Phase Center of Horn Antenna

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Using NEC2++, I've been simulating parabolic reflector antenna components one by one, including the feed horn, sub-reflector, and main reflector. By varying the distance between the feed horn and the sub-reflector, I determined the overall gain and radiation pattern of the parabolic antenna, verifying what's commonly known as "focusing" **[1] [2]**. To clarify the relationship between the results of this focusing and the phase center of the single horn antenna, I conducted a simulation to determine the phase center of a horn antenna.

Introduction

I determined the position of the feed horn antenna that yields the maximum gain for the overall Cassegrain antenna system. I had understood that "focusing" involved aligning the phase center of the feed horn antenna with the virtual focus of the sub-reflector, but the simulation results seemed to contradict this **[2]**. Therefore, I decided to re-simulate the phase center of the horn antenna alone. A review of literature on phase centers revealed that there isn't a single definition; multiple definitions and various methods for finding the phase center exist. I'll refer to the literature for the theoretical background and focus here on the simulations I performed and the results. I will determine the phase center for the W2IMU horns, both the F=0.5 and F=0.7 types, which were used as the feed antennas in the Cassegrain antenna simulation. **Table 1** shows the dimensions of the horn antennas.

Dimension (mm)	Type : F = 0.5	Type : F = 0.7
R0	10.41	10.41
L0	23.6	23.6
R1	17.5	24.0
L1	9.54	27.01
L2	12.55	42.65

Table 1 : Dimensions of W2IMU Horn Antenna

Method 1

While researching, I found the definition and calculation method for the phase center described in the Example Guide of the electromagnetic simulation software FEKO **[3]** to be the easiest to understand, so I tried it first.

The phase center is defined as follows:

- The electric far field of the antenna should decay at *1/r* (*r* = distance).
- The origin of this decay will be the phase center of the antenna.

The calculation method is described as follows:

- Calculate the electric field at two points in the far field (100-to-150 wavelengths) on the antenna's boresight axis.
- Plot the reciprocal of the obtained electric field.
- Interpolate the plot to find the intersection (intercept) with the distance axis.
- This intersection is the phase center.

When using NEC2++ to calculate radiation patterns, I had previously been calculating the far field exclusively. Since NEC2++ can calculate the near field at a specified distance, I used that feature this time. I used the "NE" (Near Electric Field) command for the near-field calculation. The parameters for the "NE" command are defined as follows **[4]**:

- 1 NEAR – Coordinate system type. 0 = rectangular coordinates, 1 = spherical coordinates.
- 2 NRX – Number of points desired in the X, Y and Z directions re spectively.
- 3 NRY
- 4 NRZ
- 5 XNR – The (X, Y, Z) coordinate position respctively, in meters of the first filed point.
- 6 DXNR – Coordinate stepping increment in meters for the X, Y and Z coordinates respectively.
- 7 DYNR
- 8 DZNR

Here, using a Cartesian coordinate system, I found the electric field at six points on the Z-axis (the boresight) at 0.6 m intervals, starting from 1.8 m. The following "NE" command was added to the standard NEC2++ input file for calculating radiation patterns:

NE 0 1 1 6 0 0 1.8 0.6 0.6 0.6

Figure 1 and **Figure 2** plot the near-field of the W2IMU horn F=0.5 and F=0.7 types, respectively. You can see that the electric field decreases in inverse proportion to the distance. **Figure 3** and **Figure 4** plot the reciprocals of the electric fields from **Figure 1** and **Figure 2**. The equations in the graphs show the linear approximation formulas for the plots (slope *m* and y-intercept *c*).

$$y = mx + c$$

Since the phase center is the intersection with the x-axis, we can find *x* by substituting *y*=0 into the equation:

$$x = \frac{-c}{m}$$

From **Figure 3** and **Figure 4**, substituting the respective values for *m* and *c* to find the phase center *x* yields a value of *x*=+1.48 mm for the F=0.5 type and *x*=+2.87 mm for the F=0.7 type. A positive *x* indicates that the phase center is located outside the horn aperture plane, while a negative *x* means it's inside.

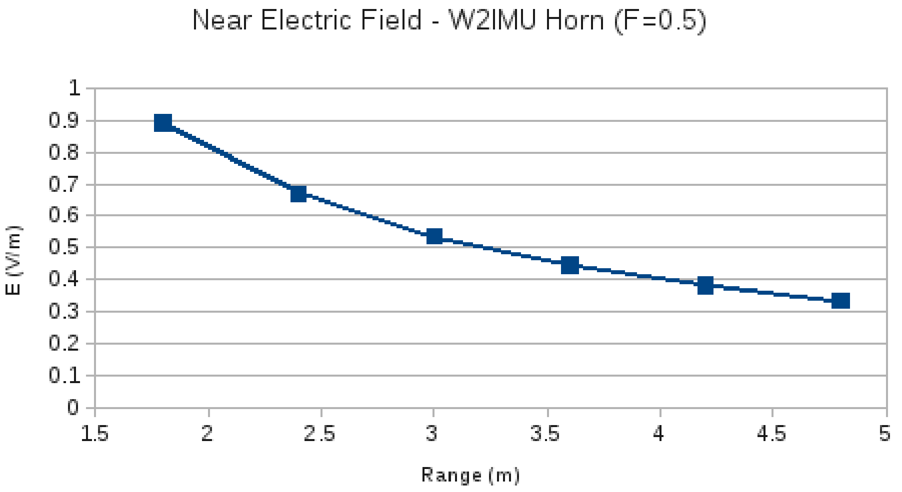

Figure 1 : Near electric field of W2IMU Horn F=0.5

Method 2

The simulation of the overall Cassegrain antenna system suggested that the phase center of the feed horn antenna was located inside the horn aperture plane. However, the analysis in the previous method resulted in the phase center of the single horn being located outside the aperture plane. As mentioned at the beginning, multiple definitions and calculation methods for the phase center exist, so another method should be tried. W1GHZ has published a tool called PHASEPAT.EXE **[5]** that calculates the phase center of a feed antenna and uses it to correct for phase errors to determine illumination efficiency. I'll omit the details of its principle and usage, which are available in the original source, and only state the calculation results here.

I prepared files with the E- and H-plane gain and phase characteristics extracted from the radiation patterns calculated with NEC2++. **Figure 5** and **Figure 6** show the results calculated with PHASEPAT.EXE. The calculations resulted in values of 0.003λ=0.08 mm inward from the aperture for the F=0.5 type and 0.0695λ=2.00 mm outward from the aperture for the F=0.7 type.

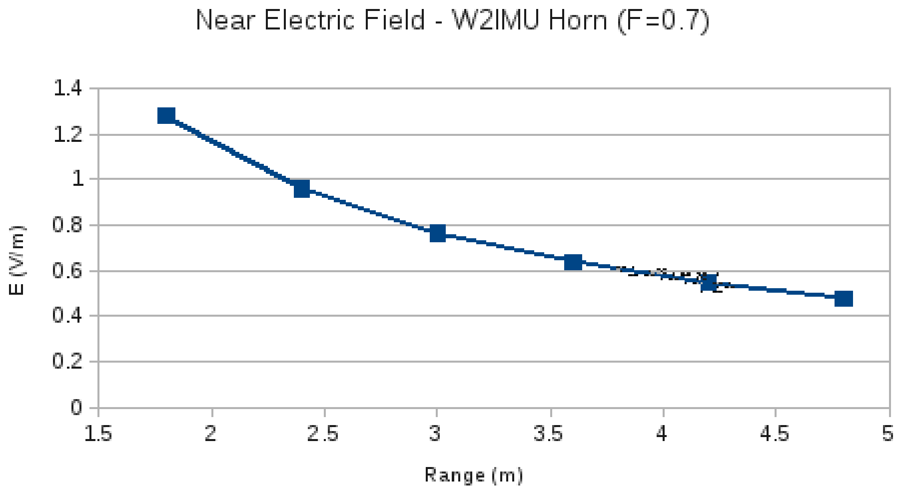

Figure 2 : Near electric field of W2IMU Horn F=0.7

Method 3

Methods 1 and 2 yielded different results. Which one is correct? Let's try one more calculation. The PHASEPAT.EXE documentation provides the following equation **[5]**:

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

where d is the offset between the phase center and the azimuth rotation axis, θ is the azimuth rotation angle, and $\Delta\boldsymbol{\phi}$ is the phase deviation from the boresight.

Since the term (1 – cosθ) was not immediately clear to me from the figure, further research revealed it to be an approximation formula that assumes the far field **[6]**. **Figure 7** shows the relationship between the phase center and the azimuth rotation axis in the far field. The assumption of the far field indicates that the parallax angle between the phase center and the azimuth rotation axis, as viewed from the electric field measurement point, becomes zero. This figure means that when measuring an antenna's radiation pattern, the phase deviation becomes zero (or minimal) if the phase center and the azimuth rotation axis are aligned. In other words, if you shift the azimuth rotation axis and rotate the antenna, the position where the phase deviation is minimal is the phase center. While it's inefficient to try multiple azimuth rotation axis positions in real world measurements, it's very easy with NEC2++. You only need to shift the coordinate origin in the antenna model description. The "GM" (Coordinate Transformation) command is available for shifting the origin **[4]**. Figure 8 shows an example of a model with the origin shifted by 5 mm.

Figure 9 and **Figure 10** show the phase characteristics of the radiation patterns calculated with NEC2++ for origins shifted by -5 mm, 0 mm, and +5 mm. The radiation pattern is generally plotted using only amplitude information (gain characteristics), but here, the phase characteristics specifically, the deviation $\Delta\boldsymbol{\phi}$ from the boresight direction (θ=0 deg.) are plotted. It's clear that the undulation in the phase deviation is smaller when the origin (rotation axis) is at 0 mm, which is likely close to the phase center, and larger when the rotation axis is shifted to +/- 5 mm.

Next, **Figure 11** and **Figure 12** show the results of searching for the position with the minimum undulation by calculating the phase deviation undulation for origins shifted by +/- 10 mm in 1 mm increments. The "undulation" of the phase deviation is evaluated using the RMS (Root Mean Square) value of the phase deviation shown in **Figure 9** and **Figure 10**. From the figures, you can see that the phase centers for the E- and H-planes are different.

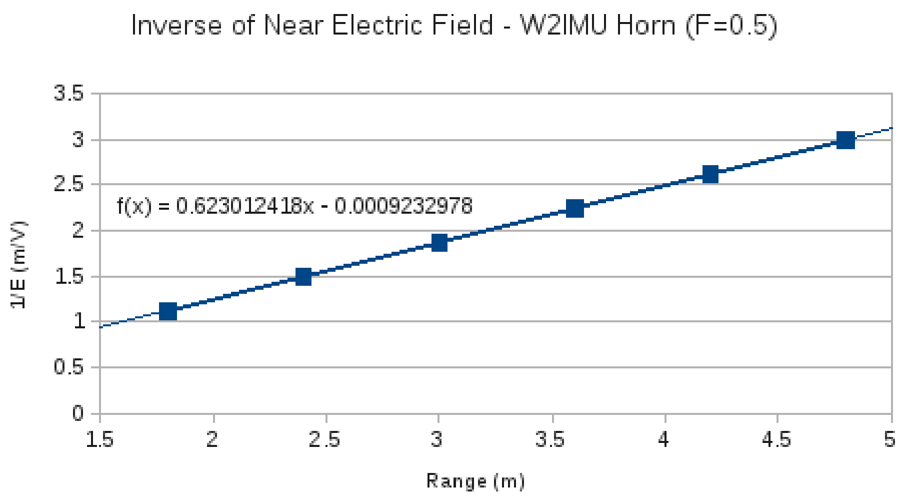

Figure 3 : Inverse of Near field – W2IMU Horn F=0.5

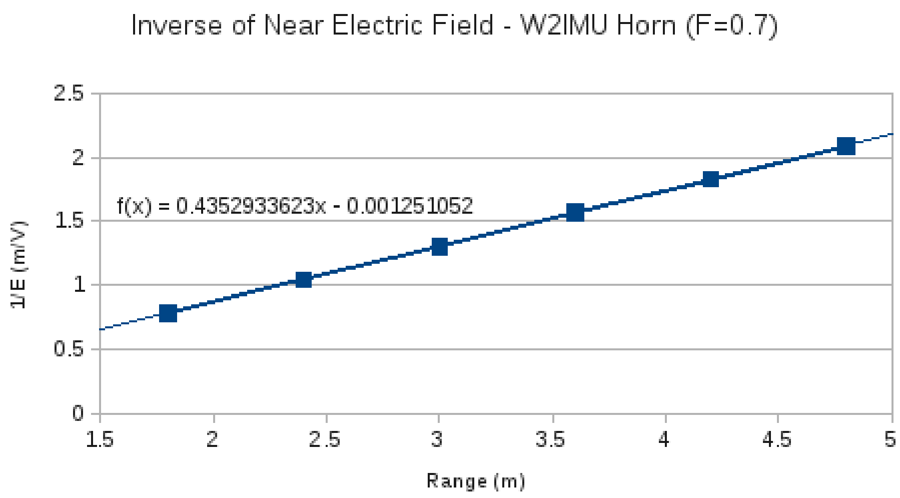

Figure 4 : Inverse of Near field – W2IMU Horn F=0.7

W1GHZ's PHASEPAT.EXE averages the E- and H-plane phase center positions to determine the antenna's phase center. By estimating the approximate average from **Figure 11** and **Figure 12**, the phase center is about +1.0 mm for the F=0.5 type and about +2.3 mm for the F=0.7 type. Both are outside the horn aperture plane.

The RMS phase deviation in **Figure 11** and **Figure 12** was calculated for the phase deviations shown in **Figure 9** and **Figure 10** in the range of θ=0 to 50 degrees for the F=0.5 type and θ=0 to 40 degrees for the F=0.7 type. This was done to eliminate calculation errors from regions with large phase deviations by setting the upper limit of θ to the illumination angle/taper (approximately -10 dB) corresponding to the F-number.

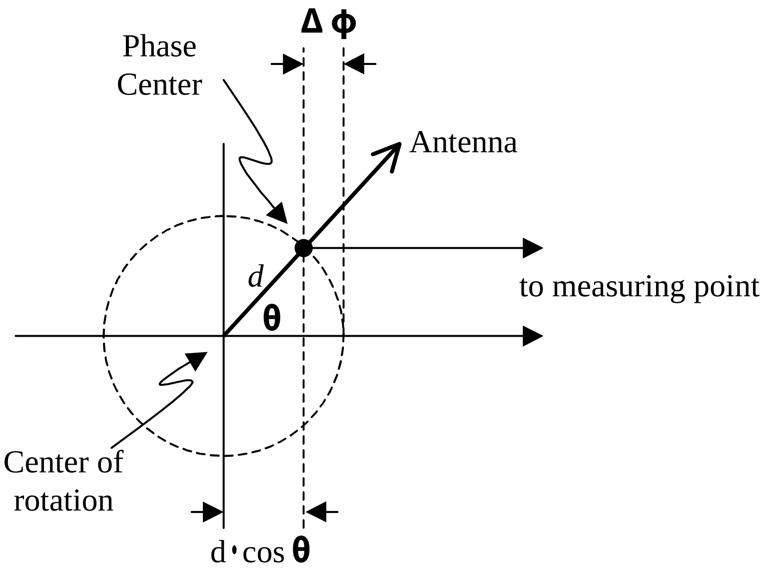

Figure 7 : Phase deviation when the antenna rotation axis is shifted from the phase center

Discussion

Table 2 summarizes the phase center calculation results from the three methods.

Method 1 uses the principle that the far-field electric field strength is inversely proportional to distance. Method 2 estimates the phase center from the phase characteristics of the radiation pattern. Method 3 simulates the trial-and-error process of measuring phase characteristics. Methods 2 and 3 are based on the definition that in the far field, the radiated wavefront is a spherical wave with uniform phase. Based on the results in **Table 2**, it can be said that the phase center of the W2IMU horn is not located inside the aperture.

So, how can we interpret the relationship between the optimal position of the feed horn antenna found for the overall Cassegrain antenna system and the phase center (i.e., moving the feed horn closer to the sub-reflector) ?

Re-examining the dimensions and relative positions of the feed horn antenna and sub-reflector in the Cassegrain antenna system reveals that the

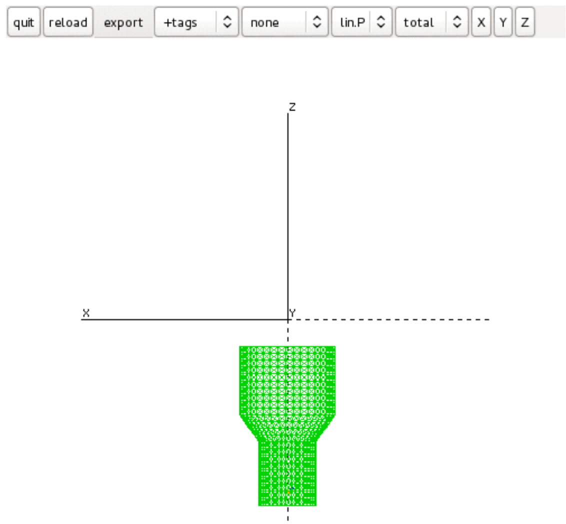

Figure 8 : Example of a model with the origin shifted

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sub-reflector is not in the far field of the feed horn antenna. The far-field is defined by:

$$R = \frac{2D^2}{\lambda}$$

where *R* is the minimum distance that can be considered far field, *D* is the antenna aperture diameter, and *λ* is the wavelength. For the F=0.5 type with *D*=35 mm, *R*=85 mm, and for the F=0.7 type with *D*=48 mm, *R*=160 mm. Therefore, in the previous calculation example **[2]** where the distance from the sub-reflector apex to the virtual focus was 95.61 mm, the F=0.5 type is just barely in the far-field relationship, while the F=0.7 type is not.

It would be inappropriate to apply methods 1 through 3, which are all based on far-field definitions, to a relationship between the feed horn antenna and the sub-reflector where the far-field assumption does not hold. W1GHZ's Cassegrain antenna design tool **[7]** issues a warning and prompts reconsideration if the dimensions and arrangement of the feed horn antenna and sub-reflector do not satisfy the far-field relationship.

In addition to the phase center definition for a horn antenna alone, there is another definition for the phase center of a feed antenna in an overall Cassegrain antenna system **[8]**. According to Kildal, who is cited in the literature, ***"the phase center is the position that yields the highest gain for the overall antenna system."*** For myself who has analyzed the entire antenna system using brute force via the Method of Moments (MoM) rather than approximate assumptions, this definition feels very accurate.

For prime-focus parabolic antennas, there are very few cases where the relationship between the feed and the main reflector is not in the far field. Therefore, it's appropriate to place the phase center of the feed antenna at the focus of the main reflector as a starting point for "focusing." However, with Cassegrain antennas, the first step in "focusing" should be to check whether the relationship between the feed and the sub-reflector is in the far field.

Phase Center (mm)	Type : F = 0.5	Type : F = 0.7
Method 1	+1.48	+2.87
Method 2	−0.08	+2.00
Method 3	+1.0	+2.3

Table 2 : Summary of phase center calculation results

Conclusion

The phase center of a single horn antenna was calculated using three different methods. While the numerical results were not a perfect match, a generally good correlation was confirmed. On the other hand, the results were different from the phase center of the feed horn antenna observed in the characteristics of the overall Cassegrain antenna system. This difference, however, likely depends on the definitions themselves and is particularly pronounced in the Cassegrain antenna system where the far-field relationship does not hold. This reinforces the significance of simulating the entire antenna system with the Method of Moments, rather than evaluating components individually and estimating overall characteristics based on approximate assumptions.

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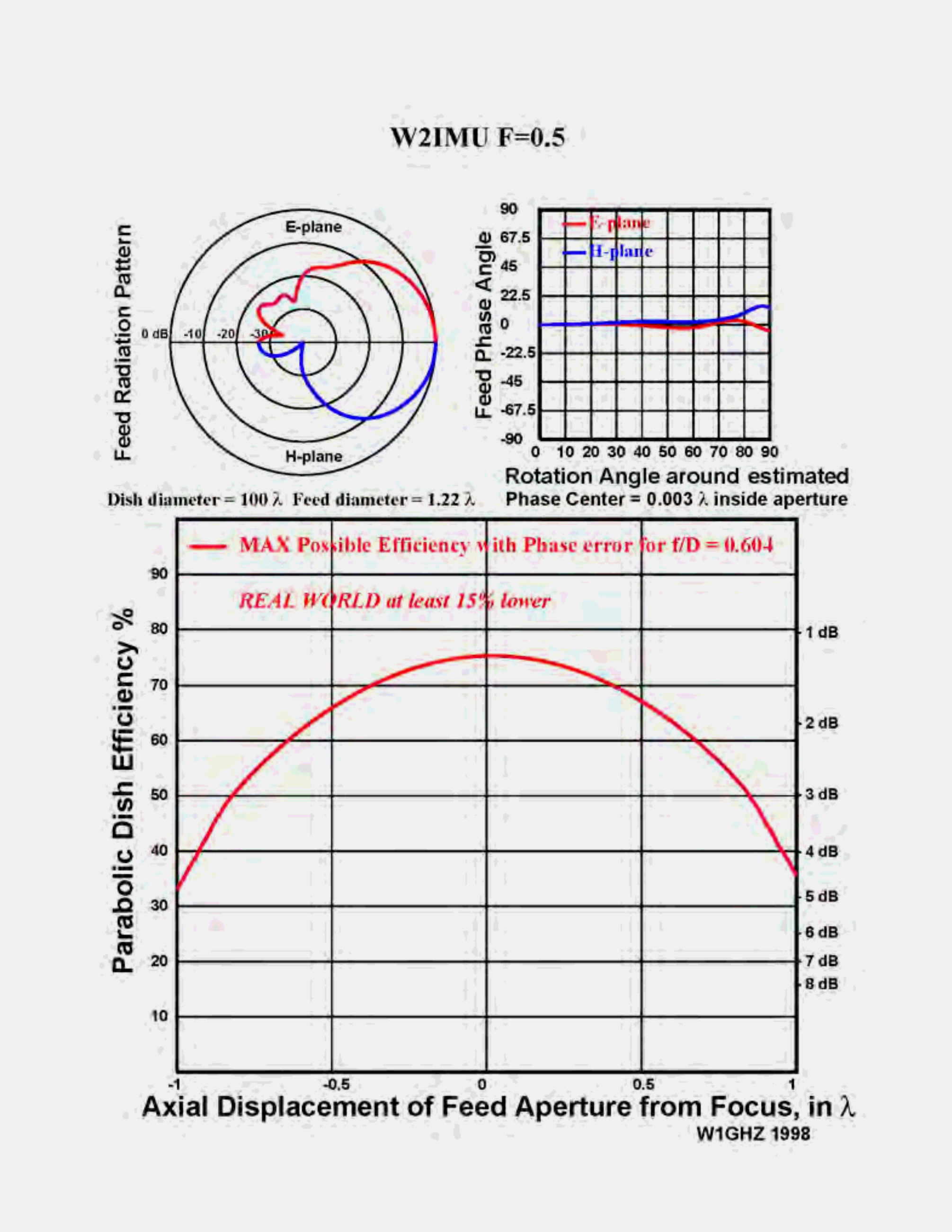

Figure 5 : Calculation by PHASEPAT.EXE – W2IMU Horn F=0.5

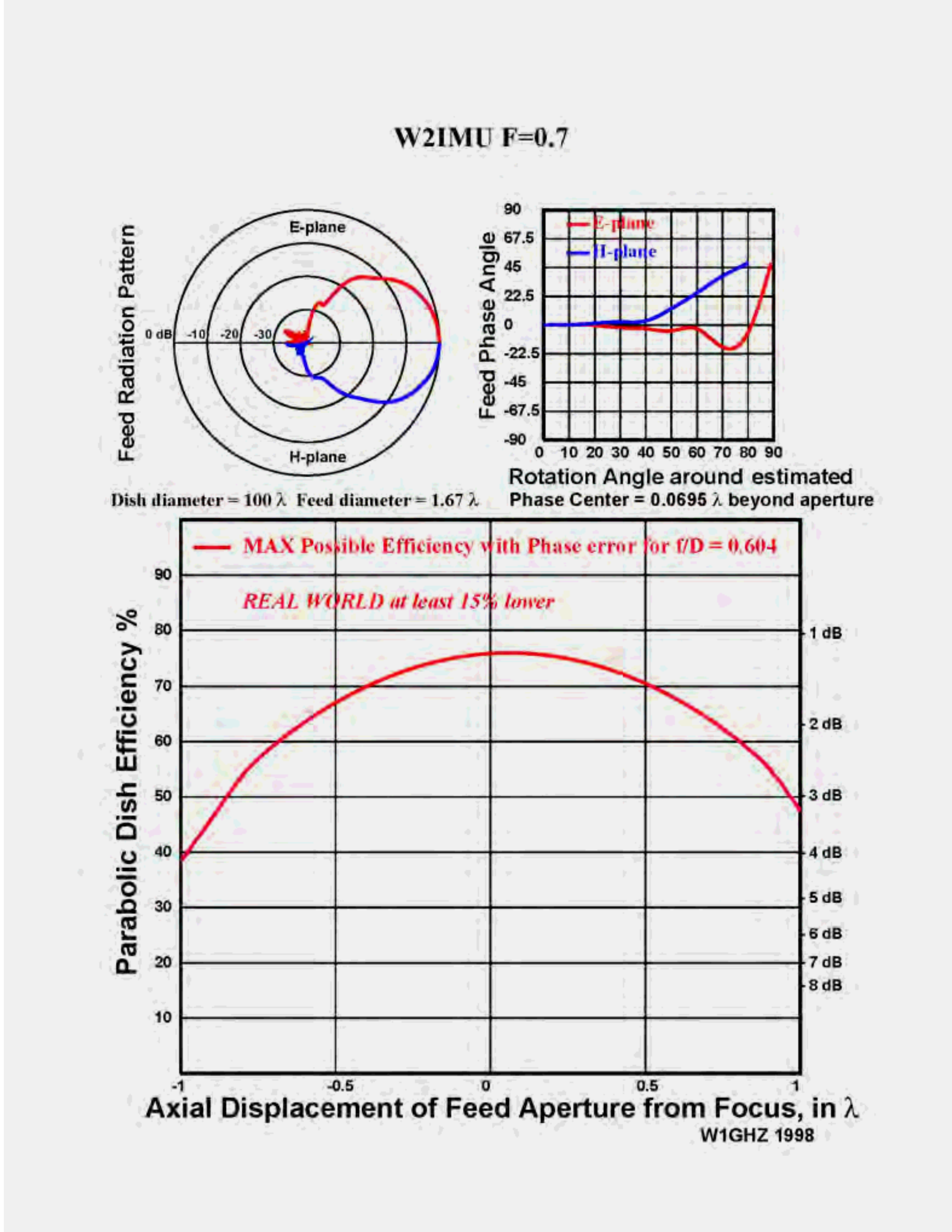

Figure 6 : Calculation by PHASEPAT.EXE – W2IMU Horn F=0.7

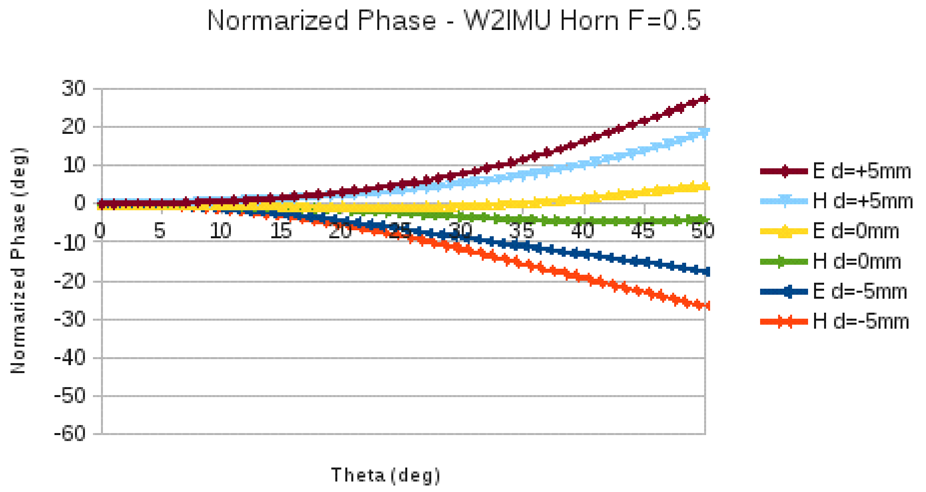

Figure 9 : Phase characteristics when the origin is shifted – W2IMU Horn F=0.5

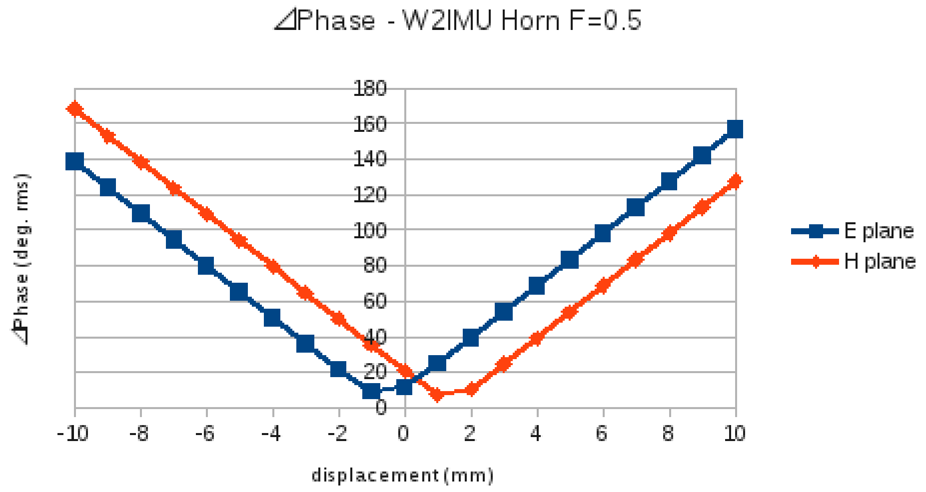

Figure 11 : Phase deviation due to origin shift – W2IMU Horn F=0.5

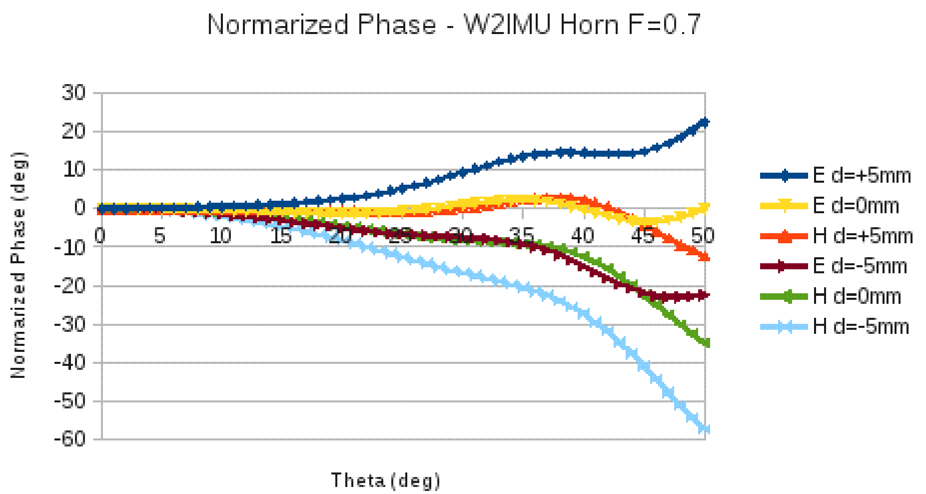

Figure 10 : Phase characteristics when the origin is shifted – W2IMU Horn F=0.7

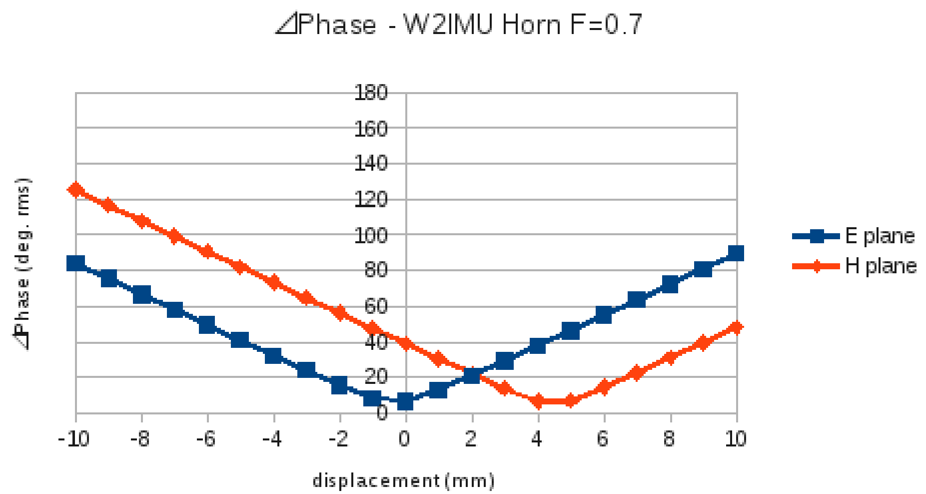

Figure 12 : Phase deviation due to origin shift – W2IMU Horn F=0.7

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