ANTENNAS

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Practical Microwave Antennas

Part 1–Antenna fundamentals and horn antennas

By Paul Wade, N1BWT

(From *QEX*, September 1994)

Antenna gain is essential for microwave communication, and since it helps both transmitting and receiving, it is doubly valuable. Practical microwave antennas provide high gain within the range of amateur fabrication skills and budgets.

Three types of microwave antennas meet these criteria: horns, lenses and dishes. Horns are simple, foolproof and easy to build; a 10-GHz horn with 17 dB of gain fits in the palm of a hand. Metal-plate lenses are easy to build, light in weight and noncritical to adjust.[1] Finally, dishes can provide extremely high gain; a 2-foot dish at 10 GHz has more than 30 dB of gain, and much larger dishes are available.

These high gains are only achievable if the antennas are properly implemented. I will try to explain the fundamentals using pictures and graphics as an aid to understanding. In addition, a computer program, *HDL_ANT*, is available for the difficult calculations and details. In this first of three parts, I'll review some basic antenna terminology and concepts and discuss horn antennas. Part 2 will treat dish antennas, and in Part 3 I'll present metal-lens antennas and discuss the microwave antenna measurements needed to verify antenna performance.

Antenna Basics

Before we talk about specific microwave antennas, there are a few common terms that must be defined and explained:

Aperture

The aperture of an antenna is the area that captures energy from a passing radio wave. For a dish antenna, it is not surprising that the aperture is the size of the reflector, and for a horn, the aperture is the area of the mouth of the horn. Wire antennas are not so simple—a thin dipole has almost no area, but its aperture is roughly an ellipse with an area of about 0.13 λ^2. Yagi-Uda antennas have even larger apertures.[2]

Gain

The hypothetical isotropic antenna is a point source that radiates equally in all directions. Any real antenna will radiate more energy in some directions than in others. Since the antenna cannot create energy, the total power radiated is the same as that of an isotropic antenna driven from the same transmitter; in some directions it radiates more energy than an isotropic antenna, so in others it must radiate less energy. The gain of an antenna in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. Usually we are only interested in the maximum gain—*in the direction in which the antenna is radiating most of* the power.

An antenna with a large aperture has more gain than a smaller one; just as it captures more energy from a passing radio wave, it also radiates more energy in that direction. Gain may be calculated as:

$$G_{dBi} = 10\log_{10}\left(\eta \cdot \frac{4\pi}{\lambda^2} \cdot \text{Aperture}\right)$$

with reference to an isotropic radiator; η is the efficiency of the antenna.

Efficiency

Consider a dish antenna pointed at an isotropic antenna transmitting some distance away. We know that the isotropic antenna radiates uniformly in all directions, so it is a simple (!) matter of spherical geometry to calculate how much of that power should be arriving at the dish over its whole aperture. Now we measure how much power is being received from the dish at the electrical connection to the feed—never greater than that arriving at the aperture. The ratio of power received to power arriving is the aperture efficiency.

How much efficiency should we expect? For dishes, all the books say that 55% is reasonable, and 70 to 80% is possible with very good feeds. Several amateur articles have calculated gain based on 65% efficiency, but I haven't found measured data to support any of these numbers. On the other hand, KI4VE suggests that the amateur is lucky to achieve 45-50% efficiency with a small dish and a typical "coffee-can" feed.[3]

For horns and lenses, 50% efficiency is also cited as typical. Thus, we should expect about the same gain from any of these antennas if the aperture area is the same.

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[1] Notes appear at the end of this section.

Reciprocity

Suppose we transmit alternately with a smaller and a larger dish and note the relative power received at a distant antenna. Then if we transmit from the distant antenna and receive alternately with the same two dishes, would we expect to see the same relative power? Yes. Transmitting and receiving gains and antenna patterns are identical. This is hard to prove mathematically, but it is so.[4, 5]

However, the relative noise received by different types of antennas may differ, even with identical antenna gains. Thus, the received signal-to-noise ratio may be better with one type of antenna than another.

Directivity and Beamwidth

Suppose an antenna has 20 dB of gain in some direction. That means it is radiating 100 times as much power in that direction as would an isotropic source, which uniformly distributes its energy over the surface of an arbitrarily large sphere that encloses the antenna. If all the energy from the 20-dB-gain antenna were beamed from the center of that same sphere, it would pass through an area 100 times smaller than the total surface of the sphere. Since there are 41,253 solid degrees in a sphere, the radiation must be concentrated in 1/100th of that, or roughly 20° of beamwidth. The larger the gain, the smaller the beamwidth.

The directivity of an antenna is the maximum gain of the antenna compared to its gain averaged in all directions. It is calculated by calculating the gain, using the previous formula, with 100% efficiency.

Sidelobes

No antenna is able to radiate all the energy in one preferred direction. Some is inevitably radiated in other directions. Often there are small peaks and valleys in the radiated energy as we look in different directions (Fig 1). The peaks are referred to as sidelobes, commonly specified in *dB down from the main lobe*, or preferred direction.

Are sidelobes important? Let's suppose that we could make an antenna with a 1-degree beamwidth, and in all other directions the average radiation was 40 dB down from the main lobe. This seems like a pretty good antenna! Yet when we do the calculation, only 19.5% of the energy is in the main lobe, with the rest in the other 41252/41253 of a sphere. The maximum efficiency this antenna can have is 19.5%.

E-plane and H-plane

An antenna is a transducer which converts voltage and current on a transmission line into an electromagnetic field in space, consisting of an electric field and a magnetic field oriented at right angles to one another. An ordinary dipole creates an electric-field pattern with a larger amplitude in planes which include the dipole than in other planes. The electric field travels in the E-plane; the H-plane, perpendicular to it, is the field in which the magnetic field travels. When we refer to polarization of an antenna, we are referring to the E-plane. However, for three-dimensional antennas like horns, dishes and lenses, it is important to consider both the E-plane and the H-plane, in order to fully use the antenna and achieve maximum gain.

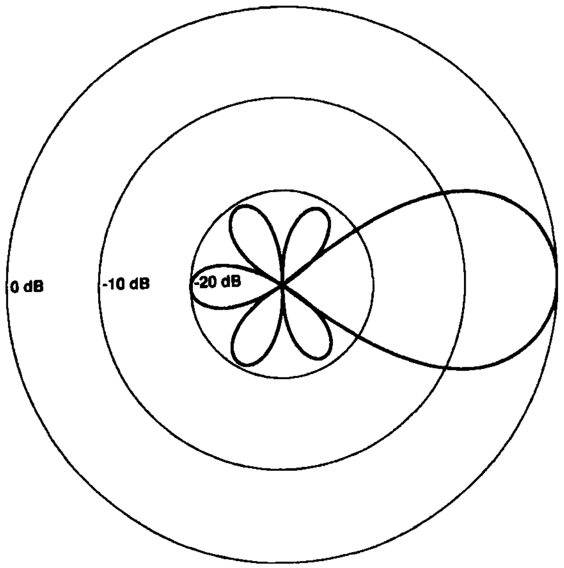

Fig 1—A typical antenna pattern showing the main lobe and sidelobes.

Phase Center

The antenna pattern in Fig 1, and most other illustrations of antenna patterns, shows only amplitude, or average power. This is all we need to consider for most applications, but for antennas which are like optical systems, like lenses and dishes, we must also be concerned with phase, the variation in the signal as a function of time. RF and microwave signals are ac, alternating current, with voltage and current that vary sinusoidally (like waves) with time. Fig 2A shows several sine waves, all at the same frequency, the rate at which they vary with time.

Let's think about a simple example: a child's swing. We've all both ridden and pushed one at some time. If we push the swing just as it starts to move away from us, it swings higher each time. If we add a second pusher at the other end, it will increase faster. Now if we tie a rope to the swing seat and each pusher takes an end, we can try to add energy to the swing throughout its cycle. This will work as long as we keep the pulling synchronized with the motion of the swing, but if we get *out of phase*, we will drag it down rather than sending it higher.

The motion of a swing is periodic, and the height of the swing varies with time in a pattern similar to a sine wave of voltage or current. Look at a sine wave in Fig 2A, considering the highest point of the waveform the height the swing travels forward, and the lowest point as the height the swing travels backward, both repeating with time. If there are two swings side-by-side and both swings arrive at their peak at the same time, they are in phase, as in Fig 2A.

When two electromagnetic waves arrive at a point in space and impinge on an antenna, their relative phase is combined to create a voltage. If they have the same phase, their voltages add together; in Fig 2A, the two dashed waveforms are in phase and add together to form the solid waveform. On the other hand, when signals are exactly out of phase, the addition of positive voltage to negative voltage leaves only the difference, as shown in Fig 2B. If the two signals are partially out of phase, the

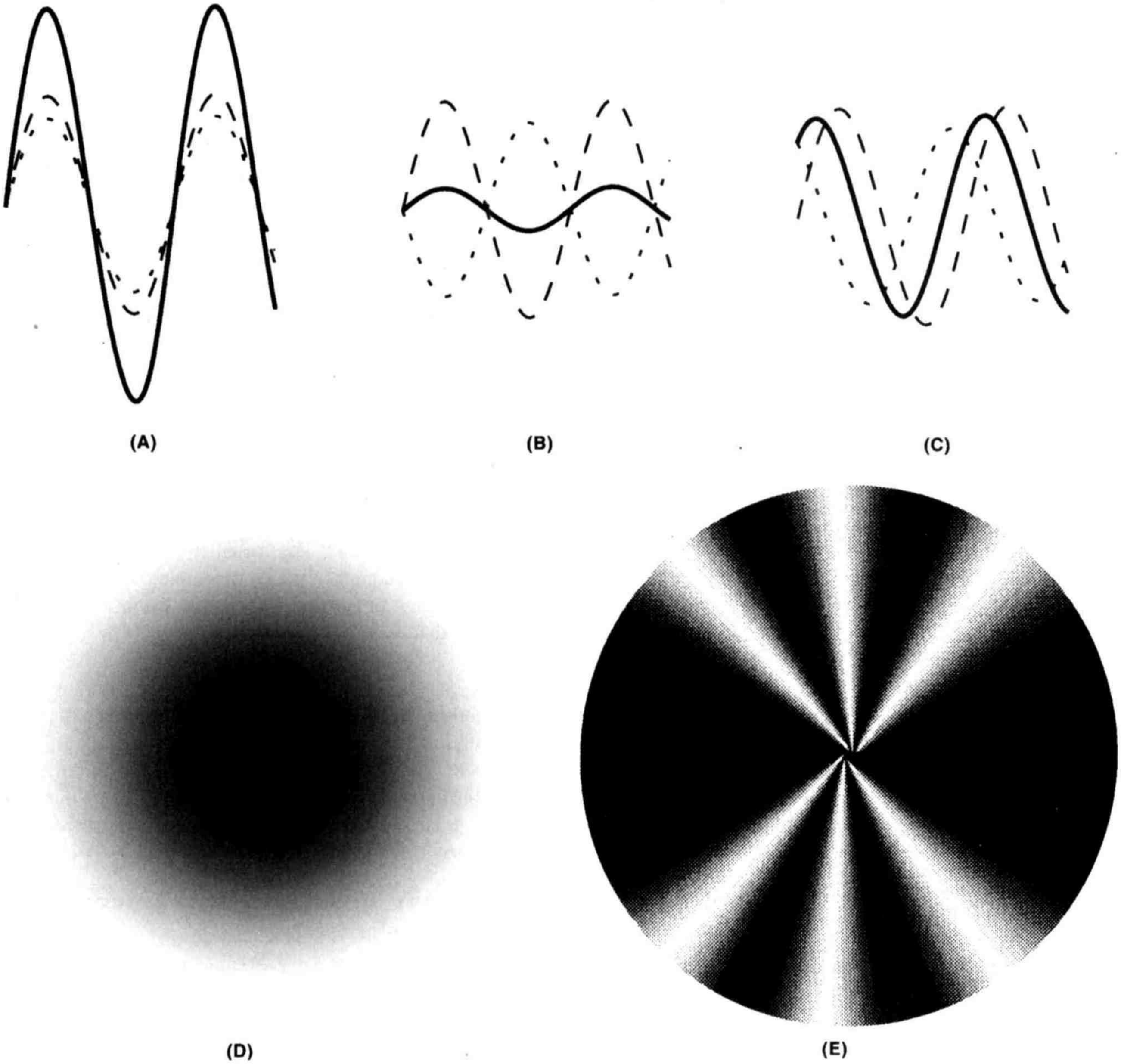

Fig 2—The result of multiple signal sources depends on the phase difference between them. At (A), two signals are shown in phase and add together. At (B), the signals are 180° out of phase and tend to cancel, while the signals at (C) are out of phase by less than 180°, with the result being a signal at a phase and amplitude different from either of the two source signals. The plot at (D) shows the amplitude around a single-source antenna, while (E) shows the interference pattern created by having two sources.

resultant waveform is found by adding the voltage of each at each point in time; one example is shown in Fig 2C. Notice that the amplitude of the resultant waveform is dependent on the phase difference between the two signals.

If our signal source is a point source, then all waves are coming from that one point in space. Each wave has a wavefront, like a wave arriving on a beach. The wavefront from the perfect point source has a spherical shape. Consider its *amplitude*. First, we place an antenna and power meter at some distance from the source and take a reading, then when we move the antenna around to other places that create exactly the same power reading, we will draw a sphere around the source. Thus, the amplitude has a uniform distribution like Fig 2D; dark areas have higher amplitude than lighter areas, and the amplitude decreases as we move away from the source according to the inverse square law described below (the shading has a few small concentric rings due to the limitations of computer graphics, but is really a continuous smooth function).

The *phase* of this wavefront as it propagates in space appears to also have a spherical shape. If frozen in time, one sphere would represent a positive peak of a sine wave. One half wavelength inside would be another sphere representing a negative peak of the sine wave, and another half wave inside again is a positive peak. The *phase center* of an antenna is the apparent place from which the signal emanates based on the center of a sphere of constant phase.

However, no real antenna is small enough to be a point source, so the radiation must appear to emanate from a larger area. If we consider a simple case, where the radiation appears to come from two points, then two signals will arrive at each point in space. A point in space is typically farther from one radiating point than from the other, and since the time it takes for each signal to arrive depends on the distance to each of the radiating points, there will be a phase difference between the two signals. This phase difference will be different at each point in space, depending on the relative distances, and the amplitude of the resultant signal at each point depends on the phase difference. An example of a pattern created by two radiating sources is shown in Fig 2E, where the dark areas have the greatest amplitude, due to the two signals arriving in phase, and the light areas are areas where phase cancellation, like that of Fig 2B, has reduced the amplitude.

A well designed feed for a dish or lens has a single phase center, so the radiation appears to emanate from a single point source. This must be so for at least the main beam, the part of the pattern that illuminates the dish or lens. Away from this main beam, the phase center may move around and appear as multiple points, due to stray reflections and surface currents affecting the radiation pattern. However, since these other directions do not illuminate the dish or lens, they can be ignored.

Inverse Square Law

As two antennas are moved farther apart, received power decreases in proportion to the square of the distance between them; when the distance is doubled, only 1/4 as much power is received, a reduction of 6 dB. This is because the area illuminated by a given beamwidth angle increases as the square of the distance from the source, so the power per unit area must decrease by the same ratio, the square of the distance. Since the area of the receiving antenna has not changed, the received power must decrease proportionally.

The phase center pattern in Fig 2E does *not* include the effect of inverse square law in the pattern, in order to emphasize the phase cancellation. The effect of including inverse square law would be to lighten the pattern as distance from the phase center increased.

Free Lunch

Since gain is proportional to aperture, larger antennas have more gain than smaller antennas, and poor efficiency can only make a small antenna worse. In spite of various dubious claims by antenna designers and manufacturers, "There's no such thing as a free lunch."[6] All else being equal, the larger the antenna, the greater the gain. But a large antenna with poor efficiency is a waste of metal and money.

Recommended Reading

For those interested in pursuing a deeper understanding of antennas, a number of books are available. A good starting point is *The ARRL Antenna Book* and *The ARRL UHF/Microwave Experimenter's Manual*. [Volume 1 of this book illustrates, by way of projects, many antenna concepts.—Ed.] Then there are the classic antenna books, by Kraus, Silver and Jasik.[2,4,7] Lo and Lee have edited a more recent antenna handbook, and Love has compiled most of the significant papers on horns and dishes.[5,8,9] For those interested in computer programming for antenna design, Sletten provides a number of routines.[10] Be warned that the math gets pretty dense once you get beyond the ARRL books.

Summary

This concludes our quick tour through basic antenna concepts and definitions. Now let's apply these concepts to understanding actual microwave antennas, starting with horns.

The *HDL_ANT* Computer Program

The intent of the *HDL_ANT* program is to aid the design of microwave antennas, not to be a whizzy graphics program. The program does the necessary calculations needed to implement a horn, dish or lens antenna, or to design an antenna range and correct the gain measurements. The basic data is entered interactively and results are presented in tabular form. If you like the results, a table of data or a template may be saved to a file for printing or further processing; if not, try another run with new data.

The C++ source code is also included, for those who wish to enhance it or simply to examine the more complex calculations not shown in the text. It has been compiled with Borland C++ version 3.1 and is available from the ARRL BBS at 860-594-0306, or can be downloaded via the Internet from ftp.cs.buffalo.edu in the /pub/ham-radio/qex directory. Alternately, go to the ARRL home page at **http://www.arrl.org** and choose **links**, then **ARRL ftp, QEX** and select *HDL_ANT.ZIP*.

Electromagnetic Horn Antennas

A horn antenna is the ideal choice for a contest rover station. It offers moderate gain in a small, rugged package with no adjustments needed, and has a wide enough beam to be easily pointed under adverse conditions. Fig 3 is a photograph of a homebrew horn mounted on an old Geiger counter case which houses the rest of a 10-GHz wide-band FM transceiver. I have worked six grid squares on 10 GHz from Mt. Wachusett in Massachusetts using a small horn with 17.5 dB of gain.

Horn Design

An antenna may be considered as a transformer from the impedance of a transmission line to the impedance of free space, 377 ohms. A common microwave transmission line is *waveguide*, a hollow pipe carrying an electromagnetic wave.[11] If one dimension of the pipe is greater than a half wavelength, then the wave can propagate through the waveguide with extremely low loss. And if the end of a waveguide is simply left open, the wave will radiate out from the open end.

Practical waveguides have the larger dimension greater than a half wavelength, to allow wave propagation, but smaller than a wavelength, to suppress higher-order *modes* which can interfere with low-loss transmission. Thus the aperture of an open-ended waveguide is less than a wavelength, which does not provide much gain.

For more gain, a larger aperture is desirable, but a larger waveguide is not. However, if the waveguide size is slowly expanded, or tapered, into a larger aperture, then more gain is achieved while preventing undesired modes from reaching the waveguide. This taper is like a funnel, called a conical horn, in cylindrical waveguide. The conical horn for 2304 MHz shown in Fig 4 was made by pop-riveting aluminum flashing to a coffee can. With common rectangular waveguide, the taper creates a familiar pyramidal horn, like those shown in the photograph, Fig 5.

To achieve maximum gain for a given aperture size and maximum efficiency, the taper must be long enough so that the phase of the wave is nearly constant across the aperture. An optimum horn is the shortest one that approaches maximum gain; several definitions are available. The *HDL_ANT* program uses approximate dimensions from a set of tables by Cozzens to design pyramidal horn antennas with gains from 10 to 25 dB.[12] Higher gains are possible, but the length of the horn increases much faster than the gain, so very high gain horns tend to be unwieldy.

Kraus gives the following approximations for beam width in degrees:

$$W_{E-\text{Plane}} = \frac{56}{A_{E\lambda}} \qquad W_{H-\text{Plane}} = \frac{67}{A_{H\lambda}}$$

and dB gain over a dipole:

$$\text{Gain} = 10\log_{10}\left(4.5 \cdot A_{E\lambda} \cdot A_{H\lambda}\right)$$

where $A_{E\lambda}$ is the aperture dimension in wavelengths in the E-plane and $A_{H\lambda}$ is the aperture in wavelengths dimension in the H-plane. The *HDL_ANT* program uses a more accurate gain algorithm which corrects the phase error of different taper lengths; for a given aperture, efficiency and gain decrease as the taper is shortened.[13]

Horn Construction

If you are fortunate enough to find a suitable surplus horn, this section is unnecessary. Otherwise, you may want to homebrew one. Horn fabrication is quite simple, so you can homebrew them as needed, for primary antennas with moderate gain or as feeds for higher gain dishes and lenses. Performance of the finished horn almost always matches predictions, with no tuning adjustments required.

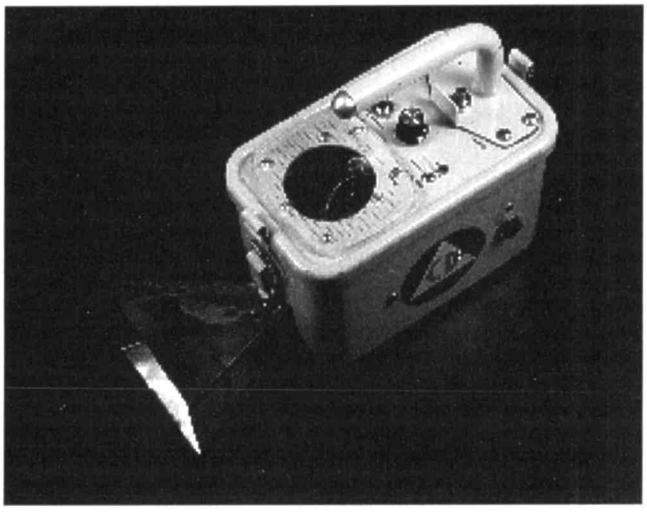

Fig 3—A homebrew horn for 10 GHz, made from flashing copper and designed using the *HDL_ANT* program.

The *HDL_ANT* program will design a horn with any desired gain or physical dimensions and then make a template for the horn. The template is a Postscript file; print the file on a computer printer to generate a paper template, tape the paper template to a sheet of copper or brass, cut it out, fold on the dotted lines, and solder the metal horn together on the end of a waveguide. The horn shown in Fig 3 used flashing copper from the local lumberyard, which I soldered together on the kitchen stove.

Fig 6 is a template for a nominal 14-dB horn for 5760 MHz generated by *HDL_ANT*. Try it: copy it on a copier and fold up the copy to see how easy it is to make a horn. It's almost as easy with thin copper. Fig 7 is another template example, a nominal 18-dB horn for 10368 MHz. For horns too large to fit the entire template on one sheet of paper, *HDL_ANT* prints each side on a separate sheet.

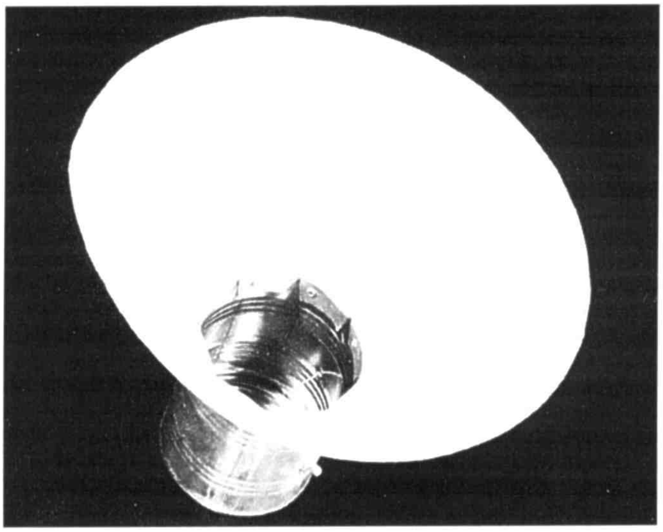

Fig 4—A homebrew conical horn for 2304 MHz.

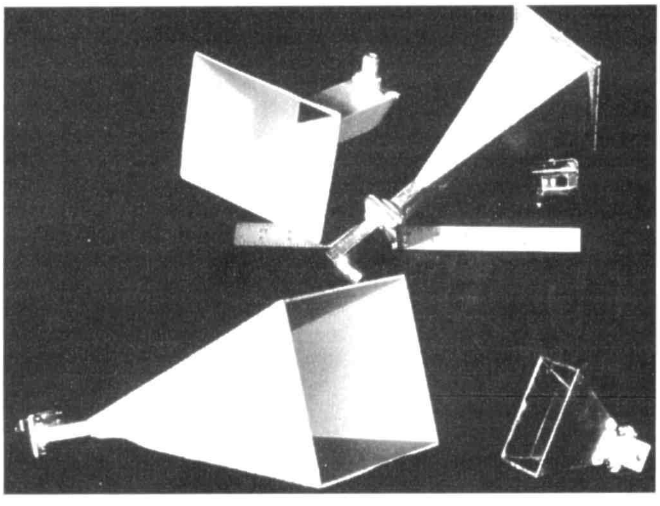

Fig 5—A variety of rectangular horn antennas.

Feed Horns

For horns intended as feed horns for dishes and lenses, beam angle and phase center are more important than horn gain. The *HDL_ANT* program calculates these values in both the E-plane and the H-plane, then allows you to enter new horn dimensions to adjust the beam angle or phase center before making a template. The phase center calculation is a difficult one involving Fresnel sines and cosines, so interactive adjustment of horn dimensions is a lot easier than having the computer try to find the right dimensions.[14,15] The template in Fig 8 is one example of a feed horn—it may be used to make a rectangular horn optimized to feed a dish with f/D = 0.5 at 10 GHz.[16] Feed horn design for dishes and lenses will be described in more detail in the next two sections.

Conclusion

Horns are versatile microwave antennas, easy to design and build with predictable performance. They should be the antenna of choice for all but the highest gain applications.

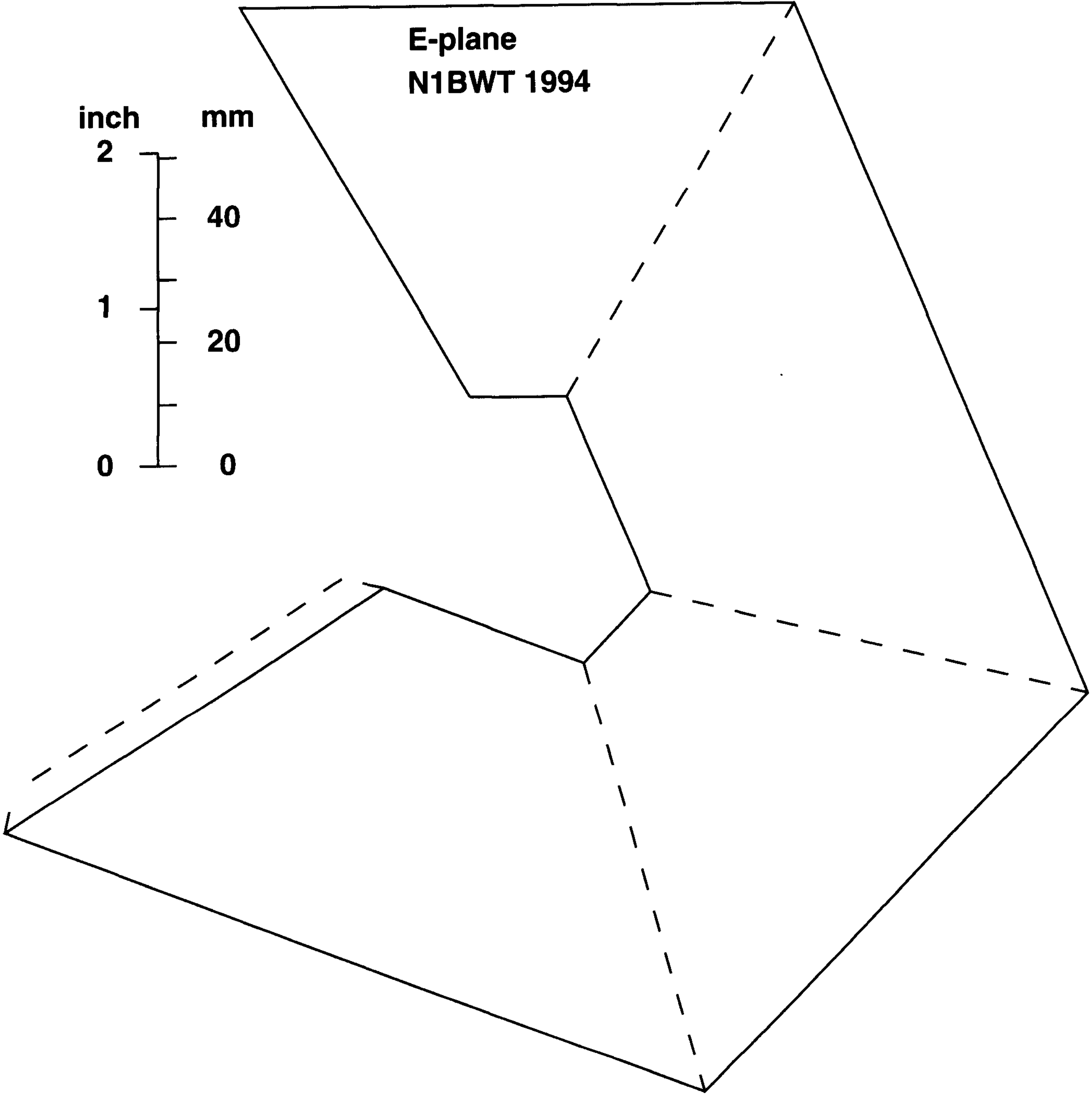

Fig 6—This full-scale template can be used to construct a horn antenna for 5760 MHz. Tape a copy to a piece of flashing copper and cut along the solid lines. Then fold at the dotted lines to form the rectangular horn. Solder the small flap to complete the horn, then solder the narrow end of the horn to a piece of waveguide. This antenna gives 13.8 dBi of gain.

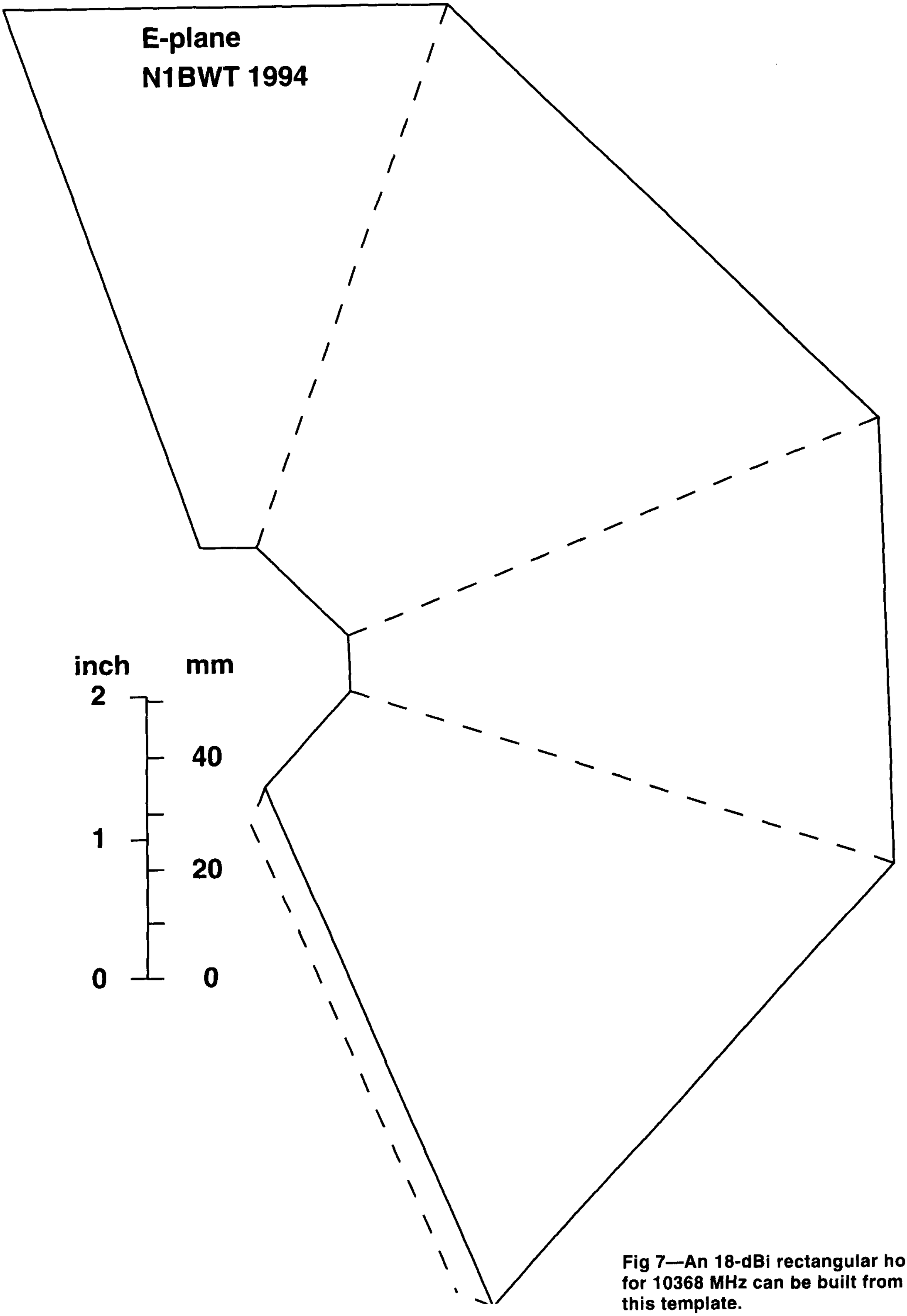

Fig 7—An 18-dBi rectangular horn for 10368 MHz can be built from this template.

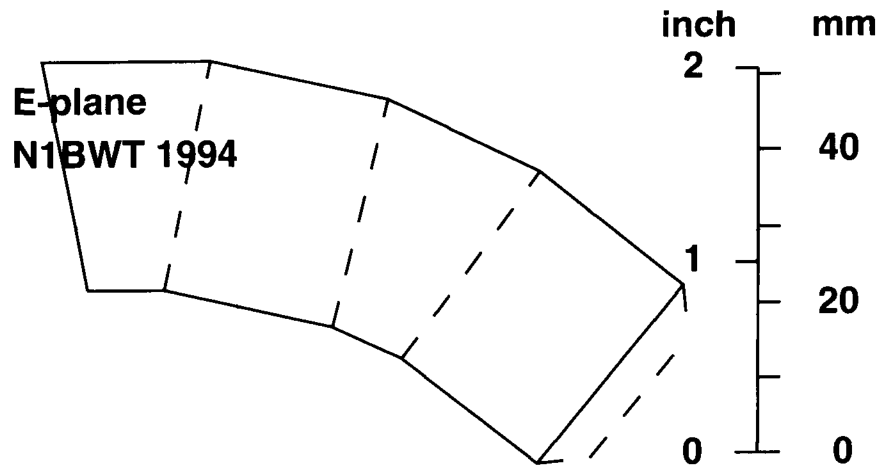

Fig 8—A template for a 10368-MHz, 8-dBi horn, suitable for feeding an f/D=0.5 dish.

Notes

[1] Wade, P., N1BWT, and Reilly, M., KB1VC, "Metal Lens Antennas for 10 GHz," *Proceedings of the 18th Eastern VHF/UHF Conference*, ARRL, 1992, pp 71-78.

[2] Kraus, John (W8JK), *Antennas*, McGraw Hill, 1956.

[3] Ralston, M., KI4VE, "Design Considerations for Amateur Microwave Antennas," *Proceedings of Microwave Update '88*, ARRL, 1988, pp 57-59.

[4] Silver, Samuel, *Microwave Antenna Theory and Design*, McGraw-Hill, 1949. (Volume 12 of Radiation Laboratory Series, reprinted 1984.)

[5] Lo, Y. T. and Lee, S. W., editors, *Antenna Handbook: theory, applications, and design*, Van Nostrand Reinhold, 1988.

[6] Attributed to economist Milton Friedman.

[7] Jasik, Henry and Johnson, Richard C., *Antenna Engineering Handbook*, McGraw-Hill, 1984. (Also first edition, 1961.)

[8] Love, A. W., *Electromagnetic Horn Antennas*, IEEE Press, 1976.

[9] Love, A. W., *Reflector Antennas*, IEEE Press, 1978.

[10] Sletten, Carlyle J. (W1YLV), *Reflector and Lens Antennas*, Artech House, 1988.

[11] *The ARRL UHF/Microwave Experimenter's Manual*, ARRL, 1990, pp 5-21 to 5-32.

[12] Cozzens, D. E., "Tables Ease Horn Design," *Microwaves*, March 1966, pp 37-39.

[13] Balanis, C. A., "Horn Antennas," in *Antenna Handbook: theory, applications, and design* (see Note 5).

[14] Muehldorf, Eugen I., *The Phase Center of Horn Antennas*, reprinted in *Electromagnetic Horn Antennas* (see Note 8).

[15] Abramowitz, Milton and Stegun, Irene A., *Handbook of Mathematical Functions*, Dover, 1972.

[16] Evans, D., G3RPE, "Pyramidal horn feeds for paraboloidal dishes," *Radio Communication*, March 1975.

Printing Postscript Files

The easiest way to print Postscript files is with a Postscript compatible laser printer. These have become more affordable and are becoming more common; for instance, the public library in my small town has one attached to a public-access computer. However, they are still roughly twice as expensive as the dot-matrix printers that most of us use with our personal computers.

An alternative to a laser printer is software that interprets Postscript language commands for display on a computer VGA display or a dot-matrix printer. I know of several versions of this type of software. Three commercial products, *GoScript*, *Ultrascript* and *Freedom of Press* perform this function. *Ghostscript*, a freeware program from the Free Software Foundation is available on many bulletin boards and Internet locations. The files are in ZIP format, so they must me downloaded, unZIPped, and installed according to the README documentation.

I have only used *Ghostscript*, version 2.5 and later. The latest versions, *Ghostscript* 5.03 and *Ghostview* 2.3, work very well under Windows 95 and NT; they are available from **http://www.cs.wisc.edu/~ghost/index.html**. They use Unix-style command strings which are difficult to remember, so I've included two BAT files to help: GS_VIEW.BAT for viewing on a screen, and GS_PRINT.BAT for printing on an Epson dot-matrix printer. For other brands of printer, the command will have to be changed appropriately, which will require reading of the documentation. Type GS_VIEW <filename.ps> or GS_PRINT <filename.ps> to use them. Be sure to type QUIT when you are through or your PC may be left in an unhappy state requiring rebooting.

I've included with *HDL_ANT* a sample Postscript file, SQUARE.PS, which draws a four-inch square. Use this to make sure that templates will be drawn to scale. A sample horn template, HORN18.PS, is included, too, to get you started. If the dimensions of the printed square are slightly off, you can correct the scaling. Each template has a line near the beginning of the file:

```
1.0 1.0 scale
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The first number is the scale factor in the x (horizontal) direction, and the second is the scale factor in the y (vertical) direction. Edit the SQUARE.PS file with an editor to change these numbers slightly; when you find a combination that prints a square exactly four inches on a side, then you have compensated for your printer. Edit these same numbers into any template to be printed on that printer and the dimensions will come out right.

I have not used any of the commercial products, but I would expect a commercial product to be much easier to install and use than freeware or shareware.

Batch Files

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GS_VIEW.BAT
gs %1
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```
GS_PRINT.BAT
gs -sDEVICE=epson -r60x60 %1
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Practical Microwave Antennas

Part 2–Parabolic Dish Antennas

By Paul Wade, N1BWT

(From *QEX*, October 1994)

Parabolic dish antennas can provide extremely high gains at microwave frequencies. A 2-foot dish at 10 GHz can provide more than 30 dB of gain. The gain is only limited by the size of the parabolic reflector; a number of hams have dishes larger than 20 feet, and occasionally a much larger commercial dish is made available for amateur operation, like the 150-foot one at the Algonquin Radio Observatory in Ontario, used by VE3ONT for the 1993 EME Contest. But these high gains are only achievable if the antennas are properly implemented, and dishes have more critical dimensions than horns and lenses.

Background

Last September (1993), I finished my 10-GHz transverter at 2 PM on the Saturday of the VHF QSO Party. After a quick checkout, I drove up Mt. Wachusett and worked four grids using a small horn antenna. However, for the 10-GHz Contest the following weekend, I wanted to have a better antenna ready.

Several moderate-sized parabolic dish reflectors were available in my garage but lacked feeds and support structures. I had thought this would be no problem, since lots of people, both amateur and commercial, use dish antennas. After reading several articles in the ham literature, I had a fuzzy understanding and was able to put a feed horn on one of the dishes and make a number of contacts of over 200 km from Mt. Washington, in horizontal rain.

But I was not satisfied that I really understood the details of making dishes work, so I got some antenna books from the library and papers from IEEE journals and did some reading. This article is an attempt to explain for others what I've learned. The 10-GHz antenna results from the 1993 Central States VHF Conference suggest that I might not be the only one who is fuzzy on the subject—the dishes measured had efficiencies of from 23% to less than 10%, while all the books say that efficiency should typically be 55%. On the other hand, there are enough hams doing successful EME work to suggest that some have mastered feeding their dishes. One of them, VE4MA, has written two good articles on TVRO dishes and feed horns for EME.[1,2]

There have been some good articles written by antenna experts who are also hams, like KI4VE, K5SXK and particularly W2IMU in *The ARRL UHF/Microwave Experimenter's Manual*, which is an excellent starting point. However, as I struggled to understand things that are probably simple and obvious to these folks, I did some reading and then used my personal computer to do some of the more difficult calculations and plot them in ways that helped me to understand what is happening. Many of us find a picture easier to comprehend than a complex equation. What I hope to do here is to start at a very basic level and explain the fundamentals, with pictures and graphics, well enough for hams to implement a dish antenna that works well. An accompanying computer program, *HDL_ANT*, is provided to do the necessary design calculations and to draw templates for small dishes in order to check the accuracy of the parabolic surface. *HDL_ANT* can be downloaded from the ARRL BBS (860-594-0306) or via the Internet from ftp.cs.buffalo.edu in the /pub/ham-radio/qex directory.

Dish Antenna Design

A dish antenna works the same way as a reflecting optical telescope.Electromagnetic waves, either light or radio, arrive on parallel paths from a distant source and are reflected by a mirror to a common point, called the focus. When a ray of light reflects from a mirror or flat surface, the angle of the path it takes leaving the surface (angle of reflection) is the same as the angle at which it arrived (angle of incidence). This optical principle is familiar to anyone who misspent a part of his youth at a pool table! If the mirror is a flat surface, two rays of light that arrive on parallel paths leave on parallel paths; however, if the mirror is curved, two parallel incident rays leave at different angles. If the curve is parabolic , then all the reflected rays meet at one point, as shown

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[1] Notes appear at the end of this section.

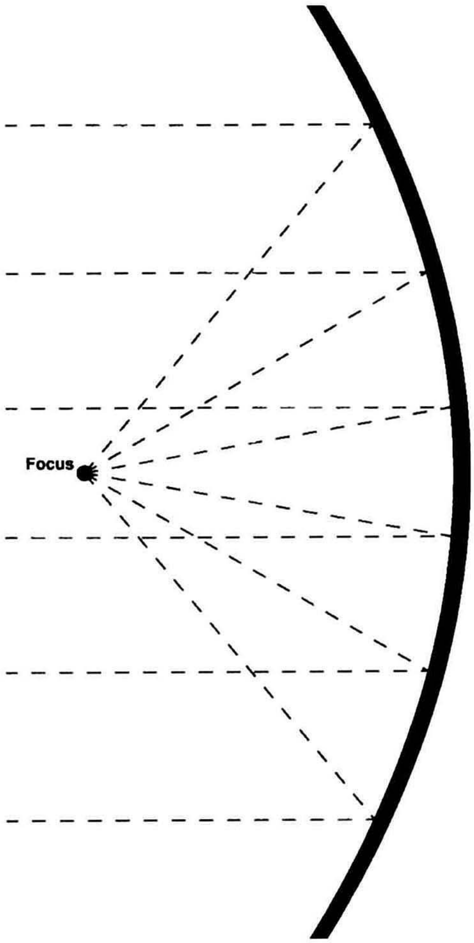

Fig 1—The geometry of a parabolic dish antenna.

in Fig 1. A dish is a parabola of rotation, a parabolic curve rotated around an axis that passes through the focus and the center of the curve.

A transmitting antenna reverses the path: the light or radio wave originates from a point source at the focus and is reflected into a beam of rays parallel to the axis of the parabola.

Illumination

Some of the difficulties found in real antennas are easier to understand when considering a transmitting antenna but are also present in receiving antennas, since antennas are reciprocal. One difficulty is finding a point source, since any antenna, even a half-wave dipole at 10 GHz, is much bigger than a point. Even if we were able to find a point source, it would radiate equally in all directions, so the energy that was not radiated toward the reflector would be wasted. The energy radiated from the focus toward the reflector illuminates the reflector, just as a light bulb would. So we are looking for a point source that illuminates only the reflector.

Aperture, Gain, and Efficiency

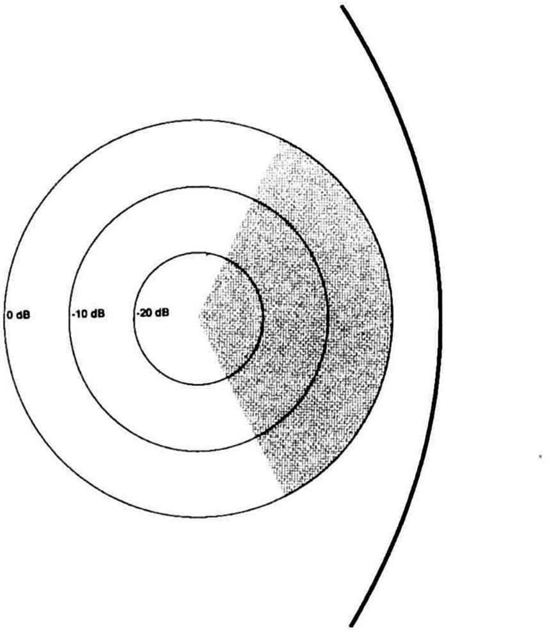

Fig 2—A parabolic dish antenna with uniform feed illumination.

The aperture, gain, and efficiency of an antenna were all defined for antennas in general in Part 1 of this series of articles. The aperture of a dish antenna is the area of the reflector as seen by a passing radio wave: Aperture = πr^2, where r is the radius, half the diameter of the dish.

If we replace a dish antenna with a much larger one, the greater aperture of the larger dish captures much more of the passing radio wave, so a larger dish has more gain than the smaller one. If we do a little geometry, we find that the gain is proportional to the aperture.

The gain of a dish is calculated as described in Part 1:

$$G_{dBi} = 10\log\left(\eta \cdot \frac{4\pi}{\lambda^2} \cdot \text{Aperture}\right)$$

with reference to an isotropic radiator, η is the efficiency of the antenna. It might be amusing to calculate the gain of the VE3ONT 150-foot dish at various frequencies; use 50% efficiency to make the first calculation simpler, then try different values to see how efficiency affects gain.

How much efficiency should we expect? All the books say that 55% is reasonable, and 70 to 80% is possible with very good feeds. Several ham articles have calculated gain based on 65% efficiency, but I haven't found measured data to support any of these numbers. On the other hand, KI4VE suggests that the amateur is lucky to achieve 45-50% efficiency with a small dish and a typical "coffee-can" feed.[3]

Practical Dish Antennas

When we first described a parabolic dish antenna, we put a point source at the focus, so that energy would radiate uniformly in all directions both in magnitude and phase. The problem is that the energy that is not radiated toward the reflector will be wasted. What we really want is a feed antenna that radiates only toward the reflector and has a phase pattern that appears to radiate from a single point.

Feed Patterns

We have already seen that efficiency is a measure of

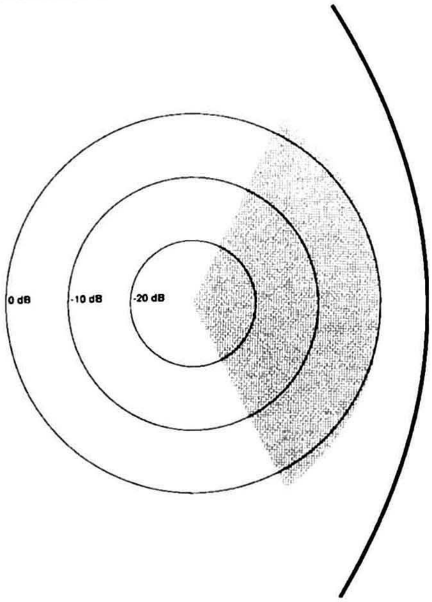

Fig 3—The desired dish illumination would provide uniform field intensity at all points on the reflector.

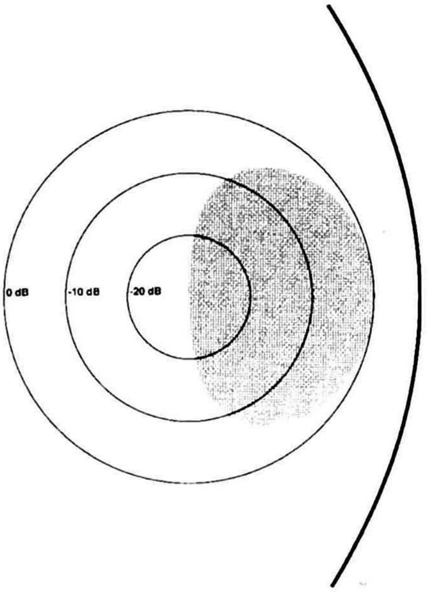

Fig 4—Typical illumination of a dish using a simple horn feed.

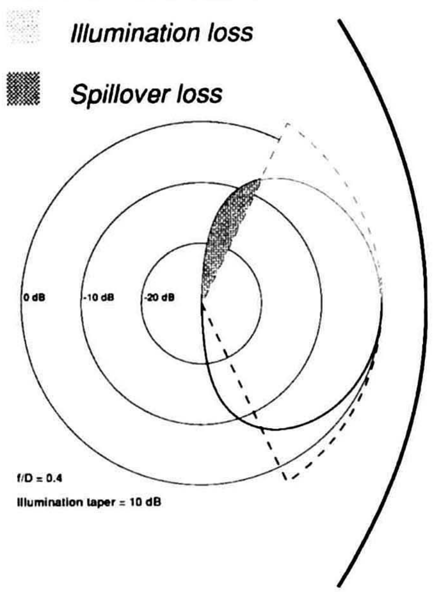

Fig 5—A comparison of typical dish illumination with the desired illuminaton.

how well we use the aperture. If we illuminate the whole reflector, we will be using the whole aperture. Perhaps our feed pattern should be as shown in Fig 2, with uniform feed illumination across the reflector. But when we look more closely at the parabolic surface, we find that the focus is farther from the edge of the reflector than from the center. Since radiated power diminishes with the square of the distance (inverse-square law), less energy is arriving at the edge of the reflector than at the center; this is commonly called space attenuation or space taper. In order to compensate, we must provide more power at the edge of the dish than in the center by adjusting the feed pattern to that shown in Fig 3, in order to have constant illumination over the surface of the reflector.

Simple feed antennas, like a circular horn (coffee-can feed) that many amateurs have used, have a pattern like the idealized pattern shown in Fig 4. In Fig 5 we superimpose that on our desired pattern; we have too much energy in the center, not enough at the edges, and some misses the reflector entirely. The missing energy at the edges is called illumination loss, and the energy that misses the reflector is called spillover loss. The more energy we have at the edge, the more spillover we have, but if we reduce spillover, the outer part of the dish is not well illuminated and is not contributing to the gain. Therefore, simple horns are not ideal dish feeds (although they are useful). In order to have very efficient dish illumination we need to increase energy near the edge of the dish and have the energy drop off very quickly beyond the edge.

Edge Taper

Almost all feed horns will provide less energy at the edge of the dish than at the center, like Fig 4. The difference in power at the edge is referred to as the *edge taper*, or *illumination taper*. With different feed horns, we can vary the edge taper with which a dish is illuminated. Different edge tapers produce different amounts of illumination loss and spillover loss, as shown in Fig 6: a small edge taper results in larger spillover loss, while a large edge taper reduces the spillover loss at the expense of increased illumination loss.

If we plot these losses versus the energy at the edge of the dish in Fig 7, we find that the total efficiency of a dish antenna peaks with an illumination taper, like Fig 6, so that the energy at the edge is about 10 dB lower than the energy at the center.[4,6] This is often referred to as 10-dB edge taper or edge illumination—often recommended but not explained.

G/T

When an antenna is receiving a signal from space, such as a satellite or EME signal, there is very little background noise emanating from the sky compared to the noise generated by the warm (300 K) Earth during terrestrial communications. Most of the noise received by an antenna pointed at the sky is earth noise arriving through feed spillover. As we saw in Fig 6, the spillover can be reduced by increasing the edge taper, while Fig 7 shows the efficiency, and thus the gain, decreasing slowly as edge taper is increased. The best compromise is reached when *G/T*, the ratio of gain to antenna noise temperature, is maximum. This typically occurs with an edge taper of about 13 dB, but the optimum edge taper for *G/T* is a function of receiver noise temperature and sky noise temperature at any given frequency.[2]

Focal Length and *f/D* Ratio

All parabolic dishes have a parabolic curvature, but some are shallow dishes, while others are much deeper and more like a bowl. They are just different parts of a parabola that extends to infinity. A convenient way to describe how much of the parabola is used is the *f/D* ratio, the ratio of the focal length *f* to the diameter *D* of the dish. All dishes with the same *f/D* ratio require the same feed geometry, in proportion to the diameter of the dish. The figures so far have depicted one arbitrary *f/D*; Fig 8 shows the relative geometries for commonly used *f/D* ratios, from 0.25 to 0.65, with the desired and idealized feed patterns for each.

Notice the feed horn patterns for the various *f/D* ratios in Fig 8. As *f/D* becomes smaller, the feed pattern to illuminate it becomes broader, so different feed horns are needed to properly illuminate dishes with different *f/D* ratios. The feed horn pattern must be matched to the reflector *f/D*. Larger *f/D* dishes need a feed horn with a moderate beamwidth, while a dish with an *f/D* of 0.25 has the focus level with the edge of the dish, so the subtended angle that must be illuminated is 180 degrees. Also, the edge of the dish is twice as far from the focus as the center of the dish, so the desired pattern would have to be 6 dB stronger (inverse-square law) at the edge as in the center.

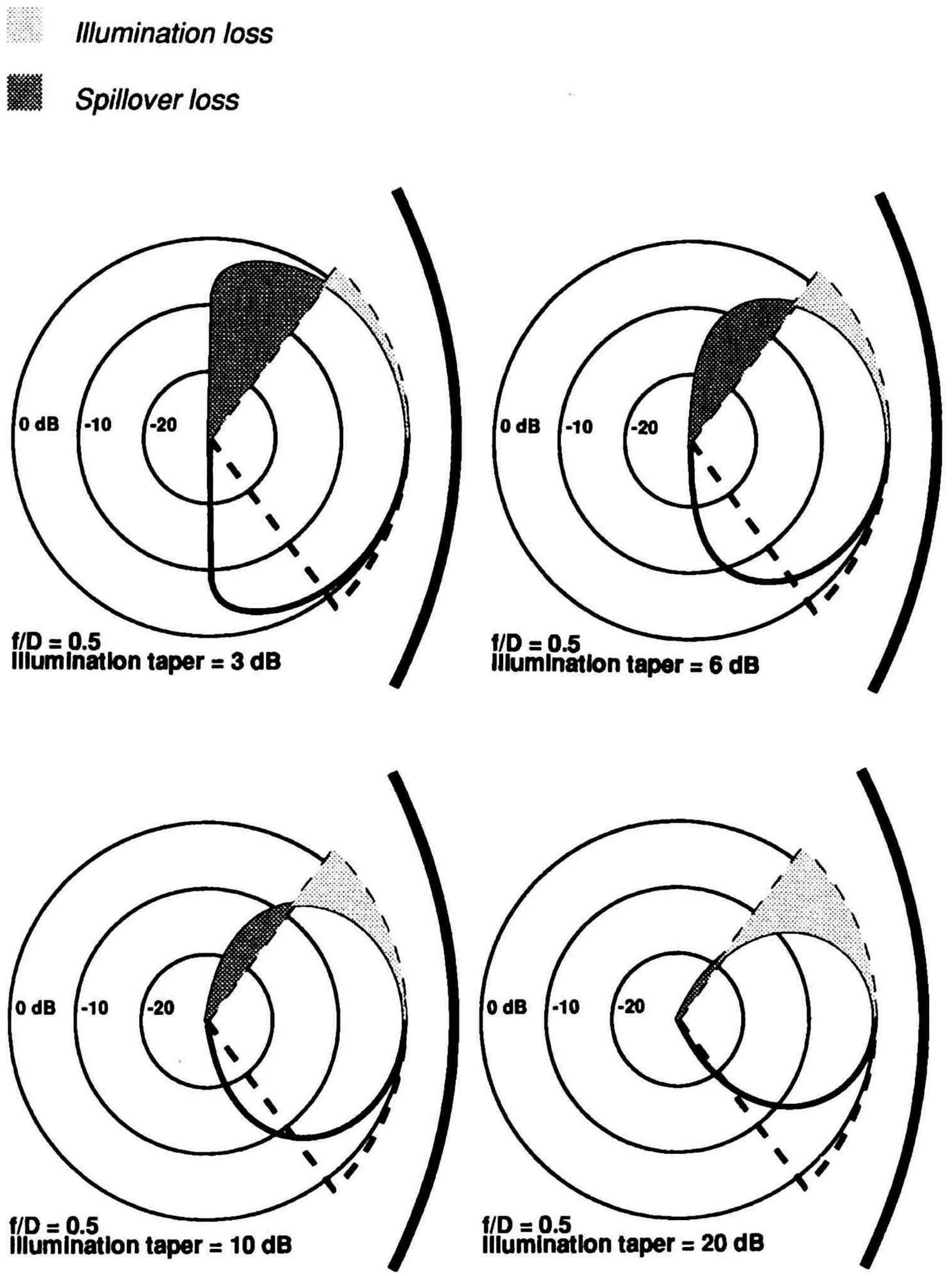

Fig 6—Dish illumination at various values of illumination taper.

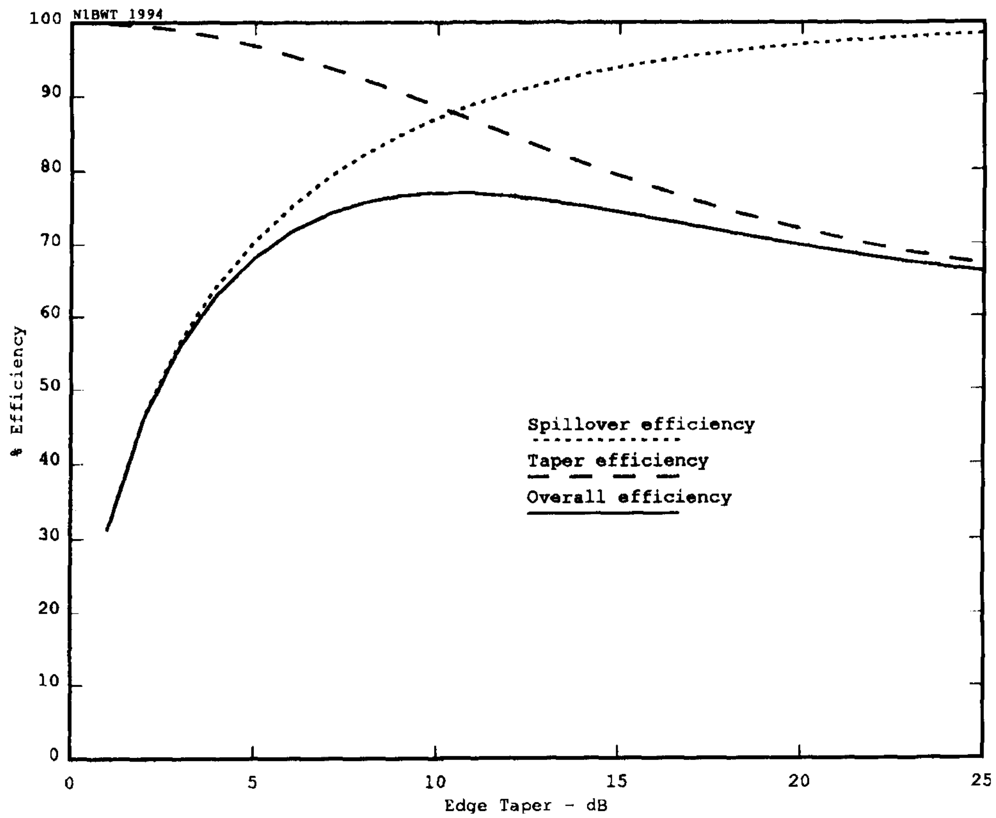

Fig 7—Dish efficiency versus edge taper. The peak efficiency occurs at a taper of about 10 dB.

This is an extremely difficult feed pattern to generate. Consequently, it is almost impossible to efficiently illuminate a dish this deep.

Phase Center

A well-designed feed for a dish or lens has a single phase center, as described in Part 1 of this series of articles, so that the feed radiation appears to emanate from a single point source, at least for the main beam, the part of the pattern that illuminates the dish or lens. Away from the main beam, the phase center may move around and appear as multiple points, as stray reflections and surface currents affect the radiation pattern. Also, the phase center will move with frequency, adding difficulty to broadband feed design. Fortunately, we are only considering narrow frequency ranges here.

Symmetry of E-Plane and H-Plane

On paper, we can only depict radiation in one plane. For a simple antenna with linear polarization, like a dipole, this is all we really care about. A dish, however, is three-dimensional, so we must feed it uniformly in all planes. The usual plane for linear polarization is the E-plane, while the plane perpendicular to it is the H-plane. Unfortunately, most antennas not only have different radiation patterns in the E- and H-planes, but also have different phase centers in each plane, so both phase centers cannot be at the focus.

Table 1
Measured Effect of Focal Length Error at 10 GHz

Feed Distance (in)	*Relative Gain (dB)*
8.125	−0.6
8.25	0
8.375	−0.3
8.625	−1.7

Focal Length Error

When I started actually measuring the gain of dish antennas, I discovered the most critical dimension to be the focal length—the axial distance from the feed to the center of the dish. A change of ¼ inch, or about a quarter-wavelength, changed the gain by a dB or more, shown in Table 1 as measured on a 22-inch dish with $f/D = 0.39$.

I was surprised at this sensitivity, since my experience with optics and photography suggested that this is not so critical—it would be extremely difficult to adjust a lens or telescope to an optical quarter wavelength. But lenses become more critical to focus as the *f*-stop is decreased—an *f* 2 lens is considered to have a very small depth of field, while an *f* 16 lens has a large depth of field, or broad focus. The *f*-stop of a lens is the same as the f/D ratio of a dish—both are the ratio of the focal length to the aperture diameter.

A typical reflector telescope has a parabolic reflector of *f* 8, but a dish antenna with *f*/*D* = 0.4 has an *f*-stop of 0.4, so focusing is much more critical.

More reading located an article which described how to calculate the loss due to focal length error.[7] Fig 9 shows the loss as the feed horn is moved closer and farther than the focus for various *f*/*D* dishes with uniform illumination; the tapered illumination we use in practice will not have nulls as deep as the curves shown in Fig 9. It is clear that dishes with small *f*/*D* are much more sensitive to focal length error.

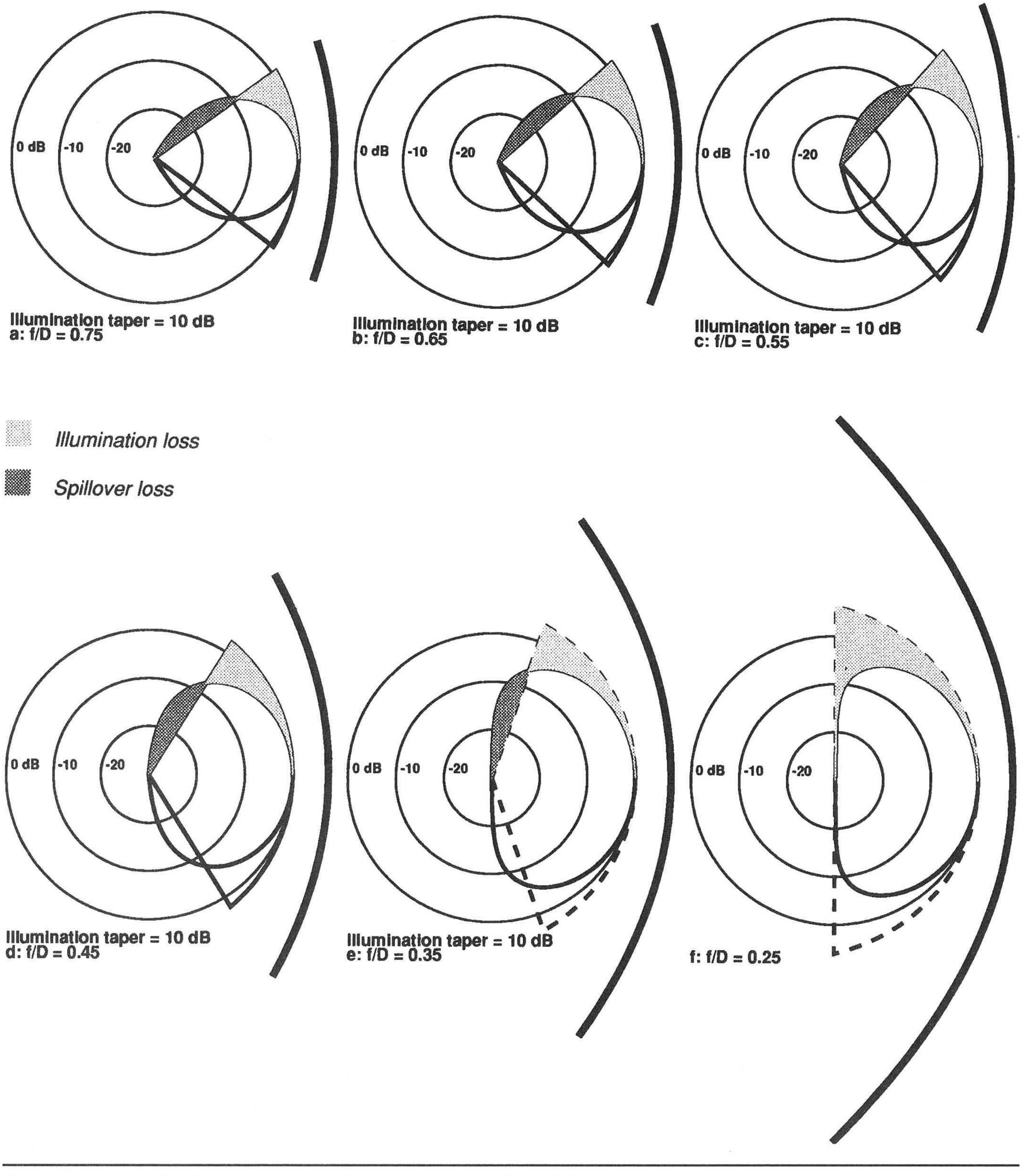

Fig 8—Dish illumination patterns for dishes of various *f*/*D* ratios.

Remember that a wavelength at 10 GHz is just over an inch.

The critical focal length suggests that it is crucial to have the phase center of the feed exactly at the focus of the reflector. Since the phase center is rarely specified for a feed horn, we must determine it empirically, by finding the maximum gain on a reflector with known focal length.

If we are using a feed horn with different phase centers in the E- and H-planes, we can also estimate the loss suffered in each plane by referring to Fig 9.

Lateral errors in feed horn position are far less serious;

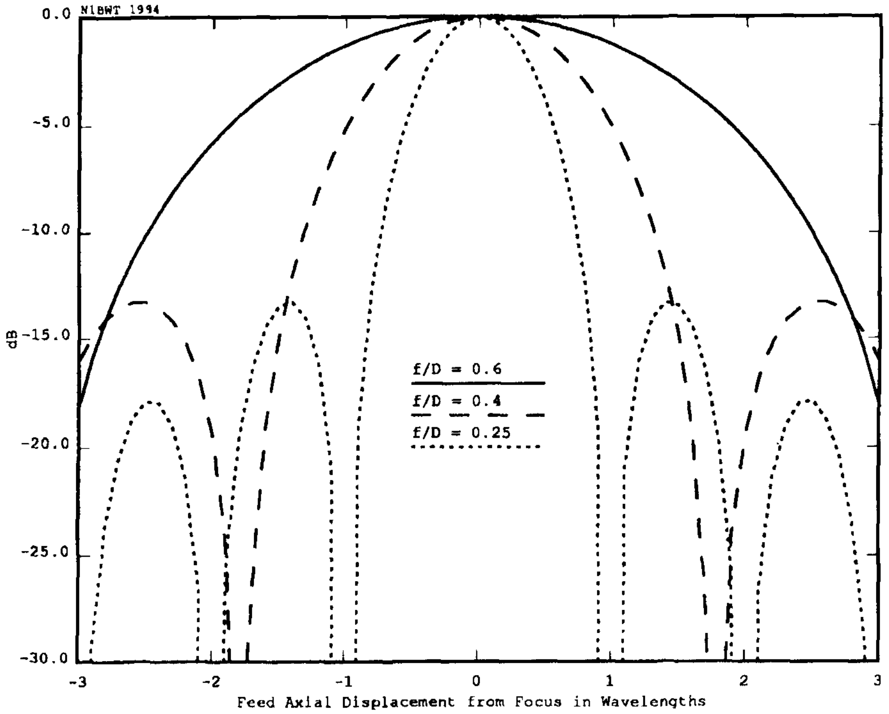

Fig 9—The loss due to axial displacement of the feed from the focus point is highly dependent on the *f/D* ratio.

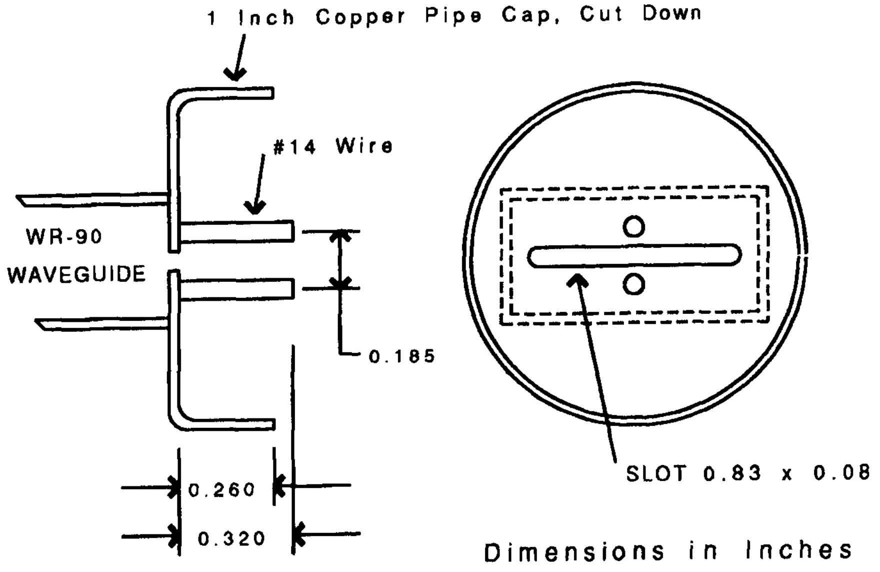

Fig 10—A Clavin feed for 10 GHz, made from a 1-inch copper pipe cap.

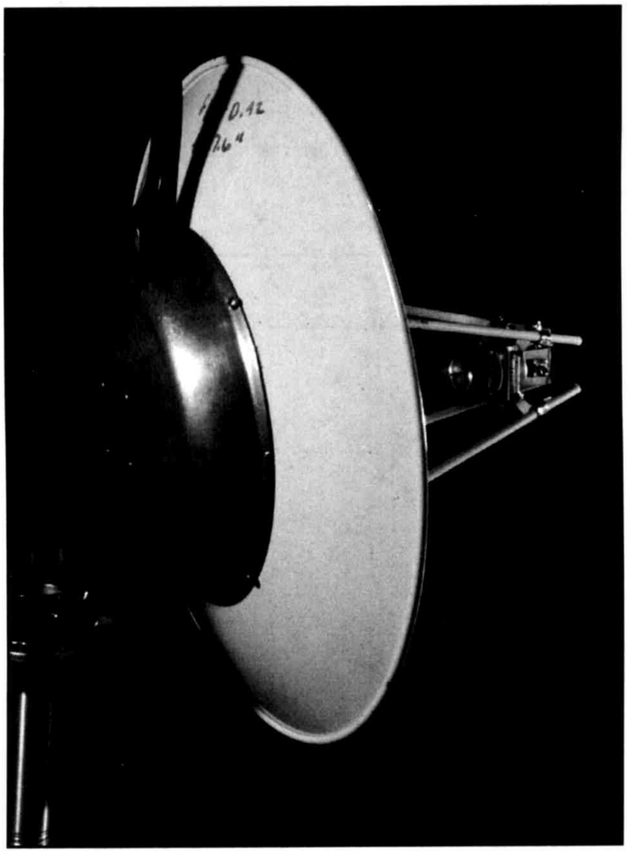

Fig 11—This photo shows the technique of mounting a dish using a frying pan with a rolled edge. Also note the Clavin feed used with this dish.

small errors have little effect on gain, but do result in shifting the beam slightly off bore-sight.

Notice that the focal-length error in Fig 9 is in *wavelengths*, independent of the dish size. A quarter-wavelength error in focal length produces the same loss for a 150-foot dish as for a 2-foot dish, and a quarter-wavelength at 10-GHz is just over ¹/₄ inch. Another implication is that multiband feeds, like the WA3RMX triband feed, should be optimized for the highest band, since they will be less critical at lower bands with longer wavelengths.[8]

Total Efficiency

It has been fairly easy to calculate efficiency for an idealized feed horn pattern due to illumination taper and spillover, but there are several other factors that can significantly reduce efficiency. Because the feed horn and its supporting structures are in the beam of the dish, part of the radiation is blocked or deflected. A real feed horn also has sidelobes, so part of its radiation is in undesired directions and thus wasted. Finally, no reflector is a perfect parabola, so the focusing of the beam is not perfect. We end up with quite a list of contributions to total efficiency:

- illumination taper
- spillover loss
- asymmetries in the E- and H-planes
- focal point error
- feed horn sidelobes
- blockage by the feed horn
- blockage by supporting structures
- imperfections in parabolic surface
- feed line loss

KI4VE suggests that the amateur is lucky to achieve 45-50% efficiency with a small dish and a typical coffee-can feed.[3] I suspect that the only way to find total efficiency, or to optimize it, is to make gain measurements on the complete antenna.

Practical Feed Systems

An optimum feed would approximate the desired feed pattern for the *f/D* of the parabolic reflector in both planes and have the same phase center in both planes. Let's examine some of the available feed horn designs to see how well they do:

1. Dipole

Most hams know what the pattern from a dipole looks like—in free space, it looks like a donut with the dipole through the hole. If it is near ground or a reflector, the pattern in the plane perpendicular to the dipole (H-plane) is distorted to emphasize radiation away from the reflector. The shape of the radiation in this plane is controlled by the distance from the reflector, while the shape of the radiation in a plane parallel to the dipole (E-plane) does not change significantly. This suggests that the best we could do is to find a dish with an edge angle that approximates the E-plane beamwidth and adjust the reflector spacing so that the H-plane beamwidth matches the E-plane. Round disc reflectors are frequently used, but it turns out that the pattern is the same as a half-wavelength rod reflector.

2. Dual Dipole

The H-plane beamwidth can be narrowed by adding a second parallel dipole over a plane reflector, such as the EIA (sometimes erroneously called NBS) reference antenna.[9] This is a reasonably good feed with good symmetry for reflectors with *f/D* around 0.55 and has been used with good success for 432-MHz EME.

3. Penny-Splasher

The penny-splasher feed is equivalent to a dual dipole with reflector—the slots in the waveguide act as dipoles.[10] In practice, however, it has poor sidelobes that result in low efficiency.

4. Rectangular Horn

The beamwidth of a horn antenna is controlled by the horn aperture dimension, but a square horn has different E- and H-plane beamwidths. We can make it rectangular with the aperture dimensions adjusted so that the E- and H-plane patterns and beamwidths are similar. G3RPE described this technique and showed that at 10 GHz it can only illuminate dishes with *f/D* greater than 0.48 if the horn is driven by common WR-90 waveguide.[11] However, the smaller WR-75 waveguide is also suitable for 10 GHz and could drive horns which would illuminate an *f/D* as small as 0.43.

With a rectangular horn, it is difficult to achieve both a common phase center for the E- and H-planes and similar patterns in both planes. The horn section of the *HDL_ANT* computer program calculates the phase centers and allows adjustment of dimensions to change them. Kraus shows a series of patterns for horns with different flare angles, and some of them approximate the desirable feed pattern of Fig 3.[12] However, no phase information is given; W2IMU once told me they were terrible, and I accept his authority.

5. Circular Horn

A circular horn antenna, since it is symmetrical, might be expected to provide a fairly symmetrical pattern. Unfortunately, it doesn't, and the phase centers are different for the E- and H-planes. The beamwidth is controlled by the diameter of the horn—for wide beamwidths, the horn may have no flare, like the coffee-can feed, or cylindrical horn, often used at 1296 MHz.[13]

Some improvement in the pattern may be provided by adding a choke flange to a cylindrical horn.[14] Further improvement is possible by adding slots in the flange, though radiation patterns are shown in only one plane.[15]

All of the above feeds have patterns similar to Fig 4. Many of these were developed for radar applications, where feed inefficiency may be compensated by increased power. More recently, satellite communication has prompted research into more efficient feed antennas, particularly for deep dishes (small f/D*) with reduced sidelobes and better* G/T. *Here are a few of the many variations that have been described, chosen for their potential for construction without elaborate machining:*

6. Clavin Feed

The Clavin feed is a cavity antenna fed by a resonant slot, with probes that excite a second waveguide mode to broaden the pattern in the H-plane to match the E-plane.[16] Radiation patterns approximate our desired feed pattern, Fig 3, while maintaining a good phase center. Fig 10 is a sketch of one I made from a 1-inch copper plumbing pipe cap. It is best for deep dishes with *f/D* in the 0.35 to 0.4 range. The resonant slot makes it more narrowband than the others (not a problem for amateur use), and the smaller size would have less feed blockage than the "Chaparral" or Kumar feeds, so it might provide better performance on smaller dishes.

A scalar feed is one that has no inherent polarization; the word "scalar" means that the electric field distribution is independent of the axis in which you look at the distribution. The result is that scalar horns have equal beamwidths and sidelobes in both azimuth and elevation. This can't be achieved with a standard flared horn, so scalar horns are usually preferred for dish feeds. The symmetry also makes them suitable for both linear and circular polarization. The W2IMU dual-mode horn and the "Chaparral" and Kumar feeds below are scalar feeds.

7. W2IMU Dual-Mode Horn

Diffraction from the edge of a horn causes sidelobes that reduce efficiency. In the W2IMU dual-mode horn design, there is a flare from a small section, which only supports the lowest waveguide mode, to a larger section that supports two waveguide modes.[5,17,18] The size of the flare controls the relative amplitude of the two modes, and the length of the large section is chosen so that the two modes cancel at the edge of the horn because they travel at different phase velocities in the waveguide. The cancellation eliminates the sidelobes and thus puts more energy onto the reflector. The requirement for a larger horn makes this feed optimum for larger *f/D* reflectors, in the 0.5 to 0.6 range.

8. Chaparral Feed

The "Chaparral" feed is a type of scalar feed horn often found on TVRO dishes, with a series of cavity rings surrounding a circular waveguide.[19,5,4] The rings modify the pattern to approximate our desired feed pattern, Fig 3, while maintaining a good phase center. This feed is best for deep dishes, with *f/D* in the 0.35 to 0.45 range. Fine adjustment of the pattern is possible by changing the protrusion of the central waveguide in relation to the surrounding rings.

Note: I have not seen any mention of the location of the phase center, but my experiments show that it is controlled by the location of the outer rings, not the central waveguide.

9. Kumar Feed

The Kumar feed is a scalar feed horn similar to the Chaparral feed, but with a single larger outer ring, so construction is somewhat simpler.[20] Radiation patterns approximate our desired feed pattern, Fig 3, while maintaining a good phase center. Ham-band versions of this feed have been described by VE4MA for 1296, 2304 and 3456 MHz.[2,21] Like the Chaparral feed, it is best for deep dishes, with *f/D* in the 0.35 to 0.45 range, with similar fine adjustment.

Complete Dish Antennas

Many of the papers describing feed horns show great detail of the horn performance, but very few even mention what happens when a reflector is added. The reflector may add too many uncertainties for good research, but our goal is to make a good working antenna. We want high efficiency because a dish has the same size, wind loading, and narrow beamwidth regardless of efficiency—we should get as much performance as possible for these operational difficulties. In other words, if I am going to struggle with a one-meter diameter dish on a windy mountain top, I certainly want one meter worth of performance!

In order to compare the different feeds, I wanted to measure the gain of several of them with the same reflector, to find their performance as complete antennas. I made a mechanism from an old slotted-line carriage and some photographic hardware that allows the feed to be moved in three dimensions with fine control of adjustment, so the feed position can be adjusted for maximum gain.

The emphasis here is on smaller dishes intended for mountaintopping and other portable operation, so maximum gain with minimum size and weight is a definite consideration. For other applications, there would be other considerations; EME, for instance, would mandate maximum performance.

Parabolic Reflector

I have managed to collect a half-dozen parabolic reflectors of various sizes and origins, and I wanted to know if they were useful at 10 GHz. First, for each dish I measured the diameter and depth in the center of the dish in order to calculate the focal length and *f/D* ratio . This can only be an approximation for some dishes, due to holes or flat areas in the center. The focal length is calculated as:

$$f = \frac{D^2}{16 \cdot \text{depth}}$$

The *HDL_ANT* computer program does the calculation and then generates a Postscript plot of a parabolic curve for the specified diameter and *f/D* ratio. For each reflector, I made a series of plots on a laser printer for a range of *f/D* values for antennas in general near the calculated value, cut out templates, then fitted them to the surface to find the closest fit. For 10 GHz, the surface must be within ±1 mm of a true parabola for optimum performance, although errors up to ±3 mm result in only 1 dB degradation.[22] I selected several reflectors with good surfaces and discarded one that wasn't even close.

Given a choice, a reflector with a large *f/D* (0.5 to 0.6) would be preferable. As described earlier, dishes with small *f/D* are hard to illuminate efficiently and are more sensitive to focal length errors. On the other hand, a dish that is available for the right price is always a good starting point!

Parabolic reflectors can come from many sources, not just antenna manufacturers. Some aluminum snow coasters (now unfortunately replaced by plastic, but aluminum foil glued to the surface might make them usable) are good, and hams in Great Britain have put dustbin lids into service as effective parabolic reflectors for years.

Homebrewing a parabolic reflector is possible, but great difficulty is implied by the surface accuracy cited above. The surface accuracy requirement scales with wavelength, so the task is easier at lower frequencies. Of course, hams are always resourceful—N1IOL found that the cover from his 100-pound propane tank was an excellent 14-inch parabolic surface and has used it to mold a number of fiberglass reflectors. K1LPS then borrowed a larger cover from a different type of propane tank and found it to be nowhere near a parabola!

Recommended Feed Systems

Since no single feed system is optimum for all dishes, a good feed recommendation depends on the *f/D* of the particular dish. For shallow dishes (*f/D* of 0.5 to 0.6), I'd recommend the W2IMU dual-mode horn or a pyramidal horn designed for the exact *f/D*.[5,11] The horn section of the computer program will design the horn and plot a construction template. For deeper dishes (*f/D* of 0.3 to 0.45), I'd recommend the Chaparral, Kumar or Clavin feeds.[5,20,16] For 10 GHz, a Chaparral horn designed for 11-GHz TVRO use works well; your local satellite TV dealer might be persuaded to order it as an "11 GHz Superfeed."

Mechanical Support

There are two critical mechanical problems: mounting the feed horn to the dish and mounting the dish to the tripod. Most small dishes have no backing structure, so the thin aluminum surface is easily deformed. K1LPS discovered that some cast-aluminum frying pans have a rolled edge that sits nicely on the back of a dish; Mirro is one suitable brand. This is a good use for that old frying pan with the worn-out Teflon coating, so buy a new one for the kitchen. Tap a few holes in the edge of the old pan, screw the dish to it, and you have a solid backing. A solid piece of angle iron or aluminum attaches the bottom of the frying pan to the top of a tripod. The photograph in Fig 11 shows a dish mounted using a frying pan. WA1MBA uses this technique for a 24-inch dish at his home and reports that it stands up well to New England winters.

The mounting structure for the feed horn is in the RF field, so we must minimize the blockage it causes. We do this by using insulating materials and by mounting the support struts diagonally, so they aren't in the plane of the polarization. Fiberglass is a good material; plant stakes or bicycle flags are good sources, and WA5VJB recommends cheap target arrows. Use of four rather than three struts is recommended—if they are all the same length, then the feed is centered. The base of the struts should be attached to the backing structure or edge of the frying pan; the thin dish surface is not mechanically strong.

Aiming

A quality compass and a way of accurately aligning the antenna to it are essential for successful operation. Narrow beamwidth and frequency uncertainty can make searching for weak signals frustrating and time-consuming. A heavy tripod with setting circles is a good start; hang your battery from the center of the tripod and it won't blow over as often. Calibrate your headings by locating a station with a known beam heading rather than by eyeballing the dish heading; small mechanical tolerances can easily shift the beam a few degrees from the apparent boresight. As W1AIM can testify, having the wind blow a dish over can distort it enough to move the beam to an entirely different heading.

Alternatives

The narrow beamwidth may actually make contacts more difficult, particularly in windy conditions. I have worked six grids from Mt. Wachusett in central Massachusetts using a small Gunnplexer horn. The longest path, 203 km, required a 12-inch lens for additional gain to make the contact on wideband FM; it would have been easy with narrowband SSB or CW.[23]

For a rover station, a reasonable size horn might be a good compromise, with adequate gain and moderate beamwidth for easy aiming. I often use the 17.5-dBi Gunnplexer horn, with a 12-inch lens ready to place in front of it when signals are marginal.

Conclusions

A parabolic dish antenna can provide very high gain at microwave frequencies, but only with very sharp beamwidths. To achieve optimum gain, careful attention to detail is required: checking the parabolic surface accuracy with a template, matching the feed horn to the *f/D* of the dish, and, most importantly, accurately locating the phase center of the feed horn at the focus.

Notes

[1] Malowanchuk, B. W., VE4MA, "Use of Small TVRO Dishes for EME," *Proceedings of the 21st Conference of the Central States VHF Society*, ARRL, 1987, pp 68-77.

[2] Malowanchuk, B. W., VE4MA, "Selection of an Optimum Dish Feed," *Proceedings of the 23rd Conference of the Central States VHF Society*, ARRL, 1989, pp 35-43.

[3] Ralston, M., KI4VE, "Design Considerations for Amateur Microwave Antennas," *Proceedings of Microwave Update '88*, ARRL, 1988, pp 57-59.

[4] Reasoner, H., K5SXK, "Microwave Feeds for Parabolic Dishes," *Proceedings of Microwave Update '89*, ARRL, 1989, pp 75-84.

[5] Turrin, D., W2IMU, "Parabolic Reflector Antennas and Feeds," *The ARRL UHF/Microwave Experimenter's Manual*, ARRL, 1990.

[6] Rahmat-Samii, Y., "Reflector Antennas," *Antenna Handbook: theory, applications, and design*, Y.T. Lo and S.W. Lee, editors, Van Nostrand Reinhold, 1988, p 15-42.

[7] Ingerson, P. G. and Rusch, W. V. T., "Radiation from a paraboloid with an axially defocused feed," *IEEE Transactions on Antennas and Propagation*, Vol AP-21 No. 1, Jan 1973, pp 104-106.

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Practical Microwave Antennas

Part 3–Lens antennas and microwave antenna measurements.

By Paul Wade, N1BWT

(From *QEX*, November 1994)

In the previous parts of this series we discussed horn antennas and parabolic dish antennas. We now turn our attention to the third type of practical microwave antennas: lenses. I'll also describe microwave antenna measurement techniques and conclude with a discussion of actual measurement results and a comparison of the three types of antennas.

Lens Antennas

For portable microwave operation, particularly if backpacking is necessary, dishes or large horns may be heavy and bulky to carry. A metal-plate lens antenna is an attractive alternative. Placed in front of a modest-sized horn, the lens provides some additional gain, much like eyeglasses on a near-sighted person. The lens antennas I have built and tested are cheap and easy to construct, light in weight and noncritical to adjust. The *HDL_ANT* computer program makes designing them easy, as well.

There are other forms of microwave lenses—for instance, dielectric lenses and Fresnel lenses—but the metal-plate lens is probably the easiest to build and lightest to carry, so it is the only type I'll describe here.

The metal-lens antenna is constructed of a series of thin metal plates with air between them. The curvature of the edges of the plates forms the lens, and the space between the plates forms a series of waveguides. Fortunately, we can get "air" in a solid form to make construction easier: Styrofoam looks just like air to RF, and it keeps the metal plates accurately spaced. We use aluminum foil for the plates, attaching it to the Styrofoam with spray adhesive and shaping the curvature with a hobby knife on a compass. Designs are limited to those using circles, to ease construction.

Background

These metal-plate lenses were originally described for 10 GHz by KB1VC and me at the 1992 Eastern VHF/UHF Conference, but there is no good reason to limit them to that band.[1] The need for more gain became apparent to us during the 1991 10-GHz Contest. We were atop Burke Mountain in Vermont, on a day as clear as the tourist brochures promise. We could see Mt. Greylock in Massachusetts, where KH6CP was located, but it was too far to work with horn antennas on our Gunnplexers. After K1LPS humped his two-foot dish up the fire tower, we knew that wasn't the best answer for portable work.

Later, we found an article in *VHF Communications* on lens antennas by Angel Vilaseca, HB9SLV, which intrigued us.[2] It described how to design a metal-lens antenna but did not present expected gain or measured results.

We then searched through the references to try to understand how these antennas work, finally discovering that the best work was done before we were born, by Kock.[3] Kock's paper makes it clear how the metal-lens antenna works, and, more importantly, that it *does* work!

Lens Basics

The metal-plate lens works, in principle, like any other lens. A similar optical lens would take a broad beam of light and shape it, by refraction, into a narrower beam.[4] Refraction occurs at the interface of two materials in which light travels at different speeds and changes the direction of travel of the beam of light. If the beam is formed of many rays of light, each one may be bent; the ones at the edge of the beam bend more so they end up parallel to the center rays, which are hardly bent at all. For this to work, each ray must take exactly the same time to travel from its source, at the focal point of the lens, to its destination. Since light travels more slowly in glass, a lens is thicker at the middle, to slow down the rays with a shorter path, and thinner at the edges, to allow the rays with longer paths to catch up, as shown in Fig 1. The needed curvature of the lens to form the beam exactly is an ellipse, but for small bending angles a circle is almost identical to an ellipse, and nearly all optical lenses are ground with spherical curves.

Since light and RF are both electromagnetic waves, we could use glass—or any other dielectric—to make a lens for 10 GHz. For example, a recent article described a dielectric lens made of epoxy resin.[5] But for larger sizes this quickly

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[1] Notes appear at the end of this section.

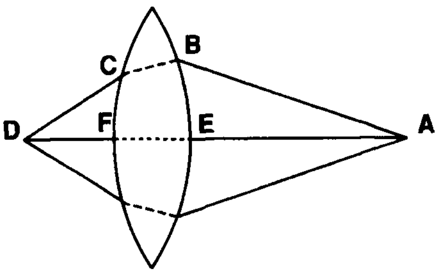

Fig 1—A simple lens. The travel time for each of the rays must be the same, so the time along the line ABCD is the same as that along the line AEFD.

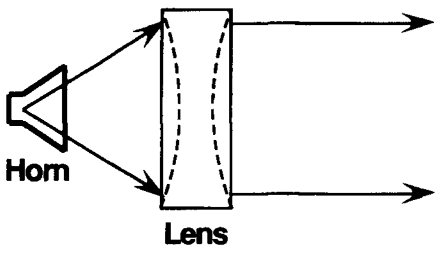

Fig 2—Feeding a lens with a horn lets the horn provide part of the beam shaping.

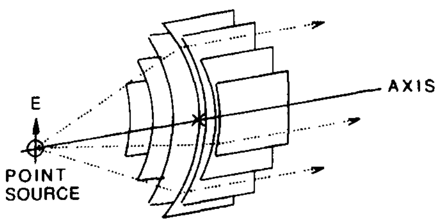

Fig 3—A spherical lens can be formed by a series of spaced plates.

becomes less attractive, and most dielectrics are rather lossy at 10 GHz. Low-loss materials are available but are costly and relatively heavy and difficult to shape.

The Metal-Plate Lens

Since electromagnetic waves travel at different speeds in waveguide and in free space, why not use waveguides of different lengths to form a lens? This has been done and is known as an "eggcrate" lens.[6] However, it is easier to make a group of parallel plates that form wide parallel waveguides, simply shaping the input and output edges of these waveguides to change the path lengths and form the lens surface. This differs from an optical lens in that the phase of the electromagnetic wave travels *faster* in a waveguide than in free space.[7] Thus, the required curvature of a metal lens antenna is the *opposite* of an equivalent optical or dielectric lens—in this case, concave instead of convex. We can still get away with using circular curvatures instead of ellipses as long as we aren't trying to bend the rays too sharply. For that reason, we feed the lens with a small horn, which does part of the beam forming, as shown in Fig 2. Of course, if we want both horizontal and vertical beam shaping, we need a spherical shape, so we must shape the surface described by the edges of the metal plates into a sphere like that of Fig 3.

Lens Design

While the *HDL_ANT* program removes the drudgery from lens design and makes it available to amateurs, a general description of lens design might aid in understanding what is happening and what the computer is telling you.

First, some design objectives are needed: how big a lens is desired, and what are the dimensions of the horn feeding it? Gain is determined by aperture (roughly the diameter for dishes, horns and lenses). A good rule of thumb is that doubling the aperture will increase the gain by 6 dB. For instance, an 8-inch lens in front of a 4-inch horn would add 6 dB to the gain of the horn, and a 16-inch lens would add 12 dB. So, modest gain improvements take modest sizes, but really large gains require huge antennas no matter what kind. However, a 6-dB increase in gain will double the range of a system over a line-of-sight path.

The horn dimensions may be determined by availability, or you may have the design freedom to build the horn as well. The beam width of the horn (which is usually smaller than the physical flare angle of the horn) is used to determine the focal length of the lens. Kraus gives the following approximations for beam width in degrees and dB gain over a dipole:[8]

$$W_{\mathrm{Eplane}} = \frac{56}{A_{E\lambda}} \qquad \text{(Eq 1)}$$

$$W_{\mathrm{Hplane}} = \frac{67}{A_{H\lambda}} \qquad \text{(Eq 2)}$$

$$\mathrm{Gain} = 10\log_{10}\left(4.5 A_{E\lambda}\, A_{H\lambda}\right) \qquad \text{(Eq 3)}$$

where $A_{E\lambda}$ is the aperture dimension in wavelengths in the E-plane, and $A_{H\lambda}$ is the aperture in wavelengths in the H-plane. These approximations are accurate enough to begin designing. From the beam width and desired lens aperture, finding the focal length *f* is a matter of geometry:

$$f = \frac{\text{Lens diameter}}{2\tan\left(\frac{W_{\mathrm{Eplane}}}{2}\right)} \qquad \text{(Eq 4)}$$

The final and most critical dimension is the spacing of the metal plates. The blue Styrofoam sheets sold as insulation have excellent thickness uniformity, and $^3/_4$ inch is pretty near optimum for 10 GHz, but the actual dimension should be measured carefully. The thickness determines the index of refraction:

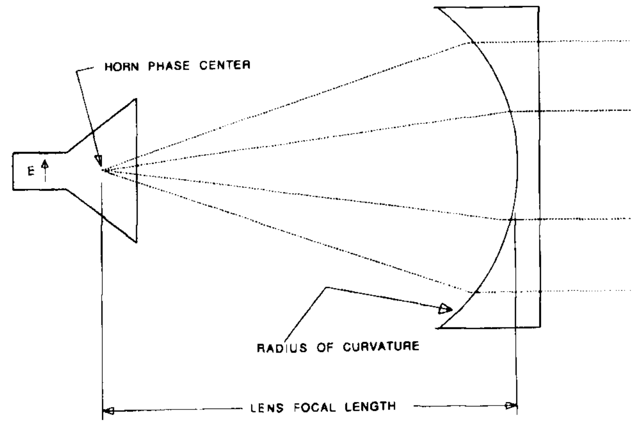

Fig 4—A single-curved lens. The radius of curvature is found using Eq 6, with the radius of the flat side set to infinity.

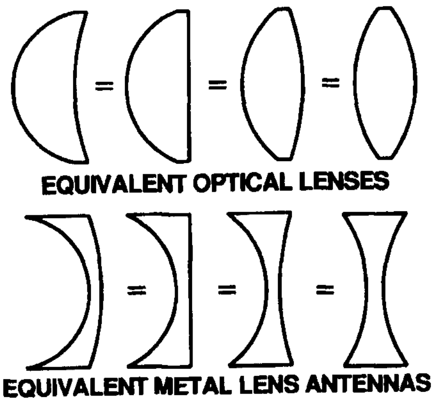

Fig 5—Each of the lenses shown has the same focal length, per Eq 6.

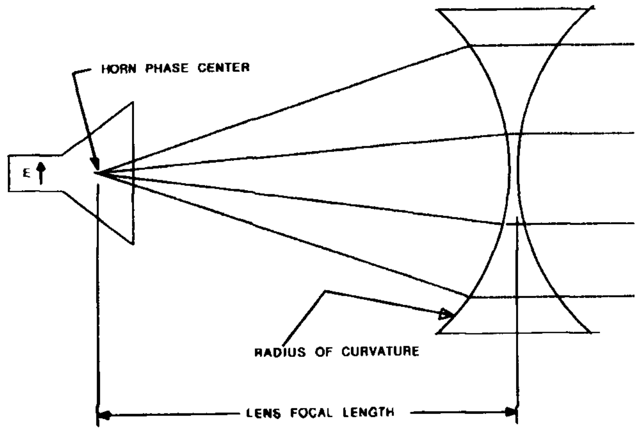

Fig 6—A double-curved lens. *HDL_ANT* provides both single-curved and double-curved lens designs.

$$\text{index} = \sqrt{1 - \left(\frac{\lambda_0}{2 \times \text{spacing}}\right)^2} \qquad \text{Eq 5}$$

which is the ratio of the wavelength in the lens to the wavelength in free space.

Next comes calculation of the lens curvature. The optimum curve is an ellipse, but we know that spherical lenses have been used for optics since Galileo, so a circle is a usable approximation. We can show that the circle is an excellent fit if the focal length is more than twice the lens diameter; photographers will recognize this as an *f*/2 lens. This suggests that the feed horn have a beam width of no more than 28°, or a horn aperture of at least two wavelengths.

The radius of curvature of the two lens surfaces is calculated from the lensmaker's formula (see Note 4):

$$\frac{1}{f} = (\text{index} - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \qquad \text{Eq 6}$$

where a negative radius is a concave surface. For the single-curved surface of Fig 4, one radius is set to infinity. All combinations of R1 and R2 that satisfy the formula are equivalent, as shown in Fig 5; the computer program calculates the single-curved and symmetrical double-curved solutions (Fig 6). The radius of curvature calculated above is for the surface, and thus the central plate, which has the full curvature. The rest of the plates must be successively wider and have smaller radii so that the edges of all the plates form a spherical lens surface. This is more geometry, and the program does the calculations for each plate.

The final calculation involves the phase centers of the horn, so that the lens-to-horn distance matches the focal length. This is a difficult calculation involving calculation of Fresnel sines and cosines; KB1VC deserves credit for the programming.[9,10] Without a computer, you would use trial-and-error looking for best gain. What the calculations will show is that many horns, particularly the "optimum" designs, have much different phase centers in the E- and H-planes. The program offers to make a crude compensation for this, but, if possible, the H-plane aperture of the horn should be adjusted slightly to match the phase centers. A few trial runs of the program should enable you to find a good combination. If you already have a horn, either try the compensation or just use the E-plane phase center.

For very large lenses, the size may be reduced by stepping the width of the plates into zones which keep transmission in phase, as shown in Fig 7. The program will suggest a step dimension if it is useful. At 10 GHz, a step is useful only for lenses larger than 2 feet in diameter.

Construction

Construction is straightforward, using metal plates of aluminum foil spaced by Styrofoam, as suggested by HB9SLV (see Note 2). A 2-foot by 8-foot sheet of blue Styrofoam, $3/4$-inch thick, is less than $5 at the local lumberyard and will make several antennas. The aluminum foil is attached to the foam using artist's spray adhesive, available at art supply stores. Spray both surfaces lightly, let them dry for a minute or two, then spread the foil smoothly on the

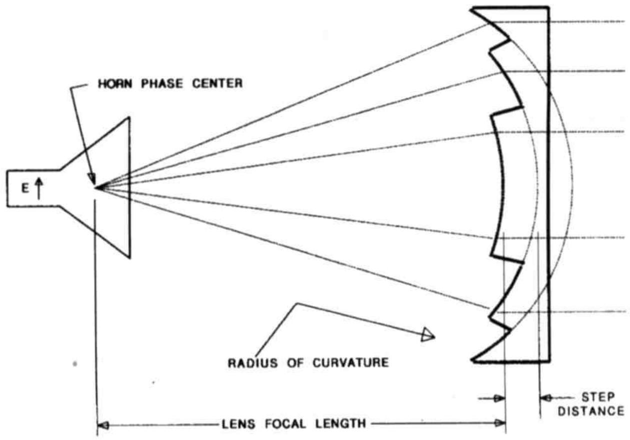

Fig 7—A zoned lens can be used to implement large lenses, reducing the needed thickness.

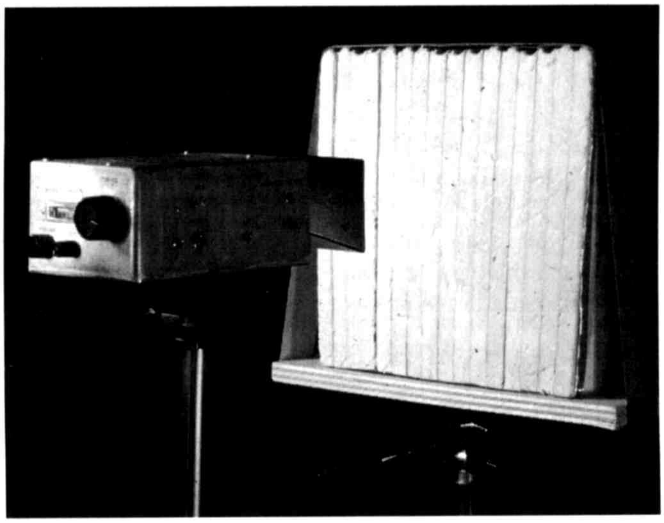

Fig 8—A 300-mm lens placed in front of a Gunnplexer transceiver provides about 10 dB of additional gain over that of the horn alone.

foam. If the adhesive melts the foam, you are using too much.

Next mark the outline of a rectangle for each metal plate on the foil. These will be used later to cut the foam and line up the plates, so they should all be the same size. Then mark the center of each curve and measure off the radius to the center of the circle. Using a compass with a hobby knife attached, place the point at the center of the circle and cut the curve through the foil into the foam. When all the curves are cut, peel off the unwanted foil, leaving the lens plates. Then cut up the rectangles with a razor blade and stack the blocks into a lens. (You did number them, didn't you?) Each rectangle should have foil on one side. If it looks good, glue them up two at a time. The final antenna will be a block of foam—there is no need to shape the foam to the lens curve. Shrink-wrapping the lens with thin plastic makes nice weatherproofing.

A few helpful hints are in order. Sharp knife blades really help in this process, and permanent markers don't smear. Also, if the foam is cut halfway through, it will snap cleanly on the line.

Adjustment

A metal-lens antenna only works in the E-plane. This is parallel to the elements of a dipole or Yagi but perpendicular to the wide dimension of a waveguide. The plates *must* be perpendicular to the wide dimension to provide gain.

The horn should point through the center of the lens, but the focus distance is not as critical as with a dish. Aiming is done by pointing the feed horn; the lens focuses the beam more tightly but does not change the beam direction. Tilting the lens will *not* steer the beam—if you don't believe this, take an optical lens, like a magnifying glass, focus it on something, and tilt it.

We found that the best gain was with the horn slightly closer to the lens than calculated, probably because of edge effects. Making the size of the plates slightly larger than calculated would probably eliminate this effect and make the gain a bit higher; since a wavelength at 10 GHz is about an inch, an inch or two oversize is plenty.

One other interesting effect was found with Gunnplexers: since the transmitter is also the receiver local oscillator, reflected power from the lens adds to the LO power, or subtracts when out-of-phase. This makes the received signal strength vary with every half-inch change in lens-to-horn distance, with very little change in signal strength observed at the other station. So, adjust the spacing for the best received signal. Of course, this effect does not exist on a system with low LO radiation.

Using the *HDL_ANT* Program

The lens section of *HDL_ANT* calculates the dimensions for the plates of a lens. Since all curves are circles that are easily drawn with a compass, templates are not generated. The basic input data is entered interactively, then results are presented in tabular form. If you like the results, they may be saved to a file for printing or further processing; if not, try another run with new data.

All dimensions are in millimeters. There are two reasons for this: the first is that odd fractions lead to errors in measurement, and the second is that one millimeter is a good tolerance for 10-GHz lens dimensions. If all measurements are made to the nearest whole millimeter, good results can be expected. The only exception is in the plate spacing, and that is accurately controlled by the foam thickness.

Results

We have constructed and tested three metal-plate lens antennas to date: a 150-mm single-curved version, and 150-mm and 300-mm double-curved versions. Fig 8 shows the 300-mm lens fed by a WBFM Gunnplexer system, and Listing 1 shows the *HDL_ANT* design of this antenna. All the lenses are designed to be fed with the standard Gunnplexer horn, which has well-matched phase centers, whether by design or by accident. Gain measurements are shown in Table 1. The lenses perform with about 50% efficiency if we consider them as having a round aperture; the corners do not contribute significantly, but we made them square for convenient fabrication and mounting.

We also used the lenses during several contests during 1992, 1993 and 1994. The 300-mm lens increased the range of our WBFM Gunnplexer transceivers by approximately 50%, to over 200 km, enabling contacts over new paths. The equipment was still highly portable due to the light weight of the lens, and they have survived mishaps with only a few harmless dents in the foam.

Further Uses for Metal Lenses

The metal-lens antenna could be useful at other frequencies: for 5.76 GHz a foam thickness of around 35 mm would be good, and at 24 GHz approximately 8-mm-thick foam might work, though it could be lossy at that frequency.

A lens can also be part of a more complex antenna system. For instance, a divergent lens can be used to provide better illumination for some of the very deep dishes that are sometimes available as surplus. A book on optics (such as Note 4) will show how to change the focal points appropriately.

Lens Summary

We have demonstrated that metal-lens antennas may be easily designed and constructed using the *HDL_ANT* computer program and that a book-sized lens, light and rugged enough for backpacking, provides gain enhancement adequate to double the range of a Gunnplexer system.

Antenna Gain Measurement

Hams have been measuring antennas for many years at VHF and UHF frequencies, and we have seen marked improvement in antenna designs and performance as a result. Very few serious antenna measurements have been made at 10 GHz; the additional difficulties at these frequencies are not trivial. I'll describe a few new twists that make it more feasible.

Overview

Antenna measurement techniques have been well described by K2RIW and W2IMU;[11,12] the latter also appears in the *ARRL Antenna Book* and is required reading for anyone considering making antenna measurements.[13]

The antenna range is set up for antenna ratiometry so that two paths are constantly being compared, both originating from a common transmitting antenna. (See Note 11.) These two paths are called the "reference" and "measurement" paths. The reference path uses a fixed antenna that receives what should be a constant level. In reality, there are continuous small fluctuations in the received signal at microwave frequencies, even over a short distance like an antenna range. Using ratiometry, the reference path allows these random variations in the source power or the path loss to be corrected by an instrument that constantly compares the signal from the measurement path with that of this reference path. First, a standard antenna with known gain is measured and the reading is recorded. Then, when an unknown antenna is measured, the difference between it and the standard antenna determines the gain of the unknown antenna.

Instrumentation

One measuring instrument commonly used is the venerable HP 416 ratiometer, with crystal detectors used to sense the RF. Basically, this technique compares the outputs of two crystal (diode) detectors. The crystal detectors present a problem: a matched pair is needed, and these are hard to find for 10 GHz. Also, diode detectors have poor sensitivity and dynamic range, so it is necessary to provide adequate power to keep the detectors operating in the square-law region where they are accurate. Another problem is drift in the old vacuum-tube HP 416.

It seemed to me that a superheterodyne technique was needed. If the signal could be converted to some lower frequency, it could be received on a better receiver. If the two channels had separate converters, the comparison could be made at the lower frequency. Finally, if we simply switched between the two channels at the lower frequency, the output would be an AM signal. If the switching rate were at an audio frequency, an AM receiver would thus have an audio output amplitude proportional to the difference in signal level between the two channels. Once the signals are combined by the switch, they may be easily amplified as needed at the lower frequency.

At 10-GHz, frequency stability is always a problem, so a normal communications receiver might be too sharp. From work with 10-GHz WBFM, I know that most signals are stable to within a few hundred kHz after warm-up, so a receiver with a 1-MHz bandwidth should be acceptable. While I was wondering if there might be something usable in a surplus catalog, it occurred to me that I already owned a perfectly usable solid-state wideband AM receiver—an AILTECH Model 75 Precision Automatic Noise Figure Meter (PANFI), which I found at a surplus auction. Not only that, it also has a synchronous detector and an output to synchronously switch the input signal (normally the noise source). The meter reads the difference in signal level as the input is switched; in this application, instead of the difference with a noise source switched on and off, it reads the difference as it switches between the two channels, with excellent resolution. If a signal much stronger than the noise is applied, the meter responds only to the signal rather than noise. (While checking the references for this paper, I discovered that K2RIW—see Note 11—had suggested use of the AILTECH Model 75 PANFI in 1976, but no one had remembered so I had to rediscover it!)

The only problem with the PANFI is that it is calibrated to solve the noise equation:

$$F_{dB} = T_{ex(dB)} - 10\log_{10}(Y - 1) \qquad \text{(Eq 7)}$$

This requires a bit of arithmetic on a calculator or using the *HDL_ANT* computer program to undo the results and find the difference in dB:

Table 1—Summary of 10.368-GHz Antenna Measurements (N1BWT 12/18/93, 5/14/94, 9/15/94)

Antenna	*Focal distance*	*Gain (dBi)*	*Efficiency*
Standard Gain Horn, (22.5 dBi calculated) Scientific-Atlanta Model 12-8.2, courtesy KM3T, gain thanks to John Berry, Scientific-Atlanta.		22.45	43%
Gunnplexer Horn (17.45 dBi calculated)		17.5	57%
+ 6" lens	~8"	20.9	45%
+ 12" lens	~21"	27.4	50%
Surplus horn (19.4 dBi calculated)		19.6	67%
W1RIL loop Yagi		16.0	
22" dish, *f/D* = 0.39, surplus, feed = 11 GHz Superfeed:[*]			
unmodified feed	8.25"	33.1	55%
with feed line to reflector		32.2	45%
modified feed		32.9	53%
25" dish, *f/D* = 0.45, Satellite City, with the following feeds:			
11 GHz Superfeed[*]	10.875"	34.4	58%
Clavin feed	11.125"	34.1	54%
Rectangular Horn,			
E=0.9", H=1.38"	10.625"	33.7	49%
E=1.14", H=0.9"	10.625"	32.9	41%
WR-90 to coax Transition	11.0"	32.7	39%
WA1MBA log periodic	10.94"	32.4	37%
18" dish, *f/D* = 0.42, Satellite City, with the following feeds:			
11 GHz Superfeed[*]	7.75"	31.7	60%
Clavin feed	7.875"	31.2	53%
Rectangular Horn E=0.9", H=1.38"		31.5	57%
WR-90 to coax Transition, rect flange		30.2	42%
WR-90 to coax Transition round flange, od = 2.15"		30.2	42%
Cylindrical horn with slotted choke ring	7.875" to choke ring	~28[**]	~26%[**]
WA3RMX Triband feed		~17[**]	
24" Commercial (Prodelin) dish antenna: feed is rectangular horn fed by WR-90 waveguide "shepherd's crook"		33.6	52%

RANGE LENGTH = 102 feet. $2D^2/\lambda$ = 91 feet. Test height ~ 8 feet.

FOCAL DISTANCE SENSITIVITY: each feed was adjusted for max gain.
Gain was down 1 dB about ¼" either way from peak.

Notes: [*] 11 GHz Superfeed is a Chaparral feed horn for 11-GHz TVRO.
[**] These feeds were not positioned accurately—more gain is possible.

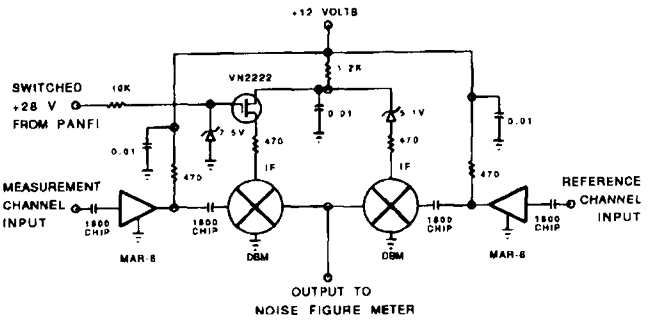

Fig 9—This switch can be used to automatically switch between the reference and measurement paths of the antenna gain measurement system.

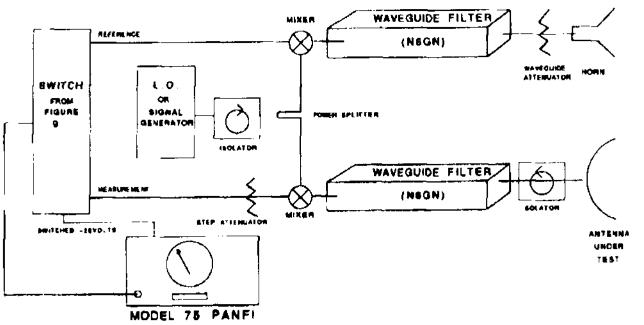

Fig 10—Test setup for 10-GHz antenna measurements.

$$Y_{dB} = 10\log_{10}\left(1+10^{\left(T_{ex(dB)} - F_{dB}\right)/10}\right) \qquad \text{(Eq 8)}$$

Otherwise, the indicated gains are very optimistic.

The input to most noise figure meters is at 30 MHz, so I used a surplus signal generator to generate an LO 30 MHz away from 10368 MHz and used my 10-GHz transverter as the source transmitter. The signal generator provides the LO for two surplus waveguide diode mixers, but a pair of mixers like the ones in the transverter would also be fine.[14] Matched mixers aren't needed since they are linear mixers with wide dynamic range. I preceded each mixer with a band-pass filter, but there probably aren't many stray 10-GHz signals around. An isolator in the antenna line is useful when the antennas may have high SWR.

Everything after the mixers is at 30 MHz, so ordinary cables and components complete the setup. I included a step attenuator in the measurement path to double-check the meter readings.

The switch, shown schematically in Fig 9, uses a common double-balanced mixer (DBM) as an attenuator in each path. Applying a dc current though the diodes in a DBM varies the attenuation;. the DBM has high loss with no dc current, and low loss with dc current applied; I measured 54 dB of loss at 0 mA and 2.8 dB at 20 mA. An FET and some Zener diodes provide a crude switching circuit to switch the

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                ****************
                *              *
                *    HDL_ANT   *
                *              *
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       Version 1.0E with option for the metric impaired.

       Any licensed radio amateur may use this program without
       charge; all other persons must send $73 to the
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       Metal plate lens antenna for microwaves

         ALL dimensions are in millimeters!

           ------------
          |     E      |
          |     ^  -->H|   waveguide
          |     |      |
           ------------

   At a center frequency of 10.265 GHz

   For a lens with a diameter of 301.55 mm. and a plate spacing of
 18.847 mm.

   Fed by a horn of axial length = 76.2 mm,
       H-plane aperture = 90.5 mm
       E-plane aperture = 73 mm
        and a Gain of 17.41 dB over isotropic

    E-Plane phase center is 1.57 wavelengths inside horn mouth
    H-Plane phase center is 1.59 wavelengths inside horn mouth
   Calculations for an f/2.52 lens with a focal length of 761.33 mm.
       providing an estimated gain of 12.32 db over the horn

   Distance from horn mouth to center of lens curve is 715.38 mm.
```

```
 Radius of Curvature of lens plates starting from center plate

  Plate  Single radius   double radius   plate width
  --- -     -------        ----------      --------

  ctr      280.01 mm.     560.03 mm.     min
   1       279.38 mm.     559.71 mm.     min + 0.63
   2       277.46 mm.     558.76 mm.     min + 2.55
   3       274.25 mm.     557.16 mm.     min + 5.77
   4       269.67 mm.     554.93 mm.     min + 10.34
   5       263.68 mm.     552.04 mm.     min + 16.33
   6       256.16 mm.     548.49 mm.     min + 23.85
   7       246.99 mm.     544.26 mm.     min + 33.03
   8       235.95 mm.     539.35 mm.     min + 44.06


    ****** UNBELIEVABLY CRUDE GRAPHICS ******

             Single Curve        Double Curve

                       ------------       --------------
                        ----------          ----------
                         ---------   ^      ---------
    |--|                  --------   |       -------
    |  |     <            --------   H|      ---+---
    |  |     horn         --------   .       -------
     --                  ---------          ---------
   waveguide            ----------         -----------
                       -----------        -------------
                                                +
                             centerline         +
                                                +
                       -----------        -------------
                        \  LENS  |        \   LENS   /
   waveguide             \ PLATE |    ^    \  PLATE /
                          \      |    |     \      /
   |------| <              )<--->|   E|      )<-+->(
    -----   horn          / min. |    |     /  min. \
                       -->/ thick.|     -->/  thick. \
                       /  /      |     /  /           \
                      /  ---------    /   -------------
                     /               /
                    Radius of curvature
```

Listing 1

current in response to the 28-V output from the PANFI.

Fig 10 shows the antenna measuring setup for 10 GHz. The reference path uses a small horn as the receiving antenna, and the source antenna is another horn. After completing all connections, the signal generator is adjusted for maximum received signal, as indicated with the PANFI switched to the noise OFF position. Then the PANFI is switched to AUTO to display the difference between the paths, which is converted to relative gain using the above equation.

Antenna Range

The length of the antenna range is important: if it is too short, there will be significant phase difference over the aperture of the antenna being tested, resulting in low measured gain. The minimum range length to avoid this error is the Rayleigh distance:

$$\text{Rayleigh distance} = \frac{2D^2}{\lambda} \qquad \text{Eq 9}$$

A few trial calculations will show that this requires miles of range for large dishes. Fortunately, the Rayleigh distance for the 25-inch dish that I wanted to measure is only 91 feet at 10 GHz.

The antenna range is a ground-reflection range, as shown in Fig 11, where the range is designed to account for ground reflection and control it. One alternative would be to place the antennas high enough that ground reflection would be insignificant; however, in order to keep the reflected signal contribution from the ground to less than 0.5 dB, both ends of the range would have to be 122 feet high for a range length of 91 feet. Another type of range requires the signal path to be at a 45° angle to the ground, so the antenna height would only be 91 feet. For most amateur work, antenna heights like these are impractical, so the ground-reflection range is used.

In order to have the phase error as low in the vertical plane as in the horizontal plane, the height of the antenna being measured must be at least *four* times its aperture diameter, which is 100 inches for the 25-inch dish.[15] I suspect that most amateur antenna ranges have had insufficient antenna height and consequently have had trouble measuring higher-gain antennas accurately. My first measurements, at a height of about 4 feet, showed lower than expected efficiency for the larger dishes. Raising the height made the measured efficiency greatest for the larger dish, as you would expect, since the feed horn blocks a smaller percentage of the aperture.

The received energy should be at a maximum at the height of the antenna being measured. For a ground-reflection antenna range, this is controlled by the height of the source antenna:

$$h_{\text{source}} = \frac{\lambda}{4}\left(\frac{\text{Range length}}{h_{\text{receiving}}}\right) \qquad \text{Eq 10}$$

which works out to about 3 inches for the 91-foot-long range with the receiving antenna 100 inches high. Therefore, by adjusting the reference and measurement antennas to over 8 feet high (easily done on the back of a pickup truck or a porch) and placing the height of the source and antenna around 3 inches, good, reliable and accurate results may be obtained (see Table 1).

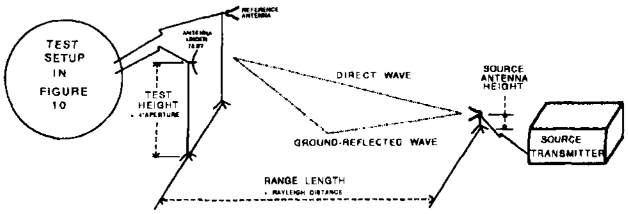

Fig 11—A ground-reflection antenna range with ratiometry. The required range length and antenna heights depend on the frequency and the characteristics of the antennas.

The Standard-Gain Antenna

In order to measure meaningful antenna gains, an antenna with known gain is required. Recall that all measurements are relative to a known standard. A dipole is useless as a standard—its broad pattern receives so many stray reflections that repeatable readings are nearly impossible, and its gain is so much lower than a 30+ dB dish that equipment accuracy is a problem; few instruments are accurate over a 30-dB (1000:1 power ratio) range.

What is required is an antenna with a known gain, preferably a gain of the same order of magnitude as the antennas to be measured. At microwave frequencies, the gain of a horn antenna can be calculated quite accurately from the physical dimensions. The algorithm used in the *HDL_ANT* program will be accurate within about 0.2 dB if good construction techniques are used.

For even better accuracy, several companies make standard-gain horns with good calibration data. For 10 GHz, a standard-gain horn was lent to me by KM3T—he was lucky enough to find one surplus. Mr. John Berry of Scientific-Atlanta was kind enough to provide the gain calibration curve.

Measurements

Once the antenna range is designed and set up, it must be checked out before making actual measurements. This is best done with an antenna with a fairly broad pattern, like a medium-sized horn, as the test antenna. First, the attenuators are adjusted for a convenient meter reading. Then the field uniformity is probed by moving the test antenna horizontally and vertically around the intended measurement point. The indicated gain should peak at the center and should not vary significantly over an area larger than any antenna to be tested; the variation should be less than 1 dB. At this point, the height of the source antenna usually needs to be adjusted to get the vertical peak at the intended receiving height. Finally, the test antenna is held stationary, and calibrated attenuation steps are added in the test path to make sure the indicated gain (after correction if using a PANFI) changes by the amount of attenuation added. With a ratiometer, the attenuation must be added at the microwave frequency, but a PANFI system like Fig 10, with a linear mixer, allows the use of an IF attenuator; step attenuators are much easier to find (or build) for 30 MHz than for 10 GHz.

Now the range is ready to make measurements. The standard-gain antenna is inserted as the test antenna, aimed for maximum indication, and the attenuators adjusted for a meter reading that will keep expected gains within the range of the meter. All gain measurements will be the difference from this standard reading added to the gain of the standard-gain antenna. The standard-gain antenna is replaced by an antenna to be tested, the new antenna is aimed for maximum gain, and its indicated gain is recorded. The difference between this indicated gain and the standard reading, after correction, added to the known gain of the standard-gain antenna, is the gain of the test antenna. The reading with the standard-gain antenna should be checked frequently to correct for instrumentation drift; ratiometry with the reference antenna corrects for other sources of drift.

Measurement Results

I set up a 10-GHz antenna range in my yard that was 102 feet long, more than the Rayleigh distance, with the equipment described above. The received field was probed for uniformity, and the height of the source antenna was adjusted for a flat field at the required height. Then I was able to start measurements, using a standard-gain horn for comparison. The results are shown in Table 1.

The first thing that became apparent is that all adjustments on a dish are critical. In the field, looking at a tiny S-meter, it doesn't seem so difficult to point a dish with a beamwidth of only about 3 degrees. The PANFI, however, has a large meter with 1 dB expanded out to nearly an inch. On this meter, even tiny adjustments have obvious effects, demonstrating how touchy aiming a dish is.

The most critical dimension of a dish is the focal length—the axial distance from the feed to the center of the dish. A change of $^1/_4$ inch, or about a quarter-wavelength, changed the gain by a dB or more.

The critical focal length suggests that it is crucial to have the phase center of the feed exactly at the focus of the reflector. Since the phase center is rarely specified for a feed horn, we must determine it empirically by finding the maximum gain on a reflector with known focal length, which we can estimate from templates for various *f/D*. Thus we can estimate the phase centers for all the feeds in Table 1.

For the Chaparral style feed horns, we can deduce some further information. Several different feeds were measured, with two different dimensions, and with adjustable choke rings. Regardless of where the choke ring was set, maximum gain occurred with the choke ring the same distance from the reflector. This implies that the phase center is controlled by the position of the choke ring, not the central waveguide. The version designed for 11-GHz TVRO use, with the gain shown in Table 1, has an apparent phase center in front of the choke ring, while a larger one, dimensioned for 10 GHz, has the apparent phase center behind the choke ring (inside the ring) and provides gain similar to the smaller one.

As for efficiency, none of the dish measurements in Table 1 exceeds 60%, and it is obviously easy to get efficiencies less than 50%. This suggests to me that the 55% quoted in the books is far from typical, and careful design and measurement is needed to reach or exceed it. As illustrated in Part 2 of this series, dishes with small *f/D* (less than 0.3) may be very difficult to feed efficiently.

On the other hand, several of our amateur feeds have higher efficiencies than the commercial dish antenna shown in Table 1. If you find a surplus dish with a feed, don't assume it is the best possible one—different applications may require optimization of other parameters. For instance, WA1MBA has been working on a broadband log-periodic feed. The efficiency at 10 GHz shown in Table 1 is rather poor by comparison, but having a single dish feed that offers reasonable performance at several amateur microwave bands is an exciting possibility.

Several of the dish measurements in Table 1 were made with a coax-to-waveguide transition as a feed—the open-ended waveguide flange acts as a small horn. This is not an optimum feed, as shown by the low efficiency, but it is one that is readily available for comparisons. If the feed for your dish does not perform significantly better than a plain waveguide flange, it can certainly stand improvement.

Measured horn and lens efficiencies are comparable to dish efficiencies, so we can conclude that all three types of antennas can provide the same gain for the same aperture area. This leaves us free to choose the type of antenna best suited to the application.

Conclusion

Horns, dishes and lenses are all high-performance microwave antennas well-suited for amateur communications. Horns are small, rugged, and reliable, good for rover operation; they may be supplemented with a lens acting as an "amplifier" for increased gain. Dishes offer the ultimate in gain, at the expense of size and narrow beamwidth.

Horn and lens construction is easily within amateur capability, but parabolic reflectors at microwave frequencies require construction accuracy that is difficult to achieve. A dish antenna using a manufactured reflector still requires careful attention to detail to realize high efficiency.

Amateur antenna gain measurement at 10 GHz with good results has been demonstrated using ratiometry, and a noise figure meter is a good solid-state replacement for a vacuum-tube ratiometer. Antenna gain measurements are valuable for making critical adjustments and for verifying that an antenna is providing the performance expected. Better antenna gain measurements should bring the same improvement to amateur microwave antennas that years of antenna measuring contests have brought to VHF and UHF antennas.

Acknowledgments

I'd like to thank Bob Egan, N1BAQ; Larry Filby, K1LPS; Dick Knadle, K2RIW; Barry Malowanchuk, VE4MA; Dave Pascoe, KM3T; Matt Reilly, KB1VC; Ken Schofield, W1RIL; Dan Thompson, N1IOL; and Tom

Williams, WA1MBA, for their help, and Beth Wade, N1SAI, and Filomena Didiano for locating obscure references. I'd also like to remember the late Dick Turrin, W2IMU, who generously shared his vast knowledge of antennas and antenna measurement with many hams—he taught me more than I'll ever remember.

Notes

[1] Wade, P., N1BWT, and Reilly, M., KB1VC, "Metal Lens Antennas for 10 GHz," *Proceedings of the 18th Eastern VHF/UHF Conference*, ARRL, May 1992, pp 71-78.

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[7] We will not attempt to explain this seeming magic here. Refer to "phase velocity" in any good book on microwaves. Rest assured that no laws of physics are being violated.

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More on Parabolic Dish Antennas

Offset dishes, penny feeds and sun noise

By Paul Wade, N1BWT

(From *QEX*, December 1995)

Introduction

In the past year, you have probably noticed little gray dish antennas sprouting from rooftops and appearing for sale in stores as part of satellite TV systems. One common version is the RCA DSS system, which uses an 18-inch offset-fed dish.

In previous articles about parabolic dish antennas, I described only conventional axial-feed dishes because other types weren't readily available.[1,2] Now, with the introduction of the DSS system this is no longer true—inexpensive offset-feed dishes are readily available, and they offer excellent performance at 10 GHz.

This article is the "fourth part" of my three-part series of *QEX* articles on practical microwave antennas.[1,3,4] In order to show how to use offset dishes effectively, some familiarity with antenna terminology and concepts is required, so I urge the reader to review the earlier articles. In addition to offset-feed dishes, this article will also discuss the "penny" feed for conventional dishes, dishes with multiple reflectors and the use of sun noise to verify antenna and system performance.

Offset-Feed Dishes

An offset-feed dish antenna has a reflector that is a section of a normal parabolic reflector, as shown in Fig 1. If the section does not include the center of the dish, none of the radiated beam is blocked by the feed antenna and support structure. For small dishes, feed blockage in an axial-feed dish causes a significant loss in efficiency. Thus, we might expect an offset-feed dish to have higher efficiency than a conventional dish of the same aperture.

In addition to higher efficiency, an offset-feed dish has another advantage for satellite reception. The dish in Fig 2, aimed upward toward a satellite, has its feed horn pointing toward the sky. A conventional dish would have the feed horn above it, pointing toward the ground, as shown in Fig 3. Any spillover from the feed pattern of the conventional dish would receive noise from the warm earth, while spillover from the offset dish would receive less noise from the cool sky. Since a modern low-noise receiver, such as a satellite TV LNB, has a noise temperature much lower than the earth, the conventional dish will be noisier. This is *G/T*, which I described in the previous series of articles; the offset dish offers higher gain, *G*, since the efficiency is higher,

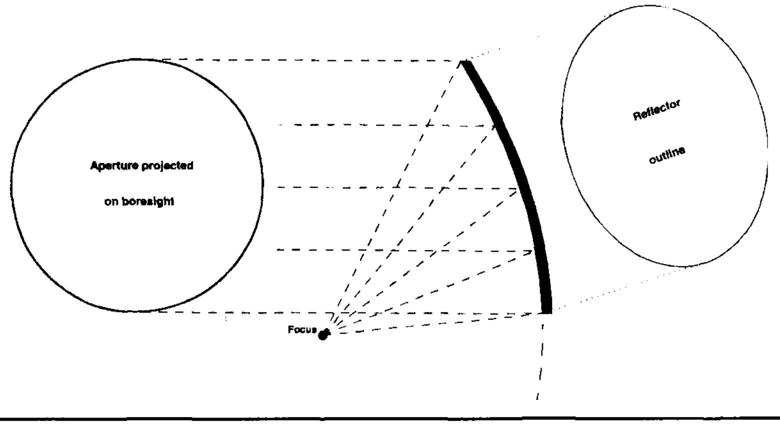

Fig 1—Geometry of an offset parabolic dish antenna.

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[1] Notes appear at the end of this section.

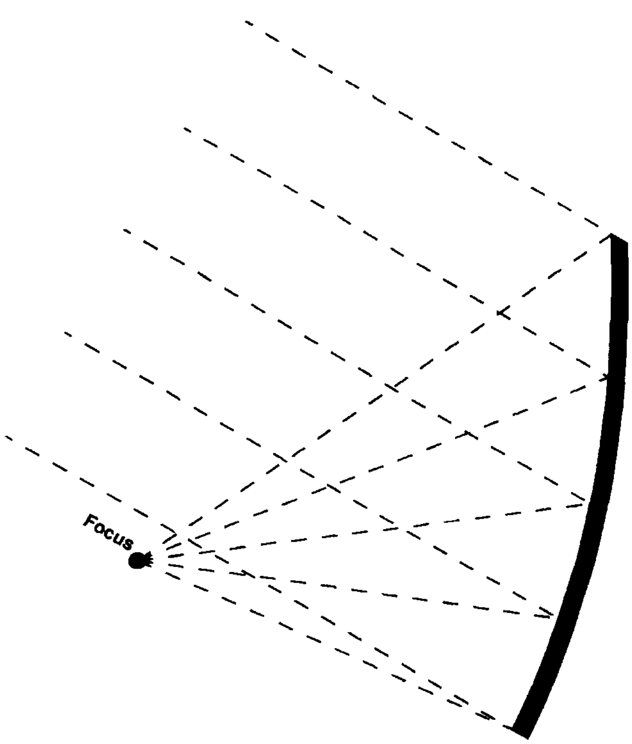

Fig 2—An offset parabolic dish antenna aimed at a satellite.

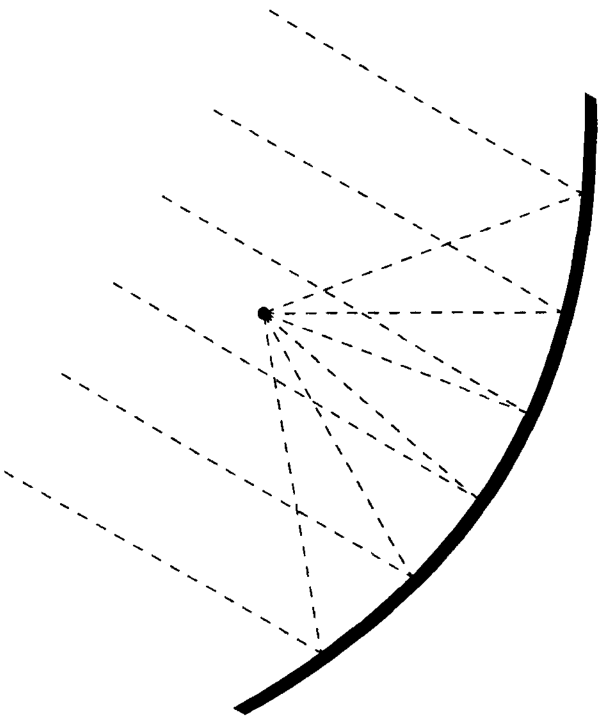

Fig 3—An axial-feed parabolic dish antenna aimed at a satellite.

plus reduced noise temperature, *T*, so both terms in the *G*/*T* ratio are improved. The higher gain means more signal may be received from a source, and the lower noise temperature means that less noise accompanies it, so a higher *G*/*T* offers a higher signal-to-noise ratio.

The RCA DSS Dish

The original incentive to use an offset-feed dish was provided by Zack Lau, KH6CP, who pointed out that the 18-inch RCA DSS dishes are available by mail order for about \$13.[5] I ordered a dish and a mounting bracket to see if I could figure out how to use one at 10 GHz.[6] When it arrived, it wasn't obvious where the feed point should be, so I took a trip to a local discount store to eyeball the system on display.

Now I had an idea where to put the feed, but not the exact location. The RCA reflector is oval shaped, but Ed, W2TTM, provided the needed insight: the dish aperture should appear circular when viewed on boresight, as shown in Fig 1. Thus the dish must be tilted forward for terrestrial operation. Although the reflector is an oval, the effective antenna aperture is the projected circle, with a diameter equal to the small dimension of the oval, 18 inches for the RCA dish. The tilt angle, feed point location and the rest of the dish geometry can be calculated—see the Appendix for the procedure. Version 2 of the *HDL_ANT* computer program will do these calculations. This program is available from the ARRL BBS (860-594-0306) or via the Internet at **http://www.arrl.org/qexfiles/hdl_ant2.zip** or **ftp://ftp.arrl.org/pub/qex/hdl_ant2.zip**.

The calculations show the focal length of the RCA dish to be 11.1 inches. If the dish were a full parabola rather than just an offset section, the diameter would be about 36 inches, for an *f*/*D* of 0.30, which would require a feed with a very broad pattern. However, a feed horn need only illuminate the smaller angle of the offset section, a subtended angle of about 77°. This subtended angle is the same as a conventional dish with an *f*/*D* of 0.7, so a feed horn designed for a 0.7 *f*/*D* conventional dish should be suitable. Rectangular feed horns have been shown to work well with offset reflectors and are readily designed to illuminate an *f*/*D* this large.[7] I used G3RPE's graph for rectangular feed horn design and the *HDL_ANT* computer program to design suitable rectangular horns.[8,9] I made two of different lengths from flashing copper. Subsequently, I added an approximation to G3RPE's curves to version 2 of *HDL_ANT* so the program can design feed horns for both offset and conventional dishes as well as generate templates for them.

Since the actual reflector geometry has an *f*/*D* of 0.30, the focal distance should be quite critical. As explained in Part 2 of my previous *QEX* series, this dimension is the most critical for dish antenna performance—even more critical for reflectors with smaller *f*/*D*—so the phase center of the feed should be positioned within a quarter-wavelength of the focal point. The RCA dish must be tilted forward to an angle of 66.9° from horizontal for terrestrial operation with the beam on the horizon. In this orientation, the focal point is just below the lower rim of the dish, so the feed horn is out of the beam. To locate the focus accurately, I calculated the distance to both the top and bottom of the rim, tied a knot in a piece of string and taped the string to the rim so the knot was at the focus when the string was pulled taut, as shown in Fig 4. Then I made a sliding plywood holder for the feed horn, taped it in place and adjusted it so that the knot in the string was at the phase center of the horn, about 6 mm inside the mouth of the horn, shown in Fig 5. (For visibility, the string in the photograph is much heavier than the kite string I used so a small knot could locate the focus more accurately.) Materials aren't critical when they aren't in the antenna beam!

Where should the feed horn be aimed? On a conventional dish it is obvious—at the center. However, an offset feed is much closer to one edge of the dish, so that edge will be illuminated with much more energy than the opposite edge. I read an article that did a lengthy analysis of the various aiming strategies and then suggested that small variations have little effect, so aiming at the center of the reflector is close enough.[10]

After all this analysis, it was time to see if the offset dish really works. We (W1RIL, WB1FKF, N1BAQ, and N1BWT) set up an antenna range and made the measurements shown in Table 1. The RCA dish with a simple rectangular feed horn measured 63% efficiency at 10 GHz, significantly higher than we've *ever* measured with an 18-inch conventional dish. Varying the focal distance showed that the calculations were correct and that this dimension is critical. Fig 6 is a template produced by the *HDL_ANT* program for the rectangular feed horn that gave the highest efficiency, and Fig 7 is a photograph of the feed horn I made with the template.

The higher efficiency of the offset-feed dish is mainly due to reduced blockage by the feed and supporting structure. Fig 8 is a photograph of a conventional dish while measuring sun noise, so that the shadow of the feed demonstrates the actual area blocked—neither light nor RF energy from the sun is reaching the reflector. Fig 9 is a photograph of the RCA offset dish peaked on the sun to measure sun noise; note that the shadow of the feed is only a tiny area at the bottom edge. Remember that these feed horns provide a tapered illumination, so the energy illuminating the center of the reflector is typically 10 dB stronger than at the edge. Thus, central blockage in a conventional dish is *ten times* worse than the same area blocked at the edge of an offset dish, and the photographs clearly illustrate how much more blocked area there is in a conventional axial-feed dish.

Other Offset Feeds

A rectangular feed horn is fine for linear polarization, but what if we want circular polarization? One popular feed that works well with circular polarization is the W2IMU dual-mode feed. The published amateur versions are all for *f/D* in the range 0.55 to 0.6, but Dick's original article also described another version for a different *f/D*.[11] It should be possible to make one for the 0.7 *f/D* needed for the RCA offset dish, but that would require some experimentation (or computer modeling, if you have software available) for optimum performance.

The truly adventuresome could try a trimode feed designed specifically for offset-fed dishes.[12] The math is daunting, and construction appears difficult, but I have seen one TVRO feed that may use this design.

Other Offset Dishes

I was given an offset-feed, 24-inch plastic dish with a cosmetic defect (and no other information). Measurements showed the geometry to be similar to the RCA dish, so the same feed horns would work fine. I was not able to support the feed as well on this dish, so the feed location may not have been optimum, but it still measured 61% efficiency at 10 GHz.

Two other types of offset dishes seem to be fairly common, so some will probably wind up in amateur hands eventually. Many automobile dealerships and discount stores have larger offset dishes, four feet or more in diameter, with a reflector that appears circular. The other type is another brand of TVRO system, with an oddly shaped dish about 3 feet across; the ones I've seen are marked "Primestar." I had a chance to look one over at a county fair, next to the tractor dealer. The reflector appeared to be wider than it was high, requiring a fairly wide feed angle. The feed horn had a curved plastic surface that could possibly be a molded lens.

If I were to acquire one of these reflectors, I would place it flat on the ground with the reflecting surface facing upward and fill it with water, which provides a level surface from which to take measurements. The water should fill an oval area reaching the top and bottom edges of the rim, but not the sides. Measuring this oval as described in the Appendix, and measuring the depth and location where the water is deepest, should be enough to calculate the offset geometry. The feed horn beamwidth would have to be broader from side-to-side than from top-to-bottom, but a rectangular feed horn can be designed to provide an asymmetric pattern.

Mounting an Offset Dish

To aim an offset dish at the horizon with the feed below the dish, the reflector must be tilted forward—66.9° from horizontal for the RCA dish. One way to accomplish this would be to mount it on a wedge cut at the correct angle, so that the bottom of the wedge can be mounted on a level surface or tripod. An alternative technique is to rotate the dish so that the feed is to the side, level with the center of the dish. In this configuration, the elevation uncertainty is eliminated, but an aiming device must be provided for azimuth. An accurate azimuth readout is a good idea for any dish, since aiming a narrow beam by eye is fraught with error. A settable compass rose with one-degree gradations works well for rover operations.

The Penny Feed

The "penny" feed has been used for years with good results. It consists of a metal disc, originally an old (pre-decimalization) English penny, at the end of a waveguide with slots in the broad wall of the waveguide. I built one to see how well it really works, using dimensions by G4ALN from the *RSGB Microwave Handbook, Volume 3*.[13] The only English coin I had of the right diameter was ten new pence

Fig 4—Locating feed point for offset dish using calculated string lengths.

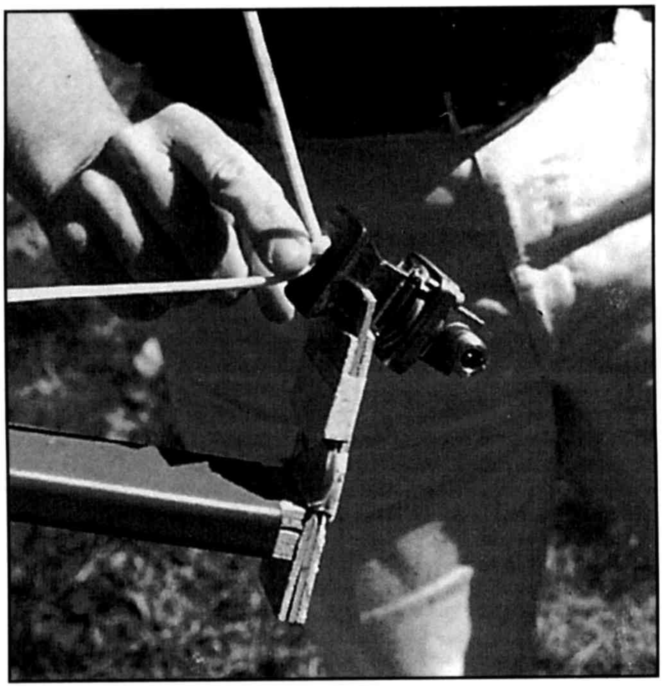

Fig 5—Knot in string accurately locates phase center of feed horn at focal point of offset dish.

Table 1
Summary of 10.368-GHz Antenna Measurements (Measurements by N1BWT, W1RIL, WB1FKF and N1BAQ, 7/6/95)

Antenna	*Focal Dist*	*Gain (dBi)*	*Efficiency*
Standard-Gain Horn (22.5 dBi calculated gain)[1]		22.45	43%
WB1FKF hombrew horn		22.05	
25-in dish, $f/D = 0.45$, from Satellite City, with the following feeds:			
11 GHz Superfeed[2]	11.187 in	34.3	56%
	11.0 in	34.0	52%
11 GHz Superfeed, modified with central waveguide flush with outer rings.[2]	11.187 in	34.6	61%
G4ALN "penny" feed	10.375	33.0	41.5%
18-in dish, $f/D = 0.42$, from Satellite City, with the following feeds:			
Clavin feed	7.875 in	31.2	53%
18-in offset dish, RCA DSS steel, with the following feeds:			
Rectangular Horn, E=31.2 mm, H=41.1 mm, Length=20 mm	11 in[3]	32.0	63.5%
	11.25 in[3]	31.0	50%
Rectangular Horn, E=31.2 mm, H=41.1 mm, Length=10 mm		31.5	57%
Rectangular Horn, surplus, E=30.1 mm H=45.2 mm, Length=42 mm	11 in[3]	31.8	61%
24-in (WB1FKF) with the following feeds:			
11 GHz Superfeed with Styrofoam housing[2]		34.4	62%
WA1MBA log-periodic		28.0	14%
24-in offset dish, plastic, with the following feed:			
Rectangular Horn, E=31.2 mm, H=41.1 mm, Length=20 mm.	14.75 in[3]	34.3	61%
30-in dish, $f/D = 0.45$, (lighting reflector), with the following feeds:			
11 GHz Superfeed, modified with central waveguide flush with outer rings[2]	13.5 in	36.4	64%

Measurement specifications:
Range: Length = 150 feet. $2D^2/\lambda$ = 135 feet. Test height ≈10 feet.
Focal distance: Each feed was adjusted for maximum gain. Axial dish focal distances measured to outermost point on feed.

Notes:
[1] Scientific-Atlanta model 12-8.2. Antenna courtesy KM3T, gain thanks to John Berry of Scientific-Atlanta.
[2] 11 GHz Superfeed is a Chaparral feed horn for 11-GHz TVRO.
[3] Offset dishes measured from bottom edge of dish to center of horn aperture.

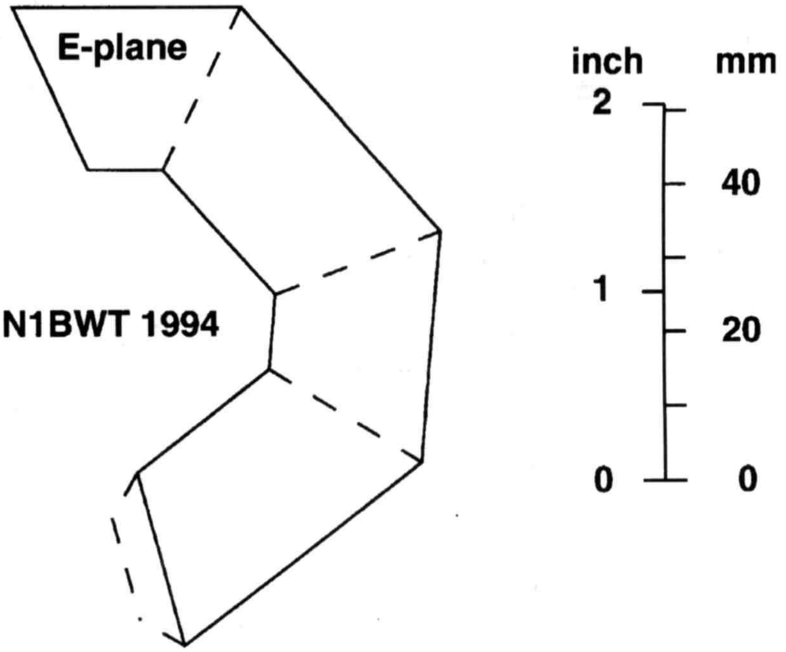

Fig 6—Template for a 10-GHz feed horn that can be used with the RCA DSS offset dish.

rather than an old penny, but silver should work at least as well as copper. The feed is easy to build, and has a good SWR, so I can see why it is popular. However, the performance was mediocre, with 41% efficiency, about the same as an open waveguide flange. Thus, the gain of a 25-inch dish fed with a penny feed is not much higher than the 18-inch offset dish fed with a simple horn.

To be fair, the dish we used, with an *f*/*D* of 0.45, is not optimum for the penny feed. The *Handbook* states that it is suitable for dishes with an *f*/*D* ratio in the range 0.25 to 0.3. A dish that deep is extremely difficult to illuminate well, so it is unlikely that this feed will deliver much higher efficiency than we measured. However, it is probably as good a feed as any for very deep dishes.

Cassegrain and Gregorian Feeds

Large professional antennas often use multiple reflector feeds, like the Cassegrain (hyperbolic subreflector) and Gregorian (elliptical subreflector) configurations.[14] Even better is a shaped-reflector system, where both reflector shapes are calculated for best efficiency and neither reflector is parabolic.[15] JPL reports 74.5% efficiency on their 34 meter high-efficiency antenna.[16]

All of these systems require a carefully shaped subreflector that is more difficult than a parabola to fabricate. For a shaped reflector to work well, it must be larger than 10 wavelengths, and the main reflector must be much larger than the subreflector to minimize blockage by the subreflector. One analysis suggested that a Cassegrain antenna must have a minimum diameter of 50 wavelengths, with a minimum subreflector diameter of 20 wavelengths, before the efficiency is higher than an equivalent dish with a primary feed.[17] This is a fairly large dish, even at 10 GHz, and shaping a 20 λ subreflector is beyond the ingenuity of most hams. However, there is probably a surplus one somewhere, and the scrounging ability of hams should never be underestimated.

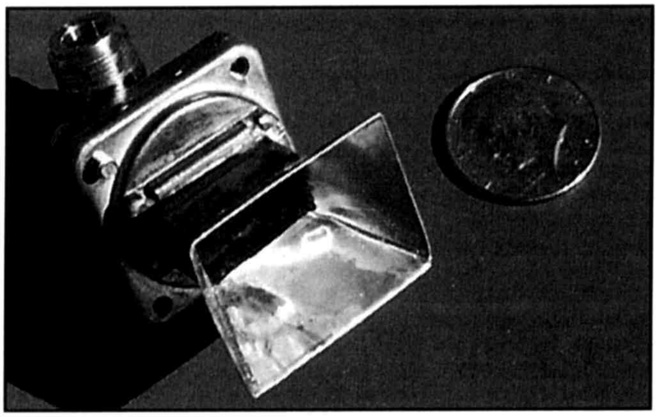

Fig 7—Photograph of 10 GHz rectangular feed horn for RCA DSS offset dish made using template in Figure 6.

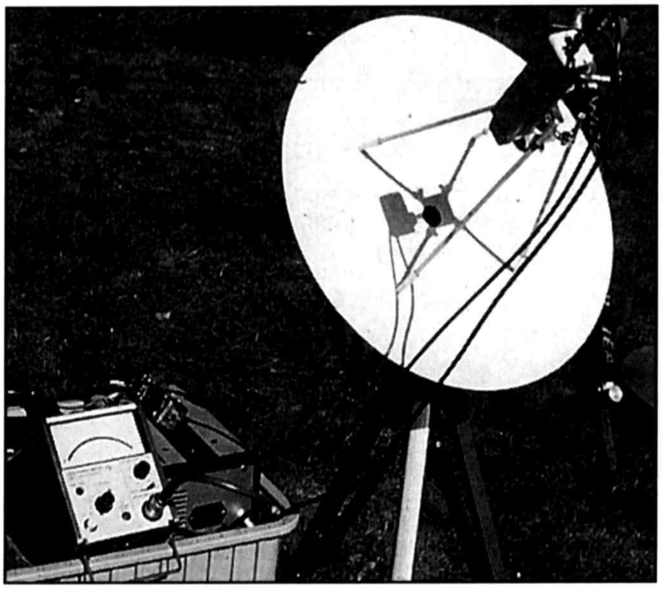

Fig 8—Conventional dish receiving sun noise. Shadow of feed horn demonstrates aperture blockage by feed.

Sun Noise Measurement

Even a modest 10-GHz system is capable of detecting sun noise, which is an excellent way of ensuring both antenna and receiver performance since we can predict how much sun noise should be received with a given antenna size and receiver noise figure.[18] Only a relatively simple setup is required to make reasonably accurate sun noise measurements.

On the other hand, setting up an antenna range to evaluate antenna performance, as described in my earlier articles, requires a significant amount of equipment and a good standard antenna of known gain, and it is still one of the most difficult measurements to perform accurately.

A good system for measuring sun noise was described by Charlie, G3WDG.[19] He built a 144-MHz amplifier with moderate bandwidth using MMICs and helical filters that amplifies a transverter output to drive a surplus RF power meter. The newer solid-state power meters, like the HP 432 and more recent models, are stable enough to detect and display small changes in noise level, and the response is slow enough to smooth out flicker. Since my 10-GHz system has an IF output at 432 MHz, duplicating Charlie's amplifier would not work. In the junk box I found some surplus broadband amplifiers and a couple of interdigital filters. I combined these to provide high gain with a few MHz-bandwidth, arranged as shown in Fig 10. The first filter limits the bandwidth so we are measuring at the desired frequency, 10.368 GHz in this case, and the second filter at the output is important to limit the noise bandwidth at the detector, since noise power is proportional to bandwidth. Without the second filter, the broadband noise generated by the amplifiers or MMICs would overwhelm the sun noise, whose bandwidth is limited by the first filter. Approximately 100 dB of total gain is required with a bandwidth of 10 MHz for an output power of one milliwatt. I found that roughly 60 dB of gain after my preamp and transverter was required to get a reasonable level on the power meter.

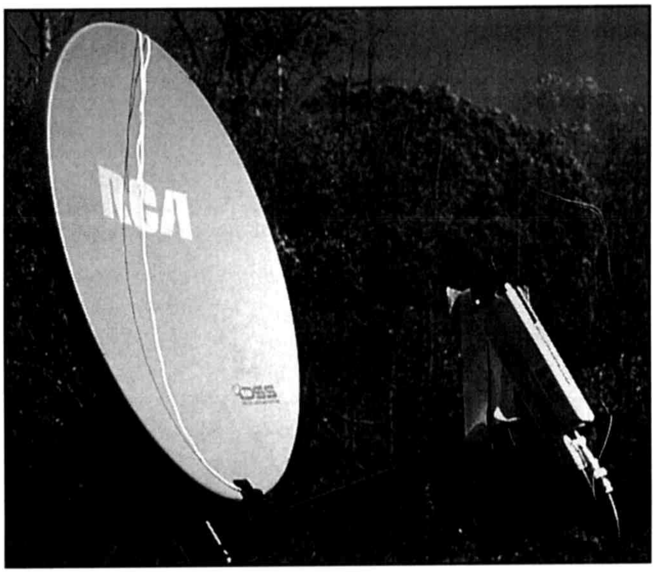

Fig 9—Offset dish receiving sun noise. Feed horn shadow at edge of dish demonstrates minimal aperture blockage by offset feed.

Operation is simple—point the dish at the sun, peak the noise, then move to clear sky and note the difference in output. Several precautions are necessary:

1. According to G3WDG, amplifiers with broadband noise output suffer gain compression at levels about 10 dB lower than found with signals, so be sure the amplifier compression point is at least 10 dB higher than the indicated noise.

2. Make sure no stray signals appear within the filter passband.

3. A clear area of sky is necessary, since foliage and other obstructions add thermal noise that can obscure the cold-sky reading. I found a large tree generated more noise than the sun because it filled the whole beam and appeared in sidelobes as well. The measurement is really comparing sun noise plus all other noise to all the other noise received, so stray sources of thermal noise can produce error. Fortunately, this error is almost always in the pessimistic direction, so we aren't led astray.

4. If the preamp is at or near the feed, don't let it heat up too much or its noise temperature can change. (Total solar radiation is about one kilowatt per square meter—that's several hundred watts on even a small dish.)

Before making measurements, I used the *NOISE* program by Mel, WR0I, to estimate expected sun noise.[18] For a 2-foot dish with 60% efficiency and a receiver noise figure of about 2.5 dB (modified TVRO LNB), the program predicted 2.4 dB of sun noise. My initial measurements using the setup described below showed 2.5 dB of sun noise on my 25-inch dish and 2.0 dB with the 18-inch, offset-fed RCA dish. However, I also measured 2.2 dB of sun noise on a 30-inch dish with a fancy "shepherd's crook" feed arrangement using copper water pipe as circular waveguide. The last mea-

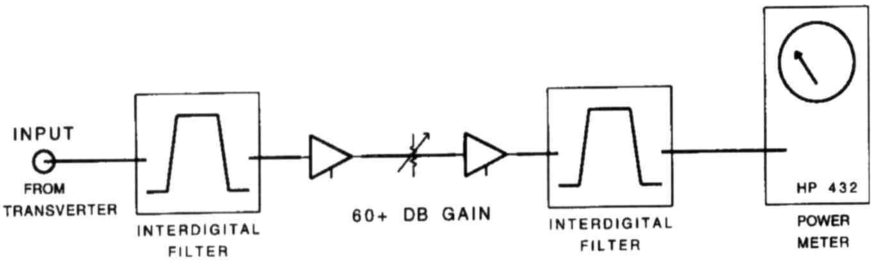

Fig 10—Block diagram of an indicator for sun-noise measurements.

Table 2: More Sun Noise Measurements

22 Oct 1995, 1:00 PM

Antenna	*Sun noise*
Standard Gain Horn	0.35 dB
30-inch dish, mod. Chaparral feed	3.2 dB
25-inch dish, Chaparral feed	2.3 dB
18-inch dish, Clavin feed	1.6 dB
18-inch offset—steel, rect. horn feed	2.4 dB
18-inch offset—SMC, rect. horn feed	2.5 dB

Note: Estimated noise figure = 2.9 dB

surement quickly highlighted the need for further adjustment of the feed arrangement. The version of the *NOISE* program I used only calculates for dish sizes in integral feet, so we can't get precise estimates for these small dishes, but an improved version is available.

After I made the equipment more portable and stable, I was able to measure sun noise on most of my 10-GHz antennas, with the results shown in Table 2. The *G/T* advantage of the offset dish for satellite communication is clearly demonstrated: the 18-inch offset dish is not only much better than the equivalent size conventional dish, but outperforms a 25-inch conventional dish that has 2 dB more gain, as shown in Table 1.

Sun-noise measurements are fine for checking system performance but less satisfactory for making adjustments. Any adjustment may change both sun and sky reading, so it is necessary to compare the two after each adjustment, and the resulting differences may be small. Make one adjustment at a time, keep careful notes and look for reproducible improvements. The process is tedious, but careful work pays off.

If you've never tried it, you are probably wondering why you can't just use your receiver to measure sun noise. The answer is that you can, but with less accuracy and more frustration because of the narrow bandwidth and short time constant of a communications receiver. First, the noise-measuring equipment described above has a bandwidth of a few MHz, while a typical receiver bandwidth is 3 kHz, a thousand times narrower. To compensate for a thousand times narrower bandwidth, a thousand times more gain, or 30 dB more, is required. Most receivers have adequate gain but use AGC to control the gain; if you can't turn off the AGC, a problem with many receivers, the audio output doesn't change linearly with input level, and the S-meter is far too small to resolve tenths of a dB. With the AGC off, the audio output follows the input noise, but the narrow bandwidth and short time constant (about one millisecond, limited by the lowest audio frequency response, typically 300 Hz) produce an output with fluctuations caused by the random nature of noise—I've typically seen one dB of flicker, making it hard to read tenths of a dB. With the power meter, the thermistor sensor has a time constant of hundreds of milliseconds, which smoothes and averages the flicker to produce a very stable meter indication.

Receiver Noise Figure Using the Sun Noise Equipment

The same equipment used for measuring sun noise can also be used to measure receiver noise figure. While measuring sun noise, I noticed that pointing an antenna at the ground produced a significant noise increase. I then realized that this is similar to a hot/cold system for noise figure measurement, where the earth is about 290 K while the cold sky at 10 GHz is around 6 K at high elevations, so the temperature difference is nearly 290 K.[20] Using the standard-gain horn, I found approximately 3 dB of difference between cold sky and warm earth; I had previously measured this LNB preamp at 2.9 dB of NF, or just under 290 K of noise temperature, so a 3-dB increase is exactly right, as shown by the following calculations.

The difference between the hot and cold noise sources is called the *Y* factor; this is used to calculate the receiver noise temperature, T_e, as follows:

$$T_e = \frac{T_{ground} - Y \cdot T_{sky}}{Y - 1}$$

where Y is a power ratio (convert from dB).

The noise temperature is easily converted to noise figure, F, if you prefer:

$$F(dB) = 10 \cdot \log\left(\frac{T_e}{290} + 1\right)$$

This technique should work with any antenna with reasonably high gain and low sidelobes, so stray noise is minimized. A long horn is a good choice. Just point the antenna at clear sky overhead, away from the sun or any obstruction, note the meter reading, then point the antenna into the ground and read the noise increase Y. For convenience, I've added these calculations to version 2 of *HDL_ANT*.

Azimuth Alignment Using the Sun

Computer programs are available that will calculate the sun's azimuth and elevation at a given place and time, so peaking on the sun can be used to calibrate both azimuth and elevation readout. For a rover without a computer, a previously calculated list giving azimuth at half-hour increments at expected rover locations is useful for setup in each location. Don, WB1FKF, suggests that if you are unable to measure sun noise, a vertical line on the dish will suffice on sunny days; simply line up the feed horn's shadow on the line.

Recommendations for Parabolic Dish Feeds

Table 3 is an update of the recommendations I made for dish feeds in previous articles. The numbers shown are my best estimates for small dishes at 10 GHz, and the recommendations should be taken as my personal opinion only. See the previous *QEX* articles for the appropriate references.

Conclusion

The new DSS offset-feed dishes are readily available small microwave dishes, and I have shown how to use them as high-performance 10-GHz antennas. Their high performance, convenient size and low cost should make them the antenna of choice for portable operation.

Sun-noise measurement capability is a valuable tool for measuring and verifying performance of both antennas and

Table 3—N1BWT Recommendations for Dish Feeds

Type of Feed	*f/D Optimum*	*Best η estimate*	*η for f/D=0.45*	*Comments*
Chaparral	0.35-0.45	55-65%	61-64%	"11 GHz Superfeed" from Chaparral dealers good at 10 GHz
VE4MA/Kumar	0.35-0.45	55-65%	61%	proven performance at 1296, 2304, and 3456 MHz
W2IMU Dual-Mode	0.5-0.6	55-60%	NR	proven performance 432 MHz to 10 GHz
Rectangular horn	>0.45	50-60%	58%	tailor dimensions for *f/D* —also good for Offset dishes
Clavin	0.35-0.4	50-60%	57%	small feed blockage
EIA Dual-dipole	0.5-0.6	50-60%	NR	better at lower frequencies
Circular horn	Function of diameter	25-50%	26%	asymmetrical E- and H-planes and phase centers
Penny (G4ALN)	0.25-0.3	30-45%	41.5%	attractive mechanically
Dipole	0.3-0.4	30-45%	NR	asymmetrical E- and H-planes
Log Periodic	?	10-40%	14%	broadband, but poor phase centers

Measurements and Calculations for an Offset Parabolic Reflector

The geometry of an offset-feed dish antenna is a bit more complicated than a conventional dish antenna, but the measurements needed to use one are straightforward. We need to first determine the tilt angle of the reflector, then do some curve fitting calculations for the dish surface, calculate the focal length and finally determine the focal point in relation to the offset reflector.

One common type of offset parabolic reflector has an oval shape, with a long axis from top to bottom and a shorter axis from side to side. However, if you were in the beam of this antenna, looking down the boresight, it would appear to be circular, with the feed at the bottom. Tilt the top of the reflector forward, until it appears circular from a distance, and it will be in the correct orientation to operate with the beam on the horizon. The tilt can be determined much more accurately with a simple calculation:

Tilt angle (from horizontal) = *arcsin* (short axis/long axis) [Note: the *arcsin* function is called *sin*$^{-1}$ on some scientific calculators.]

For the RCA 18-inch dish, the short axis is 460 mm (about 18 inches) and the long axis is 500 mm. Therefore, the tilt angle = *arcsin* (460/500) = 66.9° above horizontal. At 10 GHz, one millimeter is sufficiently accurate for most dish dimensions, so using millimeters for calculations eliminates a lot of tedious decimals.

If the offset reflector is not oval, we can still use the same calculation by placing it on the ground with the reflecting surface upward and filling it with water; the surface of the water is a level plane from which to make measurements. The surface of the water in the dish should be an oval just touching the top and bottom rims, while the other axis of the oval of water is the shorter axis.

The other dimension we need is location and depth of the deepest point in the dish. The deepest point is probably not at the center, but somewhere along the long axis. Using a straightedge across the rim for an oval dish, or the water depth for other shapes, locate the deepest point and measure its depth and distance from the bottom edge on the long axis.

For the RCA dish, the deepest point is 43 mm deep at 228 mm from the bottom edge on a line across the long axis.

When the dish is tilted forward to 66.9° above horizontal, the translated coordinates describe the curve of the long axis by three points:

0, 0 mm	(bottom edge)
49.8, 226.6 mm	(deepest point)
196, 460 mm	(top edge)

If we assume that the bottom edge is not at the axial center of a full parabola of rotation (the equivalent conventional dish of which the offset dish is a section), but rather is offset from the center by an amount X_0, Y_0, then all three points must fit the equation:

$$4*f*\left(X+X_0\right)=\left(Y+Y_0\right)^2$$

The unknowns are X_0, and Y_0, and f, the focal length; plugging in the three points gives us three equations and three unknowns, a readily soluble 3x3 matrix (actually, the 0,0 point allows reduction to a 2x2 matrix, even easier, followed by a simple calculation for X_0 and Y_0). Version 2 of the **HDL_ANT** program will do the calculations for you.

For the RCA dish, the answers are:

f = 282.8 mm = 11.13 inches

X_0 = 0.1 mm behind bottom edge

Y_0 = 11 mm below bottom edge, so the feed doesn't block the aperture at all.

So, we tilt the dish to 66.9° from horizontal, and the feed is on a line 11 mm below the bottom edge of the dish. To help locate the focal point, it is 283 mm from the bottom edge and 479 mm from the top edge, both edges on the long axis. I tied a knot in a piece of string and taped it to the top and bottom edges so that the knot locates the focal point.

For the RCA dish, we can also calculate the illumination angle to be 77° on the long axis and 79° on the short axis, so it is roughly symmetrical. The optimum feed for this illumination angle is equivalent to an axial-feed dish with *f / D* ≅ 0.7.

Although the illumination angle is equivalent to an *f / D* ≅ 0.7 , the surface is a section of a parabola about 37 inches in diameter with a focal length of about 11 inches. Thus, the real *f / D* is 0.3, so the focal distance is quite critical.

receivers, and for antenna alignment. Also, since it is much easier to achieve accurate results with sun noise than with traditional antenna-range measurements, the various VHF conferences might consider using sun noise for antenna measurement.

Notes

[1] Section 2 of this book, pp 10-19.

[2] Wade, P. C., N1BWT, "High-Performance Antennas for 5760 MHz," *QEX,* January 1995, pp 18-21.

[3] Section 1 of this book, pp 1-9.

[4] Section 3 of this book, pp 20-28.

[5] Lau, Z., KH6CP/1, "RF," *QEX,* March 1995, p 24.

[6] MCM Electronics, 650 Congress Park Drive, Centerville, OH 45459, 800-543-4330. Steel dish part number 221196 or 221197, mounting bracket part number 221199. SMC dish part number 221198, mounting bracket part number 221200.

[7] Huang, J., Rahmat-Samii, Y. and Woo, K., "A GTD Study of Pyramidal Horns for Offset Reflector Antenna Applications," *IEEE Transactions on Antennas and Propagation,* AP-31, March 1983, pp 305-309.

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[12] Rudge, A. W. and Adatia, N.A., "Offset-Parabolic-Reflector Antennas, A Review," *Proceedings of the IEEE,* December 1978, pp 1592-1618.

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[18] Graves, M. B., WR0I, "Estimating Sun Noise at Various Frequencies, Based on the 10.5 cm Flux Reported by WWV," *Proceedings of Microwave Update '94,* ARRL, 1994, pp 125-131.

[19] Suckling, C., G3WDG, "144 MHz wideband noise amplifier," *DUBUS,* 2/1995, pp 5-8.

[20] Graves, M. B., WR0I, "Computerized Radio Star Calibration Program," *Proceedings of the 27th Conference of the Central States VHF Society,* ARRL, 1993, pp 19-25.

The W3KH Quadrifiliar Helix Antenna

If your existing VHF omnidirectional antenna coverage is just okay, this twisted 'tenna is probably just what you need!

By Eugene F. Ruperto, W3KH

(From *QST*, August 1996)

I still remember that hollow, ghostly signal emanating from my receiver in 1957. The signal was noisy and it faded, but that was to be expected—it was coming from outer space. I couldn't help but marvel that mankind had placed this signal sender in space! They called it *Sputnik,* and it served to usher in the space race.

Little did I realize then that four decades later we would have satellites in orbit around Earth and other heavenly bodies performing all sorts of tasks. Now we tend to take satellites for granted. According to the latest information on the Amateur Radio birds, I count about 15 low-Earth-orbit (LEO) satellites for digital, experimental and communications work, and two in *Molniya*-type highly elliptical orbits (AO-10 and AO-13), with the probability of a third to be launched in early 1997.

The world has access to several VHF weather satellites in low Earth orbit. Unlike geostationary Earth-orbiting satellites (GOES), the ever-changing position of the LEOs presents a problem for the Earth station equipped with a fixed receiving antenna: signal fading caused by the orientation of the propagated wavefront. This antenna provides a solution to the problem. Although this antenna is designed primarily for use with the weather sats, it can also be used with any of the polar-orbiting satellites.

These days, technical advances and miniature solid-state devices make it relatively easy for an experimenter to acquire a weather-satellite receiver and a computer interface at an affordable price. So it was only a matter of time before I replaced my outdated weather-sat station with state-of-the-art equipment.

Yesterday

In the early '70s, I built a drum recorder that used a box with a light-tight lid. It was a clumsy affair. The box and photo equipment took up most of the 6×8-foot room in which it was housed. Next to the recorder, a 3×4-foot table supported a tube-type receiver, frequency converters, a reel-to-reel tape recorder (our data-storage medium), a 50-pound monitor oscilloscope, az/el rotator controls for the helical antennas and a multitude of other devices including the drum-driver amplifiers and homemade demodulator. This station provided coverage of the polar-orbiting and geostationary satellites and furnished me with "tons" of data. Over time, my weather-satellite station evolved into a replica of mission control for the manned-spaceflight program! I had so much gear, it had to be housed in a shed separate from the house.

Today

Now, my entire weather-satellite station sits unobtrusively in one corner of the shack, occupying an area of less than one square foot—about the same size as my outboard DSP filter. My PC—now the display for weather-sat photos—is used for many applications, so an A/B switch allows me to toggle the PC between the printer and the weather-satellite interface.

What I needed next was a simple antenna system for unattended operation—something without rotators—something that would provide fairly good coverage, from about 20° above the horizon on an overhead pass. It was a simple

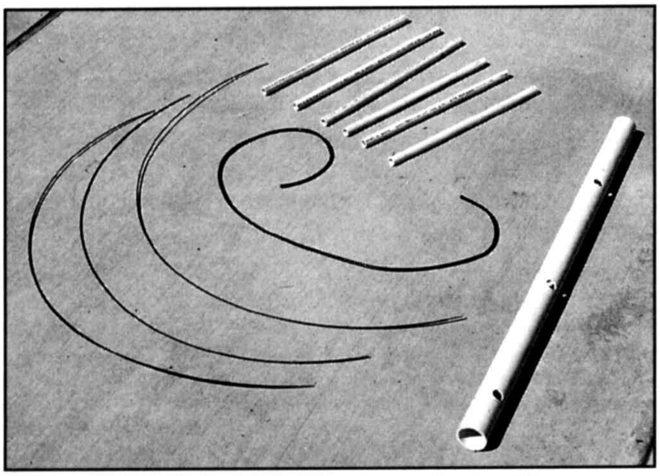

Figure 1—The humble beginnings of a terrific antenna.

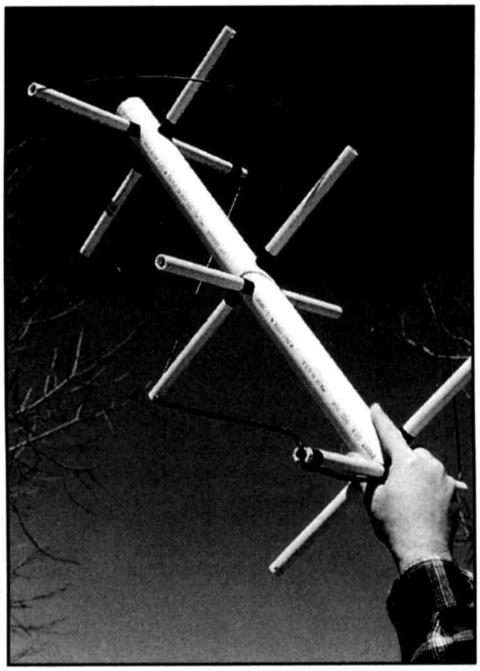

Figure 2—The quadrifilar helix antenna with two of the four legs (filars) of one loop attached.

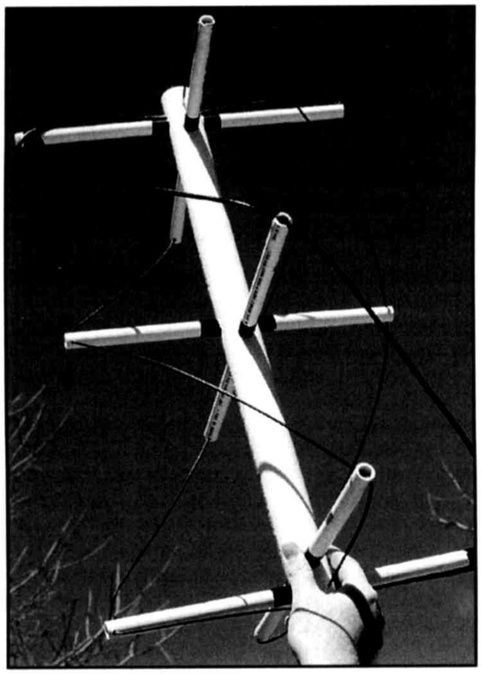

Figure 3—This view shows the QHA with all four legs in place. The ends of the PVC cross arms that hold the coaxial leg are notched; the wire elements pass through holes drilled in the ends of their supporting cross arms.

request, but apparently one without a simple solution.

Background

Initially I used a VHF discone antenna with mixed results. The discone had a good low-elevation capture angle, but exhibited severe pattern nulls a few minutes after acquisition of signal and again when the satellite was nearly overhead. The fades and nulls repeated later as it approached the other horizon. About this time, Dave Bodnar, N3ENM (who got me reinterested in the antenna project), built a turnstile-reflector (T-R) array. The antenna worked fairly well but exhibited signal dropout caused by several nulls in the pattern. Dave built two more T-Rs, relocating them for comparison purposes. Unfortunately, the antennas retained their characteristic fades and nulls. Another experimenter and I built T-Rs and we experienced the same results. I suggested that we move on to the Lindenblad antenna. The Lindenblad proved to be a much better antenna for our needs than either the T-R or the discone, but still exhibited nulls and fades. Over a period of several months, I evaluated the antennas and found that by switching from one antenna to another on the downside of a fade, I could obtain a fade-free picture, but lost some data during the switching interval. Such an arrangement isn't conducive to unattended operation, so my quest for a fade-free antenna continued.

The Quadrifilar Helix Antenna

Several magazines have published articles on the construction of the quadrifilar helix antenna (QHA) originally developed by Dr. Kilgus,[1] but the articles themselves were generally reader unfriendly—some more than others. One exception is *Reflections* by Walt Maxwell, W2DU.[2] Walt had considerable experience evaluating and testing this antenna while employed as an engineer for RCA.

Part of the problem of replicating the antenna lies in its geometry. The QHA is difficult to describe and photograph. Some of the artist's renditions left me with more questions than answers, and some connections between elements as shown conflicted with previously published data. However, those who have successfully constructed the antenna say it is *the* single-antenna answer to satellite reception for the low-Earth-orbiting satellites. I agree.

Design Considerations

I had misgivings about the QHA construction because the experts implied that sophisticated equipment is necessary to adjust and test the antenna. I don't disagree with that assumption, but I *do know* that it's possible to construct a successfully performing QHA by following a cookbook approach using scaled figures from a successful QHA. These data—used as the design basis for our antennas—were published in an article describing the design of a pair of circularly polarized S-band communication-satellite antennas for the Air Force[3] and designed to be spacecraft mounted. Using this antenna as a model, we've constructed more than six QHAs, mostly for the weather-satellite frequencies and some for the polar-orbiting 2-meter and 70-centimeter satellites with excellent results—*without the need for adjustments and tuning*. Precision construction is not my forte, but by following some prescribed universal calculations, a reproducible and satisfactory antenna can be

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[1] Notes appear at the end of this section.

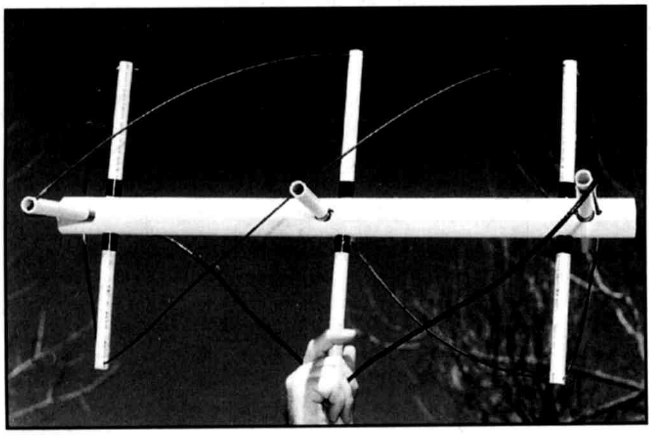


Figure 4—Another view of the QHA.

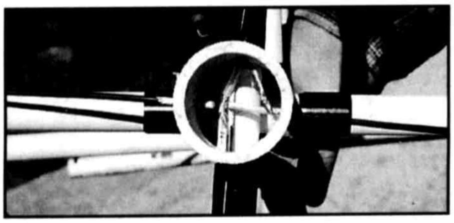


Figure 5—An end-on view of the top of the QHA prior to soldering the loops and installing the PVC cap.

built using simple tools. The proof is in the results.

The ultrahigh frequencies require a high degree of constructional precision because of the antenna's small size. For instance, the antenna used for the Air Force at 2.2 GHz has a diameter of 0.92 inch and a length of 1.39 inches! Nested inside this helix is a smaller helix, 0.837 inch in diameter and 1.27 inches in length. In my opinion, construction of an antenna *that* size requires the skill of a watchmaker! On the other hand, a QHA for 137.5 MHz is 22.4 inches long and almost 15 inches in diameter. The smaller, nested helix measures 20.5 by 13.5 inches; for 2 meters, the antenna is not much smaller. Antennas of this size are not difficult to duplicate even for those of us who are "constructionally challenged" (using pre-cut pieces, I can build a QHA in *less than an hour!*).

Electrical Characteristics

A half-turn half-wavelength QHA has a theoretical gain of 5 dBi and a 3-dB beamwidth of about 115°, with a characteristic impedance of 40 Ω. The antenna consists basically of a four-element, half-turn helical antenna, with each pair of elements described as a *bifilar,* both of which are fed in phase quadrature. Several feed methods can be employed, all of which appeared to be too complicated for us with the exception of the infinite-balun design, which uses a length of coax as one of the four elements. To produce the necessary 90° phase difference between the bifilar elements, either of two methods can be used. One is to use the same size bifilars, which essentially consist of two twisted loops with their vertical axes centered and aligned, and the loops rotated so that they're 90° to each other (like an egg-beater), and using a quadrature hybrid feed. Such an antenna requires *two* feed lines, one for each of the filar pairs.

The second and more practical method, in my estimation, is the self-phasing system, which uses *different-size loops:* a larger loop designed to resonate *below* the design frequency (providing an inductive reactance component) and a smaller loop to resonate *higher* than the design frequency (introducing a capacitive-reactance component), causing the current to lead in the smaller loop and lag in the larger loop. The element lengths are 0.560 λ for the larger loop, and 0.508 λ for the smaller loop. According to the range tests performed by W2DU, to achieve *optimum* circular polarization, the wire used in the construction of the bifilar elements should be 0.0088 λ in diameter. Walt indicates that in the quadrifilar mode, the fields from the individual bifilar helices combine in optimum phase to obtain unidirectional end-fire gain. The currents in the two bifilars must be in quadrature phase. This 90° relationship is obtained by making their respective terminal impedances $R + jX$ and $R - jX$ where $X = R$, so that the currents in the respective helices are –45° and +45°.

The critical parameter in this relationship is the terminal reactance, X, where the distributed inductance of the helical element is the primary determining factor. This assures the ±45° current relationship necessary to obtain true circular polarization in the combined fields and to obtain maximum forward radiation and minimum back lobe. Failure to achieve the optimum element diameter of 0.0088 λ results in a form of elliptical, rather than true circular polarization, and the performance may be *a few tenths of a decibel* below optimum, according to Walt's calculations. For my antenna, using #10 wire translates roughly to an element diameter of 0.0012 λ at 137.5 MHz—not ideal, but good enough.

To get a grasp of the QHA's topography, visualize the antenna as consisting of two concentric cylinders over

Table 1

Quadrifilar Helix Antenna Dimensions

	Wavelength		*Small Loop*			*Big Loop*	
Freq (MHz)	*λ (inches)*	*Leg Size (0.508 λ)*	*Diameter (0.156 λ)*	*Length (0.238 λ)*	*Leg Size (0.560 λ)*	*Diameter (0.173 λ)*	*Length (0.26 λ)*
137.5	85.9	43.64	13.4	20.44	48.10	14.86	22.33
146	80.9	41.09	12.6	19.25	45.30	14.0	21.03
436	27.09	13.76	4.22	6.44	15.17	4.68	7.04

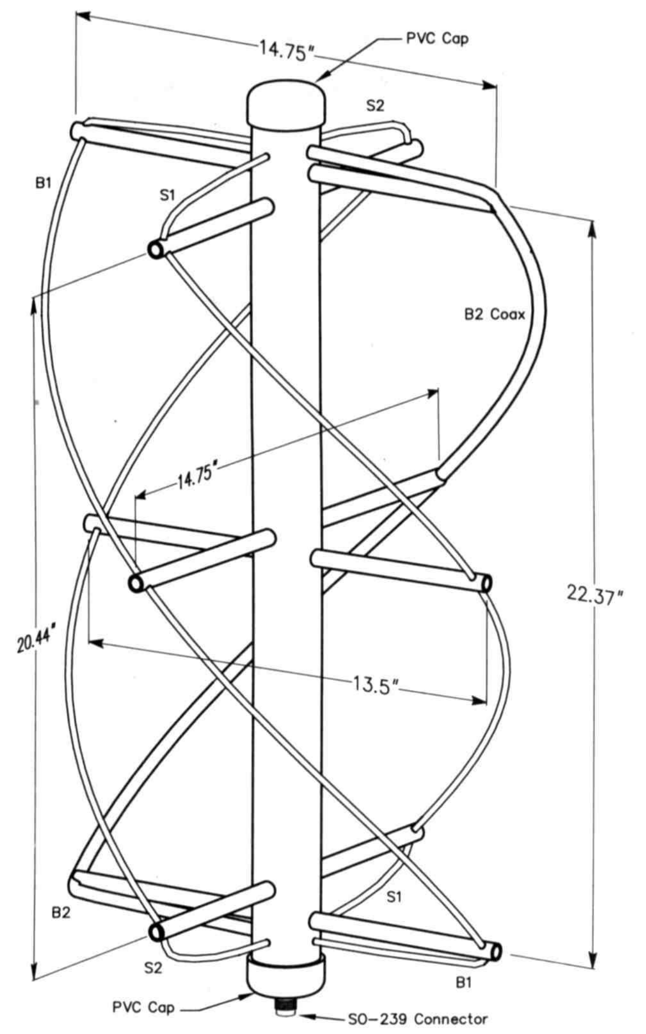


Figure 6—Drawing of the QHA identifying the individual legs; see text for an explanation. You may want to add an inch or two of PVC pipe at the bottom (and extend the coax to match) to make mounting easier.

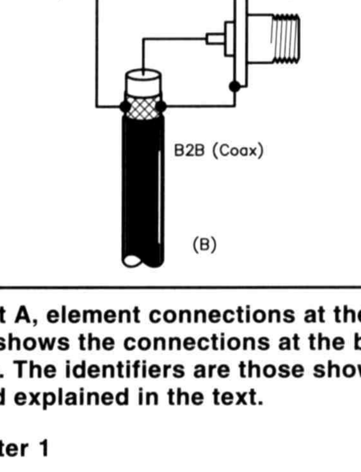


Figure 7—At A, element connections at the top of the antenna. B shows the connections at the bottom of the antenna. The identifiers are those shown in Figure 6 and explained in the text.

Figure 8—It's said that "The proof of the pudding is in the eating." To a weather-satellite tracker, clear, no-fade, no-noise pictures such as this one—compliments of W3KH's quadrifilar helix antenna—are delicious fare!

which the helices are wound (see Figures 1 through 5). In two-dimensional space, the cylinders can be represented by two nested rectangles depicting the height and width of the cylinders. The width of the larger cylinder (or rectangle) can be represented by 0.173 λ, and the width of the smaller cylinder represented by 0.156 λ. The length of the larger cylinder or rectangle can be represented by 0.260 λ, and the length of the smaller rectangle or cylinder can be represented by 0.238 λ. Using these figures, you should be able to scale the QHA to virtually any frequency. Table 1 shows some representative antenna sizes for various frequencies, along with the universal parameters needed to arrive at these figures.

Physical Construction

After several false starts using plywood circles and plastic-bucket forms to hold the helices, I opted for a simple PVC solution that not only is the simplest from a constructional standpoint, but also the best for wind loading. I use a 25-inch-long piece of schedule 40, 2-inch-diameter PVC pipe for the vertical member. The cross arms that support the helices are six pieces of $^1/_2$-inch-diameter PVC tubing: three the width of the large rectangle or cylinder, and three the width of the smaller cylinder. Two cross arms are needed for the top and bottom of each cylinder. The cross arms are oriented perpendicularly to the vertical member and parallel to each other. A third cross arm is placed midway between the two at a 90° angle. This process is repeated for the smaller cylindrical dimensions using the three smaller cross arms with the top and bottom pieces oriented 90° to the large pieces. Using $^5/_8$-inch-diameter holes in the 2-inch pipe ensures a reasonably snug fit for the $^1/_2$-inch-diameter cross pieces. Each cross arm is drilled (or notched) at its ends to accept the lengths of wire and coax used for the elements. Then the cross arms are centered and cemented in place with PVC cement. For the weather-satellite antennas, I use #10 copperclad antenna wire for three of the helices and a length of RG-8 for the balun, which is also the fourth helix. (I do not consider the velocity factor of the coax leg for length calculation.) For the UHF antennas, I use #10 soft-drawn copper wire and RG-58 coax. Copperclad wire is difficult to work with, but holds its shape well. Smaller antennas can be built without the cross arms because the wire is sufficiently self-supporting.

To minimize confusion regarding the connections and to indicate the individual legs of the helices, I label each loop or cylinder as B (for big) and S (for small); T and B indicate top and bottom. See Figures 6 and 7. I split each loop using leg designators as B1T and B1B, B2T and B2B, S1T and S1B and S2T and S2B, with B2 being the length of coax and the other three legs as wires. For right-hand circular polarization (RHCP) I wind the helices *counterclockwise* as viewed from the top. This is contrary to conventional axial-mode helix construction. (For LHCP, the turns rotate *clockwise* as viewed from the top.) See Figure 7 for the proper connections for the top view. When the antenna is completed, the view shows that there are two connections made to the center conductor of the coax (B2) top. These are B1T and S1T, for a total of three wires on one connection. S2T connects to B2T braid. The bottom of the antenna has S1B and S2B soldered together to complete the smaller loop. B1B and the braid of B2B are soldered together. I attach an SO-239 connector to the bottom by soldering the center conductor of B2B to the center of the connector and the braid of B2B to the connector's shell. The bottom now has two connections to the braid: one to leg B1B, the other to the shell of the connector. There's only one connection to the center conductor of B2B that goes to the SO-239 center pin.

Insulator Quality

A question arose concerning the dielectric quality of the tubing and pipe used for the insulating material. Antennas—being reciprocal devices—exhibit losses on a percentage basis, the percentage ratio being the same for transmit and receive. Although signal loss may not be as apparent on receive with a 2-µV signal as with a transmitted signal of 100 W (ie, it would be apparent if dielectric losses caused the PVC cross arms to melt!), signal loss could be a significant factor depending on the quality of the insulating material used in construction. As a test, I popped the pipe into the microwave and "nuked" it for one minute. The white PVC pipe and the tan CPVC tubing showed no significant heating, so I concluded that they're okay for use as insulating materials at 137.5 MHz or thereabouts.

The antennas cost me nothing because the scrap pieces of PVC pipe, tubing and connectors were on hand. Total price for all new materials—including the price of a suitable connector—should be in the neighborhood of $8 or less.

Results

I use a 70-foot section of RG-9 between the receiver and antenna, which is mounted about 12 feet above ground. As with the earlier antennas, I use a preamp in the shack. With AOS (acquisition of signal) on the first scheduled pass of NOAA-14, I was pleasantly surprised to receive the first of many fade-free passes from the weather satellites, including some spectacular pictures from the Russian Meteors! Although the design indicates a 3-dB beamwidth of 140°, an overhead pass provides useful data down to 10° above the horizon. (My location has a poor horizon, being located in a valley with hills in all directions but south.) I've also received almost-full-frame pictures of the West Coast and northern Mexico at a maximum elevation angle of only 12° at my location. (The 70-cm antenna works fine for PACSATs, although Doppler effect makes manual tracking difficult.) The weather-satellite antenna prototype worked better than expected and a number of copies built by others required no significant changes. The quadrifilar helix antenna is *definitely* a winner! And believe me, *it's easy to build!*

Acknowledgments

Thanks to Chris Van Lint, and Tom Loebl, WA1VTA, for supplying me with the necessary technical data to complete this project. A special thanks to Walt Maxwell, W2DU, for his review and technical evaluation and for sharing his technical expertise with the amateur satellite community.

Notes

[1] C. C. Kilgus, "Resonant Quadrafilar Helix," *IEEE Transactions on Antennas and Propagation,* Vol AP-17, May 1969, pp 349 to 351.

[2] M. Walter Maxwell, W2DU, "Reflections, Transmission Lines and Antennas," (Newington: ARRL, 1990). [This book is now out of print.—*Ed.*]

[3] Randolph W. Brickner Jr and Herbert H. Rickert, "An S-Band Resonant Quadrifilar Antenna for Satellite Communication," RCA Corp, Astro-Electronics Division, Princeton, NJ 08540.

Photos by the author

Application of Circular Waveguide With an 11-GHz TVRO Feed

The circular waveguide (3/4-inch copper type M) shepherd's crook feed described by WA6EXV in the San Bernardino Microwave Society's December 1993 newsletter was utilized in conjunction with a "Chaparral" brand 11-GHz TVRO Super- feed described by N1BWT. This feed system, with a 30-inch diameter, 0.375 F/D ratio, aluminum dish has been successfully used and has resulted in 2.8 dB of sun noise. This combination is being explored by the Long Island based TEN-X Group.

By Bruce Wood, N2LIV

(From *The 22nd Eastern VHF/UHF Conference*)

Crook

A sketch of the shepherd's crook feed is provided in Figure 1 with a listing of the pipe lengths utilized to construct it for this dish size, F/D ratio, and 11.25-inch focal length. These section lengths may be adjusted for various other size dishes. "NIBCO" brand pipe fittings were used for the elbows and couplings. The pipe lengths indicated includes the length of pipe recessed within the fittings.

Launcher

Several styles of SMA to round waveguide launchers were constructed as shown in Figure 1. The basic dimensions followed WA6EXV's design. Thread-in SMA connectors were used, Amphenol #901-9027. To gain more thread depth 1/2of a coupler sleeve was soldered on, or a small brass block constructed. The simplest method of launcher construction provided a rear wall for the waveguide and sufficient additional thread depth utilizing a 3/4 inch "NIBCO" pipe end cap. The NIBCO pipe end cap technique is unpopular in some areas because of so called slightly unpredictable results. When soldering the end cap, make sure the pipe and cap is super cleaned, coated with liquid rosin flux, and be sure the solder "wicks" all the way to the bottom of the end cap. Failure to do this could result in a "microwave choke joint" that could make tune up more difficult.

Feed

The "Chaparral" brand Model #11-0148 feed horn was connected directly to the circular shepherd's crook feed by cutting off the existing waveguide flange on the Chaparral feed horn and enlarging with a lathe the existing remaining 3/4" hole section to 7/8". This will allow the 3/4" copper pipe to be mounted directly within the feed to a depth of approximately 1/2". Anti oxidant grease was applied to help prevent corrosion between the copper and aluminum and the feed horn was finally epoxied in place.

Dish Mounting

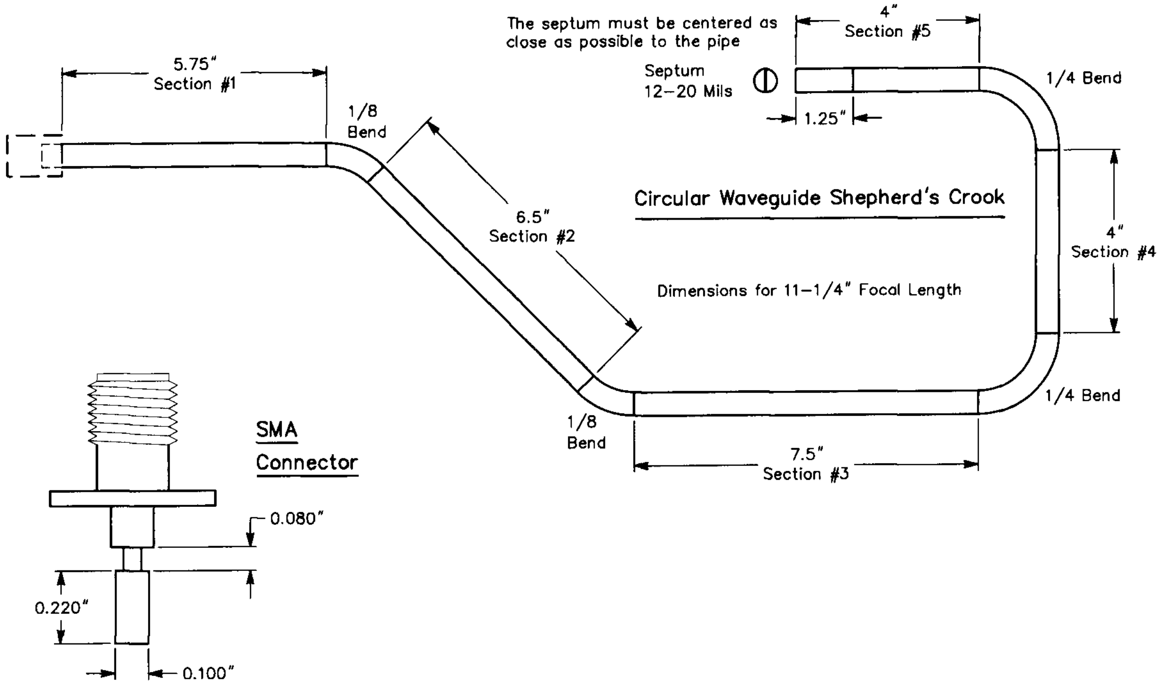
The shepherd's crook was secured to the aluminum dish's center mounting plate with ordinary plumbing fittings. I originally planned to use a simple 3/4-inch pipe coupling thru the dish's center plate but was concerned about the difficulty of soldering copper pipe fittings to the aluminum plate, possible galvanic corrosion in the salt air here on Long Island, and structural strength. I then located sweat to threaded screw type fittings which were also much stronger than a simple pipe coupling fitting and required no soldering. NIBCO brand fittings were used to construct the center dish feed-thru that will allow adjustment of the focal length and polarity. A pair of 3/4-inch copper male and female adapters part #C604 & #C603, respectively, were reamed out to 7/8-inch ID to allow the shepherd's crook to pass through them.

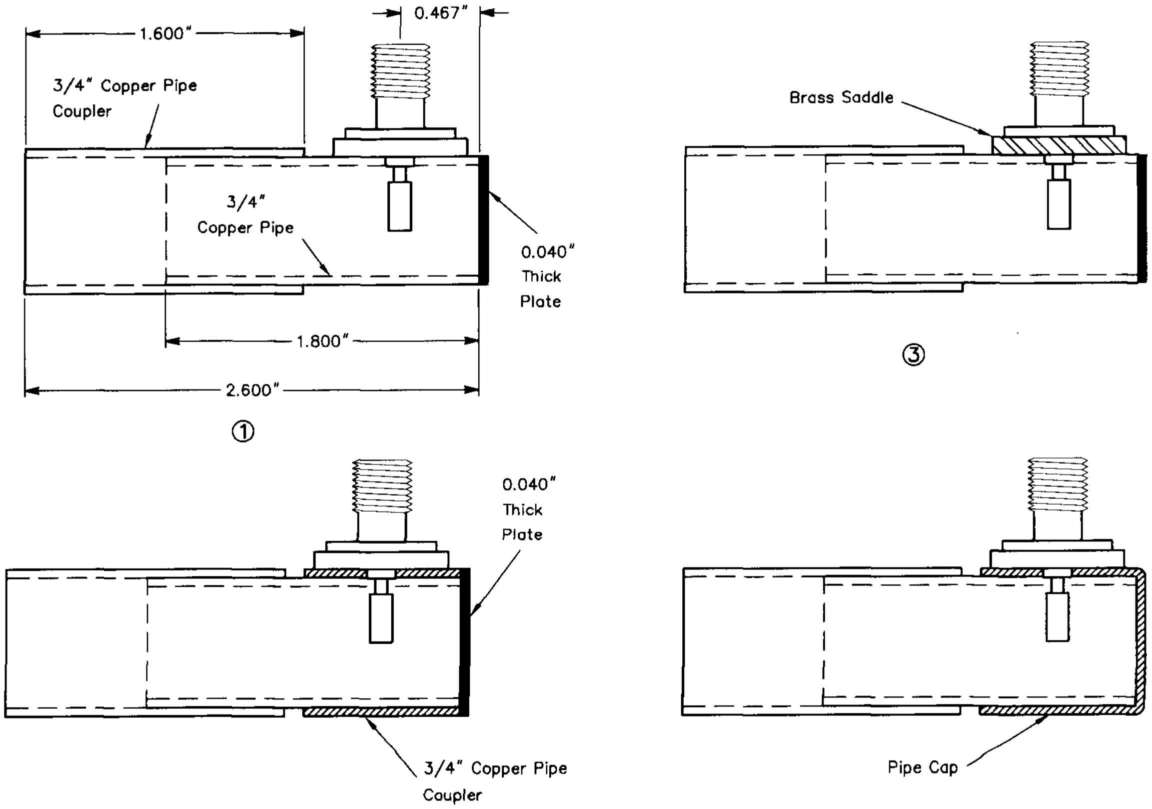
Two adjustable reamers from MSC Model 02239069 and 02239077 with a large tap handle were used to cut the hole. Approximately one hour was required to perform this operation. Screw the male threaded adapter pipe into the female before placing both into the vise, and performing the reaming operation. This supports the male adapter properly. The adapter becomes quite thin after the reaming. Be sure to insert a piece of 3/4-inch pipe before applying a wrench to the male adapter. The 3/4-inch pipe will keep it from deforming during the tightening operation. If a 3/4-inch to 1-inch NIBCO threaded pipe adapter is used, the amount of reaming required is drastically reduced to approximately 10 minutes). In addition, the resulting couplings are much stronger. The slight disadvantage is that a large hole is required in the center of the dish. If a lathe is available this is a second option. The rear male adapter was slotted in four places and a stainless steel hose clamp was used to apply sufficient compressive forces as to not deform the shepherd's crook and to also secure the feed in place after adjustment of the focal length and polarity. Large washers may be used to take up any slop.

Results

The dish has a theoretical gain of 33.6 dBd and a 2.43 degree beam width. While on the antenna test range the polarity, focal length and coax to waveguide adapter (for phase and polarization rotation within the crook) were adjusted for maximum signal strength. Measurements on the antenna range were curtailed due to rain. Subsequent sun noise measurements resulted in 2.8 dB of sun noise, when using a 2.2 dB NF sun noise measurement instrumentation.

A Return Loss of better than 20 dB was obtained by launcher probe adjustment.





Circular Waveguide to SMA Launchers

Dual-Band Feedhorn for the DSS Offset Dish

5760 and 10368 MHz

By Paul Wade, N1BWT
n1bwt@qsl.net

(From *Microwave Update '97*)

I recently completed a new transverter for 5760 MHz in a fairly small package. It fits on top of my 10 GHz transverter next to the wedge that supports the RCA DSS offset dish. I designed a 5760 MHz feed horn for the dish using my *HDLANT21* computer program (**http://www.arrl.org/qexfiles**), built one, and modified the transverter slightly to allow for quick changing of the feed horns with two wingnuts. Now I had a package, shown in Figure 1, for a compact two-band rover station.

I was wondering if it was possible to make a good dual-band feed when Dick, K2RIW, mentioned that WR-112 waveguide covers both 5760 MHz and 10368 MHz; even though the handbooks don't list it as usable for 5760, the cutoff frequency is slightly lower so it still works.

The next problem was designing a feed horn to cover both bands with decent illumination for the dish. A few trial calculations showed that a 10 GHz horn providing –10 dB edge illumination taper would provide a –3 dB edge illumination at 5760 MHz—most of the energy would miss the dish! On the other hand, a horn designed for 5760 would have a much narrower beam at 10 GHz, so the outer portions of the dish would receive very little illumination energy; only the performance of a much smaller dish would result. After some fiddling of the numbers, I found a compromise which might have the same loss of efficiency at both frequencies.

The final design, using the*HDLANT21* template shown in Figure 2, has an illumination taper of roughly –16 dB at 10.368 GHz, so it is somewhat under-illuminated, and roughly –5 dB at 5760 MHz, somewhat over-illuminated. I adjusted the horn length to match the phase centers at 10.368 GHz, since it is most critical at the higher frequency.

The next problem was getting a good VSWR at both frequencies. The surplus WR-112 waveguide-to-coax transitions I had weren't very good at 5760 MHz, so tuning was required. I put a small ball bearing inside the waveguide and moved it around with a magnet on the outside until I located a spot which improved the VSWR at 5760 MHz without making the 10368 MHz VSWR too much worse. Then I marked the spot, drilled and tapped the waveguide, and put in a tuning screw. Next I adjusted the screw for best VSWR at 5760 MHz, then put the BB back in and looked for a spot that improved both frequencies. A second screw was added here, then both screws adjusted for a compromise with reasonable VSWR at both frequencies. The final tuning had a VSWR under 1.6 at both 5760 MHz and 10368 MHz, but it is *not* a broadband match.

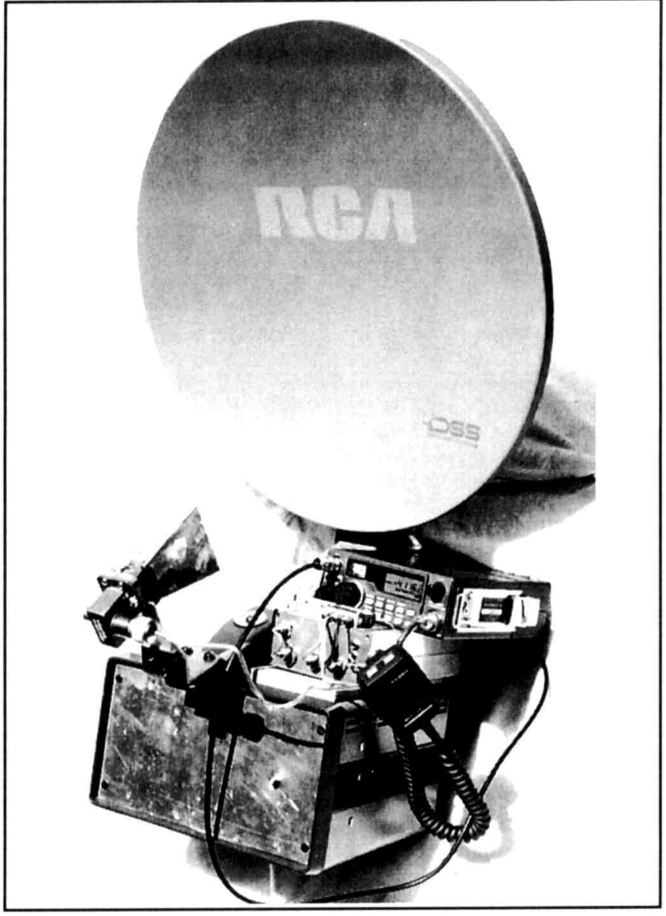


Figure 1—Dual-band rover system for 5760 and 10368 MHz.

Does it work? YES!

I completed it just in time for sun noise measurements at the July 1997 N.E.W.S. meeting, and tested it there on 10368 MHz. The DSS dish with a single-band horn feed has an efficiency better than 60%, while the dual-band feed is around 50%; the gain difference works out to about 1.2 dB.

The next day, I set up a sun noise measurement at 5760 MHz, with similar results: the DSS dish with a single-band horn feed has an efficiency of about 60%, while the dual-band feed is around 50%; the gain difference works out to about 1 dB on this band.

Summary

An RCA DSS dish with this dual-band feed horn provides two band performance only 1 dB down from a single band feed horn on each band. I've never seen a multiband feed with performance this good. This compact antenna is ideal for rover operations.

Questions

Q — Is a tri-band feed horn possible?

A — Not with ordinary waveguide, which cover a frequency range of less than 2 to 1 between cutoff and an upper frequency where other modes can propagate. Ridged waveguide can cover a wider range, but the horn design involves even more compromises.

Q — Is a dual-band horn possible for lower bands?

A — Yes, with a larger offset dish. A dish should be at least 10 λ in diameter for good performance, so the 18 inch RCA dish isn't big enough below 5760 MHz.

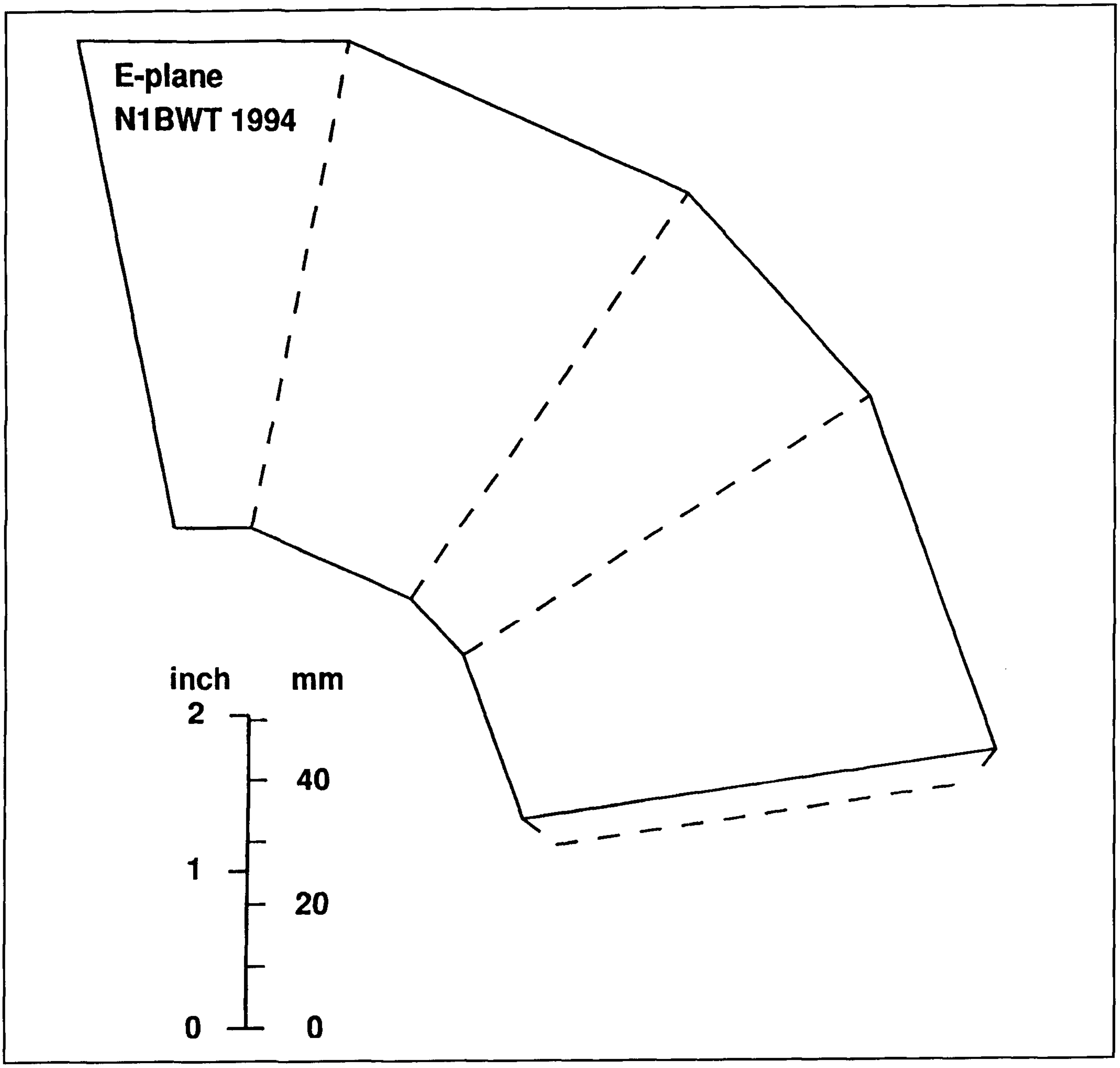


Figure 2—Dual-band feed horn template for RCA DSS offset dish; 5760 and 10368 MHz, WR-112 waveguide. Phase center is about 5 mm inside horn.

Dual-band Feed Horns for 2304/3456 MHz and 5760/10,368 MHz

By Al Ward, WB5LUA

(From *1997 Central States VHF Conference Proceedings*)

Background

Numerous articles have been written by WA9HUV, VE4MA, N1BWT and others on the proper illumination of a parabolic reflector. Joel Harrison has documented most of these works.[1] The proper illumination of a parabolic reflector with a given F/d (focal length to diameter ratio) requires the careful balance of both the E and H plane beamwidths of the feed horn. The problem on the microwave frequencies is one of putting several feed horns for individual frequencies at the same focal point—a nearly impossible task. Attempting to put multiple feeds at the focal point of the dish generally compromises performance on all bands. The satellite industry has had reasonable success by putting a 12 GHz feed in the middle of a 4 GHz feed. This is most likely due to the significantly smaller diameter of the 12 GHz feed versus the 4 GHz feed. With the relatively closer spacing of the 2304, 3456, 5760, 10,368 MHz bands this technique becomes difficult. Multiple feeds that are slightly offset are one way of obtaining multiband operation but there are some disadvantages, such as pointing offsets for each band. In order to get around the offset pointing problem I began work on in-line feeds, which will be the subject of this article. Any multiband feed will have compromises but I believe the techniques described herein will still result in a high performance antenna system.

Early Experiments on 2304 and 3456 MHz

I first experimented with inline multiband feeds back

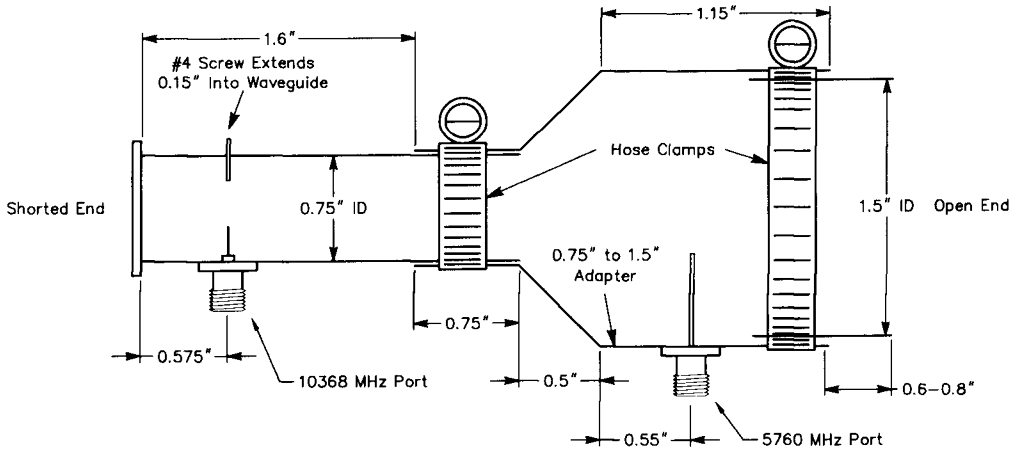


Fig 1—WB5LUA dual 5760 and 10,368 MHz feed horn.

Notes

1) 10,368 MHz probe is made from the center conductor of an SMA connector or 0.141" semi-rigid cable. 0.07" of the Teflon dielectric extends into waveguide. Length of pin above dielectric is 0.3" Tuning screw is diametrically opposite probe and is adjustable.
2) 5760 MHz probe is 0.6 to 0.7" in length and can be made from tubing 0.07 to 0.1" in diameter.
3) Tuning of both frequencies can be accomplished by tuning either probe length or waveguide length.
4) Isolation:
   10,368 MHz signal@5760 MHz port = –19 dB
   5760 MHz signal@10,368 MHz port = –45 dB
5) Return loss < 23 dB at both ports

in 1989 when I wanted a 2304 and 3456 feed that could be placed at the focal point of the dish and not require an offset in pointing between bands. I got the idea for the inline feed after analyzing the single band dual mode W2IMU feed, which has been used successfully on 1296, 2304 and 10,368 MHz, primarily for EME. The W2IMU feed has two different diameter circular waveguide sections which are designed to equalize the resultant E and H-plane beamwidths. The equal E and H-plane beamwidths with the appropriate taper contribute to a well illuminated high gain antenna. My thought was, what about feeding the larger outer section on the next lower amateur band? I decided to apply this concept to a dual band feed horn for 2304 and 3456 MHz. I used a standard 4 inch coffee can for 2304 MHz followed by a standard soup can for 3456 MHz. The results were very encouraging. This feed has been duplicated by several people over the years including K2DH, AA5C and W5ZN with good results. The construction of this feed and performance on a 32 inch dish is covered in detail in Joel Harrison's article.

Adding 5760 MHZ to Make a Three-Band Feed

I wanted to add 5760 to the original 2304/3456 MHz feed so I decided what would be easier than to just add a 1.5 inch diameter copper pipe to the end of the 3456 MHz can. The results were mixed. Yes, the horn worked but as I found out, the gain was considerably lower than theoretical. This was probably due to the fact that with the large aperture of the multiband feed at 5760 MHz, the feed was under-illuminating the dish.

Separate Dual Band Feed

I decided that the optimum combination would be to just duplicate the 2304/3456 feed for 5760 and 10,368 MHz. The result actually looks very similar to a W2IMU feed for 10,368 MHz. The resultant feed horn, shown in Figure 1, worked very well on 5760 MHz and was only slightly lower than expected on 10.368 MHz. The feed was tried on several dishes with varying F/d ratios and diameters. The resultant antennas were tested during a recent North Texas Microwave Society antenna workshop hosted by Kent Britain, WA5VJB. The results are documented in Table 1.

Test Results

Starting at 5760 MHz, the dual band feed worked very well, producing gains within a dB or two of theoretical 55% numbers when installed on 48 and 55 inch solid dishes and 55 and 72 inch perforated dishes. The new dual band 5760/10,368 MHz feed actually had 6 dB greater gain on 5760 MHz than did the original three band feed as measured on the same 55 inch dish.

On 10,368 MHz, the numbers were down a little but the 72 inch perforated dish, which was the only dish rated for 12 GHz, was still measuring 40.7 dBi. I did not optimize the actual position of the feed. The feeds were placed with the focal point slightly in the mouth of the feed.

The dual 2304/3456 MHz feeds were tested in the same dishes but were slightly offset as only the dual 5760/10,368 MHz feed was at the focal point. As the results show, the gain numbers were somewhat lower than expected but the antenna range was only about 125 ft long and it could be that the larger dishes were underilluminated for the tests.

Construction

The length of both circular waveguide sections was made variable in order to improve the tunability of the feed horn. The monopoles can be preset as shown in Figure 1 and final tuning if needed can be accomplished by tuning the length of the waveguides. The resultant isolation between bands is very good and allows each band to be individually tuned. See Figures 2 and 3. The very good isolation also

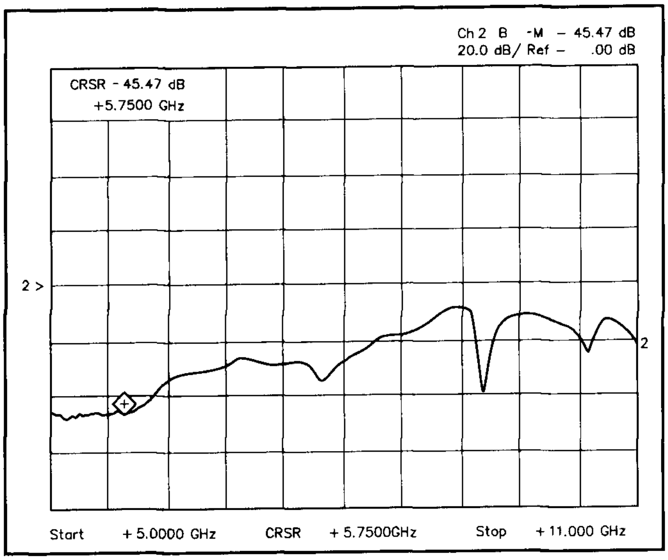


Fig 2—WB5LUA dual 5760 and 10,368 MHz feed horn —5760 MHz port to 10,368 MHz port isolation.

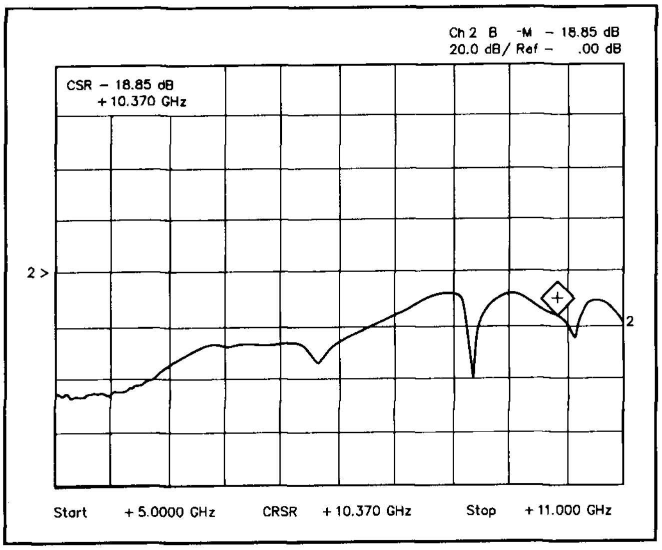


Fig 3—WB5LUA dual 5760 and 10,368 MHz feed horn—10,368 MHz port to 5760 MHz port isolation.

Table 1
1997 NTMS Antenna Gain Measuring Party

Conducted by WA5VJB on March 23, 1997

Compiled by WB5LUA

Antenna range may have been too short for larger dishes, as gain numbers appear compressed.

Band (MHz)	*Call*	*Design*	*Gain (dBi)*	*Theoretical 55% Gain (dBi)*
1296	KA5BOU	15 el Yagi	16	
2304	WB5LUA	72" perf dish with coffee can feed	27	30
	AA5C	6' 40 el Yagi	20.4	
	WB5LUA	55" solid dish with coffee can feed	24.4	27
	WA5VJB	Reference horn	13.5	
3456	WB5LUA	72" solid dish with dual 2304/3456 feed	27.9	34
	WB5LUA	48" solid dish with offset soup can feed	25.7	30
	WB5LUA	55" solid dish with dual 2304/3456 feed	23.9	31
	WB5LUA	DEM loop Yagi	19.5	
	WA5VJB	Reference horn	16.9	
5760	WB5LUA	72" perf dish with dual 5760/10,368 feed	37.0	38
	WB5LUA	48" solid dish with 1.5" diam copper feed	33.5	34
	WB5LUA	55" perf dish with dual 5760/10,368 feed	33.0	35
	WB5LUA	55" solid dish with dual 5760/10,368 feed	32.5	35
	W5ZN	39" solid dish with scalar feed	31.3	32
	WA5TKU	30" solid dish with 1.5" diam copper feed	27.5	30
	AA5C	24" solid dish with dual 5760/10,368 feed	27.5	28
	WB5LUA	55" solid dish with old WB5LUA 3-can feed	27.0	35
	WB5LUA	12"×18" horn	21.0	
	WA5VJB	Reference horn	15.5	
10,368	WB5LUA	72" perf dish with dual 5760/10,368 feed	40.7	43
	WB5LUA	55" solid dish with dual 5760/10,368 feed	38.7	41
	WB5LUA	55" perf dish with dual 5760/10,368 feed	37.7	41
	WA5TKU	30" solid dish with 1.5" diam feed	33.7	36
	AA5C	24" solid dish with dual 5760/10,368 feed	33.2	34
	W5ZN	24" solid dish with WR90 to scalar feed	32.5	34
	WB5LUA	18" fiberglass dish with WR90 feed	28.7	31
	WA5VJB	Reference horn	17.7	

minimizes the additional isolation required in order to keep from destroying the front-end of the receiver for the other band. I believe part of the increased success of the 5760/10,368 MHz feed horn in regards to low frequency to high frequency isolation may, in part, be due to the smoother transition from the small section to the large section. Secondly it could be due to the 5760 MHz port having a poorer return loss at 10,368 MHz. Be aware that there are several different types of 0.75" to 1.5" transitions available and all may tune slightly differently.

Conclusion

I am very encouraged by the initial results of the multiband feeds. I now have one dish for 2304, 3456, 5760 and 10,368 MHz. The 5760 and 10,368 MHz feed is at the focal point with the 2304/3456 MHz feed slightly offset. End result is that if 5760 MHz is peaked on a particular station then 10,368 MHz is also peaked. Same is true of 2304 and 3456 MHz. Good luck. Feedback is greatly appreciated.

Note

[1] "Horns for the Holidays", *1997 Proceedings of the Central States VHF Society Conference*, p 53-63.