Design of Optimized Cassegrain Antenna Systems

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The focal point of a parabolic dish is at a physically inconvenient location, and getting a signal to and from the feedhorn requires a significant amount of feedline. At the higher microwave frequencies, the feedline loss is significant, and intolerable above 10 GHz.

One compromise is to move the equipment to the feed location. This adds possible additional feed blockage, plus significant weight at the feed location – in most amateur mounting schemes, the additional weight further unbalances a poorly balanced system, with all of the antenna weight on one side of the pivot. Offset dishes can have the equipment placed out of the RF path with short feedline but are still often unbalanced.

A Cassegrain antenna[1] system, with a subreflector to redirect the RF to the dish surface from a more conveniently placed feedhorn, can place the equipment at a location which is more convenient, both electrically and mechanically, without compromising dish performance. In the case of very deep dishes, the performance can be improved by fully illuminating the dish surface. However, the Cassegrain antenna only achieves good performance for large dishes, greater than perhaps 40 wavelengths in diameter – few amateurs have dishes large enough for lower frequencies.

For EME or radio astronomy, the Cassegrain antenna offers the additional advantage that the primary feed spillover is directed toward cold sky for improved **G/T**, as illustrated in Figure 1, except at low elevations. For the very deep dish on the right, the feedhorn is inside the parabola, minimizing spillover and noise.

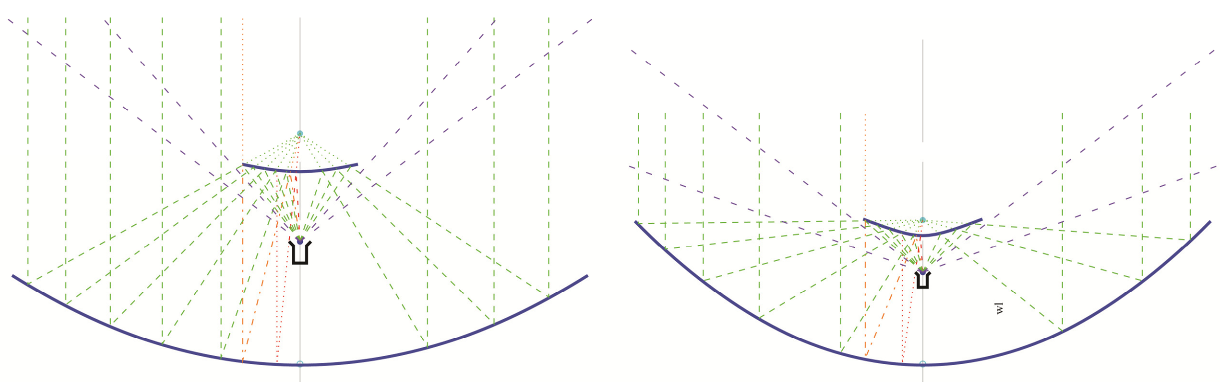

Figure 1 – Spillover from feedhorn is directed at cold sky

The Cassegrain subreflector, shaped to a hyperbolic curve, has been difficult to fabricate, so hams were limited by the availability of existing subreflectors, usually from surplus sources. The recent development of inexpensive, computer-driven, tabletop routers and 3D printers makes it possible to easily fabricate custom subreflectors and other shapes. In the USA, the Makerspace movement has made CNC machinery with more capability accessible to ordinary people.

A custom subreflector may be designed to place the feedhorn at a desired location for a given dish ***f*/D** and feedhorn. Deep dishes are difficult to illuminate well; the Cassegrain system allows high-performance feedhorn to efficiently illuminate deeper dish.   Of course, there are tradeoffs to be considered. Some examples, with some performance data, will illustrate the tradeoffs.

Cassegrain Geometry

A hyperbola is a conic section, a slice through a cone, with two mirror-image curves, shown in Figure 2.

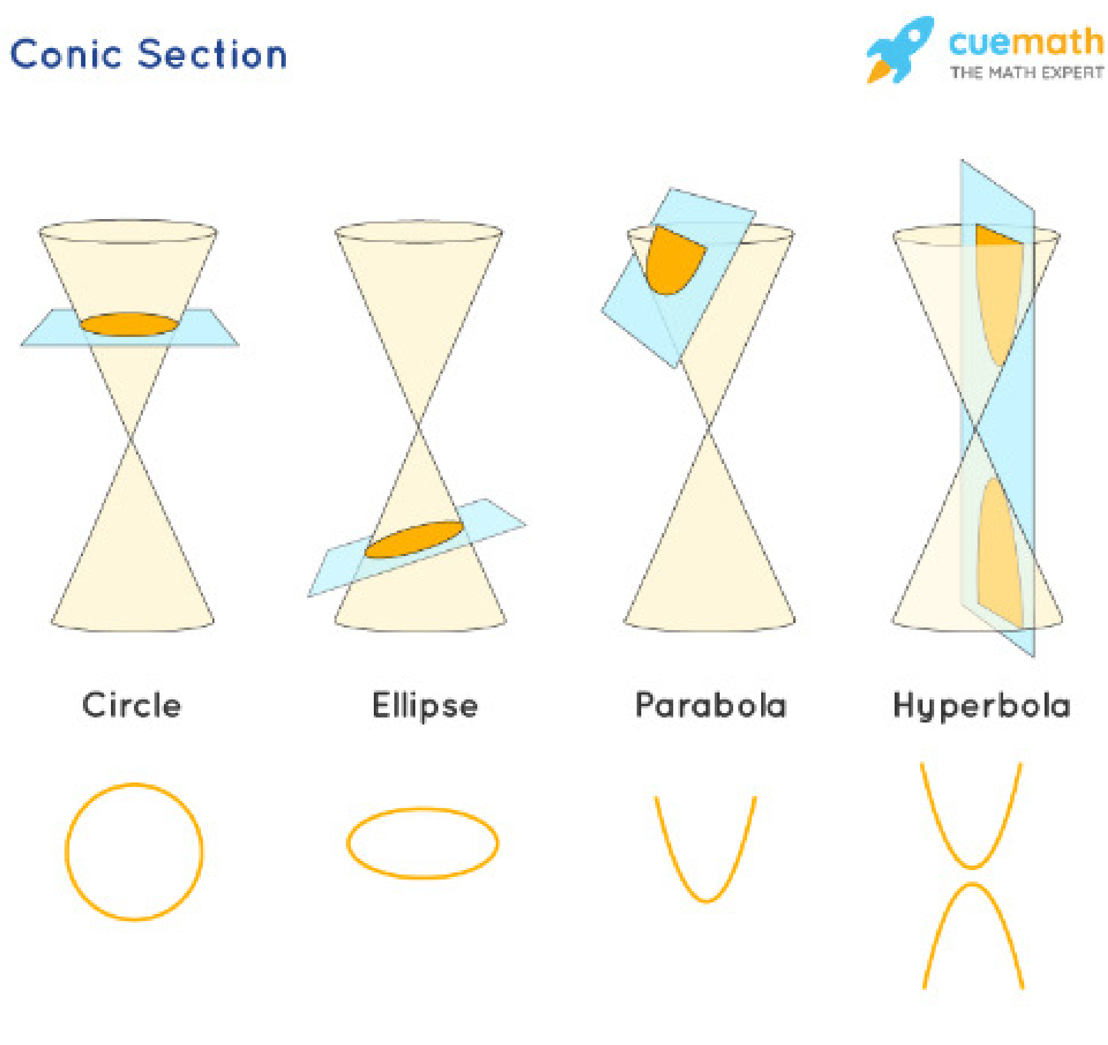

Figure 2 – Conic sections (from cuemath.com)

The geometry and equation of a hyperbola are shown in Figure 3. Each half of the hyperbola has a focus, with the useful property that a ray, the path followed by a beam of light or RF, starting at one focus is reflected from the other half of the hyperbola as though it originated from the other focus, like the heavy black line.

The equation for a hyperbola has two variables, **a** and **b**, which determine the curvature a hyperbola. Thus, there are an infinite number of hyperbolic curves, but only one reflects the rays correctly to focus a specific parabola.

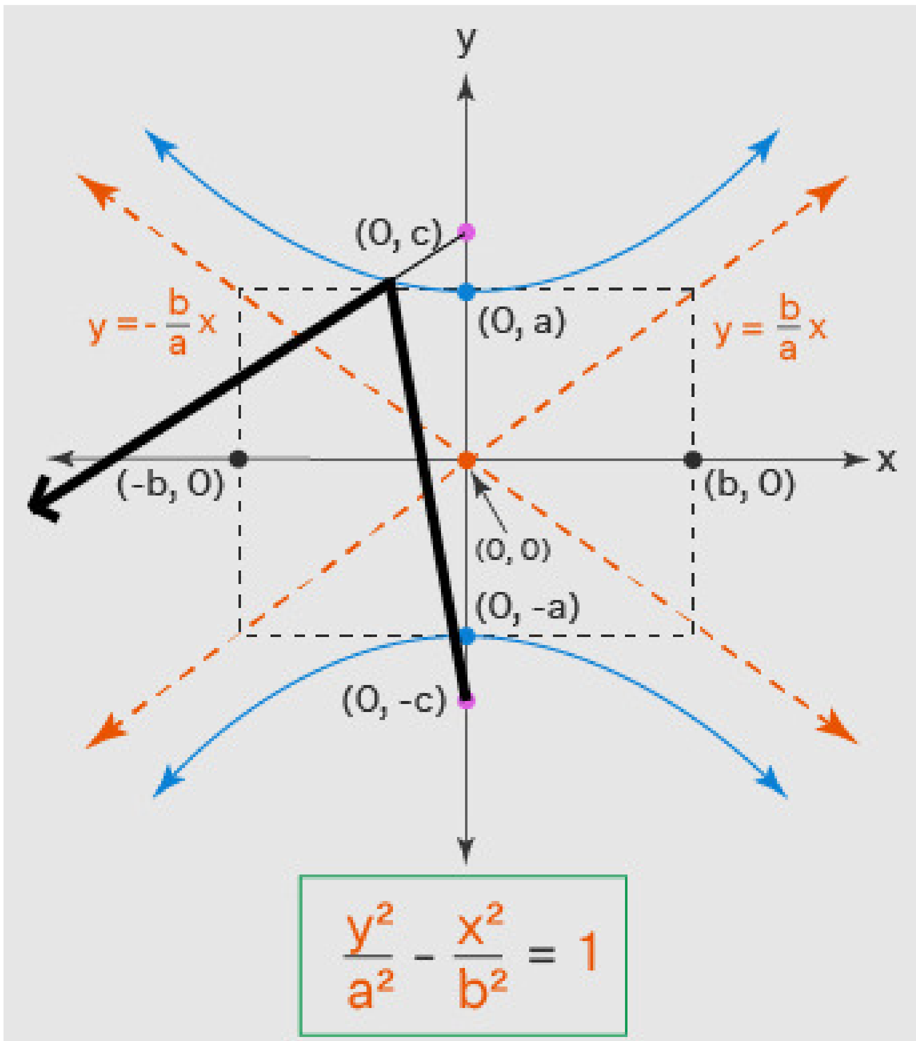

Figure 3 – Geometry and equation of hyperbola (from cuemath.com)

In a Cassegrain antenna, only one of the two hyperbola curves is used for the subreflector, with its focus at the focal point of the parabolic main reflector. The feed is placed with its phase center at the other focus of the hyperbola, pointed at the center of the subreflector. RF energy from the feed is reflected from the subreflector as though it originated from the focal point of the parabolic main reflector. Figure 4 shows the Cassegrain antenna geometry.

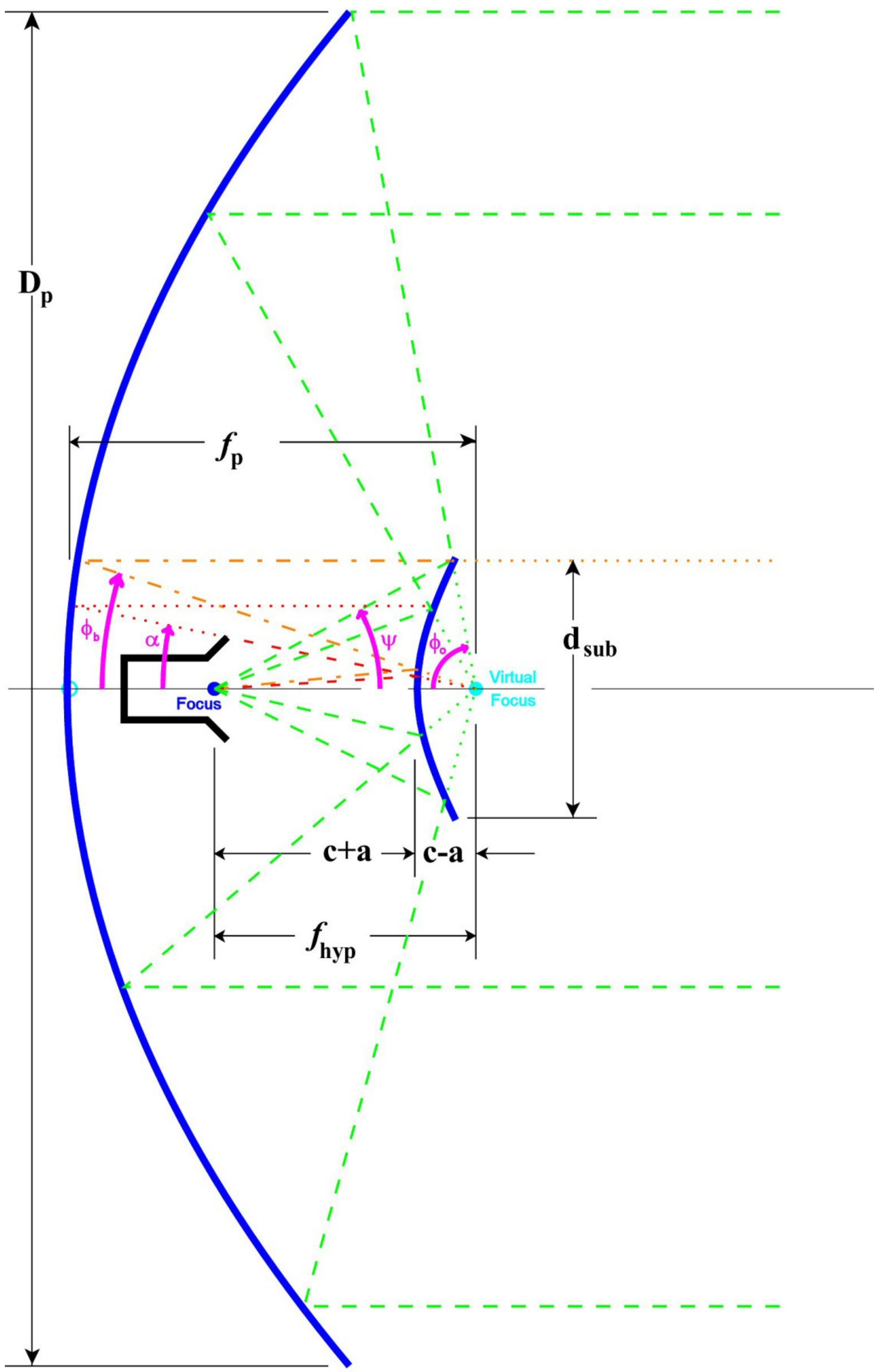

Figure 4 – Geometry of Cassegrain antenna

Custom Geometry

We would like to have control of the feedhorn location and the subreflector size; place the feedhorn at a preferred location, with a subreflector that is large enough to mimimize diffraction loss but small enough to that blockage by the subreflector does not cause significant loss.

My previous Cassegrain antenna paper[2] at EME2010 considered the case, based on a paper by Kildal[3], where the diffraction loss and blockage loss are equal, which might be the smallest total loss. However, for small dishes that most amateurs use, it resulted in a relatively small subreflector. Diffraction tends to scatter signal in all directions, while the blockage rays (see Figure 1) will probably be somewhere in the forward direction, though not adding to the desired signal. Thus, a somewhat larger subreflector with less diffraction loss might be preferable for EME.

A few sketches (made with a Perl script) of some possible Cassegrain antenna variations will illustrate some of the possibilities:

Figure 5 illustrates the effect of moving a feedhorn further from the primary focus of the parabolic dish. The subreflector size must increase to cover the subtended angle of the feedhorn radiation pattern. The subreflector also move away from the primary focus as required by the hyperbola equation. The sketch at the far right has a higher gain feedhorn, with a smaller subtended radiation angle (equivalent to a larger ***f*/D**) – the feedhorn can be further away with a smaller subreflector. Compare the second and fourth sketches.

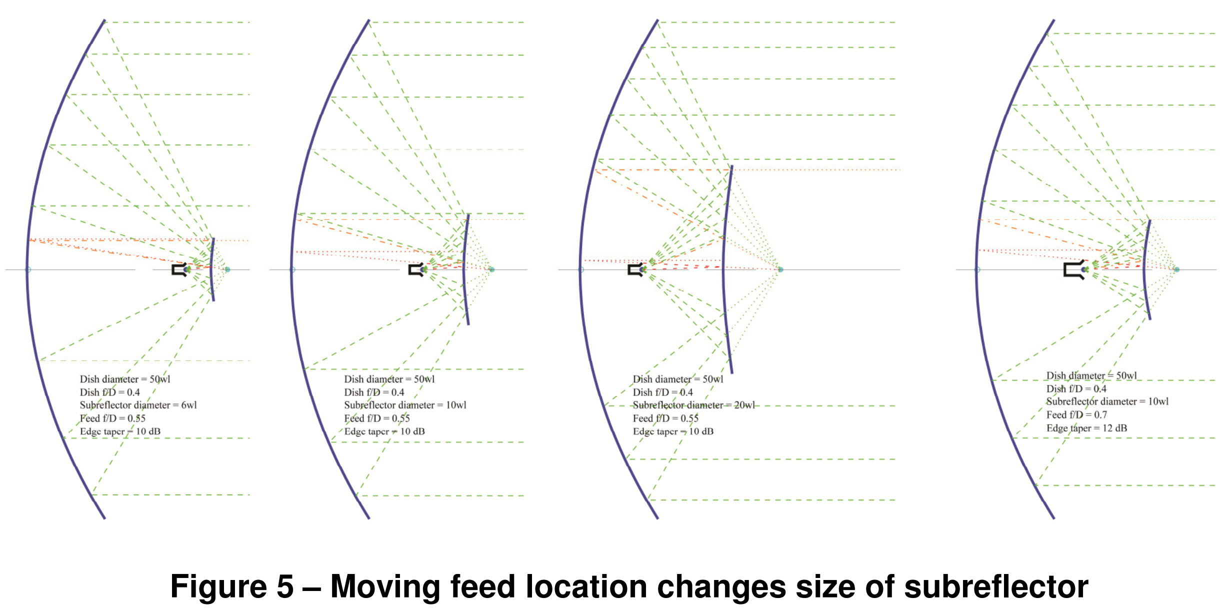

Figure 5 – Moving feed location changes size of subreflector

Figure 6 illustrates the possibilities with a very deep dish, ***f*/D = 0.25**, a dish that would be very difficult to feed efficiently. The leftmost sketch shows a feedhorn for a fairly deep dish, ***f*/D = 0.35**, which might be used as a prime-focus feed for this dish even though it would not fully illuminate the dish. Moving to the right, successively higher gain horns with narrower radiation angles are shown. The feedhorn moves further away from the primary focus and toward the dish without increasing subreflector size. At the right, a very high gain horn can be placed behind the parabolic reflector, radiating through a hole in the dish. A horn like this is quite large, requiring a large hole in the dish, so it is not useful for small dishes.

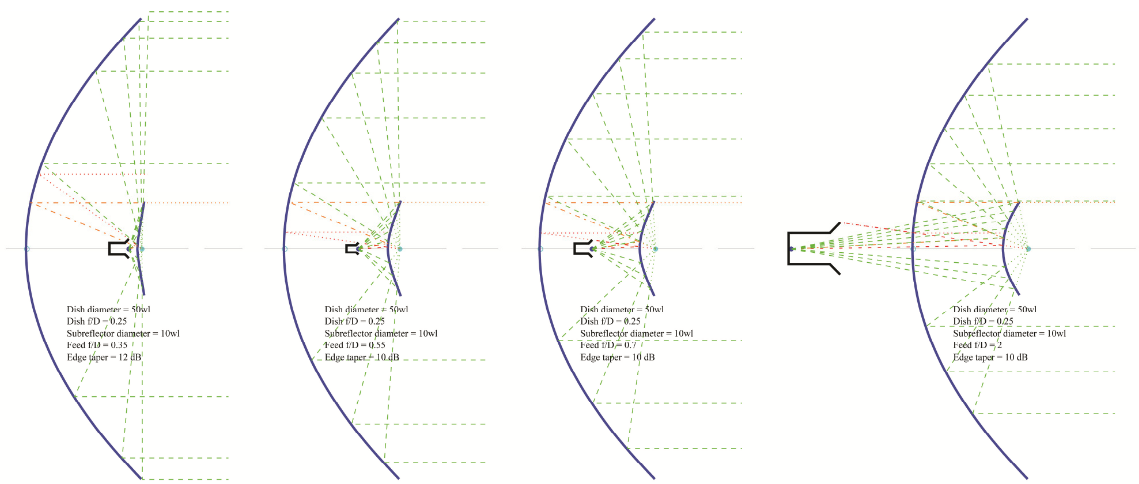

Figure 6 – Higher gain feedhorns with narrower beams are located further from subreflector

Cassegrain Antenna Calculations

So the feed can be inside the main reflector or even behind it. The problem is to choose the unique hyperbolic curvature that has the desired distance between the two foci which also reflects the feed radiation pattern from a desired subreflector diameter to fully illuminate the parabolic main reflector with a specified ***f*/D**. We must calculate the parameters **a**, **b**, and **c** for the hyperbola equation shown in Figure 3.

The first parameter, **c**, is set by the desired feedhorn location – the distance between the two foci of the hyperbola is 2**c**, and the phase center of the feedhorn is at the second focus. The subreflector diameter is determined from the radiation angle of the feedhorn at the desired illumination taper, say 10 or 12 dB. Then the parameters **a** and **b** are calculated for the hyperbolic curve which will correctly illuminate the ***f*/D** of the parabola.

All of the calculations are independent of frequency – a Cassegrain antenna will work on any frequency as long as the subreflector is large enough to minimize diffraction. The feed for each frequency must provide the desired radiation pattern.

The necessary equations came from a paper by Granet[4]. To enable the required calculations and easily consider tradeoffs, a **MATLAB**[5] script was developed which calculates the subreflector size and hyperbola parameters for a chosen feed location, dish ***f*/D,** and feedhorn. Several interations are usually needed to find a good compromise. Once a suitable combination is determined, the hyperbolic curve is output, either as an X-Y table or directly as G-code for a CNC machine or 3D printer. The **MATLAB** script is easily modified for different machinery. It will probably also run on the free **GNU Octave** interpreter.

Examples

Several examples for the higher microwave bands have been built and tested, with good measured performance. An EME system for 10 GHz is in development. Higher feedline losses make the Cassegrain system more desirable at the higher frequencies, but it could be used at any frequency if the dish is large enough; Hannon[1] suggests that a minimum diameter is 50λ is needed to equal performance of a prime-focus dish.

Example 1: 122λ Diameter, 14.8λ Subreflector, *f*/D = 0.25

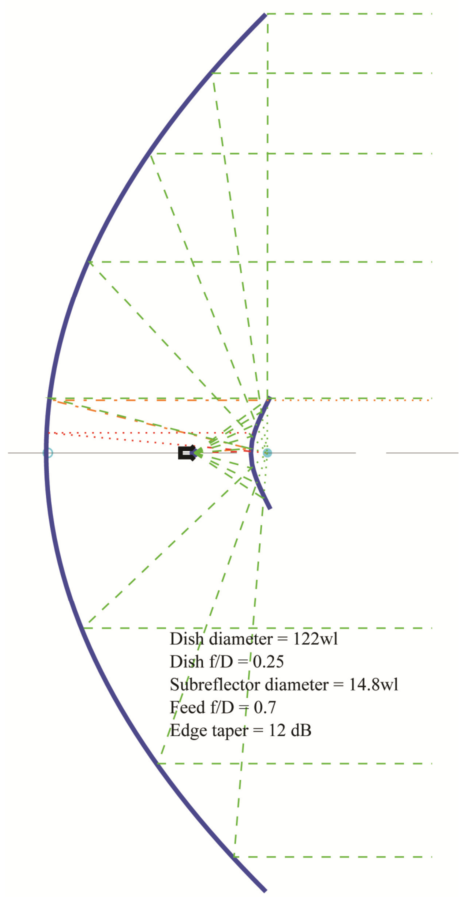

Figure 7 – Cassegrain antenna for 122 GHz with 305mm dish, *f*/D = 0.25

The recent 122 GHz project[6] transverter designed by VK3CV created a need for a simple and inexpensive dish antenna to make contacts possible at interesting distances. Inexpensive parabolic reflectors with near-optical surfaces are available from Edmund Optics[7], with an ***f*/D =** 0.25; these deep dishes are difficult to illuminate efficiently, and the corrugated feedhorns used at lower frequencies are very difficult to machine at this frequency. The smallest size, 305 mm in diameter, or 122λ, is about as large as one could hope to aim.

The few previous dish antennas at this frequency used an open waveguide as the feed with a flat plate subreflector – a simple but less than optimum system.

Several years ago, W1RIL (SK) had made a hyperbolic reflector on a manual lathe, using my spreadsheet[2] for design dimensions. Using the **MATLAB** routines, I calculated hyperbolic subreflectors 38mm (1.5 inches) in diameter for several feedhorns, and made a few on a CNC lathe at the local makerspace. The most feasible feedhorn is a large W2IMU dual-mode horn[8], 1.9λ in diameter, which is relatively easy to make on a manual lathe. The beamwidth is 38.5° for a 12 dB illumination taper, sketched in Figure 7. Several local hams have used my subreflectors on the Edmund reflectors – Figure 8 is a photo of one by W1FKF.

Figure 8 - Cassegrain antenna for 122 GHz with 305mm dish by W1FKF

Performance testing is done by removing the subreflector so that the only the feedhorn is active. A direct comparison of received signal level is made between the feedhorn and the complete Cassegrain antenna – the difference is added to the calculated feedhorn gain for the total gain. VE2UG made a made a printed subreflector support that is easily removed and did the comparison; he reported nearly 50% efficiency, good performance for an inexpensive dish at this frequency. .

A higher gain feedhorn would reduce or possibly eliminate the short but lossy waveguide (2mm brass tube). However, the larger Skobolev[9] or Pickett-Potter[10] dual-mode feeds are beyond my machining skills – I broke several tiny but expensive boring tools attempting to make one.

Example 2: 48λ Diameter, 12λ Subreflector, *f*/D = 0.6

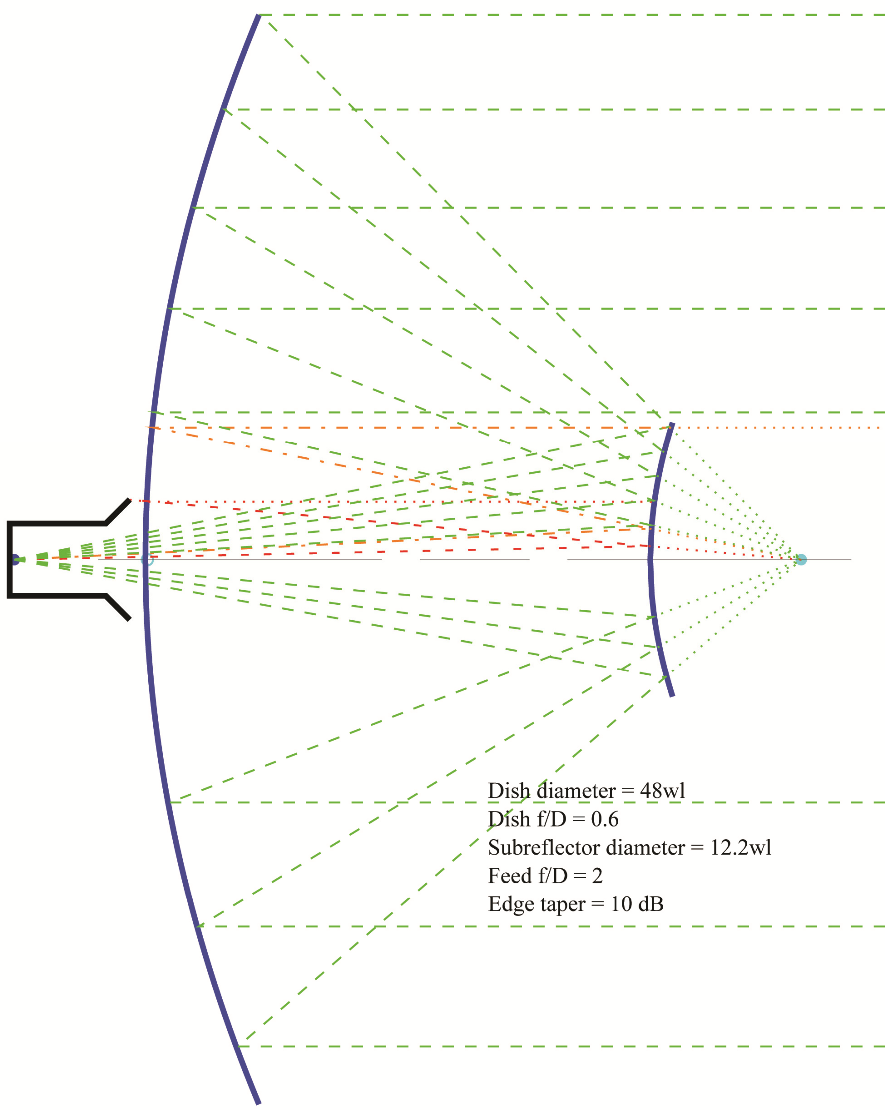

Figure 9 - Cassegrain antenna for 47 GHz with 305mm dish, *f*/D = 0.6

This example has a 48λ diameter ***f*/D** = 0.6 dish with a 12λ subreflector at 47 GHz. It was designed to fit a DB6NT transverter with *zero* feedline loss.

When I first received the transverter, I wanted to get it on the air and work out higher performance later. I made two Skobolev-style dual-mode horns, 5.6λ in diameter, on a CNC lathe at the local makerspace, one for the transmit port and the other for the receive port – see Figure 10. Simulated gain of each horn is about 22 dB. This simple breadboard system worked quite well, with longest DX of 114km.

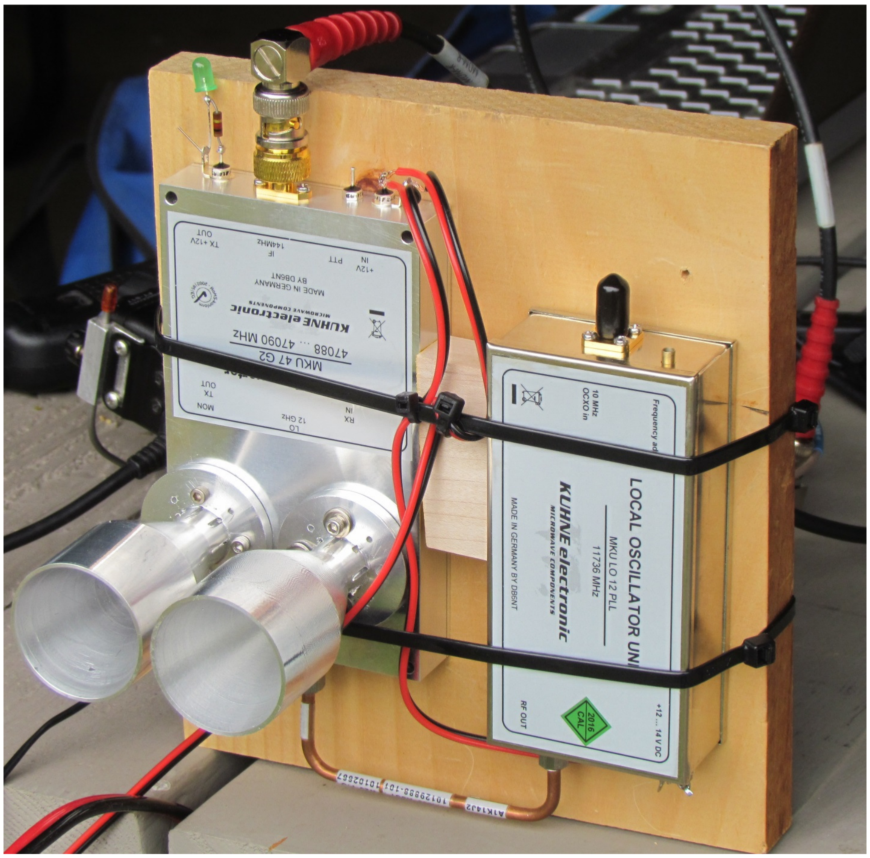

Figure 10 – DB6NT 47 GHz transverter with separate feedhorns

The next step was a waveguide switch and a dish. After I saw a photo of a one integrated into a system by VE3FN, with WR-19 waveguides manually bent into a convoluted assembly, I designed an inline 3-port switch which could mate directly with the transverter. Testing showed about 2 dB of loss, which is tolerable, but it was about 100mm long and would make a long, heavy extension behind the feedhorn.

Since a Cassegrain antenna appeared to work at 122 GHz, I started calculations for a 47 GHz system, developing the **MATLAB** routines, which could have the horns in Figure 8 behind the reflector. I started with an inexpensive 300mm dish from SHF Microwave[11] – the 0.6 ***f*/D** should make dimensions less critical. The phase center of the horns is 5.3λ inside the horn, so the total distance between the two hyperbolic foci is quite large. I chose to use 10 dB illumination taper to reduce the feedhorn size. The 10 db half-beamwidth of the horns is about 11 degrees resulting, after several iterations, in a 76 mm (3 inches) subreflector diameter, The feedhorn rim is just behind the parabolic reflector, shown in Figure 9, but the phase center is 5.3λ further back. Although the subreflector diameter is 25% of the dish diameter, it only blocks 6.25% of the dish area. The **MATLAB** routine outputs Gcode for the CNC lathe to machine the subreflector.

I assembled the dish, subreflector, and transverter using 2020 makerbeam stock, shown in Figure 11. The transverter slides on a linear bearing to move between transmit and receive horns. Assembly was to calculated dimensions, and the subreflector, adjustable on threaded rod, required about 1 mm of final adjustment for maximum gain. Note the small hole in the center of the subreflector – a small rod may be inserted to aid in alignment.

To test the performance, the subreflector supports are designed to swing out of the way, leaving the feedhorn looking through the dish. Removing the feedhorn reduced the signal level by 18 to 19 dB. Since the feedhorn gain is about 22 dBi, the total antenna gain is about 40 dBi, which is roughly 50% efficiency – a satisfactory result.

Figure 11 – Cassegrain antenna system for 47 GHz with *zero* feedline

Example 3: 42λ Diameter, 7λ Subreflector, *f*/D = 0.375

I was recently given a 1.2 meter diameter dish with *f*/D = 0.375, previously used at 14 GHz, that should work well for 10 GHz EME. Since it is a bit heavy, a Cassegrain system with the equipment behind the dish should be easier to work with.

The rest of the system is constrained by available materials. A large W2IMU dual-mode horn is convenient to make using 2 inch copper water pipe, 1.76λ inner diameter. The subreflector size is 7λ, which is 8 inches, probably as large as I can machine or afford. I chose to use 10 dB illumination taper for the small subreflector.

With these constraints, the feedhorn phase center is 275mm in front of the parabolic reflector, sketched in Figure 12, allowing the horn to fit comfortably with only a short section of waveguide.

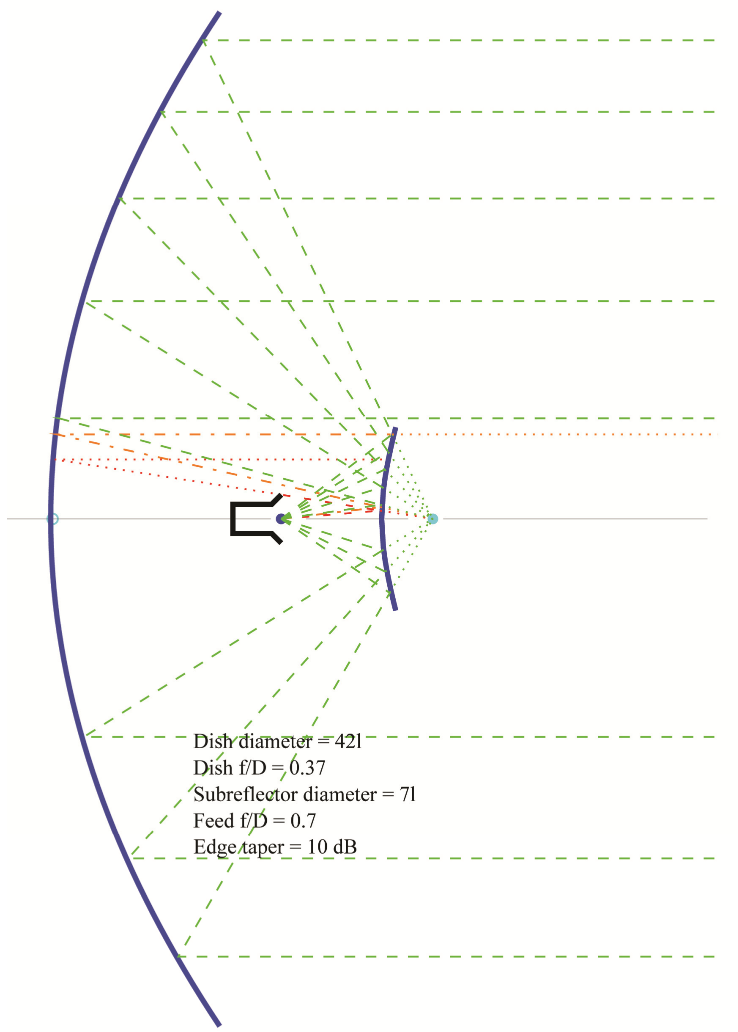

Figure 12 - Cassegrain antenna for 10 GHz EME with 1.2m dish, *f*/D = 0.375

Example 4: 96λ Diameter, 20λ Subreflector, *f*/D = 0.25

The largest parabolic reflector from Edmund Optics is 24 inches in diameter. VE2UG asked me to calculate a Cassegrain antenna using this dish at 47 GHz.

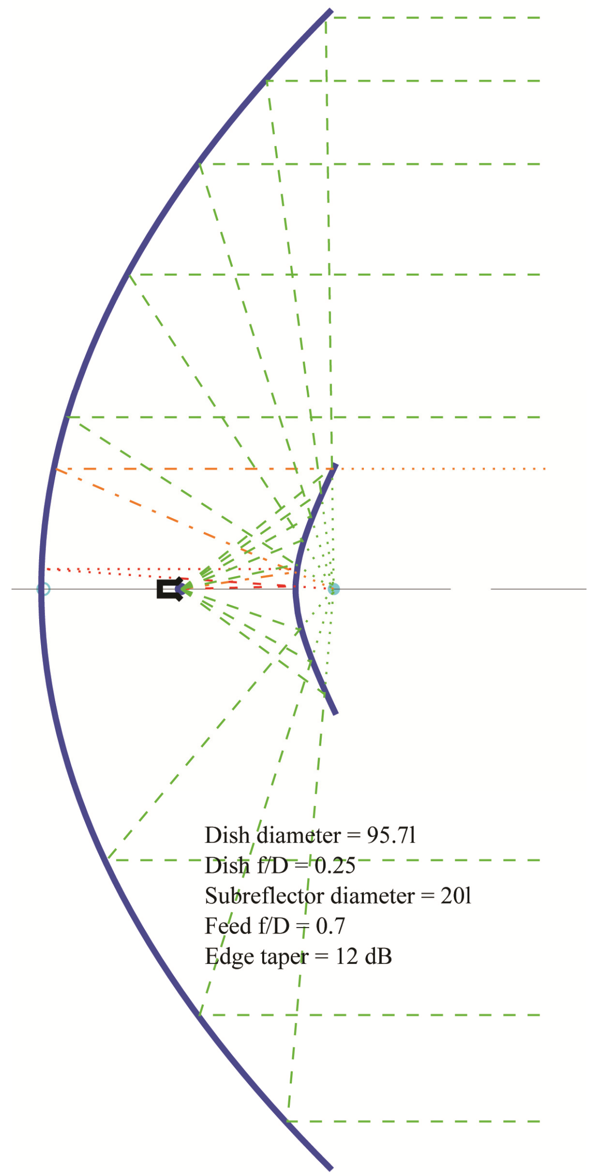

Figure 13 - Cassegrain antenna for 47 GHz with 609mm dish, *f*/D = 0.25

I thought this dish to be large enough to use the full 20λ subreflector diameter recommended by Hannon[1]. The large W2IMU dual-mode feedhorn is fairly easy to machine for 47 GHz on a manual lathe. For 12 dB edge taper, it has a radiation half-angle of 38.5 degrees. The resultant feedhorn position puts the phase center 72mm from the vertex of the parabola, sketched in Figure 13.

An additional goal for this antenna was to compare performance of a machined metal subreflector to a 3D printed subreflector with metal coating. The available 3D printer at VE2UG limited subreflector diameter to 4 inches, so the metal subreflector was machined to 4 inches also, about 16λ diameter. This put the phase center 89mm from the vertex of the parabola.

Figure 14 – 24-inch Cassegrain antenna for 47 GHz by VE2UG

Rene also 3D printed and metallized a large W2IMU dual-mode feedhorn to match the metal one.

Performance was measured with the same technique used in Example 2, comparing signal level of the whole antenna with that of the feedhorn alone in identical conditions, by removing the subreflector. The difference in signal level is added to the calculated feedhorn gain of 13.9 dBi to estimate the gain of the Cassegrain antenna and calculate the aperture efficiency. Rene estimates the efficiency at 46% to 48%; he describes this more fully in a separate paper.

Example 5: 3 meter Diameter, *f*/D = 0.29

The DL0SHF 10 GHz EME beacon has proven to be very valuable. Per, DK7LJ, has acquired some new 3 meter dishes for 24 and 47 GHz beacons, and asked me for feed suggestions. My first thought was a Cassegrain system to provide good illumination for the deep dish.

A few trial calculations with modest sized subreflectors showed that the feed to subreflector spacing would be similar to Example 4 above, putting the feed much further from the parabolic reflector with a long waveguide. A larger subreflector and a higher gain feed, the Skobolev-style dual-mode horns, 5.6λ in diameter in Example 2 yielded a more reasonable system geometry, shortening the feed waveguide, as shown in Figure 14.

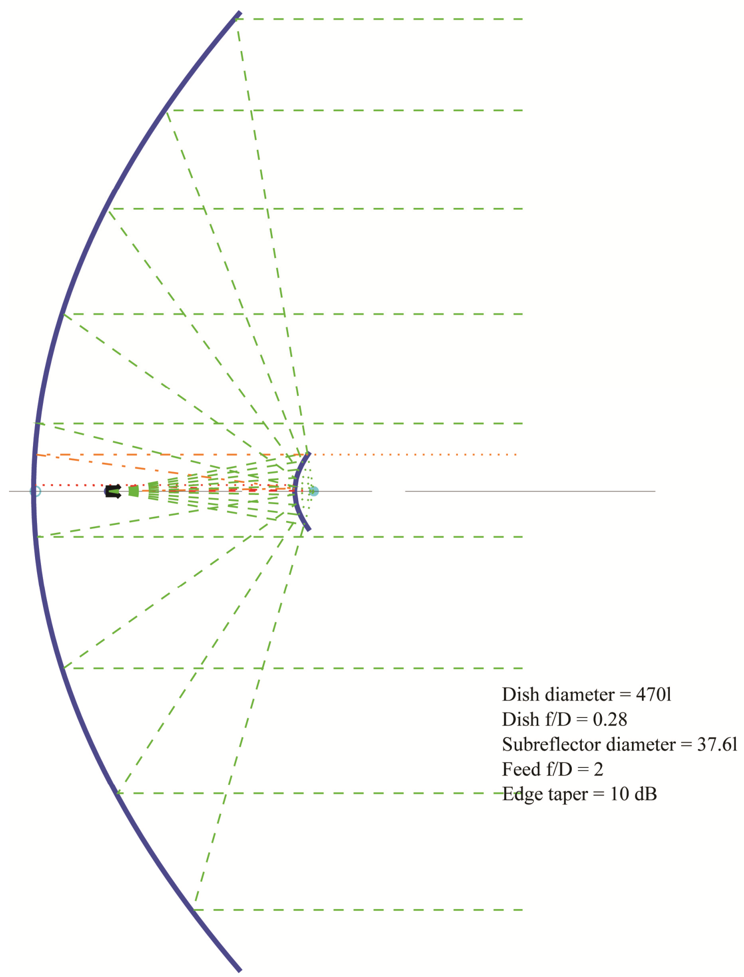

Figure 15 - Cassegrain antenna for 24 or 47 GHz with 3m dish, *f*/D = 0.29

I chose a subreflector diameter of 240 mm, 20λ at 24 GHz, so it is large enough to work well on either band. All the other dimensions are the same for either band with the exception of the feedhorn – the horn placement must put the Phase Center 240 mm from the vertex of the parabolic reflector.

These dimensions are just a first iteration, and will probably change, if Per chooses to implement a Cassegrain feed. The large dish has room to work with – all the equipment might fit inside the dish, close to the feedhorn, and in the subreflector shadow so it would not affect performance.

Summary

A Cassegrain antenna can provide improved system performance with large dishes, particularly with very deep reflectors which are otherwise difficult to illuminate. Other possible system advantages are reduced feedline loss, more convenient equipment placement, and better mechanical balance. Availability of CNC machining and 3D printing makes custom subreflector design and fabrication more practical.

Demonstration of aperture efficiency close to 50% at 47 GHz in two separate examples shows that a properly designed and implemented Cassegrain antenna can provide excellent performance at the higher microwave frequencies.

References

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