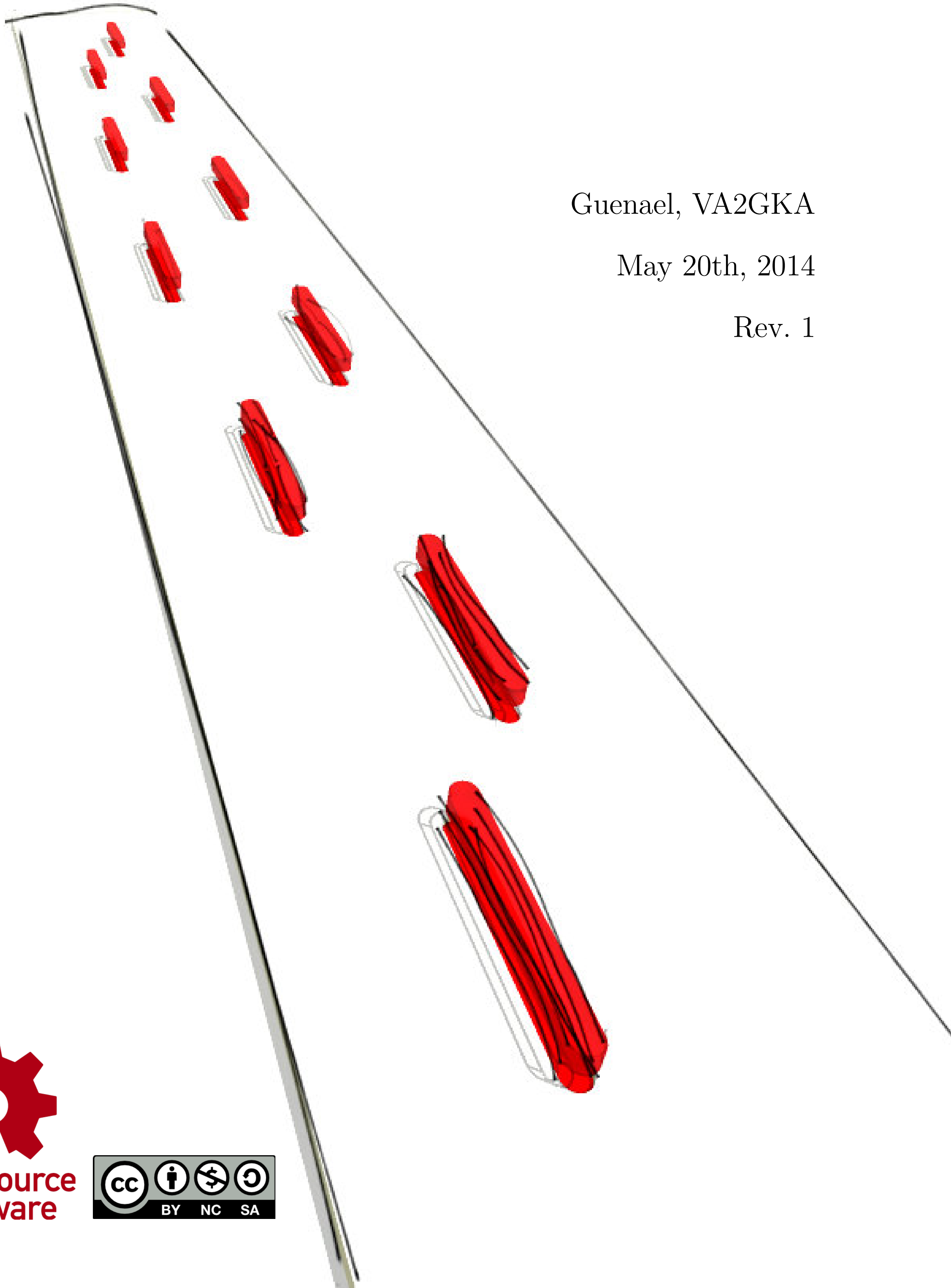
Slot antennas for amateur radio bands

Calculations & simulation with OpenEMS



Guenael, VA2GKA

May 20th, 2014

Rev. 1

Slot antennas for amateur radio bands

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Abstract: *This paper presents designs and calculations for a set of slot antennas centered on the amateur microwave bands. Special attention has been given to ease of construction, using simple supply materials available in standard sizes in the construction industry. Also, the traditional calculation formulas, which are only valid with a perfect waveguide, have been extended using iterative simulation and optimization to apply to common materials, while maintaining good performance.*

1 The slot antenna

Slot antennas are widely used in professional RF applications, especially for cellular networks, due to their high gain and their flat radiation pattern in the horizontal plane. A set of three antennas arranged at 120° to each other is commonly used to cover the entire horizon. In the amateur radio field, this kind of antenna is used as an omnidirectional antenna in beacon systems, by placing slots on both opposite sides.

The theory and the design of slot antennas has been widely explored and described for more than half a century. The book of Samuel Silver [1] written in 1949 covers all the calculations for almost all topologies of this kind of antenna. Other subsequent works (e.g. [2]) further detail the calculations related to the design of these antennas.

However, it is important to note that in all these publications, the authors used an ideal waveguide in perfect conditions. Furthermore, for all the calculations, some physical constraints must be observed, like the ratio width / height, which must be equal to 1/2 for the TE_{10} mode.

Unfortunately, the materials easily available to the amateur never have those exact dimensions. In most cases, metal rails can be found with a ratio of 1 or ½, but this is the ratio of the external dimensions. As the thickness of the material is unchanged on the two adjacent faces, the internal dimensions of interest do not follow exactly the desired ratio.

To overcome this, machining a waveguide is an elegant option, but this is expensive and difficult to achieve for the lower wavelengths.

Alternatively, I evaluated the possibility of using readily available construction materials (rectangular aluminum rails) and making them usable by adjusting some calculations to compensate for this non-ideal ratio. Overall, it works pretty well and this document presents my findings and calculations.

To achieve my goal, I used a hybrid method by calculating a first approximation with the known formulas, then adjusting and correcting the dimensions using iterative numerical simulation. Until recently, this tweaking and simulation step was only possible with expensive electromagnetic simulation software (EM), which can deal with full 3D volumes, unlike amateur software using wire segments (e.g. the NEC family).

Fortunately, freeware and open-source programs for electromagnetic modeling have recently emerged and this kind of simulation is now available to the amateur without spending a dollar. (However, supporting open-source projects by making donations is appreciated.) For my simulations, I used OpenEMS [3], developed by the German Thorsten Liebig, which uses a Finite-Difference Time-Domain (FDTD) approach to solve the EM system: http://openems.de [4]

OpenEMS uses Octave or Matlab, which empowers the user to create parametric models and to perform post-processing. Finally, OpenEMS has a great wiki which is frequently updated and it's a tool to discover for all antenna designers and EM enthusiasts.

Returning to our construction concerns, the chosen approach was to use metal tubing close to the desired dimensions and adapt the cutting slot dimensions. For the material, aluminum is a good choice because of its excellent electrical properties and its acceptable mechanical strength. So I chose rectangular aluminum tubing for my designs. In this paper, I will consider the band from

23cm to 3cm. Beyond 10GHz (3cm), it is possible to machine a waveguide directly, because the dimensions stay very small.

Professionally, the normalized waveguide (WRxxx and WGxx) are specified for a given frequency range. For our application, a wide range of sizes could be used and will not involve a loss of performance as they remain within the tolerance margin. This range is simply defined by the cutoff frequency for the first mode (TE_{10}) and the second (TE_{20}). The first step is to calculate the ideal length of the antenna to achieve resonance on the desired frequency, depending on the cross-section that is available. In North America, the imperial system is still in use, and in the following I will choose to keep the both measurement for the materials available in inches and millimeters. There is no benefit in one way or another, the final dimensions are close (e.g. 200x100 and 8"x4"), but of course we have to recalculate based on the actual the dimensions to maintain good performance.

Throughout this article, I will present the calculations for a waveguide centered on 1.296 GHz (23cm band) as example, but the complete calculations for all amateur bands are presented in the Appendix (Using the standard available sizes of rectangular aluminum tubing: 200x100x4mm – 120x60x3mm – 80x40x3mm 45x25x2mm – 25x15x1.5mm and 8"x4"x1/8" – 4"x2"x1/8" – 3"x1.5"x1/8" – 2"x1"x1/16" – 1"x½"x1/16")

1.1 Ideal resonance calculations

The slot antenna can be considered as a series of dipoles fed by a resonant volume. The first step is to calculate the elementary resonant volume, then simply stack as many blocks as required for each slot. This resonant volume will be powered on one side, and the other side is closed.

This problem does not have a unique solution because of the bandwidth of the waveguide. With 3 sides of the rectangular volume noted a, b and d (Figure 1), we can write for the excitation mode TE_{10}:

- Example of solution n°1:

$$a = \frac{5}{6}\omega_0 \qquad b = \frac{a}{2} \qquad d = \frac{3}{4}a \quad \text{with} \;\; \omega_0 = \frac{c_0}{f_0} \tag{1}$$

- Example of solution n°2:

$$a = \frac{4}{5}\omega_0 \quad b = \frac{a}{2} \qquad c = \frac{4a}{5} \tag{2}$$

As mentioned above, these ideal dimensions do not match the sizes of the building materials, and we have to recalculate the length d depending on the other two constraints.

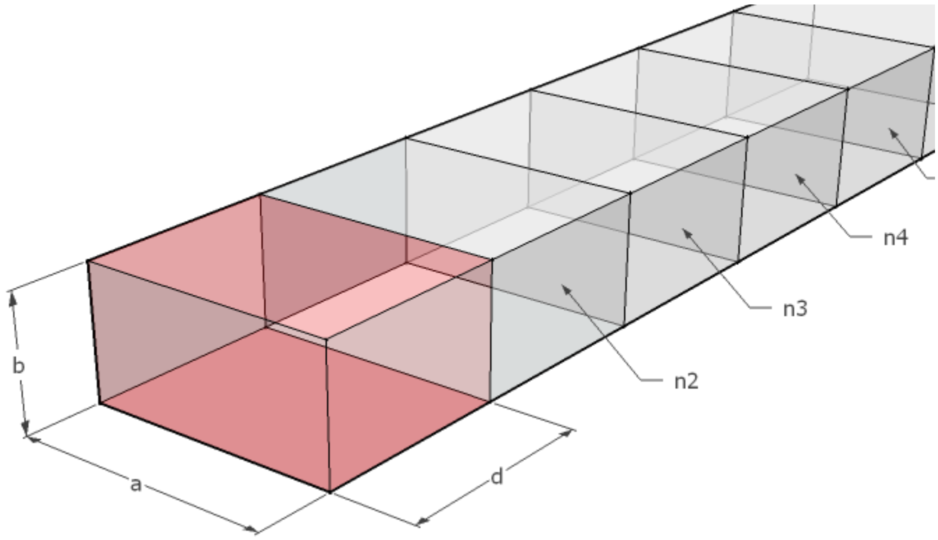

Figure 1: Dimensions for volume in resonance

However, this first approximation helps select a good potential candidate from the set of available materials. A check based on the cutoff frequencies must then be made to eliminate those with unusable dimensions.

1.2 Cutoff frequency calculation

The cutoff frequency of a wave guide with a rectangular section may be calculated as follows:

$$f_{mn} = \frac{c_0}{2\sqrt{\mu_r \varepsilon_r}} \cdot \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \tag{3}$$

Which for a TE_{10} mode, can be simplified as:

$$f_{10} \approx \frac{c_0}{2a} \qquad \text{Considering air as propagation media.}$$

For example using the 23cm band, this gives us a cutoff frequency equal to 0.749GHz for a waveguide having an inner section of 200x100mm. The second mode is equal to twice this value, and equal to 1.499 GHz. This gives us the limits of usability for the waveguide, which can be taken within these two values.

We see here that an aluminum tube with dimensions close to 200x100mm is quite acceptable as a waveguide for our slot antenna centered on 1.296 GHz.

1.3 Adjustment to real dimensions

Calculating a resonance volume is done similarly considering an additional dimension.

$$f_{mnp} = \frac{c_0}{2\sqrt{\mu_r \varepsilon_r}} \cdot \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2} \qquad \langle 4 \rangle$$

And we can write for a TE_{10} excitation mode:

$$f_{101} = \frac{c_0}{2\sqrt{\mu_r \varepsilon_r}} \cdot \sqrt{\frac{1}{a^2} + \frac{1}{d^2}} \qquad \langle 5 \rangle$$

With air as the propagation media, we can derive d as :

$$d = \sqrt{\frac{1}{\left(\frac{2f_0}{c_0}\right)^2 - \frac{1}{a^2}}} \qquad \text{(with } b = \frac{a}{2} \text{)} \qquad \langle 6 \rangle$$

Of course, this formula applies only to TE_{10} and b must be equal to half a.

I noticed that a non ideal waveguide having a ratio approaching the ideal, could be used if the difference does not exceed +/- 10% for b (or b = [0.45, 0.55]). These limits were determined by simulation. Also, this is the main purpose of this article.

1.4 Gain & application

The size of the total height of the antenna depends mainly on the desired gain. *Hyperistes* often use parabolics, which excel in terms of gain, but aiming them is not always easy or quick. With its wide horizontal opening (azimuth) and its very thin vertical beam (elevation), the slot antenna may be interesting for beacons, transponders, and RX stations (e.g. SDR systems broadcasting over the Web).

To maximize the antenna gain, we simply increase the number of slots, resulting a thinner beam in the vertical plane. However, the bandwidth decreases too. For the amateur bands with a non digital modulation (e.g. Morse and voice), this is not a problem because the bandwidth required is low for these modes. This is not true for business applications that require several hundred megahertz in digital modes. For the amateur, the main danger of using a very narrow bandwidth is making the antenna too demanding in terms of precision and ending up with a result outside the desired working frequency, without any flexibility (in other words, ending up with an unusable antenna).

Another important criterion for the amateur is clutter. It is always tempting to aim for very high gain and end up designing a cathedral, but the implementation will become painful... For this reason, I chose not to exceed 2 meters for the largest size of the lowest band. It is modest, but when you get into the gigahertz, it's good enough.

Here are selected frequencies for the different bands, with the number of slots used for the equivalent gain selected.

- 1.296GHz (23cm): height ~1.9m with 10 slots, gain 16.2 dB
- 2.320GHz (13cm): height ~1.5m with 16 slots, gain 18.5 dB
- 3.400GHz (9cm): height ~1m with 16 slots, gain 18.5 dB
- 5.760GHz (5cm): height ~0.6m with 16 slots, gain 18.5 dB
- 10.368GHz (3cm): height ~0.4m with 16 slots, gain 18.5 dB

Note: Total heights are given without the coaxial coupling (discussed later in this document).

1.5 Practical implementation

Returning to the practical aspects of constructing this 23cm antenna, I chose a rectangular aluminum profile of 200x100mm, having a wall thickness of 4mm. The side *d* of the resonant volume calculated above is multiplied by the number of slots to get the overall length. Moreover, to prevent the elements at the ends being too close to the edges, a good practice is to add a distance equivalent to a mode at each end of the waveguide.

Both lengths a and b are determined by the interior dimensions of the aluminum tube (192x92mm), the calculation gives a length of 144.90mm at 1.296 GHz. The total height will therefore be equal to 1738.83mm (calculated without the feeder system). As we leave an additional length of one mode at each end, the center of the first slot will be at 1.5x144.90mm, equal to 217.35mm. The height d describing the volume in resonance is also the distance between the centers of neighboring slots.

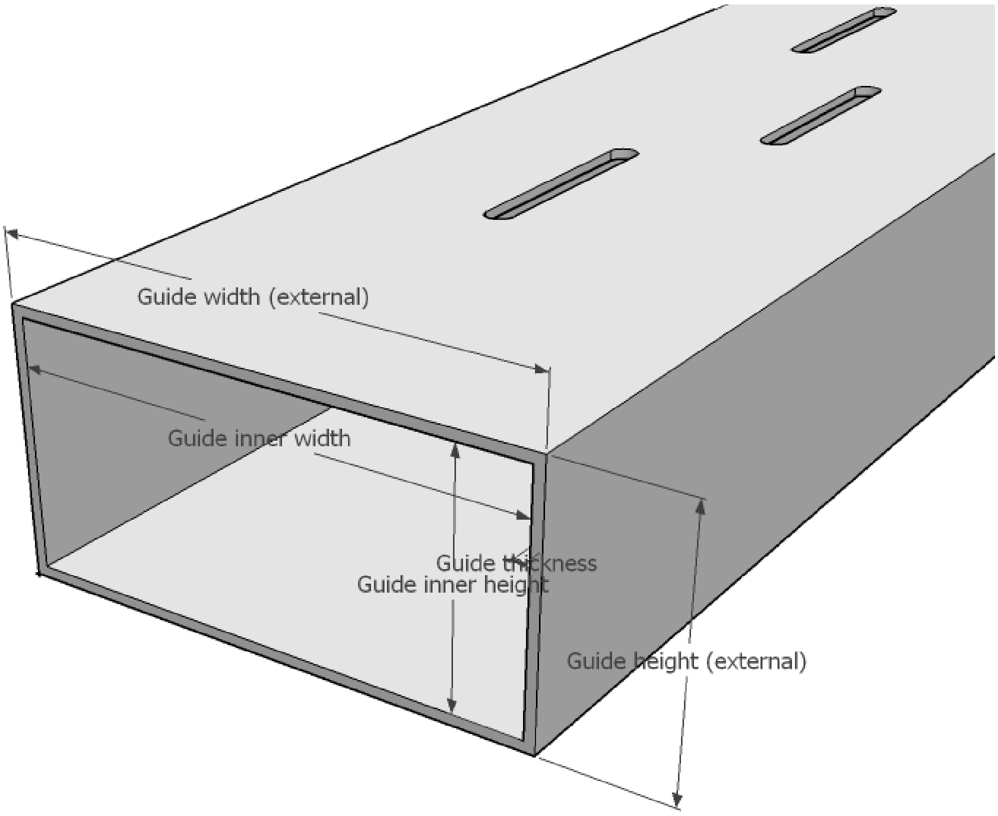

Figure 2: Physical dimensions of the guide

1.6 Slot offsets

There are several possible topologies for positioning the slots (vertical, horizontal, inclined, on the widest side, shortest side, etc...). All have their advantages and inconveniences, but I would start with the most common arrangement in the amateur world: slot cut out on the widest side, and kept aligned in the vertical direction (as shown in the figure above).

For this arrangement, the slots are distributed alternately on left and right to maintain a phase alignment, and the vertical orientation of the slot defines a horizontal polarity (unlike a single dipole in free space). The deviation from the center is chosen to adjust the impedance of the slot, and to achieve a better adaptation. The formulas to calculate the best offset to apply are widely available in the literature (e.g. [1] [2] [3]), but once again, the calculations are only applicable to a perfect waveguide with ideal dimensions.

$$g = g_1 \cdot sin^2\left(\frac{z \cdot \pi}{a}\right) \quad \text{where } z \text{ is the offset of the slot from the center}$$

$$g_1 = 2.09 \cdot \frac{\omega_s}{\omega_0} \cdot \frac{a}{b} \cdot cos^2\left(\frac{\pi}{2} \cdot \frac{\omega_0}{\omega_s}\right)$$

To solve this issue, I chose to use a simulation to consider these non-ideal dimensions for the waveguide and try to find the best match. After a first sweep to find an acceptable value, I started the optimization process and for our example (23cm band), I found an offset (relative to the center) for each slot equal to 27.31mm (this optimization addresses gain and efficiency only, without trying to minimize parasitic side lobes).

1.7 Slot size

Regarding the slot width (or drill bit diameter), we commonly use 1/20 of the wavelength. The slot length should be a little less than half a wavelength, with a first approximation of 95%. Notice that the adjustment of the slot length is inversely proportional to the offset of the slots (a slot is shorter if it is far from the center of the antenna). However, like the offset search, the exact sizing will be adjusted by multiple simulations / optimization. Also note that the thickness of the metal influences the length of the slot.

For our antenna centered on 1.296 GHz, $w_0/20 = 11.566$mm and we will select a drill bit of 11.5mm, or if that is unavailable: 29/64" (11.51mm), 15/32" (11.91mm), or 12.0mm. In making this choice, we have to take care not to change the total length of the slot, due to a change in the size of the cutting tool selected.

With the dimensions of our non-ideal waveguide as input, the solver yields, after optimization, an optimal dimension of 107.75mm for the length of the slot.

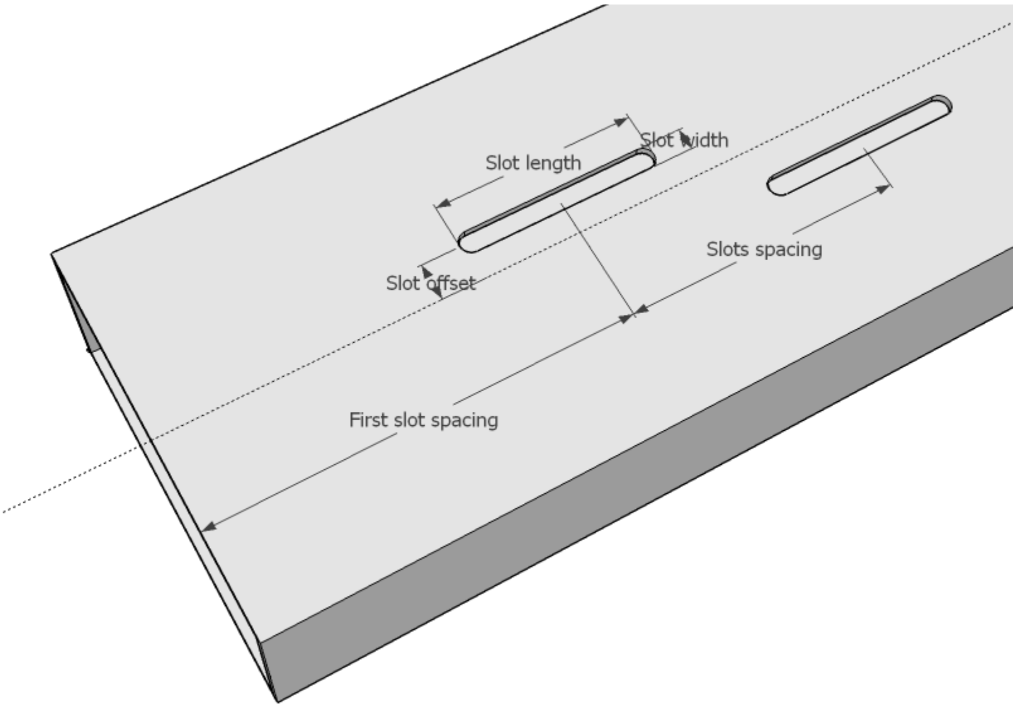

Figure 3 : Slot layout

1.8 Feeder

Until now, we have calculated our antenna without the feeder system, considering an ideal rectangular wave source at the base of the antenna. The coaxial adapter presented below is simply added at the base of the antenna but, in practice, the antenna will be constructed in one block, to keep the construction simple and avoid any mechanical issues. Only one small passage hole will be necessary for the monopole, connected to the coaxial connector (N or SMA).

For the monopole itself, we will use a simple metal rod. As the antenna response has a narrow band, there is no reason to use a more complex system (flared cone) and a simple metal rod is fine.

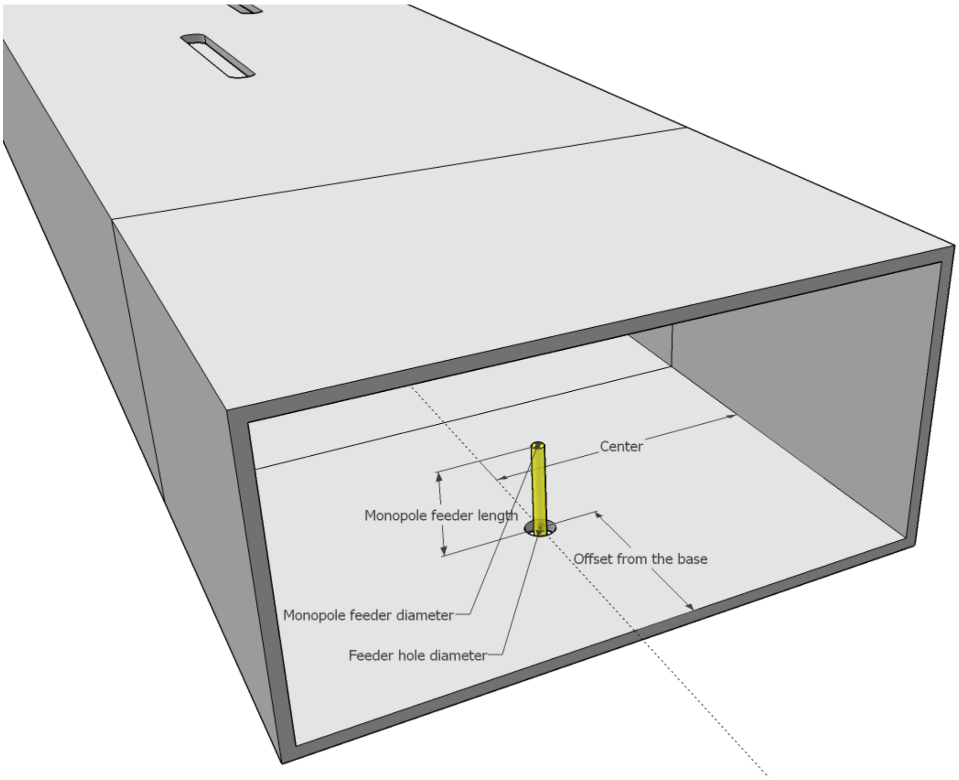

Figure 4: Feeder system

Selected dimensions for our antenna coupler, centered on 1.296 GHz :

- Monopole height: 56.28 mm (from the base of the connector)
- Monopole offset, relative to the base of the antenna (offset): 49.44 mm
- Hole diameter: 10 mm
- Monopole diameter: 4mm

The final dimensions for all antennas with feeder systems are described in the appendix.

2 Simulations & results

I wrote a parametric model for OpenEMS to estimate the performance of slot antennas with different configurations and bands. The model permits specifying the real dimensions of our rectangular metallic cross-section, the number of slots wanted, and the desired working frequency. The result is calculated by OpenEMS and the frequency response of the antenna (S11) is extracted with the radiation pattern (far field).

The code is available in the Appendix 2, using the rectangular slot antenna described as an example, but the parametric model can be adapted to any other dimensions. For those who have never used OpenEMS or Octave, simply copy/paste these few lines of code to start the calculation (the PATH of OpenEMS must be defined before this, follow the "first steps" tutorial).

Illustrations of the results obtained for our example are shown in the following figures.

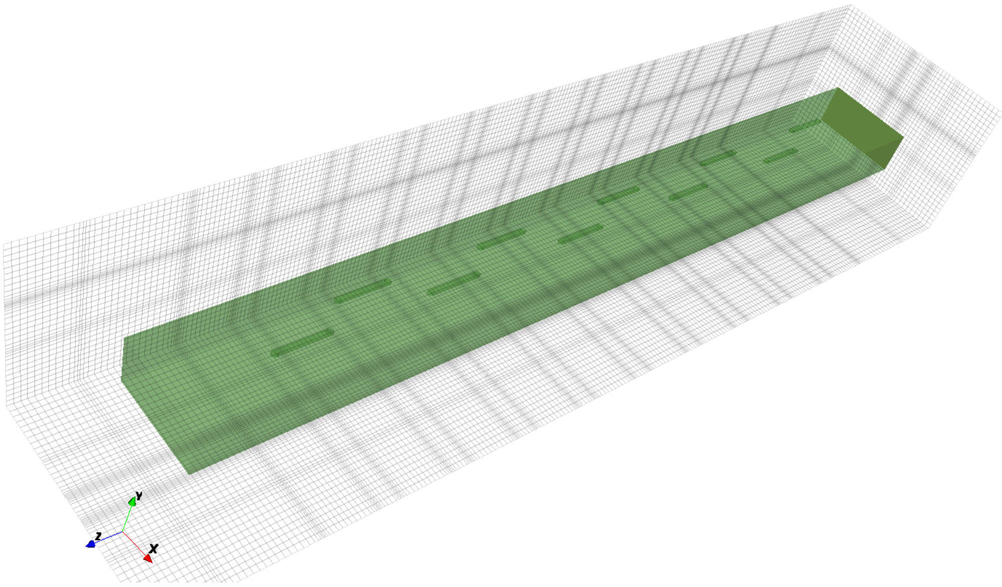

Figure 4: Antenna model view in OpenEMS

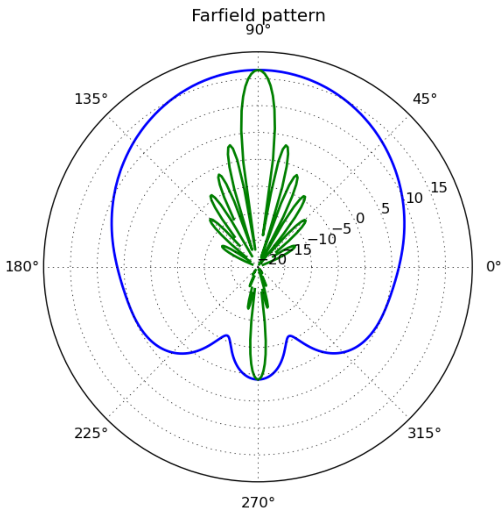

Figure 4: Radiation pattern of the antenna (farfield)

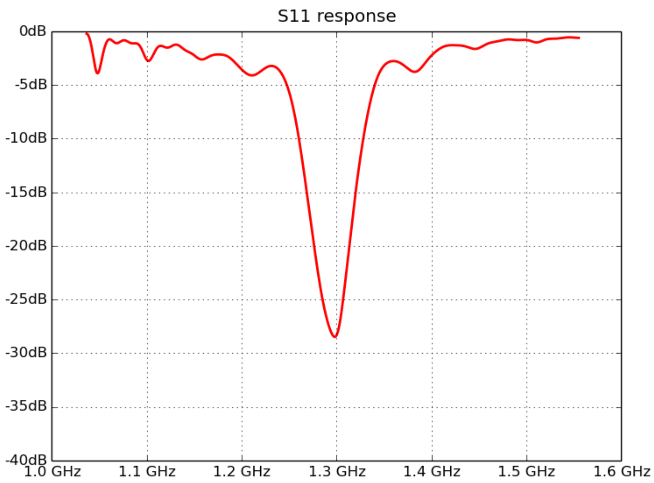

Figure 4: S11 response

3 Gaussian distribution for the slots

The presence of unwanted side lobes in the radiation pattern is quite noticeable in the results presented above. It is possible to reduce the magnitude of these side lobes, by adopting a non-linear power distribution, but the trade off is a slight decrease of the gain (on the main lobe).

Depending your main goal, these additional adjustments may have some interest or not. For a beacon system, we will usually seek to maximize the gain, and the use of a simple linear distribution will be perfect. Conversely, for a monitoring system, a Gaussian distribution may be of interest because the unwanted lobes will almost disappear. So, theoretically, the antenna will become less noisy and more interesting on the reception side. However, this point is debatable and YU1AW (Dragoslav) has written some excellent articles about low noise antennas. The reader can find additional information in these 3 articles: [5] (Yagi Antenna Improvement Thirty-Year Old Dead End?), [6], [7].

For radar applications, we can easily understand that it is very important to have a very clean and perfect radiation pattern. But in the case of terrestrial communications, I have difficulty justifying this choice, and I'm pretty convinced by the explanation given by Dragoslav.

Indeed, although the antenna is theoretically less noisy (i.e. no parasitic lobes in the ground and space directions), amateur communication targets the horizon and in all cases, this remains noisy. So the advantage of an optimum layout remains negligible. However, I will present these optimizations for this non-linear arrangement and let the reader decide for himself.

To achieve this nonlinear distribution of power, it is necessary to change the offsets of each slot to make them have higher or lower conductance, depending on their position. The construction will be more complicated because the offsets and lengths will vary for each slot.

To optimize the radiation pattern, I chose a double sigmoid, close to a Gaussian distribution, and this for both offset and sizes. The formula applied has the form: $y = a + b \cdot \arctan(x \cdot c)$ where a is the base of the offset, and b is the increment of the slope, with $x \in [-1, 1]$.

The parametric model allows calculations using Aa, Ab and Ac to define the offsets, and Ba, Bb and Bc to define the lengths of the slots. Note that parametric model presented above remains the same, except that Ab and Bb were previously initialized to zero, which was equivalent to a linear distribution.

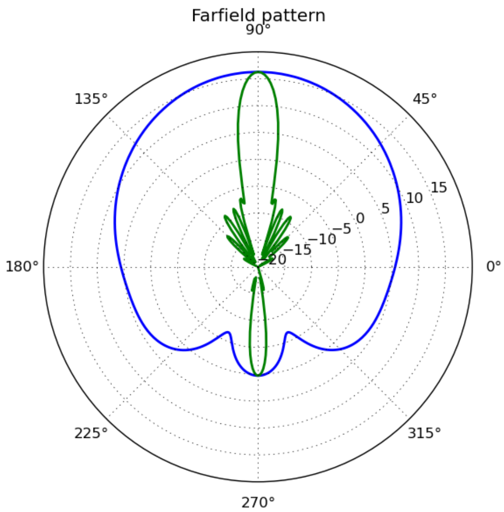

Figure 5: Optimized radiation pattern

4 More bandwidth

Until now, I have considered the use of narrow-band modes with a low bandwidth. The resulting antenna is still quite usable for amateur television on its working frequency, but at some point it could be desirable to extend the bandwidth.

Several solutions are possible. The first is to tune the position and width of the slots. Like the calculation of a filter, we can choose to not align the resonance of all the components (slots) on a single point, but on several. In this way, it is easy to get decent performance for two resonance points and have a wider bandwidth for the response. Of course, this comes at the price of a poorer response on the S11/SWR graph.

Another possible solution is to tilt the slots alternately. The bandwidth increases with the slope, but it is necessary to adjust the offset and length of the slots.

The parametric model presented previously also includes a tilt parameter for the slots. So far, it was left at zero for the previous calculations.

5 Vertical polarization

In the amateur field, although horizontal polarization is used *de facto* for terrestrial communications, some applications may benefit by using a vertical polarization (like a mobile TV antenna).

The slot antenna may be adapted for this purpose by setting the slots on the short side, and installing it horizontally relative to the ground (tilted by 90° relative to the arrangements presented so far). The slots should also be inclined, and a non-linear distribution can be applied. This topology is often applied for radar antennas.

Again, the model presented in the appendix allows us to perform calculations for this kind of topology, by simply exchanging the dimensions a and b, and defining an inclination. Moreover, we need to ensure that the width of the slots is greater than the wall-thickness of the guide. An additional depth of cut may be applied to tweak the impedance of the slots.

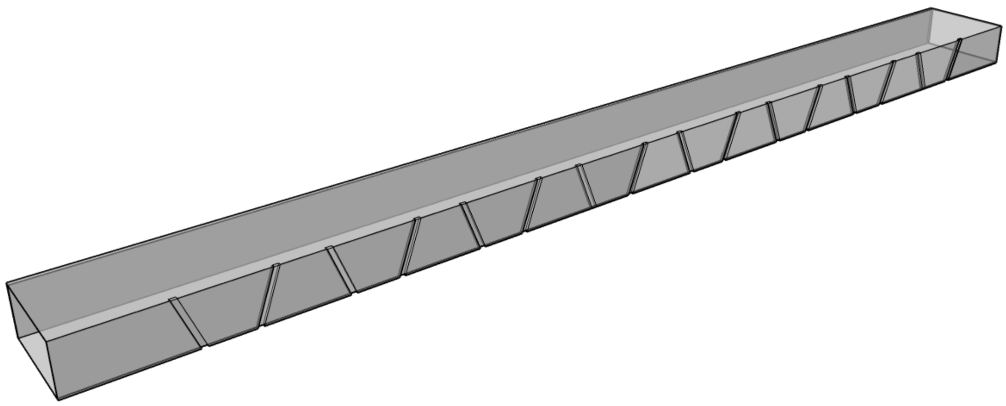

Figure 6: Slot antenna with tilde slots

6 Omnidirectional pattern

Our reference antenna presented so far only had slots on one face. Replicating a set of slots on the opposite face allows us to get an omnidirectional antenna, at the expense of some gain (-3 dB). This kind of topology is very interesting for microwave beacons.

However, the calculations must be entirely revised because the addition of this set of slots changes the impedance of the system.

The calculations for this type of antenna are not presented in this document but can be easily performed. This may be the subject of an updated, future version of this paper.

7 Slotted tube

Finally, all the calculations presented above can be applied to the case where we replace the rectangular waveguide by a cylindrical waveguide. Indeed, circular tubes are also commonly available for higher frequency ranges and brass tubes with circular cross-sections can be easily obtained.

On the other hand, it becomes more complex to correctly construct the antenna because of the difficulty of machining curved surfaces (fine angle measurement is required).

The propagation mode is TE_{11} and the calculations are easy to adjust. Furthermore, OpenEMS has recently been updated to allow processing curved surfaces, which makes it perfectly suited for these calculations.

Cutoff frequency calculation for a cylinder :

$$f_{mn} = \frac{X_{mn}}{2\pi \cdot a \cdot \sqrt{\mu_r \varepsilon_r}} \qquad \langle 7 \rangle$$

Which for a TE_{10} mode, could be simplified as:

$$f_{11} \approx \frac{1.841}{2\pi a} \text{ Considering air as the propagation media.}$$

Frequency resonance calculation :

$$f_{mnp} = \frac{c_0}{2\pi\sqrt{\mu_r \varepsilon_r}} \cdot \sqrt{\left(\frac{X_{mn}}{R}\right)^2 + \left(\frac{p \cdot \pi}{L}\right)^2} \qquad \langle 8 \rangle$$

And we could write for a TE_{11} excitation mode:

$$f_{111} \approx \frac{c_0}{2\pi\sqrt{\mu_r \varepsilon_r}} \cdot \sqrt{\left(\frac{1.841}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2} \qquad \langle 9 \rangle$$

Using air as the propagation media, we can derive L to be:

$$L \approx \sqrt{\frac{\pi^2}{\left(\frac{2\pi f_0}{c_0}\right)^2 - \left(\frac{1.841}{R}\right)^2}} \tag{10}$$

The results obtained with this kind of topology are very interesting. This simulation may be also be updated in a future version of this document.

8 Conclusion

The calculation of slot antenna parameters is usually performed by professionals for professionals, having a large budget. Waveguide is then used *de facto* because it is designed for this purpose, but unfortunately, its high price puts it beyond the reach of radio amateurs.

Through this document, I wanted to validate and demonstrate that standard industrial materials could be used as waveguide, by adapting some critical dimensions.

The calculations required to properly adjust this imperfect guide are complex, but with the rise of cheap and massive computing power, a second option emerged. Simulation and iterative optimization allow us to find the best design parameters and have a perfectly usable and efficient antenna.

Greetings

(in alphabetical order)

F5LEN (Pascal)	For sharing me a few parts of contest at JN38, in a post-apocalyptic landmark, filled with cables, toaster amps and many small flashing lights.
F5MBM (Alex)	For all the electricity he initiated in my tiny neurons in respond to our surreal technical exchanges.
F5MUX (Laurent)	For all our many friendly exchanges, and also to be Breton, buddy :p
VA2WHY (Rupert)	For reviewing my article and his many comments
VE3NEA (Alex)	For all its great software, and particularly for his work on The CW.
YU1AW (Dragoslav)	For all these excellent articles more valuable than each other.
YU1LM (Tasa)	For his magnificent work on the SDR transceivers.

Annexes

[1] Construction dimensions & parametric sheet

[2] Souce code – Simulation example

References

[1] Microwave Antenna - Theory and design, by Samuel Silver

[2] Antenna Engineering Handbook, Dr. John L. Volakis

[3] Microwave Engineering, David M. Pozar

[4] Open EMS : http://openems.de

[5] Yagi Antenna Improvement Thirty-Year Old Dead End?
http://www.qsl.net/y/yu1aw/Misc/yagi_old.pdf

[6] Yagi Antenna Design Sensitivity
http://www.qsl.net/y/yu1aw/Misc/yagi_design_sens.pdf

[7] Yagi Antenna Design Sensitivity in Practice
http://www.qsl.net/y/yu1aw/Misc/yagi_sens_pract.pdf

Revision

1 Initial publication

Planned updates

1 Annexe - Construction dimensions for Gaussian distribution

2 Annexe - Construction dimensions for double sided slots

3 Annexe - Construction dimensions for slotted tube

4 Annexe - Construction dimensions for WiFi slot antennas (2 & 5G)

Annexe 1 Parametric sheet for slot antennas (linear)

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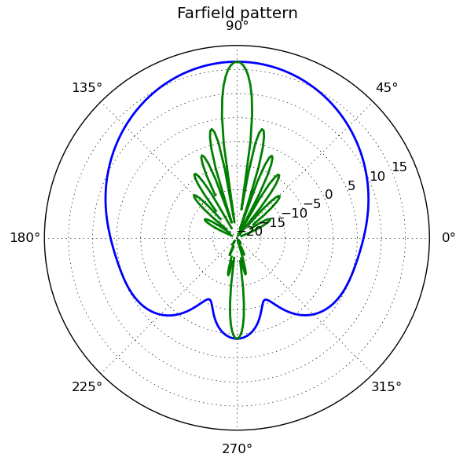
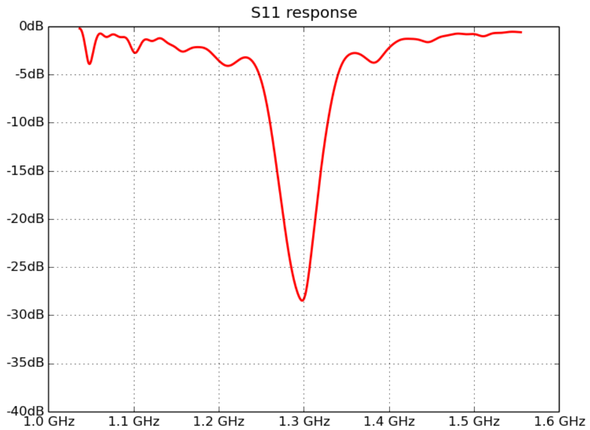
Center Frequency	1.296 GHz		2.320 GHz		3.400 GHz		5.760 GHz		10.368 GHz	
Dimensions (metric, imperial)	200x100x4mm	8"x4"x1/8"	120x60x3mm	4"x2"x1/8"	80x40x3mm	3"x1.5"x1/8"	45x25x2mm	2"x1"x1/16"	25x15x1.5mm	1"x$\frac{1}{2}$"x1/16"
Inputs										
f0 (center frequency, GHz)	1.296	1.296	2.320	2.320	3.400	3.400	5.760	5.760	10.368	10.368
n (slots numbers)	10	10	16	16	16	16	16	16	16	16
Guide Height (external, mm)	100.00	101.60	60.00	50.80	40.00	38.10	25.00	25.40	15.00	12.70
Guide Width (external, mm)	200.00	203.20	120.00	101.60	80.00	76.20	45.00	50.80	25.00	25.40
Guide Thickness (mm)	4.000	3.175	3.000	3.175	3.000	3.175	2.000	1.588	1.500	1.588
Monopole Feeder Diameter (mm)	4.00	4.00	4.00	4.00	4.00	4.00	1.50	1.50	1.50	1.50
Feeder Hole Diameter (mm)	10.00	10.00	10.00	10.00	10.00	10.00	3.50	3.50	3.50	3.50
Deducted & control										
w0 (wavelength @f0, mm)	231.321	231.321	129.221	129.221	88.174	88.174	52.047	52.047	28.915	28.915
Guide Inner Height (mm)	92.00	95.25	54.00	44.45	34.00	31.75	21.00	22.23	12.00	9.53
Guide Inner Width (mm)	192.00	196.85	114.00	95.25	74.00	69.85	41.00	47.63	22.00	22.23
Cutoff T10 approx. (GHz)	0.749	0.738	1.249	1.475	1.874	1.967	3.331	2.951	5.996	5.901
Cutoff T20 approx. (GHz)	1.499	1.475	2.498	2.951	3.747	3.934	6.662	5.901	11.992	11.803
Ratio h/w (min/max .45/.55)	0.479	0.484	0.474	0.467	0.459	0.455	0.512	0.467	0.545	0.429
Estimated Gain (@ f0)	16.6	16.6	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7
Calculated										
Slots Spacing (mm)	144.903	142.935	78.422	87.934	54.893	56.839	33.677	31.073	19.181	19.036
First Slot Spacing (x1.5 s.sp.)	217.35	214.40	117.63	131.90	82.34	85.26	50.52	46.61	28.77	28.55
Slots ideal Width (w0/20, mm)	11.57	11.57	6.46	6.46	4.41	4.41	2.60	2.60	1.45	1.45
Real drill bit used (mm)	11.50	11.50	6.50	6.50	4.50	4.50	2.60	2.60	1.50	1.50
Parametric model optimized by simulation – LINEAR										
Aa (slot size factor)	0.93161	0.91927	0.91112	0.95412	0.93942	0.95278	0.94263	0.90722	0.94805	0.97049
Ba (slot offset factor)	0.94434	1.02264	0.90408	0.51239	0.76623	0.63832	0.66241	0.99319	0.59220	0.55408
Ca (monopole length factor)	0.97313	0.96593	0.99925	0.94074	1.00722	0.99204	1.02343	1.02500	1.04447	1.02763
Cb (monopole offset factor)	0.85495	0.86602	0.87313	0.76699	0.83219	0.78451	0.80462	0.87000	0.79816	0.72036

Annexe 1 Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	23cm
Center frequency (GHz)	1.296
Estimated gain (dB)	16.6
Size	200x100x4mm
Total antenna length with feeder	1883.74
with top & bottom metal hat	1891.74
Slots cutting (mm)	
Number of slots	10
Slots total lengths (round included)	107.75
Drill length for all slots	96.25
Slots offsets (from the center)	27.31
Drill bit diameter	11.50
Drill start point – Slot 1 (mm, from the base)	314.13
Drill start point – Slot 2	459.03
Drill start point – Slot 3	603.94
Drill start point – Slot 4	748.84
Drill start point – Slot 5	893.74
Drill start point – Slot 6	1038.65
Drill start point – Slot 7	1183.55
Drill start point – Slot 8	1328.45
Drill start point – Slot 9	1473.35
Drill start point – Slot 10	1618.26
Feeder position & size (mm)	
Monopole feeder length (from the connector)	56.28
Monopole feeder offset (from the base)	49.44
Monopole feeder diameter	4.00
Feeder hole diameter	10.00





Annexe 1 Slot antennas Construction dimensions Linear distribution

Guenael, VA2GKA

Band	23cm
Center frequency (GHz)	1.296
Estimated gain (dB)	16.6

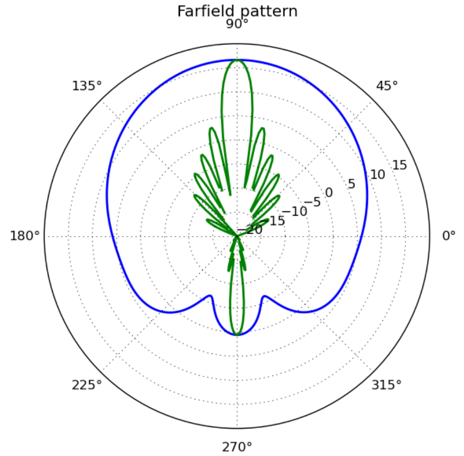
Size	8"x4"x1/8"

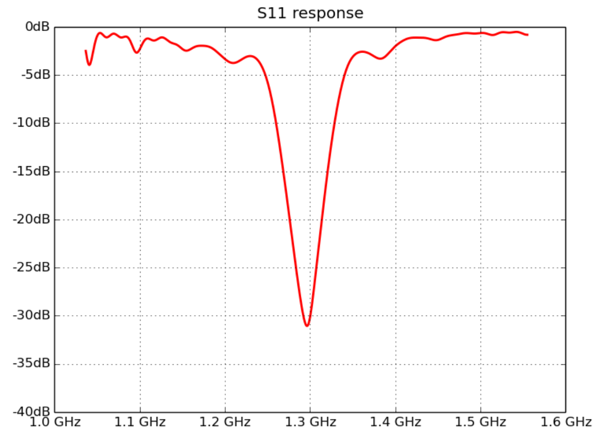
Total antenna length with feeder	1858.16
with top & bottom metal hat	1864.51

Slots cutting (mm)	
Number of slots	10
Slots total lengths (round included)	106.32
Drill length for all slots	94.82
Slots offsets (from the center)	29.57
Drill bit diameter	11.50

Drill start point – Slot 1 (mm, from the base)	309.93
Drill start point – Slot 2	452.86
Drill start point – Slot 3	595.80
Drill start point – Slot 4	738.73
Drill start point – Slot 5	881.67
Drill start point – Slot 6	1024.60
Drill start point – Slot 7	1167.54
Drill start point – Slot 8	1310.47
Drill start point – Slot 9	1453.41
Drill start point – Slot 10	1596.34

Feeder position & size (mm)	
Monopole feeder length (from the connector)	55.86
Monopole feeder offset (from the base)	50.08
Monopole feeder diameter	4.00
Feeder hole diameter	10.00

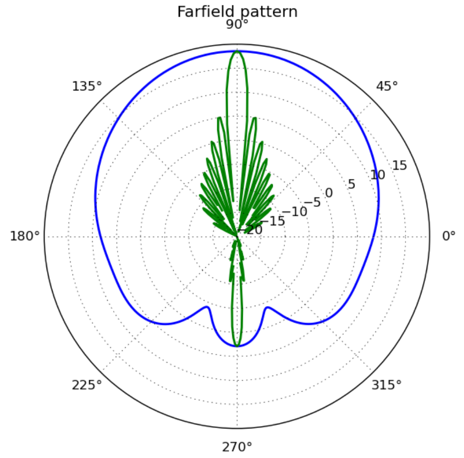


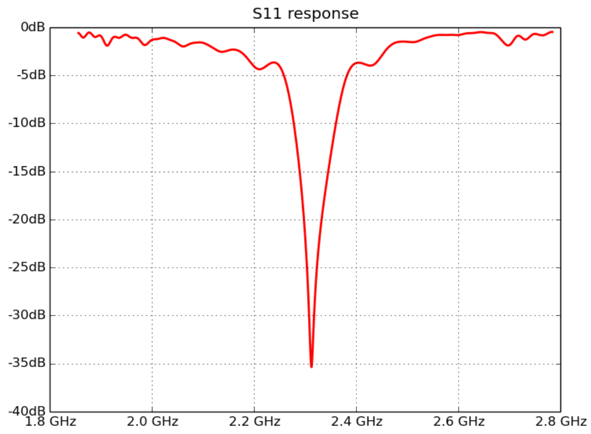


Annexe 1 Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	13cm
Center frequency (GHz)	2.320
Estimated gain (dB)	18.7
Size	120x60x3mm
Total antenna length with feeder	1490.01
with top & bottom metal hat	1496.01
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	58.87
Drill length for all slots	52.37
Slots offsets (from the center)	14.60
Drill bit diameter	6.50
Drill start point – Slot 1 (mm, from the base)	169.87
Drill start point – Slot 2	248.29
Drill start point – Slot 3	326.71
Drill start point – Slot 4	405.14
Drill start point – Slot 5	483.56
Drill start point – Slot 6	561.98
Drill start point – Slot 7	640.40
Drill start point – Slot 8	718.82
Drill start point – Slot 9	797.24
Drill start point – Slot 10	875.67
Drill start point – Slot 11	954.09
Drill start point – Slot 12	1032.51
Drill start point – Slot 13	1110.93
Drill start point – Slot 14	1189.35
Drill start point – Slot 15	1267.77
Drill start point – Slot 16	1346.20
Feeder position & size (mm)	
Monopole feeder length (from the connector)	32.28
Monopole feeder offset (from the base)	28.21
Monopole feeder diameter	4.00
Feeder hole diameter	10.00





Annexe 1 Slot antennas Construction dimensions Linear distribution

Guenael, VA2GKA

Band	13cm
Center frequency (GHz)	2.320
Estimated gain (dB)	18.7

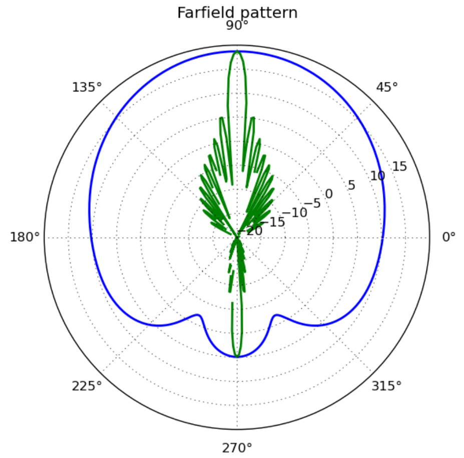
Size	4”x2”x1/8”

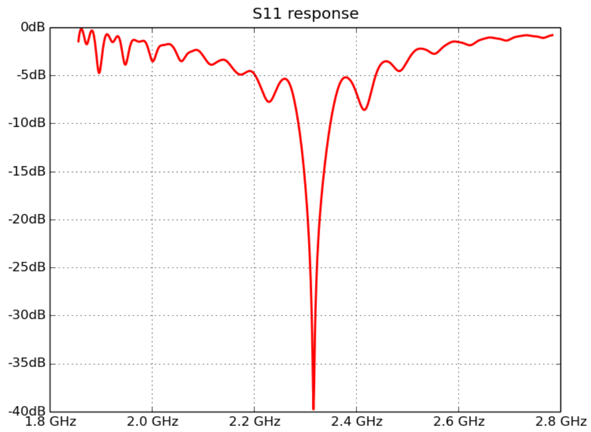
Total antenna length with feeder	1670.74
with top & bottom metal hat	1677.09

Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	61.65
Drill length for all slots	55.15
Slots offsets (from the center)	8.28
Drill bit diameter	6.50

Drill start point – Slot 1 (mm, from the base)	192.26
Drill start point – Slot 2	280.20
Drill start point – Slot 3	368.13
Drill start point – Slot 4	456.06
Drill start point – Slot 5	544.00
Drill start point – Slot 6	631.93
Drill start point – Slot 7	719.86
Drill start point – Slot 8	807.80
Drill start point – Slot 9	895.73
Drill start point – Slot 10	983.67
Drill start point – Slot 11	1071.60
Drill start point – Slot 12	1159.53
Drill start point – Slot 13	1247.47
Drill start point – Slot 14	1335.40
Drill start point – Slot 15	1423.33
Drill start point – Slot 16	1511.27

Feeder position & size (mm)	
Monopole feeder length (from the connector)	30.39
Monopole feeder offset (from the base)	24.78
Monopole feeder diameter	4.00
Feeder hole diameter	10.00

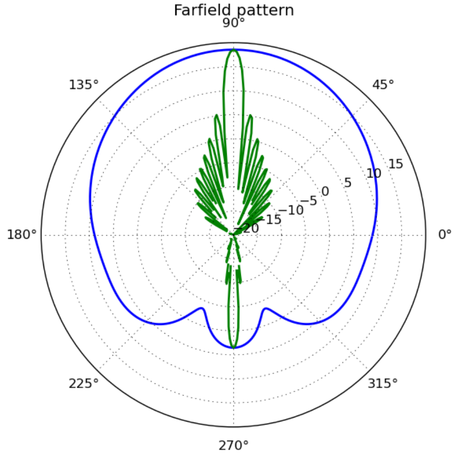


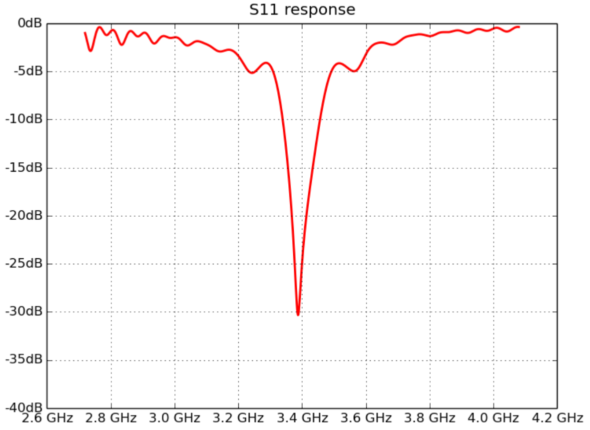


Annexe 1 — Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	9cm
Center frequency (GHz)	3.400
Estimated gain (dB)	18.7
Size	80x40x3mm
Total antenna length with feeder	1042.96
with top & bottom metal hat	1048.96
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	41.42
Drill length for all slots	36.92
Slots offsets (from the center)	8.45
Drill bit diameter	4.50
Drill start point – Slot 1 (mm, from the base)	118.77
Drill start point – Slot 2	173.67
Drill start point – Slot 3	228.56
Drill start point – Slot 4	283.45
Drill start point – Slot 5	338.34
Drill start point – Slot 6	393.24
Drill start point – Slot 7	448.13
Drill start point – Slot 8	503.02
Drill start point – Slot 9	557.91
Drill start point – Slot 10	612.81
Drill start point – Slot 11	667.70
Drill start point – Slot 12	722.59
Drill start point – Slot 13	777.48
Drill start point – Slot 14	832.38
Drill start point – Slot 15	887.27
Drill start point – Slot 16	942.16
Feeder position & size (mm)	
Monopole feeder length (from the connector)	22.20
Monopole feeder offset (from the base)	18.34
Monopole feeder diameter	4.00
Feeder hole diameter	10.00

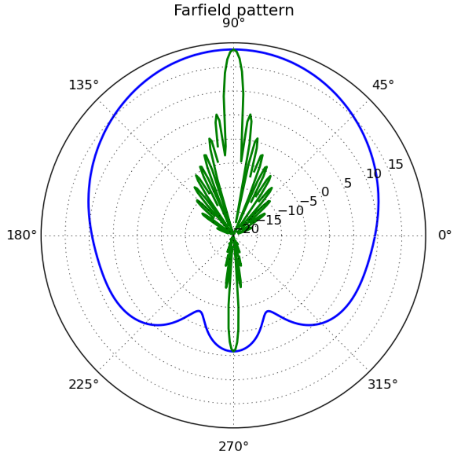


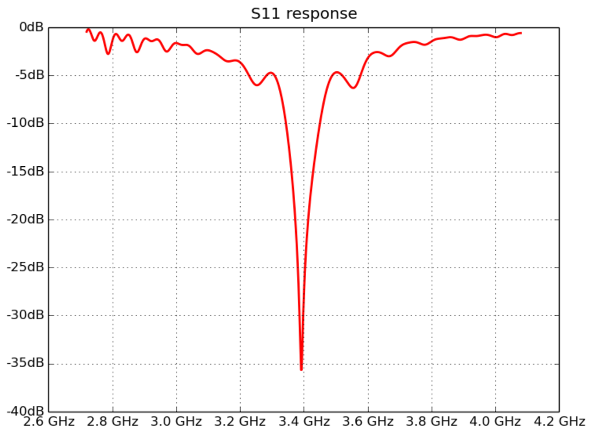


Annexe 1 Slot antennas Construction dimensions Linear distribution

Guenael, VA2GKA

Band	9cm
Center frequency (GHz)	3.400
Estimated gain (dB)	18.7
Size	3"x1.5"x1/8"
Total antenna length with feeder	1079.95
with top & bottom metal hat	1086.30
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	42.01
Drill length for all slots	37.51
Slots offsets (from the center)	7.04
Drill bit diameter	4.50
Drill start point – Slot 1 (mm, from the base)	123.35
Drill start point – Slot 2	180.18
Drill start point – Slot 3	237.02
Drill start point – Slot 4	293.86
Drill start point – Slot 5	350.70
Drill start point – Slot 6	407.54
Drill start point – Slot 7	464.38
Drill start point – Slot 8	521.22
Drill start point – Slot 9	578.06
Drill start point – Slot 10	634.90
Drill start point – Slot 11	691.74
Drill start point – Slot 12	748.58
Drill start point – Slot 13	805.42
Drill start point – Slot 14	862.26
Drill start point – Slot 15	919.09
Drill start point – Slot 16	975.93
Feeder position & size (mm)	
Monopole feeder length (from the connector)	21.87
Monopole feeder offset (from the base)	17.29
Monopole feeder diameter	4.00
Feeder hole diameter	10.00

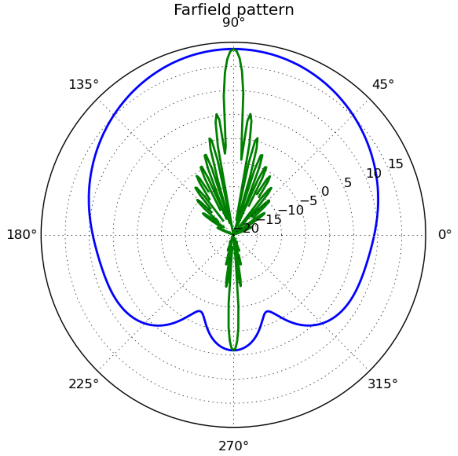


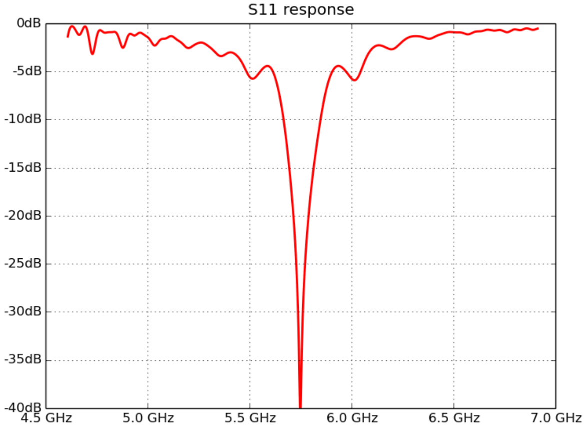


Annexe 1 Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	5cm
Center frequency (GHz)	5.760
Estimated gain (dB)	18.7
Size	45x25x2mm
Total antenna length with feeder	639.87
with top & bottom metal hat	643.87
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	24.53
Drill length for all slots	21.93
Slots offsets (from the center)	4.31
Drill bit diameter	2.60
Drill start point – Slot 1 (mm, from the base)	73.23
Drill start point – Slot 2	106.90
Drill start point – Slot 3	140.58
Drill start point – Slot 4	174.26
Drill start point – Slot 5	207.94
Drill start point – Slot 6	241.61
Drill start point – Slot 7	275.29
Drill start point – Slot 8	308.97
Drill start point – Slot 9	342.64
Drill start point – Slot 10	376.32
Drill start point – Slot 11	410.00
Drill start point – Slot 12	443.68
Drill start point – Slot 13	477.35
Drill start point – Slot 14	511.03
Drill start point – Slot 15	544.71
Drill start point – Slot 16	578.38
Feeder position & size (mm)	
Monopole feeder length (from the connector)	13.32
Monopole feeder offset (from the base)	10.47
Monopole feeder diameter	1.50
Feeder hole diameter	3.50

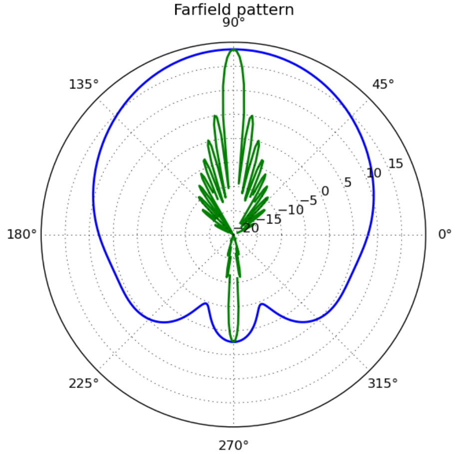


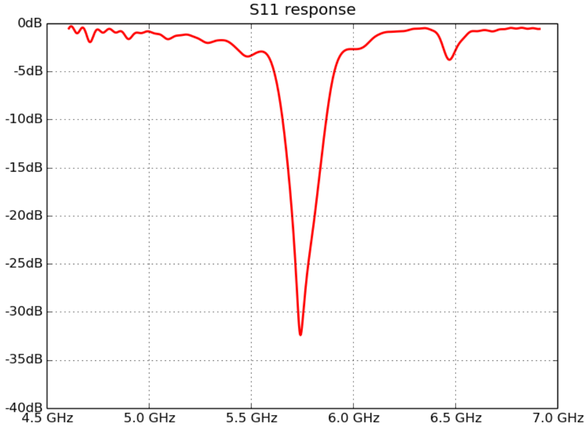


Annexe 1 Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	5cm
Center frequency (GHz)	5.760
Estimated gain (dB)	18.7
Size	2"x1"x1/16"
Total antenna length with feeder	590.38
with top & bottom metal hat	593.56
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	23.61
Drill length for all slots	21.01
Slots offsets (from the center)	6.46
Drill bit diameter	2.60
Drill start point – Slot 1 (mm, from the base)	67.18
Drill start point – Slot 2	98.25
Drill start point – Slot 3	129.32
Drill start point – Slot 4	160.40
Drill start point – Slot 5	191.47
Drill start point – Slot 6	222.54
Drill start point – Slot 7	253.61
Drill start point – Slot 8	284.69
Drill start point – Slot 9	315.76
Drill start point – Slot 10	346.83
Drill start point – Slot 11	377.91
Drill start point – Slot 12	408.98
Drill start point – Slot 13	440.05
Drill start point – Slot 14	471.12
Drill start point – Slot 15	502.20
Drill start point – Slot 16	533.27
Feeder position & size (mm)	
Monopole feeder length (from the connector)	13.34
Monopole feeder offset (from the base)	11.32
Monopole feeder diameter	1.50
Feeder hole diameter	3.50

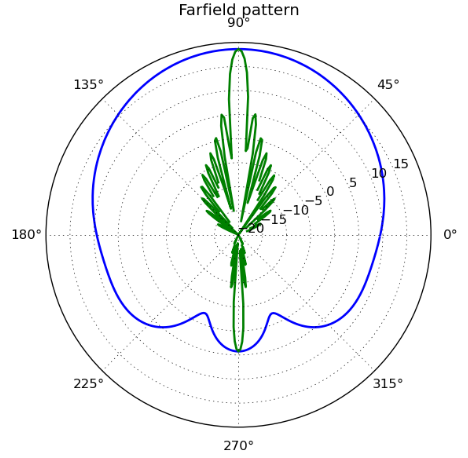


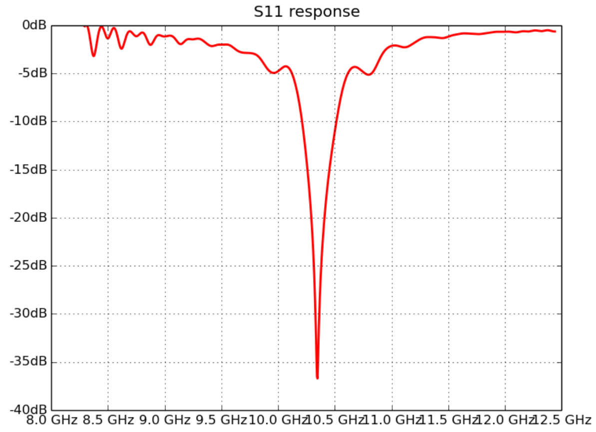


Annexe 1 Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	3cm
Center frequency (GHz)	10.368
Estimated gain (dB)	18.7
Size	25x15x1.5mm
Total antenna length with feeder	364.44
with top & bottom metal hat	367.44
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	13.71
Drill length for all slots	12.21
Slots offsets (from the center)	2.14
Drill bit diameter	1.50
Drill start point – Slot 1 (mm, from the base)	41.85
Drill start point – Slot 2	61.03
Drill start point – Slot 3	80.21
Drill start point – Slot 4	99.39
Drill start point – Slot 5	118.57
Drill start point – Slot 6	137.75
Drill start point – Slot 7	156.93
Drill start point – Slot 8	176.12
Drill start point – Slot 9	195.30
Drill start point – Slot 10	214.48
Drill start point – Slot 11	233.66
Drill start point – Slot 12	252.84
Drill start point – Slot 13	272.02
Drill start point – Slot 14	291.20
Drill start point – Slot 15	310.38
Drill start point – Slot 16	329.56
Feeder position & size (mm)	
Monopole feeder length (from the connector)	7.55
Monopole feeder offset (from the base)	5.77
Monopole feeder diameter	1.50
Feeder hole diameter	3.50

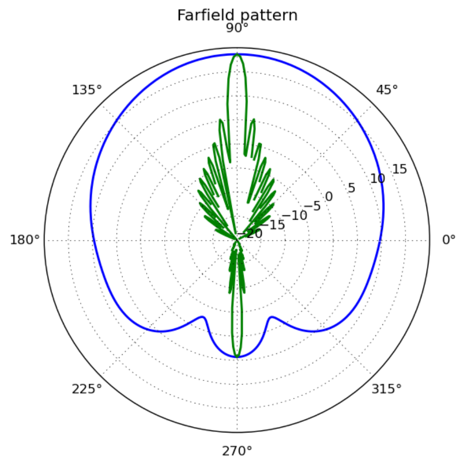


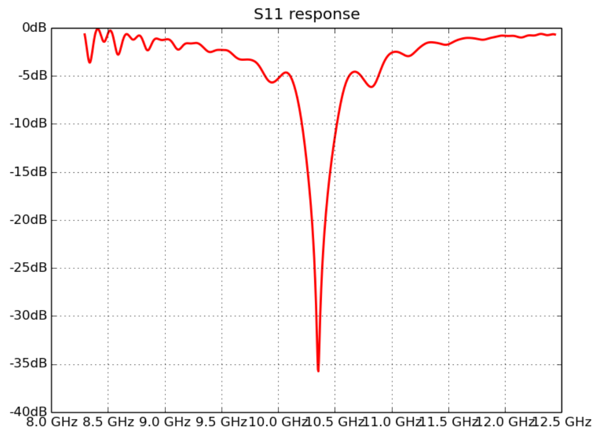


Annexe 1 Slot antennas
Construction dimensions
Linear distribution

Guenael, VA2GKA

Band	3cm
Center frequency (GHz)	10.368
Estimated gain (dB)	18.7
Size	1"x½"x1/16"
Total antenna length with feeder	361.68
with top & bottom metal hat	364.85
Slots cutting (mm)	
Number of slots	16
Slots total lengths (round included)	14.03
Drill length for all slots	12.53
Slots offsets (from the center)	2.00
Drill bit diameter	1.50
Drill start point – Slot 1 (mm, from the base)	41.32
Drill start point – Slot 2	60.36
Drill start point – Slot 3	79.40
Drill start point – Slot 4	98.43
Drill start point – Slot 5	117.47
Drill start point – Slot 6	136.50
Drill start point – Slot 7	155.54
Drill start point – Slot 8	174.57
Drill start point – Slot 9	193.61
Drill start point – Slot 10	212.65
Drill start point – Slot 11	231.68
Drill start point – Slot 12	250.72
Drill start point – Slot 13	269.75
Drill start point – Slot 14	288.79
Drill start point – Slot 15	307.82
Drill start point – Slot 16	326.86
Feeder position & size (mm)	
Monopole feeder length (from the connector)	7.43
Monopole feeder offset (from the base)	5.21
Monopole feeder diameter	1.50
Feeder hole diameter	3.50





```
%%%
%%% Slot antenna dimensions - WITHOUT FEEDER
%%% Structure Only
%%%
%%% Guenael, VA2GKA
%%%

close all
clear
clc

% setup the simulation
physical_constants;
unit = 1.0e-3; % all length in mm

% frequency of interest (Hz)
f0 = 1.296e9;

% wavelenght of interest
w0 = c0/f0/unit;

% frequency range analysed
f_min = f0 * 0.8;
f_max = f0 * 1.2;

% number of slots
N = 10;

% physical extenal dimentions for the guide
guideHeight = 100.0;
guideWidth  = 200.0;
metalThickness = 4.0;
addCut = 0.0;

% coefficients for the slot (size & offset)
gamma_Aa = 0.93161;
gamma_Ab = 0.0;
gamma_Ac = 0.5;
gamma_Ba = 0.94434;
gamma_Bb = 0.0;
gamma_Bc = 0.5;

% physical dimentions for the slots
slotWidth = w0/20.0;
slotSpacing = sqrt(1/((2*f0/c0)^2-1/((guideWidth-2*metalThickness)*unit)^2))/unit;

slotTilt = 0.0;
slotOffset = gamma_Ba*w0/8;
slotSize = gamma_Aa*w0/2;

% total lenght for the resonnant volume
guideLenght = (N+2)*slotSpacing;

% first slot spacing = 1 mode, center of the slot = 1.5 slotSpacing
firstSlotSpacing = 1.5*slotSpacing;

wallSpace = w0 / 2;
```

```
% mesh and submesh size. Default cell size = lambda/30
stdMeshSize = w0 / 20;
fineMeshSize = stdMeshSize / 5;

% waveguide TE-mode definition (TE10 for the feeder)
TE_mode = 'TE10';

% setup FDTD parameter & excitation function
FDTD = InitFDTD('EndCriteria', 1e-3);
FDTD = SetGaussExcite(FDTD,0.5*(f_min+f_max),0.5*(f_max-f_min));
BC = {'PML_8' 'PML_8' 'PML_8' 'PML_8' 'PML_8' 'PML_8'}; % boundary conditions
FDTD = SetBoundaryCond( FDTD, BC );

% setup CSXCAD geometry & mesh
CSX = InitCSX();

% X Plane fine meshing
a = guideWidth;
b = guideHeight;
xSubCells = [ -a/2-wallSpace -a/2 (-a/2)+metalThickness ( a/2)-metalThickness a/2 a/2+
wallSpace ];
slotOffset = gamma_Ba*w0/8;
psc1A = slotOffset-slotWidth/2;
psc1B = slotOffset+slotWidth/2;
psc2A = -slotOffset-slotWidth/2;
psc2B = -slotOffset+slotWidth/2;
xSubCells = [xSubCells psc1A:fineMeshSize:psc1B psc2A:fineMeshSize:psc2B ];
mesh.x =  sort( unique(xSubCells));
mesh.x = SmoothMeshLines( mesh.x, stdMeshSize, 1.4 );

% Y Plane fine meshing
ySubCells = [ -b-wallSpace -b -b+metalThickness -metalThickness -metalThickness:fineMeshSize:
0 0 wallSpace ];
mesh.y = sort( unique(ySubCells));
mesh.y = SmoothMeshLines( mesh.y, stdMeshSize, 1.4 );

% Z Plane fine meshing
zSubCells = [-wallSpace 0-metalThickness 0 guideLenght+metalThickness guideLenght guideLenght
+wallSpace 0.5*slotSpacing ];
for x=0:(N-1)
    if (x>(N/2-1)) num=(N-1)-x; else num=x; end
    slotSize   = gamma_Aa*w0/2-gamma_Ab*w0/2*(1-atan(gamma_Ac*pi*(-1+num*2/(N/2-1))));

    psc1A = firstSlotSpacing+x*slotSpacing-slotSize/2;
    psc1B = firstSlotSpacing+x*slotSpacing-slotSize/2+slotWidth/2;

    psc2A = firstSlotSpacing+x*slotSpacing+slotSize/2-slotWidth/2;
    psc2B = firstSlotSpacing+x*slotSpacing+slotSize/2;

    pscenter = firstSlotSpacing+x*slotSpacing;

    zSubCells=[ zSubCells psc1A:fineMeshSize:psc1B psc2A:fineMeshSize:psc2B pscenter ];
end
mesh.z = sort( unique(zSubCells));
mesh.z = SmoothMeshLines( mesh.z, stdMeshSize, 1.4 );
```

```
CSX = DefineRectGrid( CSX, unit, mesh );

% external dimention for the guide
start = [ -a/2  0 -metalThickness ];
stop  = [  a/2 -b  guideLenght+metalThickness ];
CSX = AddMetal(CSX, 'PEC'); % define materials (PEC)
CSX = AddBox(CSX,'PEC',1,start,stop);

% extrution guide with piriorities
start = [ (-a/2)+metalThickness -metalThickness 0 ];
stop  = [ ( a/2)-metalThickness -b+metalThickness guideLenght  ];
CSX = AddMaterial( CSX, 'Air' ); % define materials (Vaccum/Air)
CSX = SetMaterialProperty( CSX, 'Air', 'Epsilon', 1, 'Mue', 1 );
CSX = AddBox(CSX,'Air',2,start,stop); % higher priority (2)

disp(['']);
disp(['=== Slot antenna dimensions - WITHOUT FEEDER ===']);
disp(['']);
disp(['Guide Height ................ = ' num2str(guideHeight) ' mm']);
disp(['Guide Width ................. = ' num2str(guideWidth) ' mm']);
disp(['Guide Length ................ = ' num2str(slotSpacing*(N+2)) ' mm']);
disp(['Metal Thickness ............. = ' num2str(metalThickness) ' mm']);
disp(['Number of slots ............. = ' num2str(N)]);
disp(['Add. cut size ............... = ' num2str(addCut) ' mm']);
disp(['Ideal drill bit size ........ = ' num2str(slotWidth) ' mm']);
disp(['']);

% extrude slots
for x=0:(N-1)
    if (bitand (x,1)) pos=1; else pos=-1; end
    if (x>(N/2-1)) num=(N-1)-x; else num=x; end

    disp(['== Slot number ' num2str(x+1)]);

    slotOffset = gamma_Ba*w0/8-gamma_Bb*w0/8*(1-atan(gamma_Bc*pi*(-1+num*2/(N/2-1))));
    slotSize   = gamma_Aa*w0/2-gamma_Ab*w0/2*(1-atan(gamma_Ac*pi*(-1+num*2/(N/2-1))));
    disp(['Slot offset (from the center) = ' num2str(slotOffset) ' mm']);
    disp(['Slot size (total length) .... = ' num2str(slotSize) ' mm']);
    disp(['Slot size (center-center) ... = ' num2str(slotSize-slotWidth) ' mm']);

    start = [ pos*slotOffset-(slotWidth/2) 0                      firstSlotSpacing+x*
    slotSpacing-(slotSize/2)+slotWidth/2 ];
    stop  = [ pos*slotOffset+(slotWidth/2) -metalThickness-addCut firstSlotSpacing+x*
    slotSpacing+(slotSize/2)-slotWidth/2 ];
    CSX = AddBox(CSX,'Air',2,start,stop);
    disp(['Drill start point ........... = ' num2str(start(3)) ' mm']);
    disp(['Drill end point ............. = ' num2str(stop(3)) ' mm']);
    disp(['']);

    start = [pos*slotOffset 0                      firstSlotSpacing+x*slotSpacing-(slotSize/2
    )+slotWidth/2 ];
    stop  = [pos*slotOffset -metalThickness-addCut firstSlotSpacing+x*slotSpacing-(slotSize/2
    )+slotWidth/2 ];
    CSX = AddCylinder(CSX,'Air',2,start,stop,slotWidth/2);

    start = [pos*slotOffset 0                      firstSlotSpacing+x*slotSpacing+(slotSize/2
    )-slotWidth/2 ];
```

```
    stop  = [pos*slotOffset -metalThickness-addCut firstSlotSpacing+x*slotSpacing+(slotSize/2
    )-slotWidth/2 ];
    CSX = AddCylinder(CSX,'Air',2,start,stop,slotWidth/2);
end

% prepare simulation folder & run
Sim_Path = 'tmp_slot_antenna';
Sim_CSX = 'slot_antenna.xml';

[status, message, messageid] = rmdir( Sim_Path, 's' ); % clear previous directory
[status, message, messageid] = mkdir( Sim_Path ); % create empty simulation folder

% write openEMS compatible xml-file
WriteOpenEMS( [Sim_Path '/' Sim_CSX], FDTD, CSX );

% show the structure
CSXGeomPlot( [Sim_Path '/' Sim_CSX] );

% Special thanks to Thorsten Liebig & OpenEMS team
```