Chapter 6

Feeds for Parabolic Dish Antennas

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Section 6.1 Phase and Phase Center

The antenna computer analysis that I have seen has only considered the amplitude of the radiated pattern. For instance, Chapter 11 covers the analysis of parabolic dish feeds, using the amplitude pattern for analysis. While I was doing this analysis, a nagging voice in my head kept saying, “What about the phase?”

While measurement of the phase pattern of an antenna is extremely difficult, calculation of an antenna pattern with both amplitude and phase is much easier. With today’s fast personal computers, it is possible to calculate the radiation pattern of most common feed antennas, including both amplitude and phase. Chapter 12 describes how I calculate radiation patterns and extract the phase information for analysis.

The personal computer is also valuable in helping us to understand the radiation pattern data, by transforming it into a graphical format so that we may visually comprehend the result. These plots make it possible to quickly see not only the radiation pattern of a feed antenna, but also how a dish will perform with the feed.

The results of these calculations and plots show that most of the feed antennas in common use have good phase performance. Another result is that the phase center of each feed may be calculated, so that the feed may be accurately located with its phase center at the focus of a parabolic dish, an essential ingredient for good dish performance.

6.1.1 Phase

For a parabolic dish antenna to good perform well, the feed must provide good illumination to the reflector, as we saw in Chapter 4; Figure 4-5 illustrates dish illumination. The illumination energy leaving the feed must not only have good amplitude characteristics, but also must all have the same phase. Energy that is out of phase can subtract from the total radiated power, so that the effect is worse than energy which is simply lost, such as spillover which misses the reflector. Figure 1-2 in

Chapter 1 illustrates phase cancellation: a, b, and c illustrate two in-phase signals adding, two out-of-phase signals canceling, and partial cancellation when two signals are partially out-of-phase. Figure 1-2d shows the uniform amplitude around a single-source antenna, while 1-2e shows the interference pattern created by having two sources; the lighter areas are directions where there is little radiated energy due to phase cancellation. A feed whose radiation does not all have the same phase will appear to have multiple sources which may produce an interference pattern when illuminating a dish, thus reducing the effective radiation illuminating the dish.

It is possible to measure the phase of an antenna pattern as well as the amplitude, perhaps by using an Automatic Network Analyzer. Since only the relative phase is important, it might even be possible to make the measurement manually using phase cancellation techniques; it would definitely be tedious. However, it is extremely difficult to make the phase measurement accurately — Dyson[1] suggests making the measurement several times around different centers of rotation, attempting to bracket the phase center.

Calculation of an antenna pattern with both amplitude and phase is much easier, as we shall see in Chapter 12. While measurement of the phase pattern of an antenna is extremely difficult, it is impossible to calculate an antenna pattern without using phase — the electromagnetic field is described using complex vectors, which have both magnitude and phase. Once we have calculated the phase, why not extract it and make use of it? An antenna radiation pattern may be calculated using a personal computer with a fast Pentium™ or even faster Alpha™ microprocessor in a few minutes — a few years ago it would have taken longer even on a supercomputer, and at a prohibitive cost.

I have used two techniques to calculate antenna patterns. The first, for wire-like antennas and simple horns, uses the **NEC2** program[2] which uses the method-of-moments to calculate radiation patterns. The original Fortran program has phase information available in the output, unlike some of the derivative versions with Windows™ interfaces. For more complex antennas like horns and dishes, I used Physical Optics (**P.O.**) routines from Milligan and Diaz[3]. (A description by Rusch[4]: "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.")

Of course, a computer model of an antenna is only an approximation of a real antenna, achieved by segmenting the antenna into a number of small pieces for purposes of calculation. The calculated patterns may be compared with published results and with measurements, which have their own inaccuracies. What we find, for a reasonably detailed model, is that the calculated forward patterns, out to about 90º rotation from the axis, are fairly accurate in amplitude and phase. The back half of the patterns, from 90º to 180º, are less accurate, particularly for the Physical Optics technique, which finds spurious sidelobes at about ±150º and a null at 180º. However, it is only the forward half of the feed pattern that illuminates a dish — even a very deep dish, with ***f*/D**=0.25, has an illumination angle of 180º, or ±90º from the axis. The back half of the pattern is just spillover that does not contribute to useful radiation. Thus the amplitude and phase of the spillover at any particular angle does not matter; only the total amount of power lost is needed for efficiency calculation. If the forward half of the pattern is accurate, then, by conservation of energy, the total power in the back half of the pattern is known, so we can also calculate efficiency with reasonable accuracy.

6.1.2 Phase Center

For all of the energy illuminating a parabolic reflector to have the same phase, the energy must emanate from a single point at the focus of the reflector. Since all real antennas have physical size, radiation from a single point is impossible. However, over a limited angle, the radiation from most antennas has a spherical wavefront, so that the radiation appears to emanate from the center of a sphere, the apparent phase center of the antenna.

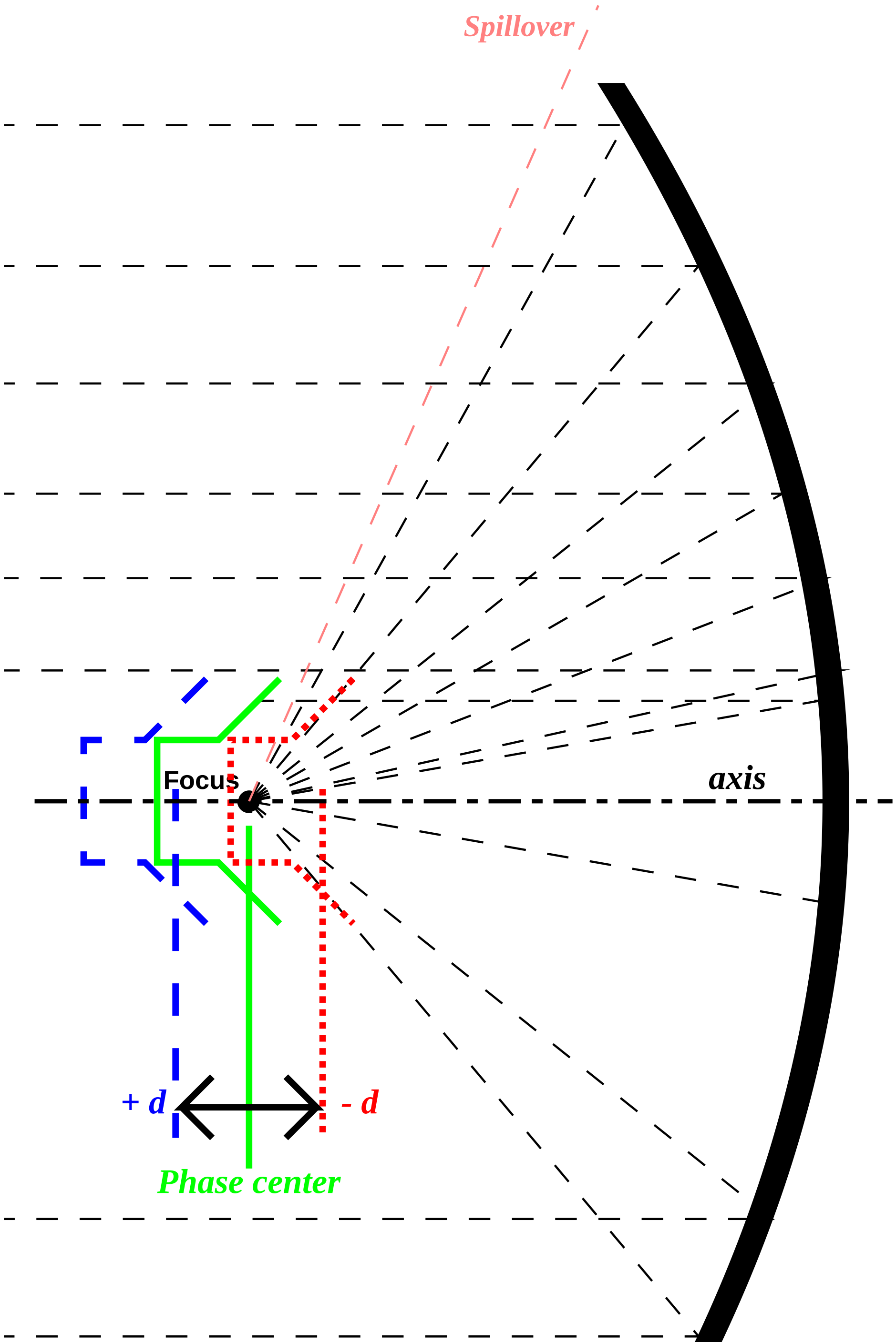
A feed antenna should have a spherical wavefront over the full illumination angle, so that the whole reflector is illuminated from a single phase center. When this phase center is at the focus of the parabola, then all of the energy radiated in the main beam of the dish is in phase and efficiency is maximized. Taking a rule-of-thumb from optics, we can estimate that a feed antenna whose phase changes less than 1/16 λ, or 22.5°, over the illumination angle will provide good performance and high efficiency.

If the phase center of the feed is not at the focus of the parabola, then additional phase error will be present (we will examine the error in more detail later). Thus it is important to locate the phase center accurately. When the phase pattern of a feed is calculated or measured, it is around some arbitrary reference point such as the center of the aperture of a horn. The phase data is a series of data points, each consisting of a phase angle ϕ and an associated pattern rotation angle $\boldsymbol{\theta}$**.** The phase center is probably on a line through the center of the feed; unless we were very lucky and chose a reference point at the phase center, the measured phase ϕ will vary with rotation angle θ. If we didn't choose a reference point at the phase center, we must calculate[5] the axial distance **d** from the reference point to the apparent phase center using:

$$d = \frac{\Delta\phi \cdot \lambda}{2\pi(1 - \cos\theta)}$$

where $\Delta\phi$ is the change in phase from the on-axis phase, and **d** is the displacement of the phase center toward the source as illustrated in Figure 6.1-1: if **d** is positive, then the phase center is closer to the dish (or the test range source if we are only measuring a feed), and a negative **d** is farther away from the dish (or source). For example, if the phase reference point is at the aperture of a horn and **d** is negative, then the phase center is inside the horn.

A good first approximation in finding the phase center is to calculate **d** for the rotation angle θ where the amplitude is –10dB, or for the desired illumination half-angle. Later we will see how to place phase center to deliver best efficiency.



Axial Feed Displacement

Figure 6.1-1

Once we have determined the distance **d** to the phase center, we must adjust all of the phase data so that the new reference point for the feed antenna pattern is the phase center. We do this by turning the above equation around to calculate a new $\Delta\phi$ for each rotation angle θ:

$$\Delta\phi = \frac{2\pi(1 - \cos\theta)\cdot d}{\lambda},$$

then adjusting the original phase angle ϕ by adding $\Delta\phi$.

We can also verify this phase center calculation by adjusting the reference point in the NEC model and showing that the resulting phase pattern is the same as the one adjusted by the above calculations.

To illustrate the effect of feed phase on dish performance, I modified the **FEEDPATT** program (Chapter 11) to calculate and plot dish efficiency including the effects of phase as well as for amplitude only. Figure 6.1-2 is our first example of an output plot including phase from the modified program, called **PHASEPAT.** The original amplitude-only efficiency is shown as a dashed line, so that the effect of phase error is quickly apparent. The output now also includes a phase plot for the feed in the upper right part of the page, in addition to the common amplitude radiation pattern for the feed at the upper left. As described in Chapter 12, I used the modified program, **PHASEPAT,** to make plots for the feed patterns I was able to calculate. The modified program may be downloaded from http://www.qsl.net/n1bwt/phasepat.zip .

Real antennas have a number of other small losses that can add up to a significant loss of efficiency. My empirical estimate is that careful work can keep the loss to about fifteen percentage points. Thus, each plot includes the statement, "*REAL WORLD at least 15% lower*."

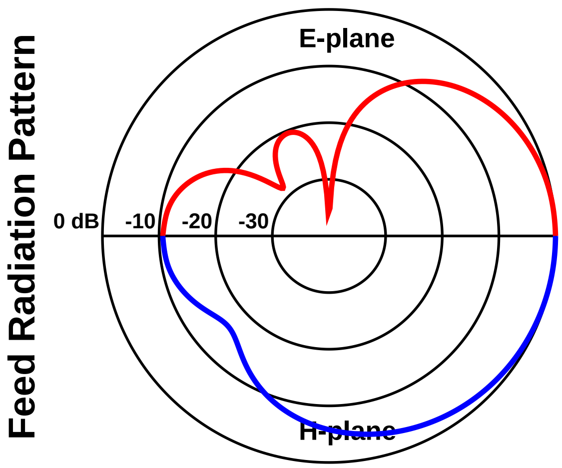
6.1.3 Phase performance of feed antennas

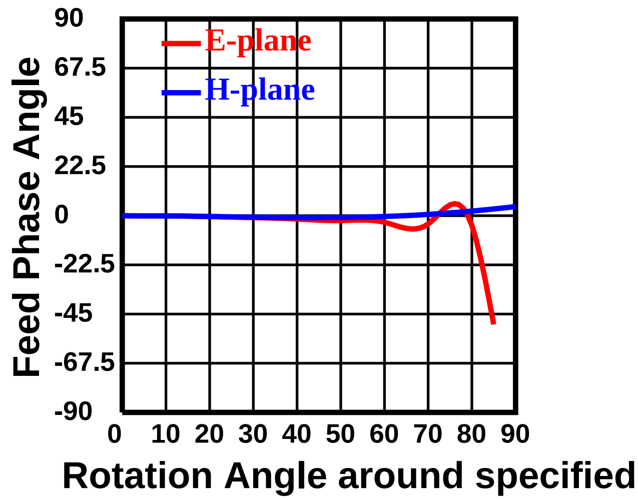
Most of the feeds we commonly use are popular because experience has shown that they work well. Thus, it is not surprising that most also have good phase performance — the phase of the radiation is nearly constant as the feed is rotated around its phase center. Let's take a look at a few examples of common feeds, both good and bad. The rest of Chapter 6 will have similar illustrations for many different feeds.

Dipole — A simple example is a dipole with a "splash plate" reflector spaced 0.3λ; Figure 6.1-2 plots the efficiency based on patterns calculated by NEC2 from dimensions in the RSGB Microwave handbook[6]. The phase plot in the upper right of Figure 6.1-2 shows that the feed phase is quite uniform over a wide illumination angle and efficiency is reasonably good for deep dishes, with ***f/D*** around 0.25 to 0.3. The calculated phase center is 0.11λ behind the dipole, not far from the recommended starting point of halfway between dipole and reflector.

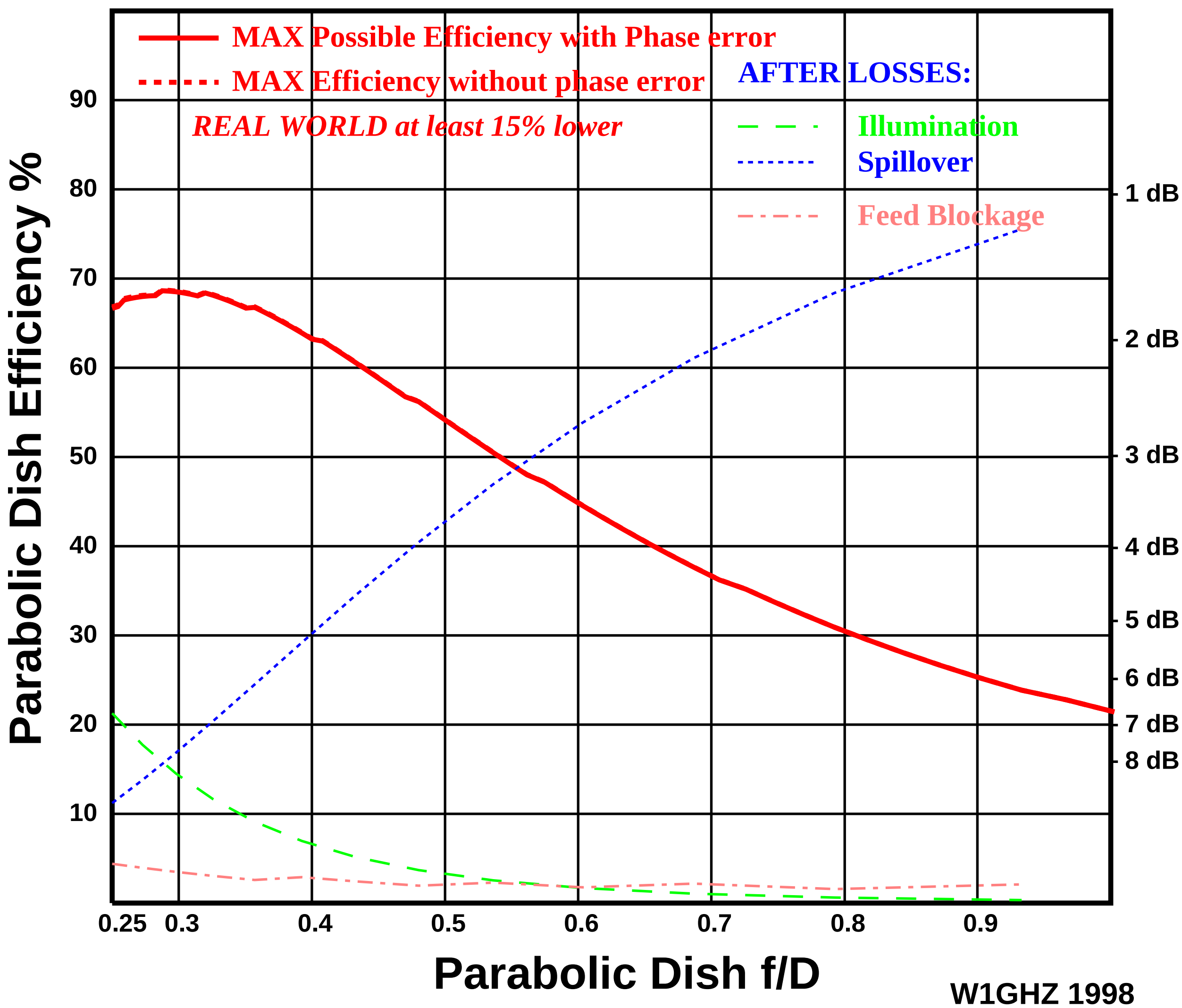
RSGB dipole-splashplate feed, by NEC2

Figure 6.1-2





Dish diameter = 10 λ   Feed diameter = 1 λ   Phase Center = 0.11 λ behind dipole



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EIA dual-dipole — The EIA reference antenna[7], a dual-dipole over a ground plane, is a popular feed at UHF frequencies. The feed pattern calculated by NEC2, shown in Figure 6.1-3, has some interesting features. The phase is fairly constant over about ±50º, then starts to change, with a wild variation around an E-plane null at 90º. However, since the ***f*/D** for best efficiency is around 0.5, the phase variation is outside the desired illumination angle or 106º, or ±53º, and misses the reflector. The phase center is about 0.15λ behind the dipoles.

W2IMU — For shallower dishes, the W2IMU dual-mode feed[8] is a popular choice. The feed pattern in Figure 6.1-4, calculated by NEC2, has uniform phase over the narrower illumination angle suitable for a shallow dish. As a result, the calculated efficiency for an ***f*/D** around 0.5 to 0.6 is excellent. The phase center is at the center of the aperture.

However, not all antennas have good phase performance. The W2IMU dual-mode feed requires two critical dimensions[9] so that the two modes arrive at the aperture out of phase to achieve cancellation of edge currents in the rim of the horn. Any current in the rim will add sidelobes and affect the clean pattern shown in Figure 6.1-4. As an example, I took an off-the-shelf plumbing adapter — at first glance, it looks like a dual-mode feed for 10 GHz. A typical ham practice would be to try it and see if it is close enough. Unfortunately, the dimensions aren't right, and the calculated pattern, shown in Figure 6.1-5, is rather ugly. If we were to consider amplitude only, as we did in the past, the calculated efficiency would be mediocre, but the poor phase performance results in really low efficiency.

Rectangular horn — Offset dishes, like the DSS dish, require narrower illumination angles. Chapter 5 described the use of a small rectangular horn as a feed. Figure 6.1-6 shows the pattern calculated using Physical Optics, with excellent phase uniformity and efficiency for an ***f*/D** around 0.6. The phase center is about 0.2λ inside the aperture. While Figure 6.1-6 only shows the **E**-plane and **H**-plane patterns, the 45 degree planes also have excellent patterns. I was really lucky in designing this horn.

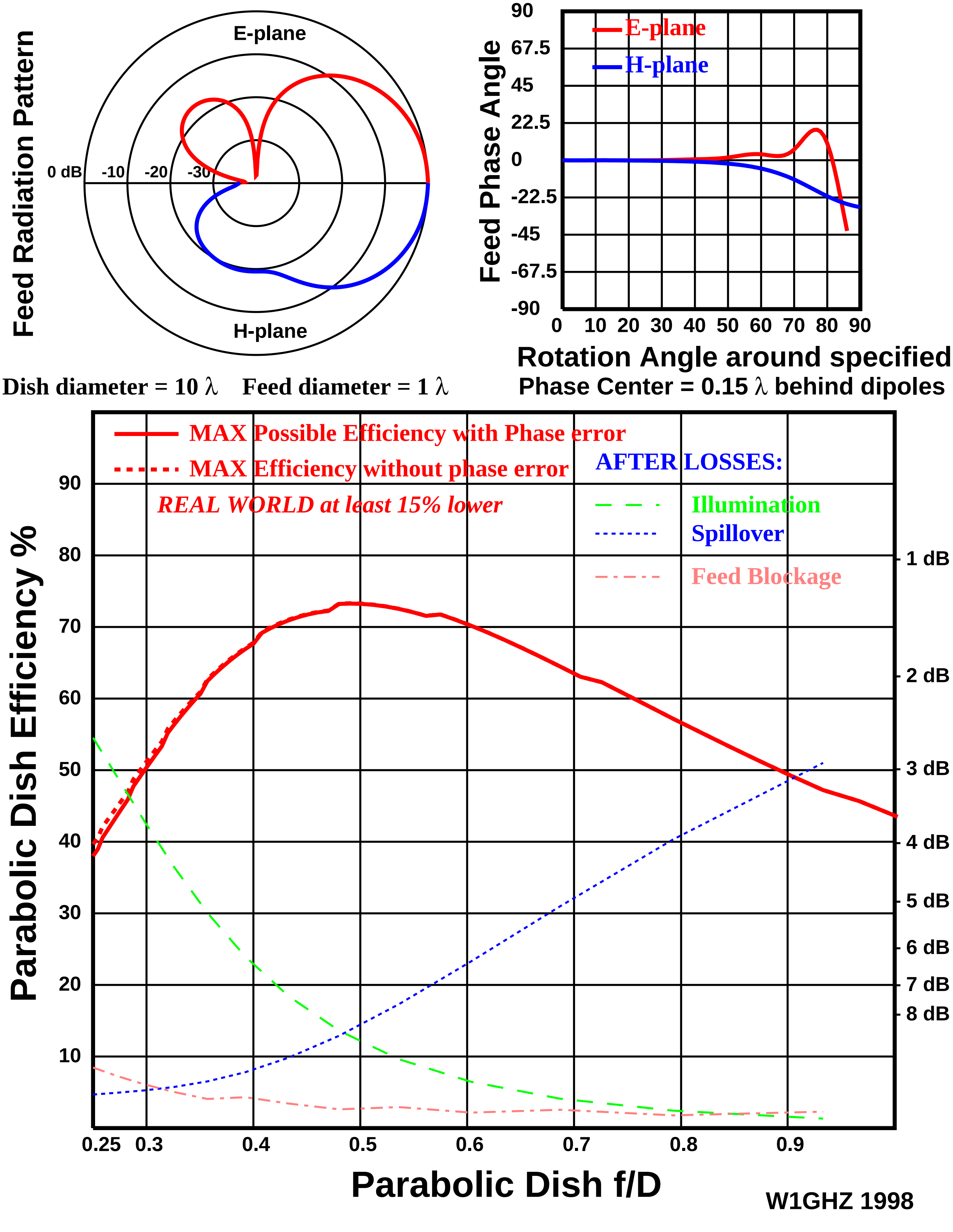
Multi-band feeds — Multi-band feeds present another problem: the phase center usually has a different location at each frequency. Complex structures with poor symmetry like log-periodic arrays are particularly bad. Therefore, we need to calculate radiation patterns and phase centers for each frequency of interest, and choose some compromise for positioning the feed with respect to the focal point of the dish. The next section suggests that the highest frequency is the most critical one for phase center location.

6.1.4 Axial Displacement Error

When the phase center of a feed is not at the focus, but at some other distance from the reflector, the resulting phase error causes a loss in efficiency referred to as axial displacement error. In Chapter 4, Figure 4-9 shows curves for axial displacement error based on uniform illumination, a much simpler calculation. Now that we can calculate feed patterns and phase centers, we can also calculate the axial phase error for actual feeds.

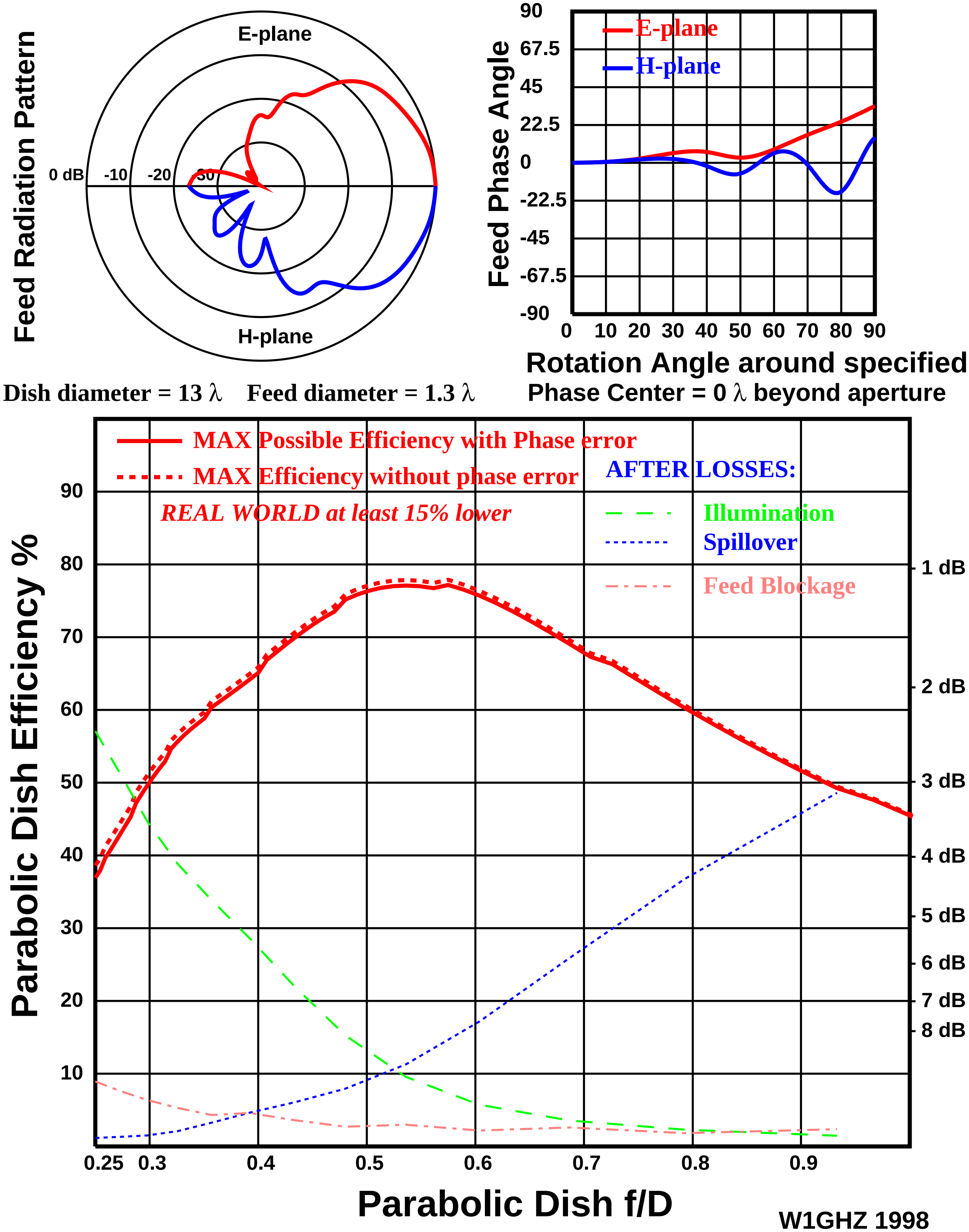
EIA dual-dipole reference antenna as feed, by NEC2

Figure 6.1-3



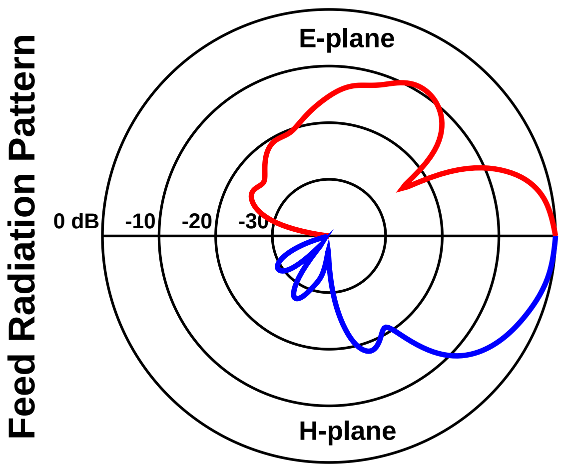
W2IMU dual-mode feedhorn, by NEC2

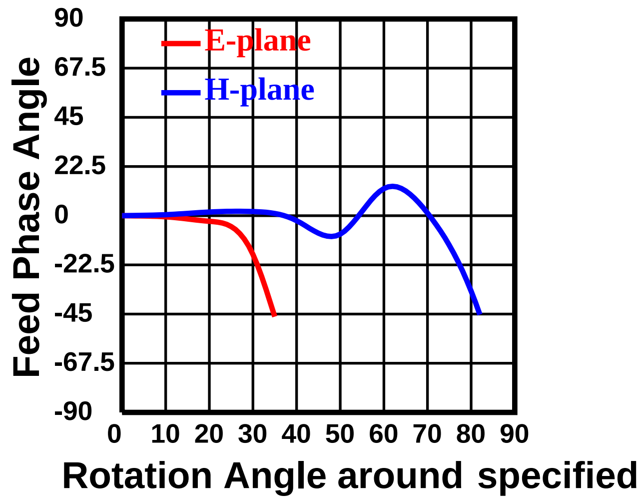
Figure 6.1-4



W2IMU feed - bad imitation, by NEC2

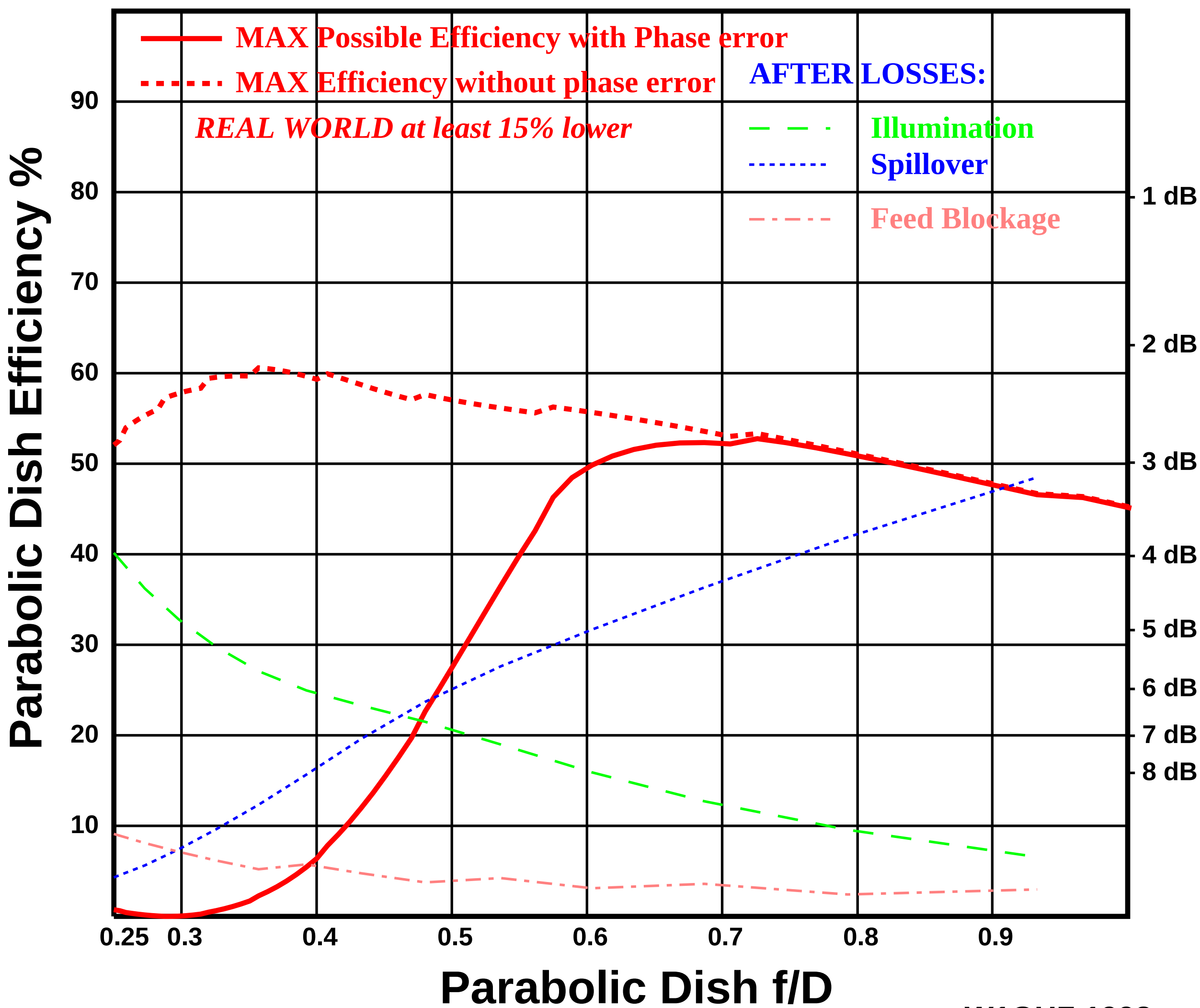
Figure 6.1-5





Dish diameter = 14.3 λ Feed diameter = 1.43 λ

Phase Center = 0 λ beyond aperture



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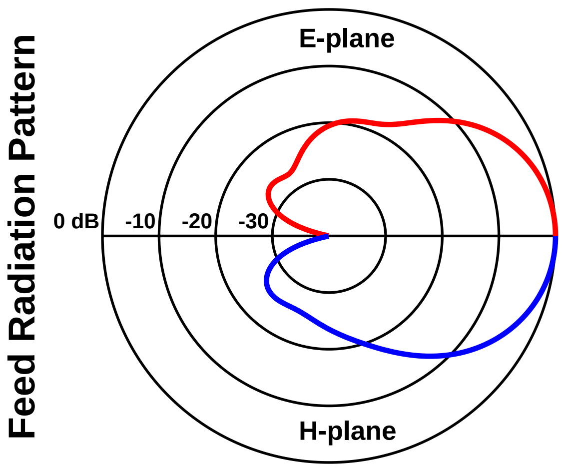
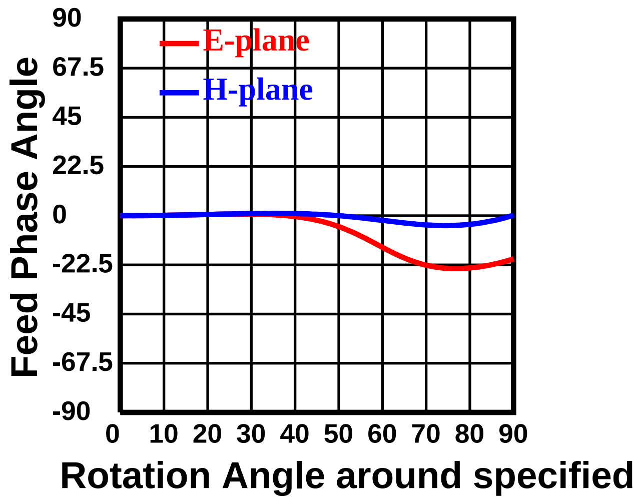
WR-90 horn for DSS offset dish at 10.368 GHz, by P.O.

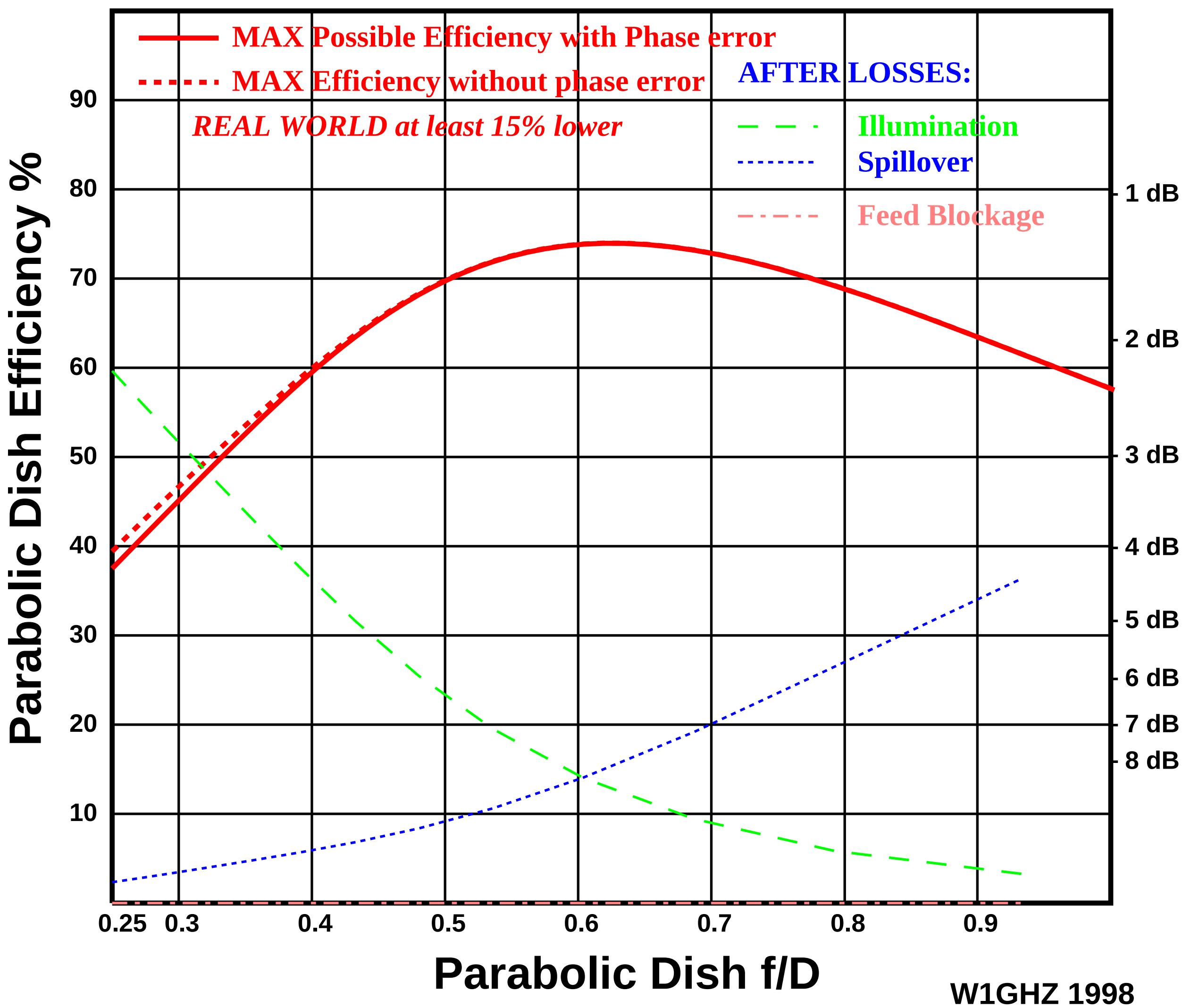
Figure 6.1-6





Dish diameter = 15.8 λ Feed diameter = 0.05 λ

Phase Center = 0.2 λ inside aperture



In the same way that we adjust the phase pattern to the desired phase center, we may adjust it to some other point along the axis and calculate a new phase pattern, so that the phase pattern around this new point is the feed pattern at the focus of the dish. Then we can plot the resulting efficiency curve. Figure 6.1-7 shows a family of efficiency curves for axial displacement in 0.25λ steps toward the dish, using an EIA dual-dipole feed as an example. Clearly, the peak efficiency decreases with axial feed displacement from the focus, and decreases faster at smaller ***f*/D**. Displacement in the other direction, away from the dish, produces a similar family of efficiency curves.

If we plot the peak efficiency vs. axial displacement, then we can clearly see the sensitivity of efficiency to axial displacement. Figure 6.1-8 shows this relationship for the dipole-splashplate feed; zero displacement on this plot is with the dipole at the focus. However, best efficiency is not at zero displacement, but with the dipole displaced toward the reflector by 0.11λ. This position is obviously the best phase center for this feed and ***f*/D**, so we can conclude that the best phase center is 0.11λ behind the dipole. This is the technique used to find all the phase centers previously cited.

Similar plots of peak efficiency vs. axial displacement are shown in Figure 6.1-9 for the EIA dual-dipole feed and Figure 6.1-10 for the rectangular horn feed for the DSS dish. When we plot the curves for the three feeds on the same graph in Figure 6.1-11, it is quickly apparent that deep dishes, with small ***f*/D**, are much more sensitive to axial displacement error.

It might be informative to evaluate this sensitivity. Returning to the equation we used to find the phase center:

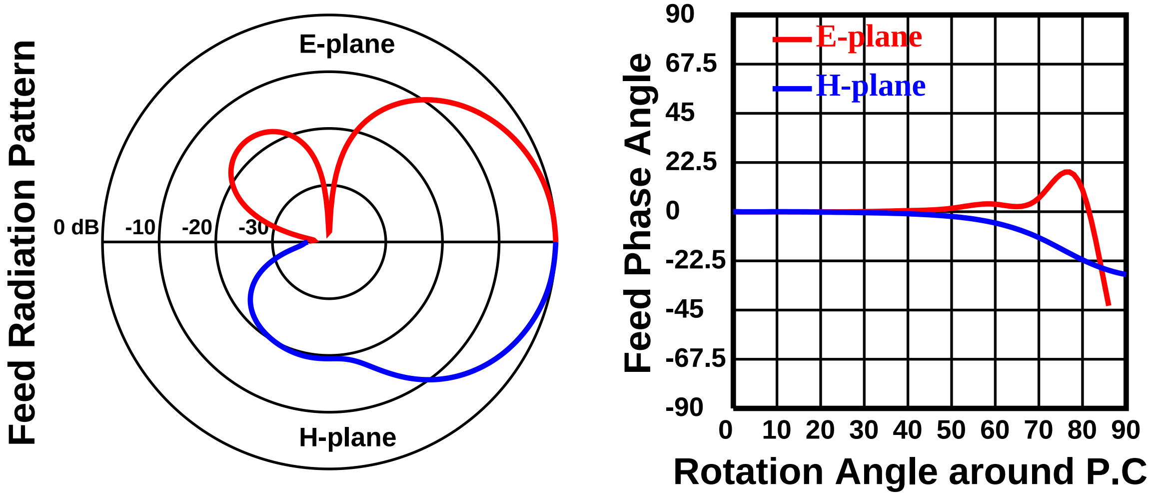
$$\Delta\phi = \frac{2\pi(1 - \cos\theta) \cdot d}{\lambda},$$

we can see that the phase error for a given axial displacement **d** is a function of the rotation angle, so it increases as the illumination angle of the dish becomes larger. A larger illumination angle is more sensitive to phase error in the feed.

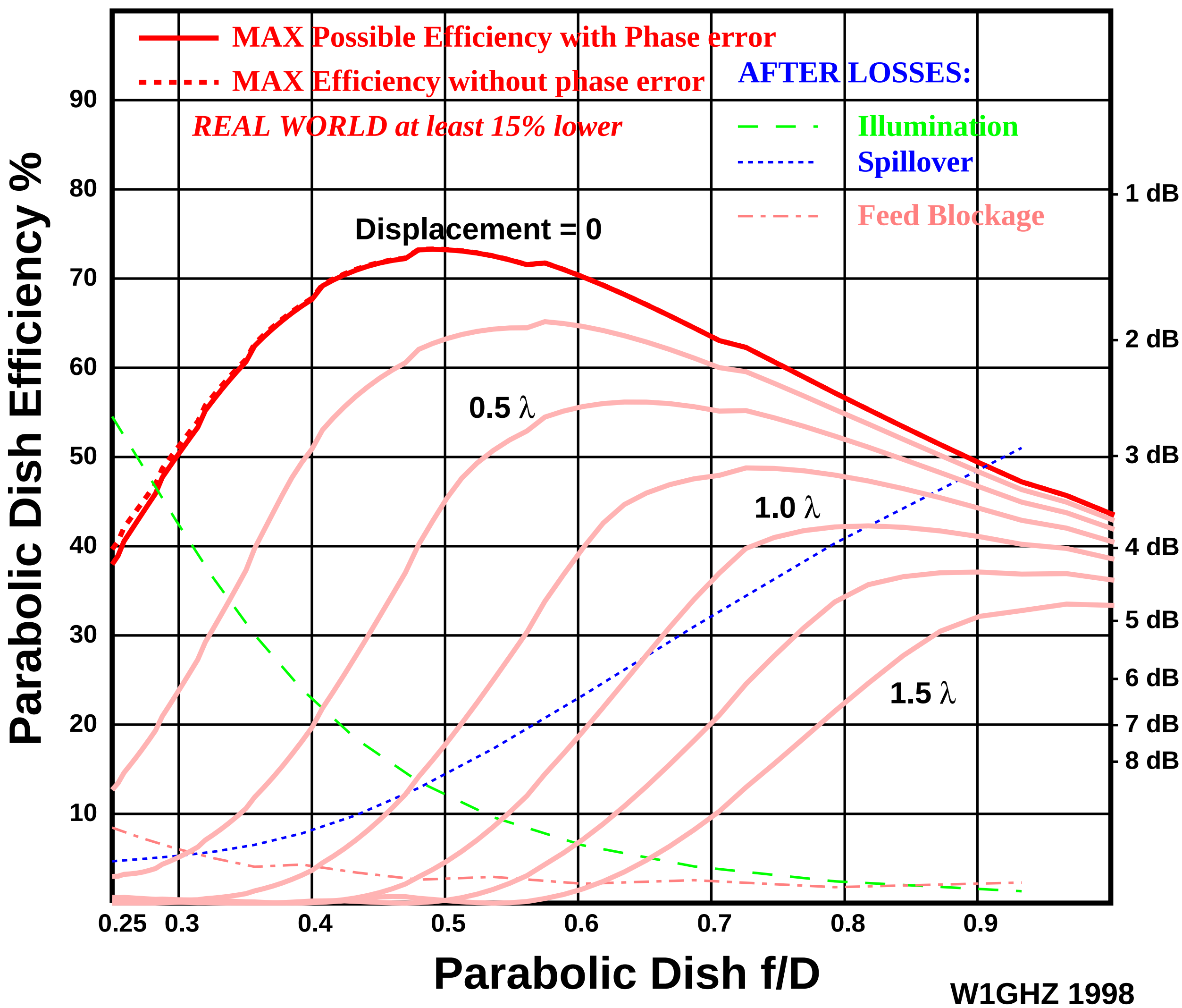
Since most offset-fed reflectors need a small illumination angle, equivalent to a large ***f*/D**, the phase error resulting from a given feed displacement is the same as for a dish with a large ***f*/D**. Thus, the efficiency of an offset dish has a low sensitivity to axial feed displacement errors. The combination of this low sensitivity with the other advantage of offset dishes, elimination of feed blockage, makes the offset dish highly attractive.

EIA feed with axial feed displacement in 0.25 λ steps

Figure 6.1-7



Dish diameter = 10 λ   Feed diameter = 1 λ



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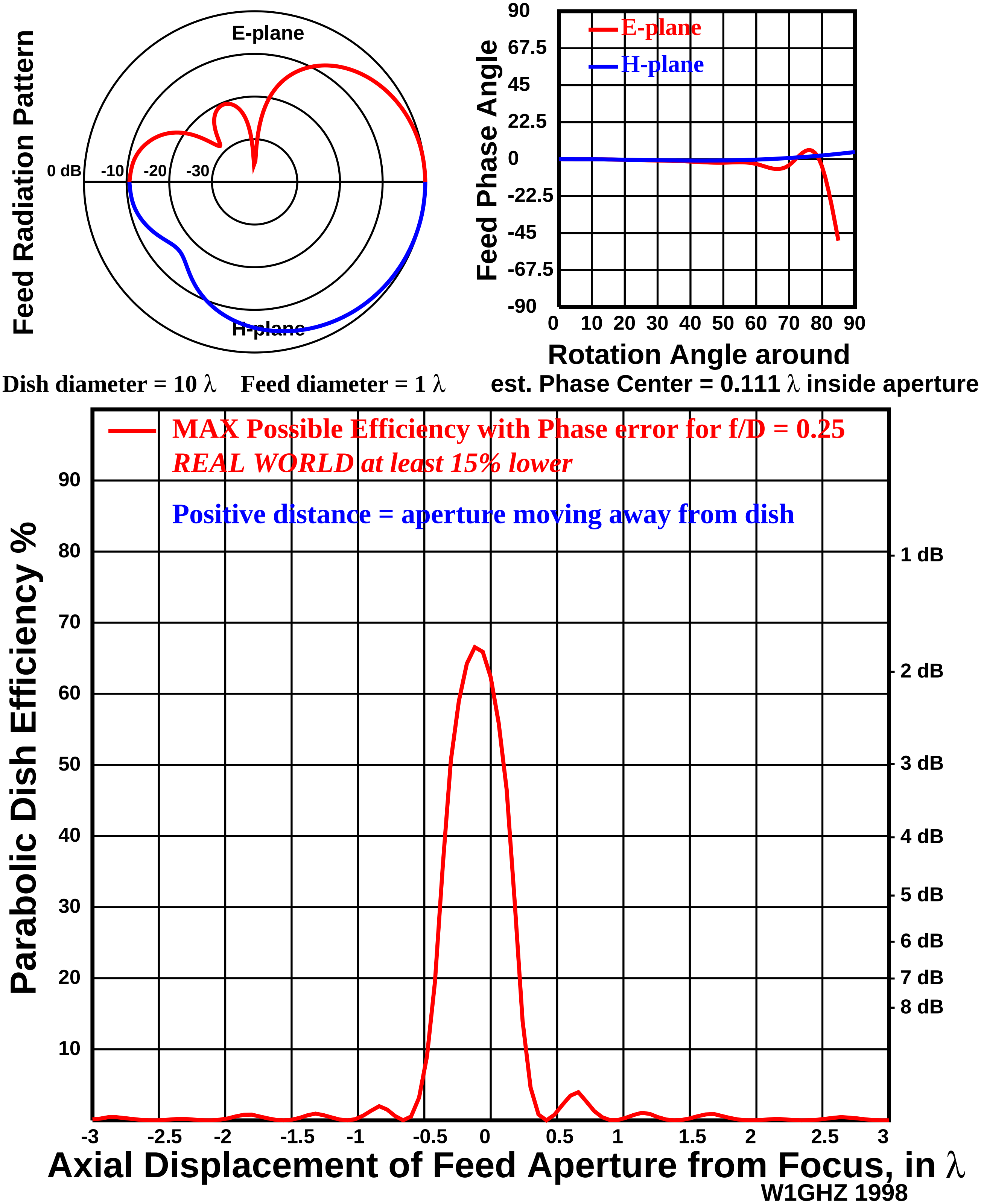
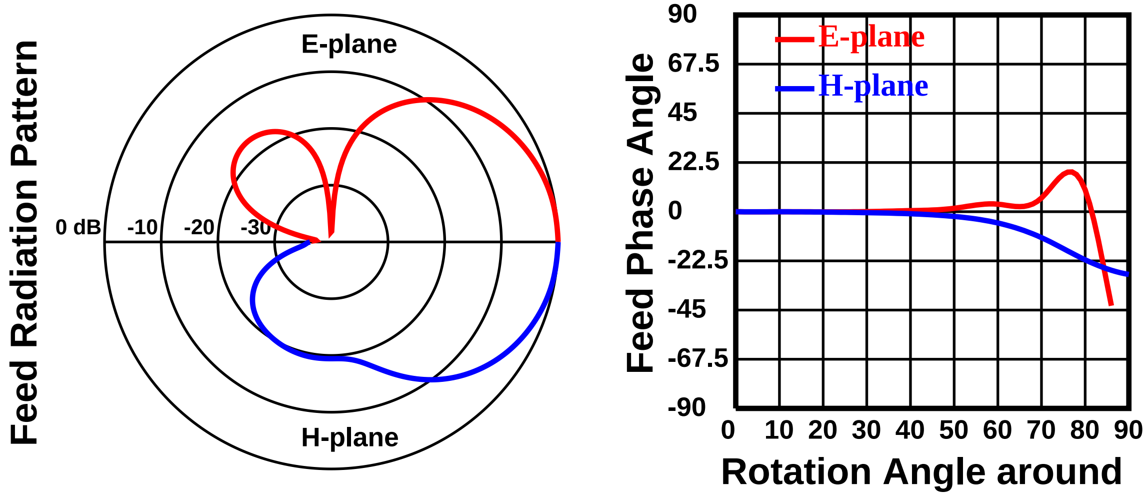
RSGB dipole-splashplate feed, by NEC2

Figure 6.1-8

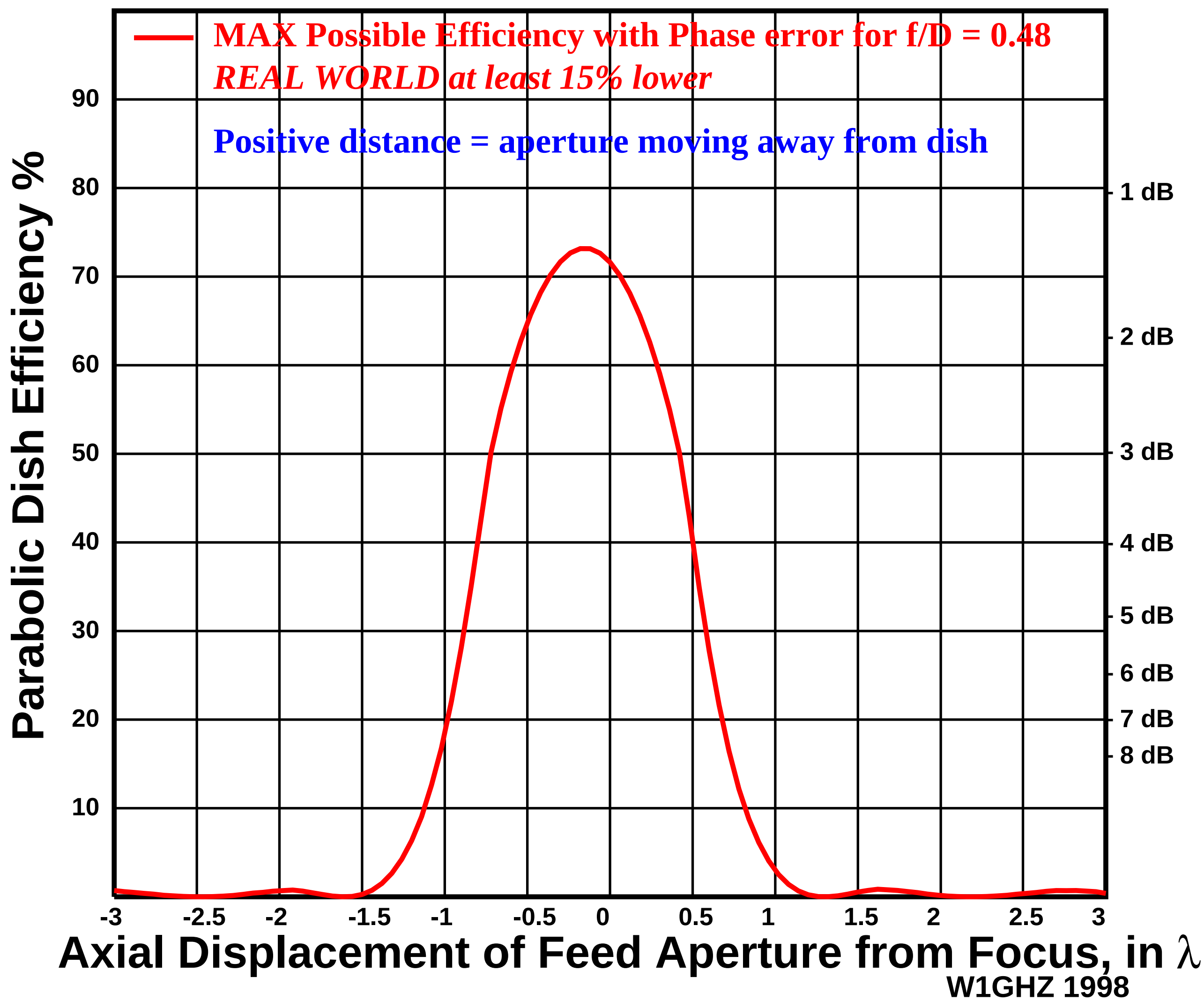


EIA dual-dipole feed, by NEC2

Figure 6.1-9

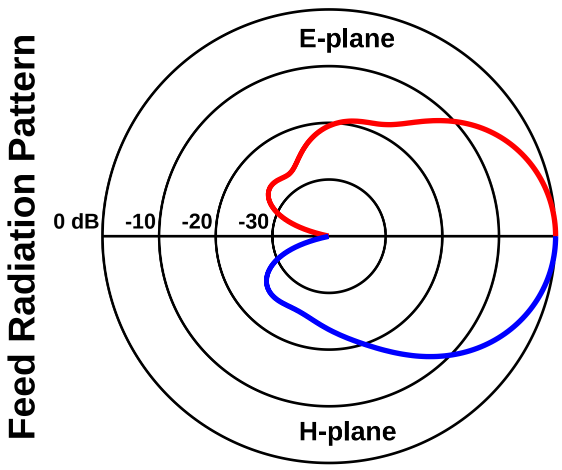


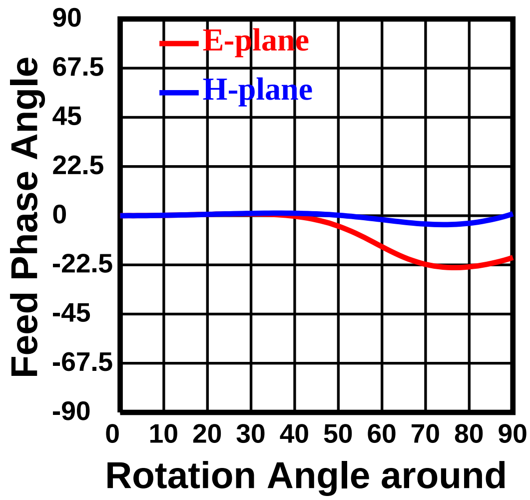
Dish diameter = 10 λ   Feed diameter = 1 λ   est. Phase Center = 0.148 λ inside aperture



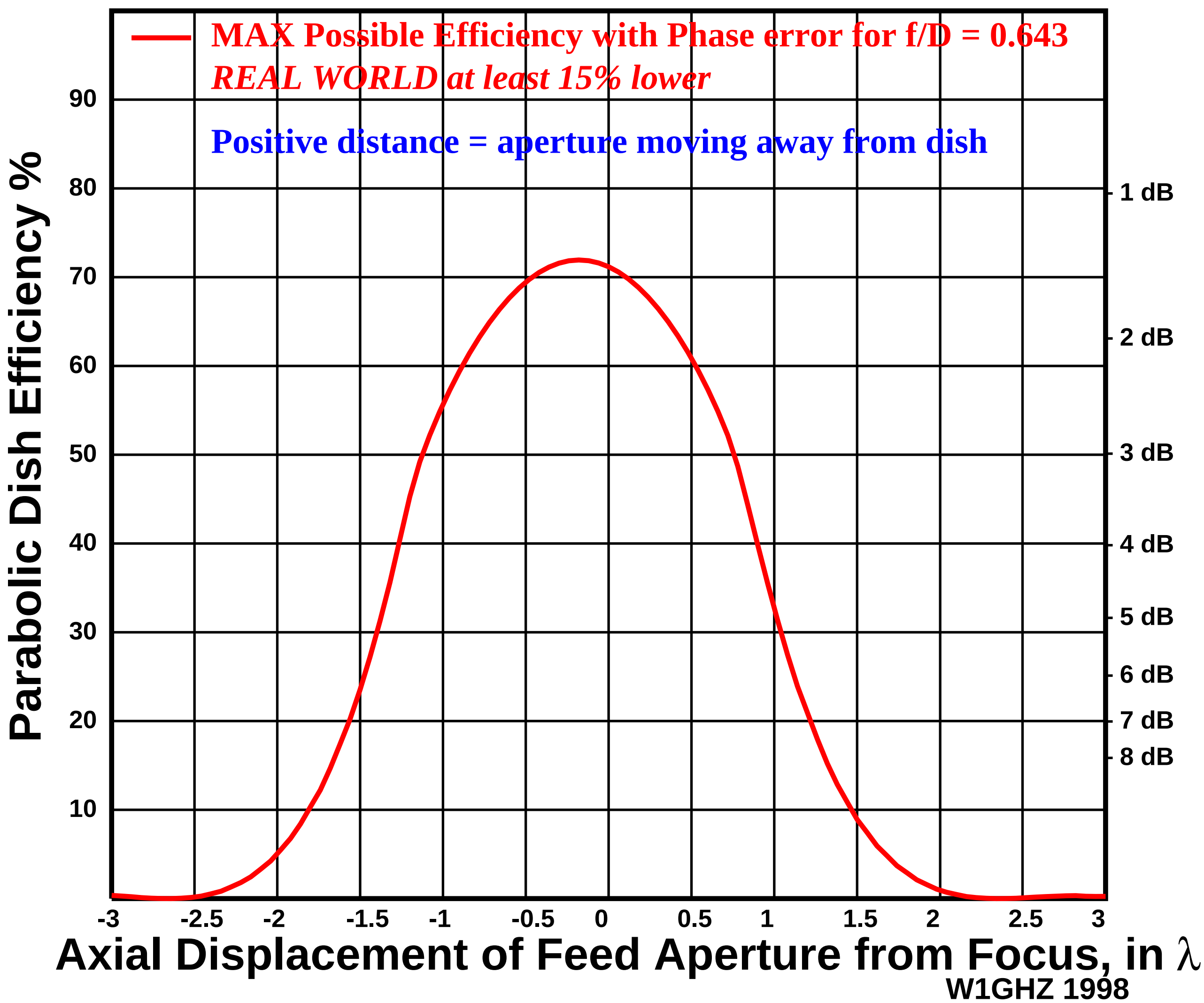
WR-90 horn for DSS offset dish at 10.368 GHz, by P.O.

Figure 6.1-10





Dish diameter = 15.8 λ Feed diameter = 0.1 λ est. Phase Center = 0.203 λ inside aperture



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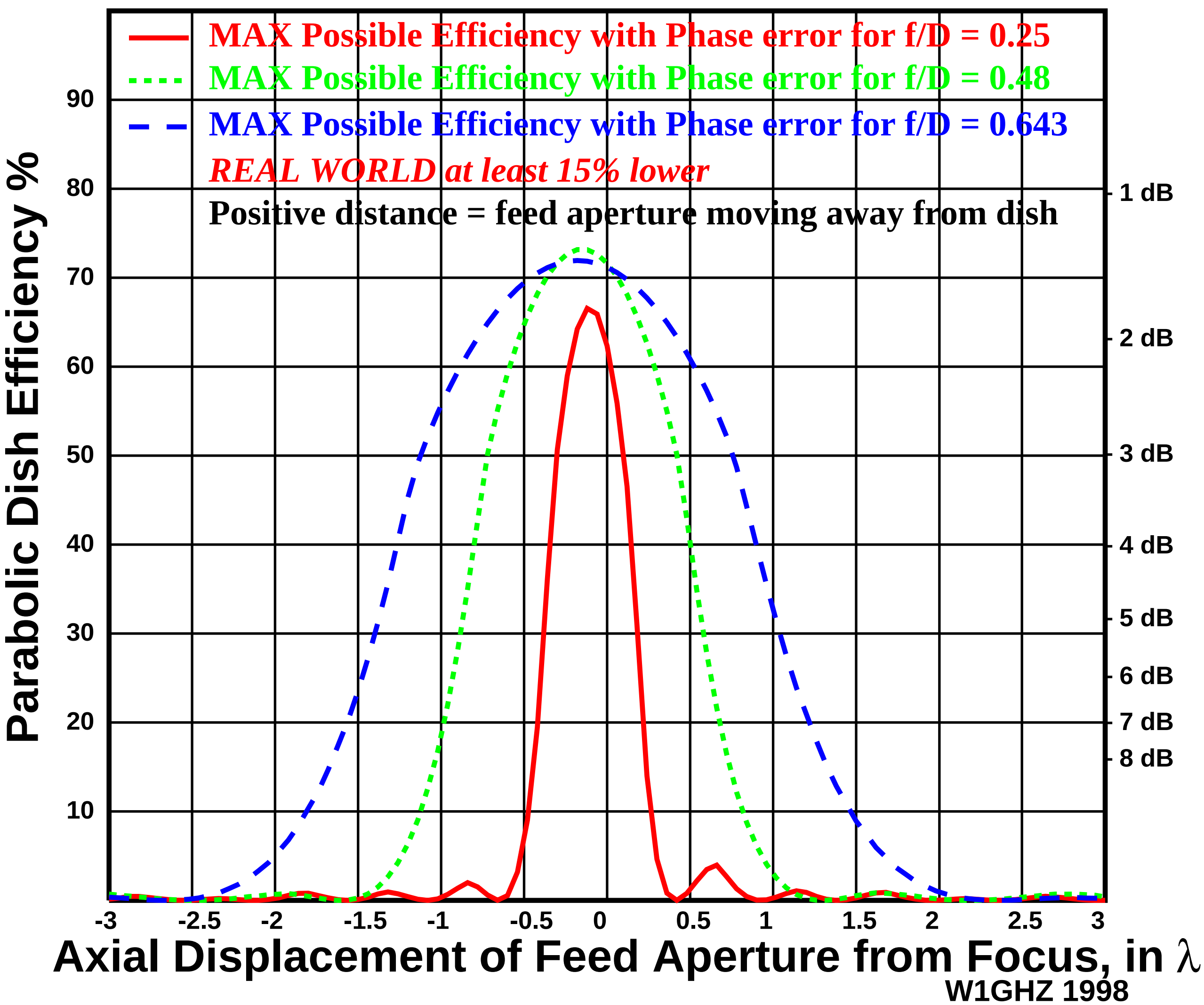
Focal Point Sensitivity of Real Feeds
Figure 6.1-11

f/D = 0.25: RSGB dipole-splasher feed, by NEC2

f/D = 0.48: EIA dual-dipole feed, by NEC2

f/D = 0.64: WR-90 horn for DSS offset dish at 10.368 GHz, by P.O.



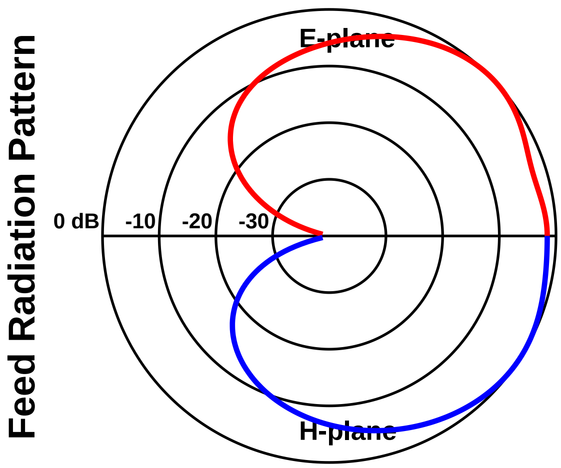
Before doing the analysis of phase center sensitivity, I had thought that the sensitivity to axial displacement error would be related to the ***f*/D** of the full parabola. Since the DSS offset-fed dish is a section of a full parabola with a small ***f*/D** of about 0.3, I had concluded that the offset dish would be sensitive to axial displacement error[10]. Now that it is clear that the axial displacement error is due to the phase error resulting from feed displacement and is a function of illumination angle, we can see that the offset dish is insensitive to feed positioning errors.

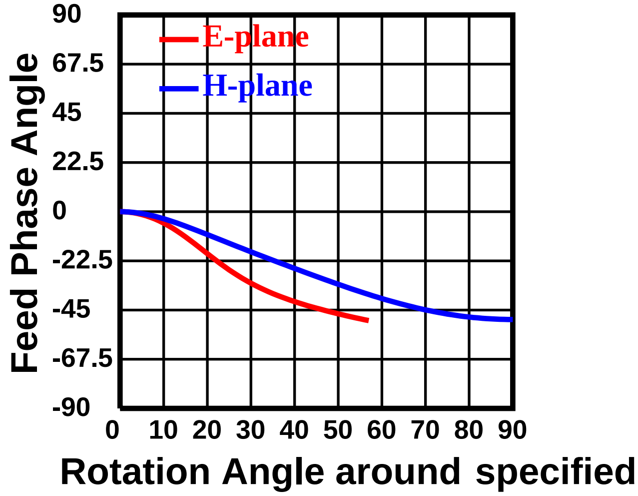
An important point to note in Figure 6.1-11 is that the feed axial displacement is in wavelengths, regardless of dish size. A one wavelength error in feed placement will result in the same efficiency reduction whether the dish is one foot or 50 feet in diameter. For multiband feeds, the error is larger at higher frequencies, since each millimeter is a larger part of wavelength at the higher frequency. Thus, the feed placement should be chosen to favor the phase center at the highest frequency.

For the three feeds illustrated in Figure 6.1-11, an intuitive location for the phase center would be at the aperture of the horn or the plane of the dipole. Calculating the actual location of the phase center provides some improvement, but these feeds would work pretty well using the intuitive location. However, some feeds are not so forgiving. While looking through W8JK's famous book[11], ***Antennas***, I noticed that some of the rectangular horn patterns have a cardioid shape which might provide increased illumination at the edge of a dish, like the desired illumination pattern of Figure 4-5. After calculating a few trial patterns for small horns, I arrived at one that seemed promising, and used an early version of **PHASEPAT**, without phase center correction, to analyze its performance as a feed. The resulting dish efficiency, shown in Figure 6.1-12, was abysmal. A plot of axial displacement error, Figure 6.1-13, shows why: the phase center is about 0.4λ inside the horn, with a large axial displacement error at the aperture; the efficiency without correcting for phase center is very low. An efficiency plot for the best phase center, Figure 6.1-14, shows dramatic improvement, but the best calculated efficiency is around 66% for a small ***f*/D** around 0.25. The efficiency on a real dish would likely be around 50%, which isn't bad for a very deep dish. However, I have not actually tried this feed.

WR-90 small horn with cardiod pattern, by P.O.

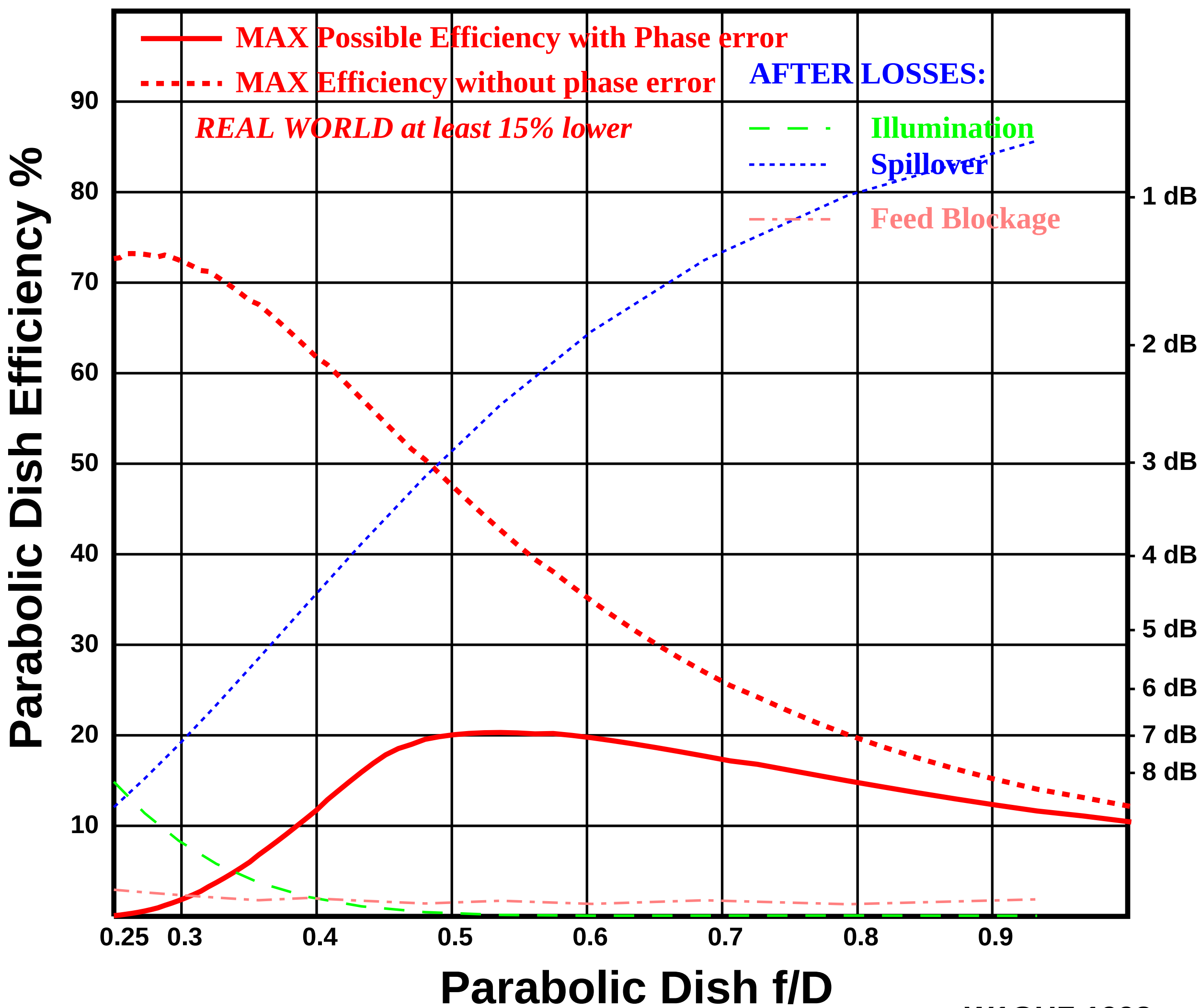
Figure 6.1-12





Dish diameter = 20 λ   Feed diameter = 2 λ

Phase Center = 0 λ beyond aperture



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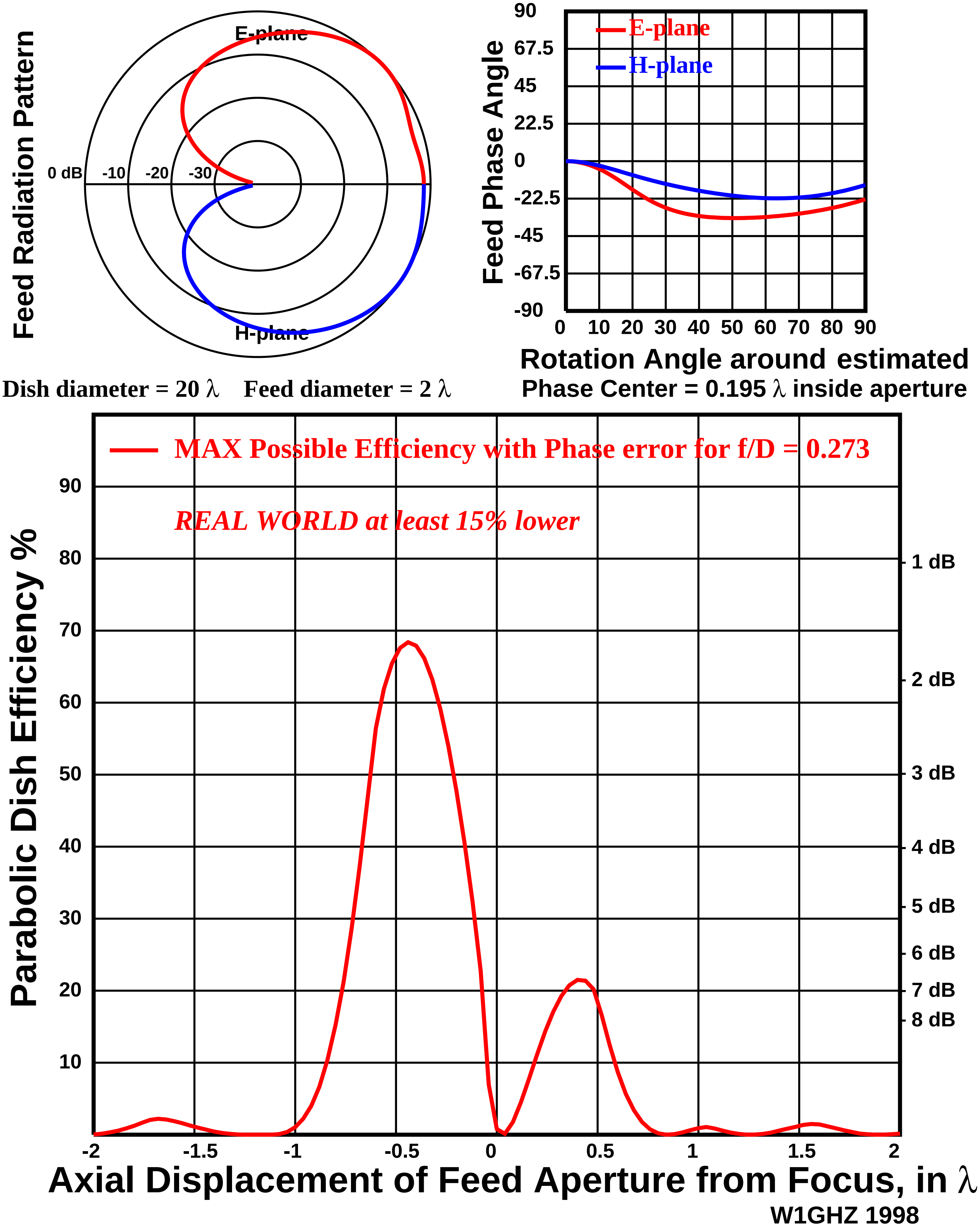
WR-90 small horn with cardiod pattern, by P.O.

Figure 6.1-13



WR-90 small horn with cardiod pattern, PC at focus, by P.O.

Figure 6.1-14