Simple antenna for 13cm

A two-part article on designing and then improving a simple tube antenna

PHOTO 1: The finished basic 2.4GHz tube antenna gives around 9dB of gain.

INTRODUCTION. For those interested in a relatively easy to build antenna for the 2400MHz band, the design described here might be the answer. It features high gain, good capture area and directivity, with shielding from strong local signals. The antenna will operate in either vertical or horizontal polarisation as a function of mounting. Design data with complete construction and tuning procedures take the guesswork out of building this wonder antenna, out of a simple copper pipe. It can be used over quite a wide bandwidth centred on 13cm, including the amateur and Wi-Fi allocations.

This article has a step-by-step description of the design and construction of the basic 'tube' antenna that boasts some 9dBd of gain. Next month we will add a capture hood that increases the gain by 3dB for only a small additional effort.

APPLICATIONS. This antenna is currently in use to link the author's radio shack with the home, a distance of around 200m. A pair of these horn antennas can easily link data services using milliwatt-power Wi-Fi access points. The antenna can in fact be used for any 2.4GHz point to point communication. A one watt amateur television signal has been sent over a pair of these horn antennas at a distance of six miles with good P5 results. With appropriate respect for F/d ratio, this horn antenna could be utilised to illuminate a dish antenna. Polarisation is a function of the direction of the probe. Up and down is vertical and 90° to that is horizontal. Both ends of a path need to be orientated in the same polarisation. Your imagination is the limiting factor in applications for this antenna.

THEORY. According to Kraus **[1]** a horn antenna is regarded as an opened-up waveguide. The function of this arrangement is to produce an in-phase wave front thus providing signal gain in a given direction. Signal is injected into the waveguide by means of a small probe that must be critically placed. The type of horn described in this article is known as a cylindrical horn. It was chosen for simplicity of construction utilising available copper pipe.

Sometimes relationships that appear to be relatively simple are in fact very complex. This is certainly the case for the horn antenna. First, the only thing that determines the lowest and highest operating frequencies is the tube diameter. These are referred to as the upper and lower cut off frequency; above and below these, performance deteriorates rapidly. Secondly, there is a critical optimum location for a probe that excites the waveguide horn cylinder. Finally, the length of the tube, shorted on one end, is a modified version of wavelength, but not in free space.

What goes on inside a waveguide is complex to say the least. Instead of propagating in straight lines, the energy bounces off the walls of the cylinder, causing constructive interference due to multiple reflections. The wavelength inside the closed cylinder is different from the wavelength in free space, being rather longer. The reasons it's stretched out are due to in-phase and group velocities within the cylinder. The critical placement of the injection probe reinforces these wave fronts within the pipe waveguide, thus providing signal gain out of the open end of the cylinder. This cylindrical waveguide is physically closed on one end and can be thought of as a shorted piece of coaxial cable.

DESIGNING YOUR ANTENNA. To begin our design, a suitable cylinder must be found. The author used three inch inside diameter (ID) copper pipe since it was surplus from the local public TV station. Offcut pieces of rigid hard line work well and so does copper pluming pipe. Any type of cylinder will work including coffee cans, but thin walled tinplate does not seem very stable and has lower surface conductivity compared to copper. Larger diameter copper pipe sections can sometimes be obtained from pluming/heating contractors. Many commercial boilers utilise 3-4 inch diameter copper pipe. There are often small cut-off pieces (under two feet) that could be available for the asking. *[Editor's note: in this article WA0IUJ uses 3 inch inside diameter copper pipe that is fairly readily available in the USA. Pipes between 76mm and 90mm diameter will work, but will require the dimensions to be re-calculated. Details of how to do this are contained later in the article, and a possible UK source is at* ***[2]****.]* No matter what material you want to use, it must pass the frequency cut-off tests. If the diameter is too large or too small, the pipe will not function properly at your frequency of your choice. The lowest frequency that this cut-off phenomenon occurs is known as the horn low cut-off diameter **[3]**. Without getting into propagation modes, let's refer to this number as the low cut-off frequency. There is also a high cut-off frequency, but we will deal with that later. This low cut off-frequency can be found using the equation below **[4]** (all dimensions in mm).

$\lambda c = \pi \times d/2$
where λc = cutoff wavelength, $\pi = 3.142$ and d is the inside diameter of the tube

Re-arranging slightly,
$\lambda c = 1.706 \times d$
(Equation 1)

PHOTO 2: Raw 76mm copper tube cut to length.

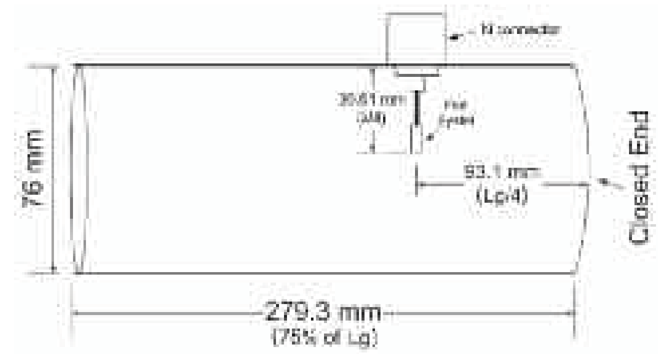

FIGURE 1: Calculated dimensions of the 2.4GHz horn antenna.

The low cut-off frequency fl is then found by using a modified version of the standard wavelength formula:

Critical frequency fl = 300/λc (GHz)
(Equation 2)

The low cut off frequency is a function of only the diameter of the pipe and can be calculated for any diameter.

(Step 1) In the author's particular case, the 76mm (3 inch) diameter copper pipe gave

λc = 1.706 x 76mm
= 129.656mm

Critical frequency in GHz, fl = 300 / λc
= 300 / 129.656
= 2.307GHz

This is the lowest critical frequency that the 76mm diameter pipe will operate.

Step 2 is to calculate the highest cut off frequency (λh) that this diameter pipe will operate as a waveguide antenna [4].

λh = 1.3065 x d

So, using the 76mm example,
λh = 1.3065 x 76
λh = 99.29mm

So, 99.29mm is the critical upper wavelength of this 76mm pipe.

Using Equation 2 again, we can calculate the critical upper frequency:
Critical frequency in GHz, fl = 300 / λh
= 300/ 99.29
= 3.02GHz

So the upper critical frequency for λh is 3.02GHz.

You now have the critical lower and upper frequencies that your pipe will operate as a circular waveguide antenna. For a 76mm pipe, these are 2.30GHz and 3.02GHz, which (just) encompasses the 2.31-2.45GHz 13cm amateur band. A slightly larger diameter pipe of ~80mm would give a more comfortable lower frequency cutoff.

Repeat this process for every diameter pipe you measure until you find one that will operate in the frequency range you desire – you can do the calculations for any pipe diameter or frequency band.

The lower cut-off must be below the lowest frequency on which you want to operate and the high cut-off must be above the highest frequency. Pipes of 76-95mm.

We now have to choose a design frequency within this critical frequency range that you intend to operate this antenna. Let's decide on a design frequency of 2.45GHz for our example. It is at the top end of the amateur band and allows some crossover into the Wi-Fi world.

Step 3 is to calculate the free space wavelength for your design frequency.

λ = 300 / Frequency in GHz
(Equation 3)

λ = 300/ 2.45
= 122.44mm

So the wavelength in free space of 2.45GHz is 122.44mm.

Step 5 is to calculate the overall cylinder length of the horn antenna. The travelling waves inside the tube travel slower than the speed of light, which means that a slightly more complex formula must be used to figure these physical length dimensions of the tube. This modified wavelength distance will be called Lg, the wavelength inside the waveguide. The cylinder is cut to 75% of Lg **[5]**.

$$Lg = \frac{1}{\sqrt{\left(\frac{1}{\lambda}\right)^2 - \left(\frac{1}{\lambda c}\right)^2}}$$

(Equation 4)

λ = 122.44mm (from Equation 3)

λc = 129.656mm (from Equation 1)

$$= \frac{1}{\sqrt{\left(\frac{1}{122.4}\right)^2 - \left(\frac{1}{129.6}\right)^2}}$$

Lg = 372.39mm

The cylinder length is 75% of Lg, ie
Cylinder length = 0.75 x Lg (Equation 5)

= 279.29mm

The cylinder should therefore be 279.29mm long, closed at one end.

CONNECTING IT UP. Now that we know the critical dimensions of your ready-made cylindrical waveguide, some means of feeding this antenna is needed. The behaviour of microwaves inside the waveguide is similar to that of a shorted coaxial cable. The excited signal inside the cylinder reflects off of the closed end of the tube and sets up standing waves that travel through the cylinder toward the opening and are radiated out. If some sort of voltage measuring device (signal probe) was slid inside along the length of the cylinder, we would see points of signal maximum and minimum. Starting at the closed end, the voltage would be zero and maximum at odd quarter wave intervals all along the distance of Lg. The first signal maximum from the closed end occurs at one quarter wavelength in, and this is the best place to excite this waveguide antenna. Now, we have to find this distance **[6]**.

Calculating the distance and depth so a suitable N connector can be installed on the side of the cylinder is done with Equations 4, 5, 6 and 7.

Probe distance from closed end = Lg / 4
(Equation 6)

Lg = 372.39 (from equation 4)

Probe distance = 372.39 / 4

= 93.09mm

An N female chassis connector will be mounted on the side of the cylinder at 93mm from the closed end with a stiff 2mm (14SWG) wire soldered to the connector's centre conductor. This wire needs to be a quarter of the free space wavelength at the operating frequency (2.45GHz).

Referring to Equation 3, the free space value of wavelength (λ) for 2.45GHz is 122.44mm.

Probe length = λ / 4
(Equation 7)

= 122.44mm / 4

= 30.61mm

So the probe length is 30.61mm.

PUTTING IT TOGETHER. Now the hard mathematical work is done, let's start construction of this new horn antenna.

PHOTO 3: The hole for the N connector. Note that the slot either side of the hole is not necessary, although you will need mounting holes for the N connector flange.

Our final dimensions are as follows:

Cylinder (tube) inside diameter = 76mm

Design frequency = 2.45GHz

Free space wavelength, λ = 122.44mm (from Equation 3)

Wavelength inside tube, Lg = 372.39mm (from Equation 4)

Cylinder length, ¾ Lg = 279.29mm (from Equation 5)

Probe distance, Lg / 4 = 93.09mm (from Equation 6)

Probe depth, $\lambda/4$ = 30.61mm (from Equation 7)

Don't be put off by the fact that all of these dimensions are specified to a hundredth of a millimetre. You do not need to be able to work to anything like this sort of tolerance – the nice thing about waveguide aerials is that they are quite wideband and forgiving! As long as you try to work to the nearest millimetre or two you will be fine.

The feed point will be a chassis N connector mounted 93mm from the closed end. A 2mm diameter (14SWG) wire stub will be soldered to the centre conductor of the N connector and will protrude 30.61mm into the cylinder, including a flat eyelet soldered to the end. The eyelet helps broaden the frequency response. The general layout of the basic horn antenna is shown in **Photo 1** and **Figure 1**.

CONSTRUCTION. The first step is to cut the copper tube to the correct length. In our example, Equation 5 showed this to be 279.29mm. Cut the cylinder to length using a hacksaw (**Photo 2**). It is important that the ends of the tube are cut 'true' and square. De-burr and remove tooling marks after cutting.

Next, the hole for the probe should be measured and drilled. In the prototype, the end plate was soldered first but it was quickly learned that this only made it very difficult to put the screws on the connector inside the cylinder! So, first, measure the quarter wave

PHOTO 4: The completed feed assembly.

distance from the closed end of the tube to the centre of your N connector. This would be the probe distance, from Equation 6, 93.09mm (3.66 inches on my ruler). Mark this point and drill out the hole, starting with a small 'pilot' hole and then widening the opening progressively to fit the inner edge of the N connector. In the prototype, a slot (**Photo 3**) was made to move the connector for best output. After testing, there was no improvement in signal within a quarter inch of the exact quarter wave point. The lesson here is that the precise feed position is not that critical – 93mm plus or minus a few mm is close enough.

At this point, the probe must be carefully fabricated to fit into the cylinder hole at the length specified. In our example, this is the result of Equation 7, 30.61mm (1.2 inches), see **Photo 4**. Note the small crimp connector soldered to the top of this wire. In experimenting with the probe depth and SWR, the flat crimp-on connector improved the match over a plain wire. Please make sure that the overall length is exact to the end of the crimp connector and solder all connections.

Now place this entire N connector assembly into the hole and secure with bolts and nuts. Note that the bolt head should be inside the cylinder and the nut on the outside. When things are secure, it is time to solder the end plate.

Cut a flat plate of copper, brass or copper-clad printed circuit board that is larger than the diameter of the tube as shown in **Photo 5**. Place the tube on the plate solder all the way round. You will need a substantial soldering iron to do this, or possibly a gas torch – there's a lot of copper in that tube to heat up.

Mark the diameter of the cylinder end onto flat copper stock or PC board, Place the cylinder over the plate and solder neatly,


PHOTO 5: The end plate can be any shape as long as it's larger than the outside diameter of the tube.


PHOTO 6: The end plate is soldered to the tube. The corners can be trimmed off after soldering.

as shown in **Photo 6**. The corner excess copper can be trimmed after the plate has cooled, but leaving the plate square will have no negative effect on the operation of the antenna.

Once cool, the antenna is ready for testing and can be used in its present form. It will boast a good match and offer about 9dB of gain with a good directional pattern. Next month we will look at how to add a simple capture hood to the antenna that will add an extra 3dB of gain. We will also look at scaling the antenna for use on other amateur bands.

REFERENCES

[1] John Kraus, *Antennas*, McGraw-Hill, 1988, pp 644-653

[2] One possible source for 3.1/8" copper tube is Abacus Tubes Ltd, 01484 515 386; cost is likely to be around £10-£15 plus VAT and delivery. See www.abacus-tubes.co.uk/pages/view_products.php?category=half_hard_copper_tubes

[3] Wheeler, Gershon, *Introduction to Microwaves*, Prentice-Hall, 1963, pp 60-63

[4] G R Jessop, *VHF-UHF Manual*, 4th edition, RSGB, 1985, p9.27

[5] Andy Barter, *International Microwave Handbook*, RSGB, 2002, p58

[6] Norm Foot, Cylindrical Feed Horn, *Ham Radio*, May 1976, p18

Simple antenna for 13cm

Part 2 - double your signal strength by adding a capture hood

PHOTO 1: The completed antenna with the add-on hood that gives an extra 3dB of gain.

INTRODUCTION. Last month we built a simple tube antenna with wide bandwidth and about 9dBd of gain. By adding a simple cone to the antenna aperture we can increase its directivity by 3dB – doubling its effectiveness for a very modest outlay of time and materials. Adding the hood effectively collects signal from a larger area to provide the extra signal gain. Think of it as a funnel.

Recapping, we also learned last month that a common microwave transmission line can be made out of a simple copper plumbing pipe. Our copper pipe became waveguide allowing microwave energy to propagate through the cylinder. If one dimension of the (waveguide) is longer that a half wavelength it will pass microwave energy with extremely low loss [1]. Therefore, if the end of the (waveguide) pipe is simply left open, microwave energy will radiate out from the open end. This pipe waveguide then becomes the horn antenna you built.

In antenna terminology, gain is proportional to aperture size. In so many words the larger the antenna, the more ability that the given antenna has to capture signal. All literature reflects the premise that larger antennas have more gain than smaller antennas. In spite of the dubious claims by some antenna designers and manufactures, there is no such thing as a free lunch. All else being equal, the larger the antenna capture area, the more gain. But a large antenna with poor efficiency is a generic waste of metal. Horn antennas, depending on the propagation mode, must conform to specific dimensions in order for the waveguide to function as an antenna [2]. The previously calculated low cut off λc and high cut off λh basically determine the size, shape and the frequency range for your home made pipe waveguide. Making the pipe longer will not always provide more gain and may even introduce some serious propagation mode problems.

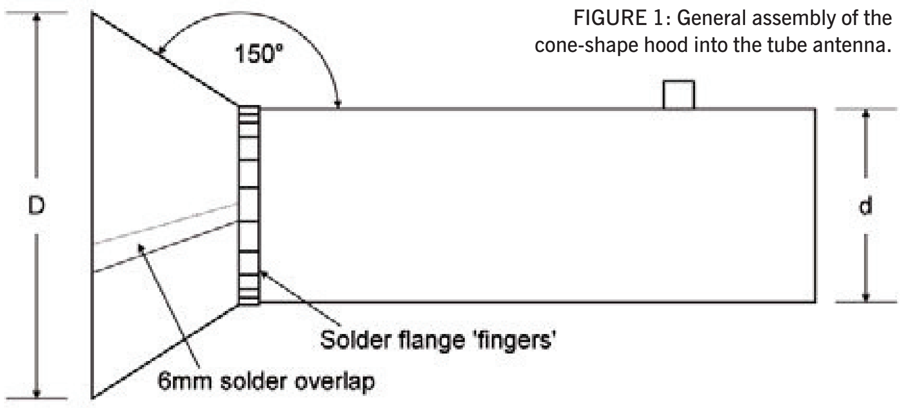

FIGURE 1: General assembly of the cone-shape hood into the tube antenna.

Knowing this information, to improve the horn antenna you built last month, the efficiency or capture area must be modified. For more gain, a larger aperture is desirable, but a larger waveguide is definitely not [3]. What we need to do is to make the waveguide think it's operating within the wave propagation mode inside the pipe but with an aperture actually bigger than the critical waveguide diameter. If the waveguide size is slowly tapered into a larger aperture opening, then more gain is achieved while keeping the undesirable propagation modes out of the pipe. This tapered aperture over the open end of your pipe gives the antenna its characteristic name, a cylindrical conical horn.

Maximum efficiency and gain for a given aperture diameter dictates that the taper must be long enough so that the phase of the microwave front is nearly constant across the aperture [4]. Therefore, the angle and the diameter of the aperture taper are critical to the frequency and waveguide dimensions. For most conical horns, this taper is around 30°, with the cone extension width derived from 1.5 times the free space wavelength dimension λ at the desired frequency. What we have done is to attach a specific type of funnel to the mouth of your waveguide cylinder to improve its overall performance. So the question is, how large does this funnel need to be and fit over the end of the cylinder? Back to the drawing board for a moment and some geometry to find the right size hood for this particular frequency and antenna. What needs to be done is to calculate the radius and diameter of a copper flange that will be soldered to the front of your antenna. The actual hood will end up as a curved copper strip soldered to the outside of the antenna's open end. **Photo 1** shows the general view of the completed antenna and **Figure 1** identifies the measurements necessary to derive the dimensions of the hood.

PHOTO 2: The copper sheet rolled into a cone, with strip cuts into the solder flange section.

PHOTO 3: Soldering the conical hood to the tube.

PHOTO 4: Prototype mounting strap made from aluminium strip.

CALCULATING THE HOOD SIZE. Step 1 is to determine D, the outer diameter of the hood. The outer diameter of the hood should be 1.5 times the free space wavelength λ, which we calculated at 122.44mm for 2.45GHz in Equation 3 last month.

D = 1.5 * λ
= 1.5 * 122.44mm
= 183.6mm

Step two is to calculate d, the inner diameter of the hood. It is simply the measured outside diameter of the cylinder (or the internal diameter plus twice the thickness of the pipe).

In our case,
d = 76 + 2 x 1mm
= 78mm

CONSTRUCTION. Step three is to carefully lay out the above radii over a sheet of thin copper, as shown in **Figure 2**. Remember, the diameters become the radius for d and D. Using a compass, measure from a reference line, 183.68mm and draw the outer arc on the copper sheet. Along the same reference line, measure 78mm and draw the inner arc. Move down below this inner arc 6mm and draw a small arc. This will allow about 6mm (1/4") tabs on the shorter radius for soldering to the outer cylinder end. On one side, extend the D and d lines down about 6mm (see Figure 2) to provide an overlap so you can later solder the shape into a cone. Use tin snips or aviation shears to cut out the outer and inner lines of the copper hood. Roll the strip into a cone shape and make small strip cuts into the 6mm (¼") flange (**Photo 2**) to aid in soldering the hood to the cylinder. Hold the flange together with G-clamps or mole grips and then solder the overlap.

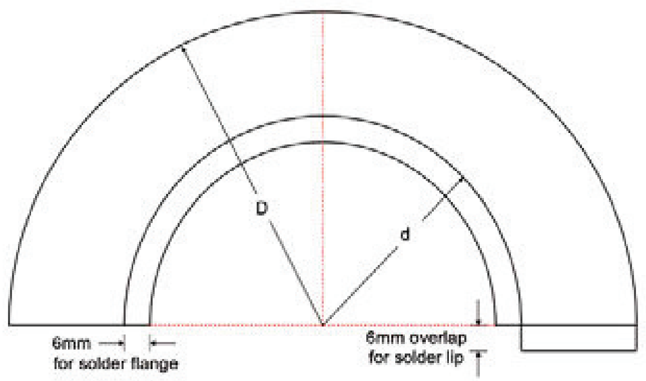

FIGURE 2: Marking out hood dimensions on the copper sheet.

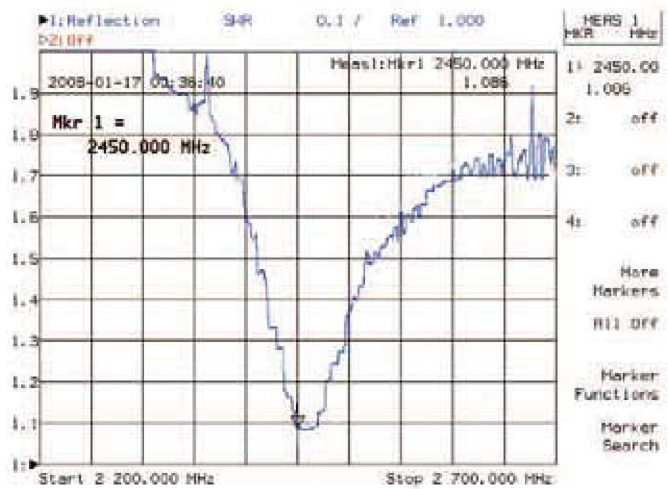

FIGURE 3: SWR plot of the finished antenna.

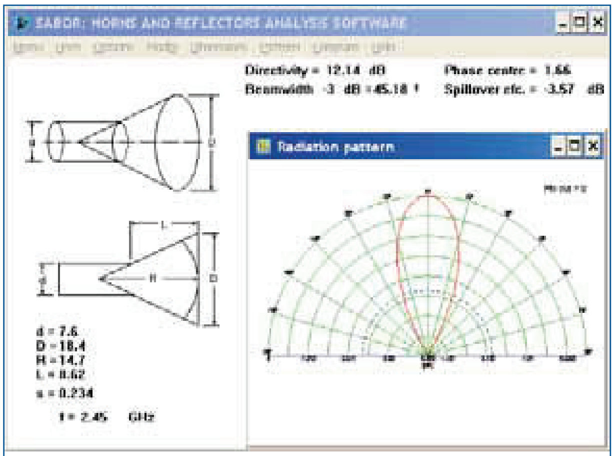

FIGURE 4: *SABOR* simulation of the antenna.

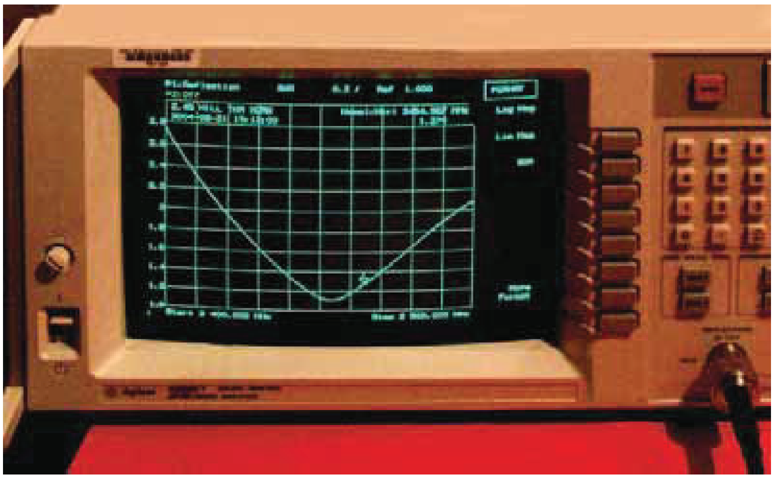

PHOTO 5: SWR plot of the finished antenna, 2.4-2.5GHz (10MHz/division).

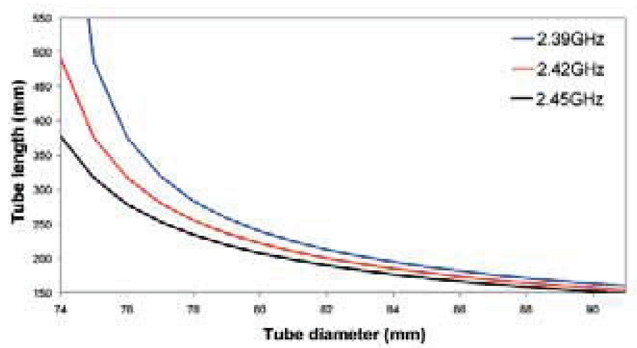

FIGURE 5: Altering the tube diameter and frequency affects the overall length.

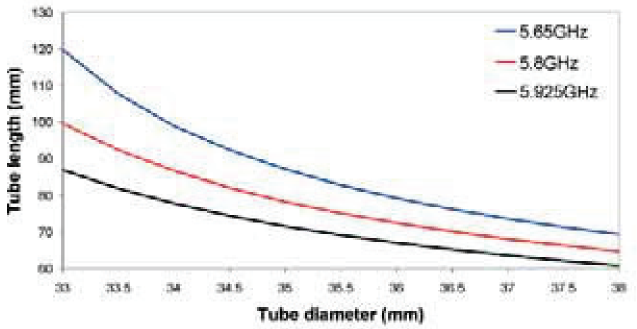

FIGURE 6: Typical tube diameters and lengths for various centre frequencies in the 9cm band.

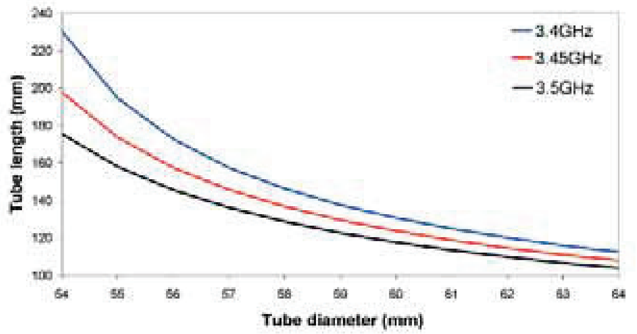

FIGURE 7: Typical tube diameters and lengths for various centre frequencies in the 6cm band.

When you are ready, mould the flange over the end of your cylinder and carefully solder the tabs onto the cylinder, as shown in **Photo 3**. It will probably take quite a lot of heat since copper conducts very well.

MOUNTING BRACKET AND CAP. To complete the project, some form of mount is required to attach your high gain horn antenna to a tower or building. After some consideration, bending a one inch width of aluminium stock worked out well. Bend the flat stock over the horn, then around a former the same size as the mast tube you want to attach it to. Drill appropriate holes for mounting hardware and wing nuts. You should now have a custom horn antenna mounting bracket like mine (**Photo 4**).

In order to prevent water and insect ingress, see if you can find a cover for the mouth of this antenna. Any plastic can be used that passes the 'microwave oven test' (put it in a microwave oven with a cup of cold water. After a minute of heating the plastic should still be cold – if it isn't, it has absorbed microwave energy and will attenuate signals in and out of your horn antenna). At a pinch, and certainly for test purposes, cling film can be used as a short-term fix.

TESTING AND MEASUREMENTS. When I finished my prototype, I decided I would test it. I'm lucky enough to have access to an HP 8714 network analyser that had 3GHz capability. I stood the horn upright with the opening at least a metre away from metal surfaces I configured the analyser for return loss measurement. This provided a nice curve showing a very good match of 1.08 SWR at 2.45GHz (see **Photo 5** and **Figure 3**). The SWR bandwidth below 1.6:1 was 2.40GHz to 2.51GHz. Putting my hand over the front of your antenna hood caused the reading to change drastically – a crude indication that there is an energy field focused in front of the horn.

TESTING IN SIMULATION. In order to test the antenna's theoretical performance, I used a little-known program called *SABOR* **[5]**. This is by the University of Madrid's Engineering department and is available as freeware on the internet. The program was initially written to evaluate several types of waveguide horn antennas. It is perfect for calculating maximum gain, bandwidth, phase centre and generating a plotted pattern of your antenna for evaluating the power gain at different beamwidths.

The program opens up with a welcome page from Madrid, Spain. Hit OK at the bottom, then select Horn … Circular from the menu at the top. You will now see the screen change to a conical circular horn diagram similar to the one we've just built. Please note that the program uses centimetres as its measurement unit – just divide our mm measurements by 10.

Select Options … Frequency and enter the antenna centre frequency in GHz (ie 2.45), then click OK. Ignore (OK) any error message.

Select Dimensions. A window opens that asks for several parameters, several of which we have already calculated so that we could build the antenna. *SABOR* asks for Waveg, Horn radius and a radius value for R1. Knowing our example hood dimensions, d=76mm and D=183.6mm is all that is necessary to utilise *SABOR*.

Waveg is half the cylinder internal diameter, d. In our case, this is 76mm/2 = 38mm, or 3.8cm. Horn radius is half of the hood diameter, D: 183.68/2 = 91.84mm or 9.184 cm. R1 is calculated by dividing D by 1.25. For our antenna it's 83.68/1.25 = 147, or 14.7cm. s is calculated automatically. Enter the figures and click OK.

Now we can start seeing the polar pattern. Select Options … Automatic and Options … Polar. Finally, select Pattern, and the familiar radiation plot will appear (**Figure 4**). Using the dimensions and frequency data we've entered, the program has calculated a forward gain of 12.4dB and a 3dB beamwidth of a touch over 45°. Not bad for a bit of pipe!

DIFFERENT PIPES, DIFFERENT BANDS. Part 1 of this article mentioned that a range of different pipe diameters were suitable for use at 13cm. However, the pipe diameter has a significant effect on the tube length (as does, to a lesser extent, the frequency). **Figure 5** shows the effect on the tube length of altering the diameter and frequency.

The same calculations from Part 1 can be used to determine the dimensions of tube antennas for any frequency, although the pipe diameters become impractical if you go much below the 1200MHz band. At 144MHz, for instance, you could easily drive a large car through the pipe… However, higher bands are eminently suitable. **Figures 6** and **7** show the tube length and diameters for various frequencies in the 9cm and 6cm bands.

Have fun experimenting! The maths in this article lends itself quite readily to what-if calculations in a spreadsheet and you can see what sort of results you'll get by using *SABOR*.

ACKNOWLEDGEMENTS. I would like to thank Dustin Larson who fabricated prototypes of this antenna during the development and testing phases and Jeremy Vogel, KC0OQR for his assistance with the graphing programs.

WEBSEARCH

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[3] John Kraus, Antennas, MCGraw-Hill, 1988, p653-654

[4] Stephen Adams, Microwave Theory and Applications, Prentice-Hall, 1969, p61-63

[5] SABOR can be downloaded for free personal use at www.gr.ssr.upm.es/sabor.htm. The University asks for a small donation if you use it a lot.