

3D Printed 122GHz Cassegrain Assembly by Michelle W5NYV

Introduction

The amateur microwave community has a band at 122GHz¹. There's a need for more equipment, more results, more rigs, and more activity. The big challenges are very large atmospheric absorption (Oxygen absorption is very strong near 122GHz), unknown propagation profiles, and limited or expensive components. A sounding study² at 122GHz revealed interesting polarization interactions with cirrus clouds. Obviously, a lot more can be found out about 122GHz and higher bands.

After Microwave Update 2015³, the intrepid experimenter Alan Devlin VK3XPD wrote me and asked about the possibility of designing and 3D printing models for Cassegrain sub reflectors for 122GHz and up. A Cassegrain antenna is one of several types in the category of antennas called *multi-reflector antennas*. Instead of the feed being at the prime focus of a parabolic dish, the prime focus of the dish is occupied by a *sub reflector*, and the feed is in or near the center surface of the dish. Reflection is in two stages. For a Cassegrain, the sub reflector at the prime focus of the dish is a hyperbola.

Here is a photograph⁴ of a deep space network Cassegrain antenna.



Isn't it lovely?

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The most common shortcut tactic is to use a flat sub reflector, but a hyperbola matched to the geometry of the dish gives better performance. Alan pointed me to Paul Wade's excellent paper on Multiple Reflector Antennas⁵. This is required reading and is the basis for the work described in this paper.

Paul Wade writes, "Most amateur antennas have a more definite starting point: the availability of a good dish or a good subreflector. The problem is then simplified to the optimum design of the other components. Another important question is whether the Cassegrain system is any better than a conventional prime-focus antenna using the same dish."

See a wonderful video⁶ of Chris G0FDZ and Roger G8GUB 122GHz Testing UK Microwave Group Round Table Meeting June 2017. As you can see in the videos and in the photos at the 122GHz website at Microwavers⁷, experimenters often start with commercially available dishes, such as the Procom 25cm dish with an f/D of 0.4. The price for this dish, with sub reflector and flange for waveguide, runs between €250 and €300 (\$300 to \$350).

Paul Wade continues, "Jensen's emphasis is on high performance — the additional complexity of a Cassegrain should provide some benefit. To minimize loss from diffraction and spillover, he suggests that the subreflector be electrically large, greater than 10 wavelengths in diameter, or about 1 foot at 10 GHz. The subreflector diameter should be less than 20% of the dish diameter to minimize blockage by the subreflector, so the dish should be larger than 50 wavelengths diameter. Jensen includes curves to help in comparing the various losses to make tradeoffs. The curves clearly show antenna efficiency decreasing rapidly for subreflectors smaller than ten wavelengths and for diameter ratios greater than 0.1."

122GHz wavelength is 2.5mm. For 122GHz, the sub reflector would be greater than $2.5\text{mm} \times 10$, or 25mm. About an inch. The dish should be larger than $2.5\text{mm} \times 50$, or 125mm. That's not big.

What if we made the sub reflector really large? And used a large dish?

Or, what if we make it exactly those dimensions, 25mm and 125mm, and 3D print the whole thing, with an integrated feed and sub reflector that are matched up to the dish?

Or, better yet, what if we made a model that was parameterized, so that the entire printing volume of an arbitrary 3D printer could then be used? As long as it was larger than the minimums in the Jensen paper quoted by Paul Wade, the dish assembly should work at 122GHz. The larger the better, to get away from some of the small dish problems that we will definitely experience if we hover near the minimum.

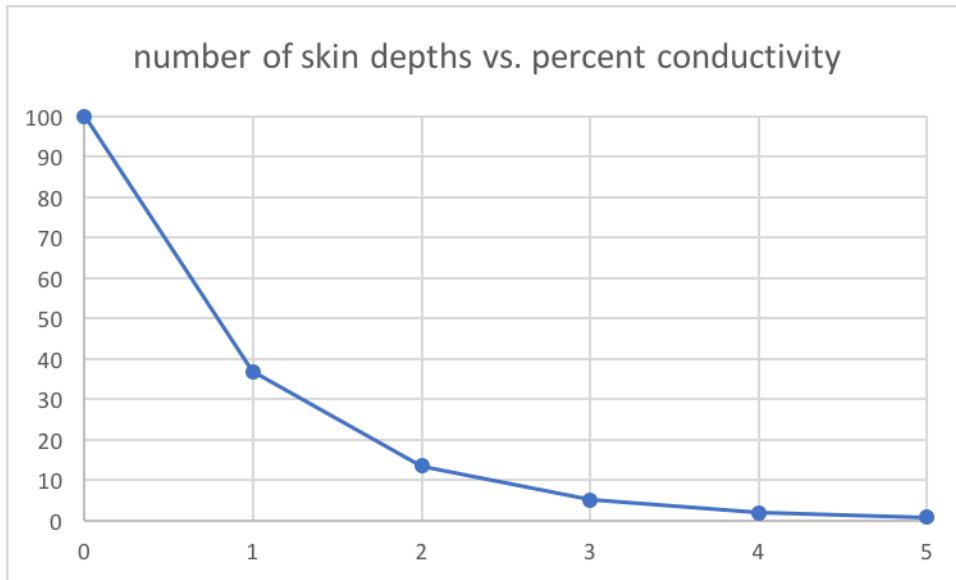
We know from 10GHz experiments that conductive paint on 3D printed plastic makes working antennas that behave the same as ones made from metal. Will conductive paint work equally well at 122GHz as it did at 10GHz? MG Chemicals Super Shield Silver Coated Copper Conductive Coating, which is what we used at 10GHz, has a *skin depth* that in theory should work at 122GHz. Skin depth is a measure of how far electrical conduction takes place in a conductor. Surface conductivity of a layer of metal, like our conductive paint on top of 3D printed plastic, is a function of frequency. Conductivity decreases exponentially from the surface down into the

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layer.

At the surface, conductivity is 100%. At one skin depth, it's decreased to 36.8%. At two skin depths, it's down to 13.5%. At three, it's at 5%. At four, 1.8%. At five, 0.7%.

If you are like me, then look at this picture instead:



With five skin depths of metal, we have covered virtually all the conduction. Losses come from the surface getting marred or corroded or scratched, but we love our surfaces and we're going to take care of them.

So what is our skin depth at 122GHz? Luckily, we can calculate that⁸ for various types of metals and frequencies.

Select the Conductor Material: <input type="button" value="Silver"/>	Resistivity (ρ): <input type="text" value="1.586"/> $\times 10^{-8} \Omega \cdot m$
Enter the required Frequency: <input type="text" value="122000"/> MHz	Relative Permeability (μ_r): <input type="text" value="0.99998"/>
	Skin Effect Depth: <input type="text" value="0.1815"/> μm

Select the Conductor Material: <input type="button" value="Gold"/>	Resistivity (ρ): <input type="text" value="2.24"/> $\times 10^{-8} \Omega \cdot m$
Enter the required Frequency: <input type="text" value="122000"/> MHz	Relative Permeability (μ_r): <input type="text" value="1"/>
	Skin Effect Depth: <input type="text" value="0.2157"/> μm
<input type="button" value="Calculate"/>	

Select the Conductor Material: <input type="button" value="Nickel"/>	Resistivity (ρ): <input type="text" value="6.84"/> $\times 10^{-8} \Omega \cdot m$
Enter the required Frequency: <input type="text" value="122000"/> MHz	Relative Permeability (μ_r): <input type="text" value="600"/>
	Skin Effect Depth: <input type="text" value="0.0154"/> μm

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So how thick is the paint? Nozzle size and spray time are the two most important factors. There's a study about this⁹. Since the skin depth for silver at 10GHz is 0.6338, and two coats of the conductive paint made a 10GHz horn that was indistinguishable from an identical metal horn, and since the skin depth for silver at 122GHz is less than 10GHz, we expect successful conductive paint results at 122GHz and therefore decided to stay with the MG Chemicals Super Shield Silver Coated Copper Conductive Coating. Only one can has leaked all over the floorboard of one car so far, and [amazon.com](#) will deliver it within the US. There's also a paint-on version that has worked just as well. See Peter Ibeling's work¹⁰ for lots more inspirational results.

For easiest use, the sub reflector and feed need to be built into the model. Paul Wade asked that the feed should be made adjustable, so that 122Ghz and 244GHz could be done on the same dish. Since the feed horn isn't electrically connected to the dish, we can make or use a connector that threads or snaps into place. This will be added to the model after 122GHz is confirmed working.

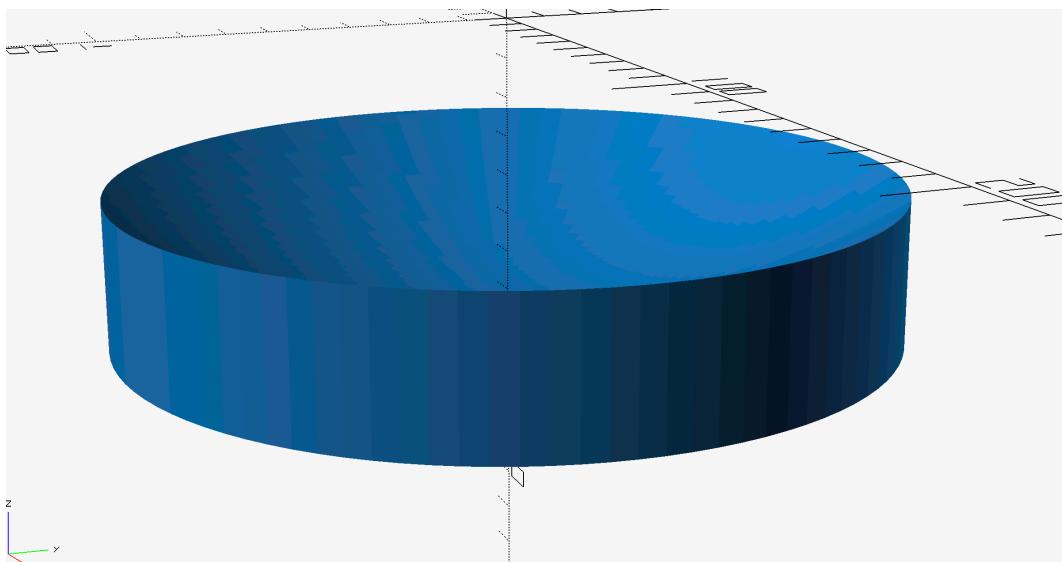
If we could make an open source 3D model, and if one could find someone to print the model, and if conductive paint or vacuum forming gold foil works well at 122GHz, and if any plastic bracing parts don't interfere too badly with the signal, then we can make a big step forward in more widely available antenna subsystems for 122GHz.

3D Model Design

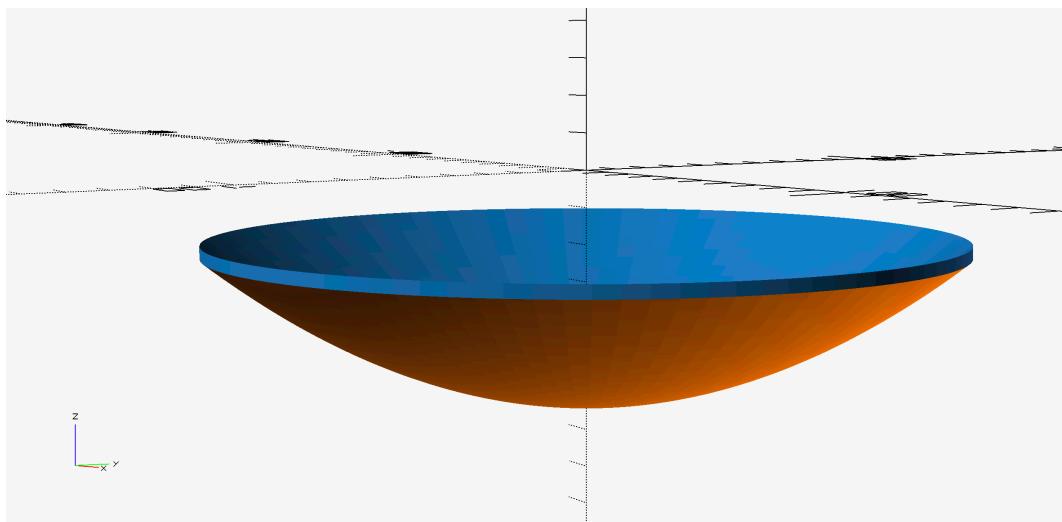
Parabolas and hyperbolas are conic sections. The first task was to create a 3D model of a parabolic dish. The tool of choice is the free and open source OpenSCAD software¹¹. After a number of hours attempting to create cones, slice the cones, and rotate the projections of those slices with non-ideal results, I found a script¹² that created a parabolic dish antenna algorithmically. This script rendered a nice-looking parabolic dish and was parameterized.

The core concept of this part of the script is to create a polygon cross-section of a parabolic dish using the power of math. The polygon is from the center axis surface of the dish, going up to the edge following a parabolic arc, then straight down to the base, and back to the center and up to close the shape. The polygon is then rotated 360 degrees to create a cylinder with a parabolic dish shape carved out of it. It looks like the shape below.

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Another shape just like this is created but moved down an amount equal to the thickness of the desired dish. That shape is subtracted from the first shape. Parabolic dish, voila!



Here's the source code of the script that was used for the parabolic dish. Current copy can be found in my [github repository¹³](#) for this project.

```
/*
parabolic_reflector module
by Kwikius
http://forums.reprap.org/read.php?340,333400,336285#msg-336285
creates a parabolic_reflector with a flat base
centered on its focus
```

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```
dia : float // diameter of the reflector
f   : float // focal length
numx : integer // the number of points to plot on the parabola
numr : integer // radial number of segments
base : float // thickness of the base.
*/
module parabolic_reflector(dia, f, numx, numr, base_thickness)
{
    // from the focus determine the quadratic constant for y = a
    x^2 + base_thickness;
    a = 1 / (4 * f);
    // from diameter and required curve points determine the
    xdecrement
    // for each iteration of the parabola_pts function below
    xdecr = dia / (2 * numx);
    /*
    parabola_pts
    recursive function that builds the basic polygon points
    sequence
    Each iteration adds a point until the terminating condition
    is reached
    N.B. If you set the initial point to [0,0]. works ok in
    draft but CGAL barfs
    x : float // the max x position
    */
    function parabola_pts(x) =
        (x <= 0.001)
        ?[[0.001,-f]] //BUG!x cannot be [[0,0]] for cgal to work
    ok in rotate_extrude
        :concat(parabola_pts(x-xdecr),[[x,a * x * x - f]]);
    // create the 3d shape from the polygon we created
    rotate_extrude(convexity = 10, $fn = numr) {
        // before the rotate_extrude add 2 points to the polygon
        // again using the builtin concat function
        // which makes the flat base
        polygon(points =
            concat([[dia/2,-(f + base_thickness)],
        [0.001,-(f + base_thickness)]],
            parabola_pts(dia / 2) )
        ) ;
    }
}

//-----
```

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```
// use the flag variables to change what's shown to show various
features...
// N.B. if you can't see anything on changing parameters try
zooming out!

// set show_offset_reflector to false to show the reflector
before chopping out only the offset part
// warning set this to true and may take a while to compile!
show_offset_reflector = false;
//show_basic_object (don't care if show_offset_reflector == true)
// otherwise set to true to see just the basic module with the
above parameters
show_basic_object = false;

// Use the module to create an object
// fill in some parameters with values dependent on the object
diameter = show_offset_reflector?820:show_basic_object?
200:200; // mm
//diameter = show_basic_object?200:show_offset_reflector?
600:100; // mm
num_x_points = show_offset_reflector?100:200; // more better
detail but slower render
num_r_points = show_offset_reflector?100:100; // more better
detail but slower render
focal_length = show_offset_reflector?50:show_basic_object?
75:60; // mm
base_thickness = 5; // mm
material_thickness = 2; //mm

-----
rotate([0,0,45])
if (show_offset_reflector == false) {

    if ( show_basic_object == true) {

parabolic_reflector(diameter,focal_length,num_x_points,num_r_poi
nts,base_thickness);
    } else {
        // subtract a nearly similar reflector to give a thin
wall reflector
        difference() {

parabolic_reflector(diameter,focal_length,num_x_points,num_r_poi
nts,base_thickness);
        //subtracting a reflector with a very slightly
bigger diameter . This prevents very thin walls due to floating
```

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```
point calcs)
    // The material thickness is the difference in focal
length
    // between the original and the subtrahend ( because
the object is centered on the focus)
    parabolic_reflector(diameter + 0.1,focal_length +
material_thickness,num_x_points,num_r_points,base_thickness);
}
} else
{
// create an offset reflector by intersecting an offset cylinder
with the reflector
// (Useful on a small reflector to prevent the antenna or
detector from masking the reflector)

intersection()
{
    union() {
        difference() {

parabolic_reflector(diameter,focal_length,num_x_points,num_r_poi
nts,base_thickness);
            //subtract a reflector with a very slightly
bigger diameter
            // The material thickness is the difference in
focal length
            // between the original and the subtrahend
            parabolic_reflector(diameter + 0.1,focal_length
+ material_thickness,num_x_points,num_r_points,base_thickness);
        }
    }

translate([0,70,0]) {
    rotate([45,0,0])
    scale([1.25,.75,1]){// elliptical cylinder
        cylinder(d = 125,h = 200,center = true, $fn = 100);
    }
}

}
}

// Put a sphere at the focus to show where the focus is
//sphere(d=10,center = true);
```

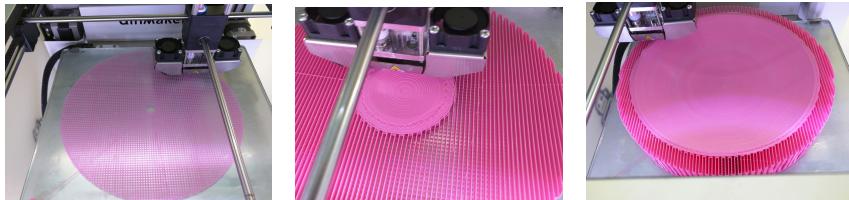
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```
//Use WR-7 waveguide flange  
// width 1.651mm    height 0.0325 0.8255mm  
waveguide_width = 1.651;  
waveguide_height = 0.8255;
```

3D Printing

I used the script to export a 3D model of the dish in STL format. I imported the STL format model into a software program called Cura, which translates the 3D model created with OpenSCAD into instructions the 3D printer can understand. Cura is a “slicer” and the output is g-code. I then took the g-code file to an Ultimaker 2+ and pressed print.

The dish is 200mm in diameter with a 0.4 f/D. The images that follow show some of the progression through the 28 hour print. The last photo in this set is partway through the removal of the support material that can be seen holding up the dish as its being printed. The dish would take less material if it was printed face down, but as one can see the support material leaves a slightly rougher finish. We want the reflective surface to be as smooth as possible, so it’s printed reflective side up in order to achieve this goal.



The vertical resolution of the printer is a very important value. We want the resolution to be less than 10% of the wavelength. With the normal setting of the model slicer software, we achieve a vertical resolution of 0.15mm, which exceeds our goal of at most 0.25mm. The 3D printer has a vertical resolution of 0.04mm or better. Worst case, we’re still within our goal at the coarsest setting. The slicing software has finer resolutions and the printer has finer settings. The downside is that the prints take longer. When prints take longer, there is an increased probability of something going horribly wrong¹⁴.



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Lots of people at GNU Radio Conference 2017 wanted to see it so I took it along. It got passed around at the Wednesday evening banquet on the sternwheeler boat operated from the Bahia Resort on Mission Bay in San Diego, CA, USA. At the end of the evening, I came back to the table, and it was gone! But, the kitchen staff, ever vigilant, were there for me. They rescued it from "The Back" and the dish lived on to fight another day.

Build

The next stage was metallizing with the conductive paint. After much shaking, the paint can was ready, and two coats applied. The dish was taken to the San Diego Microwave Group monthly meetup for consultation and review.



Above, dish ready for painting.

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Dish after one coat of conductive spray paint. You can still see a haze of Hello Kitty¹⁵ pink.



Dish after two coats of conductive spray paint. Coverage improved!

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Paul Williamson KB5MU and Kerry Banke N6IZW inspected the surface. Kerry explained several methods of basic tests to confirm the geometry. We then discussed next steps for 122GHz laboratory gear, how to structure the supports for the sub reflector, how to best incorporate an open waveguide test, and what a 122GHz rig kit would look like and potentially cost.

Vacuum forming gold foil to the 3D printed dish was proposed by both Paul Wade W1GHZ and Keith Wheeler KI7PEM. This method of metallizing will be investigated with future prints.

Alan VK3XPD proposed mounting the sub reflector with a threaded rod. This would simply

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require holes to be made in the 3D model. This means that the printed hyperbola sub reflector would have to be hand-located.

Since we already know exactly where the focal point is, the support structure can be printed along with the dish, feed, and sub reflector. Choosing a support structure that is minimally invasive to the radiation pattern in the dish is possible. The support structure can come from outside the dish, or from near the center, or from some point halfway out from the center on the surface. We have seen a variety of support structures in 122GHz dishes.

Test

Conductivity from the center of the dish to the outer edge was 500mOhm or less.

Attempts were made to confirm the prime focus with the laser pointer technique explained by N6CA for Microwave Update 2001¹⁶, but the wavelengths of visible light are not reflected as strongly by the conductive paint as they would be on a smoother surface. While good enough for 2.5mm, red light is on the order of 500nm. While something red could be seen reflected on the paper, we expect much more convincing results with the RF signal the dish was designed to reflect.

How to measure at 122GHz? The options currently are shipping dishes to people with 122GHz gear or making our own. San Diego Microwave Group has one or two 72GHz rigs, and one of them might be modifiable. Efforts to create 122GHz signals have begun.

Conclusion

A free and open source method for creating the necessary arbitrary polygon shapes (parabolas, hyperbolas, etc) and turning them into 3D models was found.

A 3D printed dish was successfully printed with a parabolic polygon.

Hyperbolic polygons that match up to the parabolic polygons and comply with basic restrictions for dish and sub reflector size will be coded next. Those shapes will be printed and metallized. The assembly will be tested.

A 3D model that combines the dish and sub reflector with support structures will be created using OpenSCAD. The entire assembly will be printed and tested and published.

All documents, OpenSCAD scripts, and results can be found at <https://github.com/Abraxas3d/122GHz>

Comment and critique welcomed and encouraged.

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Biography

Michelle Thompson W5NYV enjoys thinking and doing. Not necessary in that order. MSEE Information Theory from USC. Long-time DEFCON, Burning Man, and ham conference participant. Vice Chair San Diego IEEE Information Theory Society Chapter. Lead for AMSAT Phase 4 Ground. Lives in San Diego, CA and can be found as @abraxas3d on social media and at w5nyv@arrl.net.

¹ 122GHz is more than 121GHz, but less than 123GHz. It's like supercalifragilicous high frequency. You can't hear it, but some species of hornets can see it.

² Davis, C. P., D. L. Wu, C. Emde, J. H. Jiang, R. E. Cofield, and R. S. Harwood (2005), Cirrus induced polarization in 122 GHz aura Microwave Limb Sounder radiances, Geophys. Res. Lett., 32, L14806, doi:[10.1029/2005GL022681](https://doi.org/10.1029/2005GL022681).

³ <https://sdg-arrl.org/wp-content/uploads/2017/07/ThompsonBanke.pdf>

⁴ By Unknown - <http://deepspace.jpl.nasa.gov/dsn/gallery/goldstone.html>, Public Domain, <https://commons.wikimedia.org/w/index.php?curid=3765875>

⁵ http://www.w1ghz.org/antbook/conf/Multiple_reflector_antennas.pdf

⁶ <https://www.youtube.com/watch?v=xkXoMDLeA9Y>

⁷ <http://www.microwavers.org/122ghz.htm>

⁸ <http://chemandy.com/calculators/skin-effect-calculator.htm>

⁹ <http://www.sciencedirect.com/science/article/pii/S2212827114003874>

¹⁰ <https://twitter.com/ibelings>

¹¹ <http://www.openscad.org/>

¹² parabolic_reflector module
by Kwikius

<http://forums.reprap.org/read.php?340,333400,336285#msg-336285>
creates a parabolic_reflector with a flat base centered on its focus

¹³ <https://github.com/Abraxas3d/122GHz>

¹⁴ <https://www.flickr.com/groups/3d-print-failures/>

¹⁵ https://en.wikipedia.org/wiki/Hello_Kitty

¹⁶ http://www.ham-radio.com/n6ca/appnotes/dish/dish_lzr.html