Gunthard Kraus, DG8GB

An interesting program: Simulation and construction of a Helix antenna for 2.45GHz using 4NEC2

This article represents the revised and extended version of a lecture at the UKW conference 2010 in Bensheim. The article shows how a Helix antenna can be sketched with the 4NEC2 software. Followed by the construction of a sample antenna, measuring its characteristics and comparison with the simulation.

1.0

Simulation of wire antennas with NEC

NEC (Numerical Electric Code) was developed in 1981 by the Lawrence Livermore laboratory for the American Navy as a simulation method for wire antennas. The antenna is divided into very short pieces (segments) where the current and voltage change is almost linear. Amazingly accurate simulations can be accomplished, but naturally there are limits. Interestingly enough, a lower and an upper limit where the simulation becomes ever more inaccurate.

The lower frequency limit is defined by the recommendation that there are approximately 10 to 20 segments per wavelength but never more than 50 segments. If very low frequencies are used (e.g. below 1MHz) the wavelength rises to 300m and a segment becomes at least 6m long. The program cannot react to any more refinements of the environment (it applies the rule of linear current on the smallest segment) and the simulation quickly becomes senseless.

With high and very high frequencies the concept of an infinitely thin antenna wire does not work in the simulation any more. A supplementary product for thicker wires, the Extended thin wire kernel can be used but as soon as the relationship between of the segment length to wire radius falls below 2.5, the program ends with an error message with wild warnings to the user about this problem

NEC2 is the standard free application software. Development has continued and the weaknesses of NEC2 (e.g. incorrect computation of structures that cross very closely or wires buried in soil) were only corrected with NEC4. NEC4 was restricted for a long time and was considered as secret. Today it is also available outside of the USA, but quite expensive (normally around the $2000).

NEC2 can be downloaded from the Internet, but nothing can be done immediately. It is a pure calculating machine that was originally written in FORTRAN and available as a compiled coded program. Therefore many people added extensive

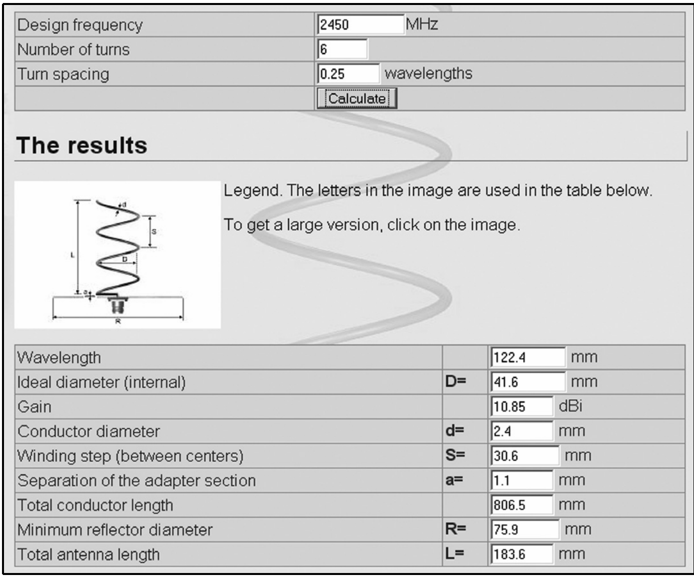

Fig 1: An online calculator like this makes the determination of the mechanical antenna data child's play.

operator interfaces and marketed these as Windows programs - some free of charge and some with substantial prices. 4NEC2 stands out by a long way because it is equipped with as many supplementary product features and facilities that it is astonishing that it is free. Therefore praise and thanks to the author of 4NEC2, Mr. Arie Voors!

Naturally such an enormous machine is not completely free from small errors, but they do not disturb and fortunately only express themselves in extreme cases (or contradictory commands e.g. moving something and forgetting the input). The software author requests that users inform him of such things immediately by email and then promptly investigates them.

2.0 The Helix antenna

2.1. Some initial words

It is a quite an interesting construction with just as interesting characteristics. It is a spiral wire with turns a wavelength long at the operating frequency and at least 3 turns. More turns increase the gain and make the beamwidth angle smaller. The typical upward gradient is about ¼ the wavelength and the reflector is arranged at the beginning of the spiral with a diameter of a wavelength.

The antenna is interesting:

- It supplies circularly polarised radiation where the rotation of the spiral specifies the polarisation.
- It exhibits amazing constant data and characteristics within a range of approximately 20% of a wavelength.
- The radiation resistance is approximately 150Ω theoretically (the practical values are between 130Ω and 200Ω) and this changes only slowly.
- Blind spots are present and are periodical, these must be considered during adjustment. They are clearly smaller than the radiation resistance and rarely exceed a value of 50Ω
- There is almost always no backward radiation due to the metal reflector and therefore an outstanding advantage.

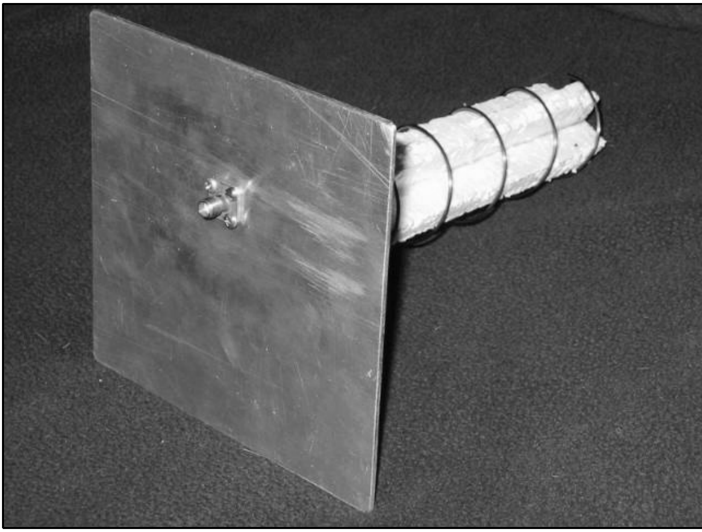

Fig 2: This is the end product, it is not a finished design but it serves as a sample to check the accuracy of the simulation.

- Altogether this antenna is extremely "good-natured" and "forgives" many errors during the mechanical conversion of the design.

Since there is usually "no rose without thorns", here are the drawbacks:

- The mechanical dimensions are unfortunately not as delicate as with some other antenna forms.
- The directivity pattern can easily become baggy compared with other antennas with similar gain.
- The amazing wide bandwidth is paid for with a decreased antenna gain that can be classified as "not top class" but rather "between centre zone and point".

2.2. Defaults

The user only needs the intended operating frequency (here: 2.45GHz) and the number of the turns to enter (with rising number of turns there is more gain and a narrower beamwidth, but also a longer antenna). Therefore for training a simple 6 turns antenna is calculated, see Fig 1.

Result:

- Wavelength = 122.4mm for a centre frequency of 2.45GHz
- Internal diameter = 41.6mm
- Gain = 10.85dBi
- Wire size = 2.4mm
- Upward gradient = 30.6mm
- Minimum reflector diameter = 75.9mm
- Entire antenna = 183.6mm = 6 x length 30.6mm

(In the result list the entire wire length is given as well as the information that the structure was raised by 1.1mm to create a place for the feed).

For the practical construction copper wire with a diameter of 1.25mm was selected because the connection at the beginning of the spiral can be manufactured more easily to connect to an SMA plug without large diameter jumps. To accept this wire size NEC would like to know the middle diameter of the spiral (using the on-line Calculators about 41.6mm + 2.4mm = 44mm).

This data was converted from the simulation into an experimental model. The reflector was a square aluminium plate 2mm thick and an edge length of 130mm (more than one wavelength as required). An SMA socket was screwed onto the lower surface of this plate with the inner pin through the reflector plate and soldered to the start of the spiral. It is

Table 1: The NEC file for the Helix antenna project.

CM Helix 2450MHz (6turns) over perfect ground									
CM Helix starts 5mm above ground									
CM Helix diameter = 44mm, spacing - 30.6mm									
CM Wire with a diameter of 1.25mm added between helix and ground									
CM Excitation at centre of this wire									
CE									
GH	1	120	0.0306	0.1836	0.022	0.022	0.022	0.022	0.0006125
GM	0	0	0	0	0	0	0	0.005	0
GW	150	1	.022	0	0	0.022	0	0.005	0.0006125
GE	1								
GN	1								
EK									
EX 0	150	1	0	1.	0				
FR	0	0	0	2450.	0				

important for the simulation that the Helix is raised by 5mm in order to copy this solder joint.

The Helix is held by two 10mm polystyrene strips stuck onto the reflector plate with UHU glue. Fig 2 shows this in good detail.

Doubts about the polystyrene material can exist; it contains the insulation material polystyrene (Styroflex) useful at high frequencies but it is 80% air. Because of the high fusing temperature of the polystyrene at over 80°C, no air humidity will be enclosed in the large pores that could cause additional absorption.

3.0

Wire antenna simulation with 4NEC2

3.1. Start and first simulation

The software can be downloaded in zipped form from different places on the Internet (see note at the end). The nucleus program 4NEC2 is installed and then the supplementary products are installed for 4NEC2X. However 4NEC2X is always used because it gives the coloured 3D diagrams of the simulation results as well as the antenna structure.

3.2. Production NEC files and the first simulation

A simple text editor is enough (e.g. Notepad) and all the necessary instructions (Cards) are typed by hand. Naturally 4NEC2 contains other good editors with easy operation but Notepad is fastest and experienced user eventually use this input method.

Note that NEC measures all dimensions entered in metres. If that is not desirable (e.g. working with inches), an additional scaling map must be used for suitable conversion. The input for the Helix is shown in Table 1.

Explanations:

- “CM” are comment cards and ignored by the program. “CE” means end of the comments.
- “GH” (Geometry of Helix) specifies the form of the Helix; the line required including the explanation is shown in Fig 3.
- “GM” (Geometry Move card) pushes the Helix upward by 5mm (Fig 4).
- “GW” (Geometry of Wire) for the connecting wire, see Fig 5. It represents the interior leader of the SMA socket and at the same time energizes

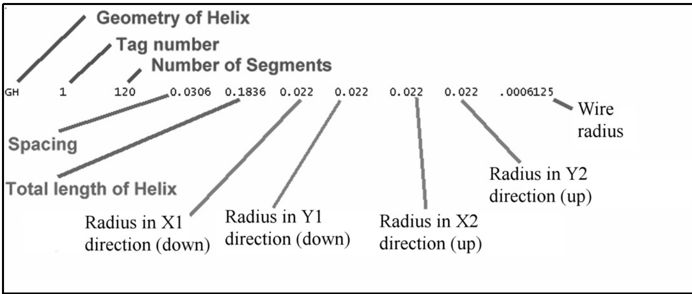

Fig 3: Unbelievably this short line contains the complete description for the Helix structure.

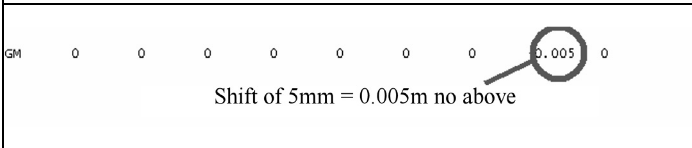

Fig 4: This raises the Helix by 5mm fro the SMA connector.

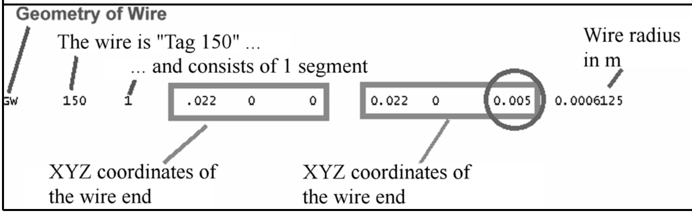

Fig 5: The inner pin of the SMA connector becomes this short piece of wire 5mm long.

the antenna. Its upper end is connected to the start of the Helix (coordinates of Helix and the upper end of the piece of wire the same). The lower end of the wire is put on the Ground level that is formed by the reflector. NEC automatically puts the feed point into the centre segment. Thus the upper end of the feed wire will meet the start of the Helix at a height of 5mm.

- The next three entries; GE/GN/EK are all shown in Fig 6. They concern the end of the geometry data, also "the Ground" and the fact that the antenna wire is not infinitely thin.
- From to Fig 7 the supply (Excitation) of the structure is programmed in the centre section of the connecting wire.
- … the conclusion (Fig 8), the indication of frequency as well as marking the end of the NEC file.

The NEC file is now saved in a suitable place with the file extension ".nec" e.g. as "helix_2450MHz.nec". 4NEC2X is started and the file loaded using "Main/file/open 4nec2 in/output file" and

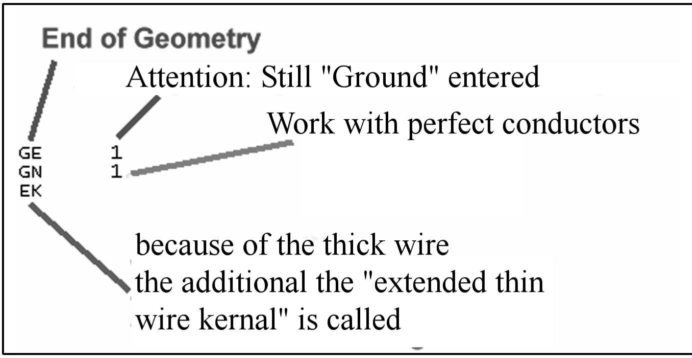

Fig 6: This defines the ground condition and the use of a thick wire in the simulation.

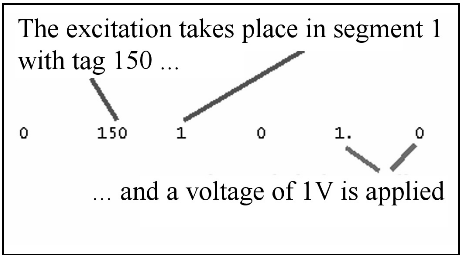

Fig 7: The exitation takes place in the middle of the wire.

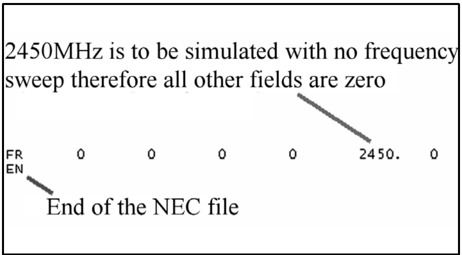

Fig 8: There is no frequency sweep, the frequency is set to 2450MHz.

the path of this antenna file. Press F7 to start the simulation after entering the attribute (Far Field pattern/fill/resolution = 5 degrees) as shown in Fig 9 and pressing "Generate".

The simulated far field radiation pattern (far field pattern) at a frequency of 2450MHz is shown in Fig 10. The azimuth angle "Phi" = zero degree (horizontal angle of rotation) is shown at the bottom on the left. The elevation angle "Theta" is from 0 to 180 degrees or from 0 to -180 degrees is shown on the bottom right.

One of the most beautiful options of 4NEC2 is the coloured 3D picture that can be opened with the key F9. The first one (Fig 11) shows the antenna structure, it can easily be zoomed to show the individual segments that the antenna divided into for the simulation. Unfortunately the pictures in VHF Communications Magazine are in black and white but the program colours the feed point in violet at the centre segment of the feed wire that makes it very easy to see. The structure can be moved and rotated using the mouse buttons.

Changing over the menu to "Multi Colour" shows the radiation pattern as well

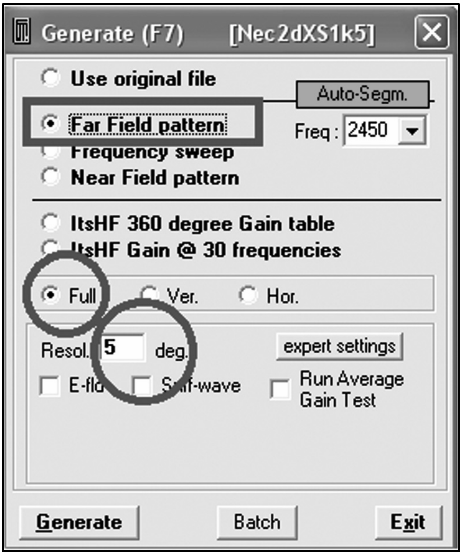

Fig 9: Pressing F7 displays these simulation parameters.

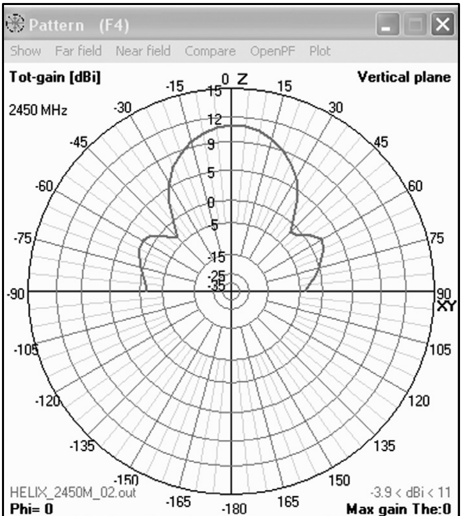

Fig 10: The simulated far field is displayed as a polar diagram.

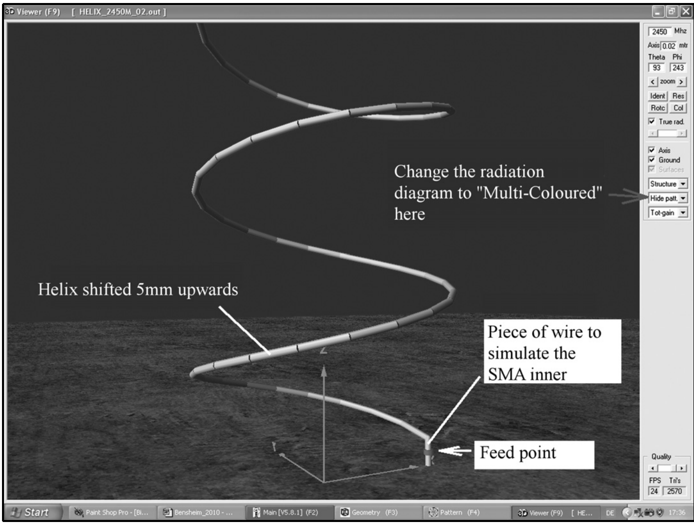

Fig 11: This is the 3D representation showing the feed point half way along the wire. This diagram is in glorious colour but VHF Communications Magazine is only printed in black and white. The feed point is shown in violet on the colour version.

as the colours for the gain scale in dBi (Fig 12).

3.2. Simulation of gain, SWR and impedance

Start the simulation menu by pressing the key F7 (Fig 13); then adjusts the following:

- Frequency sweep
- Gain (simply click to remove the message "No front/back ratio data is generated")
- Resolution = 5 degrees
- Start = 2300MHz,
- Stop = 2600MHz,
- Step = 2 MHz

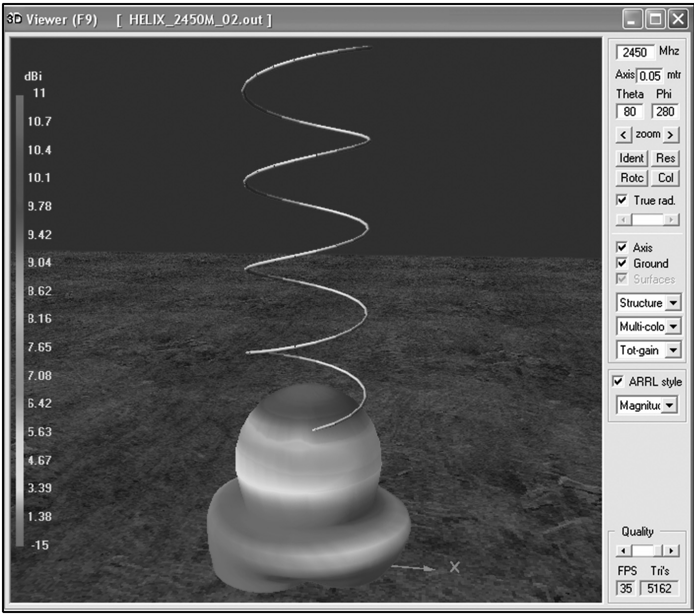

Fig 12: This is a very good view of the structure. It can be moved in any direction using the mouse.

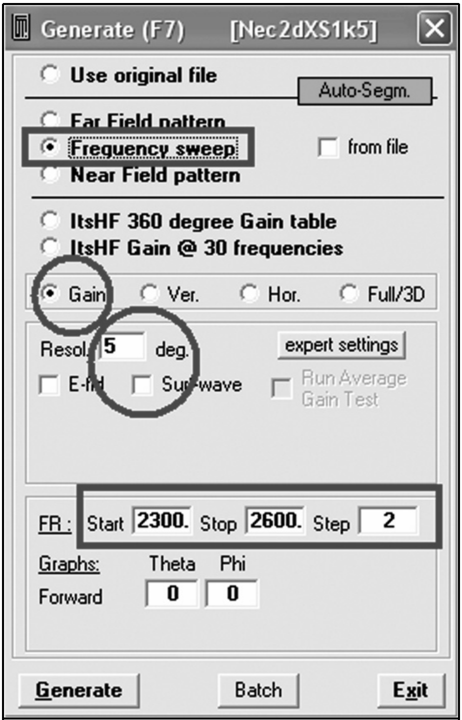

Fig 13: The simulation parameter can be set after pressing F7.

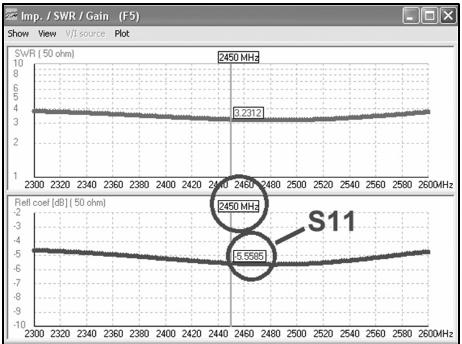

Fig 14: The SWR and reflection coefficient - see text.

(a maximum of 150 steps are possible, therefore the increment cannot be too large)

Click "Generate" to start the NEC calculating machine. Following successful simulation the screen showing the SWR and reflection coefficient is displayed (Fig 14). SWR = 3.2 and S11 = -5.85dB is relatively bad at 2450MHz but that does not have to be a bad indication: theoretically the radiation resistance is approximately 150Ω and therefore such values are to be expected.

The feed impedance (Fig 15) can be found using the "Show" menu in the top left hand corner. The theory is confirmed very beautifully because the radiation resistance is maintained between 150Ω and 190Ω over the entire frequency range from 2300 to 2600MHz. The imaginary portion only increases to - j50Ω at the lower end of the range.

Fig 16 shows the antenna gain that is

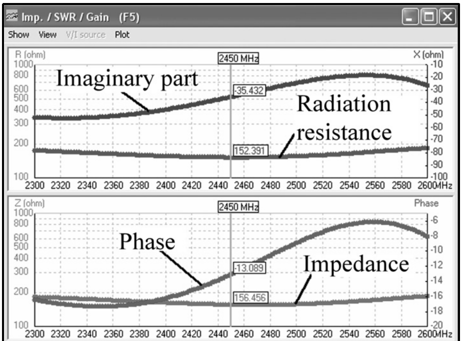

Fig 15: The mystery of the helix is the radiation resistance of 150Ω that is the cause of the large reflections.

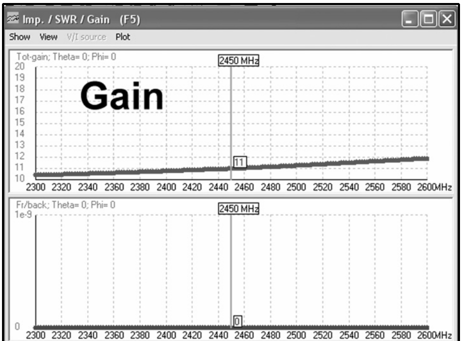

Fig 16: The gain is as promised very wide band.

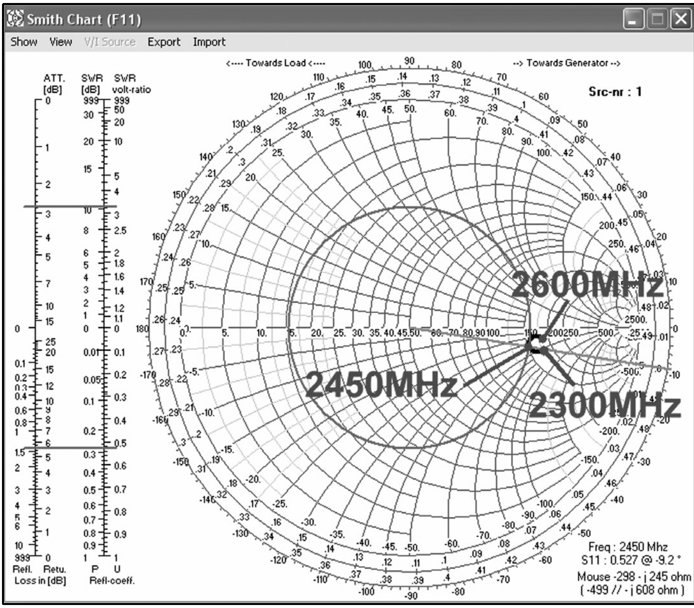

Fig 17: There is a Smith Chart for those who are familiar with this representation.

accessed using the "Show" menu. The wide bandwidth of the antenna is shown because the gain rises from 10.5dBi at 2300MHz to approximately 12dBi at 2600MHz. At 2450MHz it is exactly 11dBi. The lower diagram is empty because the earlier message stated that no front to back data would be calculated.

A Smith chart can also be displayed using the relevant button (Fig 17). This shows even better how the feed impedance behaves if the frequency is changed.

3.3. Results of measurement of the experimental model

3.3.1. Feed impedance

An HP 8410 network analyser with a magnitude and phase display module was used with a transmission reflection bridge for 2 to 12.4GHz. An HP 8690 sweeper supplied the excitation signal with a module for 2 to 4GHz. The

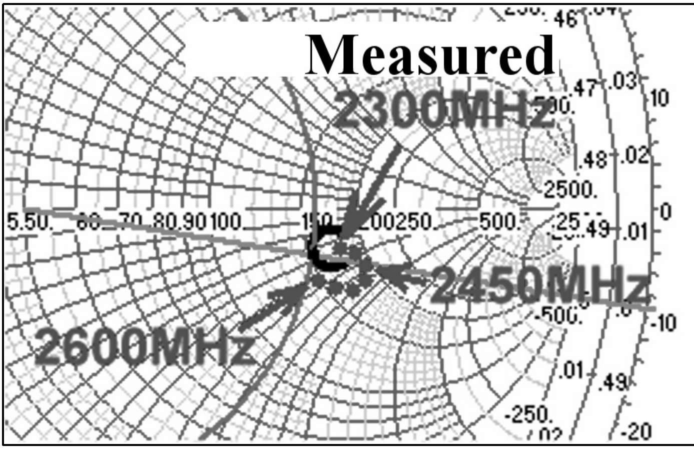

Fig 18: This shows the measured impedance on a Smith Chart from 2300 to 2600MHz.

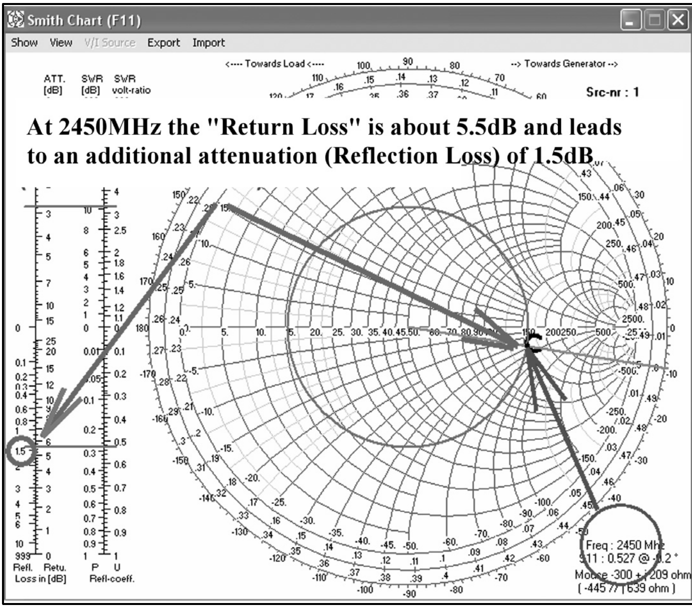

Fig 19: This shows how to determine the additional attenuation caused by the reflection.

desired frequency range was carefully controlled from 2300 to 2600MHz by a frequency counter. This counter received its signal from the sweeper using a 10dB directional coupler.

The measuring set was calibrated carefully:

Perfect adjustment using a Watkins Johnson SMA termination with more than 30dB reflection attenuation up to more than 12GHz (the expert immediately recognises these rare parts at the electronics flea market by the blue lacquer finish). Thus the bright spot was centred carefully in the centre of the magnitude and phase display.

Now the termination was replaced by a short piece of SMA semi rigid cable with the same SMA connector as used on the Helix antenna fitted to the end. First 100% reflection is exactly calibrated (bright curved path must be exactly on the outside diameter of the magnitude and phase display) AND the datum plane set by rotating the correct control on the measuring bridge to the point of the inner pin of the SMA socket (the curve diminishes to a bright spot). This exactly measures at the beginning of the Helix spiral when the antenna is attached for measurement. The result of the measurement can be seen in Fig 18 and the comment: “Not at all bad” is surely deserved.

3.3.2. Determining the antenna gain

An antenna measuring range would normally be required to determine the gain of this antenna. Unfortunately this is missing in the domestic cellar workshop. Thus the following cheat was used:

The wavelength is 122.4mm for a frequency of 2450MHz. If a transmission circuit consisting of transmitter, receiver and two identical antennas is developed with a path distance between the transmitting and receiving antenna of 120cm that corresponds to a distance of approximately 10 wavelengths and thus “genuine” far field propagation. But the following applies:

Since the radiated energy distributes over an ever-increasing solid angles when moving away from the transmitting antenna the energy per unit area decreases

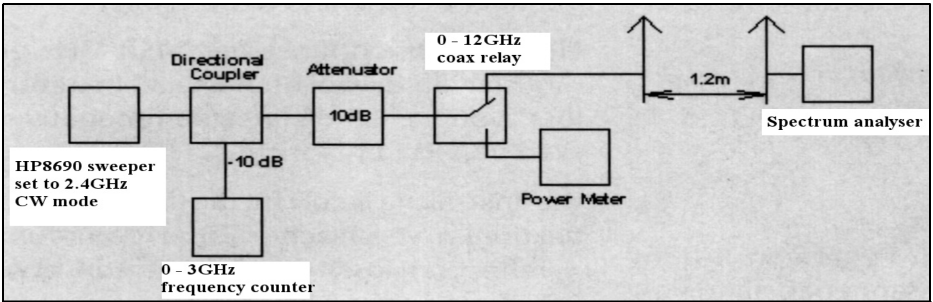

Fig 20: A block diagram of the antenna test setup.

according to the Friis transmission equation at the receiving antenna. This is the famous formula for free space path loss. If the gain of transmitting and receiving antenna is included it reads:

$$P_{Receiver} = P_{Transmitter} \cdot G_{Transmit-antenna} \cdot G_{Receive-antenna} \cdot \left(\frac{\lambda}{4\pi \cdot d} \right)^2$$

"d" is the distance between sending and receiving antennas and "λ" is the wavelength that will be used for the calculation being the speed of light divided by the transmitter frequency.

Using two completely identically manufactured patch antennas with a resonant frequency of 2.45GHz and an input reflection of less than 3% at this frequency, in the measuring position. An advantage of the patch antenna is their affiliation to the family of the planar array antennas. That means that the patch surface is at the starting point for the radiation leaving the antenna (technically the phase centre).

Using logarithmic representation in dB (with gain in dBm) for this arrangement:

$$Receivepower = Transmitpower + 2xAntennagain + 20 \cdot \log\left(\frac{\lambda}{4\pi \cdot d} \right)$$

in dB

Re-arranging for the gain:

$$Antennagain = \frac{Receivepower - Transmitpower - 20 \cdot \log\left(\frac{\lambda}{4\pi \cdot d} \right)}{2}$$

in dB

With a level of 0dBm and the antenna distance of 120cm the result is:

$$Antennagain = \frac{Transmitgain - 20 \cdot \log\left(\frac{12.24cm}{4\pi \div 120cm} \right)}{2} = \frac{Transmitgain + 41.8dB}{2}$$

With a measurement of -29dBm at the receiver (Spectrum Analyser calibrated at 2.45GHz) gives an antenna gain of 6.4dBi for the patch antenna that is about the value in the textbooks (usually: 6.5 to 7dBi, depending upon form, material and losses).

With the transmitting antenna replaced by the Helix antenna the level measured at the receiver rose to around +2dB. The input impedance of the Helix must be considered, this is approximately 150Ω therefore a large part of the available power (0dBm = 1mW) is reflected back into the generator. Calculating the additional attenuation is therefore child's play, because on the left of the Smith diagram of the 4NEC2-Simulation there are some nomograms (Fig 19). The two lower ones are important and they will be considered more closely:

For the point on the curve for 2450MHz there is a point on the right hand scale "return loss" of approximately 5.5dB that corresponds to the negative value of S11.

The left scale gives (by the reflections causing auxiliary absorption = reflection loss) the value of approximately 1.5dB and thus a measured gain for the Helix antenna of 6.4dBi + 2dB +1.5dB = 9.9dBi.

That is approximately 1dB less than the simulation stated (11 dBi) but not too far away. 1dB deviation correspond to 10% change of the voltage or approximately 20% of gain… and the losses in the polystyrene and the mounting plate have not been considered… and the skin effect at this frequency…

The layout of the measuring setup is shown in Fig 20. The principle is quite clear:

A counter is connected via a directional coupler to indicate the frequency of the transmitter signal. After an attenuator (to improve adjustment) there is a coax relay. In the lower switch position the transmit level can be measured and adjusted to 0dBm. In the upper switch position this output of 1mW goes to the transmitting antenna. The inputs to the wattmeter and the patch antenna are two identical, equal lengths but as short as possible, low-loss, SMA semi rigid cables. The accurately measured level of 0dBm = 1mW is fed to the antenna and is radiated. On the receive side the patch antenna is screwed directly onto the analyser input. The two antennas are accurately aligned at a distance 1.2m apart in poor reflection environment.

(Note: The connection between the generator and the antenna was made as short as possible otherwise the mismatch (it has a radiation resistance of 150Ω) may cause further unexpected attenuations. The reflections lead too "standing waves" in the cable and each maximum causes losses in the cable (because the voltage and current amplitudes are increased there) with this increase the SWR will raise substantial. They can increase the overall attenuation by over 4dB. Even if the cable attenuation is only 1dB with correct adjustment. A gain (in this case unfortunately energy dissipation) unfortunately always rises as a square of the current or voltage amplitude. This effect is described in the chapter "Additional power Loss due to SWR" in [2], there are also formulas and arithmetical examples as well as a beautiful auxiliary attenuation diagram for the consideration of this unpleasant effect.

4.0

Conclusion

NEC is also useful for wire antennas; no blind tests are necessary, because the NEC simulation decreases the largest part of the work and supplies, as shown, useful results.

However the learning effort is substantial and pitfalls lurk everywhere that lead to simulation errors. Often NEC or 4NEC2 does not warn of these and special knowledge of the user is required.

Also only a tiny fraction of this tremendously efficient program with its possibilities could be presented. A constantly growing 4NEC2 tutorial can be downloaded from [3] with all possible simulation examples and appropriate practical references. However if all possibilities and refinement of the program were to be discussed it would take more than 1000 sides.

Designing wire antennas with 4NEC2 makes for much joy and increases your personal knowledge. Much fun is due to my friend and 4NEC2 specialist, Hardy Lau of the Dualen University Baden Württemberg in Friedrichshafen. Without his knowledge and patient help with problems or questions and his notes on critical cases when the author was not sure or made incorrect assumptions this antenna would not work probably yet.

5.0

Literature

[1] John D. Kraus and Ronald J. Marhefka: "Antennas for all Applications".

McGraw Hill Higher Education. ISBN No.: 0-07-232103-2

[2] The ARRL Antenna Book, 21st edition. Page 24-10

[3] Homepage of the author www.elektronikschule.de/~krausg. Download address for 4NEC2: http://home.ict.nl/~arivoors/Home.htm