Chapter 6
Feeds for Parabolic Dish Antennas
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Section 6.5 Dual-Mode Feedhorns

As we saw in the preceding sections, simple cylindrical feedhorns for dishes, like the “coffee-can” type, usually have radiation patterns with poor front-to-back ratio. The backward radiation misses the reflector, resulting in a decrease in efficiency and thus gain. The unwanted backward radiation is a result of edge currents in the rim of the horn. Plain rectangular and conical horns also have undesired lobes due to edge currents.

In previous sections, we also saw choke rings employed to reduce the magnitude of the undesired lobes, and corrugated horn walls to reduce the magnitude of the edge currents and thus the undesired lobes caused by the currents. Another technique for edge current reduction is to propagate and radiate additional waveguide modes in a horn. With the proper magnitude and phase, these modes may be used to shape the radiation pattern for better illumination of the dish.

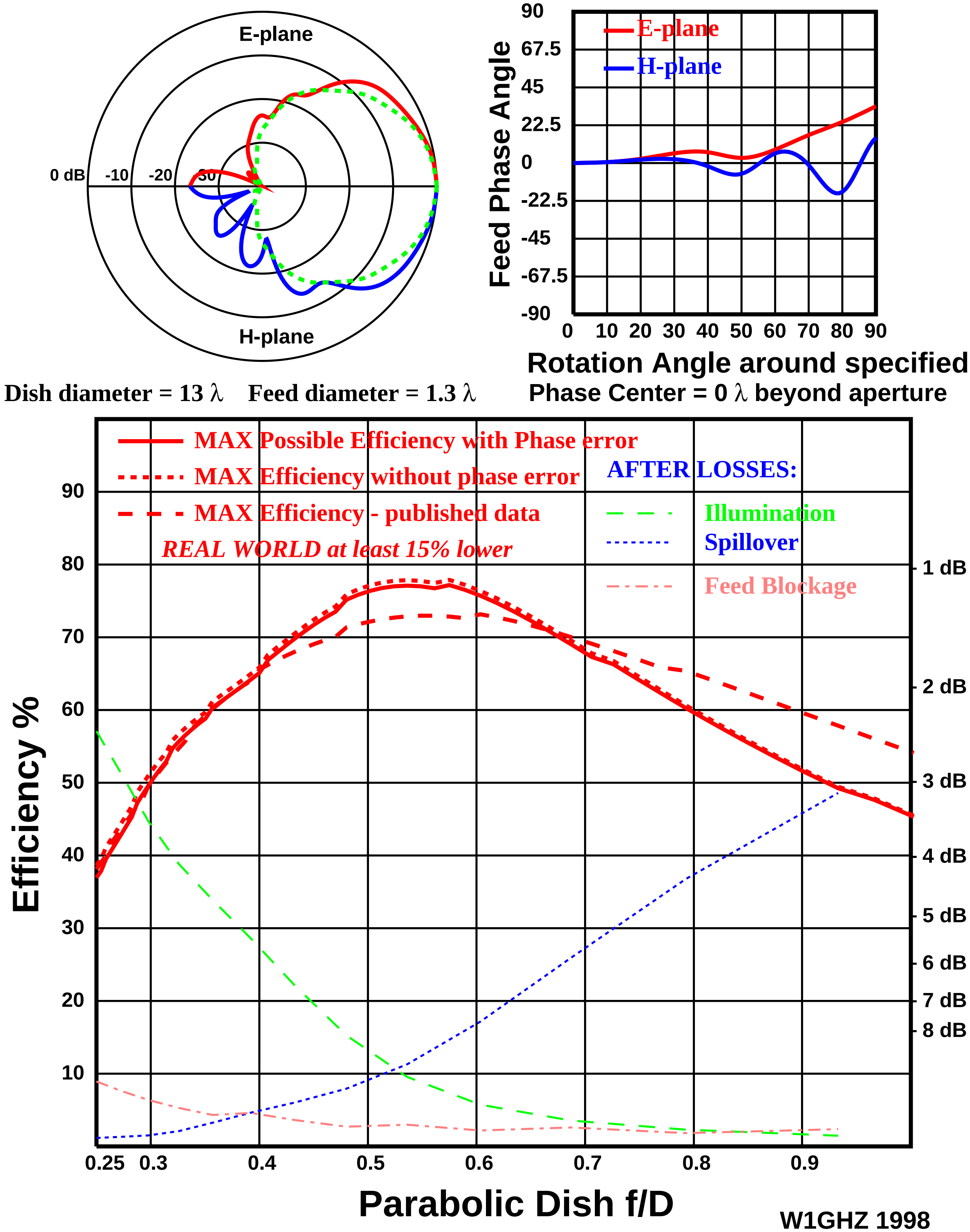
6.5.1 W2IMU dual-mode feedhorn

The W2IMU dual-mode horn eliminates undesired currents in the rim of the horn which produce sidelobes and backlobes. In the words of Dick Turrin, W2IMU[1], “The basic notion involved is to excite a circular aperture with both the $\mathbf{TE_{11}}$ and $\mathbf{TM_{11}}$ modes with their relative phases and amplitudes adjusted to cancel the electric field at the aperture boundary.” This dual-mode feed was Dick’s patented[2] invention.

I used the **NEC2** computer program to calculate the radiation pattern for several versions of the dual-mode feedhorn, as described in Chapter 12. My starting point was an input file model of the antenna originally developed by PA3AEF. Then I calculated the potential dish performance provided by the calculated feed patterns using the **PHASEPAT** program. The pattern shown in Figure 6.5-1 is very clean, with low side and back lobe levels, and compares well with the published amplitude pattern, shown as a dashed green line. The calculated efficiency is very high, with best results for a reflector ***f*/D** around 0.5 to 0.6. The phase center is at the center of the aperture, the mouth of the horn. This 1296 MHz version[3], with an output diameter of 1.31λ, is popularly known as the W2IMU feed. Dimensions for ham bands from 432 MHz to 24 GHz have been published, but they are all scaled from the 1296 MHz version. Most excite the feed with a coaxial probe in the circular waveguide, but

W2IMU dual-mode feedhorn, 1.31λ diameter, by NEC2

Figure 6.5-1



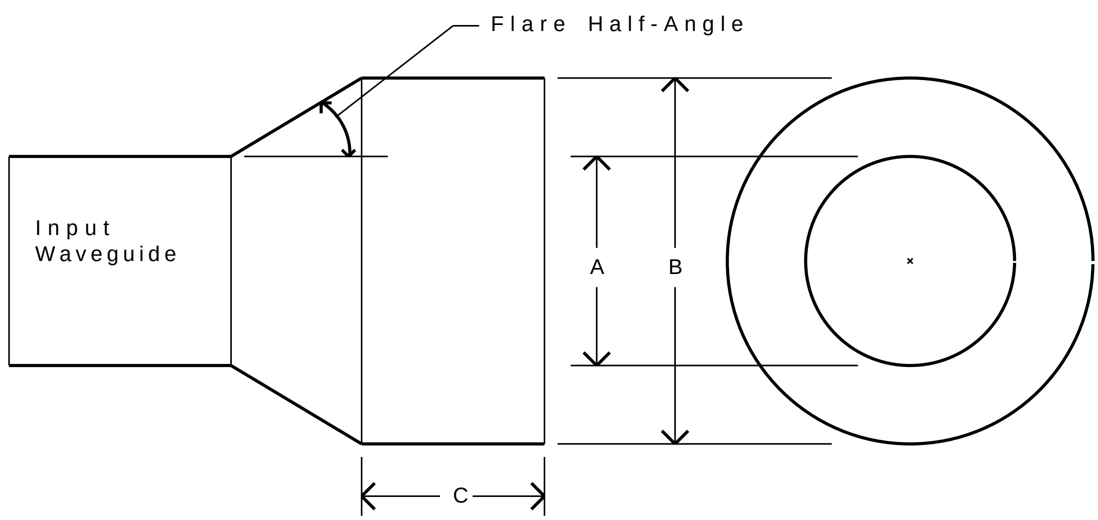
K2RIW[4] used a dipole inside the waveguide at 1296 MHz configured as a reverse feed. Of, course, the feed may be directly connected to a waveguide transmission line. W2IMU feeds have been used with good results on both conventional and offset dishes.

The original Turrin article[1] also described a larger version with an output diameter of 1.86**λ**. The graph for this larger version in Figure 6.5-2 shows that the ***f*/D** for best efficiency is about 0.8, a better match for some offset dishes. The published amplitude pattern, shown as a dashed green line, is very close to the calculated pattern. Efficiency is extremely high, and the phase center is at the center of the aperture. The calculated pattern has number of small sidelobes with nulls between them. Rapid changes in amplitude like this are usually accompanied by phase fluctuations like those in the phase plot. Fortunately, these sidelobes are more than 20 dB down, so the total power in them is small, and the resulting phase errors miss the reflector, so the net effect on efficiency is negligible.

For other ***f*/D** reflectors, we could optimize a dual-mode feed by choosing the appropriate output diameter for the ***f*/D**, then calculating the other dimensions for a dual-mode feed. But how close must the dimensions be?

In Chapter 5, we saw that the DSS offset-fed dishes work well at 10 GHz. These dishes require a feed pattern equivalent to the feed for a conventional dish with an ***f*/D** of about 0.7. The appropriate aperture for this ***f*/D** is close to 1.5 inches, so I picked up a copper plumbing adapter which flares out from ¾ inch pipe, the input waveguide, to 1½ inch pipe – it looks like a dual-mode feed. To see how well it would work as a dual-mode feed, I measured the dimensions and used **NEC2** to calculate the radiation pattern. The result, shown in Figure 6.5-3, is terrible; large sidelobes result in poor spillover efficiency, and phase errors make the total efficiency low.

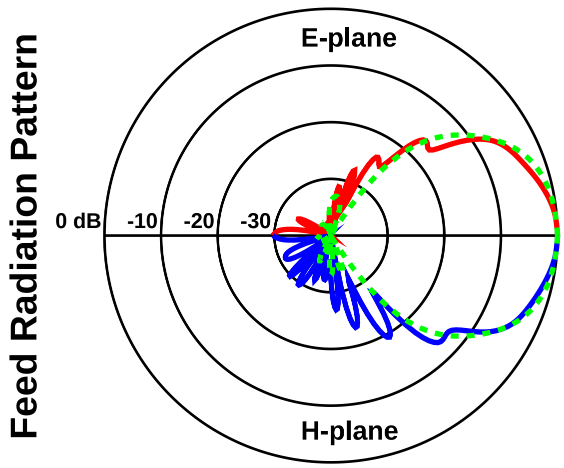
From the example in Figure 6.5-3, we can infer that the dual-mode feed must be dimensioned properly to work well.

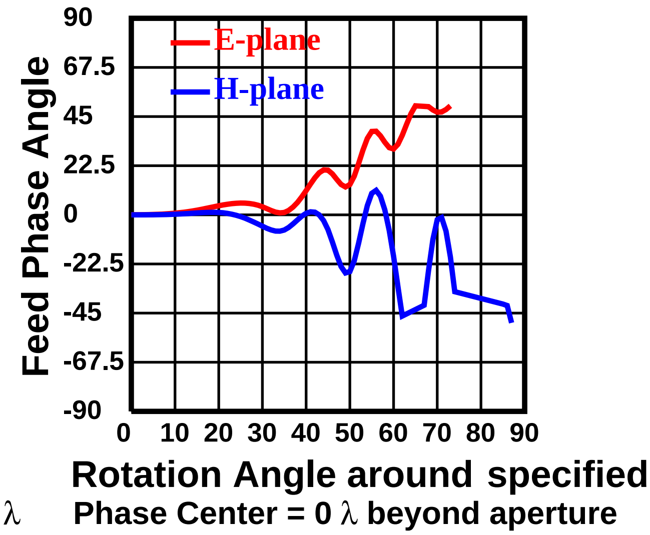


W2IMU Dual-Mode Feed
Figure 6.5-4

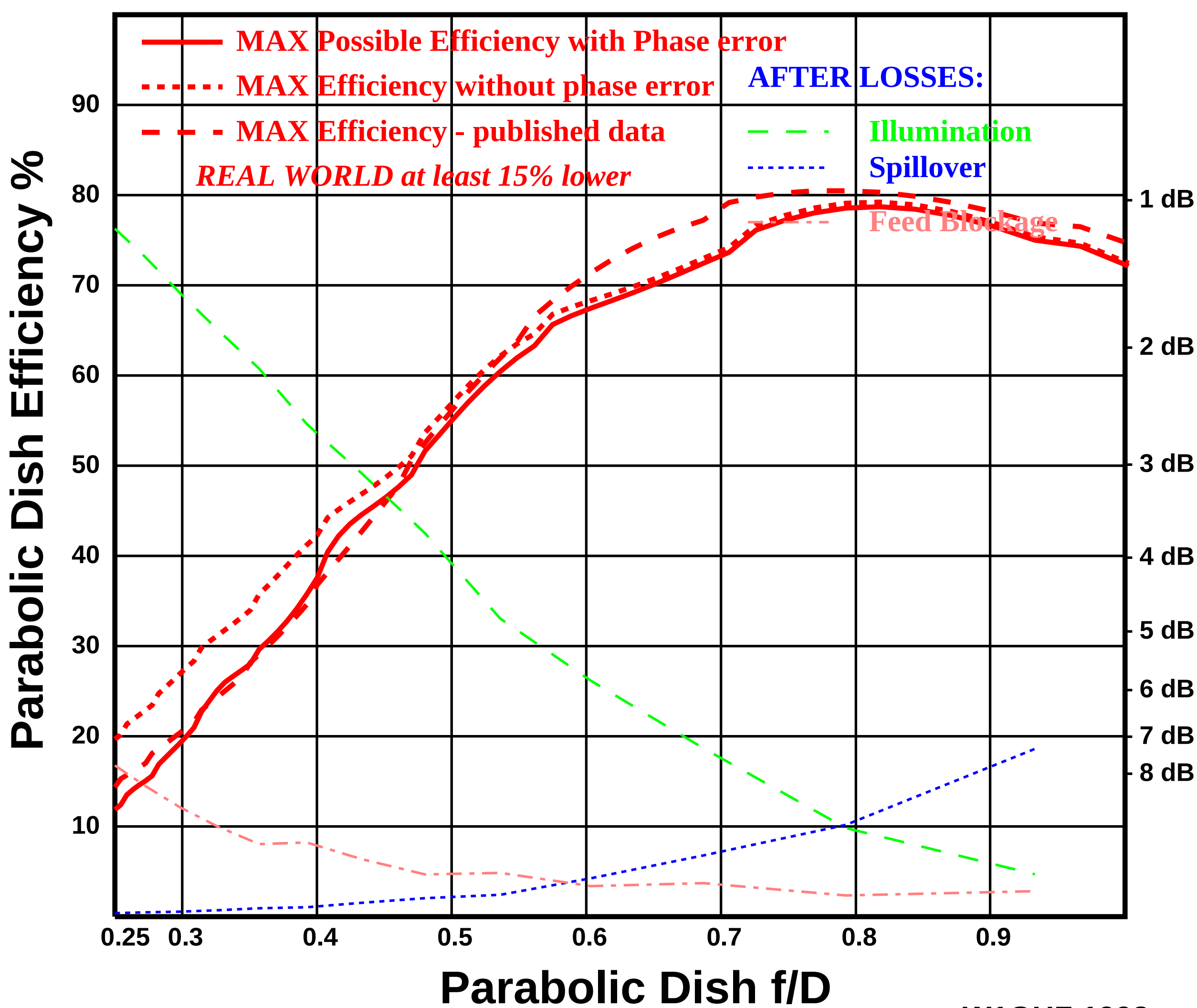
Large W2IMU dual-mode feed, 1.88λ diameter, by NEC2

Figure 6.5-2





Dish diameter = 19 λ   Feed diameter = 1.88 λ



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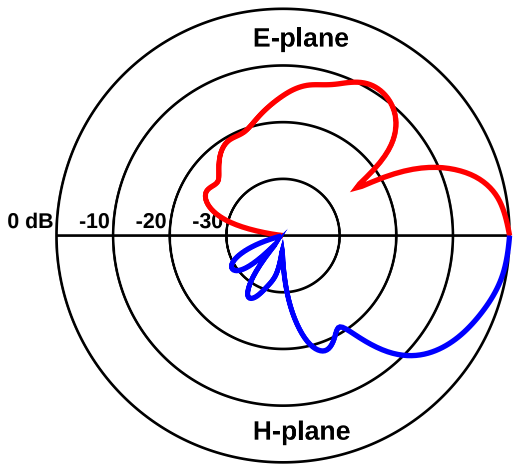
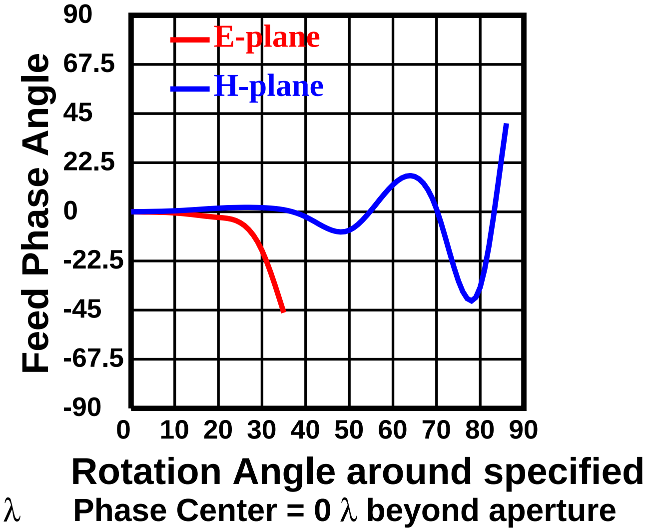
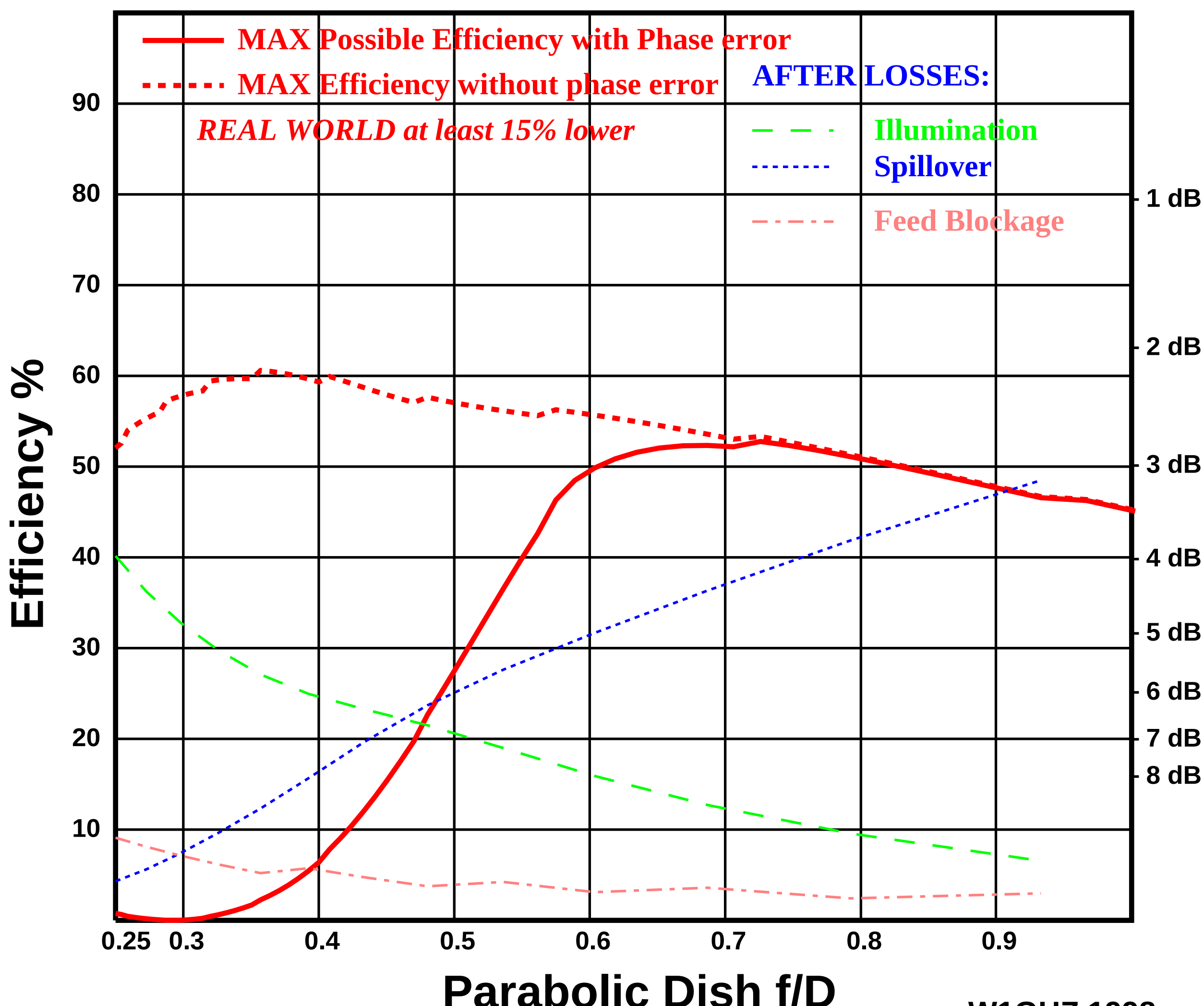
W2IMU feed - bad imitation, by NEC2

Figure 6.5-3





Dish diameter = 14.3 λ Feed diameter = 1.43 λ



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W2IMU dual-mode horn calculations

A sketch of the W2IMU dual-mode feed is shown in Figure 6.5-4. The input circular waveguide flares out to a larger output section. Only the $\mathbf{TE}_{11}$ mode will propagate in the smaller input waveguide, but both the $\mathbf{TE}_{11}$ and $\mathbf{TM}_{11}$ modes can propagate in larger output waveguide. Our goal is for the relative phases and amplitudes of the $\mathbf{TE}_{11}$ and $\mathbf{TM}_{11}$ modes to cancel the electric field at the aperture boundary.

The electric field for the $\mathbf{TE}_{11}$ mode in a circular waveguide[5] is shown in Figure 6.5-5a at an instant of peak voltage. The desired $\mathbf{TM}_{11}$ mode that will result in field cancellation at the aperture is shown in Figure 6.5-5b; note how the field arrows for the two modes are in opposite directions at the top and bottom of the waveguide, so that they cancel. In the center of the guide, the field arrows for the two modes point in the same direction, so that the fields will add together. The result is a stronger electric field in the center of the aperture and no field at the edges; this is analogous to a smaller aperture, so that the resulting radiation pattern in the E-plane will be broader and match the H-plane pattern.

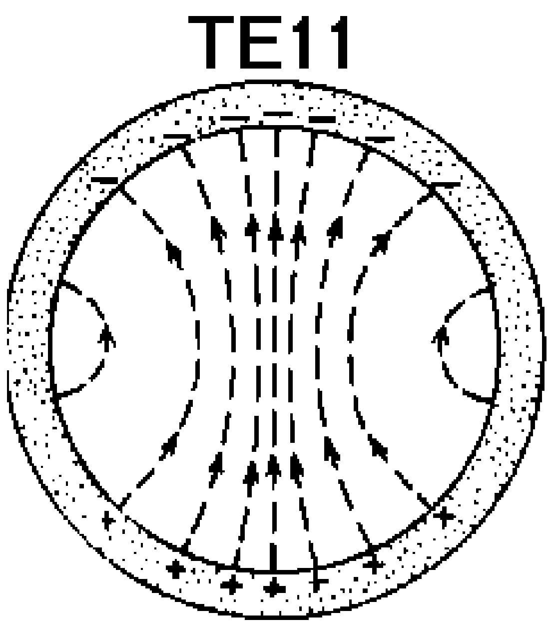


Figure 6.5-5a

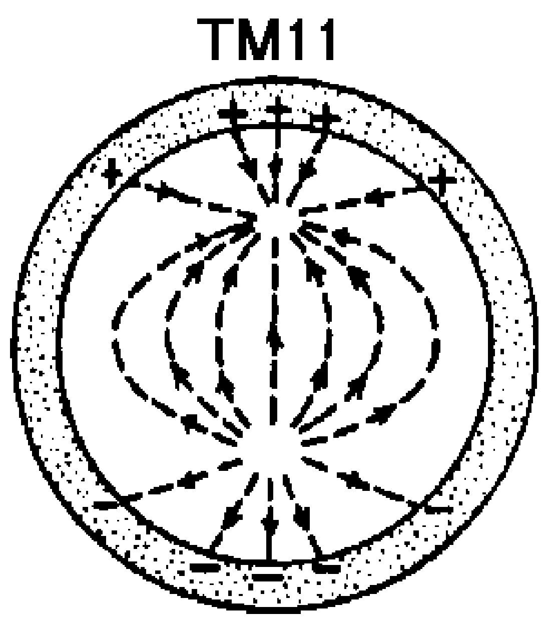


Figure 6.5-5b

The length of the output section controls the relative phase of the two modes, while the flare angle controls the relative amplitude of the two modes. To achieve cancellation of current in the rim of the horn and thus minimize lobes, we must find the right combination of flare angle and output phasing section length.

The transition between the input waveguide diameter, **A** in Figure 6.5-4, and the output section diameter, **B**, generates the **TM$_{11}$** mode; the flare angle adjusts the amplitude of the two modes. We can easily calculate[6] the desired flare angle:

$$Flare\_halfangle = \frac{44.6\,\lambda}{\mathrm{B}}$$

The phase of the electric field varies sinusoidally along the length of the waveguide, as the wave propagates through the guide. In Figure 6.5-6 we can see the phase variation over a half-wavelength of waveguide, going from a voltage maximum at the left, through a voltage minimum at the center with maximum current in the guide walls, to a voltage maximum of opposite polarity at the right. The next half wavelength would continue through another minimum to a maximum of the original (left) polarity. This pattern repeats over the length of the waveguide.

Different waveguide modes have different wavelengths in the guide — often described as travelling at different phase velocities. The distance between maxima in Figure 6.5-6 is a function of the waveguide diameter and is different for each mode. Thus, we can calculate a length, **C**, for the output phasing section that will result in the two modes arriving at the aperture with the desired phase relationship, like Figure 6.5-5 that results in cancellation. At the flare end of the phasing section, the **TM$_{11}$** mode is 90° out of phase with the **TE$_{11}$** mode. Then the phasing section should have a length **C** which results in the two modes being shifted by an additional 270°, or ¾λ. We can calculate the desired length **C** as:

$$\mathrm{C} = \frac{0.75}{\frac{1}{\lambda_g} - \frac{1}{\lambda_g^{'}}} \qquad \text{where} \qquad \lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\lambda_C}\right)^2}}$$

(λ_g is the guide wavelength for the TE$_{11}$ mode and $\lambda_g^{'}$ is the guide wavelength for the **TM$_{11}$** mode, where λ_C is the cutoff wavelength for the mode for which we are calculating λ_g.) In the output phasing section with diameter **B**, the cutoff wavelength for the **TE$_{11}$** mode λ_C = 1.706**B,** while the cutoff wavelength for the **TM$_{11}$** mode λ_C = 0.82**B**.

Thus, with a bit of arithmetic we can calculate the optimum dimensions for any desired aperture diameter. For a quick estimate of the optimum aperture diameter **B** for any ***f*/D,** try this empirical approximation: **B**$_\lambda$ = 2.35(***f*/D**). As the diameter gets larger, the length of the larger output phasing section must also increase to maintain the phasing relationship between the two modes.

The consequences of not achieving the proper phasing are clearly illustrated in Figure 6.5-3. Using the above equations, we find that the length of the larger pipe should be 2.72 inches rather than the 1.24 inch length of the fitting alone. Also, the flare half-angle should be 29.1°, while the angle in the plumbing fitting is 39°, so the fitting needs serious modification to become a dual-mode feed.

From the cutoff wavelength equation above for λ_C, the minimum aperture diameter which will propagate the $\mathbf{TM_{11}}$ mode is 1.22λ; if the diameter is any smaller, it can only be a single-mode feed. On the other hand, if the aperture diameter is too large, then additional modes may be generated. The cutoff wavelength for the next higher mode, the TE_{12} mode, is λ_C = 0.589**B**. Thus the maximum aperture diameter without additional modes is 1.7λ. Since one of Dick's original examples had an aperture diameter of 1.86λ, this limit may apparently be stretched a bit without performance degradation. From this range of aperture diameters, we can deduce that a W2IMU feedhorn may be designed for any ***f*/D** between 0.5 and 0.8. The examples in the next section include two dual-mode feedhorns for offset dishes with ***f*/D** of 0.7 and 0.8 that I successfully designed using the equations above. For larger ***f*/D**, it is possible to add another conical flare section to increase the aperture; the VK2ALU dual-mode feedhorn in section 6.5.4 is a good example.

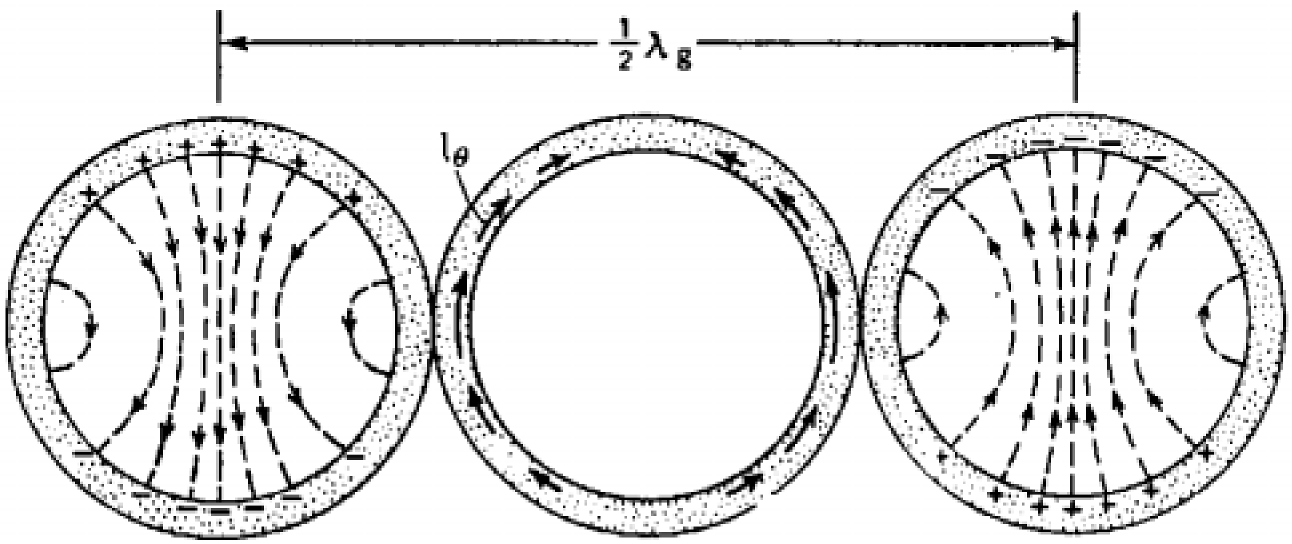


Figure 6.5-6

These calculations might seem daunting at first glance, but only require a couple of minutes on a hand calculator. As an alternative, I have included the calculations in version 3 of my **HDL_ANT** computer program – download it from www.qsl.net/n1bwt .

6.5.2 W2IMU dual-mode feed examples

As examples of actual dual-mode feeds, we will start with three versions of the W2IMU feed which have been published in Britain, then examine a dual-mode feed for 47 GHz by G0IVA, and finally look at larger dual-mode feedhorns for offset dishes. The British versions attempt to achieve proper dimensions using available materials; making some compromises in the dimensions. I modeled them using **NEC2** in order to evaluate performance — we will see if the compromise dimensions are successful.

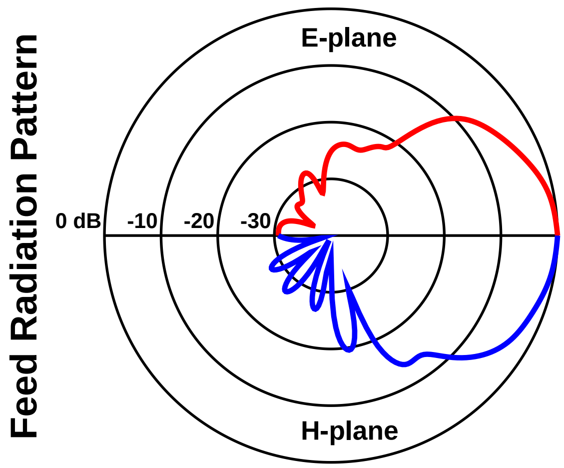
Figure 6.5-7

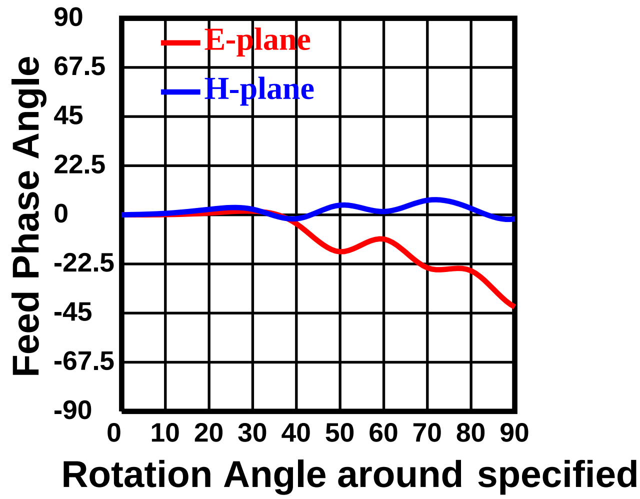
The first example is a 10 GHz version described by G3PHO[7] using British plumbing fittings, shown in the photo in Figure 6.5-7. The performance plot in Figure 6.5-8 shows a clean pattern and excellent dish efficiency for an ***f*/D** around 0.6, a bit smaller than the DSS dishes require, but very usable. The equivalent ***f*/D** for the DSS dishes, and many other offset dishes, is around 0.68; this feed would provide very slight under-illumination, but the efficiency would still be excellent. Perhaps we can find a way to import some of these plumbing fittings into the USA. The phase center of the feed is at the center of the aperture. Peter has done a good job with this version.

The second example is the 5.7 GHz “plumbers delight” by G0HNW[8]. Paul states that the aperture with the available plumbing is a bit small for an offset dish. The plot in Figure 6.5-9 bears this out, showing best efficiency for an ***f*/D** of about 0.4. In fact, the aperture diameter is 1.21λ, which is smaller than the cutoff wavelength for the **TM**$_{11}$ mode, so it is unlikely that this feed supports dual-mode operation. Further evidence is the radiation pattern with several significant sidelobes, including one rather large one. I suspect that it is behaving more like a simple coffee-can feed. Despite the sidelobes and lack of dual-mode operation, calculated efficiency is very high, so it would be quite a good feed for ***f*/D** in the 0.45 to 0.5 range. The phase center is very close to the center of the aperture. However, for a dual-mode feed to provide good illumination of an offset reflector, a larger aperture diameter around 1.5λ, or about 3 inches at 5760 MHz, would be required.

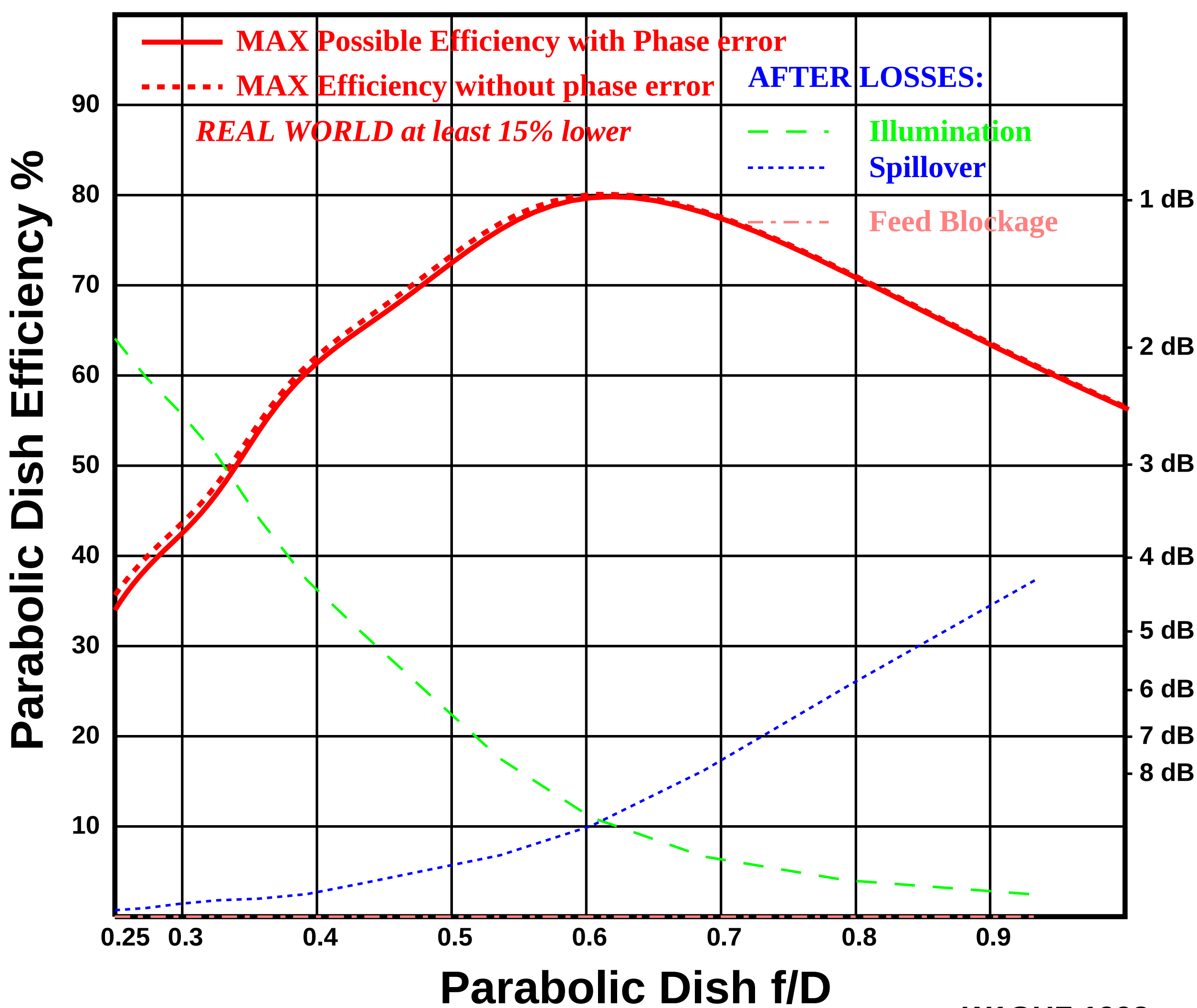
G3PHO 10 GHz dual-mode feedhorn, by NEC2

Figure 6.5-8





Dish diameter = 16 λ   Feed diameter = 0.1 λ   Phase Center = 0.06 λ inside aperture



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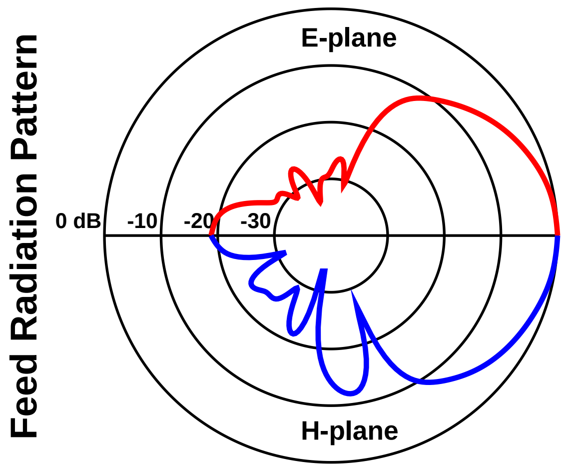
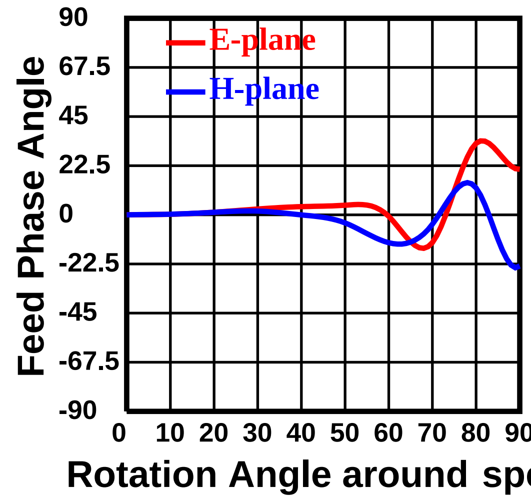
G0HNW Plumbers Delight feed for 5760 MHz, by NEC2

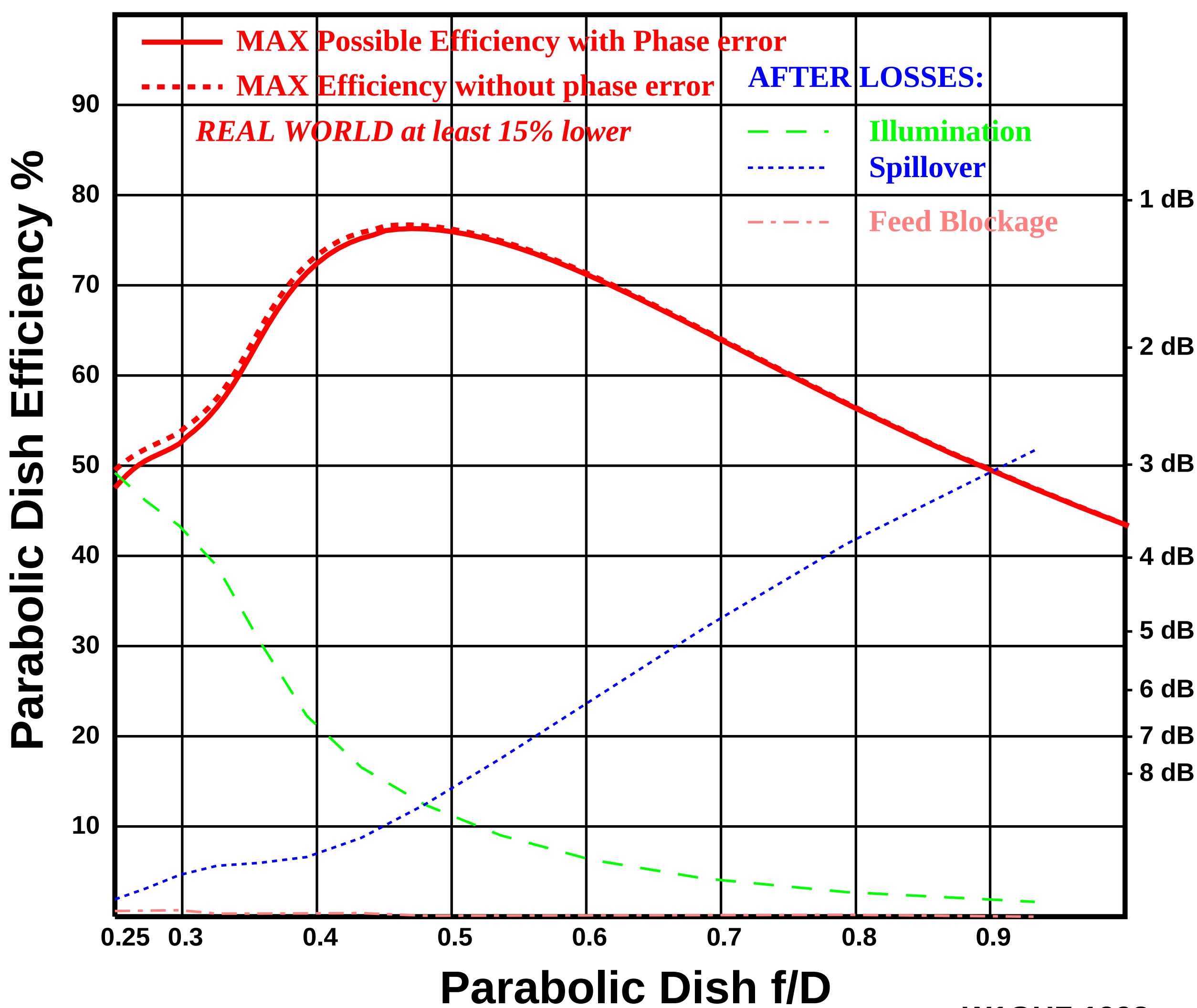
Figure 6.5-9





Dish diameter = 16 λ   Feed diameter = 0.5 λ

Phase Center = 0.04 λ beyond aperture



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Although this version is not optimized for an offset dish, Paul reports a significant improvement compared to a triband feed. Since the triband feed is basically a dipole feed, which gives best results with very deep dishes, we would expect performance like Figure 6.2-1. At the high equivalent ***f*/D** needed to feed an offset dish, efficiency is very low. In addition, the triband feed has been shown to be rather lossy at 5.7 GHz, further reducing efficiency. Almost anything is better than a triband feed for an offset dish at 5.7 GHz.

The third British dual-mode example is a 24 GHz version by G8ACE[9]. The plumbing fitting used in this version provides an aperture of 22mm, or1.75**λ**, which is about right for an offset dish. The input waveguide is 10mm pipe, and there are apparently no plumbing reducers from 22mm to 10mm. Instead, a reducer to an intermediate size of 15mm is used, so that there are two flare sections with a length of 15mm waveguide between them. This combination makes it difficult to predict how the two modes will end up, so I calculated the radiation pattern using **NEC2**. The results are shown in Figure 6.5-10. The E-plane pattern has large sidelobes and a null at about 30º off-axis, suggesting that modes do not have the desired relationship at the aperture. As a result, calculated efficiency is mediocre, and the phase center is displaced about 0.4λ inside the horn.

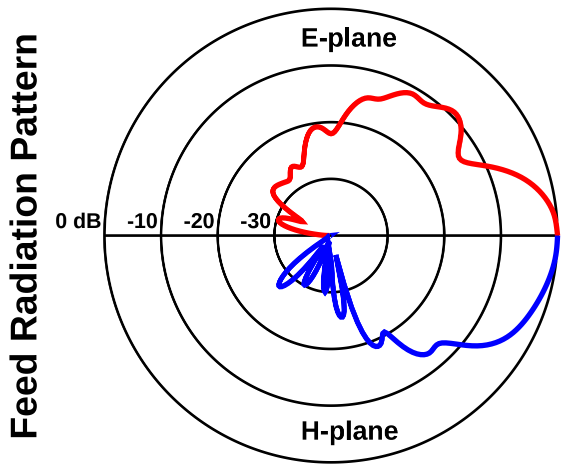
Rapid changes in amplitude, like the null in the E-plane pattern, are usually accompanied by rapid phase changes. This is clearly illustrated in Figure 6.5-10 — the feed phase plot in the upper right exhibits a large change in phase around 30º off-axis. The effect on dish efficiency is evident in the lower graph, showing significant phase error at larger illumination angles.

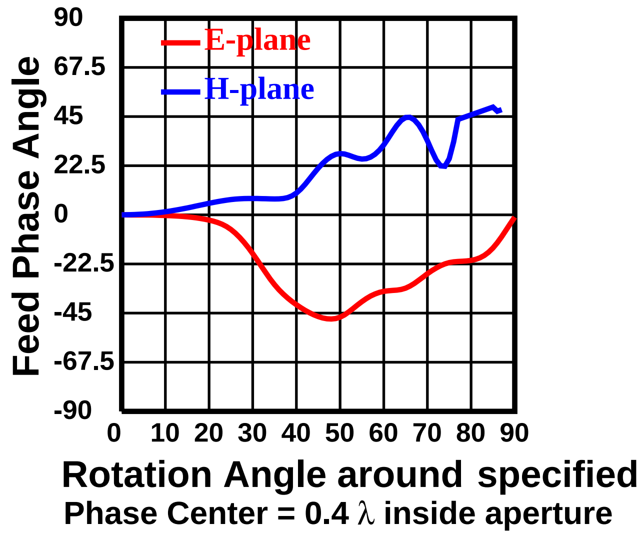
We can deduce from this last example that a single flare section offers much better mode control for dual-mode operation. At 24 GHz, dimensions are small enough so that it should be easy to fabricate a short conical section. The **HDL_ANT** program will prepare a paper template for any desired flare dimensions.

All three examples thus far are attempts at different frequencies to fabricate a W2IMU dual-mode feed using available materials. A 47 GHz feedhorn[10] by G0IVA uses the opposite approach — it is machined from solid brass. Figure 6.5-11 shows the feed attached to a DB6NT transverter; this combination plus an offset dish has been successful over distances >100km. G3PHO sent me the sketch shown in Figure 6.5-12; the dimensions are very close to being a scaled-down copy of the W2IMU 1296 MHz horn. The only difference is that the large diameter section is 0.04 wavelengths too long — and the result is slightly larger sidelobes. Calculated efficiency from the **NEC2** radiation patterns is not harmed, as shown in Figure 6.5-13. The discrepancy of 0.04 wavelengths is about 0.012 inches - about 10 strokes with a file!

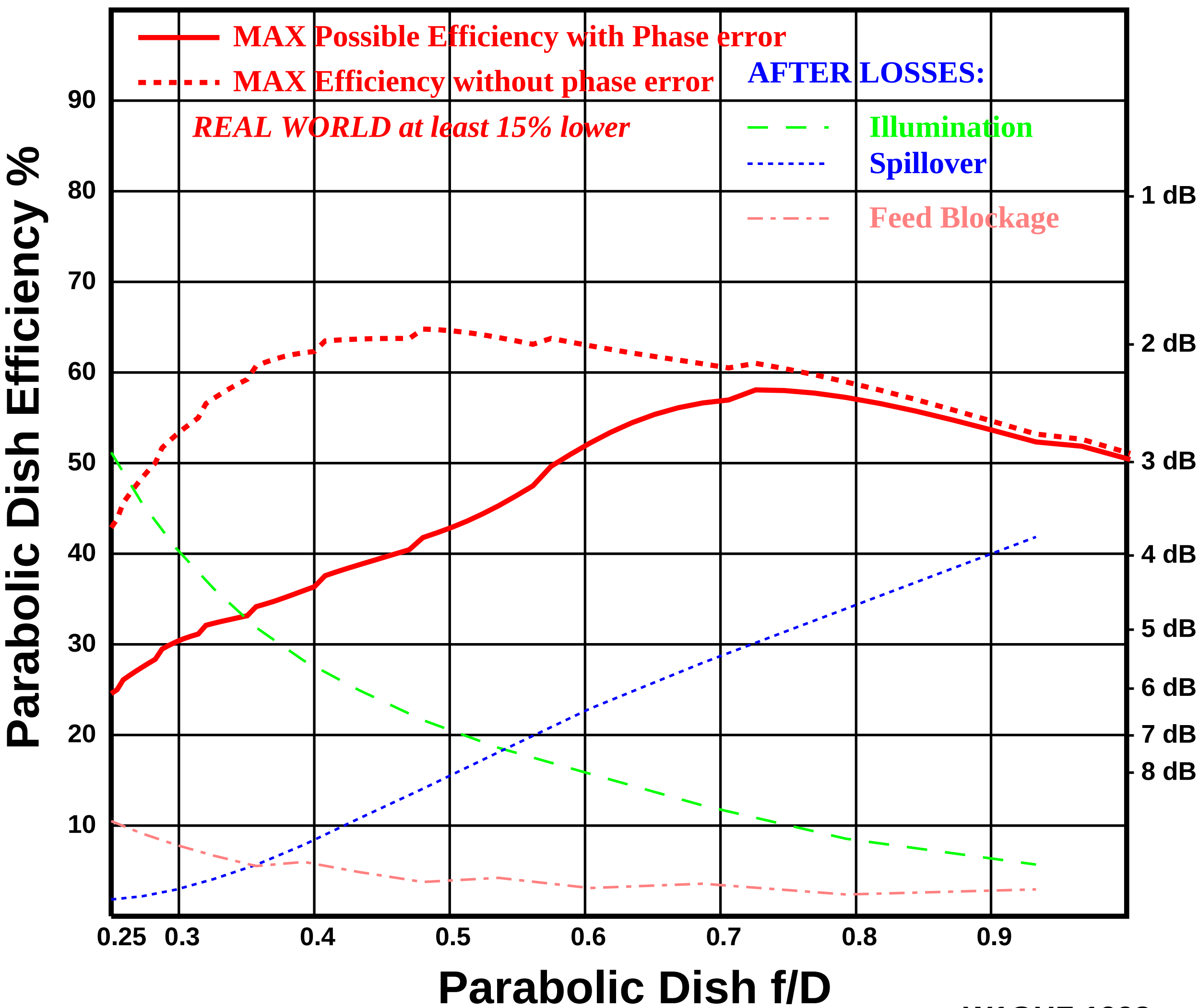
G8ACE dual-mode feed for 24 GHz, by NEC2

Figure 6.5-10





Dish diameter = 18 λ   Feed diameter = 1.8 λ



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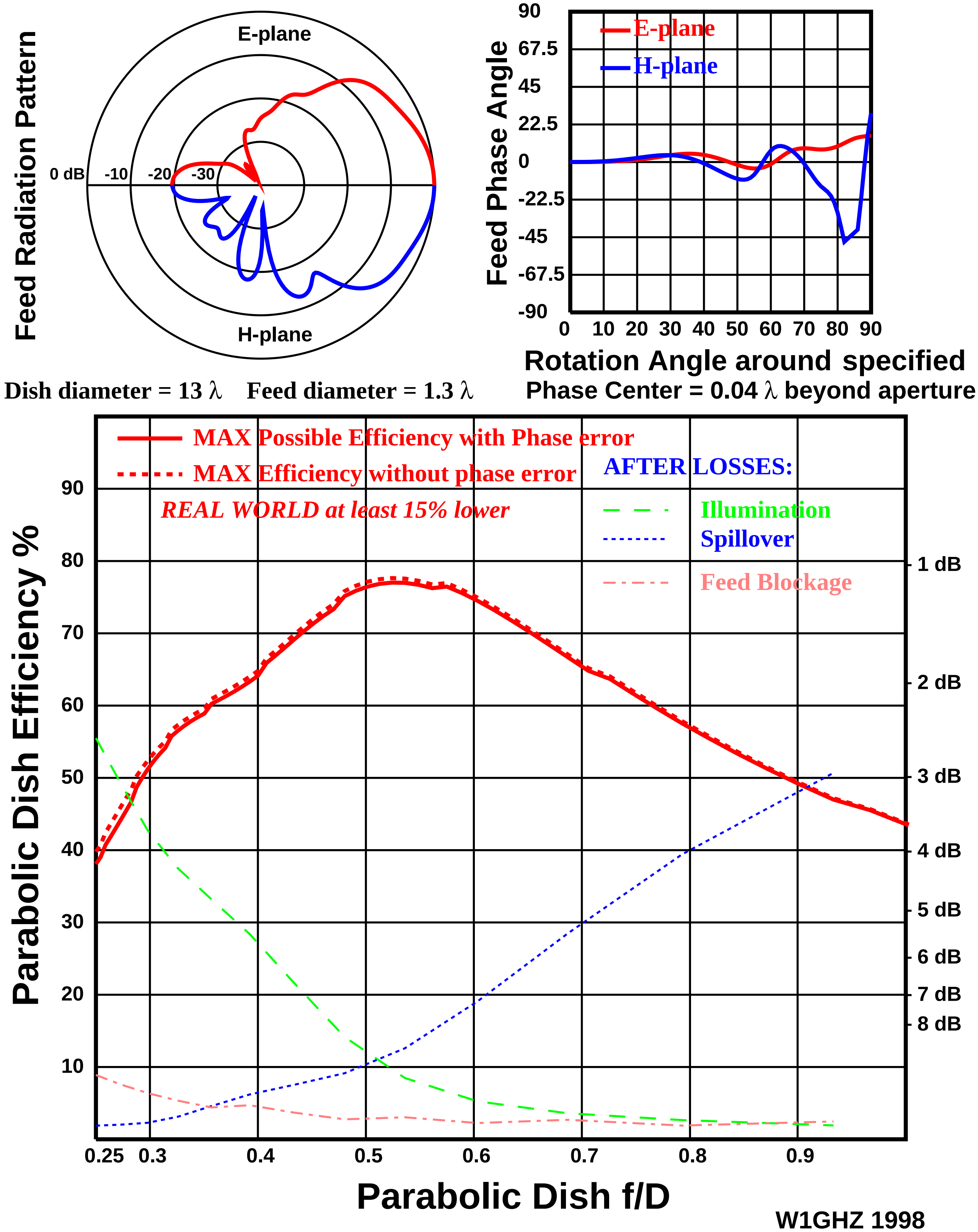
G0IVA 47 GHz dual-mode feedhorn, by NEC2

Figure 6.5-13



47 GHz Dual-mode Feedhorn

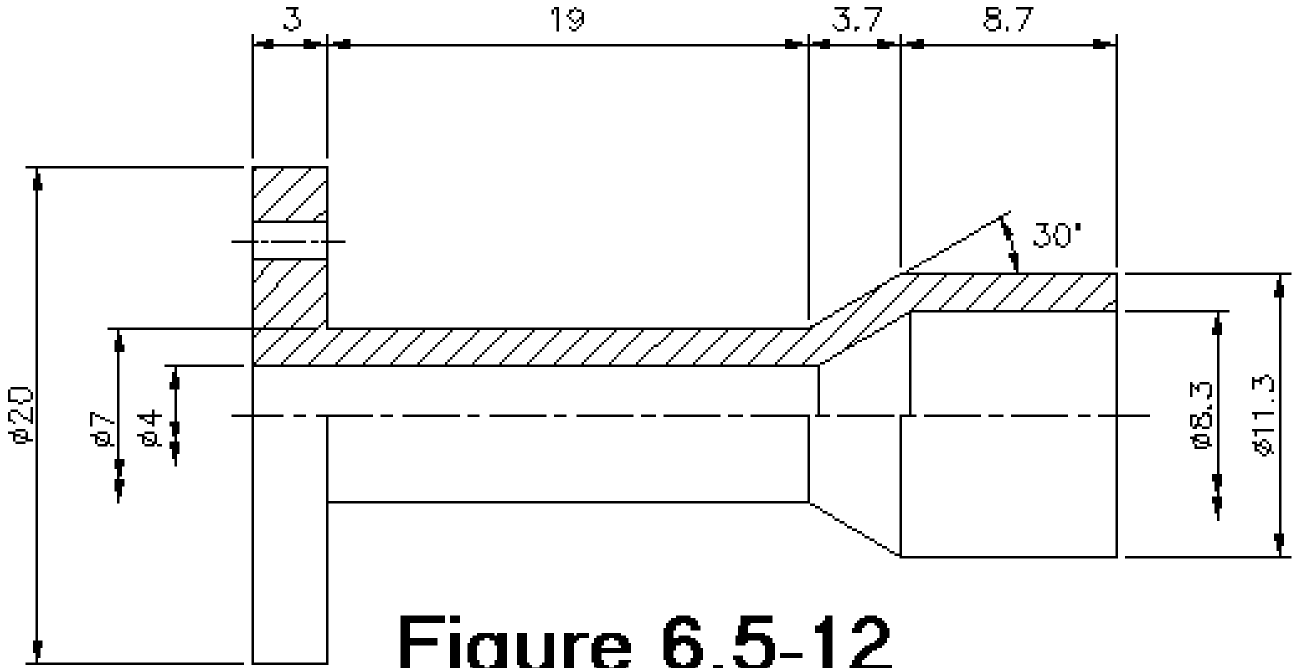


Figure 6.5-12

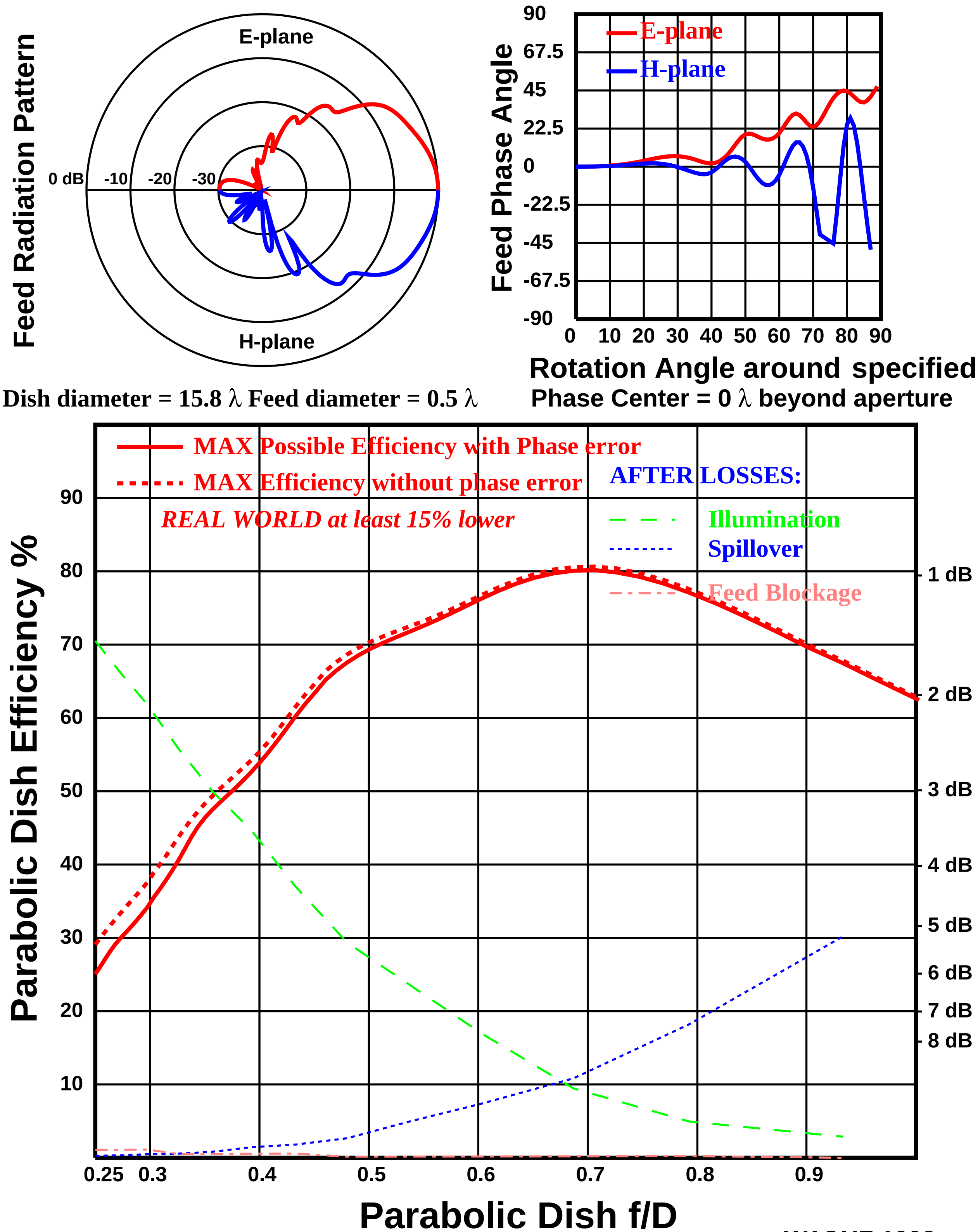
Most of the offset-fed dishes that I have found require an illumination angle equivalent to an ***f*/D** of about 0.7. The calculated efficiency for the large W2IMU feedhorn in Figure 6.5-2 is very high with best ***f*/D** around 0.8, so I thought that a slightly smaller aperture would work well for an offset feed. The optimum diameter for 10 GHz is between standard plumbing sizes, larger than 1 ½" and smaller than 2" copper pipe, so I had to search for an intermediate size. At a scrap-metal yard I located a length of brass pipe with an i.d. of 1.85", or 1.63**λ**. Using the equations seen earlier in this section, I calculated a flare half-angle of 27.4° and an output section length (**C**) of 2.8**λ,** or 3.19 inches at 10.368 GHz.

The radiation patterns calculated by **NEC2** for these dimensions, plotted in Figure 6.5-14, show low sidelobes and excellent calculated efficiency. I made a template for the flare section using **HDL_ANT** and soldered it to a length of the brass pipe, with standard ¾" copper pipe as the input waveguide. The finished horn is shown in Figure 6.5-15, along with an even larger version described below. Measured performance using sun noise is also excellent: on a one-meter offset dish, the efficiency was slightly higher than measured with the rectangular feedhorn of Figures 6.4-11 and 6.4-12. Since the rectangular feedhorn has demonstrated high measured efficiency and excellent field performance, achieving

Figure 6.5-15

W2IMU large dual-mode feed, 1.63λ diameter, by NEC2

Figure 6.5-14



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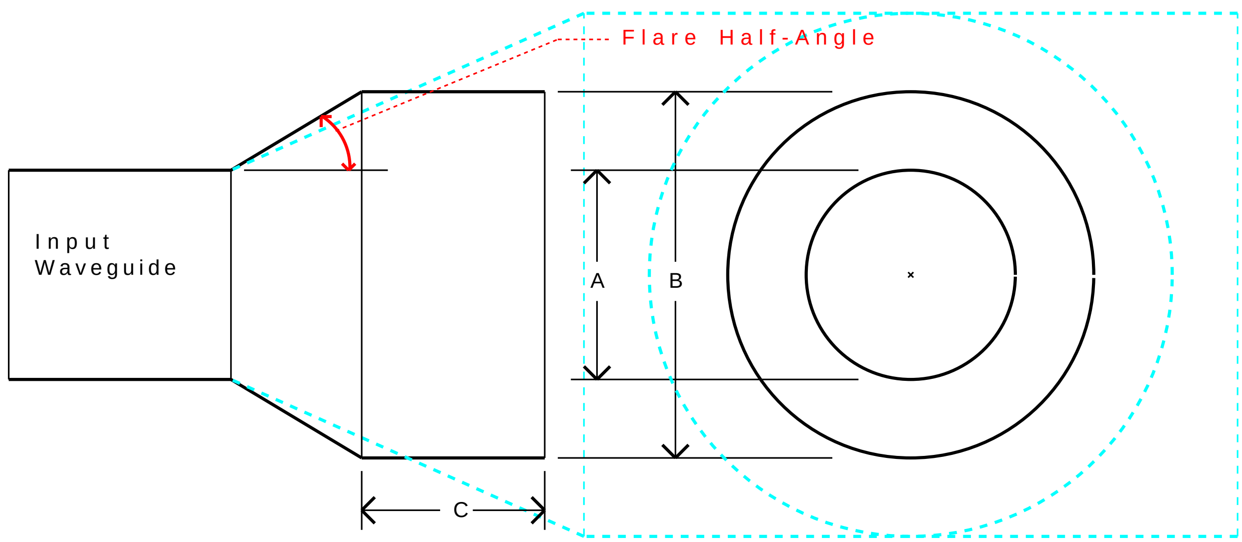
higher calculated and measured efficiency with the dual-mode feed is an accomplishment. In fact, efficiency with the dual-mode feed measured 1% higher using circular polarization than with linear polarization — a capability you can't get with a rectangular horn.

I also have another offset dish, 0.8m diameter, which requires a narrower illumination angle equivalent to ***f*/D** = 0.8, just right for the original large W2IMU dual-mode horn. The closest material I could find to the desired 1.88**λ** diameter (dimension **B**)was standard 2" copper pipe, with an i.d. of 2.04" or 1.79**λ** at 10.368 GHz (I had to buy a full ten-foot length, if anyone needs some!). The calculated dimensions for this aperture diameter are: flare half-angle = 24.9° and output section length (**C**) = 3.52**λ,** or 4.01 inches at 10.368 GHz. Figure 6.5-16 is a reminder how the flare angle decreases and the length increases with increasing diameter.



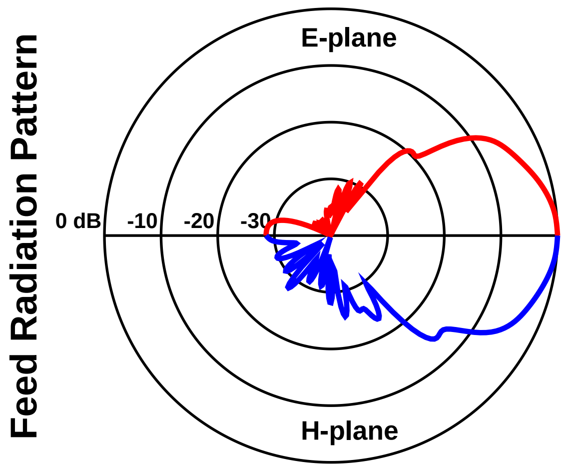
W2IMU DUAL-MODE HORN

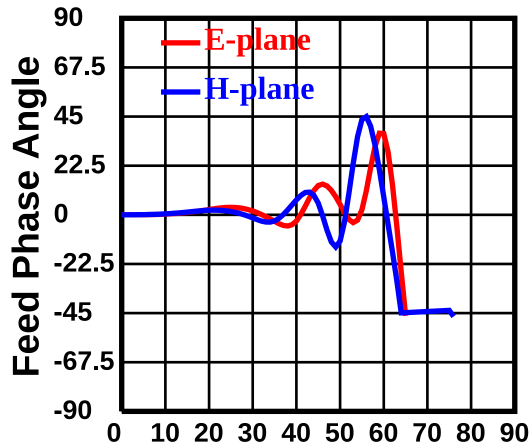
Figure 6.5-16

The larger offset dual-mode horn also exhibits excellent performance, both from the **NEC2** calculations plotted in Figure 6.5-17 and from sun noise measurements on the 0.8 meter dish. If it wasn't apparent from Figure 6.5-15, it is worth noting that these two horns are not precision fabrications; they were built in my basement with hand tools and a torch. The smaller one still has a few solder lumps inside that need to be filed down. Yet they are both good performers — so don't be afraid to build your own!

W2IMU dual-mode feed, 1.79λ diameter, by NEC2

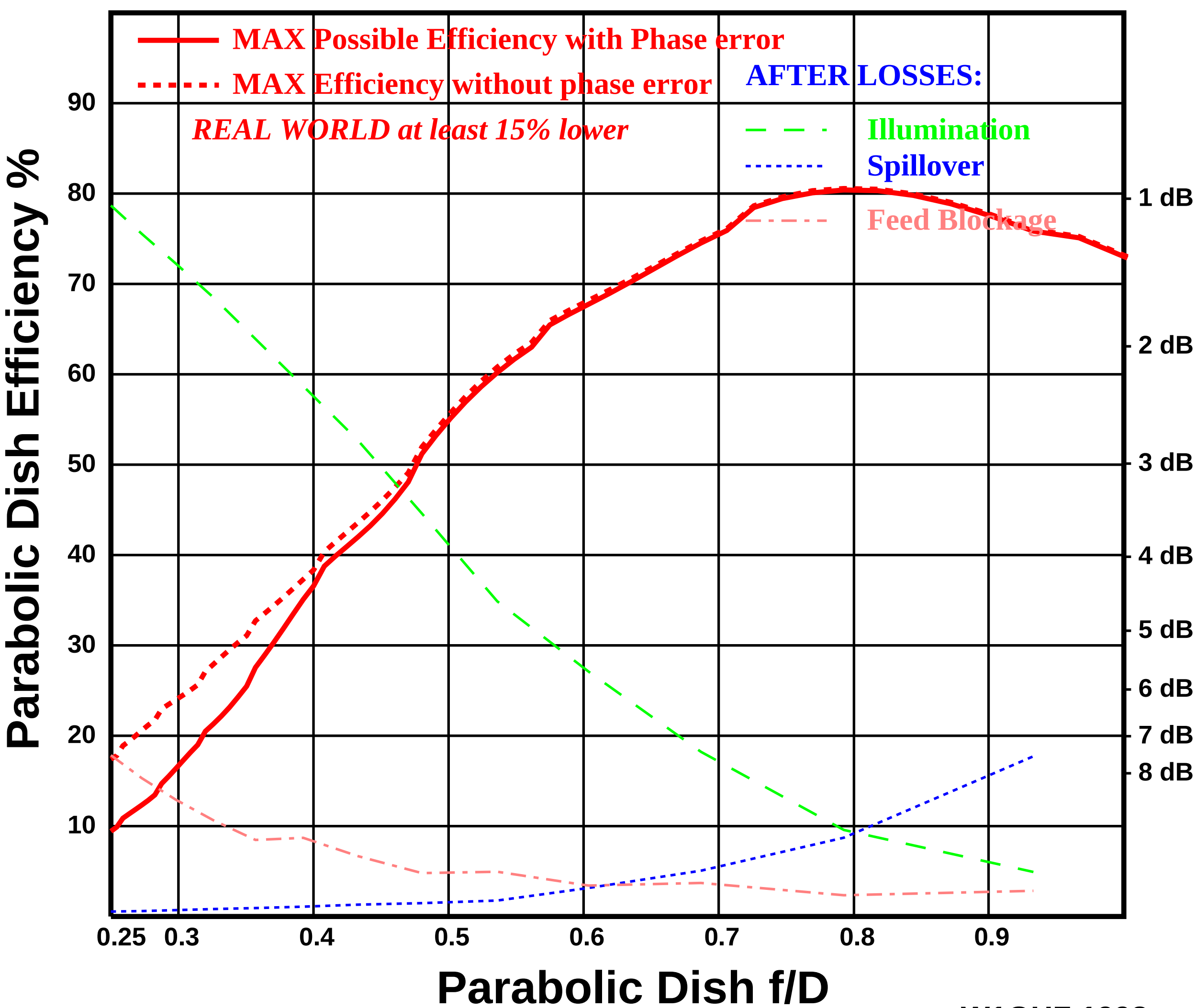
Figure 6.5-17





Dish diameter = 17.9 λ Feed diameter = 1.79 λ

Phase Center = 0 λ beyond aperture



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The W2IMU dual-mode feedhorns are well matched to the circular waveguide — the two large ones have a VSWR less than 1.2 at 10.368 GHz. While I was measuring the VSWR, I noticed the plumbing fitting from Figure 6.5-3 lying on the workbench, so I measured it also. Not only is it a poor feed, but it also has a poor VSWR. I also tried a larger plumbing fitting, a tapered adapter from ¾" copper pipe to 2" pipe. The larger fitting has a good VSWR, so I thought it might make a better feed than the smaller one. However, the measured efficiency on a one meter offset dish, using sun noise, was only 22%. I went back to **NEC2** and calculated the radiation patterns, with the result shown in Figure 6.5-18: large sidelobes and poor phase performance resulting in low efficiency. The phase performance is particularly poor because the phase centers are widely separated: the E-plane phase center is 1.6 wavelengths inside the horn, while the H-plane is 0.4 wavelengths in front of the aperture.

Summary

The W2IMU dual-mode feed can provide excellent performance for both offset and conventional parabolic dishes. Dimensions are somewhat critical, but optimum dimensions may be calculated for a range of ***f*/D**, and performance can be analyzed using the **NEC2** program.

6.5 References

1. R.H. Turrin, (W2IMU), "Dual Mode Small-Aperture Antennas," *IEEE Transactions on Antennas and Propagation*, AP-15, March 1967, pp. 307-308. (reprinted in A.W. Love, *Electromagnetic Horn Antennas*, IEEE, 1976, pp. 214-215.)

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Figure 6.5-18