A PLYWOOD Satellite-TV Dish

Can a satellite-TV dish be made out of plywood? Here's an experimental "dish" that supports the theory that says it can!

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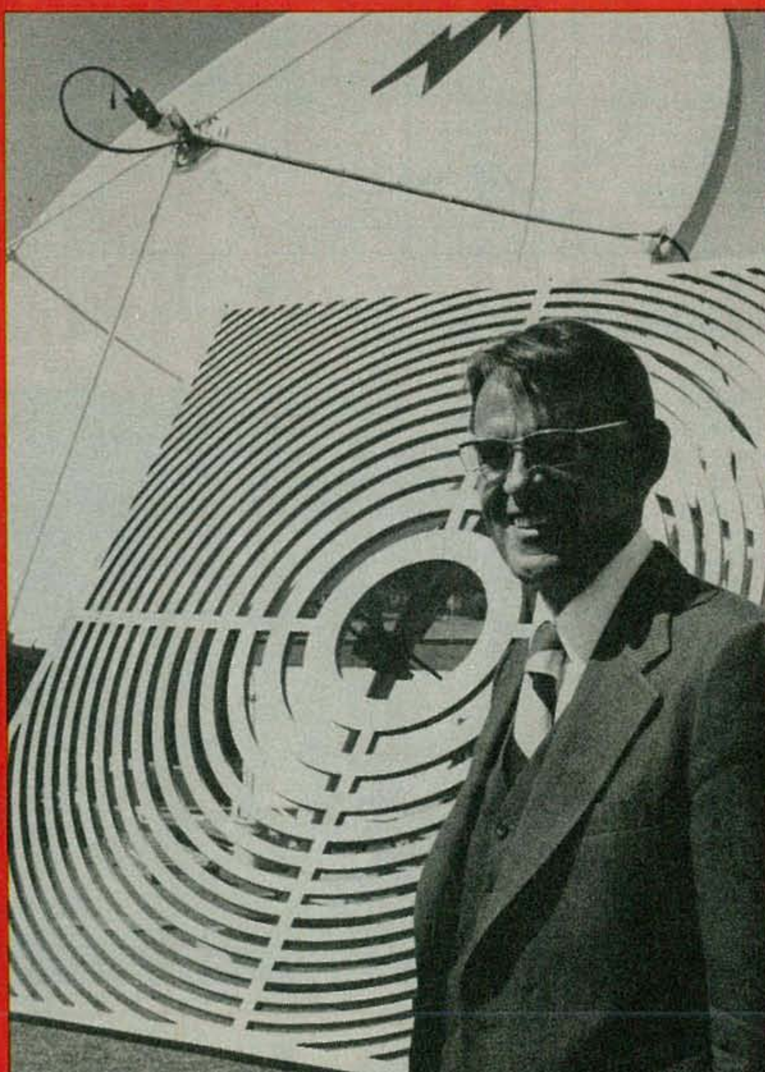
ALMOST ALL INNOVATIVE PRODUCTS come to market with a high price. But once that product develops a proven market, imitators and competitors soon appear with lower-priced products that accomplish the same task.

Consider satellite receivers, for instance. Some years back, Nieman-Marcus introduced the first such unit intended for the general public in a Christmas catalog; the cost was a "mere" $25,000. But someone quickly figured out a way to modify old radar units to do the same job for a fraction of that price. In the ensuing years, new designs and refinements have brought the cost of the satellite receiver down to under $500.

In the same vein, the traditional parabolic reflector, or "dish," used in satellite receiving setups has been challenged by other designs, such as spherical and hyperbolic dishes, and tuned Yagi arrays (which are antennas themselves, and use no dish), in an effort to reduce cost or improve performance. Rumors of yet other alternatives surface from time to time, including a persistent rumor about a "dish" built from plywood.

Well, that rumor does have a basis in fact. However, the "dish" is not a dish at all. The purpose of a dish is to concentrate the signal and focus it on the antenna, which is located inside the feedhorn. (If you are unfamiliar with satellite-TV reception systems, they were explained in a special section, "Receiving Satellite Television," that appeared in the June 1984 issue of **Radio-Electronics**.) But a dish is not the only type of device capable of concentrating and focusing a signal. Another is a lens, such as a Fresnel lens. In this article we will discuss the theory behind using a Fresnel lens as a signal concentrator, and present design criteria, as well as a short BASIC program, that will allow you to build an experimental unit using plywood.



An early TVRO lens built by Canadian scientist Dr. Bob Stewart is about the size of the dish shown in the background.

If you're wondering why such information is not usually presented in standard antenna texts, it is because the design comes from the study of optics, not communications. In fact, there has been so little published research concerning the use of Fresnel lenses for satellite reception that the field must definitely be considered experimental. Although there are a few isolated examples of the Fresnel lens in actual use for satellite reception in Canada (British Columbia), commercial production of such lenses appears to be nonexistent.

A plywood lens?

First invented by French physicist Augustin Fresnel in 1815, the lens bearing his name is commonly used in lighthouse lights, theater lights, and even flashlights. But, despite several advantages, including low cost, Fresnel lenses have found little use in microwave applications. Instead, other lenses of one sort or another have been used, including one commercial application, in the early 1960's, of a conventional lens made from styrene.

Only simple mathematics are required to understand the theory of the Fresnel lens. Central to that theory are the concepts of constructive and destructive interference. If two wavefronts of the same frequency and phase combine, then the amplitude of the resultant signal may be calculated by simply adding the amplitudes of the two waves. Here the waves are said to interfere *constructively*.

On the other hand, if two wavefronts of the same frequency, but *different* phase, combine, the amplitude of the resultant wave will be less than that of the original waves by an amount dictated by their instantaneous phases and amplitudes. In the simplest case, two waves of the same amplitude but 180 degrees out-of-phase would cancel each other out; that is, the resultant wave would have an amplitude of zero. Here the waves are said to interfere *destructively*.

Let's look at a real application. Microwave TV signals leave the satellite, and make up what can be considered to be a *uniform plane wave* at the feedhorn. If we draw a straight line at a distance F from the feedhorn (where F is the focal length of the feedhorn), we may assume that all the microwaves crossing that line will be in phase with each other. That line is labeled the EQUAL PHASE WAVEFRONT in Fig. 1.

If the wave entering the feedhorn along the horizontal axis is chosen as a reference, then waves entering the feedhorn

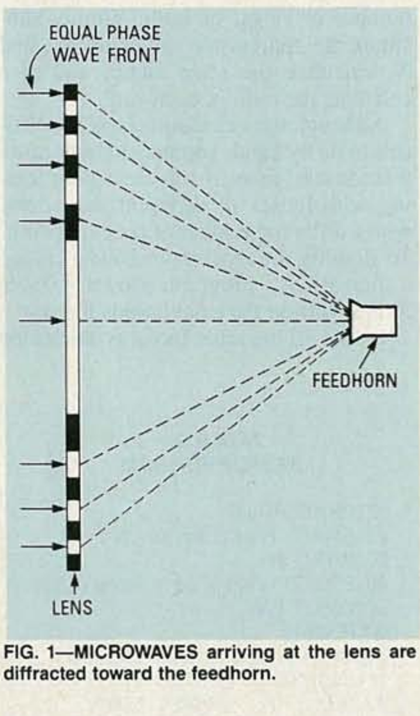


FIG. 1—MICROWAVES arriving at the lens are diffracted toward the feedhorn.

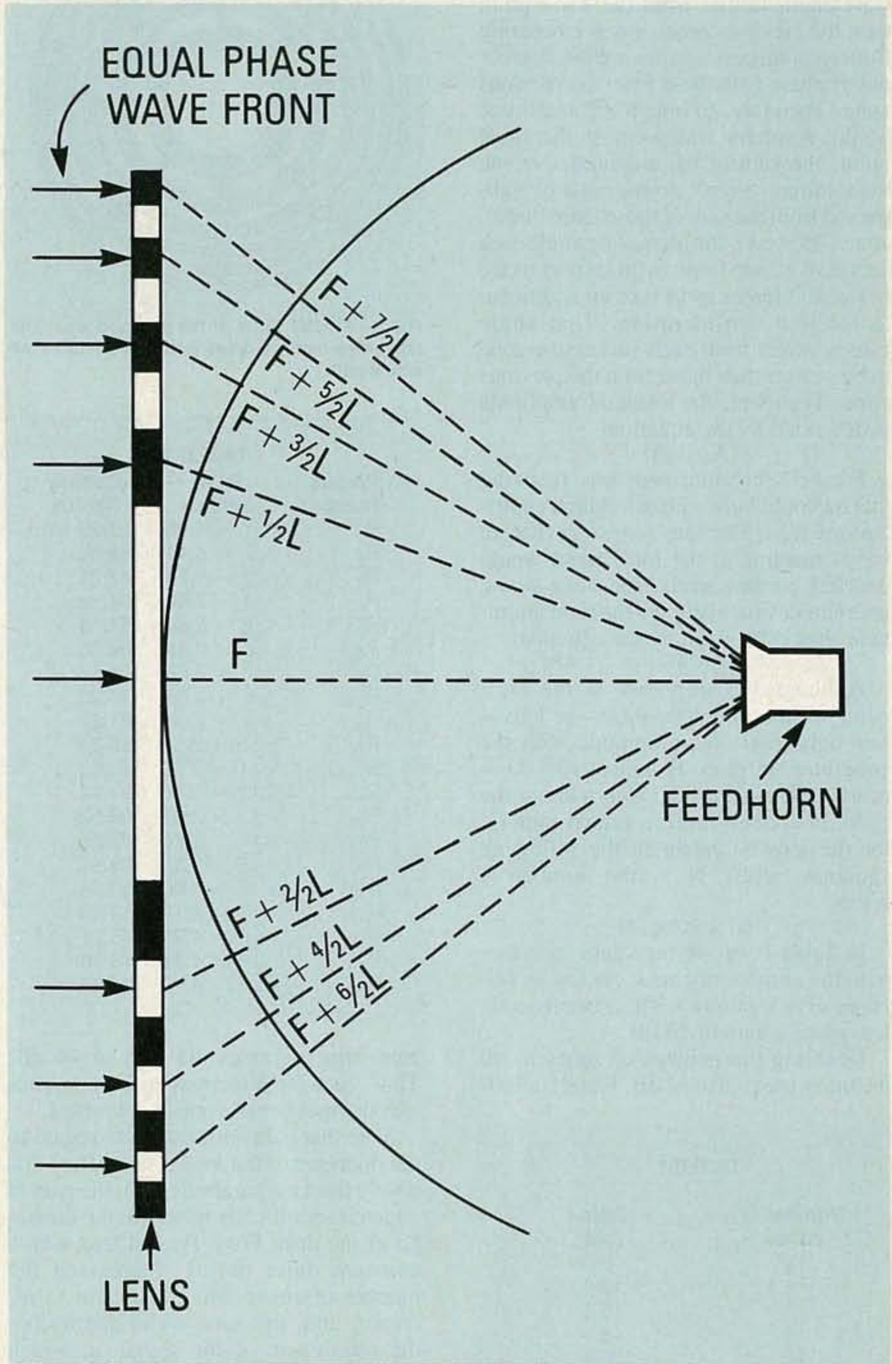


FIG. 2—DESTRUCTIVE INTERFERENCE. Waves arriving at the focal point inside the feedhorn from alternate ½-wavelength zones interfere destructively.

from above and below that line may cause destructive interference because of their phase difference. (Thanks to Huygen's principle, we can look at each point on the wavefront as a source of a secondary wave.) The phase difference is due to the increased distance the secondary waves must travel to reach the focal point. The net result is that the strength of the received signal is reduced.

Let's look at that a little closer. Divide the wavefront up into zones chosen so that, from one zone to the next, the distance from the center of each zone to the focal point increases by ½ wavelength. That means that waves arriving at the focal point from alternate zones will be 180 degrees out of phase with each other.

In Fig. 2 we have shown zones above the horizontal as being an odd multiple of ½-wavelength away from the focal point, and zones below as being an even multiple away. So the horizontal zone is at a distance of F; the first zone up is at a distance of $F + \frac{1}{2}\lambda$ (where λ is the wavelength); the first zone down is at a distance of $F + \frac{2}{2}\lambda$; and so on.

Examining the amplitude contributions from each zone at the focal point is very revealing. If the amplitude from zone 1 is A1 and the amplitude from zone 2 is A2, etc., then the sum of all contributions from the first twenty zones, A_T, is given by the equation:

$$A_T = A1 - A2 + A3 - A4 + A5 - \ldots + A19 - A20$$

Since we defined each zone to be ½-wavelength farther from the focal point than the previous zone, waves emanating from each successive zone are 180 degrees out of phase with those from the previous zone. Therefore, to obtain the amplitude of the resultant waveform at the focal point, the sum of the amplitudes of the waves from "even" zones must be subtracted from the sum of those from "odd" zones. However, the increasing angle each successive zone forms with respect to the horizontal forces us to take an additional factor into consideration. That angle causes waves from each successive zone to be weaker than those from the previous zone. Therefore, the resultant amplitude is described by the equation:

$$A_T = \tfrac{1}{2}A1$$

Fresnel's breakthrough was realizing that he could built a plate to block contributions from alternate zones, so that all waves meeting at the focal point would interfere constructively, and none would interfere destructively. So the total amplitude should be given by the equation:

$$A_T = A1 + A3 + A5 + \ldots + A19$$

Although the amplitude at the focal point without the zone plate—or lens—was only ½A1, the amplitude with the zone plate in place is almost 10×A1—nearly twenty times the gain without the plate. In decibels, the theoretical gain, G, for the lens is shown in the following equation, where N = the number of zones:

$$G = 20\log_{10}N$$

In Table 1 we see how gain increases with the number of zones. As few as two zones give a gain of 6 dB; a twenty-zone lens gives a gain of 26 dB.

Doubling the number of zones to 40 increases the gain to 32 dB. Finally, a 160-zone lens increases the gain to 44 dB. Thus, each 6-dB increase in gain requires that the number of zones be doubled.

Note that gain varies without regard to the diameter of the lens. That differs distinctly from the parabolic dish, the gain of which is specifically related to the diameter of the dish. For a Fresnel lens with a constant outer radius, increasing the number of zones will cause gain to increase, until the zone width approaches the wavelength of the signal, at which point the lens will be essentially transparent to the signal.

However, as with a parabolic dish, lens diameter does affect *resolution*, which, in this context, is the ability to distinguish signals from one of several closely spaced satellites.

Thus far we have examined our lens only from the side. Seen from the front, the zones become a series of concentric circles, as shown in Fig. 3. That lens has 12 zones, 8 radial supports, and a gain of 21 dB. The even-numbered zones are shaded, which indicates that they are transparent to the frequencies of interest.

TABLE 1

Number of zones	Gain (db)
2	6.0
4	12.0
6	15.6
8	18.1
10	20.0
12	21.6
14	22.9
16	24.1
18	25.1
20	26.0
22	26.9
24	27.6
26	28.3
28	28.9
30	29.5
32	30.1
34	30.6
36	31.1
38	31.6
40	32.0

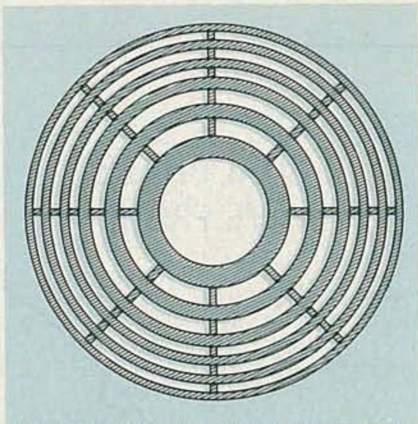


FIG. 3—FRONT VIEW of the plywood lens. The non-cross-hatched areas would be cut out of an actual lens.

TABLE 2

Radius Number	Raw Radius	Cutting Radius
R_1	$\sqrt{1}$ = 1.00	27.29 (cm)
R_2	$\sqrt{2}$ = 1.41	38.48
R_3	$\sqrt{3}$ = 1.73	47.21
R_4	$\sqrt{4}$ = 2.00	54.58
R_5	$\sqrt{5}$ = 2.24	61.13
R_6	$\sqrt{6}$ = 2.45	66.86
R_7	$\sqrt{7}$ = 2.65	72.32
R_8	$\sqrt{8}$ = 2.83	77.23
R_9	$\sqrt{9}$ = 3.00	81.87
R_{10}	$\sqrt{10}$ = 3.16	86.24
R_{11}	$\sqrt{11}$ = 3.32	90.60
R_{12}	$\sqrt{12}$ = 3.46	94.42
R_{13}	$\sqrt{13}$ = 3.61	98.52
R_{14}	$\sqrt{14}$ = 3.74	102.06
R_{15}	$\sqrt{15}$ = 3.87	105.61
R_{16}	$\sqrt{16}$ = 4.00	109.16
R_{17}	$\sqrt{17}$ = 4.12	112.43
R_{18}	$\sqrt{18}$ = 4.24	115.71
R_{19}	$\sqrt{19}$ = 4.36	118.98
R_{20}	$\sqrt{20}$ = 4.47	121.99

Designing a Fresnel lens

Table 2 shows the radii of the concentric circles used in a lens with 20 zones and an outside diameter of 244 cm, or about 8 feet. The column labeled CUTTING RADIUS shows the increasing radii of the concentric circles measured in centimeters. (We used centimeters because metric units are easier to work with than feet and inches.)

The figures shown were derived by dividing the maximum radius of the lens (in this case 244/2, or 122 cm) by the square root of the number of zones in our lens (in this case 20) to obtain a scale factor.

So if R_M is the maximum radius and N is the number of zones, the scale factor may be calculated as follows:

$$F = R_M \div \sqrt{N}$$

The scale factor for our example, then, is equal to 122/4.47 = 27.29 (the square root of 20 = 4.47). That scale factor is the radius of zone 1. To get the radius of the successive zones, multiply the square root of the zone number by the scale factor. Thus the radius of the second zone is equal to 1.41 × 27.29 = 38.48; the radius of the third zone is equal to 1.73 × 27.29 = 47.21, and so on. Note that the roots and radii are rounded off to the nearest hundredth as cutting can be no more accurate than that.

It is easy to calculate the radii of a lens with a different diameter or different number of rings, or both. Simply substitute the appropriate values for R_M and N, calculate the scale factor, and then calculate the radii of each ring.

Although the calculations are not difficult to do by hand, you may have to re-do them several times if you are experimenting with lenses of different diameters, with a different number of zones, or both. To simplify the process we have included a short BASIC program, shown in Table 3, that will do the calculations for you.

In line 70 the scale factor is calculated

TABLE 3—BASIC PROGRAM

```
10 PRINT:PRINT
20 PRINT "How many zones";
30 INPUT N
40 PRINT "What is the outside radius";
50 INPUT RM
60 PRINT
70 R1 = INT (.5 + 100 * (RM/SQR
   (N)))/100
80 PRINT "R 1";TAB(5);" 1.00";
   TAB(12);R1
90 FOR X=2 TO N
100 SX = INT(.5 + 100 * SQR(X))/100
110 RS = INT(.5 + 100 * (R1*SX))/100
120 PRINT "R";X;TAB(6);SX;TAB(12);
   RS
130 NEXT X
140 PRINT:PRINT
150 END
```

and stored in variable R1. Adding 0.5, multiplying by 100 and then dividing by 100 ensures that R1's value is rounded off correctly. The same "trick" is used in line 100, which calculates the square root of the current radius, and in line 110, which calculates its cutting radius.

After checking your calculations, mark the circumference of each circle on your working material. In order to ensure that the circles are drawn accurately, first mark off the radii of the zones; do that in several places. Then, drive a nail into the center of the lens and tie a pencil to that nail using a piece of non-stretch twine (or fishing line) so that the length of twine between the two is equal to the radius of the first zone.

Finally, inscribe the circle using the pencil. The purpose of marking the radius in several places is to ensure that the twine does not slip or stretch. If the pencil does not pass through each place where the radius has been marked, the circle is not "true" and must be redrawn. Once you are satisfied that the circle is accurate, repeat, with the length of the twine equal to the radius of the second zone. Continue in that manner until all of the needed circles are drawn.

Now you should paint the even-numbered zones and verify that your lens corresponds to the pattern shown in Fig. 3. If you are satisfied, draw in radial supports, used to hold the concentric circles of the lens together once the intervening plywood has been removed, making sure that the supports match up with any bracing on the back of the lens. (If the lens is large enough that it must be built using two sheets of material laid side-by-side, the two sheets must be tied together using radial braces.) Paint those radial supports as well, and before cutting, again verify that your lens corresponds to that shown in Fig. 3.

Finally, carefully cut out and remove the odd-numbered zones; Be sure that you don't also cut out the radial supports! If you have followed the directions above, then only the *unpainted* areas should be removed. To complete the lens, it will be necessary to cover it with metallic paint to keep the satellite signal from passing through the even-numbered zones, defeating its purpose. Several coats of a good quality aluminum paint should provide adequate shielding, as well as some weather-protection.

Calculating focal length

While the paint is drying, you can begin figuring out where the lens' focal points lie. In order to do that, you will have to calculate the focal point of the lens.

Assuming that you are interested in receiving C-band signals, the downlink frequencies vary between 3.700 GHz and 4.180 GHz, depending on the transponder. In order to calculate the required focal length, we need to know the wavelength of the downlinked signals. That is found by dividing 30 by the frequency, f, where f is measured in GHz:

$$\lambda \text{ (cm)} = 30/f$$

Wavelength varies from about 7.18 to 8.11 cm for those frequencies. The focal length, or distance from the lens to the feed point, for a Fresnel lens is given by the formula:

$$F = (R1)^2/\lambda$$

where R1 is the radius of the inner-most circle in the lens, and F is the focal length. You may calculate focal length in any desired units (feet, inches, centimeters); just be consistent. If you specify wavelength in centimeters, then R1 must also be in centimeters; of course, the final result will also be in centimeters.

The focal length of the lens described in Table 1 will range from 91.83 cm for transponder 1 to 103.72 cm for transponder 24. The center of that band falls at 97.28 cm. That is the focal length that is used for our set up. Note that the variation on either side of that center frequency to the band edges is 5.95 cm; the total variation is 11.9 cm. Most commercial waveguides have that much depth. Thus, to ensure that all of the focal lengths fall within the area of the waveguide, all that needs to be done is to measure back 5.95 cm from the waveguide opening, mark that point on the case, and mount the feedhorn so that that point is 97.28 cm from the lens.

TV satellites are all located in a geostationary orbit some 22,279 miles above the equator; that orbit is known as the Clarke belt. To aim the lens, you have to find where in the sky the Clarke belt lies relative to your location. That is done in the same manner as with a parabolic reflector. If you are not familiar with the procedure, see "Installing your own TVRO" in the June and July 1985 issues of **Radio-Electronics**.

In tracking between satellites in the Clarke belt, The Fresnel lens offers one major advantage over parabolic dishes. With dishes, the entire dish and feed assembly must be moved when you wish to focus on a different satellite. That's because such a parabolic dish can only focus on one object at a time. But a Fresnel lens can focus on several objects at a time, each with its own focal point. Thus to receive a different satellite, all that needs to be done is to move the feed to the appropriate focal point. Once you have your lens aimed at the right region of the sky, you'll have to experiment to see how many satellites you can focus on, and where their focal points fall. (When doing so remember that each focal point will be at the focal length of your lens.) If you wish to receive satellites located at the extreme ends of the belt, you can re-aim the entire lens-and-feed assembly, much as you would a standard parabolic reflector.

Other considerations

The lens requires the same sort of strong, vibration-free mount used for quality parabolic dishes. Also, care should be taken to ensure that the focal point is not obstructed by any mounting apparatus, or the edge of the feedhorn.

To decide if a Fresnel lens is suitable for your application, you should consider two things. First, as we saw above, the gain of the lens is a function of the number of zones. Material limitations will probably restrict the number of zones to less than 80, and that limits your gain to something under 38 dB; as a comparison, that's roughly the gain of a 6–8-foot dish. Of course, the fewer the zones, the lower the gain.

What that means, of course, is that a top-quality LNA, one with an exceptionally low noise-temperature rating, will be required for best results at any location. In addition, if you happen to be located in one of the "fringe" reception areas (such as New England or Florida), it is likely that you will only be able to receive the strongest transponders.

Second, as we mentioned earlier, lens resolution depends strongly on lens diameter. As a rough rule-of-thumb, figure that the lens will have to be as large as the parabolic reflectors that work well in your area. You may want to experiment a bit to find an appropriate diameter for your lens. Fortunately, working with plywood makes such experimentation relatively cheap.

As you may have guessed from the theory section presented earlier, blocking out either the even or the odd numbered zones will produce the same gain. In areas of bright sunlight, you might want to cut out the even zones and leave the odd zones, including the center zone, in place. That will prevent radiation from the sun from entering the feedhorn directly. If you do build your lens in that manner, remember that you must design it so that it has an odd number of zones (i.e. 21 instead of 20).

The lens has more than one focal length. There are increasingly fainter images at F/3, F/5, and F/7, but they are of quickly diminishing intensity due to an increasing amount of destructive interference.

The lens may be built from materials other than plywood. The thinner the material the lens is made of, the closer its gain will be to the theoretical. The only restriction is that the material must be able to withstand local weather conditions, as well as be opaque to microwave frequencies. We have specified plywood (covered with aluminum paint), but screen mesh with ⅜-inch or smaller holes could be used. In addition, sheet metal or aluminum-covered fiberglass or plexiglass could be used. **R-E**