Chapter 6

Feeds for Parabolic Dish Antennas

Paul Wade W1GHZ

Section 6.4 Horn antenna feeds

Electromagnetic horns were some of the earliest microwave antennas[1]. As we saw in Chapter 2, they are excellent primary antennas, easily fabricated and reproducibly providing good gain. For higher gains, parabolic dishes are more compact, but horns are attractive as feed antennas for the same reasons.

One way to think of a horn is as an impedance transformer, gradually transitioning from the constrained impedance of a waveguide to the impedance of free space. We can see this experimentally: an open waveguide is not matched, with a typical VSWR of perhaps 1.4:1, while almost any horn provides a better match. The size of the final aperture opening to space determines the gain of the horn.

6.4.1 Conical horn feeds

In section 6.3.1, we saw that a cylindrical waveguide, or "coffee-can," feed works well for small ***f*/D** reflectors. As the cylinder diameter is increased to provide a larger aperture for narrower beamwidth, additional waveguide modes can propagate and disturb the radiation pattern. If the diameter is increased in a gradual flare, like a funnel, we have a conical horn antenna. The gradual flare reduces the generation of additional waveguide modes and provides a cleaner pattern.

I have seen metal funnels used as small horn antennas for rover stations, but all the funnels manufactured today unfortunately seem to made of plastic. Thus, we must fabricate our own horns. As illustrated by Figure 6.4-1, the **HDL_ANT** program makes fabrication a straightforward process: print a paper template for the flared section, tape it to a piece of copper flashing, cut out the flared section, roll it to shape, and solder it to a piece of pipe.

As a simple example of a conical horn antenna, I took the **NEC** model for a large W2IMU dual-mode feed in Figure 6.5-2 and removed the output section, leaving only the flared section as a conical horn. I used **NEC2** to calculate the radiation pattern for this conical horn, with an aperture of 1.88λ and a flare angle of 58°, yielding the result shown in Figure 6.4-2. The flared horn has the same E-plane edge currents, described in section 6.3-1, as the cylindrical waveguide horn, so the E-plane pattern has a significant sidelobe as a result. Best ***f*/D** is in the range of 0.7 to 0.8, but the maximum calculated efficiency is only fair. The phase center is 0.43λ inside the aperture. The dual-mode version in Figure 6.5-2, which is intended to eliminate the edge currents, has significantly higher calculated efficiency.

NEC models for conical horns are rather tedious to make, and more complex horns are more difficult, so I use Physical Optics (**P.O.**) routines from Milligan and Diaz[2] for horns. (A description by Rusch[3]: "Physical optics, whereby the free-space dyadic Green's function is integrated over the geometrical-optics current distribution, is commonly used to analyze high-frequency reflectors, particularly, focusing reflectors.") Figure 6.4-2 also shows the radiation pattern, in green, calculated by P.O. for the same horn: the forward patterns are almost identical, and the peak sidelobe levels are very close. The calculated efficiency curves are also very similar. Thus, we can conclude that the two calculation techniques yield similar results.

For a cylindrical waveguide feed in section 6.3, the largest ***f*/D** that we could illuminate is about 0.4. The example above is best for an ***f*/D** of around 0.8; let's try another example for a more reasonable ***f*/D**. An aperture of 1.3λ should provide good illumination for a shallow dish with an ***f*/D** around 0.55, but how do we estimate the appropriate gradual flare angle? Let's calculate patterns, using P.O., for a range of flare angles and see how the pattern is affected.

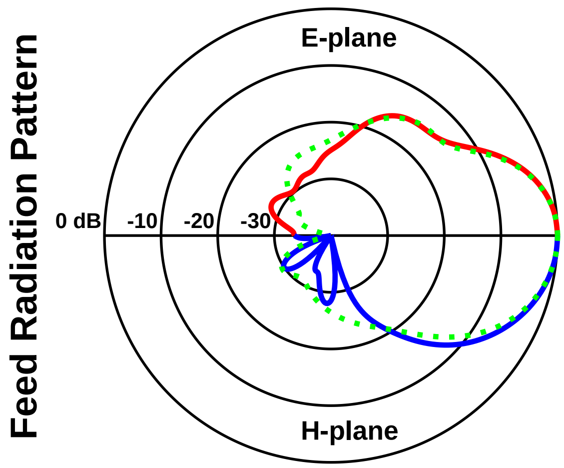
A small flare angle of 30° has the calculated pattern shown in Figure 6.4-3, with the E-plane pattern narrower than the H-plane. The resulting efficiency is pretty good for an ***f*/D** around 0.6, and the phase center is just inside the aperture.

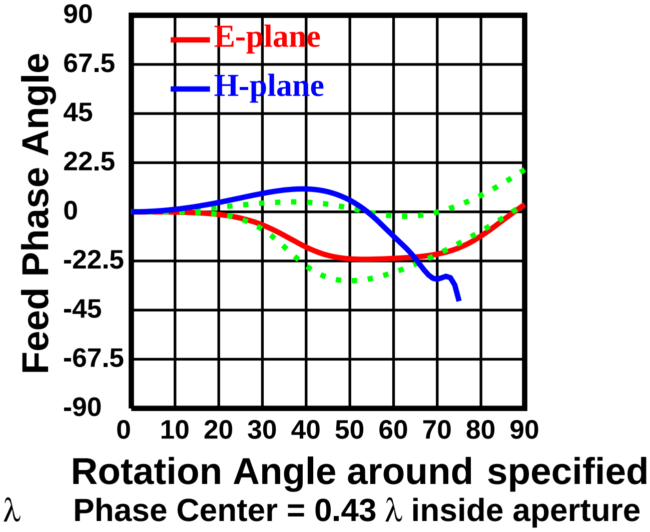
A large flare angle of 120° has more balanced illumination in the E- and H-planes, as shown in Figure 6.4-4, but a large sidelobe in the E-plane that reduces the efficiency significantly. Best ***f*/D** is around 0.5, with the phase center 0.3λ inside the aperture.

Is there some intermediate flare angle between these two extremes that provides a balanced pattern without large sidelobes? I calculated patterns for flare angles of 45°, shown in Figure 6.4-5, 60°, Figure 6.4-6, and 90°, Figure 6.4-7, as well as some intermediate angles, without finding any better compromise, and the phase center moves as the flare angle changes. The edge currents always adversely affect the E-plane pattern.

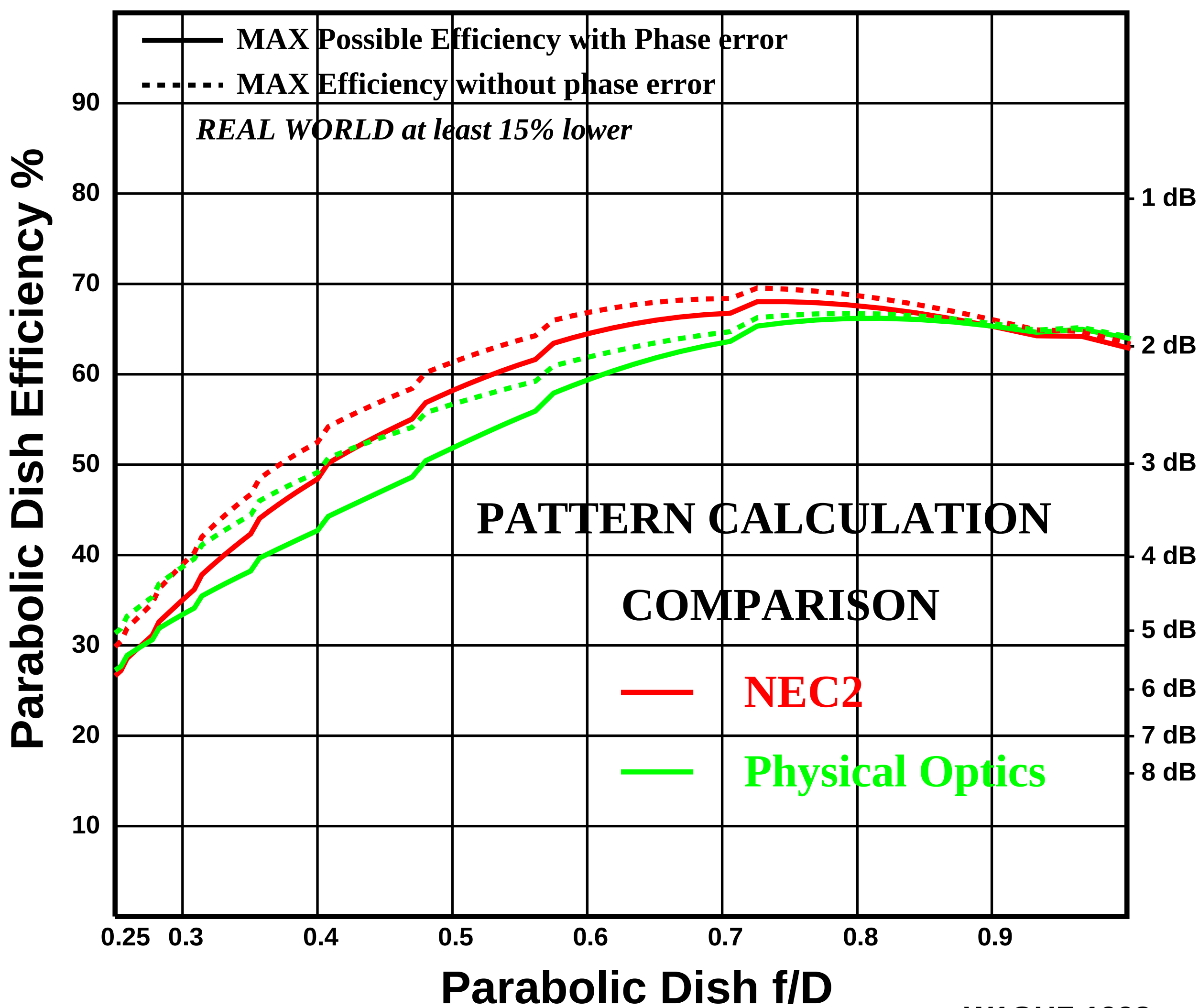
Conical horn, 1.88λ dia, 58 deg flare, by NEC2 and P.O.

Figure 6.4-2





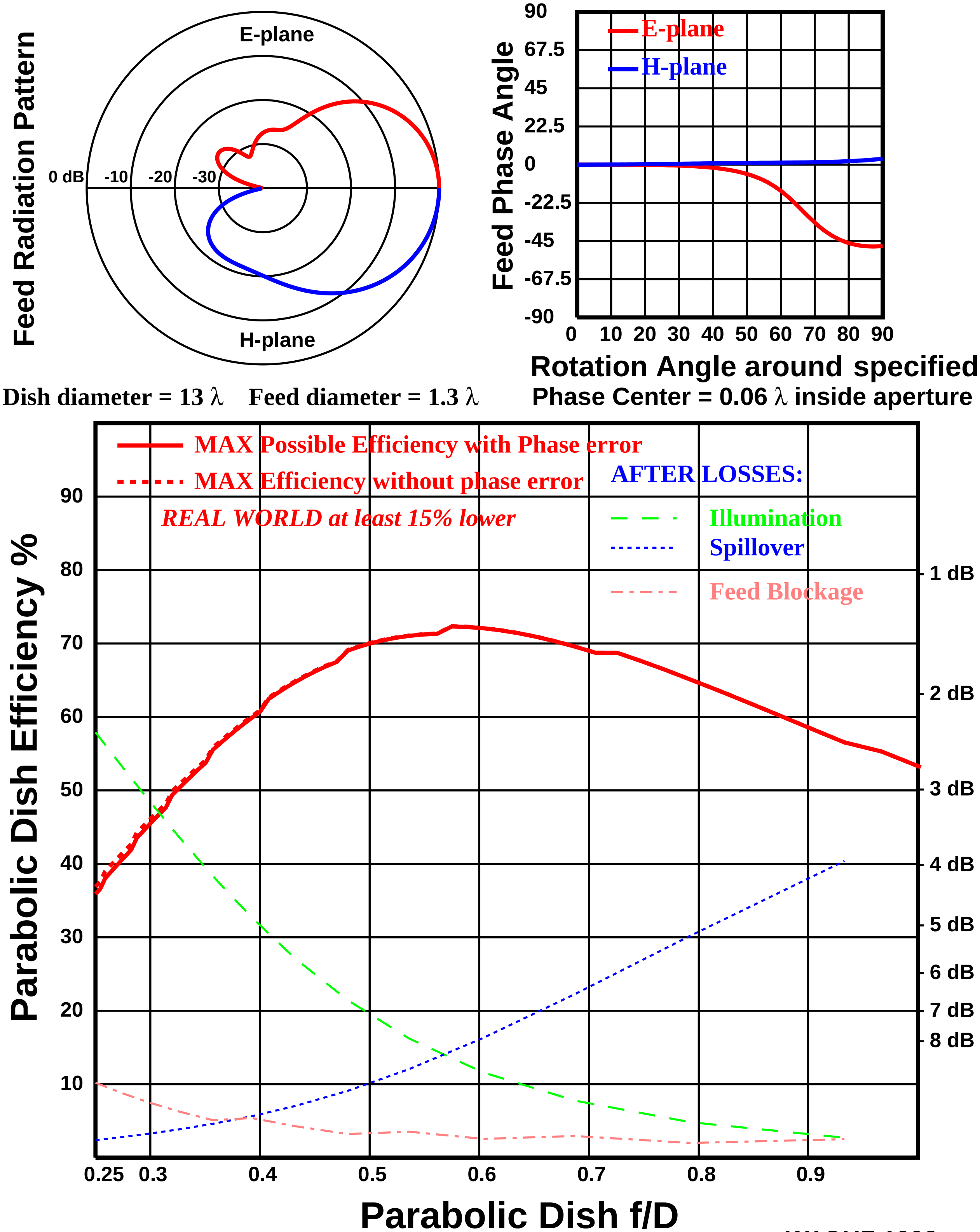
Dish diameter = 19 λ   Feed diameter = 1.88 λ



W1GHZ 1998

Conical horn 1.3λ dia, 30 deg flare, by P.O.

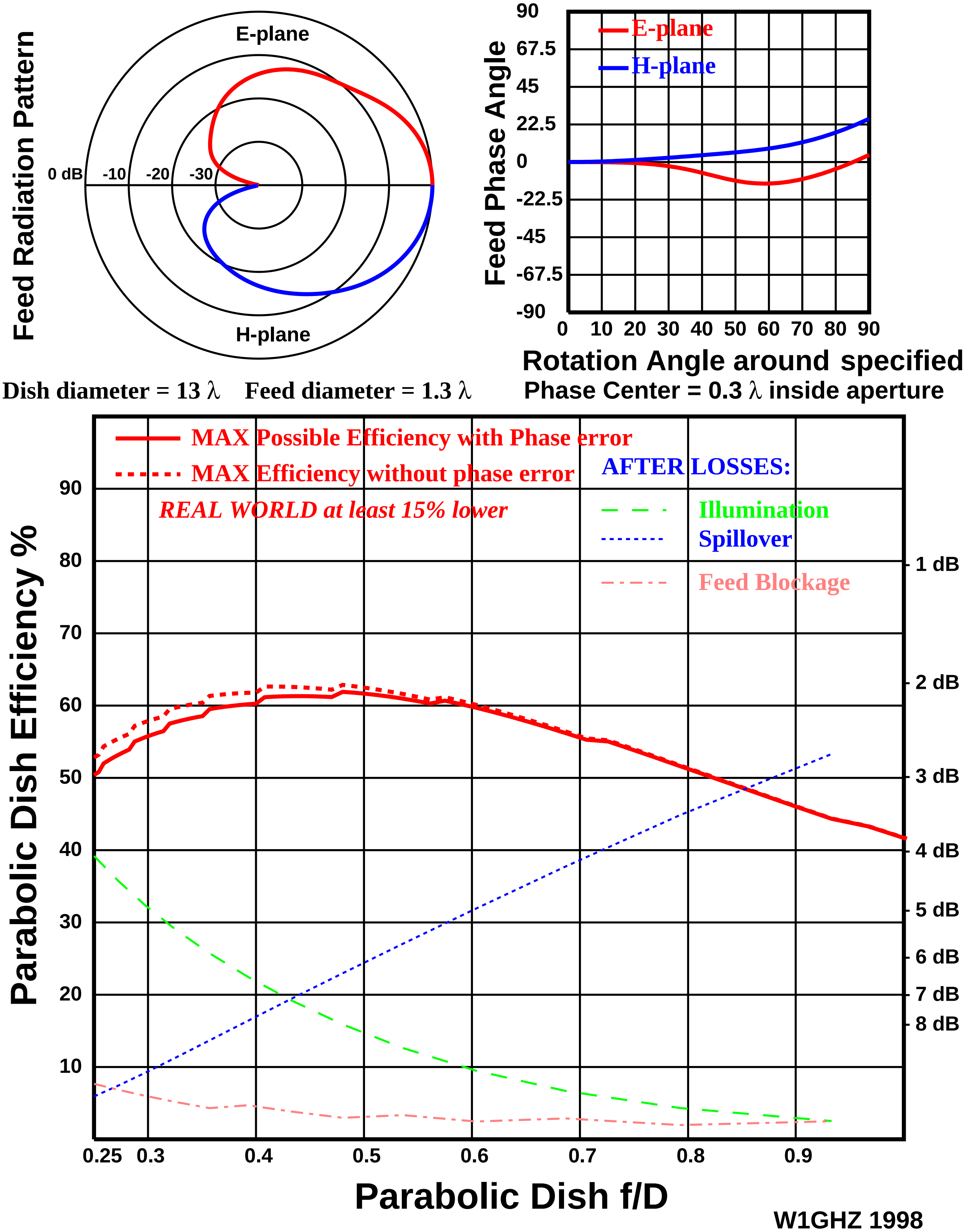
Figure 6.4-3



W1GHZ 1998

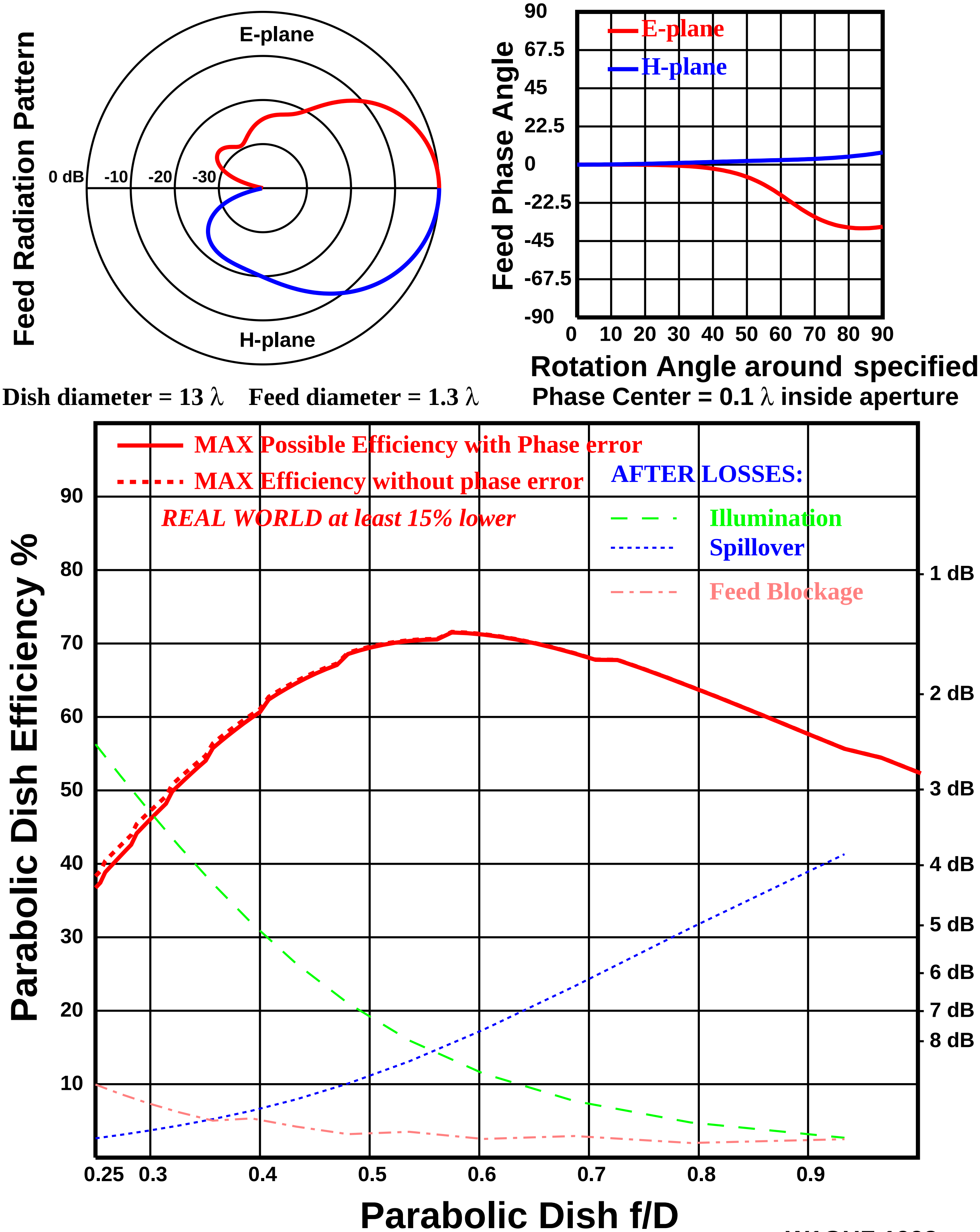
Conical horn 1.3λ dia, 120 deg flare, by P.O.

Figure 6.4-4



Conical horn 1.3λ dia, 45 deg flare, by P.O.

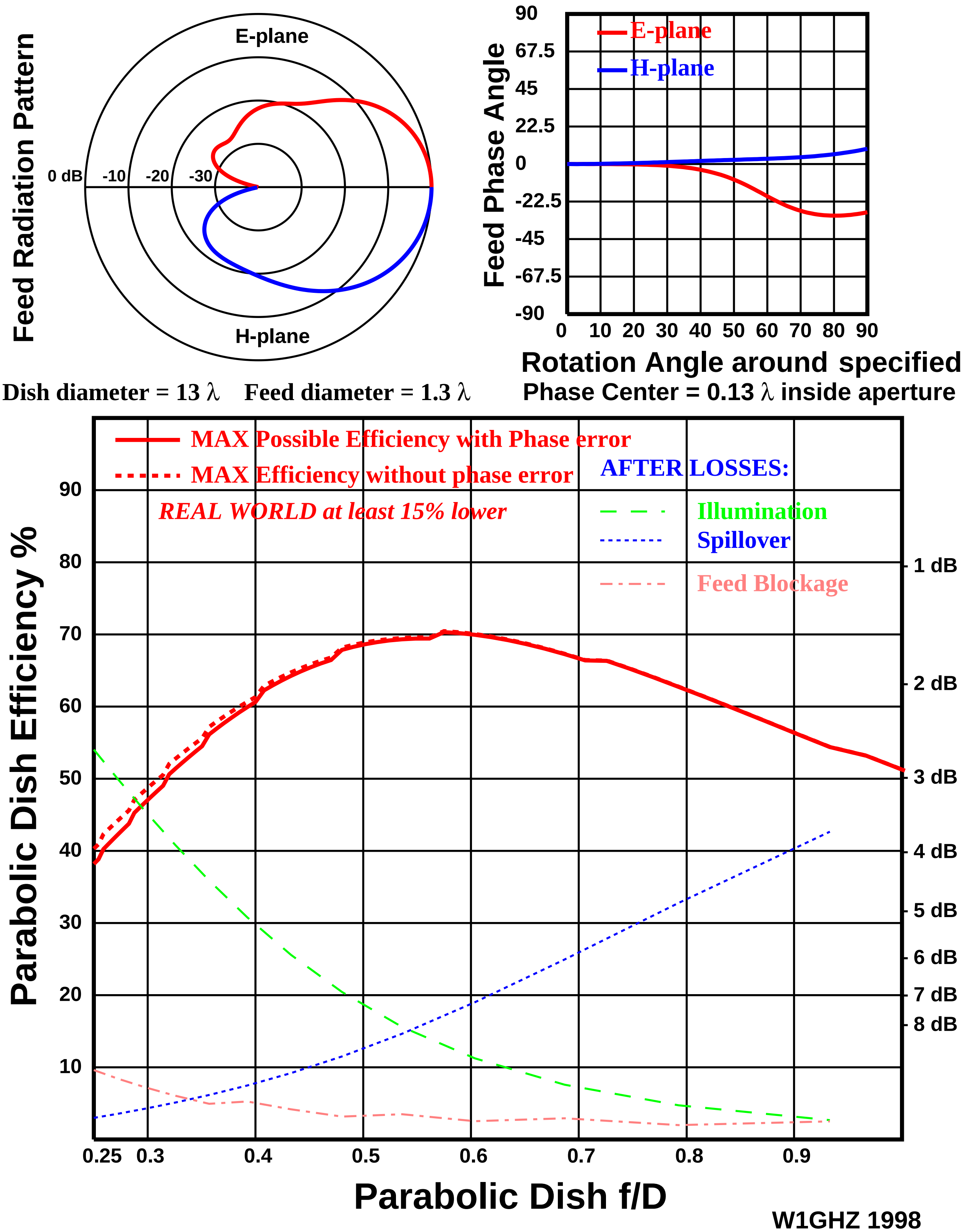
Figure 6.4-5



W1GHZ 1998

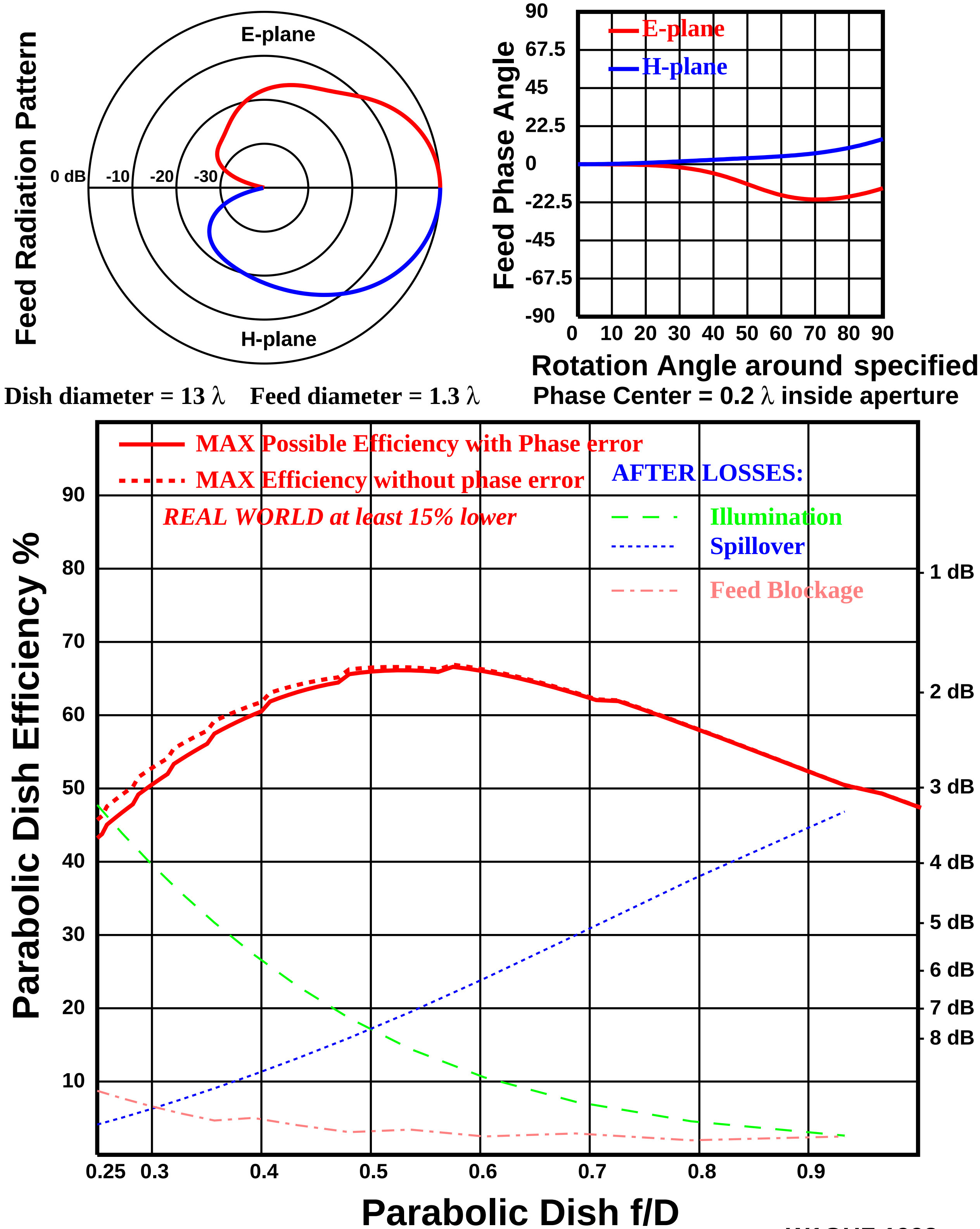
Conical horn 1.3λ dia, 60 deg flare, by P.O.

Figure 6.4-6



Conical horn 1.3λ dia, 90 deg flare, by P.O.

Figure 6.4-7



W1GHZ 1998

One suggestion, by King[4], is to distort the horn into an elliptical aperture. He reports that an ellipse 1.2 times as long as it is wide, with the narrow dimension parallel to the electric plane, provides a more balanced pattern. I have not tried this experiment, and it is really difficult to model.

A final example is a feedhorn for a DSS offset dish. The RCA DSS dish uses a corrugated conical feedhorn — a difficult thing to homebrew. If we calculate the radiation pattern for a plain conical horn with the same dimensions, an aperture of 1.95 inches and a flare angle of 58°, we can compare it to the corrugated horn pattern. Figure 6.4-8 shows the calculated pattern for the plain conical horn at 10.368 GHz, with a large E-plane sidelobe and mediocre efficiency peaking around ***f*/D** of 0.7 to 0.8. We shall see the corrugated version in section 6.4-3.

In summary, conical horns do not have symmetrical patterns or phase centers, and often have high sidelobe levels that reduce efficiency. There are better choices for feedhorns.

6.4.2 Rectangular horn feeds

Rectangular waveguide is an excellent low loss feedline for microwave frequencies. Waveguide components for C-band and X-band are common surplus items; the WR-90 waveguide is plentiful and works well at 10 GHz. If we were already using rectangular waveguide, wouldn’t a rectangular horn be easier than transitioning to circular waveguide for a conical horn?

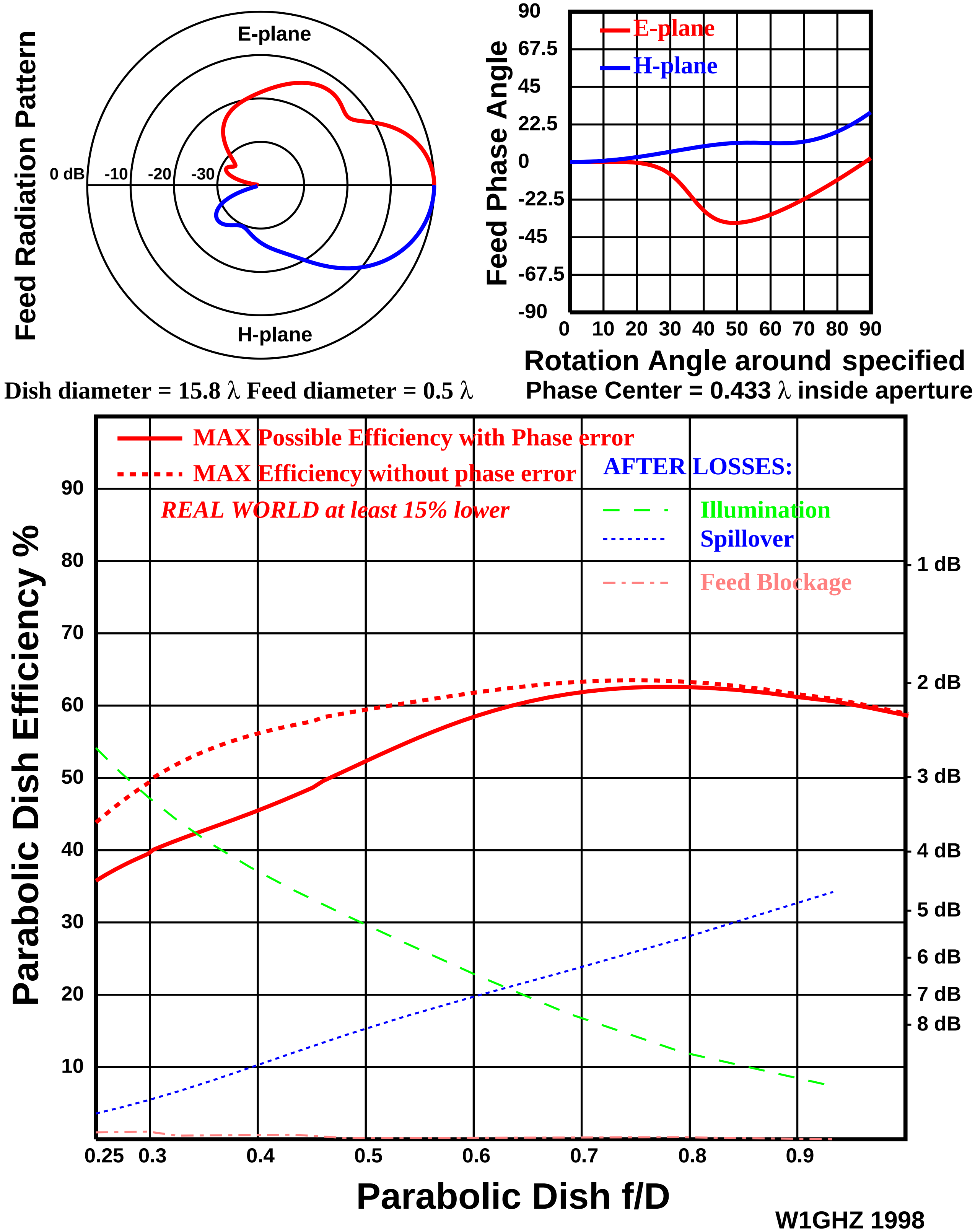
Like circular waveguide, the simplest horn for rectangular waveguide is just an open-ended waveguide. I calculated the radiation patterns for an open WR-90 waveguide at 10.368 GHz using Physical Optics routines. This particular calculation is only accurate for the forward half of the patterns, so I added published data from Jasik[5] to approximate the backward radiation pattern. Since the aperture of the open waveguide is much smaller in the E-plane than the H-plane, we would expect the E-plane pattern to be broader. The composite pattern is shown in Figure 6.4-9 shows this pattern imbalance. The open waveguide is best suited for very deep dishes, with ***f*/D** around 0.25 to 0.3. Maximum calculated efficiency is limited by poor front-to-back ratio. The phase illumination is very uniform, with the phase center at the center of the aperture, so an open waveguide might be a good choice for experimentally locating the focus of a dish.

I have seen surplus dishes with open waveguide feeds, usually in a bent-waveguide “shepherd’s crook” arrangement. Some of these dishes are shallower than the ***f*/D** range for which this feed is best suited. This might be deliberate, to under-illuminate the dish for reduced sidelobes, or it might just be to minimize size, weight, or cost. So don’t assume that a feed on a surplus dish is the optimum feed.

Following the same path we took for conical horns, we can add a gradual flare to the waveguide to increase the aperture. This is, of course, the pyramidal horn described in Chapter 2. One advantage of the rectangular shape is that we may adjust the two flare angles separately to control the radiation pattern. As an example, we flare the rectangular waveguide into a square aperture, 1.3λ on a side. The radiation pattern calculated using P.O. is shown in Figure 6.4-10. Like the pattern produced by the round aperture of a conical horn, the square horn pattern is asymmetric with a large sidelobe in the E-plane. The square and rectangular horns also suffer from E-plane edge currents like the conical and cylindrical horns.

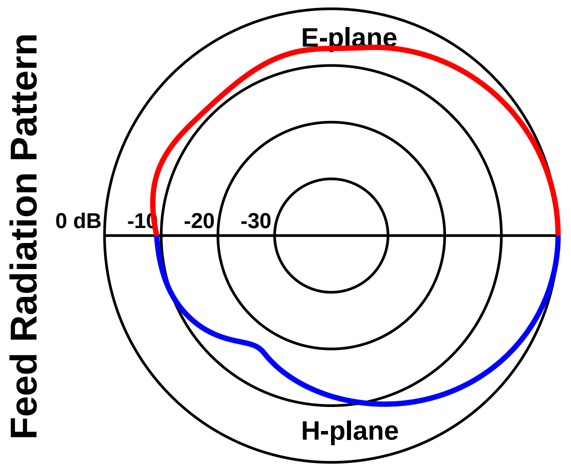
Conical horn like RCA DSS corrugated horn, by P.O.

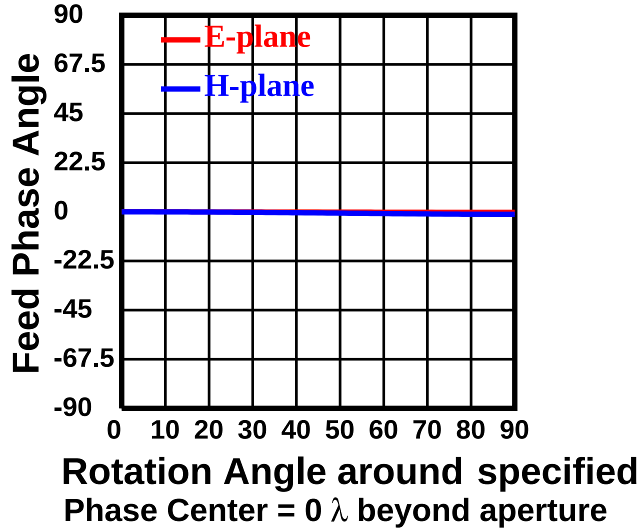
Figure 6.4-8



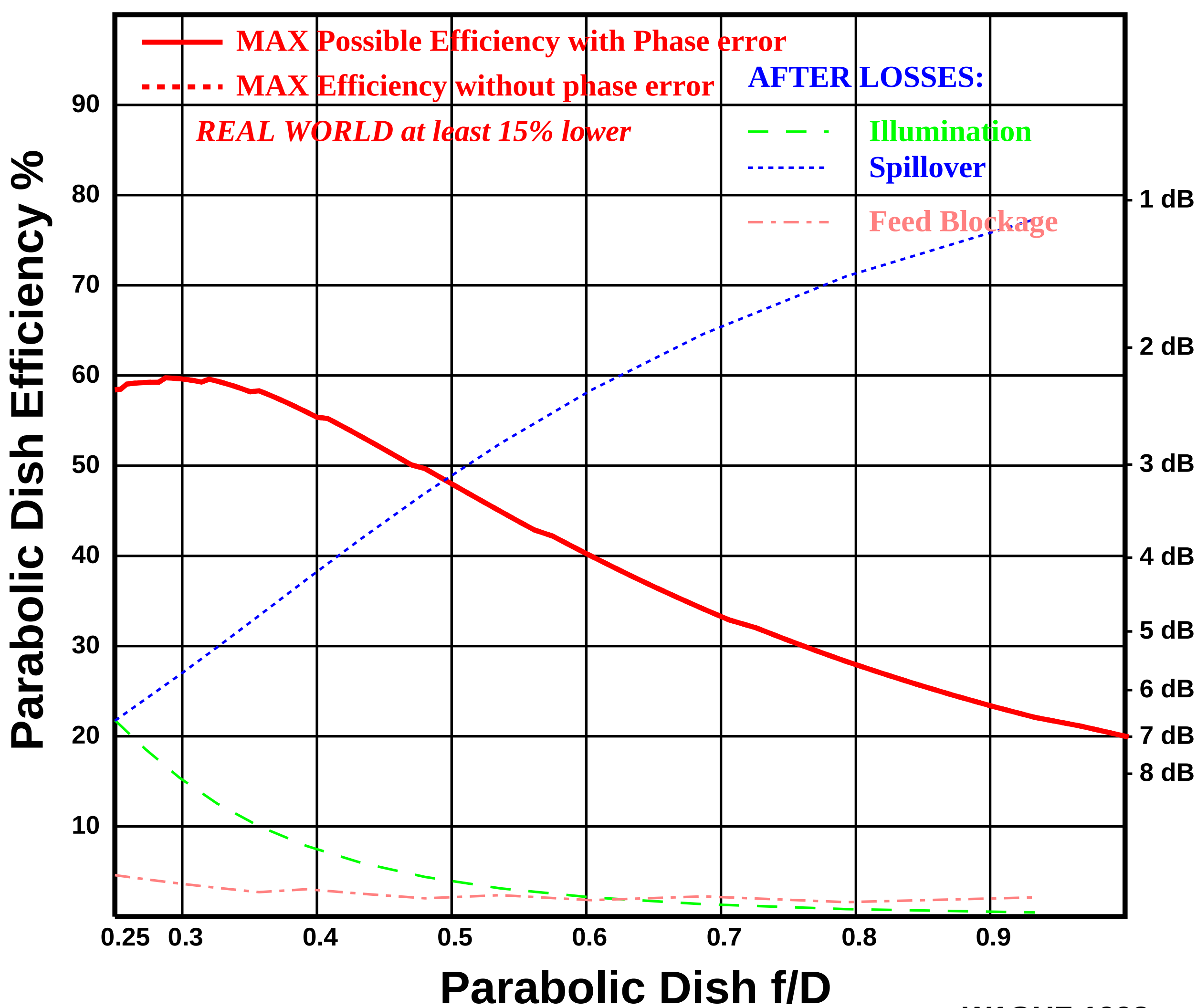
Open WR-90 waveguide as feed at 10.368 GHz, by P.O & Jasik

Figure 6.4-9





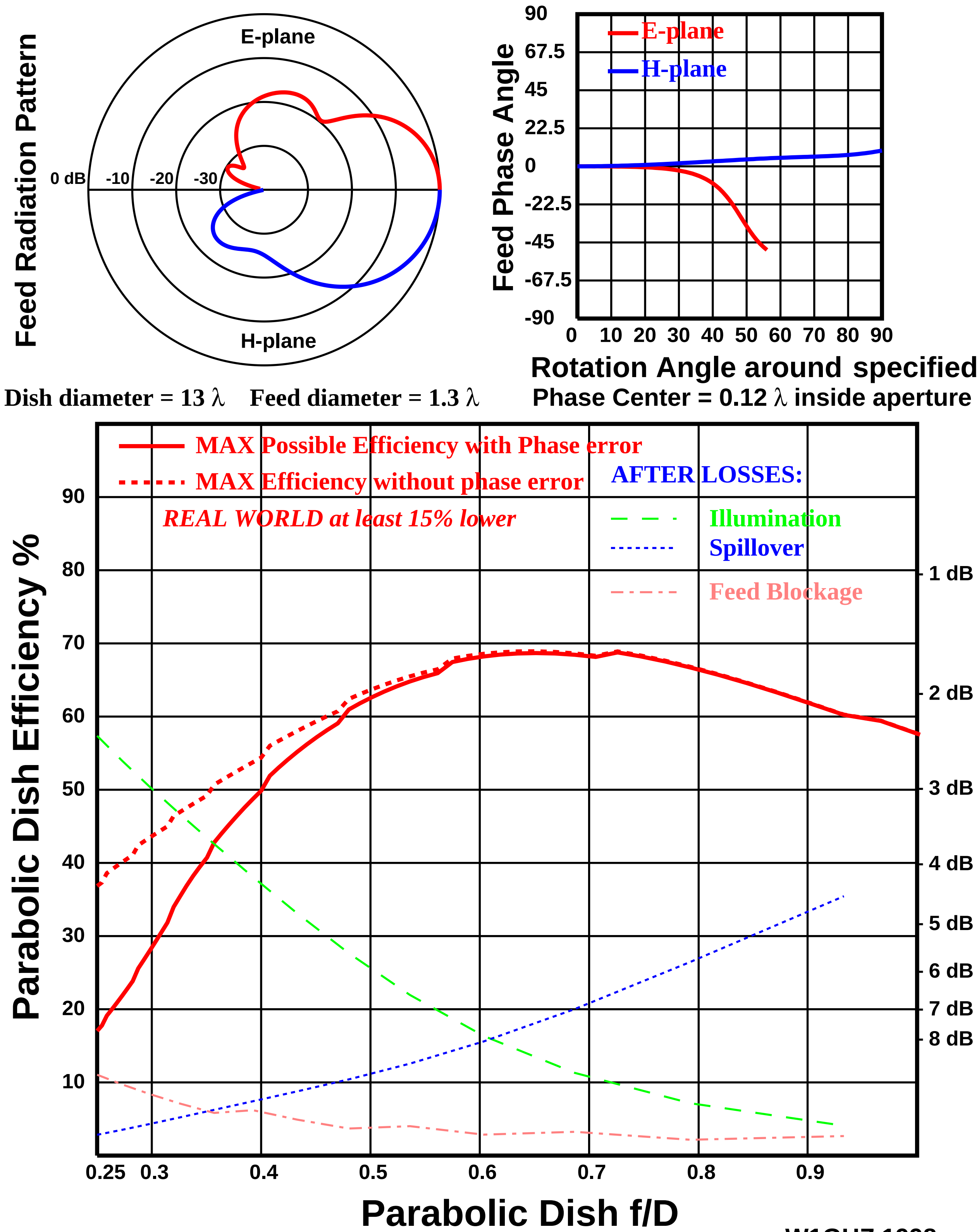
Dish diameter = 10 λ   Feed diameter = 1 λ



W1GHZ 1998

1.3λ square WR-90 horn at 10.368 GHz, by P.O.

Figure 6.4-10



W1GHZ 1998

While we can't eliminate the edge currents, we can adjust the flare angles to produce a more symmetrical pattern. G3RPE has published curves[6,7] which allow selection of the optimum E- and H-plane apertures for a given ***f*/D**. The **HDL_ANT** program incorporates an approximation to the G3RPE curves for easy horn design and construction template generation. Figure 6.4-11 shows the fabrication process: print a paper template for the horn, tape it to a piece of copper flashing, cut it out, fold on the dotted lines, and solder it to the end of a waveguide.

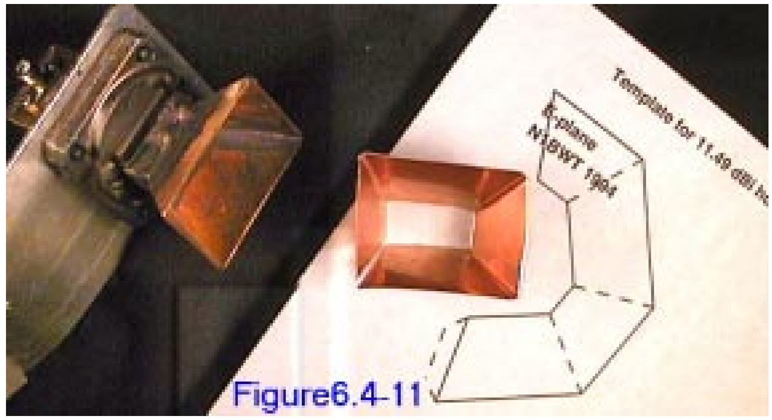


Figure6.4-11

The large H-plane dimension of rectangular waveguide is the minimum horn aperture — as a result, the minimum ***f*/D** which can be illuminated with a WR-90 waveguide is 0.48. A smaller waveguide, WR-75, also works at 10.368 GHz; using this, the minimum ***f*/D** would be 0.45. A minimum aperture horn with straight walls in the H-plane but a flare in the E-plane to make the pattern symmetrical is called an E-plane sectoral horn.

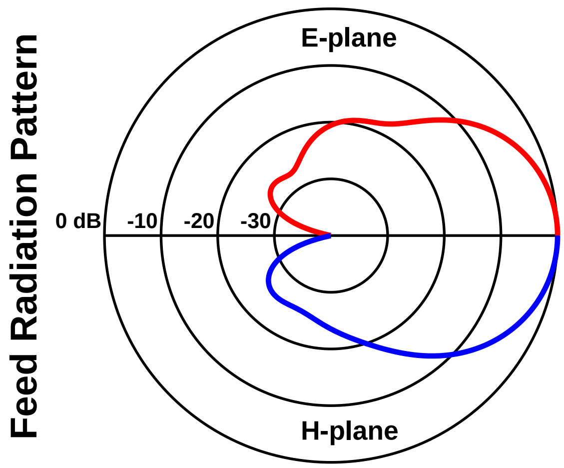
Thus, rectangular feedhorns are more suitable for shallower dishes. One obvious application is offset-fed dishes, which typically require a feed suitable for a conventional dish with ***f*/D** around 0.7. I have had excellent results using a rectangular feedhorn for a DSS offset dish at 10.368 GHz, which I designed using the G3RPE approximation in the **HDL_ANT** program. In Figure 6.4-12, the radiation patterns calculated using P.O. show good symmetry and phase uniformity over the illumination angle. There is a sidelobe in the E-plane pattern, but calculated efficiency is still very good, and measured efficiency is very high, around 63%. The phase center is 0.2λ inside the aperture. Not shown are the patterns in the 45º planes, which are very similar to the planes shown — this horn was a lucky design, as I was not able to calculate the patterns until much later. Figure 5-6 is a template for this horn.

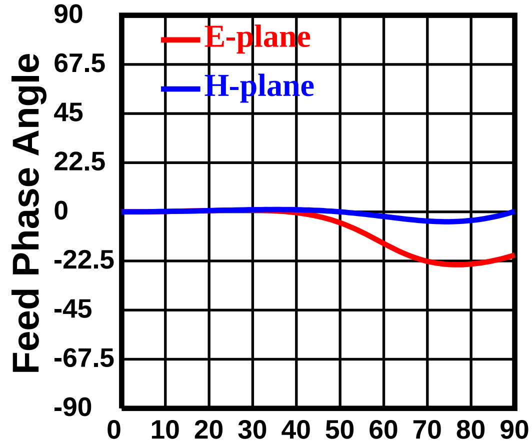
Another rectangular feedhorn for a DSS dish, using WR-137 waveguide at 5.76 GHz, is illustrated in Figure 6.4-13. When I designed this horn, I was able to calculate the patterns and adjust the horn length for good phase performance and minimum sidelobes. Success is shown by the calculated patterns — clean and symmetrical, with very good calculated efficiency. Measured efficiency is also very good.

Most surplus horns are optimized for gain rather than pattern symmetry, so they often fall short as feedhorns. I have found one notable exception, a small WR-90 horn of unknown provenance. The aperture measures 50 mm x 31 mm, and the length of the flare section is 43 mm. The radiation patterns calculated using P.O. are shown in Figure 6.4-14, as well as measured amplitude patterns shown in green. Correlation is pretty good for a backyard antenna range. Calculated efficiency is very high for ***f*/D** around 0.6 to 0.7, and phase is quite uniform over the illumination angle, with the phase center 0.12λ inside the aperture.

WR-90 rect. feedhorn for DSS offset dish at 10.368 GHz, by P.O.

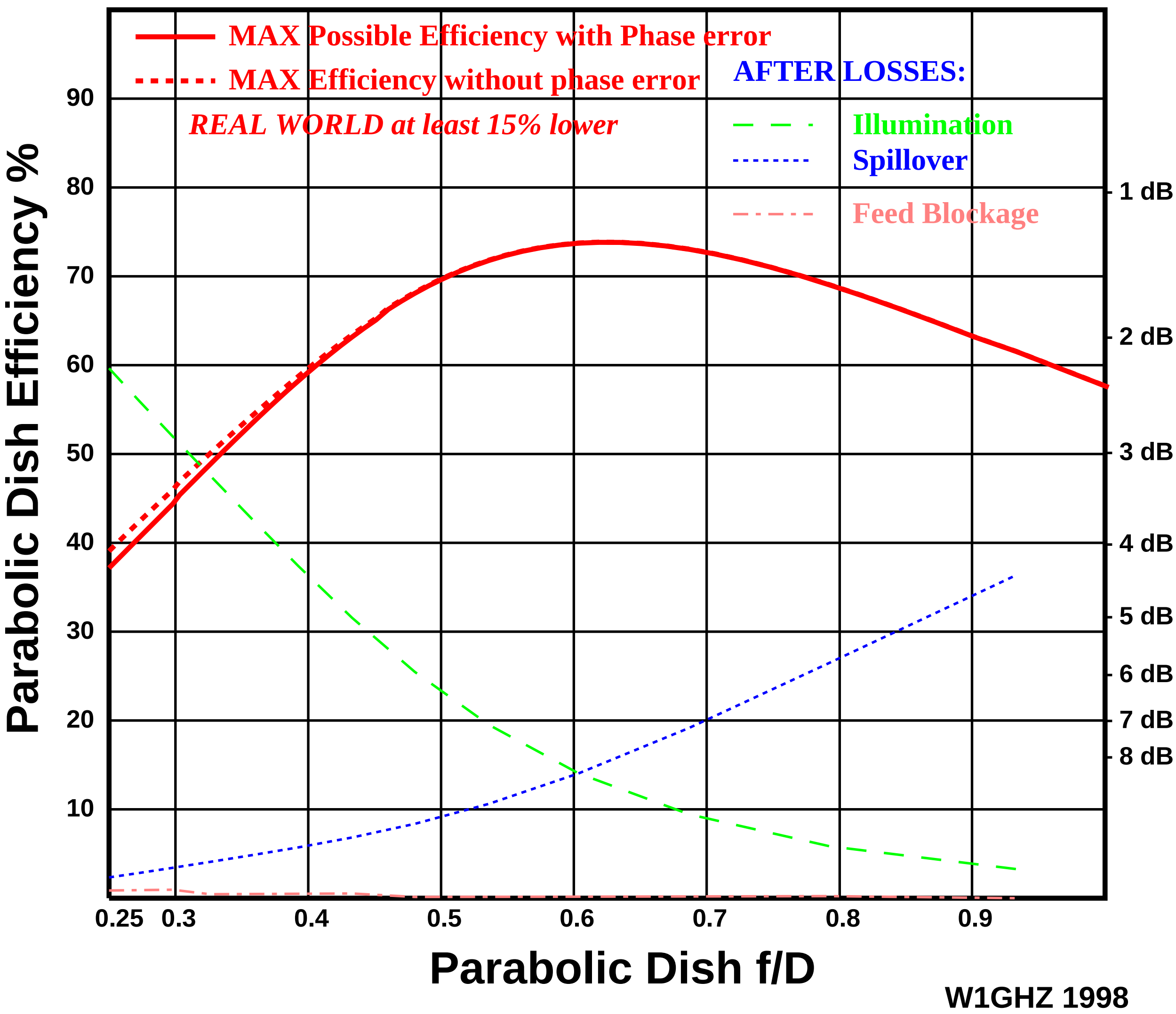
Figure 6.4-12





Dish diameter = 15.8 λ Feed diameter = 0.5 λ

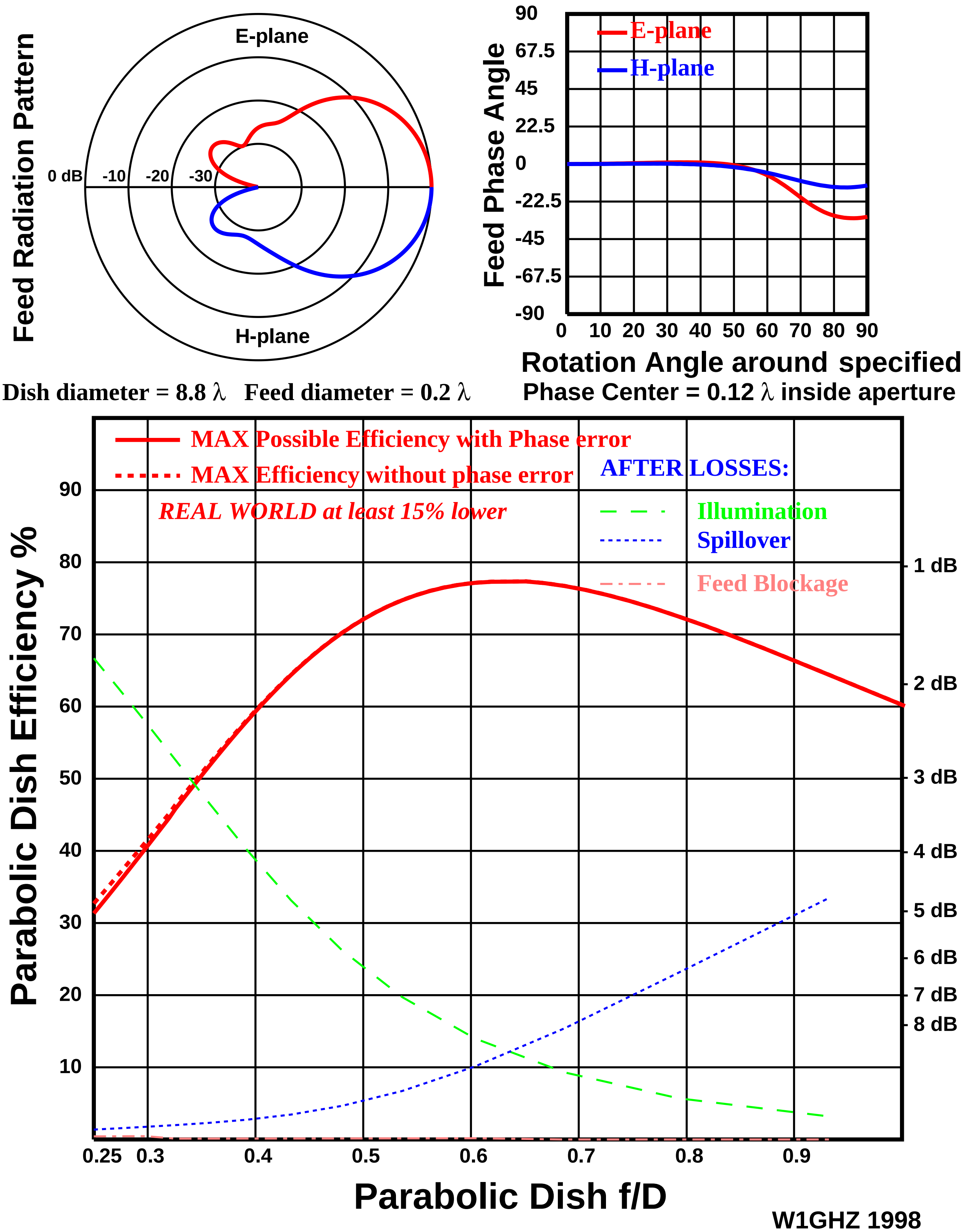
Rotation Angle around specified Phase Center = 0.2 λ inside aperture



W1GHZ 1998

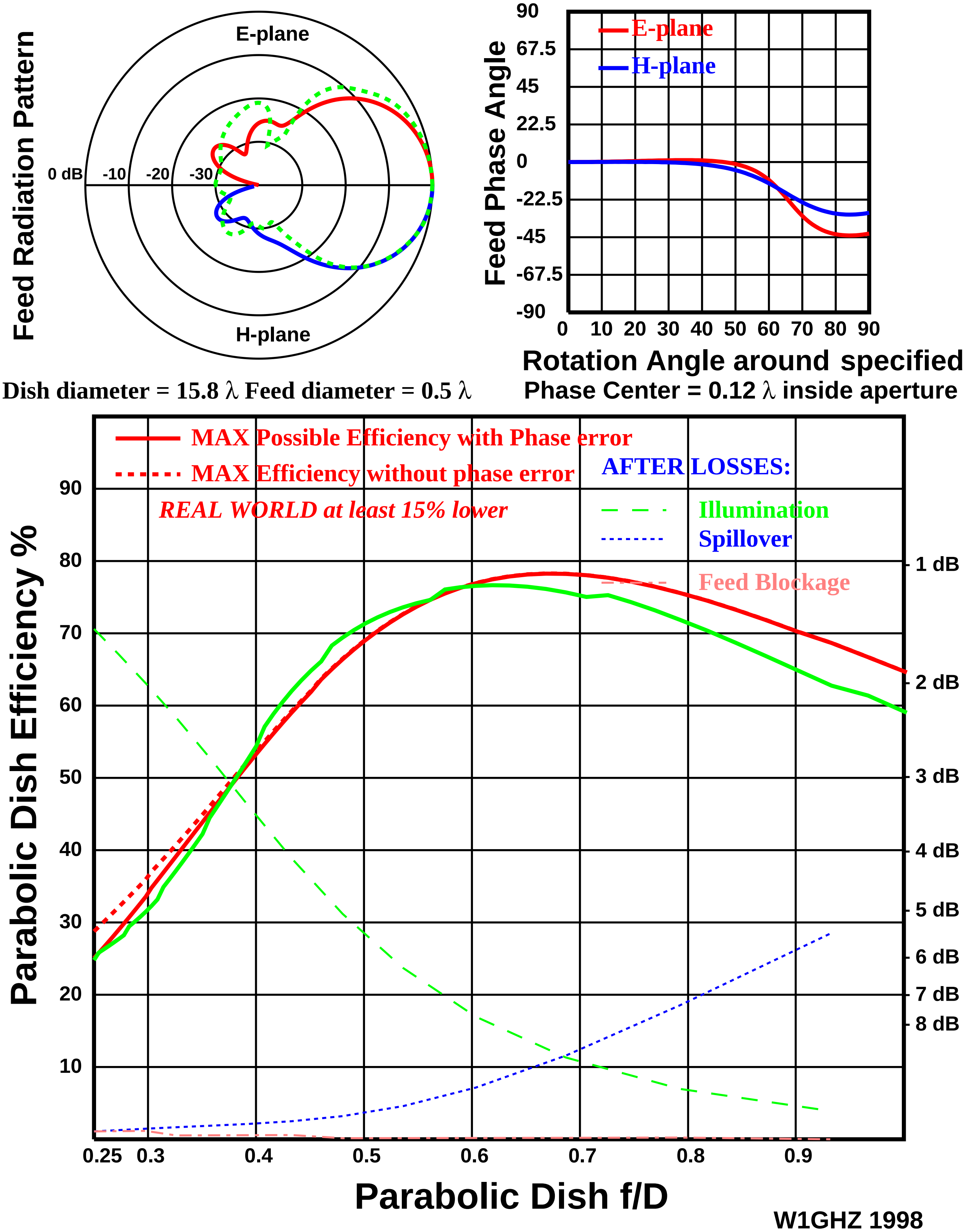
WR-137 rect. feedhorn for DSS offset dish at 5.76 GHz, by P.O.

Figure 6.4-13



WR-90 surplus rectangular horn at 10.368 GHz, by P.O.

Figure 6.4-14



My attempt to adjust the dimensions of a horn for a cardioid pattern are described in section 6.1, with the final result shown in Figure 6.1-14. For very deep dishes, the calculated efficiency is slightly higher than the open waveguide of Figure 6.4-9, but there is no experimental verification.

The flexibility provided by the rectangular horn of adjusting the two planes separately may be used to advantage in feeding odd-shaped dishes. One intriguing one is an oblong DSS dish, much wider than it is high, and usually marked "Primestar." NY2US kindly provided a used one for me to examine. I took surface measurements and used the curve-fitting routine in **HDL_ANT** version 3 to estimate the focal point and illumination angles. My estimate is that the focal length is 525 mm, with the feed in front of the notch for the feed support. Estimated illumination angles are 66° in the vertical direction, for an equivalent ***f*/D** of 0.8, and 88° in the wider horizontal direction, for an equivalent ***f*/D** of 0.65. Fortunately, for horizontal polarization, the asymmetry is in the same direction as rectangular waveguide. I used the G3RPE approximations in **HDL_ANT** to select aperture dimensions of 1.7λ in the H-plane and 1.0λ in the E-plane. Using these dimensions, I calculated radiation patterns using P.O. for different horn flare lengths. A length of 2λ yields pleasing radiation patterns, shown in Figure 6.4-15. The E-plane pattern is wider than the H-plane, to suit the oblong dish, and phase is flat over the respective illumination angles, with phase center 0.09λ inside the aperture. Calculated efficiency is very good over the 0.65 to 0.8 ***f*/D** range for a round reflector — efficiency for the oblong reflector should be in the same ballpark. I have not yet tried this feedhorn, but anticipate building and testing one in the near future.

Horn physical dimensions

Most antenna books discuss rectangular horns in terms of flare angles. After finding patterns, etc., they then go into a convoluted procedure to see if the horn is physically realizable.

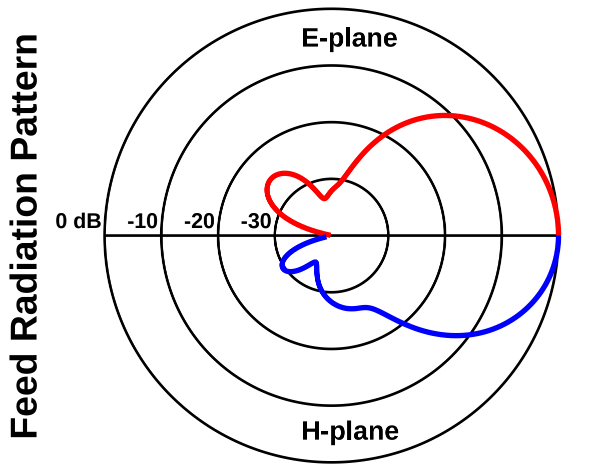
A better approach is to define a horn in terms of aperture dimensions and horn axial length, from waveguide attach to aperture. The physical pyramid is defined in three-dimensional space by eight points, the four corners of the aperture and the four corners of the waveguide. Thus we know *a priori* that the horn is physically realizable and worth doing calculations on. Calculating flare angles from the dimensions is a trivial part of the pattern calculations.

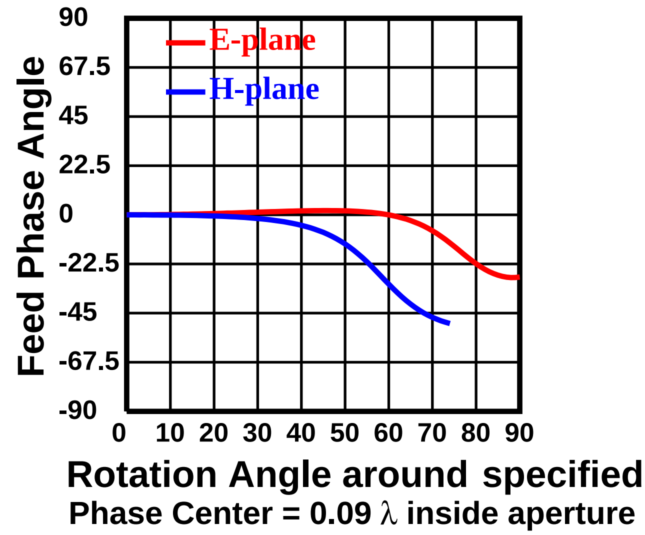
Conical horns are much simpler. Aperture diameter plus either length or flare angle completely define the horn.

In summary, the dimensions of a rectangular feedhorn may be adjusted for good performance for a range of shallower dishes. They are easy to construct with very reproducible performance. Excellent performance has been demonstrated as a feed for a DSS offset dish.

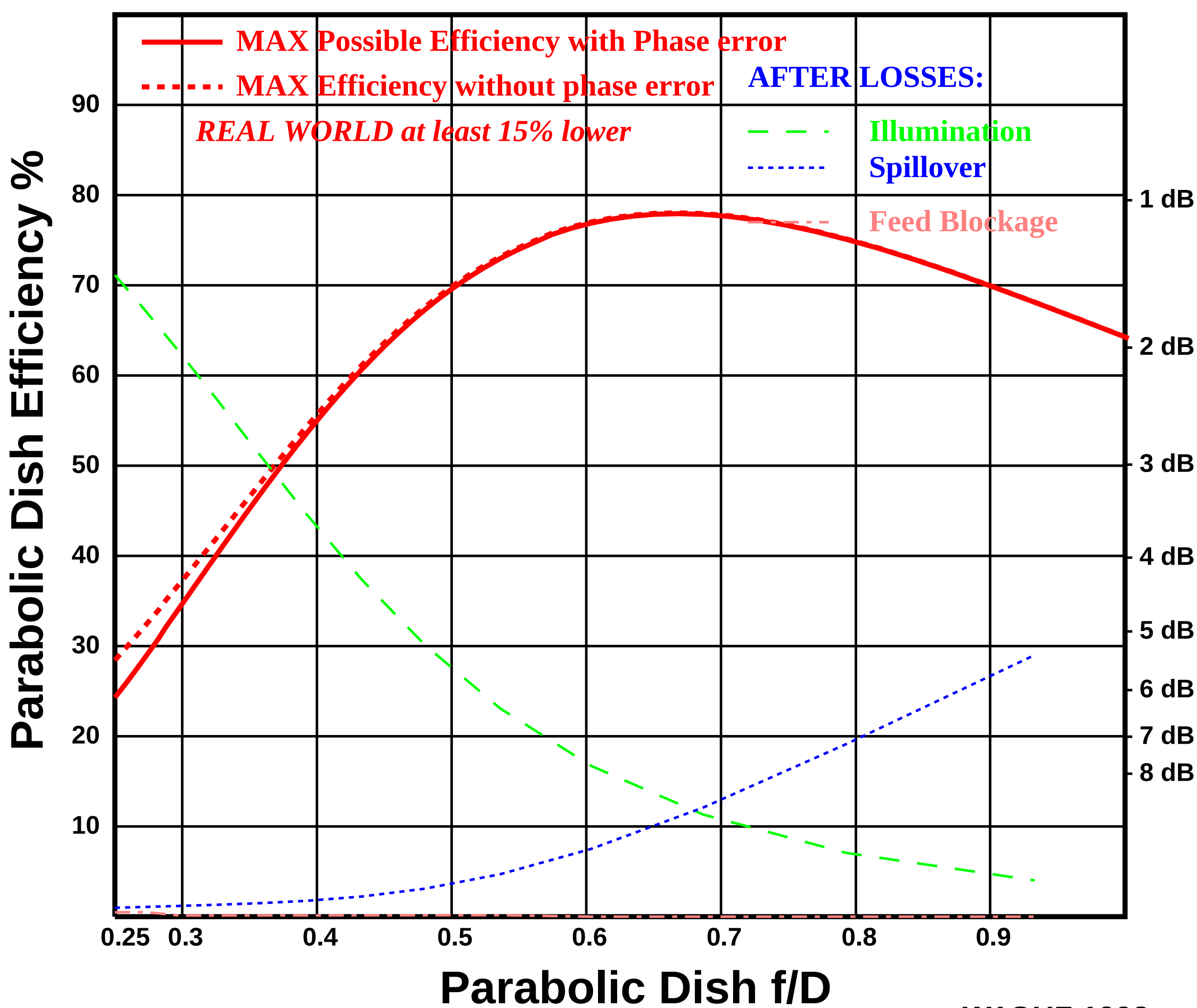
WR-90 horn for Primestar oblong offset dish, by P.O.

Figure 6.4-15





Dish diameter = 25 λ   Feed diameter = 0.5 λ



W1GHZ 1998

6.4.3 Corrugated horn feeds

The corrugated horn was first described[8] by Simmons and Kay, who called it a "Scalar" feed, because it has the same performance in all polarizations. The idea is to eliminate the E-plane edge currents in the rim of the horn by adding slots or grooves perpendicular to the wall of the horn: "If the grooves are made deep enough so that the surface reactance is capacitive, surface waves cannot be supported." The required depth[9] is greater than $\lambda/4$ and less than $\lambda/2$.

The polarization-independent properties of the corrugated wall permit propagation of hybrid modes[10], a hybrid of TE and TM modes; when the hybrid modes are balanced, the radiation patterns become very symmetrical.

A corrugated horn can operate over a wide frequency range with good performance[11], so any surplus horn we might find has potential. We would expect good performance at any frequency where the slots meet the depth requirements described above. Of course, the input waveguide must be large enough to support propagation, so the wavelength must be less than 1.706 times the diameter.

The original corrugated horns had the slots perpendicular to the horn walls, as shown in the lower sketch in Figure 6.4-16. Manufactured versions have the slots parallel to the waveguide wall, like the upper sketch, to allow rapid machining. Anyone who has used a lathe can appreciate why the upper version is easier. Two modern corrugated horns are shown in Figure 6.4-17: the lower one was sold by Chaparral as an "11 GHz offset feed," while the unmarked one at the top was found at a hamfest. Both horns appear to have been die-cast to shape in aluminum, with no further machining operations.

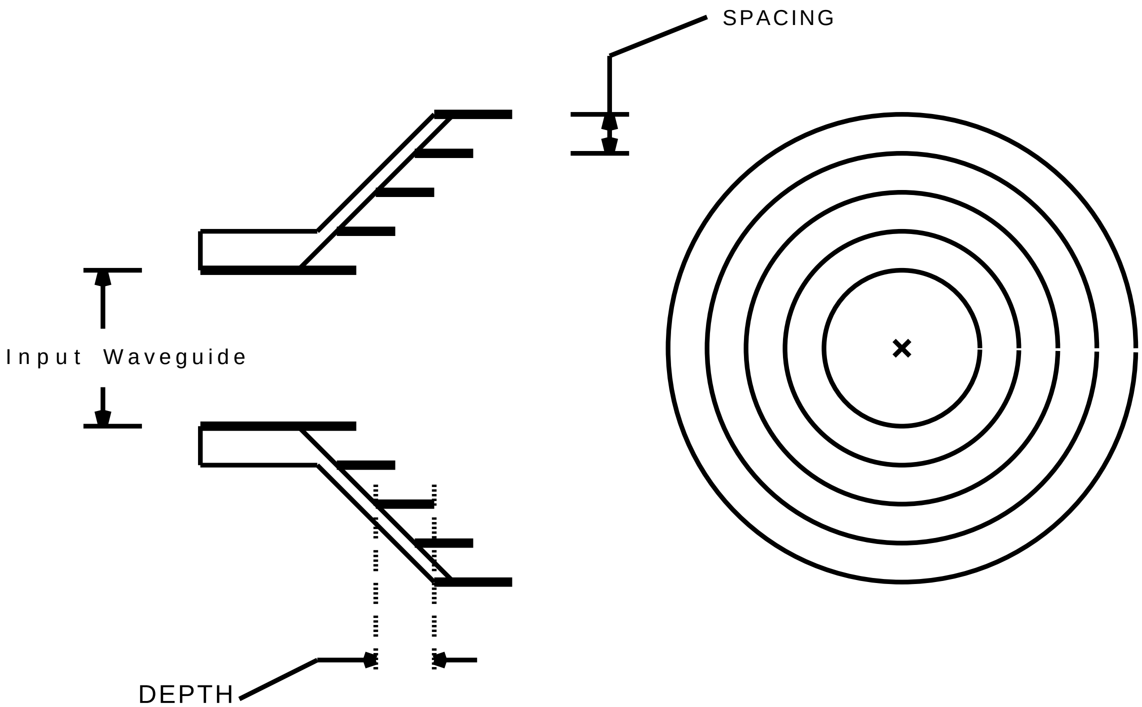
While most corrugated horns are conical, pyramidal corrugated horns have also been described. The corrugations can eliminate the E-plane edge currents and resultant E-plane sidelobes, but there is no easy way to fabricate these horns.

A popular application for corrugated horn feeds is the DSS offset-fed dishes. The corrugated wall enables good performance over a reasonable bandwidth, and the scalar property enables operation using multiple polarities or circular polarization without performance degradation.

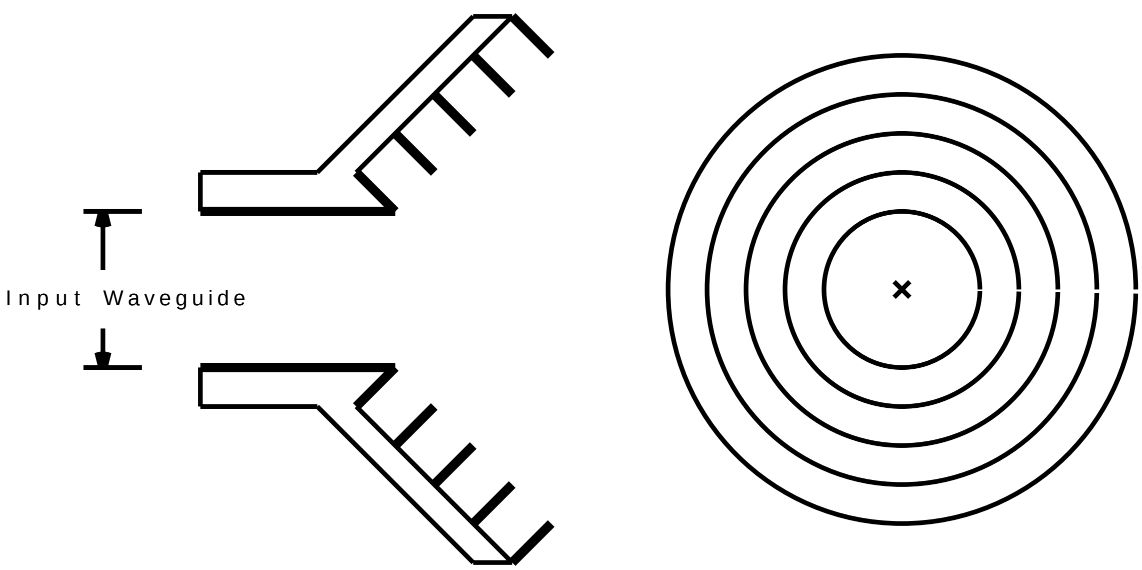
W1RIL has successfully separated the RCA DSS feed from the LNB assembly and modified it for 10 GHz operation, with excellent measured sun-noise performance. I used the horn dimensions he provided to calculate radiation patterns at 10.368 GHz. The results, shown in Figure 6.4-18, are a very clean pattern with flat phase and a phase center 0.24λ inside the aperture. Calculated efficiency is very high, peaking in the 0.6 to 0.7 ***f*/D** range suitable for the DSS offset dish. The slots are deeper than $\lambda/4$ at 10.368 GHz, so the horn still works well even though it was intended for the higher frequency DSS band.

CORRUGATED HORN FEED

Figure 6.4-16



Machinable Version

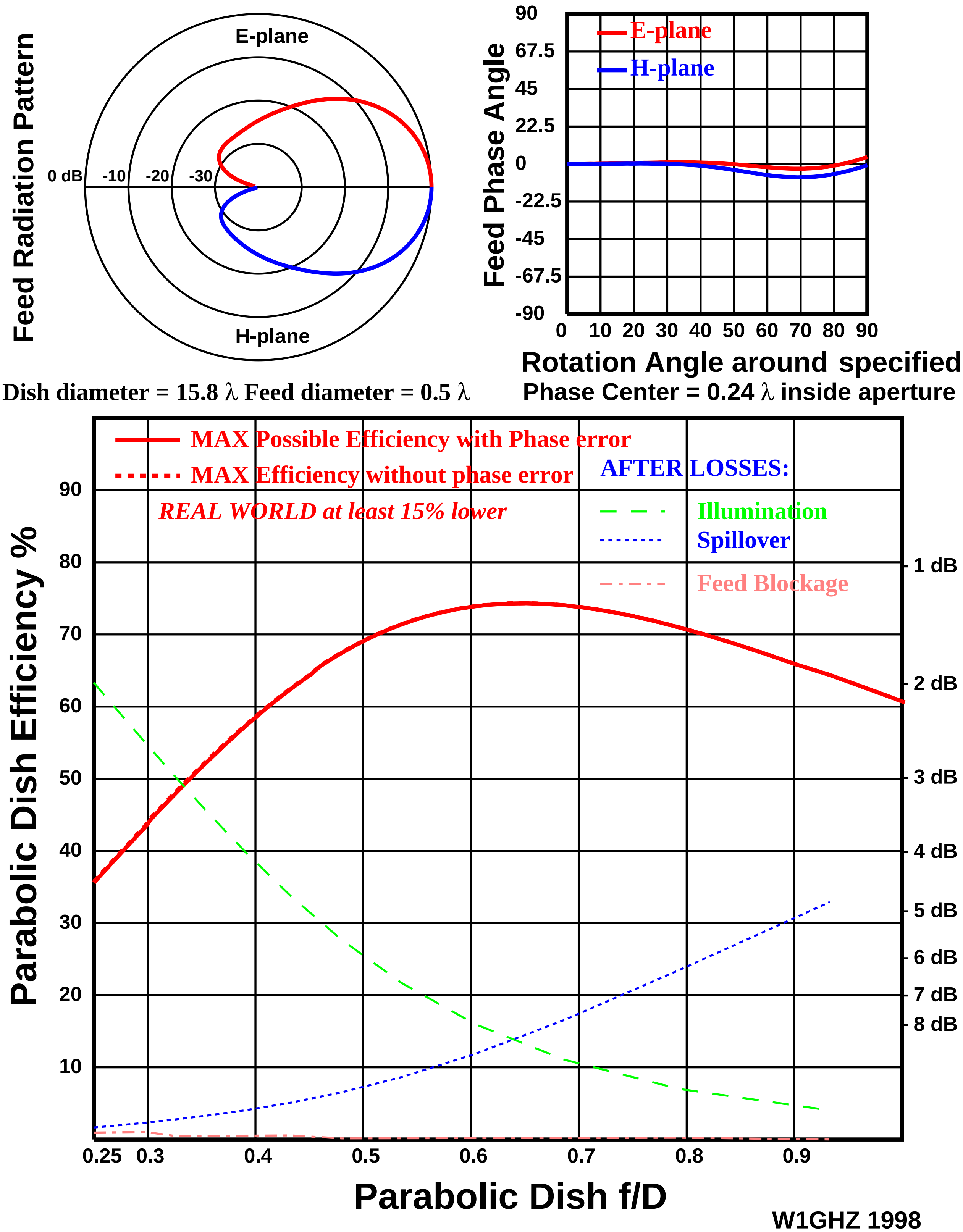


Original Version

W1GHZ 1998

RCA DSS corrugated horn, 1.95" aperture, 58 deg flare, by P.O.

Figure 6.4-18



For comparison, we previously considered a plain conical horn with the same dimensions, in Figure 6.4-8. The corrugated version has significantly higher calculated dish efficiency, or a dish gain almost a dB higher. However, the rectangular feedhorn for the DSS dish, in Figure 6.4-12, has a calculated efficiency only 1% lower than the corrugated feedhorn. The rectangular horn does have E-plane sidelobes that could add noise in a satellite application, so I would expect the corrugated horn to have a slightly larger **G/T** advantage as well as wider bandwidth. However, for terrestrial 10 GHz communications, the corrugated and rectangular horns should provide almost identical performance feeding a DSS dish.

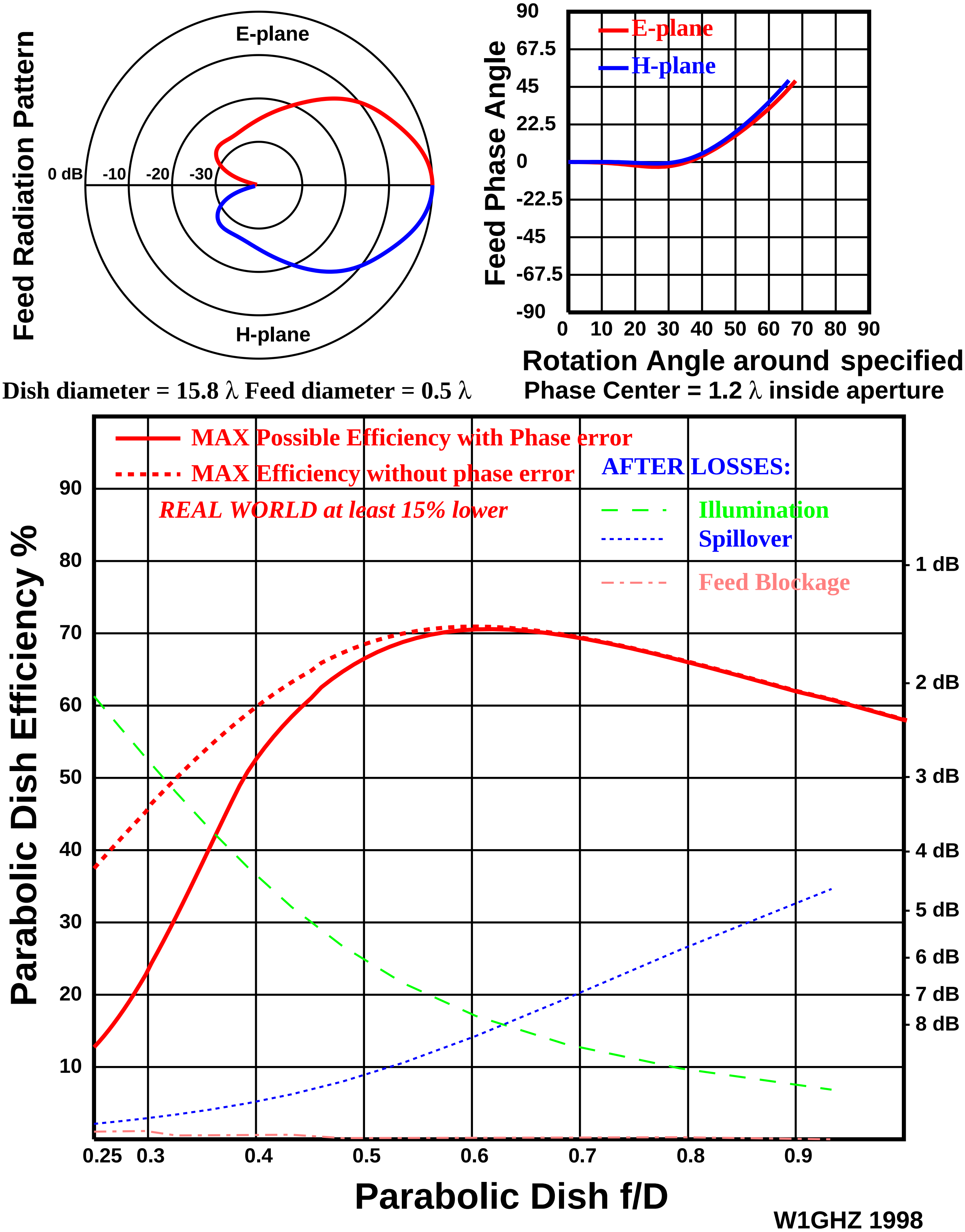
The Chaparral 11 GHz offset feed, the lower one in Figure 6.4-17, has slots less than $\lambda/4$ deep at 10.368 GHz, so edge currents are not completely eliminated. To see the effect of slot depth, I calculated radiation patterns at 12 GHz, where the slots are deeper than $\lambda/4$, as well as at 10.368 GHz. The 12 GHz patterns calculated using P.O. are shown in Figure 6.4-19, with clean, symmetrical patterns and good efficiency peaking at ***f*/D** around 0.6. At 10.368 GHz, the calculated patterns in Figure 6.4-20 show some asymmetry and E-plane sidelobes, and the calculated efficiency is reduced a bit due to phase error. On the other hand, the measured patterns, shown in green in Figure 6.4-20, are more symmetrical — perhaps the effective depth of the slanted slots is greater than the slot wall dimension shown in Figure 6.4-16. At both frequencies, the phase center is about 1.2λ inside the aperture.

The upper corrugated horn in Figure 6.4-17 has deeper slots, more than $\lambda/4$ at 10.368 GHz. However, the waveguide diameter was too small for my circular waveguide (3/4" copper pipe), but the aluminum wall was thick, so I bored it out on a lathe to fit over the pipe. The calculated radiation patterns, in Figure 6.4-21, show good symmetry and no significant sidelobes. Calculated efficiency is good, but best ***f*/D** is around 0.55, so the pattern is rather broad for an offset dish. Phase center is about 1.1λ inside the aperture.

I measured the efficiency of these last two corrugated horns at 10.368 GHz using sun noise. On a 0.85 meter offset dish requiring illumination equivalent to ***f*/D** = 0.7, both horns exhibited efficiency several percentage points lower than the rectangular horn offset feed in Figure 6.4-11 and 6.4-12. This is not unexpected — we saw in Figure 6.4-20 that the Chaparral offset feed suffers slightly in comparison to the 12 GHz performance in Figure 6.4-19.

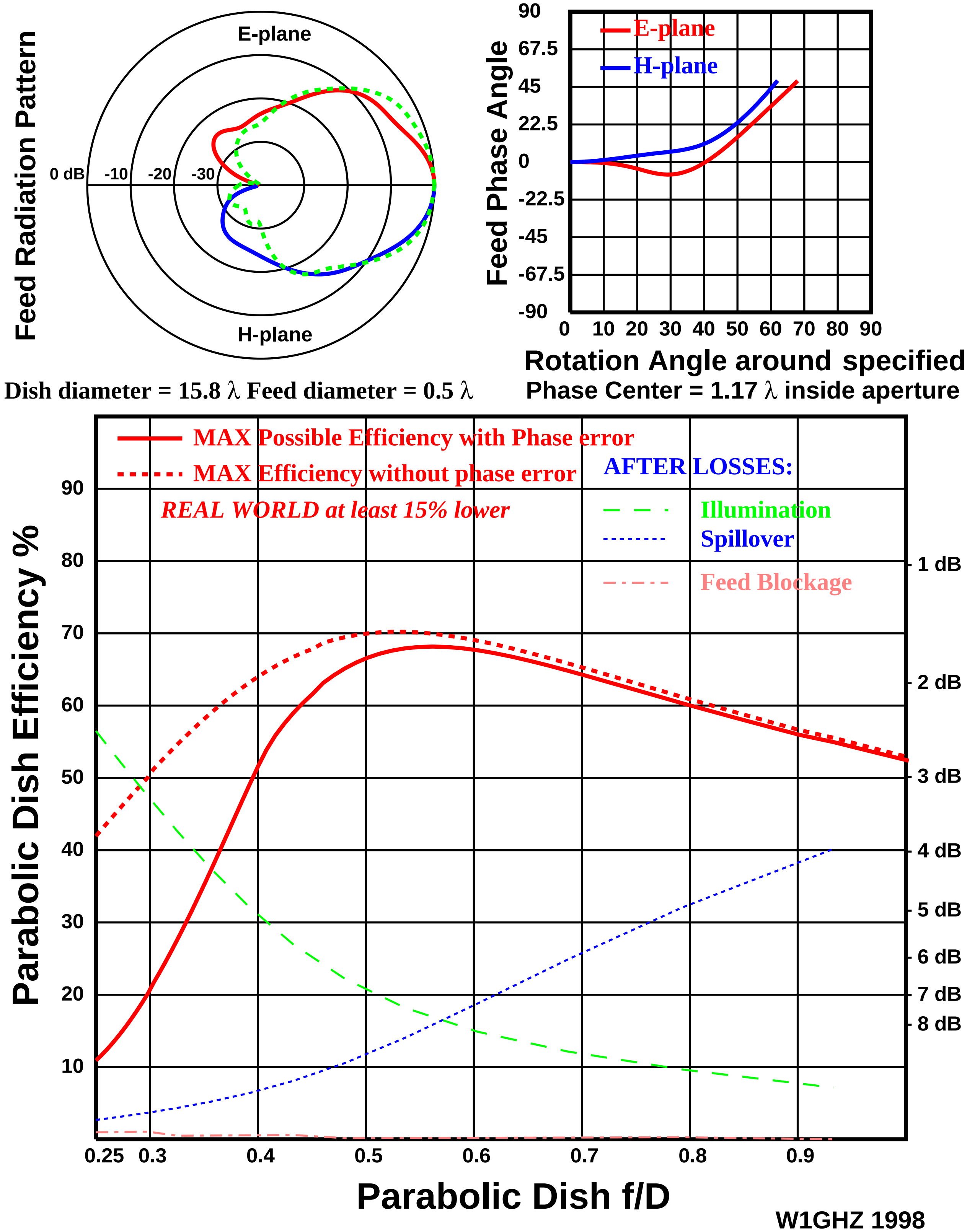
Chaparral offset feed at 12 GHz, 2.59" dia, 90 deg flare, by P.O.

Figure 6.4-19



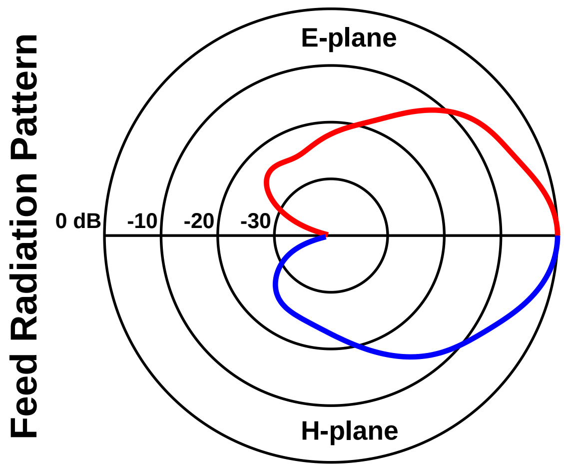
Chaparral 11GHz offset feed at 10.368 GHz, 2.59", 90 deg, by P.O.

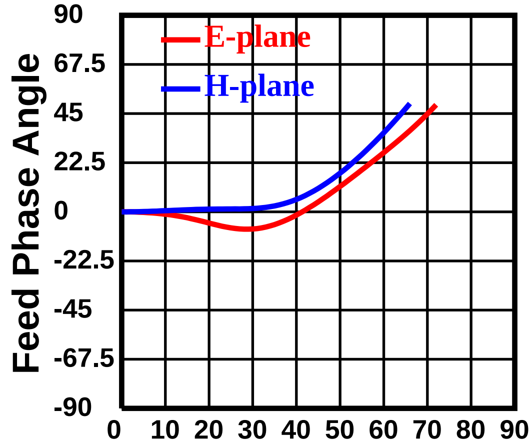
Figure 6.4-20



Corrugated horn, 2.3λ dia, 96 deg flare, at 10.368 GHz, by P.O.

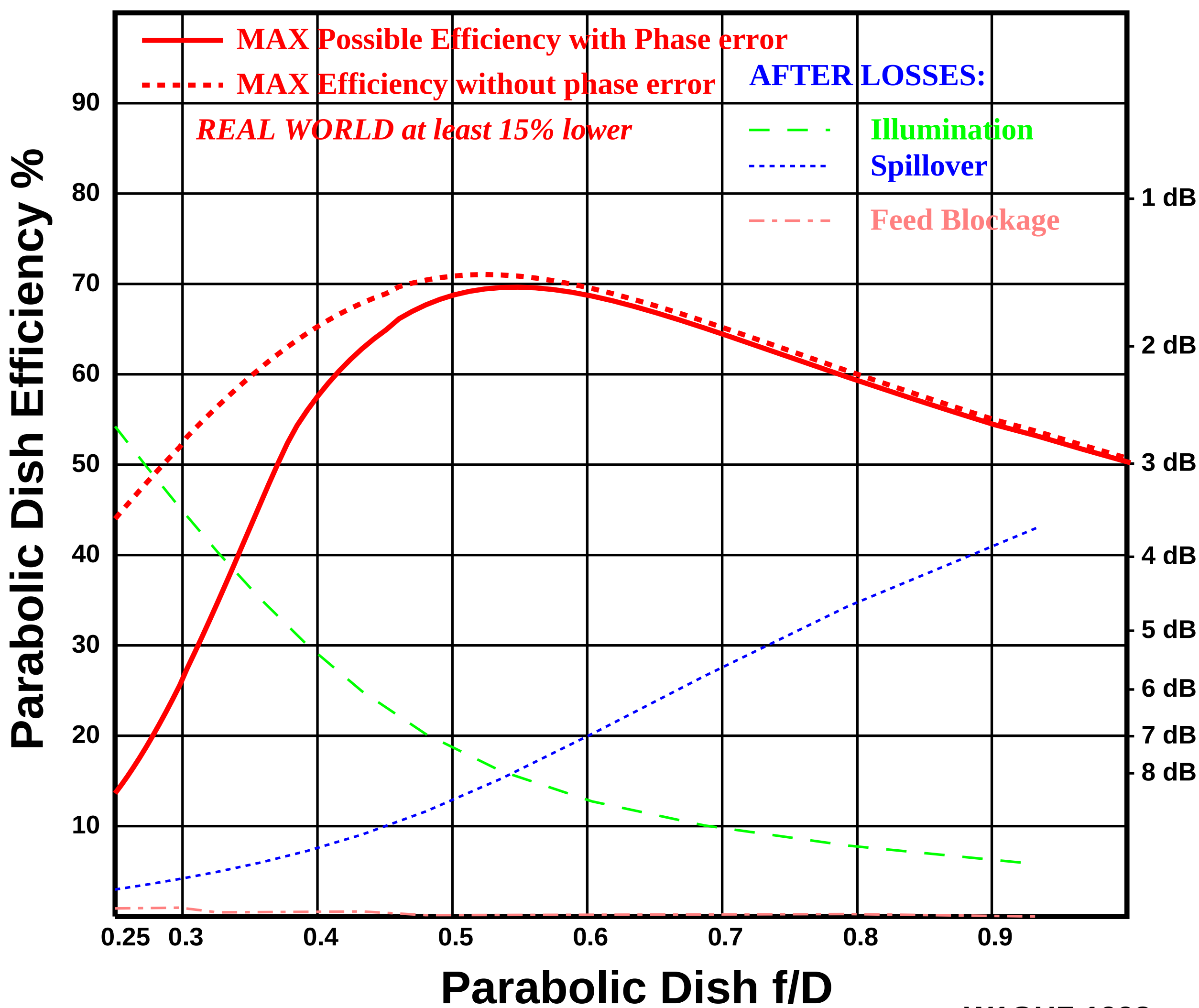
Figure 6.4-21





Dish diameter = 15.8 λ Feed diameter = 0.5 λ

Rotation Angle around specified
Phase Center = 1.1 λ inside aperture



W1GHZ 1998

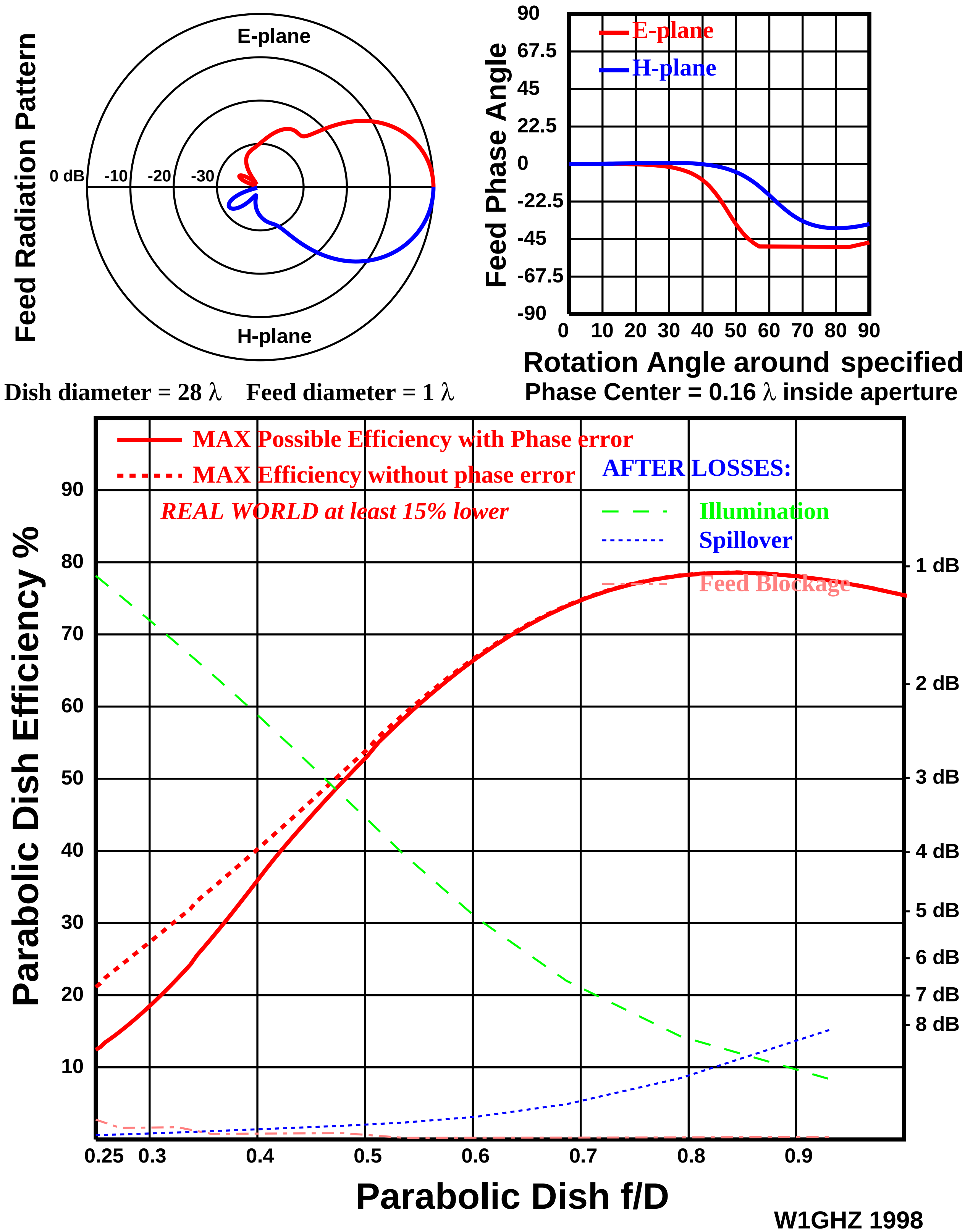
These last two corrugated feedhorns have rather wide flare angles, around 90° full flare angle. I obtained another corrugated feedhorn with a much narrower flare, about 47° full flare angle, and an aperture of 1.9 inches. This feed is intended to feed a 0.8 meter offset dish with ***f*/D** = 0.8 equivalent illumination, narrower than any other offset dish I have seen. I modeled the feedhorn at 12 GHz, with the results plotted in Figure 6.4-22: the calculated efficiency is excellent for ***f*/D** around 0.8, and better than for any of the previous corrugated horns. However, the calculated efficiency at 10.368 GHz, shown in Figure 6.4-23, peaks at ***f*/D** around 0.65 and falls off for ***f*/D** = 0.8. This feed is probably better for normal offset dishes at 10 GHz, assuming that the corrugations are deep enough. Sun noise measurements at 10.368 GHz on the 0.8 meter dish are consistent with the calculations: efficiency is around 55%, significantly lower than a W2IMU dual-mode feed designed for ***f*/D** = 0.8 which we will see in Section 6.5

A corrugated horn may be almost any size, from a corrugated cylindrical waveguide[10] to a large horn. VK2ALU was able to obtain a shaped-reflector dish 3.7 meters in diameter with a Gregorian-style feed, with a concave subreflector, but without the feedhorn. The curvature of the shaped reflectors deviates from the normal parabolic main reflector and elliptical subreflector to achieve higher efficiency. Since we do not know the exact curvature, it is difficult to design a feedhorn. However, Lyle was able to locate the corrugated feedhorn dimensions, 140 mm in diameter with a 30º flare angle, and asked me to calculate the feedhorn patterns so that he could design a 10 GHz feed to provide a similar illumination pattern. The original feed was intended for 11 to 14 GHz, so I calculated patterns at 12 GHz, shown in Figure 6.4-24. As expected, the pattern is very narrow, with –10 dB illumination angles of 28º in the E-plane and 26º in the H-plane. There are small sidelobes in the E-plane, but not significant since they are more than 20 dB down. The phase center is more than 6λ inside the aperture, as shown in Figure 6.4-25. The calculated efficiency is best for ***f*/D** around 1.5 to 2, for a conventional dish.

In summary, corrugated horns have good patterns over a wide frequency range and can provide excellent performance as feedhorns. Fabrication could be difficult, but the wide bandwidth capability makes it possible to make use of one intended for another frequency.

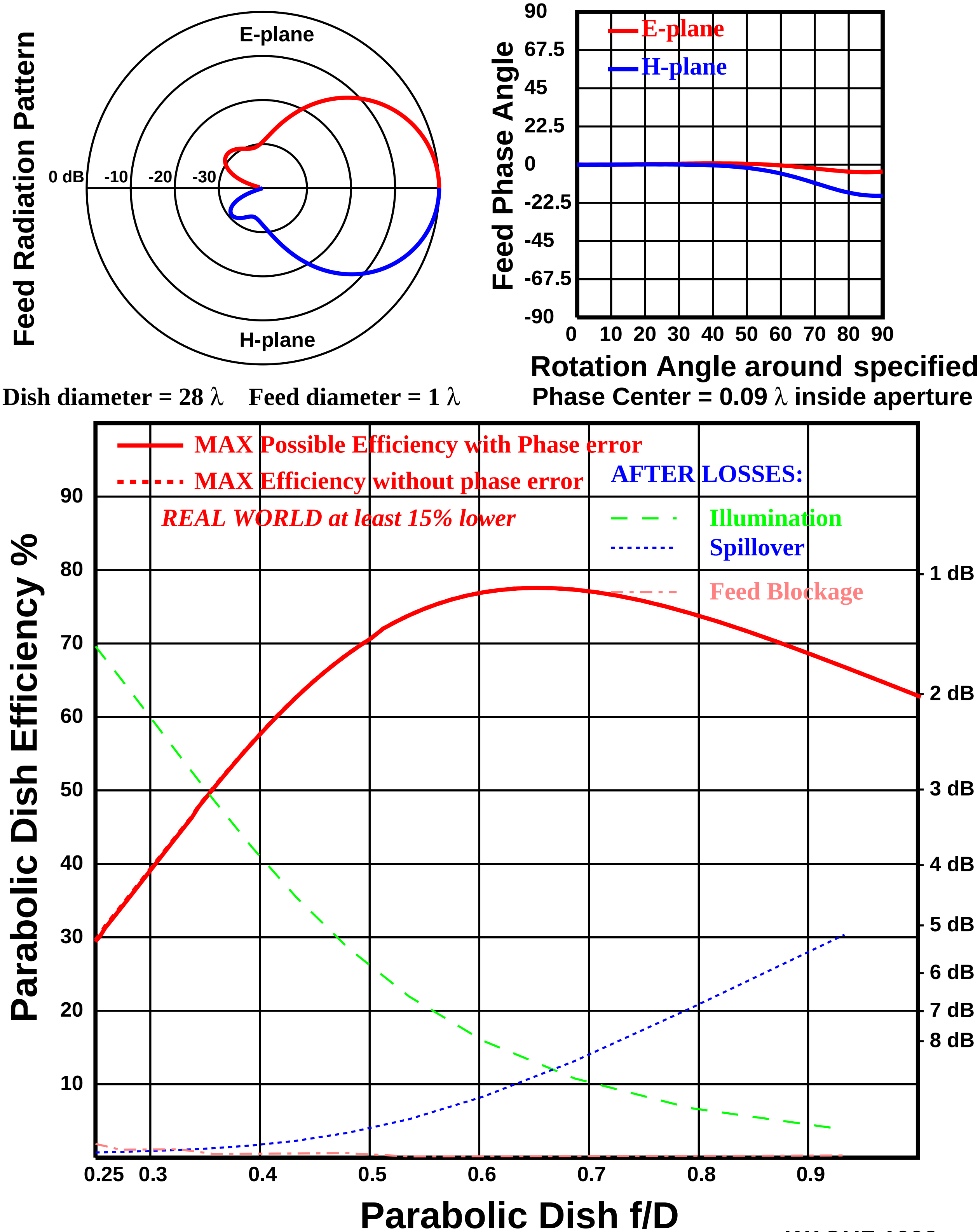
Corrugated horn for offset dish f/D=0.8 at 12 GHz, by P.O.

Figure 6.4-22



Corrugated horn for offset dish f/D=0.8 at 10.368 GHz, by P.O.

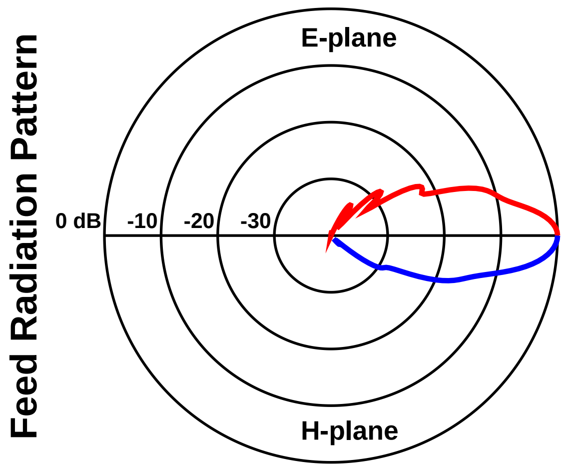
Figure 6.4-23

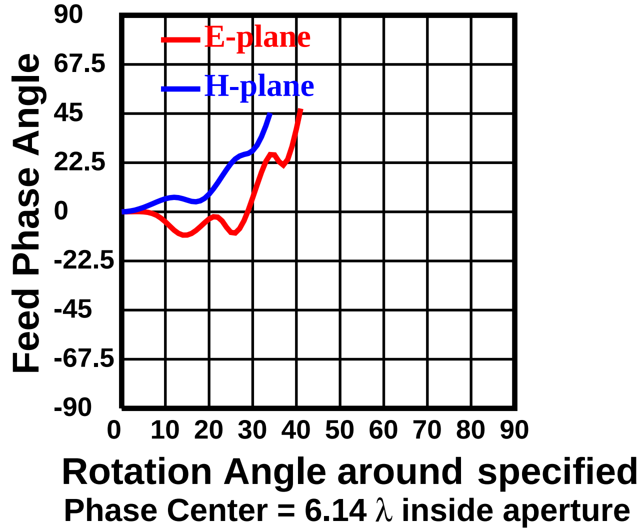


W1GHZ 1998

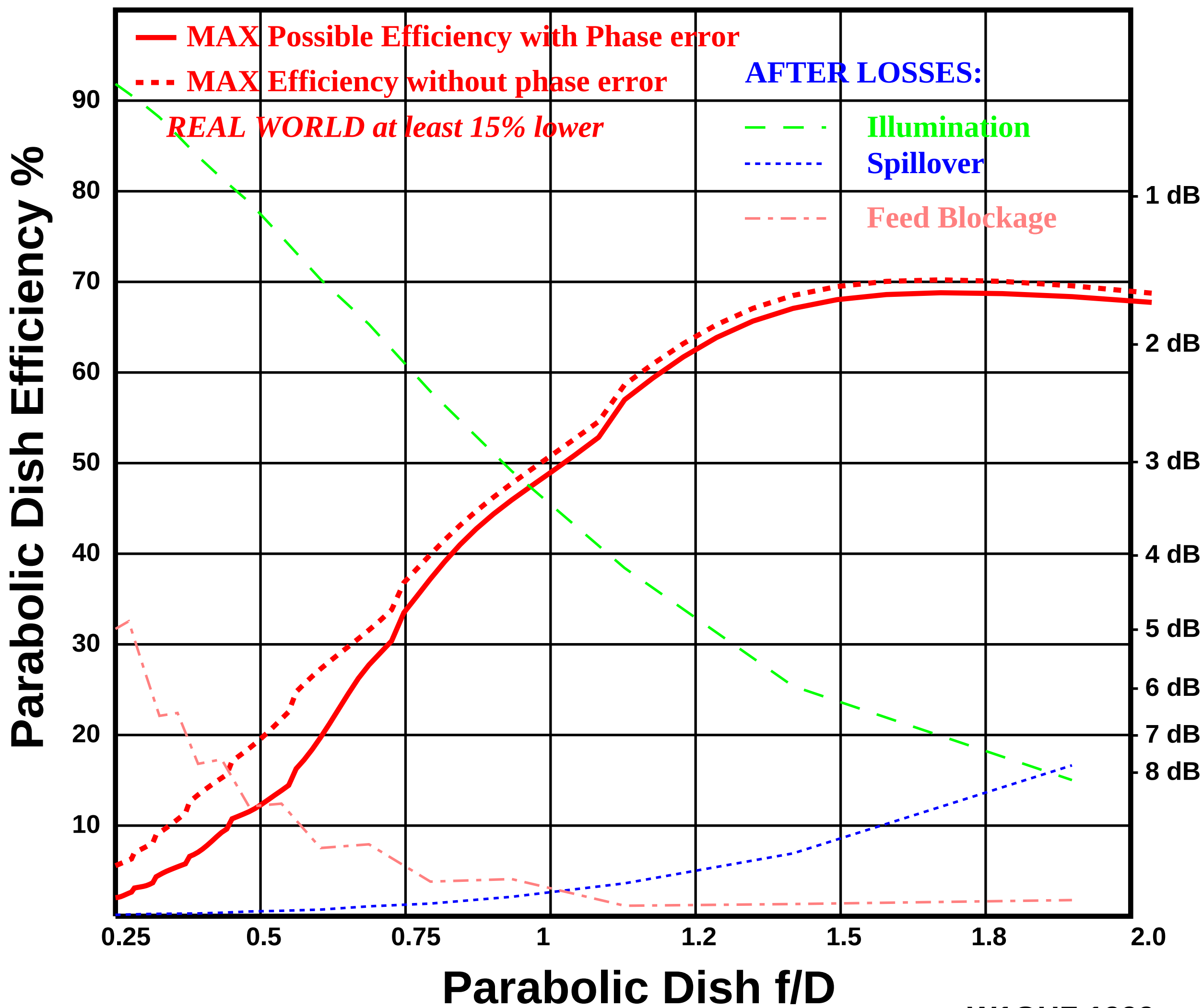
Andrew corrugated feedhorn for Gregorian at 12 GHz, by P.O.

Figure 6.5-24





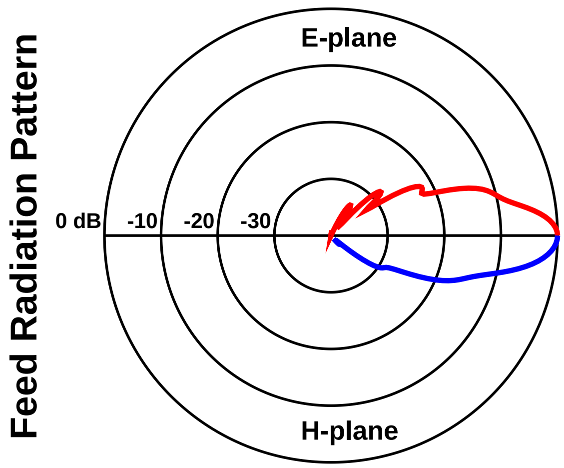
Dish diameter = 128 λ Feed diameter = 10 λ



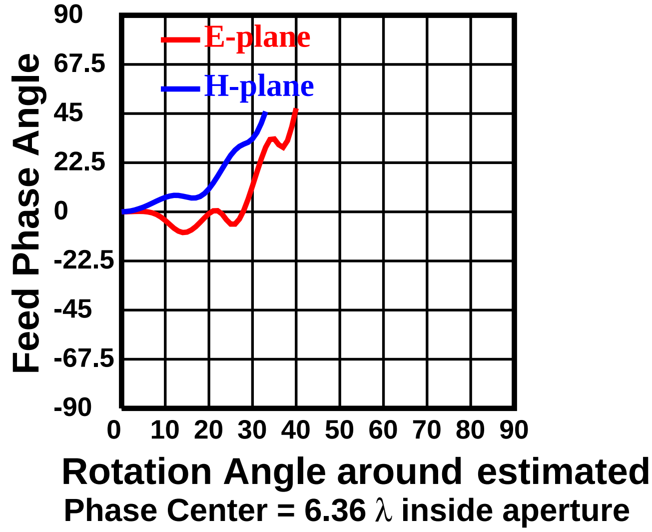
W1GHZ 1999

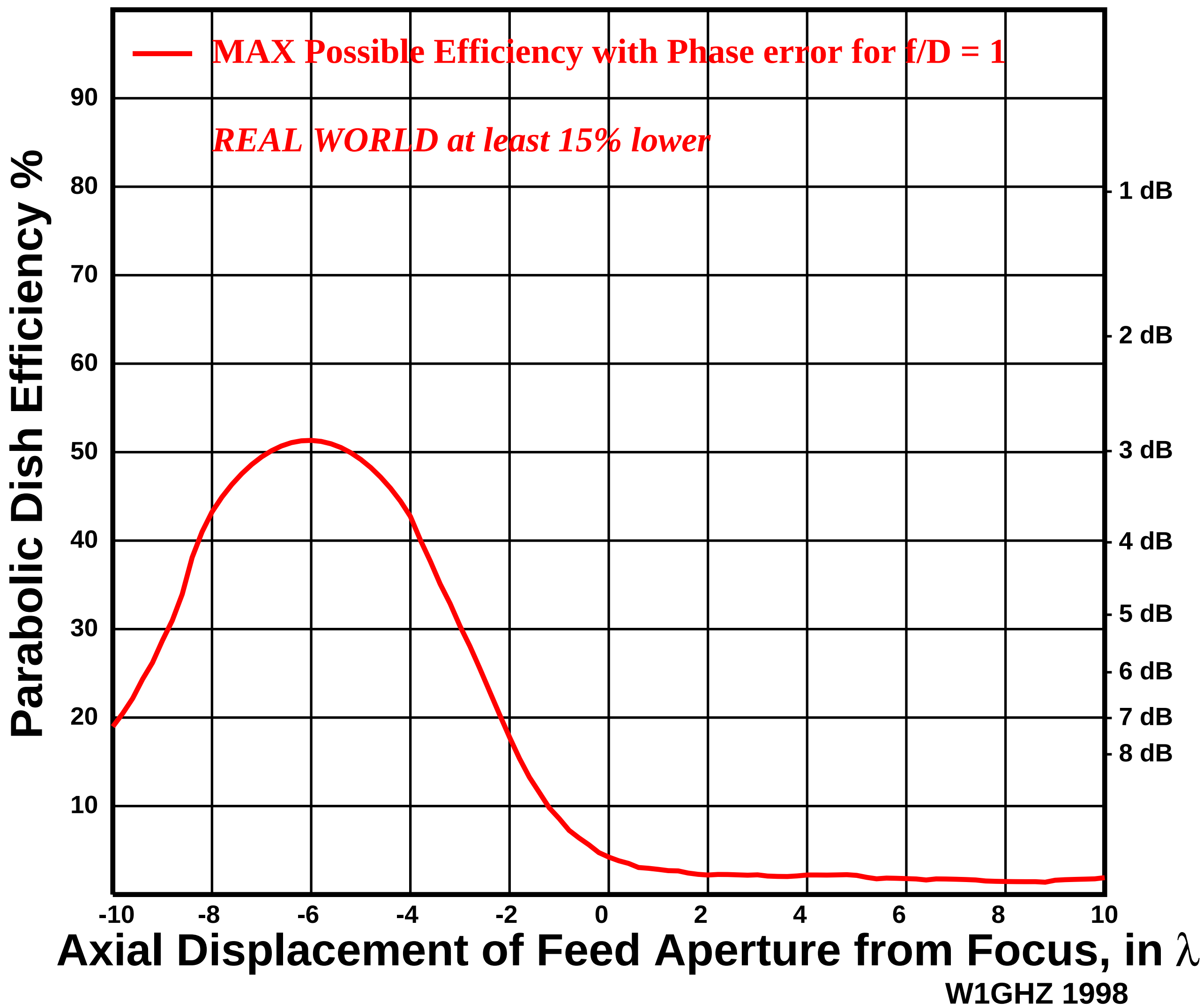
Andrew corrugated feedhorn for Gregorian at 12 GHz, by P.O.

Figure 6.4-25



Dish diameter = 150 λ Feed diameter = 5 λ





W1GHZ 1998

References

1. G.C. Southworth & A.P. King, “Metal Horns as Directive Receivers of Ultra-Short Waves,” *Proceedings of the IRE*, February 1939, pp. 95-102. (reprinted in A.W. Love, *Electromagnetic Horn Antennas,* IEEE, 1976, pp. 19-26.)

2. L. Diaz & T. Milligan, *Antenna Engineering Using Physical Optics,* Artech, 1996.

3. W.V.T. Rusch, “A Comparison of Geometrical and Integral Fields From High Frequency Reflectors,” *Proceedings of the IEEE,* November 1974, pp. 1603-1604.

4. A.P. King, “The Radiation Characteristics of Conical Horn Antennas,” *Proceedings of the IRE*, March 1950, pp. 249-251. (reprinted in A.W. Love, *Electromagnetic Horn Antennas*, IEEE, 1976, pp. 56-58.)

5. H. Jasik, *Antenna Engineering Handbook*, First Edition, Mcgraw-Hill, 1961. Fig. 10-14, p. 10-16.

6. D. Evans, G3RPE, “Pyramidal horn feeds for paraboloidal dishes,” *Radio Communications*, March 1975. also in:
7. M.W. Dixon, G3PFR, *Microwave Handbook, Volume 3,* RSGB, 1992, p. 18.85.

8. A.J. Simmons & A.F. Kay, “The Scalar Feed — A High Performance Feed for Large Paraboloid Reflectors,” *Design and Construction of Large Steerable Aerials*, IEE Conf. Publ. 21, 1966, pp. 213-217. (reprinted in A.W. Love, *Electromagnetic Horn Antennas*, IEEE, 1976, pp. 248-252.)

9. C.A. Mentzer & L. Peters, Jr., “Properties of Cutoff Corrugated Surfaces for Corrugated Horn Design,” *IEEE Transactions on Antennas and Propagation*, March 1974, pp. 191-196. (reprinted in A.W. Love, *Electromagnetic Horn Antennas*, IEEE, 1976, pp. 262-267.)

10. P.J.B. Clarricoats & P.K. Saha, “Propagation and radiation behaviour of corrugated feeds, Part 1 — Corrugated waveguide feed,” *Proc. Inst. Elec. Eng.*, Sept. 1971, pp. 1167-1176. (reprinted in A.W. Love, *Electromagnetic Horn Antennas*, IEEE, 1976, pp. 304-313.)

11. B. Maca. Thomas, “Bandwidth properties of Corrugated Conical Horns,” *Electronic Letters*, October 30, 1969. (reprinted in A.W. Love, *Electromagnetic Horn Antennas*, IEEE, 1976, pp. 287-289.)