteristic resistance of almost exactly 50Ω. A tube length of 31.7mm corresponds to a quarter wavelength. A copper disc is then slipped over the semi-rigid cable and soldered to both the end of the tube and the cable sheath. This is the short at the end of the balun! The theory also says that the distance between the antenna and the reflector must be about λ/8 = 16mm. The tube is soldered into a piece of double sided printed circuit board serving as a reflector to give that spacing.

4.2. The Reflector Design

There we can choose between two options:

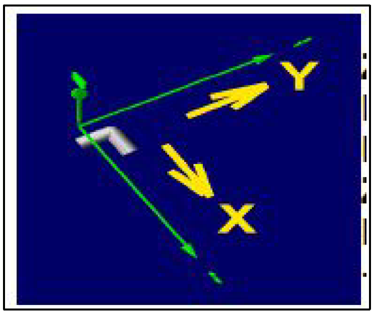
a) We work with the **4NEC2 “build” plugin** provided and create a **"Patch" 128mm x 128mm.** "Patch" is part of "build" and the design is a breeze. However, each wire is listed with its data in the resulting NEC file producing over 2000 wires on many pages of generated code.

b) You start with a very simple structure of only **two wires and use skilful multiple copying** until finally the reflector (with small compromises) is finished. But just 5 more lines of code in the NEC file are sufficient - but they have it all and require effort in the design or troubleshooting. But shorter and shorter is not possible ...

Using the option b) because it represents the smallest NEC file by an expert (Hardy Lau, DL1GLH)!

```
CM Biquad 2375MHz with reflector
CE
SY FREQ = 2375
SY dr = 0.002/2                      'radius of the copper wire = 1 mm
SY x = 300/freq/4*sin(45)*0.9928     'λ/4 - element with correction factor
SY rh = 0.016                        'Distance reflector-dipole = 16mm
'Spotlight
GW 1 1 0 -0.002 0 0 0.002 0 dr
GW 2 8 0 0.002 0 -x x 0 dr
GW 3 8 -x x 0 -2 * x 0 0 dr
GW 4 8 -2 * x 0 0 -x -x 0 dr
GW 5 8 -x -x 0 0 -0.002 0 dr
GM 4 1 0 0 180 0 0 0 2
'Reflector
GW 10 1 0 0 -rh 0 0.004 -rh dr              A
GW 11 1 0 0.004 -rh 0.004 0.004 -rh dr      B
GM 2 15 0 0 0 0 0.004 0 10                  C
GM 40 15 0 0 0 0.004 0 0 10                 D
GM 700 3 0 0 90 0 0 0 10                    E
GE
EK
EX 0 1 1 0 1 0
FR 0 1 0 0 FREQ
EN
```

Let's take a close look at the reflector design:

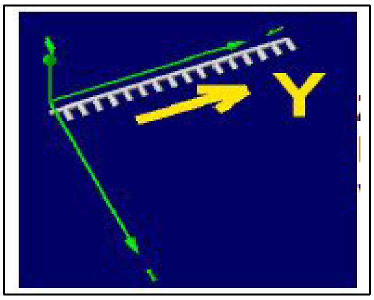


Line A:

This defines a 2mm diameter wire from y = zero mm to y = +4mm. It runs in the planes x = zero and z = -16mm

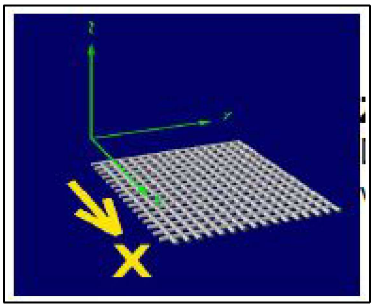
Line B:

A second wire starts (at the same z height) at x = 0 / y = +4mm and leads to x = +4mm / y = +4mm. It is therefore perpendicular to the wire of line "A".



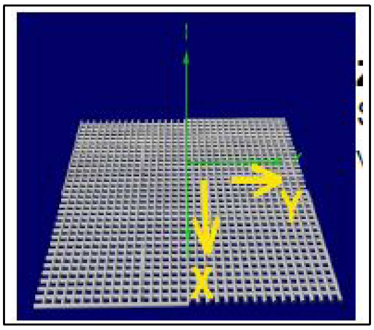
Line C:

This structure is copied 15x and shifted by 4mm in the Y direction at each copy step



Line D:

The result of "C" is again copied 15x but each copy is shifted 4mm in the X direction



Line E:

Finally, another 3 copies follow; each rotated 90 degrees around the Z axis. That's it!