Scanning Performance of the GBT at 1.4 GHz from Prime Focus

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Introduction:

The scanning properties of the GBT are characterized in order to assess the feasibility of providing multiple beams in the sky with the use of an array feed receiver. When the feed in a reflector antenna is displaced in a direction transverse to the reflector axis, the beam is displaced in the opposite direction. By providing a number of offset feeds, multiple scanned beams can be generated. The maximum number of beams that can be provided in a radio telescope is limited by the space available for positioning the feeds, loss of gain and increase in coma sidelobe levels for the off-axis feeds. In a clear aperture design such as the GBT, space is not a limitation as the feed elements do not cause any blockage. The offset geometry of the GBT is also advantageous for array feed receivers as the mutual coupling between the feed elements caused via the reflector is relatively small. However, the clear aperture design has a somewhat poorer scan performance compared to a symmetrical antenna. This memo presents the scan performance of the GBT in the symmetric and asymmetric planes of the telescope at 1.4 GHz and in the symmetric plane at 2.5 GHz.

Space needed and gain loss:

The surface of best focus for feed translation in the absence of astigmatism is called the Petzval surface. For a paraboloid, this surface is another paraboloid with half the focal length, located tangential to the focal plane at the focus. The surface contour to achieve maximum scan gain for offset feeds has been mapped and is shown to be different from the Petzval surface [1]. The offset distance of the feed (d) to produce a beam scan of N half-power beamwidths (HPBW) is given by [2], [3]:

$$d = (1.2 * N * \lambda / BDF) * (F_e / D) \qquad (1)$$

where λ is the wavelength, BDF is the beam deviation factor, D is the diameter of the circular aperture and 1.2 is a factor that is consistent with -10 dB feed illumination taper. For a prime focus symmetrical antenna, F_e is the actual focal length F. For an offset antenna, F_e is larger than F and is given by [2], [3]:

$$F_e = F * (1 + \cos\theta^*) / (\cos\theta_s + \cos\theta^*) \qquad (2)$$

Here θ_S is the offset angle which is the angle between the feed axis and the axis of the parent paraboloid and θ^* is the reflector half-angle. For the GBT, θ_S is 48.45°, $\theta^*$is 39° and using these values in (2), F_e/D is computed to be 0.74. The BDF for the GBT is 0.94 and from (1), the feed offset distance is calculated to be 0.94 λ for a beam scan of 1 HPBW.

Computed gain-loss as a function of beam scans shown in Figure 3.59 of Rudge *et al*. [2] is reproduced in Figure 1. The curves **A** (F/D = 0.93) and **B** (F/D = 0.6) are for symmetric antenna while **C** (F_e/D = 0.933) and **D** (F_e/D = 0.5) are for offset antenna. Estimating from the -10 dB curves, the GBT would have a gain loss of 1 dB for a scan about 2.8 HPBW and a feed translation distance of 2.6 λ. For a symmetric antenna of f/D = 0.42, the 1 dB gain loss occurs for a feed translation of 2.5 λ which gives a beam scan of 4.2 HPBW.

Reflector program analysis:

A reflector analysis program based on Aperture Integration and Uniform Geometric Theory of Diffraction was used to study the beam scan properties of the GBT from prime focus. Vertical polarization is used in all the cases studied here. For the zero-scan case, the feed is located at the focus and pointed at the center of the main reflector. The angle θ_S between the feed axis and the reflector axis is 48.45°. A theoretical feed pattern with -12 dB taper at the edge of the main reflector (θ^* = 39°) was used in the analysis. A feed with -12 dB taper would have an aperture diameter of about 2.6 λ. A 10 cm x10 cm grid was used on the main reflector. At 1.4 GHz, the gain of the antenna is 61.56 dB and the half-power beamwidth is 8.8 arcminutes. For the scanned cases, the feed was translated in a plane perpendicular to the feed axis for simplistic reasons, maintaining the angle θ_S at 48.45°. Feed translations of 1 λ to 5 λ in the symmetric plane and asymmetric planes were used.

In the symmetric plane, the feed was translated towards (-ve) and away (+ve) from the feed arm to study the effect of the asymmetry. Table 1 gives feed translation, scan angle (θ_{scan}), gain loss and efficiency as a ratio of the boresight efficiency in the asymmetric plane. Figures 2, 3 and 4 give the beams of the GBT for translations (-ve and +ve) in the symmetric plane and (+ve) in the asymmetric plane. Figure 5 shows gain loss and beam scan as a function of feed translations for the three cases. The 1 dB gain loss occurs at a feed translation of 2.4 λ for all three cases. The beam scan is 2.6 HPBW. The beam scan for an offset distance of 1 λ is 1.09 HPBW. Figure 6 shows the drop in efficiency as a function of feed translation. It is clear from these graphs that the drop in efficiency is the greatest for translations in the symmetric plane towards the feed arm. Pointing the translated feeds towards the center of the reflector resulted in the same amount of gain loss and beam scans. Calculation in the symmetric plane (-ve) with a -10 dB illumination taper gives 1 dB gain loss for a feed translation of 2.3 λ. However, the beam scan in arcminutes as a function of feed translation remains the same as that with the -12 dB taper.

The calculations were extended to 2.5 GHz in order to cross-check the results at 1.4 GHz. The ratio of beam scan to feed translation (HPBW / λ) at 2.5 GHz is same as at 1.4 GHz. Figure 7 shows the scanned beams of the GBT in the symmetric plane at 2.5 GHz and Figure 8 shows gain loss and beam scan versus feed offset in wavelength. The feed translation for 1 dB gain loss is again 2.4 λ. However, for 5 λ translation, the beam scan is slightly larger at 5.78 HPBW and the efficiency is 0.35 of the boresight efficiency.

Conclusion:

A feed array with one feed in the center and six feeds in an outer ring is a possible configuration. For a feed with -12 dB illumination taper, the outside diameter of the feed is 2.7 λ. The outer feeds will have gain loss between 1 and 1.5 dB. However, using a 2.38 λ outside diameter feed which will give -10 dB taper, the gain loss for the outer feeds can be limited to 1 dB. This feed at the focus results in about 3% loss in aperture efficiency and about 3 K additional spillover compared to the 2.7 λ diameter feed. In a symmetric antenna (f/D = 0.42), the outside diameter of the feed that has -12 dB taper is 1.7 λ. Hence, the outer feeds in a seven-feed array will have beams scanned by 2.8 HPBW and will have less than 0.4 dB loss. More analysis work is required to identify the Petzval surface and the surface of maximum gain for the GBT.

Table 1. Asymmetric Plane

Offset Distance (λ)	0	1	2	2.4	3	4	5
θ_{scan} (degrees)	0	0.160	0.320	0.380	0.480	0.640	0.810
θ_{scan}/HPBW	0	1.091	2.183	2.592	3.274	4.366	5.525
Gain loss (dB)	0	0.175	0.695	1.001	1.549	2.715	4.109
Fractional η	1	0.961	0.852	0.794	0.700	0.535	0.388

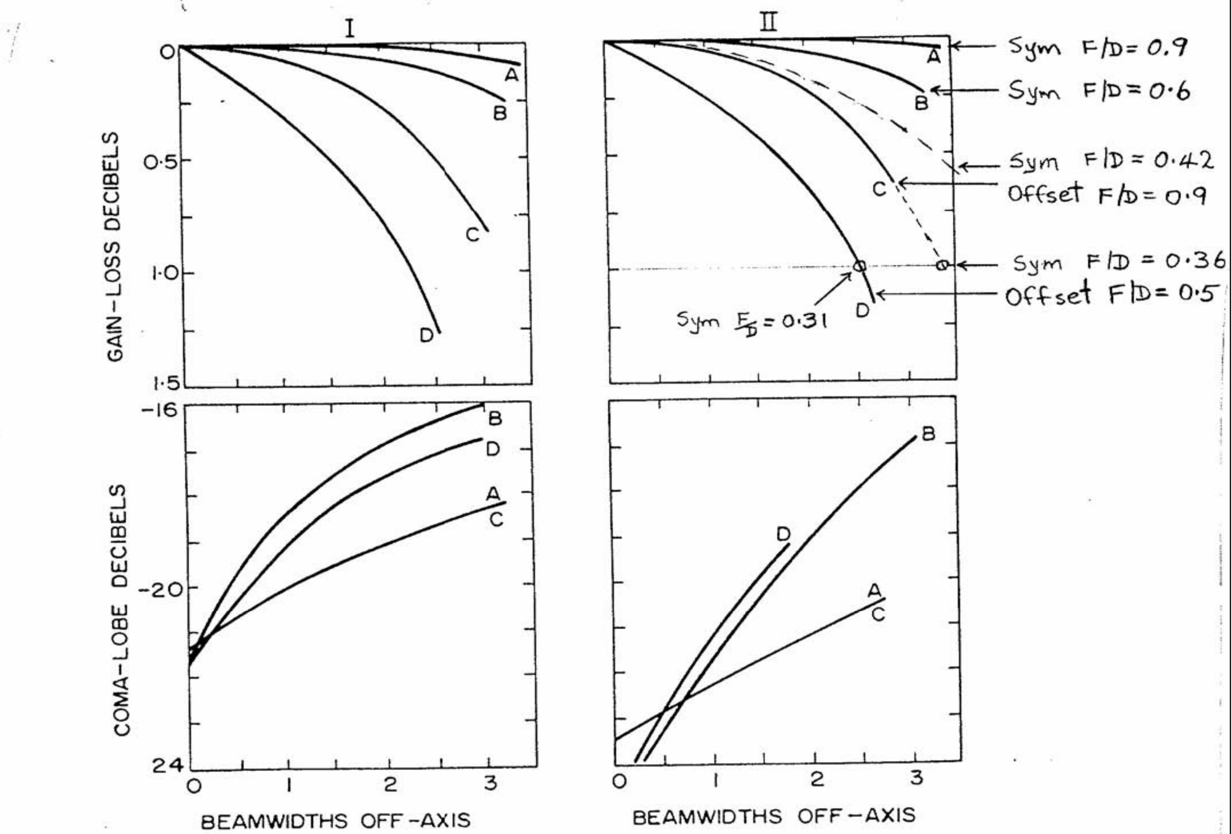

Fig. 3.59 *Beam-scanning gain loss and coma-lobe levels. illumination tapers of −6dB (column I and −10dB (column II.*

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a $\theta^* = 30^\circ, \theta_0 = 0$
b $\theta^* = 45^\circ, \theta_0 = 0$
c $\theta^* = 30^\circ, \theta_0 = 45^\circ$
d $\theta^* = 45^\circ, \theta_0 = 45^\circ$

Figure 5-1.

Figure 1. Gain loss and coma-lobe levels for -6 dB and -10 dB illumination tapers.

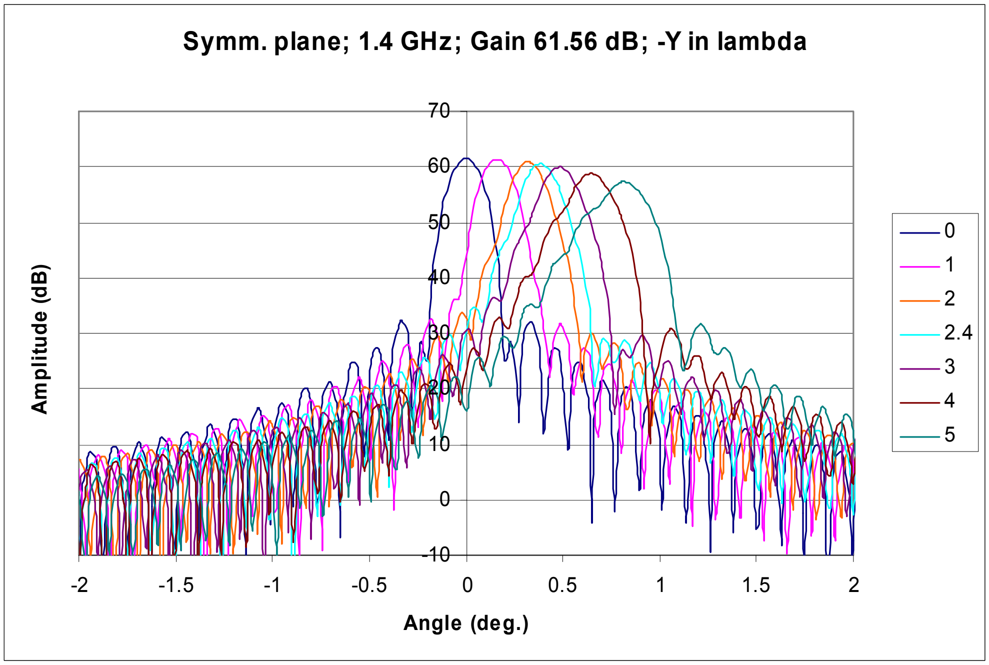

Figure 2. GBT beams at 1.4 GHz for offsets (λ) in symmetric plane towards the feed arm (-ve).

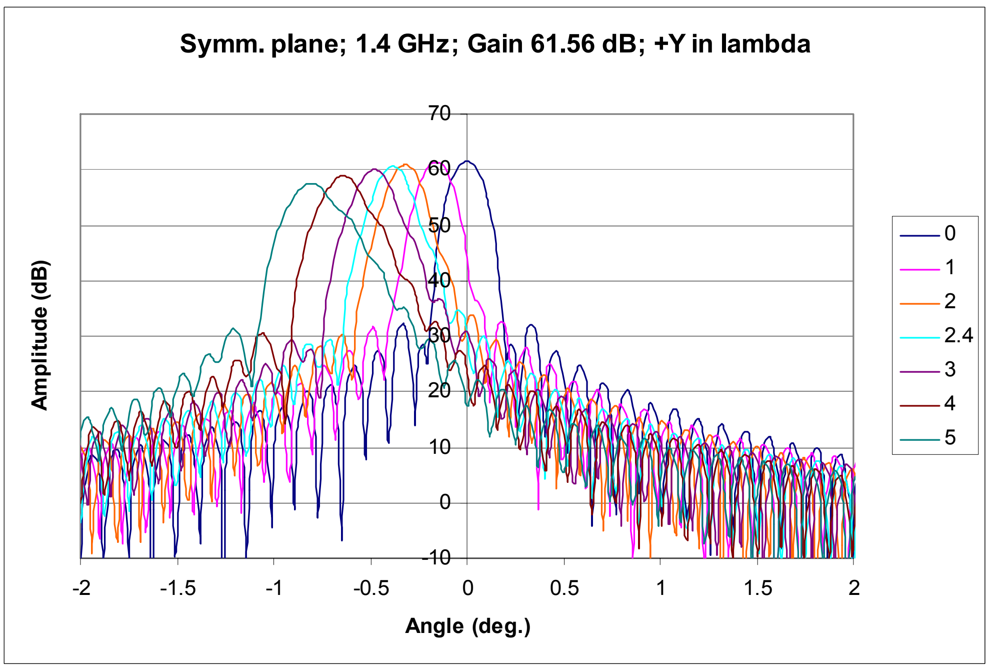

Figure 3. GBT beams at 1.4 GHz for offsets (λ) in symmetric plane away from the feed arm (+ve).

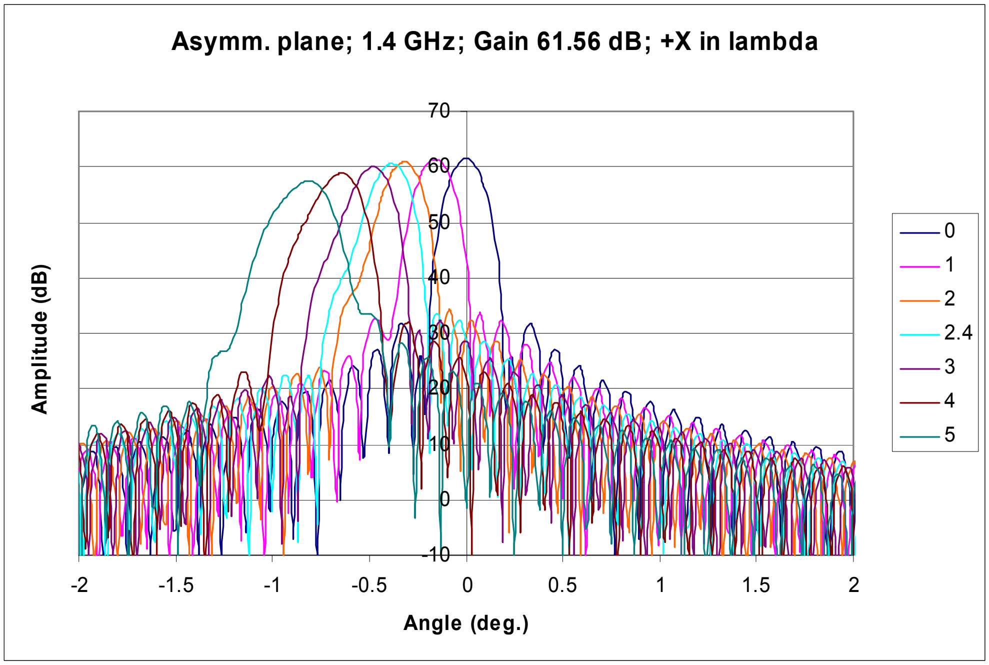

Figure 4. GBT beams at 1.4 GHz for offsets (λ) in asymmetric plane.

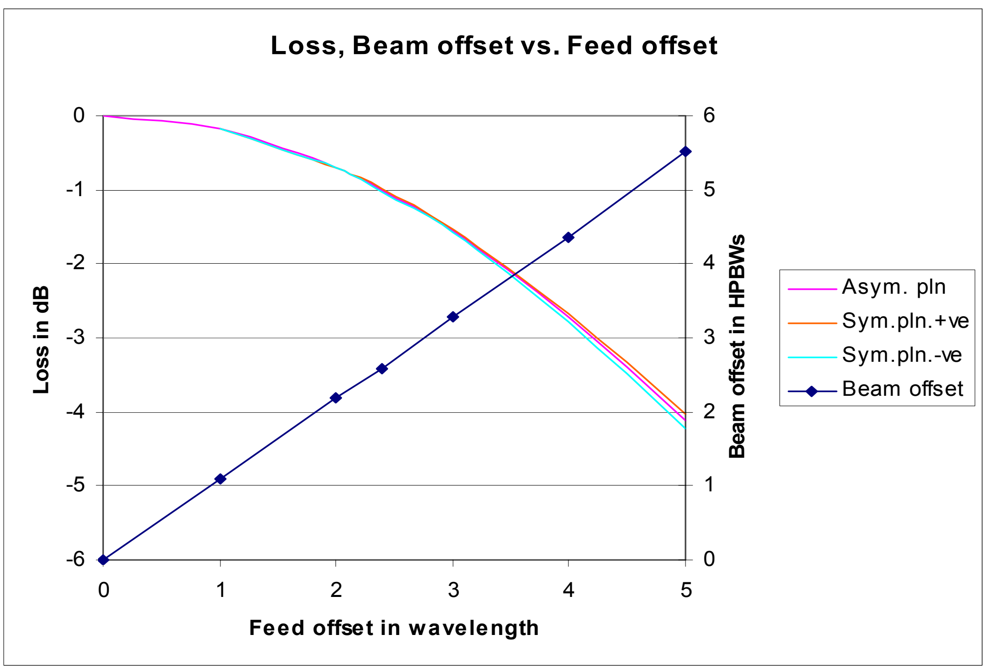

Figure 5. Gain loss, beam offset vs. feed offset at 1.4 GHz.

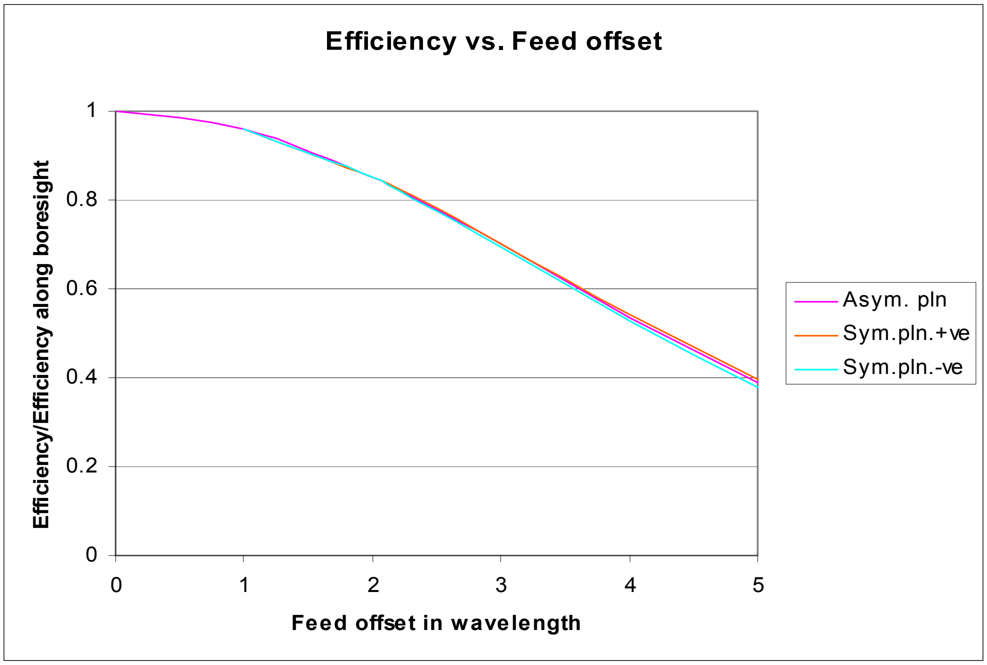

Figure 6. Efficiency/Efficiency along boresight vs. feed offset at 1.4 GHz.

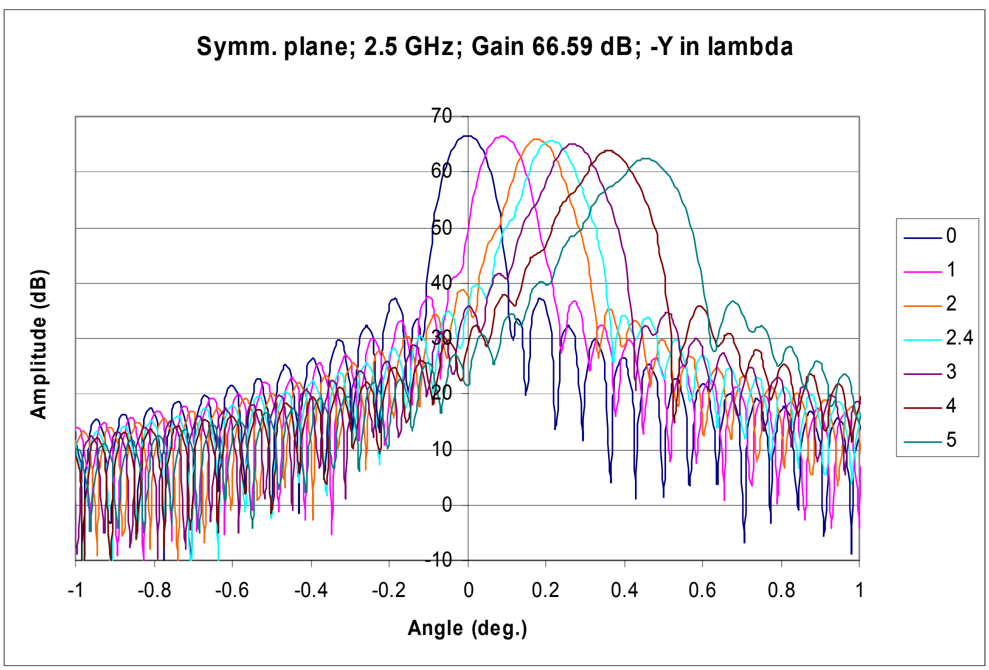

Figure 7. GBT beams at 2.5 GHz for offsets (λ) in symmetric plane towards the feed arm (-ve).

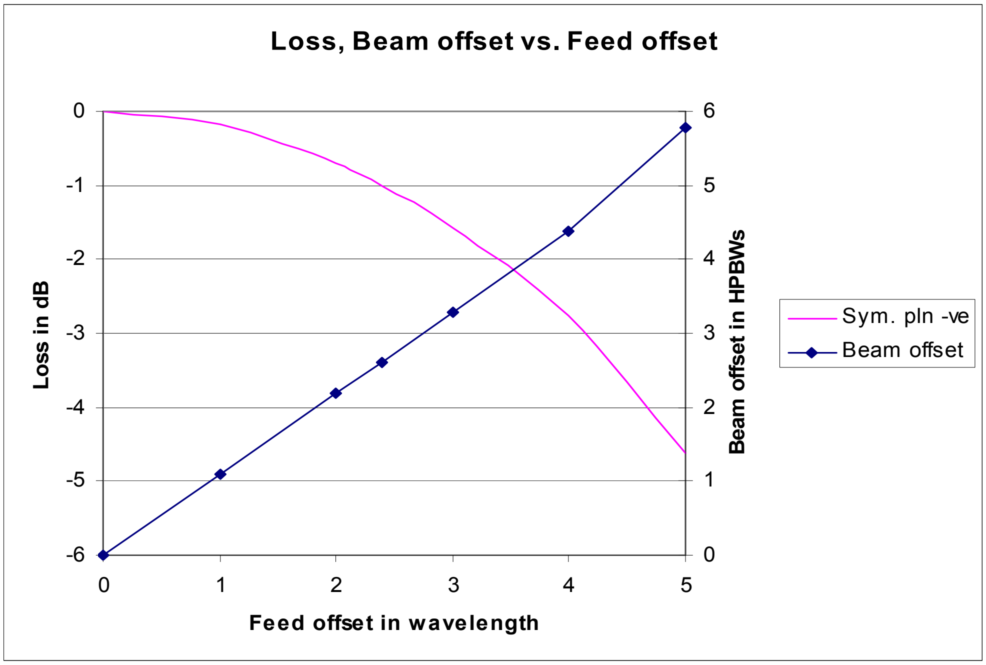

Figure 8. Gain loss, beam offset vs. feed offset at 2.5 GHz.

References:

[1] W. V. T. Rusch, and A. C. Ludwig, "Determination of the Maximum Scan-Gain Contours of a Beam-Scanning Paraboloid and Their Relation to Petzval Surface," *IEEE Trans. on Antennas and Propagation,* AP-21, pp. 141-148, March 1973.

[2] *The Handbook of Antenna Design*, vol. I, eds. A. W. Rudge, K. Milne, A. D. Olver and P. Knight, Peter Peregrinus, Ltd., London, UK, 1982.

[3] R. Norrod, *et al.*, "Performance Comparison of Symmetrical and Clear Aperture Antennas," GBT Memo 4, Section 5, July 1989.