3D Printing Microwave Antennas

VHF Super Conference 2019, By Glenn Robb, KS4VA

Can I do it?

If you have been using a 3D printer or considering buying one, then you probably have thought about 3D printing some antennas. You may have seen them in social media or even magazine articles. But do these antennas work? Has anyone properly tested them? Can I do it in my own ham shack?

Don't worry, the answers are definitely "yes"!

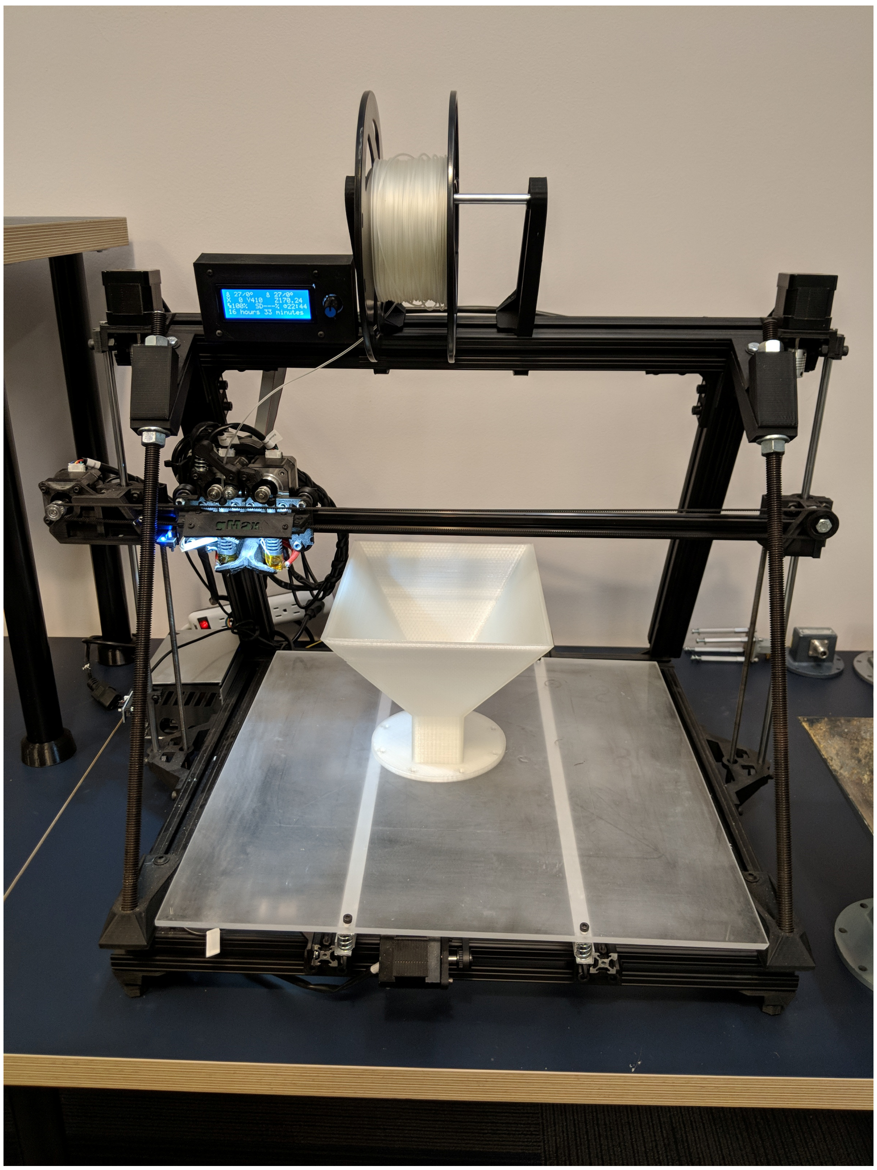

Figure 1: 3D Printing a Plastic Horn Antenna

How We Started

We decided to give it a try ourselves, and to add some value to the conversation. Since we are a commercial antenna testing service with an RF anechoic chamber, we can perform detailed free-space evaluations to see what works and what does not work. So, we embarked on the journey of building, optimizing, and testing 3D printed horns to develop and verify some simple construction processes. In the end, it turned out to be quite practical, but not without a trashcan full or horns and lots of trial and error.

We approached this in the spirit of true science, by creating plastic horns that could be verified against their commercial all-metal counterparts. So we chose to 3D print, metalize, and test the family of 15 dBi standard gain horns. Their simple rectangular horn shape design is decades old, and their standard geometries have very predictable gain. These "waveguide" horns have readily available coax launches (adapters) easily found surplus, purchased new, or even 3D printed. Despite their simplicity, commercial standard gain horns are expensive, normally priced from $500 to $1500. Contrast this to a spray metalized 3D print costing a few dollars!

Figure 2: 3D Printed Horns Smallest K-Band to Largest S-Band

We limited our scope to the 2-40 GHz frequency range. This range encompass the practical limits of common 3D filament printing. In the S Band (2-4 GHz), the standard gain 15 dBi horn is the size of a salad bowl and requires a large format printer (unless assembled from smaller partial prints). In the Ka band (26-40 GHz) the same 15 dBi horn will fit into the palm of your hand, and will challenge the tolerances of most typical 3D printers.

Metallization

When thinking about how to make the surface of a plastic part conductive, several ways come to mind.

- "Conductive" printing filaments are available, so why not just print a conductive "metal" antenna? Unfortunately, the conductive filaments available today are only modestly conductive since they contain mostly plastic for printability. Our experience in microwave antennas and experience with this project tells us that near perfect surface conductivity is required for working microwave horns.
- Foil coverings or gold leafing. This could work but was not tried by us. Getting a continuous metal surface would be tough with small patches of foil that would tend to be isolated from one another by the glue used to adhere them.
- Electroless plating is used in commercial plastic antenna parts. Unfortunately, the processes involved in plating plastics can be poisonous and complicated. There is a more obvious solution.
- Conductive paints have been available for decades and are often used for shielding in plastic enclosures. We chose the MG Chemicals brand of shielding spray paints for metallization because they are easy to buy (even on Amazon) and simple to use. "Plating" an antenna is as simple as spray painting any object.

Humble Beginnings

Our first test antenna was a popular X band horn (8-12 GHz) with a modest 4 inch aperture. Two copies were printed to evaluate two common shield paints: "841 Super Shield Nickel" and "843AR Super Shield Silver Coated Copper". Each was given two spray coats with drying time in between. The spec sheets for both paints showed impressive surface conductivity numbers and the metalized horns simply looked great! We had high expectations.

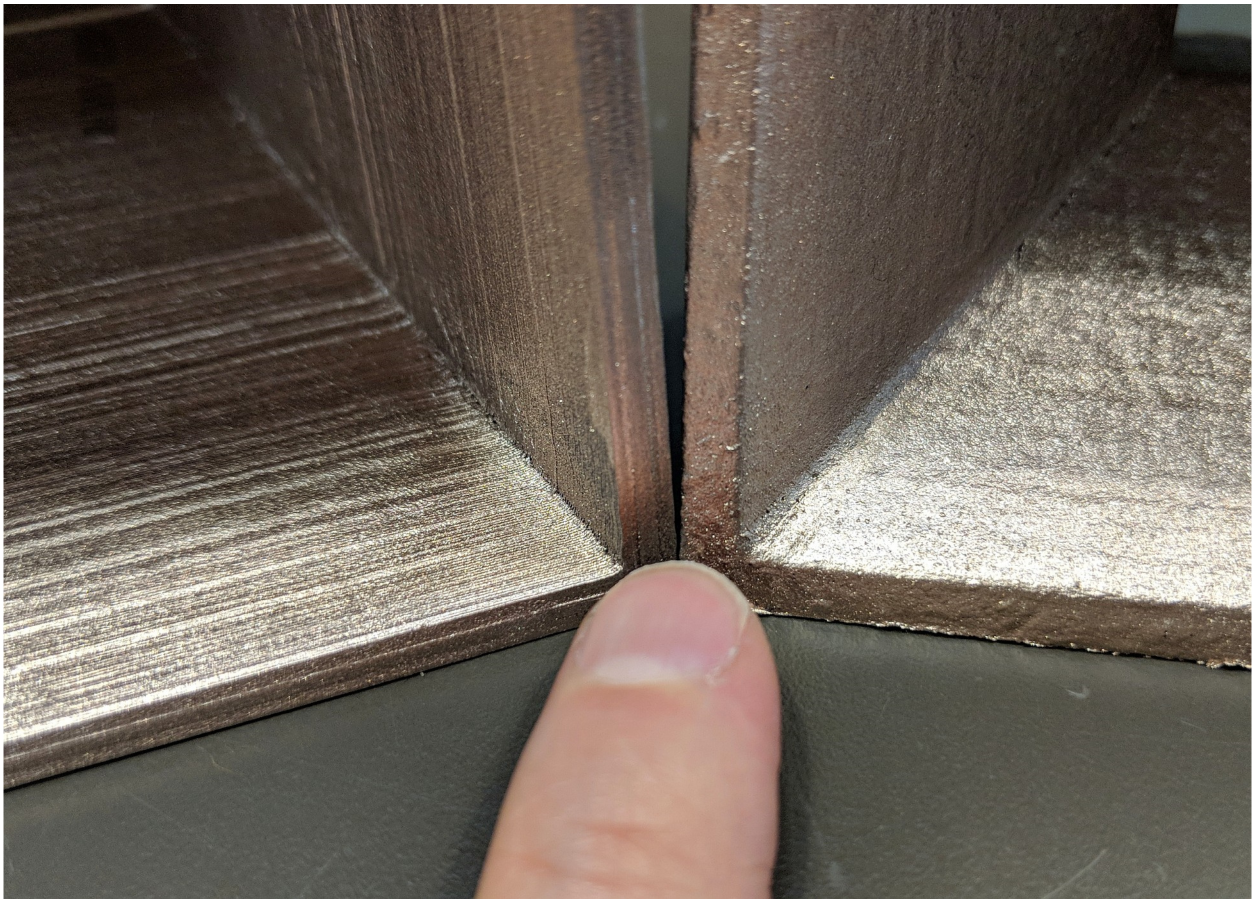

Figure 3: Surface View of an X-Band Horns (rough vs smooth)

We Had It Rough

However, when patterned in the anechoic chamber, the initial results were terrible. Forward gain was only about 5 dBi, well below the expected 15 dBi "standard". Yet a detailed review of the test results showed that something was working. Both antennas had directivity of about 15 dB and the proper beam widths. Keep in mind that absolute gain equals directivity subtract loss. So these were working horns, albeit with 10 dB of internal losses.

Their VSWR/return loss was "great" at better than 20 dB (or 1.2:1). The only explanation was that the realized surface conductivity was poor, causing the horns to suffer high radiation losses.

Pre-Testing with VSWR

We devised a simple bench test to prove out this theory so we can all "pretest" antennas for this kind of loss. Measuring the return loss (VSWR) of an antenna is the most common performance test (and does not require an anechoic chamber). The rule of thumb is that high return losses of more than 10 dB (or 2:1) point to a "good" antenna. The thinking is that 90% or more of transmitted energy sent to the "good" antenna will radiate because it does not reflect back to the source. This is common test assumes the antenna has small or zero losses. However, a lossy antenna, or even a "dummy load" also has great return loss too!

Now consider the low return loss (high VSWR) from a short circuit. If you short a coaxial cable or the aperture of a low loss metal horn antenna, you can expect a large reflection. We verified this approach on "shorted" lab grade commercial horn antennas by covering their apertures with aluminum cooking foil. The same shorted aperture test on the initial 3D printed horns showed large (> 20 dB) return losses, indicating they were better attenuators than antennas!

We deduced that surface roughness in the 3D printed plastic caused the highly conductive paint to increase in realized resistance. The insides of the test horns were smoothed and re-coated.

In the figure below you can see that the smoothed surface antenna shows the desired low return losses (high VSWR). While there is some ripple due to the imperfect cooking aluminum foil "short" on the horn, the important thing to look for is some frequencies of low (approximately 1 dB) return loss. This could not happen if the inside surface of the antenna were lossy.

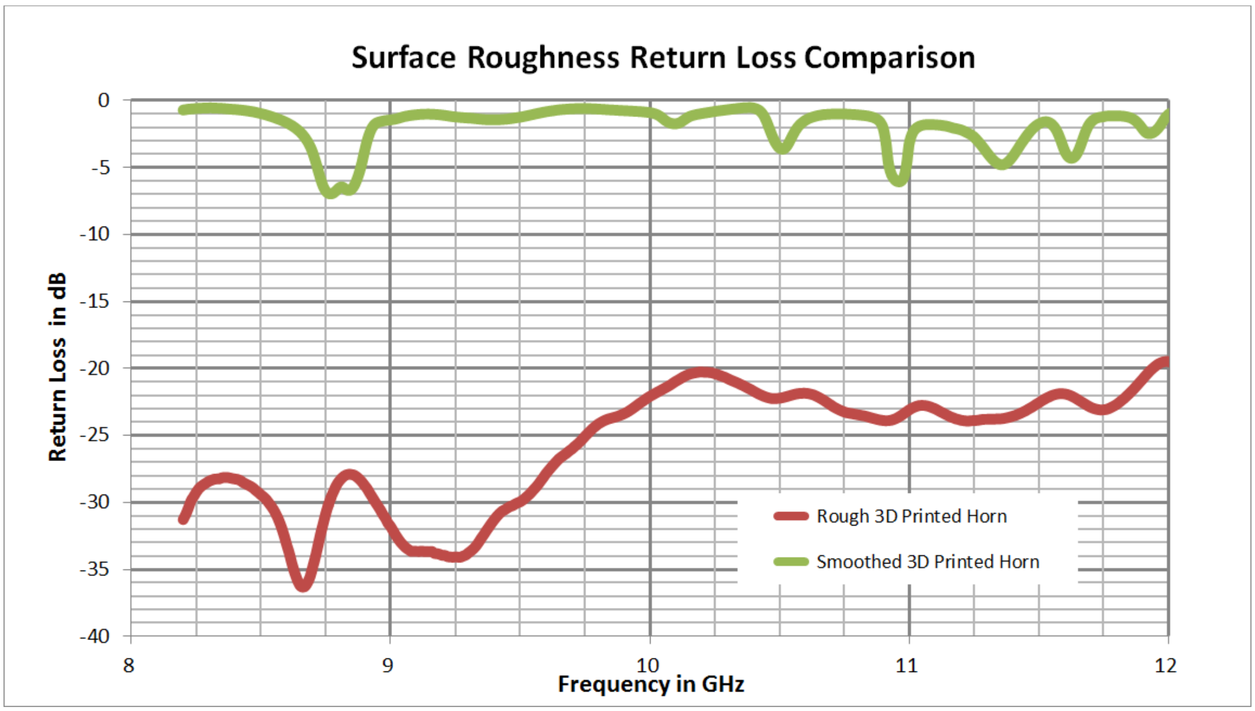

Figure 4: Return Loss of Shorted Aperture 3D Printed Horn Antennas

Despite the shiny appearance of the metalized paint, and zero-ohm meter resistance readings, the rough surface resistance was a serious loss mechanism. The tiny surface ripple artifacts of the 3D printing layers are indeed small compared to the relatively large operating wavelength (1 inch at X Band). However, surface smoothing did eventually prove to be the key to removing this loss and achieving the target 15 dBi gain across the whole family 2-40 GHz standard gain horns. Even applying multiple “liberal” coats of conductive paint did not sufficiently lower this loss without prior surface smoothing.

Be Prepared: Surface Preparation

Your goal is to remove the rough layer ridges of your 3D print, but the technique is up to you. There is no right or wrong way. The method that you prefer will probably depend on the size of the antenna and the tools at hand. Here are some options that we tried.

Sanding

Sanding is an obvious way to smooth the 3D layer surface roughness. It works well, but it is time consuming. The horn’s funnel shape also creates triangular facets that are enclosed and tapered making many power sanding tools impractical. The triangular shaped sanding pads of some oscillating sanders can reach into the mouth of a horn antenna and make progress. To sand the rectangular waveguide section, you may want to wrap a sanding block with sandpaper. You can 3D print a custom sized block that acts like a broach when slid in and out of the waveguide.

Alternatively, you can print your antenna in two halves to allow better sanding access, then glue them tighter before spray metalizing. The seams of the glued joints will fill with the liquid paint and will not be a performance issue. Sanding does not need to be mirror smooth. Using 150 grit paper is enough, just as in woodworking or decorating, where the paint viscosity is high enough to fill these small scratches. It’s only the 3D printing “ridges” you need to remove.

Filing

Our favorite technique for smaller horns (apertures under 2 inches) was simply to file them. Files are inexpensive and sets with lots of different profiles can easily be found in the home center or online. A selection of shapes and sizes allows you to reach into corners and within the waveguide section. And of course, plastic is much easier to file than metal, so the process is quick for small antennas. A rigid file often flattens better than the more conformal sandpaper. The filed surface is smooth enough and needs no other preparation before conductive paint.

Solvent Smoothing

After lots experimentation, we found that “solvent smoothing” was the most time efficient and least effort for horns bigger than 2 inches. Acetone is a well-known and useful solvent for ABS plastic prints, and it worked nicely on prints from our smaller ABS filament printer. Our large format printer only uses PLA filament, which did not seem to have a readily available solvent. However, a little research uncovered dichloromethane (methylene chloride) and a gallon was purchased on Amazon. It was highly effective at softening and smoothing the surface roughness on PLA plastic, the most common 3D printing filament.

Figure 5: Solvent Smoothing Done Outdoors

Chemical Safety

Both solvents are hazardous, but dichloromethane is especially poisonous. You will need to take a lot of personal responsibility for your own safety when using it. Historically the key ingredient in common paint stripper, dichloromethane is being phased out due to its toxicity when used for DIY home projects. After some trial and error, we found the following process worked well. The resulting smoothed surface is shown in the right of the Figure 3.

Protect Yourself

Use solvent outdoors, since the proverbial "adequate ventilation" is usually NOT practical indoors. Even outdoors, you will still need a respirator mask that is rated for organic solvents (commonly available for oil-based painting or automotive painting). Use full length chemical gloves that are specifically rated and labeled for your solvent. Since chemical gloves are usually thin and delicate, protect them by wearing "work gloves" over top of them. This is important because using steel wool will quickly wear through unprotected "rubber" gloves. You must also wear eye protection, since you will be splashing and brushing solvent.

Solvent Smoothing Outdoors

We found it convenient to pour solvent into a common metal paint-roller tray and use this to brush on, scrub, and re-catch the solvent. Disposable hog hair bristle brushes are best along with steel kitchen pot scrubbing pads or coarse steel wool. Any of these are easy to find in your home renovation center. Don't use plastic brushes or the green/blue plastic kitchen scrub pads, since the dichloromethane will soften them. It takes only a minute to smooth the inside of even the largest horn with the pot scrubber (or steel wool) if it is kept wet with solvent. A round bottle brush also easily scrubbed the waveguide portion of the horn. There is no need to smooth or metalize the outside of the horn, just work the inside surfaces and mating flange.

If you are assembling a larger antenna from smaller prints, now is the perfect time to "solvent weld" the already softened parts. Press and hold them together for about a minute while the solvent evaporates, and the plastic hardens.

Smooth Epoxy Coating

There is yet another practical option available for surface smoothing. For larger prints it is less work that sanding, and less toxic than solvents. You can cover the rough 3D printed surface with a thick paint-on two-part epoxy coating. We tried "XTC-3D" from smooth-on.com, and it worked well for prints up to 18 GHz. Use some quick pre-sanding or filing if your 3D print quality is low or flawed. The glue is easy to measure and mix according to the manufacturer's directions. Application is easy too, but the glue is a little too thick for very small parts, often those above 18 GHz.

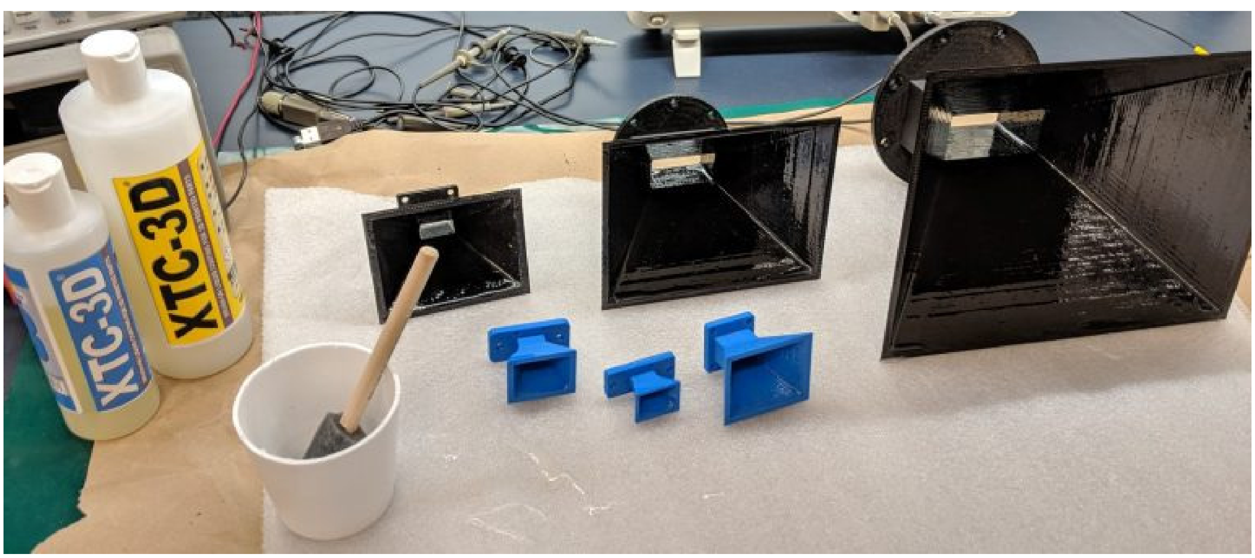

Figure 6: Smoothed Epoxy Coated 3D Prints

The cured shiny surface looks great but will not accept the metalized paint until lightly sanded. While less work than sanding smooth a rough 3D print, you will not be able to avoid this step. Any non-sanded sections of "shiny" epoxy will not accept any spray paint. We found inside corners to be problematic. In this photo, you can see blue plastic peeking through the conductive paint where the epoxy was not completely sanded in the corners.

In horns from 18 to 40 GHz, the wave-guide features were just too small for the relatively thick coating. Critical dimensions were distorted, and holes and inside radiuses were starting to get filled in. However, antennas are quite tiny at these frequencies and you can smooth them quickly with small hobby files. There is really no need for solvent or epoxy coatings for antennas this small.

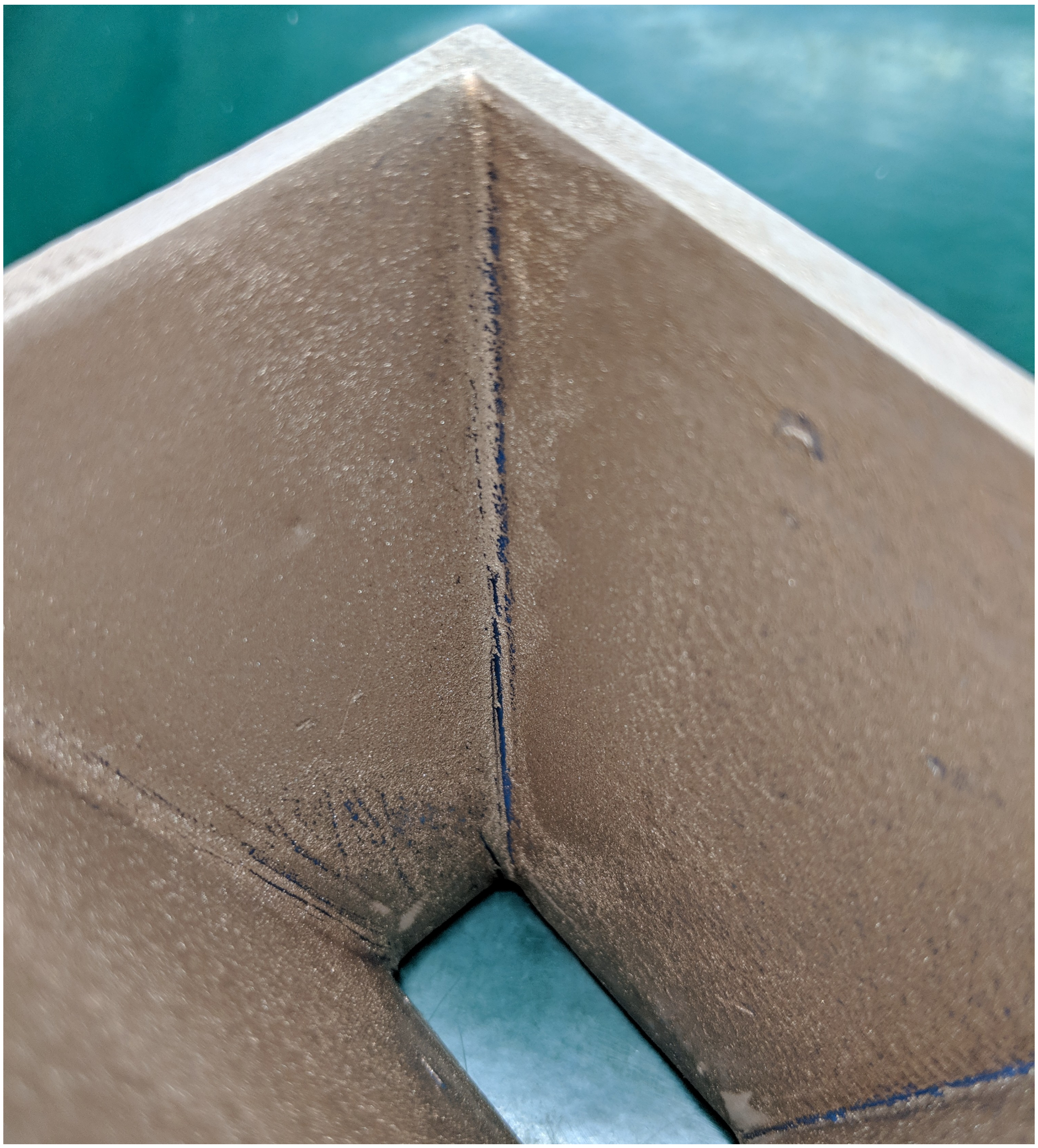

Figure 7: Conductive Paint Gaps Over Shiny Epoxy

Metalized Coating Choices

Applying the conductive spray paint is straightforward. Just proceed as you would spray paint any object. It is best done outdoors too, holding the antenna in one hand with a glove allowing easy reorientation to get at all inside surfaces and the flange. Excess paint is simply shaken off. Two coats were always used and worked well. Paint drips and drops might ruin a car paint job but they seemed to be irrelevant for antenna work. Use the spray liberally and shake off any excess.

The #841 nickel version of the paint seemed to have several dB of loss at higher frequencies despite surface smoothing. We recommend the #843 copper silver version which produced standard gain horns without any discernable efficiency losses from 2 to 40 GHz. The chart below shows the nickel paint's performance shortcoming (surface loss) in the S-band compared to the copper silver version.

Figure 8 shows just how good these horns can be. It compares a lab grade Waveline Model 299 Standard Gain Horn Antenna (15 dBi S-Band model) and two 3D printed exact copies. The plastic versions were both printed in PLA, solvent smoothed, and spray painted as described here. All three antennas were tested using the same Waveline Model 201NF Coax Adapter. The copper/silver painted 3D printed antenna's gain was only +/- 0.2 dB different from the commercial solid metal horn antenna, well within measurement repeatability. The third curve on this graph shows the poorer performance of the nickel based conductive coating. This formulation displays about 0.5 dB less gain here, and gets worse by up to 5 dB at 10 GHz.

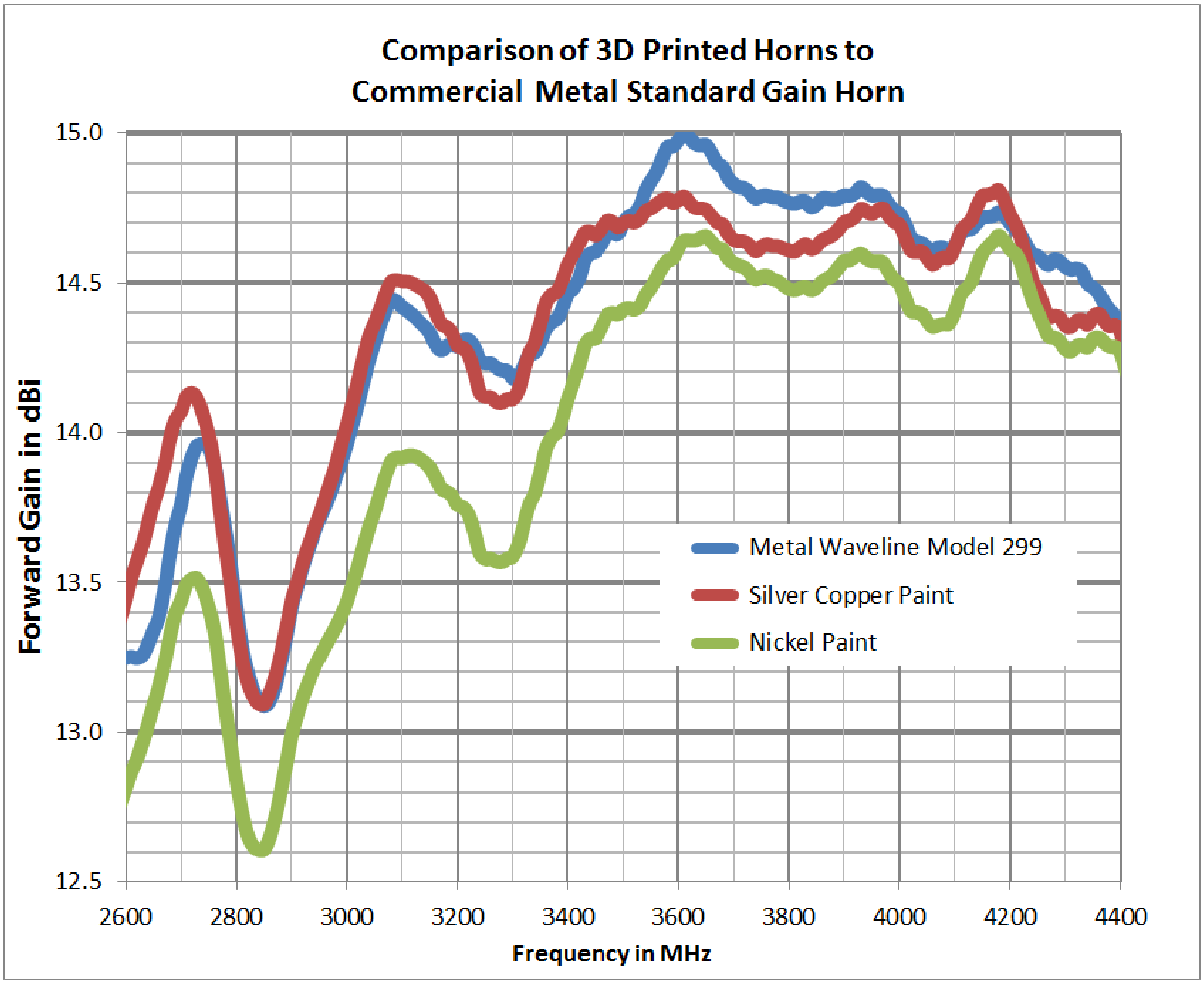

Figure 8: Comparing Spray Coated and Solid Metal S-Band Horns

Above 18 GHz

We initially found that the copper silver version spray shielding paint worked well up to 26 GHz. But from 26 to 40 GHz the tiny Ka band horns still displayed about 3 dB loss by having only 12 dBi of gain (even when solvent smoothed). This was easily solved by sanding the horn extra smooth with a tiny file and repainting it. Since this Ka band horn is only an inch in size, its soft plastic walls were trivial to file smooth in just a minute. This extra smoothing step allowed it to display very low shorted aperture return loss on the bench and fully restored its expected 15 dBi gain in the chamber.

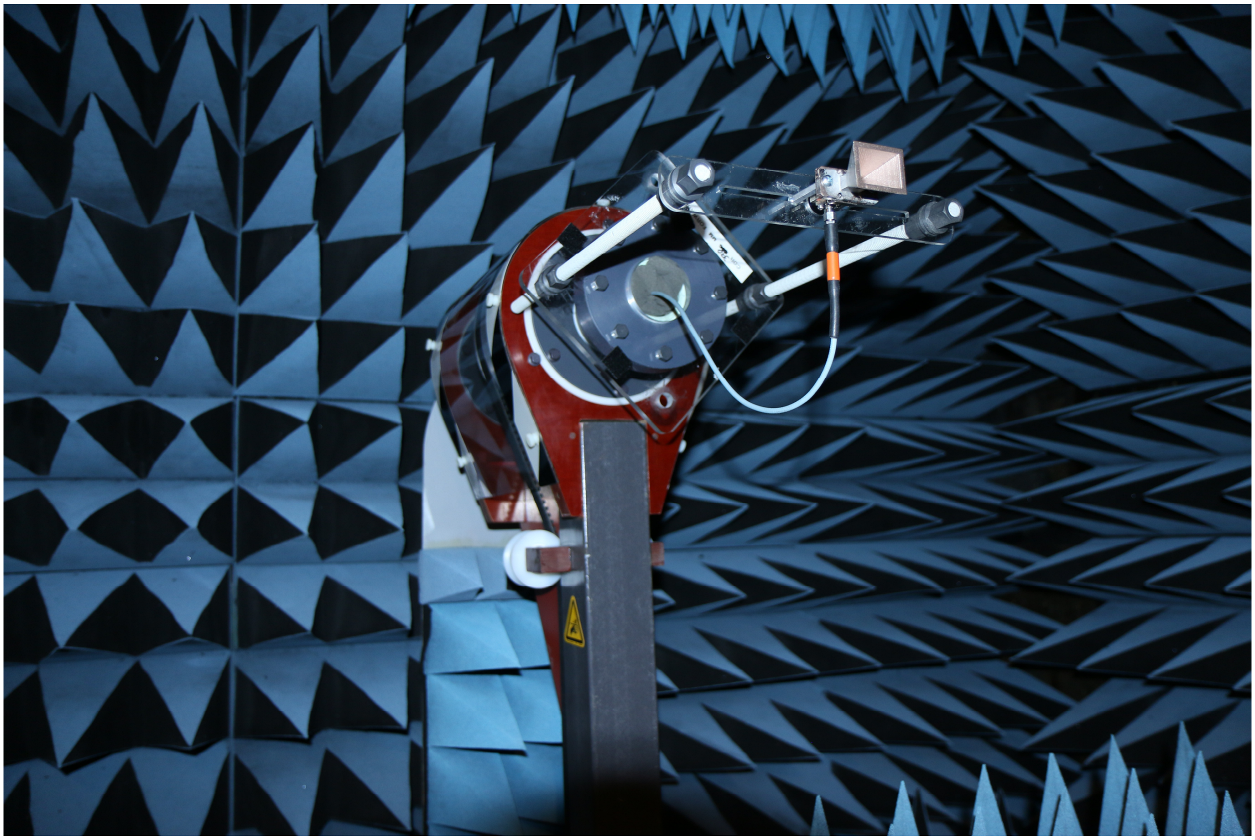

Figure 9: 3D Printed K-Band Horn Antenna in Anechoic Chamber

Success

Anyone can 3D print working microwave antennas using common materials and "home-brewing" skills. Just smooth the active surfaces with your preferred technique then use our recommended conductive paint. If you can check the shorted aperture return loss / VSWR and verify that it has very low return loss (less than 1 dB), you can reasonably expect the same antenna performance as a solid metal antenna.

Complex shapes can be accommodated by splitting 3D prints into sections that allow for sanding/smoothing access before assembly by gluing or solvent welding. You can make various "cavity" electromagnetic parts like wave guides or coax-adapters this way. The conductive spray paint easily flows over and obscures surface sanding scratches and seams.

The beauty of 3D printers is their versatility. We focused here on standard gain horns for the sake of comparison and process debugging. With 3D printing you can explore much more complicated and curved shapes that would be next to impossible to machine from metal. There is no reason to restrict yourself to horns only, you can also design and print waveguide launches and or polarizers.

As long as your geometry allows access to the inside surfaces, epoxy-coating or solvent smoothing can take care of curves and sweeps that would be hard to hand sand.

Results

The graph in Figure 10 below shows the measured gain of our entire family of 15 dBi horns from 2 to 40 GHz, all hitting their gain targets.

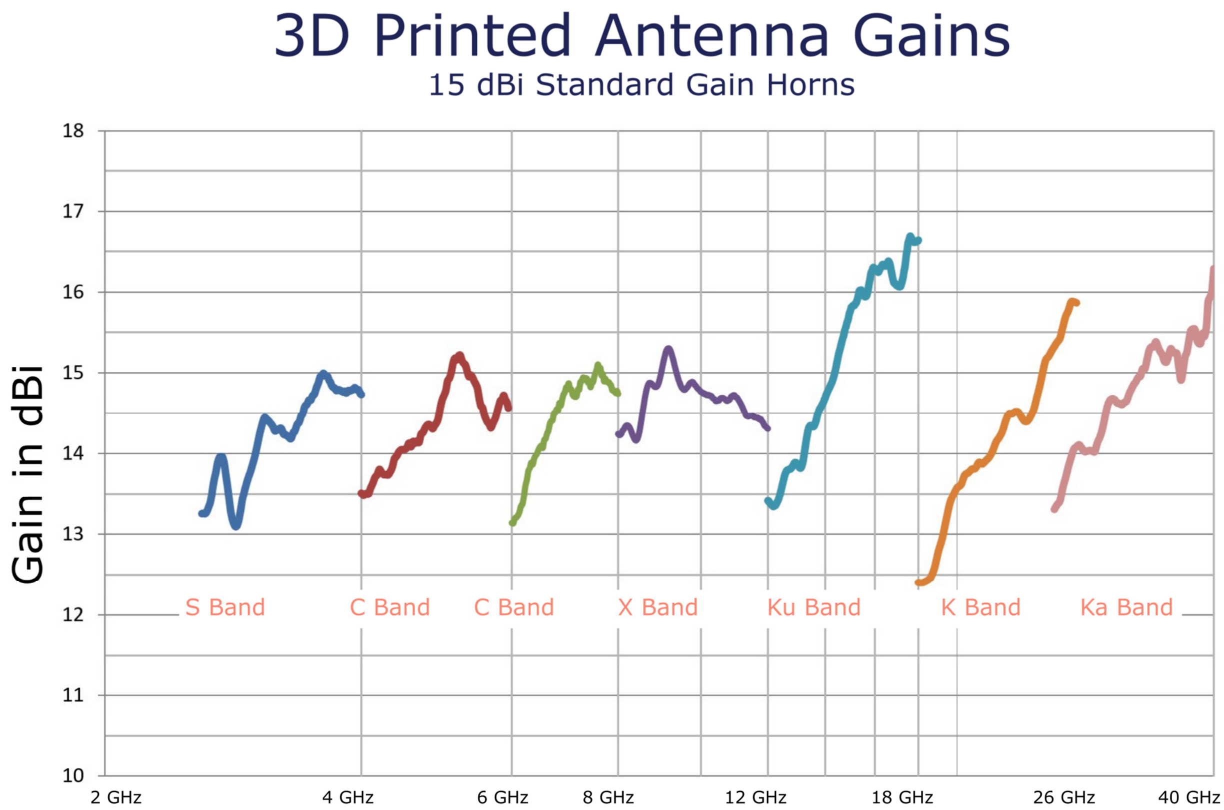

Figure 10: Antenna Performance from 2 to 40 GHz

If you would like to experiment further, we have made the STL printable files available for download. All 3D designs were done with "SketchUp Make 2017", a free 3D CAD design tool. The SketchUp files and STL files for these horns are also downloadable if you would like to edit the geometries or print your own standard gain horns. Links can be found at

www.AntennaTestLab.com\3Dprinting