# Matching Dish and Feed

## Optimising the dish - feed combination for EME-communication

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### 1 Introduction

### 1.1 Background

From time to time you see questions on the Earth - Moon - Earth (EME) forums about what feed is suitable for this and that dish. There are many different aspects coming up on this subject in these questions. I will try to clear up some of these questions in this paper as well as propose a working scheme to achieve the best possible dish - feed combination with the least amount of grief.
This paper is very much a continuation of my "Dish Feed Selection Philosophy for EME-stations" http://www.2ingandlin.se/Feed_Philosophy.html published in 2009.
There are many different aspects and parameters to optimise in a EME-communications circuit e.g. LNA's, feed line losses, Tx-power, dish surface, dish feeds etc. etc.. This paper will only focus on optimisation of the feed-dish combination, all other has been in my mind but stay the same and are not touched here.

### 1.2 Goal

Before plunging into all the technical details, please take a moment to review your goals with your dish - feed combination. Do you want to

- Optimise for Tx-performance?
- Optimise for Rx-performance?
- Find a best compromise, a balance?

Do you have plenty of Tx-power? Then you may want to focus on the low noise side in order to improve Rx-performance. With plenty of Tx-power and the dish - feed combination optimised for maximum gain, you risk being called a crocodile, with justification.
Scarce of Tx-power? Optimise for maximum gain?
But consider, you can always increase your Tx-power, but how do you get the external noise out of your system when it already has sneaked into it? You can't!

For me the choice is clear. With today's extremely good LNAs it is worth aiming for an Rx-performance optimised system.
This statement does vary a little from band to band and with dish size, as we will see later.

Nevertheless, if you can't hear them, you can't work them, is still valid!

### 2 Prerequisite

In order to understand the full picture of how to optimise the dish - feed combination it is good to have some background information regarding antenna design parameters. These parameters play a vital role in determining the quality / properties of a dish - feed combination:

- Antenna area
- Directivity
- Gain
- Near Field / Far Field
- Far Field Distance
- Aperture Efficiency
- Wave Guide Properties

These parameters are general and applicable to all antennas, not only parabolic dishes.

## 2.1 Antenna Area, Directivity and Gain

Antenna Area ($A_i$) for an isotropic radiator is

$\mathbf{A_i = \lambda^2 / 4\pi}$ (D = $D_0$, unity i.e. radiates equal in **ALL** directions (NOTE! Such a radiator does not exist, for reference only)). (Eq. 1)

The Antenna Area (A) for an arbitrary radiator with the directivity D (linear) is

$\mathbf{A = D * (\lambda^2 / 4\pi)}$ (Eq. 2).

Distinguishing Directivity and Gain where Directivity is solely dependent to Antenna Area and Gain incorporates losses such that:

$\mathbf{G = D * \eta}$ (Eq. 3)

where $\eta$ is the total efficiency (0 to 1).

## 2.2 Near Field and Far Field Distances

Antenna Radiation Patterns are always shown for the Far Field of the antenna (Plane Wave). That means you need to know at what distance an specific antenna can be considered to be in the Far Field region. In our case a feed for a dish.
If not in the Far Field when illuminating the dish surface the Radiation Pattern is not what you think it is. This is especially true for the important Phase Error. If the dish surface is not in the Far Field region you will suffer from lower efficiency due to increased Phase Error in the illumination of the dish.
There is more than one definition of the Far Field Distance (r) as can be seen below in figure 1, where it is normalised to wavelength (**λ**).

The largest **r/λ** (Y-axis) value is the applicable one.

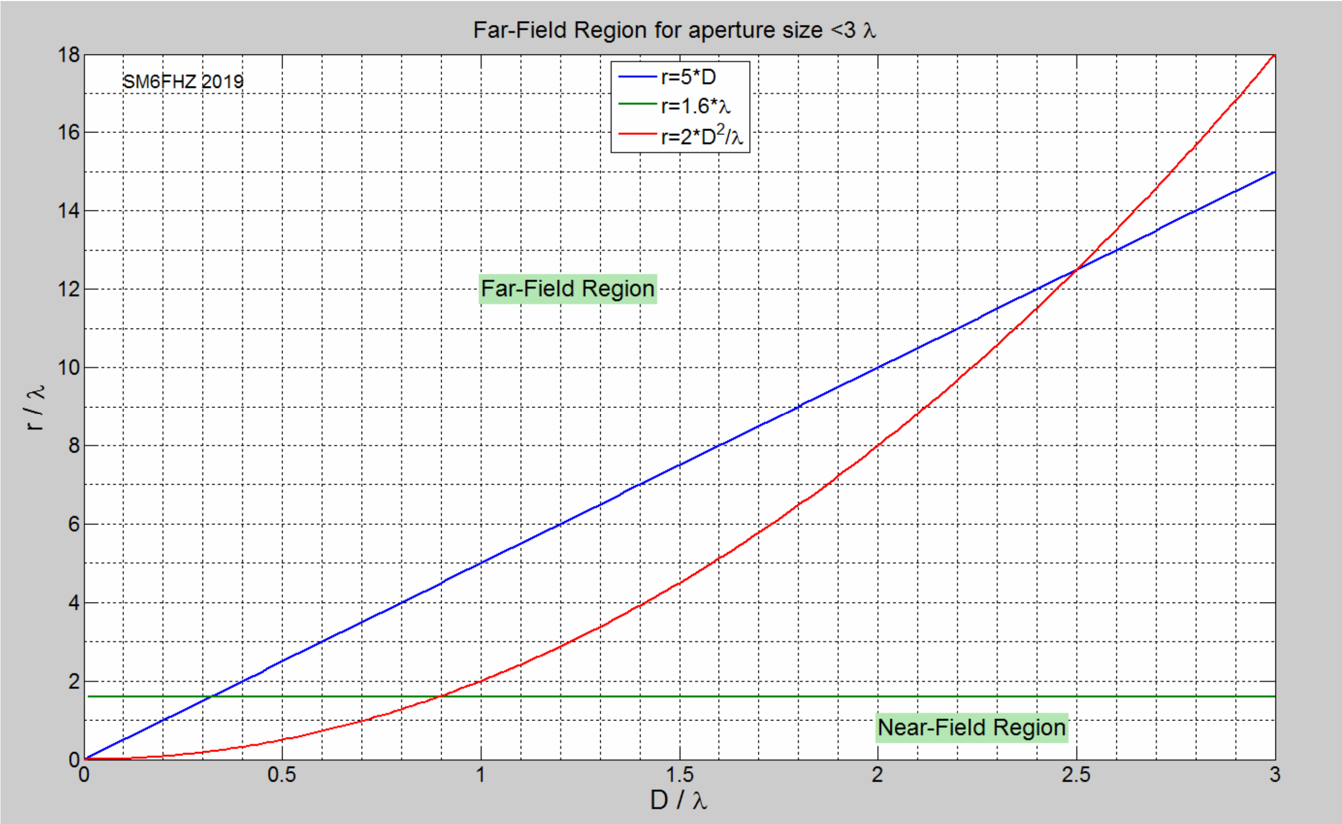



Fig. 1

The different definitions are applicable in different situations but for our purposes of feeding reflector dishes at microwave frequencies the following definition of far field distance the most applicable:

$$\mathbf{r = (2 * D^2) / \lambda} \quad \text{(Eq. 4)}$$

In Eq. 4 the definition is that the phase error across the aperture is 22.5 deg or less. This is a purely geometrical exercise; try it and you will see.

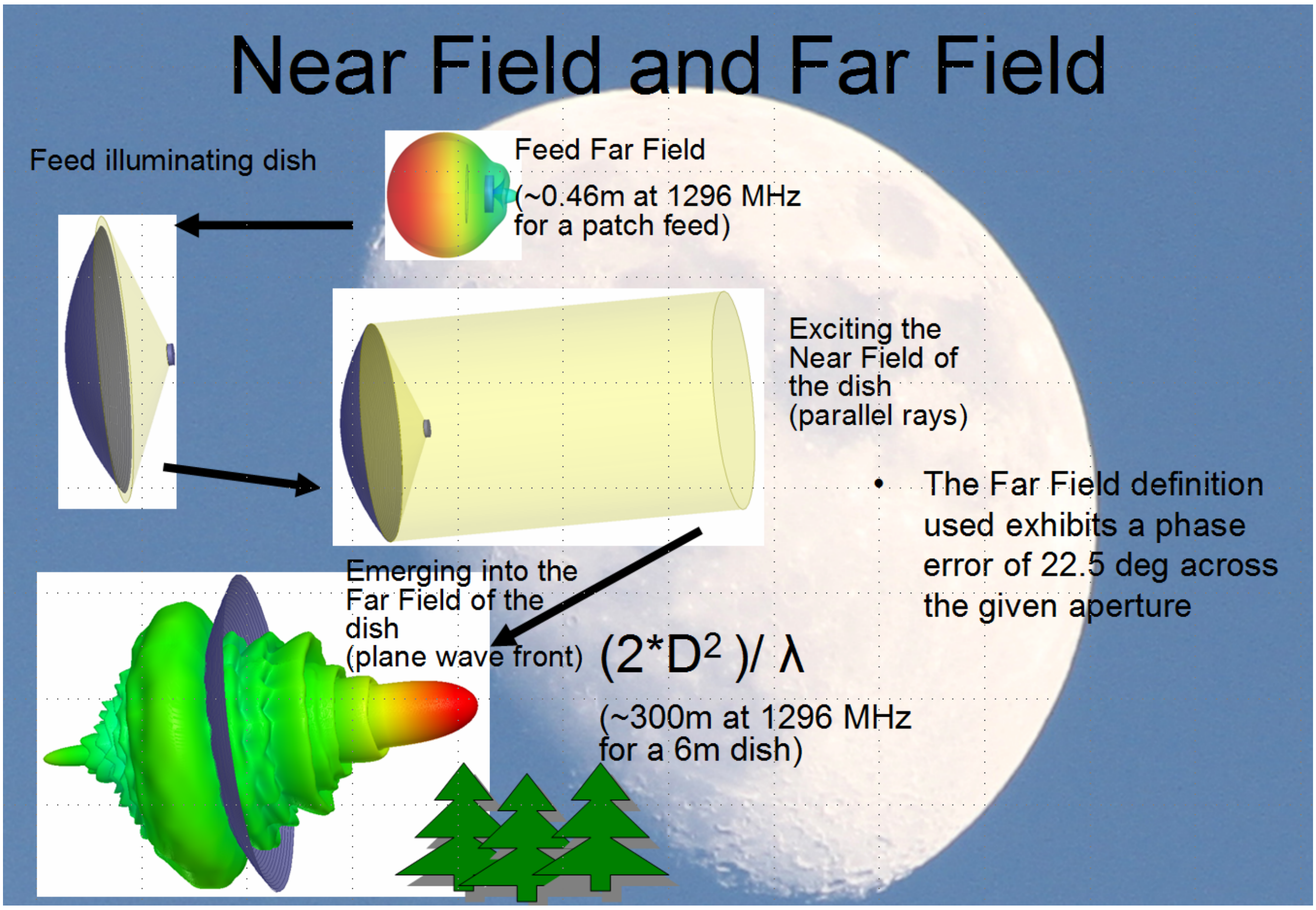



Fig. 2

What does all this then mean for us?
Increasing the antenna area will increase the directivity (as seen above) and this increased directivity is taken from the smaller angular range that the antenna aperture is illuminating on the full sphere. Larger antenna area means a narrower **Beam Width** (BW) of the antenna, and thus higher directivity. This means that we can design our feed antenna to illuminate our dish surface in an optimised way! That is good news!
NOTE: The "Gain"-figure of the feed is of low significance when feeding a dish. It is the beam widths in each plane that determine the usefulness of a specific feed for a given dish surface. The Gain (and Directivity as well) is an effect of the beam widths and of no interest of itself here. However, the efficiency is of great interest, as we want to keep any losses to an absolute minimum!

## 2.3 Aperture Efficiency

As you probably have suspected we can not make use of the full physical aperture (dish surface area). Not even in theory. We define an efficiency number: Aperture Efficiency, as unity (1) minus the losses when feeding the dish.
We can optimise the Aperture Efficiency by shaping the radiation pattern of the feed to fit the dish surface as well as possible. You can see this with e.g. the corrugated feed horn and the Kumar feed horn principles [Ref.4]. In this reference paper Paul, W1GHZ [Ref.5], points out that by using the S/W Feed_GT the important Phase Error shall be taken into account when evaluating feeds.

The major losses are:

- Illumination loss
- Phase Error loss
- Spill-over loss (can limit your antenna noise temperature)
- Feed Blockage loss
- Cross Polar loss
- Resistive losses in the feed (Ohmic, both metal and dielectric)
- Dish surface leakage loss (can limit your antenna noise temperature)
- Dish surface accuracy loss

In simulation you can achieve up to around 80% Aperture Efficiencies, but in practice you will be at least 15 %-units below that, depending on how well you have succeeded in optimising and realising your feed - dish combination.

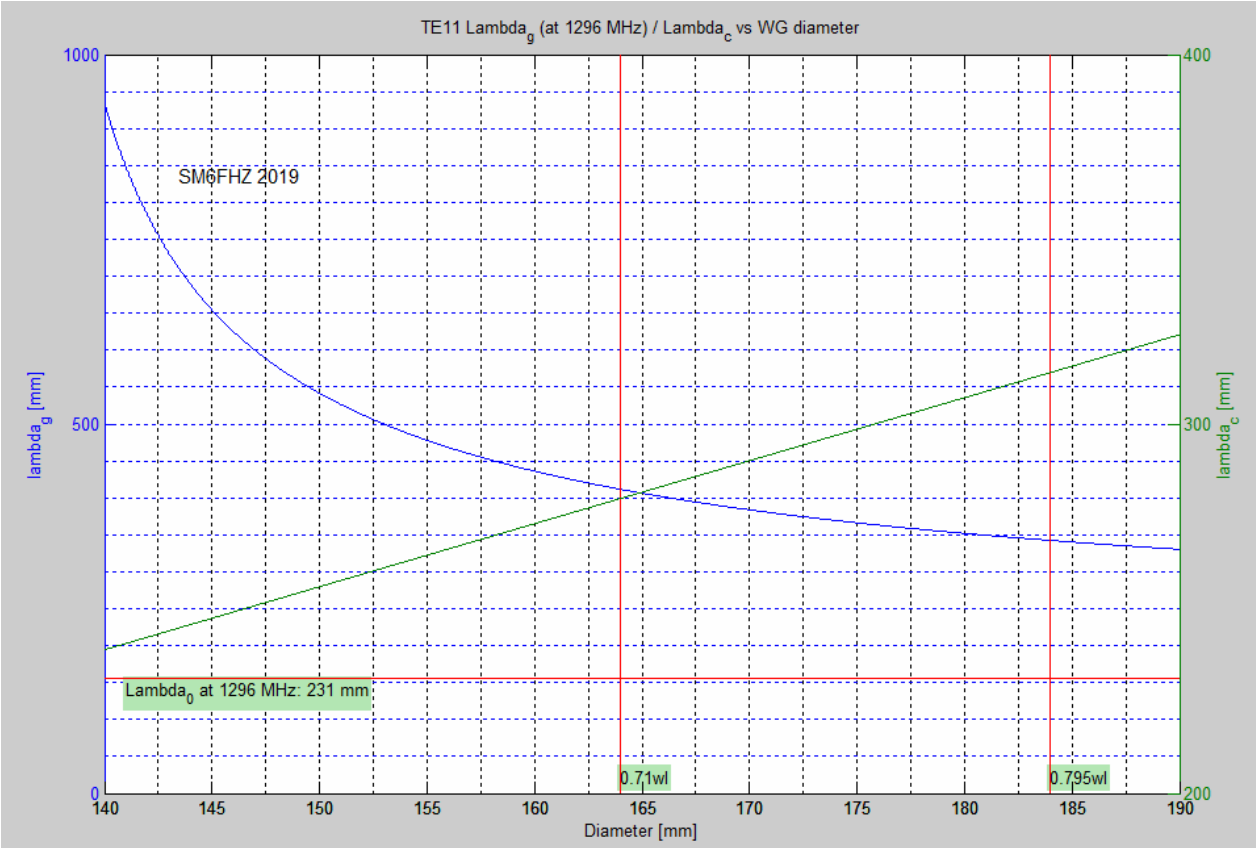
You can find this Aperture Efficiency graph in the W1GHZ "In Dish Performance" plots from his S/W-tools. We will look closer into it soon.

## 2.4 Wave Guide Properties

Since many of the feeds used are wave guide (WG) based, it is useful to have a basic understanding of some wave guide properties

- Cutoff Wavelength ($\lambda_c$) rectangular WG TE10: $\boldsymbol{\lambda_c = 2*a}$ where a is the width of the WG
- Guide Wavelength ($\lambda_g$) rectangular WG TE10: $\boldsymbol{\lambda_g = \lambda_0 / sqrt(\varepsilon_r - [\lambda_0 / \lambda_c]^2)}$ where $\lambda_0$ is the free space wavelength and $\varepsilon_r$ is the relative dielectric constant of the material inside the WG (in most cases 1 for air)
- Cutoff Wavelength ($\lambda_c$) circular WG TE11: $\boldsymbol{\lambda_c = 3.412*a}$ where a is the diameter of the WG
- Guide Wavelength ($\lambda_g$) circular WG TE11: $\boldsymbol{\lambda_g = \lambda_0 / sqrt(\varepsilon_r - [\lambda_0 / \lambda_c]^2)}$ where $\lambda_0$ is the free space wavelength and $\varepsilon_r$ is the relative dielectric constant of the material inside the WG (in most cases 1 for air)

Note that the Guide Wavelength ($\lambda_g$) changes more rapidly with frequency the closer to the cut-off frequency you are; as the speed of propagation inside the WG decreases (dispersive). $\lambda_g$ becomes exceedingly longer as you approaches the cut-off frequency.




The Guide Wavelength determines the dimensions of any polariser structure inside the WG as well as the feed probe position and length. This means that if the WG dimensions are altered the dimensions of the polariser and feed probe have to be re-optimised in order to maintain the desired performance. Do not alter any WG dimensions on a good feed design; you will be on your own and will ruin the performance of the original design! Direct scaling will not work particularly well either, you need to re-optimise the design for the new WG dimension(s).

## 3 The good feed

What is a "Good" feed? Are there any characteristics that signify a "Good" feed?
The general signs to look for can be:

- Well characterized i.e. performance well known (by simulation or measurement) and fully documented.
- It has a radiation pattern that suits your dish profile.
- Low ohmic losses.
- The E- and H-plane patterns are equal to each other out to the dish edge (in all planes).
- The phase error is low out to the dish edge (in all planes).
- The Cross Polar Ratio (CPR) (Axial Ratio for a circularly polarised feed) is good out to the dish edge (in all planes).
- Good Front to Back Ratio (FBR), at least 15 dB. This is especially important for off-set dishes as the back of the feed faces 'hot' ground over a larger angular interval, when used for EME-communication, compared to primary fed dishes.
- Low sidelobes

A good feed for your dish is the one that complies with the above and fits the profile of your dish for the optimisation of your choice.

# 4 Efficiency and G/T plot

## 4.1 General description

The G/T (Gain over Temperature) figure gives a measure of the total Rx-capability. It will take ALL noise sources into account, if so desired, as well as the gain of the antenna. This is a very powerful tool in optimising the feeding of a dish for optimum Rx-performance in any situation.

In his Feed_GT software W1GHZ, Paul, has incorporated a G/T graph into the plot output of the calculations. Let us have a look at what this plot says.

The example used shows a plot looking at SM6FHZ 70cm Super Feed, presented at the Swedish EME-meeting in Örebro, May 2015. [Ref. 1]. This feed is designed for large dishes (>10m) and is designed to optimise Rx-performance. This feed is large, the reflector is 2.2 λ in diameter.

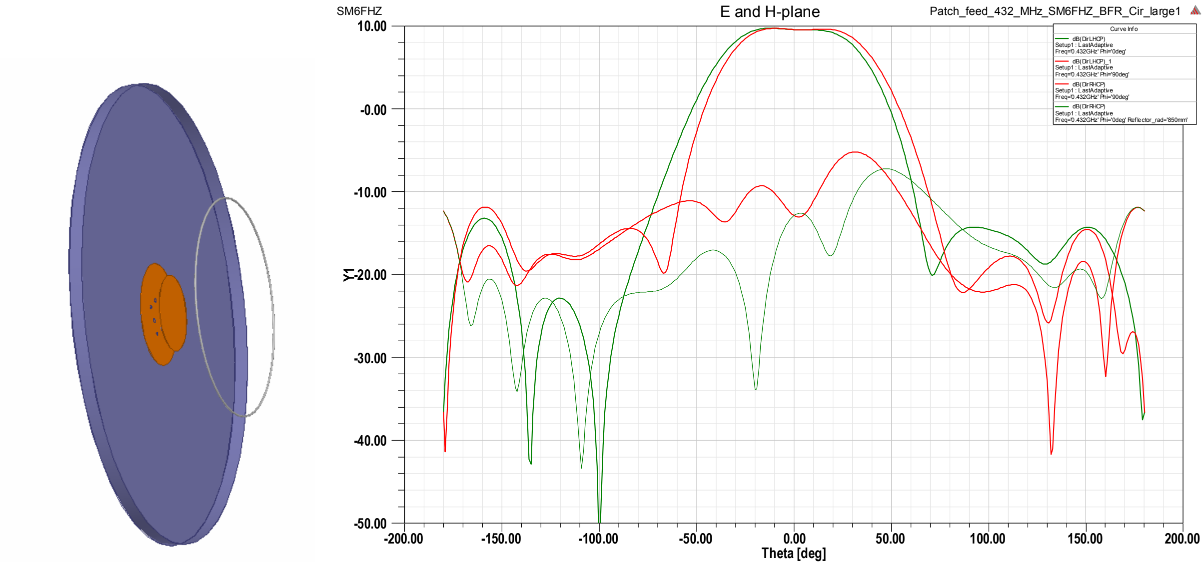



Fig. 3

Figure 3 shows the simulation model and a Co and Cross-polar radiation patterns, in two orthogonal cuts, for the SM6FHZ 70cm Super Feed.

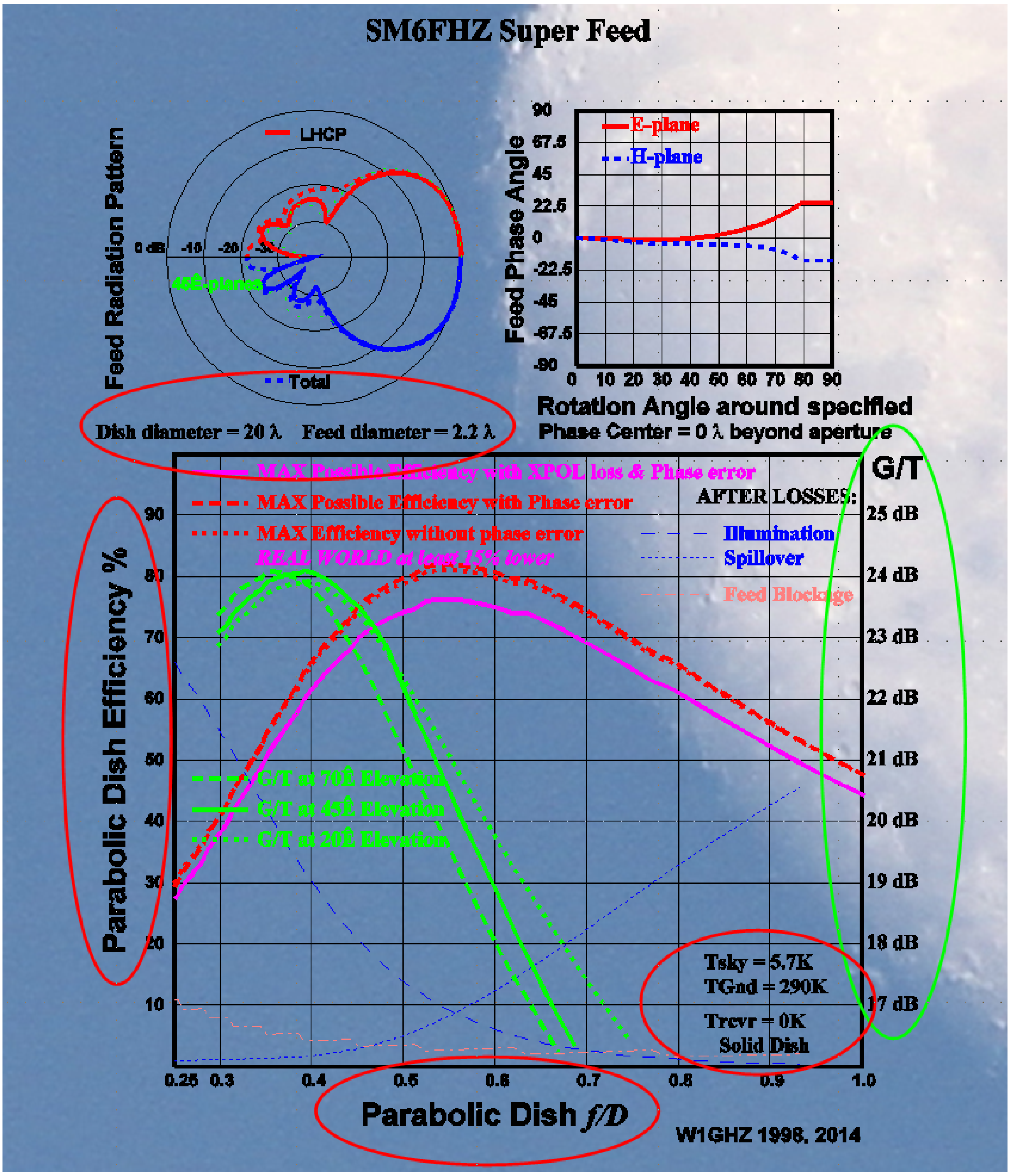



Fig. 4

Let us look into the different parameters and data available in the Figure 4 plot.
The sub-plot in the upper left part is an representation of the radiation patterns used for the calculations. Several theta-cuts are shown in this sub-plot, every 45° as well as Total Power-radiation patterns. Below this sub-plot are the dish diameter and feed diameter, in lambda stated.
In the upper right corner is a sub-plot with the phase error, for both E- and H-plane, shown as function of subtended feed angle. Below this sub-plot the phase centre position of the feed, as calculated by Feed_GT, is stated.

The Main plot area shows the Efficiency and G/T-plots. The Efficiency plot also shows the contributions used in the calculation: Illumination, Spillover and Feed Blockage. It additionally includes the total efficiency with and without Phase Error and XPOL-loss.

The X-axis of the main plot area shows the f/D of the dish, from 0.25 to 1.0. The left Y-axis shows the efficiency scale and the right Y-axis shows the G/T scale.
In the lower right corner of the main plot area are the noise temperatures used for the G/T-calculations shown. This is a very important part as we will see later.
So, how to interpret these graphs?

The easy one would be to optimise for best Tx-performance. What f/D is best suited for this particular feed? The efficiency curve peaks broadly around 0.55 f/D so anything from 0.52 to 0.6 would be just fine for optimum Tx-performance. This is quite straightforward.

The next task would be to find the optimum f/D for best Rx-performance. By just looking at the G/T-curve you would go for an f/D of 0.35 to 0.4, depending on what elevation angle to optimise for. It peaks slightly below f/D 0.4 with a small variation for different elevation angles. You will get a slightly reduced efficiency that will show up in the Tx-situation. In the Rx-situation it is already accounted for in the G/T improvement. As said before, Tx-power can compensate for this but lower G/T can not be compensated for as the noise is already in your system and can not be removed.

But wait a minute, what about the numbers in the lower right corner then? Do they do anything to this? Yes, they do indeed. They can change the optimisation criteria a lot, as they show the G/T for the dish alone in the above example plot. This will not be true for the complete system including the receiver. The Rx NF does play a significant role in optimisation of the total system for the best G/T figure possible in reality. Paul, W1GHZ, points to this in Feedhorn Analysis for Parabolic Dish G/T, 2014 [Ref. 4].

This will be explored in the following examples for 23cm and 3cm EME. I am using two of my feed designs, presented at the Swedish EME-meeting in Örebro, May 2013 and in May 2015. See Ref. 2 and Ref. 3. A Kumar WG feed for 23cm aimed at f/D's of slightly below 0.4 and a Dual Mode WG-feed for 3cm aimed at f/D's around 0.5 to 0.6.

### 4.2 23cm (1.3 GHz) example

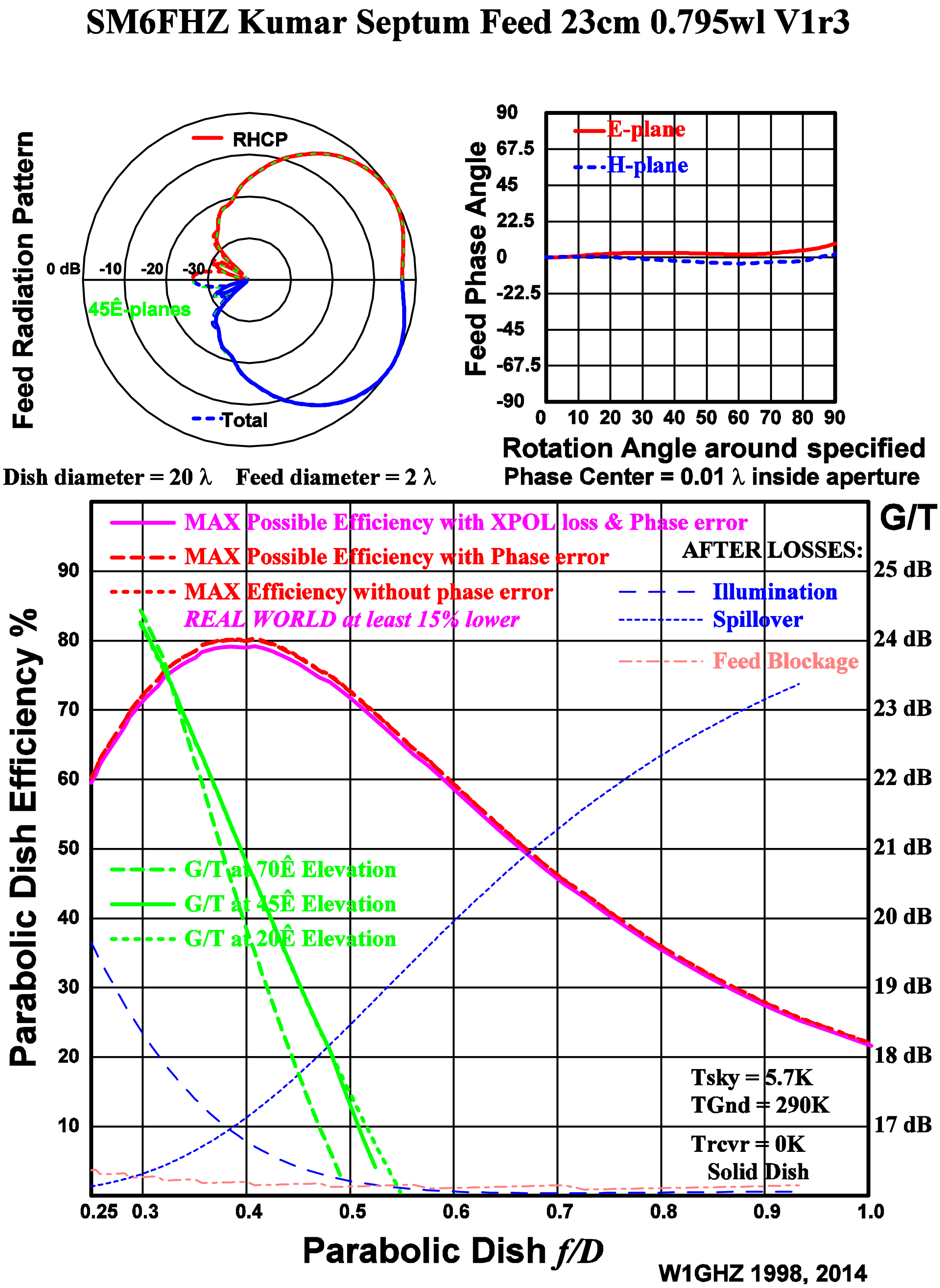



Fig. 5

In this analysis an Rx Noise Temperature of 0K has been used. This leads to an optimum G/T at a very low f/D in the graph. The optimum f/D is not even inside the plot area. Can this be correct? No, of course not. A 0K Rx is yet to be seen. A more realistic value would be around 60K for the full Rx (not only the LNA) including any losses in protection relays etc.

## SM6FHZ 23cm Kumar Septum Feed

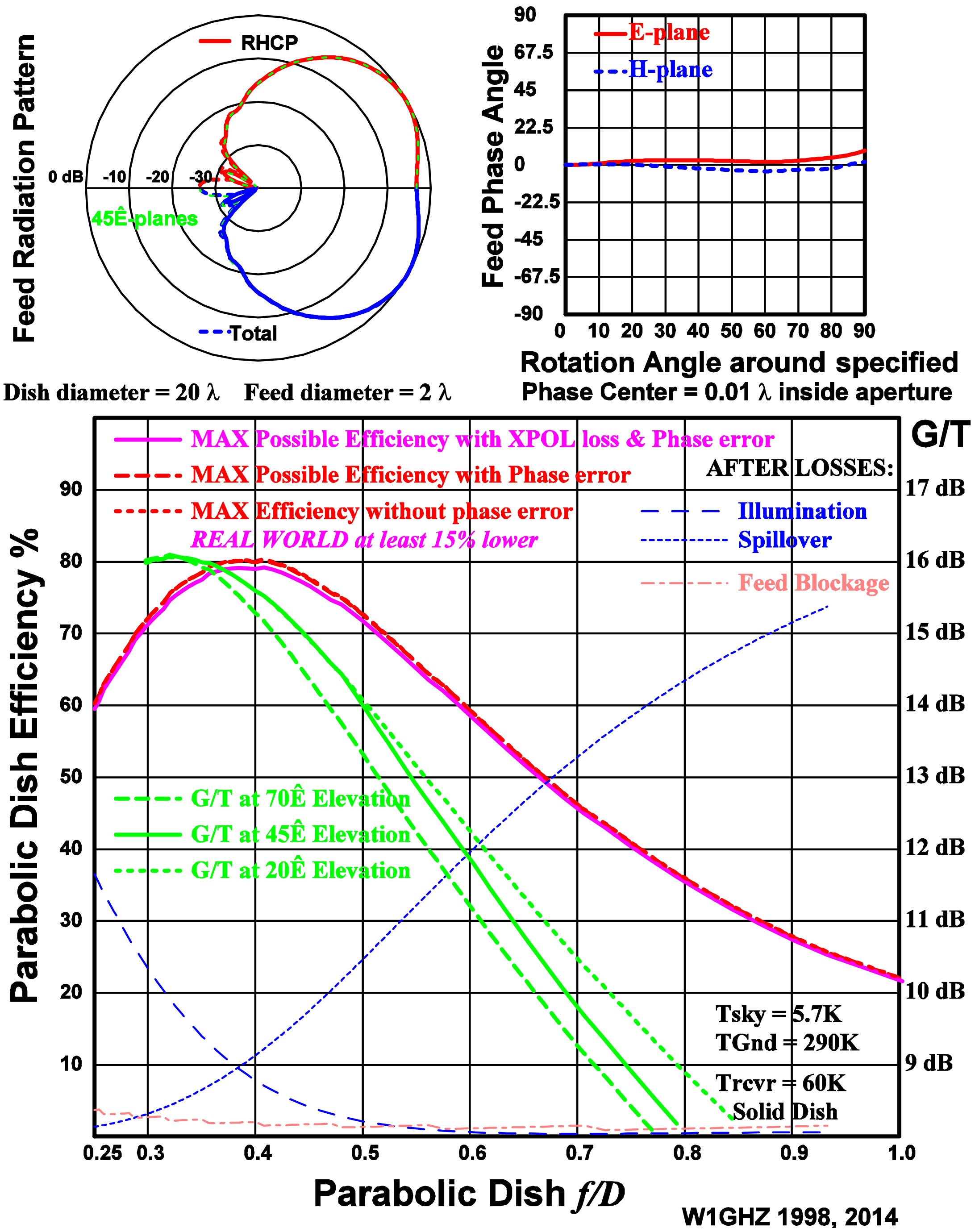



Fig. 6

With 60K Noise Temperature of the RX, the optimum G/T has now moved inside the plot area and sits at ~0.33 f/D, for this feed example. I would say this example would be very typical for any feed. It would just be at another f/D depending on the feed properties, but the general conclusion would be very much the same. The G/T number goes down of course, as you put more noise into the system you are analysing. But this would be the most realistic way to optimise this system.

On 23cm the sky background temperature would be quite easy to agree upon and will be close to the value used in the above calculations (5.7K). If you have a very large dish (on 23cm) the thermal noise from the Moon would start to alter this figure. More about that effect in the 3cm example below.

## 4.3 3cm (10 GHz) example

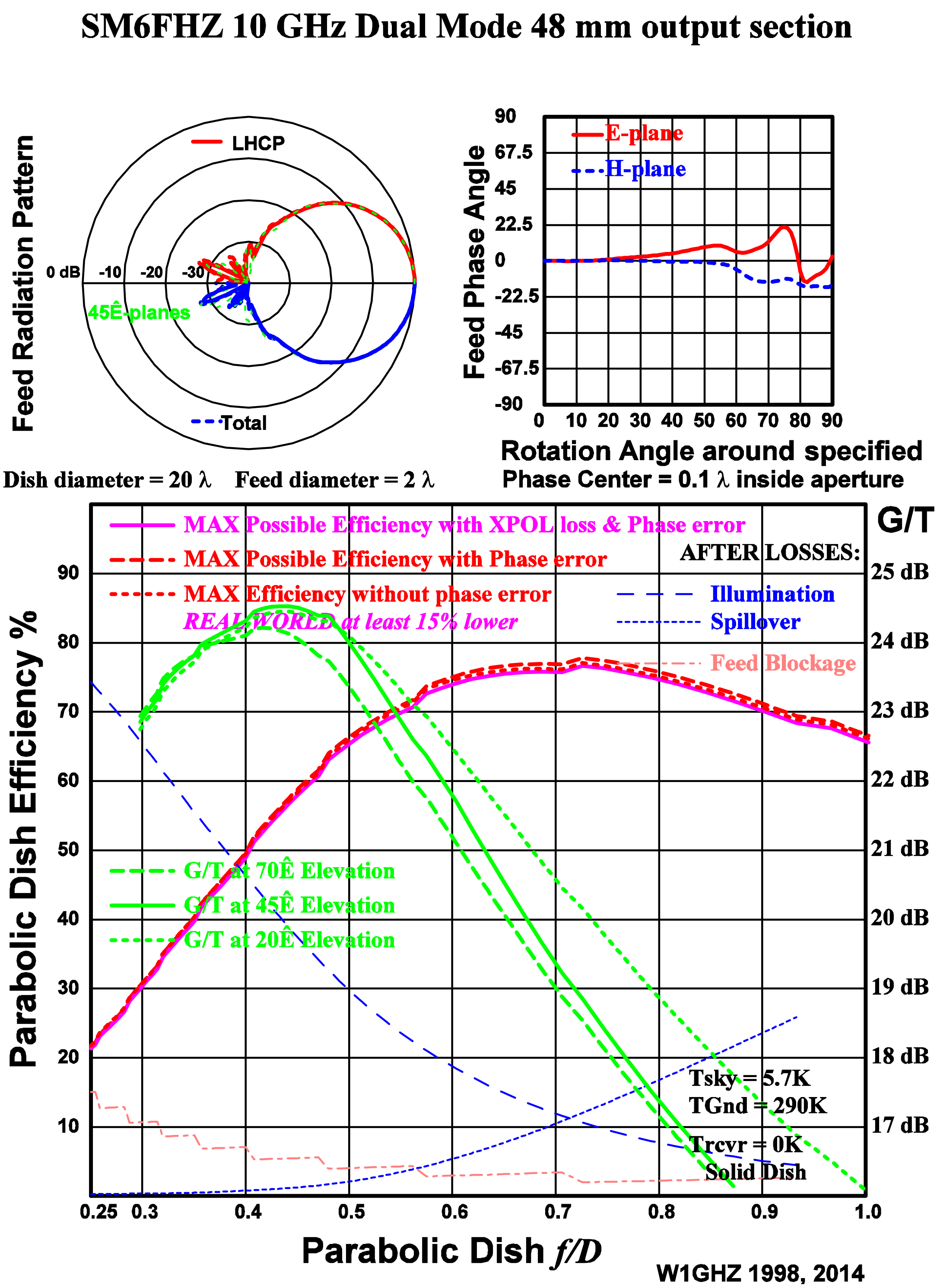



Fig. 7

On 3cm using a Dual Mode Feed we see very much the same effect. An high G/T figure with the optimum far to the left (at low f/D) using a Rx noise temperature of 0K and a sky background temperature of 5.7K. You can see that the peak G/T is at an f/D of ~0.44.

## SM6FHZ 10 GHz Dual Mode 48 mm output section 75K Rx

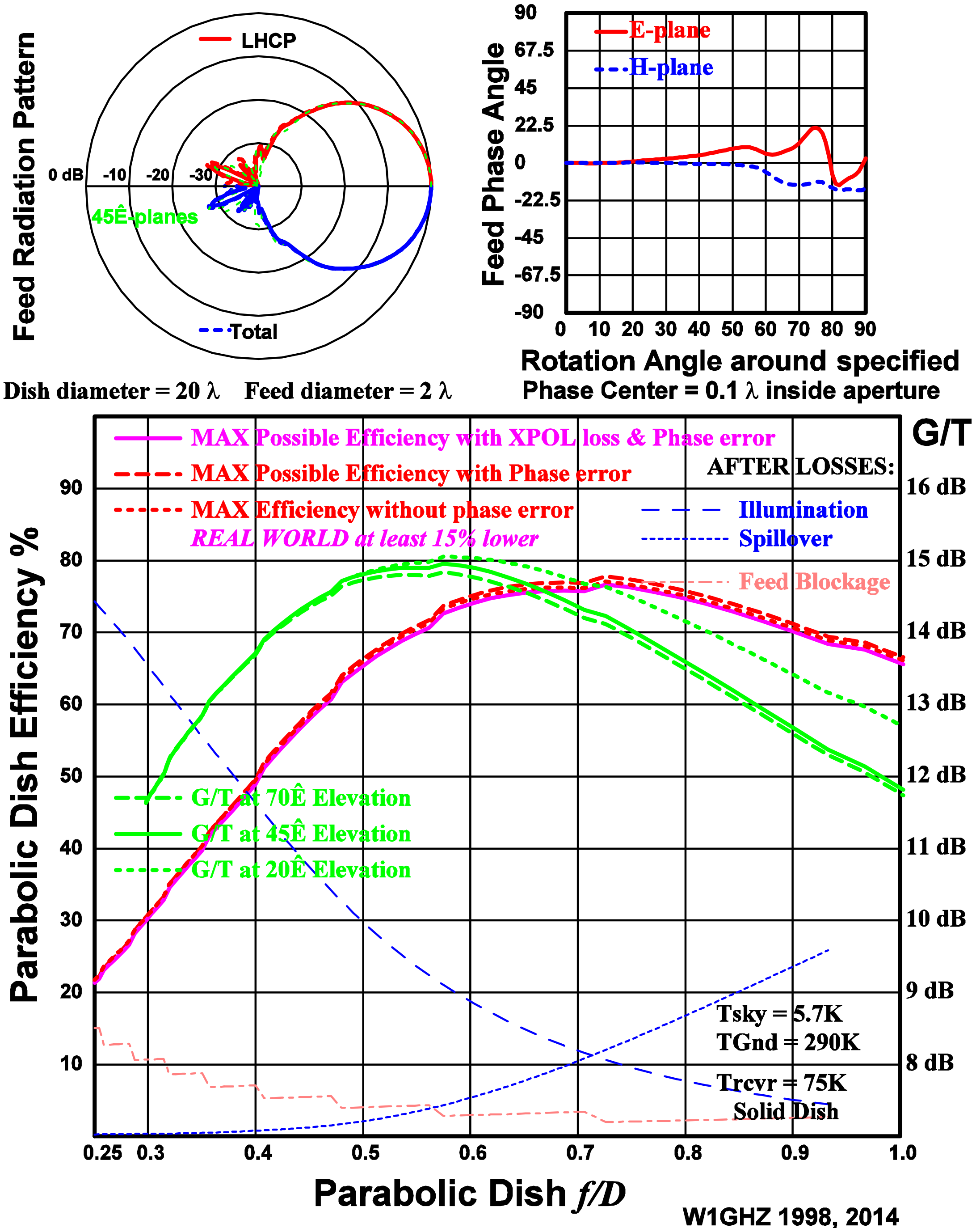



Fig. 8

By introducing a more realistic Rx Noise Temperature of 75K the G/T peak number goes down, naturally, and moves to the right in the plot to an f/D slightly below 0.6. Some may say that 75K Rx temp is pessimistic. I would say some may have a slightly lower T Rx, but most would be in this region. Make a Cold Sky to Ground (CS/G) test with your feed horn, including everything in the front, and you will see for yourself.
But this discussion is mostly semantics, as you will see further down.

# SM6FHZ 10 GHz Dual Mode 48 mm o/p section 75K Rx + moon

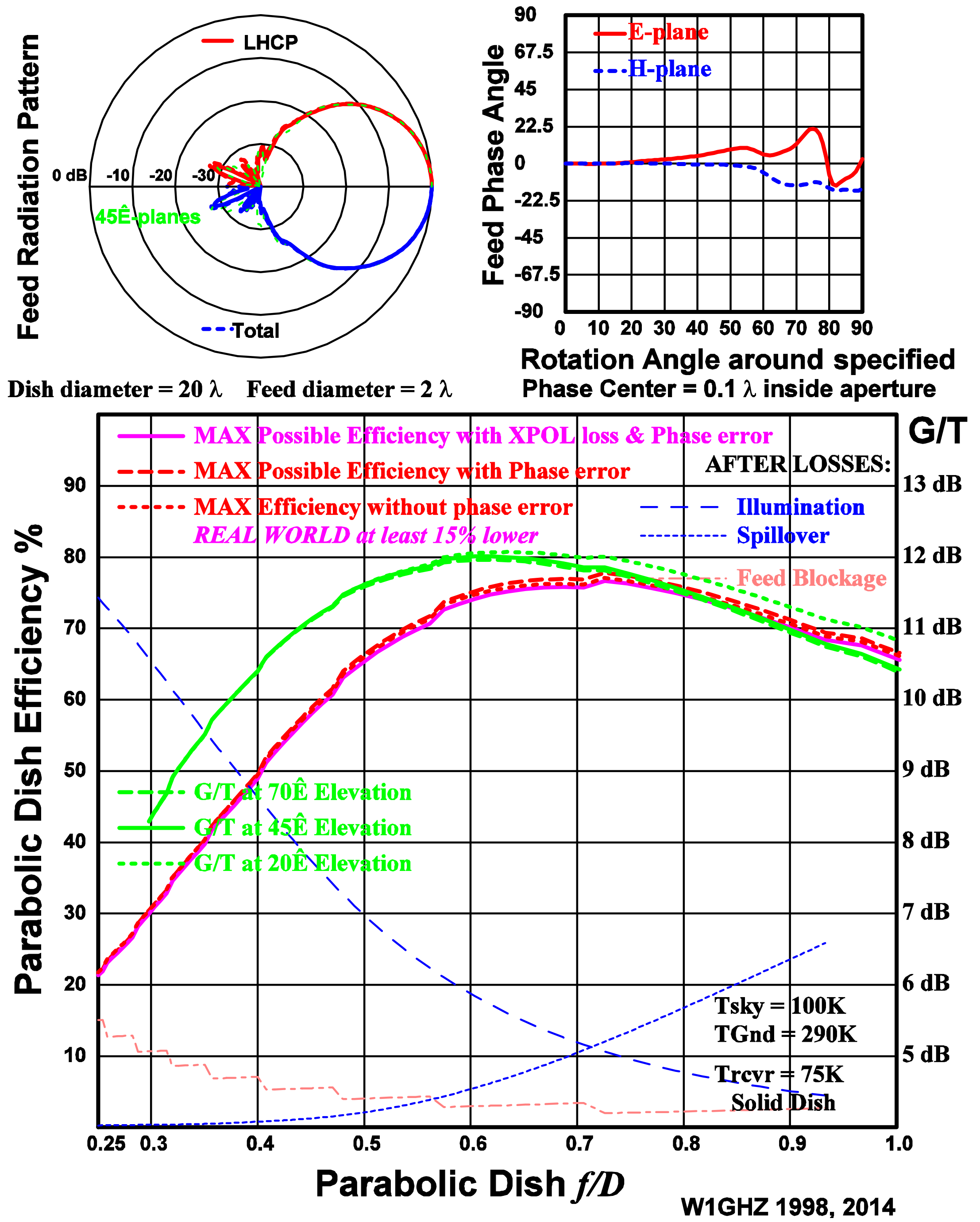



Fig. 9

Introducing the thermal radiation from the Moon into these calculations by setting the Sky Background Noise Temperature to 100K the G/T curve moves further to the right in the plot and goes down another 3 dB. Note that I have used the same dish size (20 λ), this is of course not correct with respect to the Beam Width and the amount of Moon noise (Sky Noise Temperature) received. I did this to maintain all other parameters fixed (e.g. feed blockage) in the plots.

Going to a larger dish, you will see a larger amount of Moon noise and by that a higher Sky Background Noise Temperature. Going up towards 200K would not be unrealistic. Then the Rx Noise Temperature is getting less important. Going to a lower noise LNA would increase the Cold Sky to Moon noise ratio, but not so much the receive performance on EME signals.

## 5 Feed Choice Scheme

In order to choose a feed for your dish, you can follow this scheme:

- Decide what to optimise for; Tx-performance, Rx-performance or a compromise.
- Determine your dish f/D value.
- Look for feeds with declared performance (i.e. Feed_GT plots). If not available, ask the designer for one. If the designer can not provide one, stay away from that feed. You will not know what you are getting. Neither does the designer, obviously.
- Do the above described analysis with respect to your performance characteristics choice.
- Make your choice of feed and put it into your dish.
- Optimise feed position if you do not know the focal length of your dish precisely, using CS/Sun in one ‘session’. Move feed in equal increments and plot the results to find the optimum position.
- Check the system for key parameters like Cold Sky to Ground noise ratio (CS/G), Cold Sky to Sun noise ratio (CS/Sun) or Cold Sky to Moon noise ratio (CS/Moon) depending on what band and what size of dish you are using.
- Work EME!

The VK3UM software EME Calc does have a data base of a lot of feeds with determined performance that you can use in this software to predict what performance you can expect from a feed and you can compare different feeds in this way. In EME Calc you can also change the f/D of the dish in question and see for yourself the impact of those changes on the performance. It is an excellent tool for this work.

If you are in the position that you are going to build a new dish of your own design and have the opportunity to chose the f/D from the start you may think in an slightly different way. It will probably be an iterative process comparing different feed designs in different f/D's in order to optimise for your needs. Avoid making a too deep dish (low f/D, <0.33) as it is difficult to feed in an efficient way unless you desire a ultra quiet Rx-system and can sacrifice Tx-efficiency. If your dish will be of decent size (i.e. >15 λ) you should maybe look into making an off-set dish and use a Dual Mode feed. If you want to use a Kumar type feed you will probably end up with an f/D around 0.37 or slightly below. The objectives are very similar to choosing a feed for a dish at hand with a given f/D, except that you have one more degree of freedom to optimise.

## 6 The undesirable cases

When looking into what feed to use you may run into dish - feed combinations that are very difficult to use. Avoid these.

A small (in wave lengths), flat dish is very difficult to feed in an efficient way. As we concluded in chapter 2.2, a narrow BW is needed to illuminate a flat dish. In order to achieve a narrow BW we need a larger Antenna Area which implies a larger feedhorn aperture. With a small dish the feedhorn size is large enough to block a part of the dish. It is also too close for the dish surface to be in the Far Field of the feedhorn.
Sometimes you see questions on the EME-forums, like "Can I use a 90cm off-set TVRO dish for 23cm EME?" An off-set TVRO dish would likely have an f/D >0.6-0.7. It is designed for X or Ku-band and is very small in wavelengths at 23cm (<4 λ) and will not give much gain at this low frequency. An f/D of 0.7 calls for a feed with a relatively narrow beam for proper illumination, ~39 deg to the dish edge (~10-12 dB taper). See Fig. 10 in appendix. This converts to a directivity of >13dB and a quite large antenna aperture. An W2IMU or N2UO is

not large enough to feed this 90 cm TVRO dish in a proper way. Using Eq. 2 from above gives this: D (lin) = 30, λ = 24cm, => Area = 1380 $cm^2$ . Square root of the area = 37cm (assuming a square antenna aperture). Applying Fig. 1 shows that you need to be ~8 λ away from the feed mouth to be in the far field. That is 1.9m from the dish surface to the mouth of the feed. The focal point of this 90cm dish is 0.7*90cm = 63cm away from the dish. This does not add up to a usable dish - feed system. If you put the feed in the focal point you will be far into the near field of the feed. This will lead to an antenna system with low efficiency due to improper dish illumination and large phase errors across the dish surface. You will probably also suffer from extensive feed blockage.

Very deep dishes (f/D <0.3) are also very difficult to feed in an efficient way. At an f/D of 0.3 your dish edge (subtended feed angle) is at ~80 degrees out from the feed. An f/D below this calls for very special feeds and it would be difficult to archive a good illumination efficiency. One place for very deep dishes (low f/D), would be if you strive for a very low noise set-up. If you have a extremely low noise LNA you may benefit from the low spill-over from a very deep dish, but that would be an unusual case in radio amateur EME.

## Summary / Conclusions

I would like to emphasise the following conclusions you should take away from reading this paper:

- Always use a feed that is well documented performance wise.
- Do not tamper on your own with a good feed design. That is an Non Win situation, unless you know what you are doing and have the possibility to simulate the resulting performance.
- There is no “perfect match”, you need to make a choice what to optimize for.
- The G/T figure is a powerful way to optimize your EME antenna system for Rx-performance.
- It is not more difficult to do it right from the start, but it saves you a lot of work later when trying to mend improper choices from the start. It is well spent time at the start of your microwave EME project.
- Again; You can gain dB’s in choosing the proper feed for your situation. In EME every tenth of a dB is valuable.

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Paul Wade, W1GHZ, Charles Suckling, G3WDG, and Dr. Mark Whale for reviewing and commenting on this paper.

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## Revision history

A 2022-07-14: First release

## Appendix: Extras

Feed subtended angle versus dish f/D

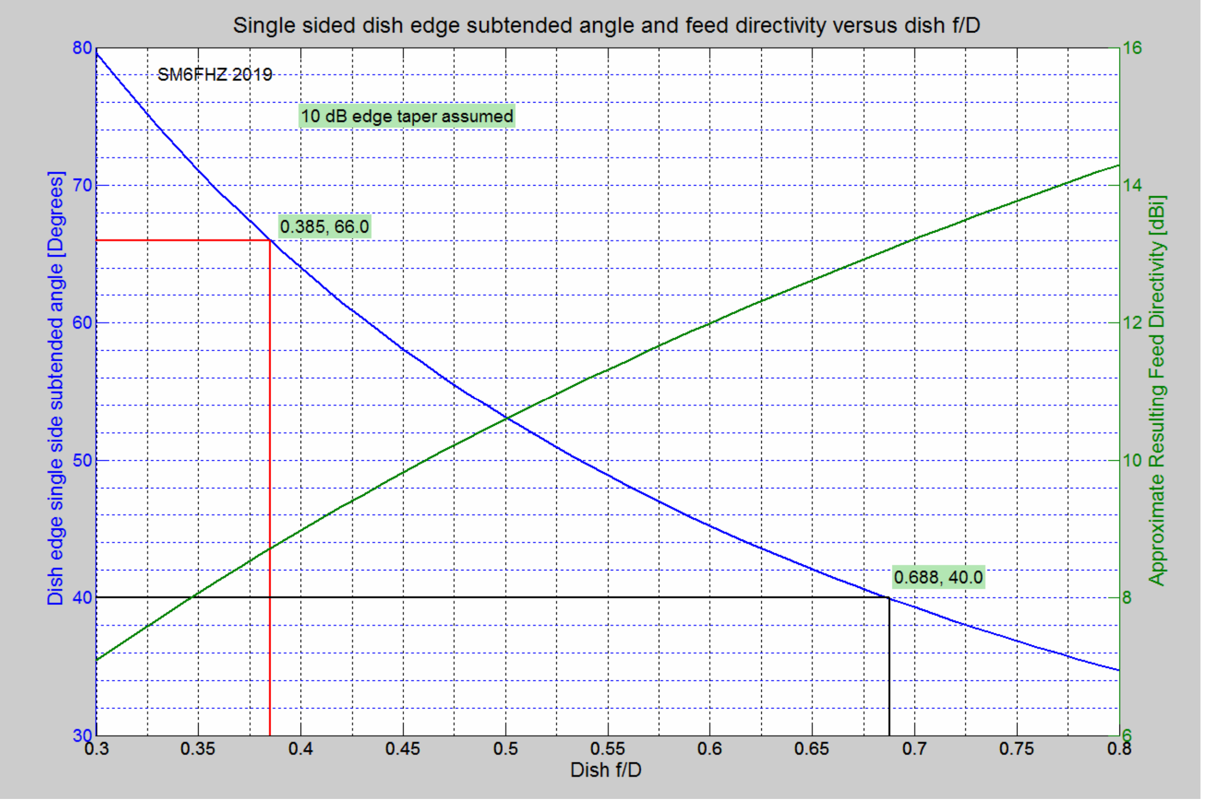


Fig. 10

Extra path loss as function of feed subtended angle

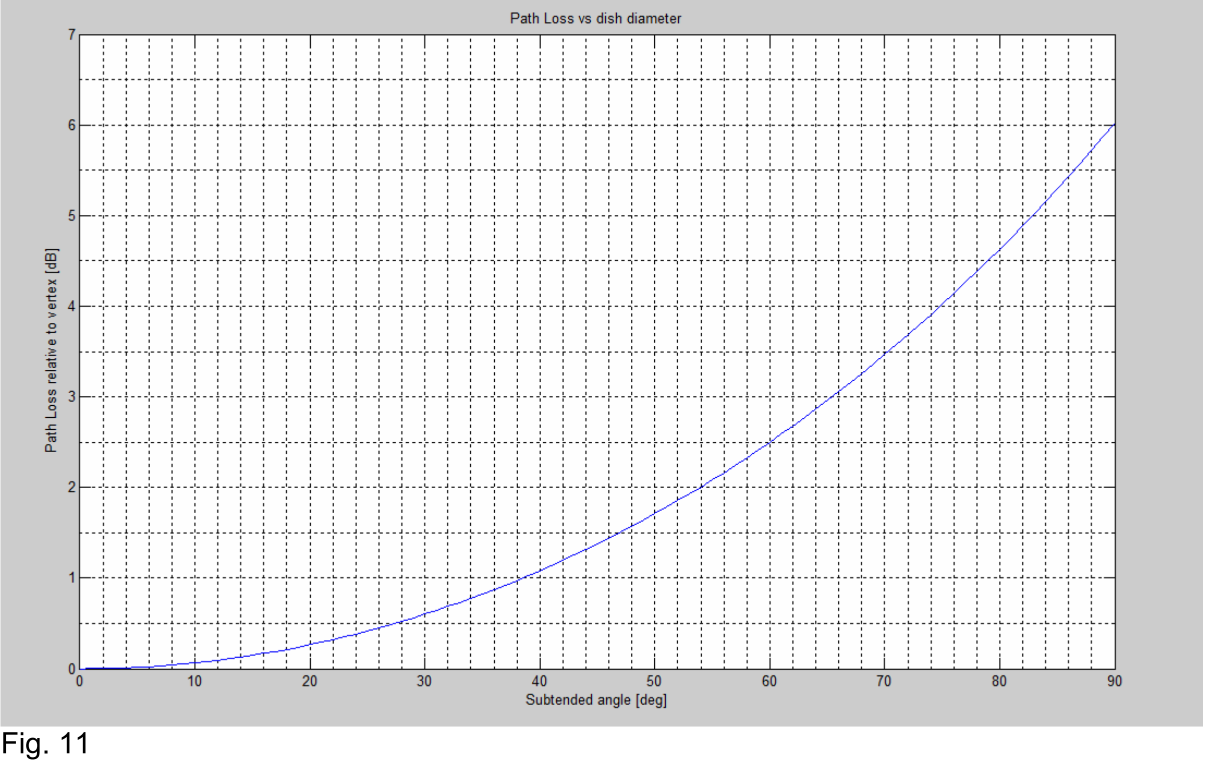


Fig. 11

G/T as function of total Rx (Antenna) Noise Temperature using a W2IMU Dual Mode Feed
The solid green line is with 0K Total Antenna Noise Temperature

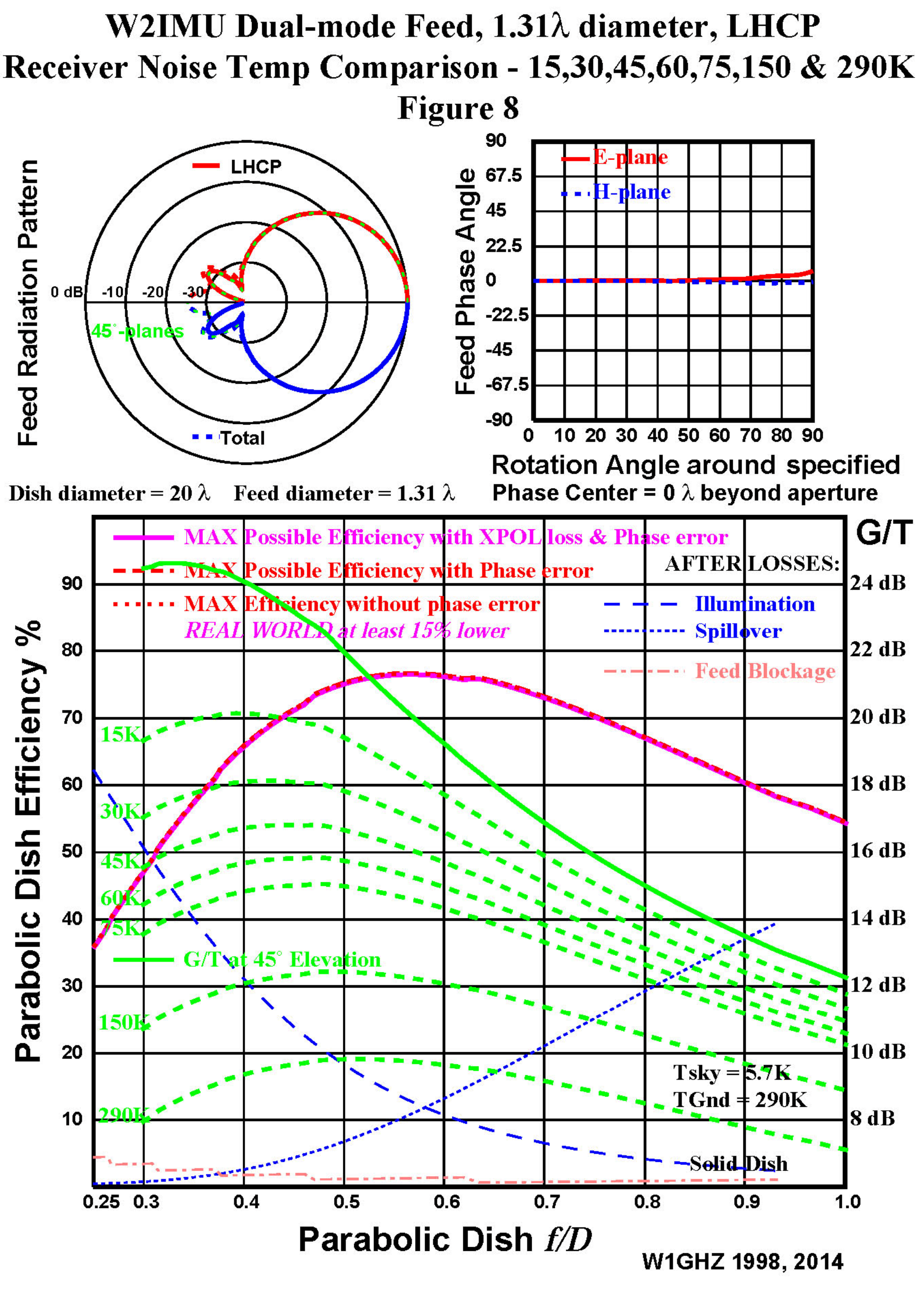


Fig. 12

Courtesy of W1GHZ