GBT Memo #296

The GBT Beam Shape at 109 GHz

David T. Frayer (Green Bank Observatory)

2017 March 31

Abstract

With the installation of the Argus 16-pixel receiver covering 75-115 GHz on the Green Bank Telescope (GBT), it is now possible to characterize the antenna beam at very high frequencies, where the use of the active surface and out-of-focus holography are critical to the telescope's performance. A recent measurement in good weather conditions (low atmospheric opacity, low winds, and stable night-time thermal conditions) at 109.4 GHz yielded a FWHM beam of $6''.7 \times 6''.4$ in azimuth and elevation, respectively. This corresponds to $(1.16 \pm 0.03)\,\lambda/\mathrm{D}$ at 109.4 GHz. The derived ratio agrees well with the low-frequency value of $(1.18 \pm 0.03)\,\lambda/\mathrm{D}$ measured at 9.0 GHz. There are no detectable side-lobes at either frequency. In good weather conditions and after applying the standard antenna corrections (pointing, focus, and the active surface corrections for gravity and thermal effects), there is no measurable degradation of the beam of the GBT at its highest operational frequencies.

1 Introduction

As of 2017, the GBT[1] has three available instruments operating within the 3mm atmospheric window: the 4mm Receiver [1], the Mustang-2 bolometer camera [2], and Argus – the 16 element 75–115 GHz array [3]. The performance of the GBT within the 3mm band depends significantly on winds and other environmental effects [4,5], tracking errors, focus errors, errors associated with the active surface corrections, and even systematic deformations of the panels [6]. The weather and instrumental effects could be expected to degrade the performance of the GBT with increasing frequency, since the errors become a larger fraction of the wavelength and the expected beam size. The purpose of this memo is to provide an estimate of the beam size using Argus near 110 GHz, since the beam of the GBT has not been previously characterized above 90 GHz.

2 Beam Size Below 100 GHz

For an idealized radio telescope assuming a Gaussian beam approximation and adopting the standard GBT feed taper of 15dB (which also corresponds to the feed taper of the Argus horns at 100 GHz [7]), the expected beam size in radians is approximately $\theta_{\mathrm{FWHM}} \approx 1.22\,\lambda/\mathrm{D}$ [8], where λ is the observed wavelength and D is the diameter of the GBT (100m). To facilitate comparisons at different wavelengths, measurements in this memo are given in λ/D. Observers using Mustang/Mustang-2 have reported typical beam sizes of $1.3\,\lambda/\mathrm{D}$ at

[1]The Green Bank Observatory is a facility of the National Science Foundation under cooperative agreement by Associated Universities, Inc.

90 GHz [2], while the beam size at 77 GHz for the 4mm Receiver has been measured as $1.34\,\lambda/\mathrm{D}$ [9]. This measurement was done before the active surface model was updated in the fall of 2014 [10] and before the new GBT servo-drive system was deployed in the summer of 2016. In summary, observations from previously seasons with the GBT within the 3mm band have been close to the theoretical expectation of $\approx 1.22\,\lambda/\mathrm{D}$, but were found to be typically slightly higher ($\sim 1.3\,\lambda/\mathrm{D}$).

For comparison with measurements at high frequency, I first measure the beam at lower frequency in X-band (9.0 GHz). At this frequency, the GBT active surface system is still used, but the instrumental and weather effects on the size of the beam are expected to be minimized. The weather was excellent for X-band at the time of these observations; the data were taken during a scheduled Argus program to provide the initial pointing solutions (AGBT17A_423_01, 2017.03.23, PI A. Lovell). Table 1 shows the beam size measured from the standard azimuth and elevation peak scans used to derive the pointing offsets. Averaging the azimuth and elevation results gives a beam size measurement of $(1.18 \pm 0.03)\,\lambda/\mathrm{D}$ at 9.0 GHz. This is slightly better than the theoretical expectation of $1.22\,\lambda/\mathrm{D}$ for the Gaussian approximation. Figure 1 shows the normalized beam profile in decibels ($\mathrm{db} = 10\log_{10}\mathrm{P}$) for the elevation scan. This figure highlights the excellent performance given by the unblocked optics of the GBT. The peak of the beam profile is well approximated by a Gaussian, but the wings of the beam profile falls off steeper than that of a Gaussian and are better approximated by a Bessel function. The first side-lobe for the Gregorian focus position of the GBT is expected to be -27dB lower than the peak [10] and is not detectable in these data. The measured X-band beam size of $1.18\,\lambda/\mathrm{D}$ is significantly better than the typical values of $1.3\,\lambda/\mathrm{D}$ previously observed above 66 GHz.

3 Beam Size Above 100 GHz

To characterize the beam properties above 100 GHz with the GBT, I used data collected at 109.4 GHz during Argus observations in good weather conditions (AGBT17A_304_06_01, 2017.03.23, PI A. Kepley). These data were collected on the same day as the comparison X-band observations presented here. The Argus data were taken after AutoOOF observations with the 4mm Receiver to optimize the active surface for the current thermal conditions. The OOF solution returned an rms of only 102μm. This is better than the typical OOF "rms" values of of $\sim 200\mu$m, implying that only small corrections were needed with respect to the default zernike model of the GBT [11] at the time of observations. Table 1 shows the beam size measured from the azimuth and elevation peak scans. The source observed was the bright radio quasar 3C273, which is estimated to be about 10 Jy [12]. Averaging the azimuth and elevation results gives a beam size measurement of $(1.16 \pm 0.03)\,\lambda/\mathrm{D}$ at 109.4 GHz. The result for Argus is consistent within uncertainties with the X-band results. Figure 2 shows the normalized beam profile in dB for the elevation scan at 109.4 GHz. This is an impressive result for the GBT system.

Table 1: Beam Measurement Results

	X-band 9.0 GHz	Argus 109.4 GHz
FWHM (Az)	80 ± 2 arcsec	6.7 ± 0.2 arcsec
FWHM (El)	82 ± 2 arcsec	6.4 ± 0.2 arcsec
Avg (Az,EL)	$(1.18 \pm 0.03)\,\lambda/D$	$(1.16 \pm 0.03)\,\lambda/D$

4 Discussion

An natural question is how typical are these results? The mean value of the observed beam measured using Argus during commissioning observations in good conditions (TGBT15A_901_34) is $(1.15 \pm 0.03)\,\lambda/D$ at 86 GHz. This is based on 17 independent measurements with a 1σ scatter around the mean corresponding to $0.11\,\lambda/D$. Including additional measurements from the pointing scans taken during the early Argus science programs (2016 December – 2017 March) over a range of conditions, the typical beam size observed is $(1.20 \pm 0.12)\,\lambda/D$. This result is based on 35 observations of bright quasars (3C273, 3C454.3, and 3C84) for a frequency range of 86–90 GHz. The range of values measured was 1.03–$1.49\,\lambda/D$. Therefore, the results obtained here at 109 GHz (Figure 2) are not unusual, which is encouraging for future high-frequency observations with the GBT. Extrapolating the results to the CO(1-0) rest frequency of 115.271 GHz, one could expect to achieve a resolution of about 6.2 arcsec in good conditions at the upper frequency end of the Argus operational range.

5 Concluding Remarks

Observations taken 2017.03.23 with Argus at 109 GHz show no measurable degradation of the beam with respect to low frequency observations. The elevation scan at 109 GHz (Figure 2) shows a beam size of $\theta_{\rm FWHM} = 6.4''(1.13\,\lambda/D)$. This is the smallest beam observed to date with the GBT. Although these observations may have benefited from better than average conditions, the results highlight the potential of the GBT at its highest operational frequencies, 100–115 GHz.

I acknowledge and greatly appreciate the efforts of the staff at the Green Bank Observatory who continue to maintain and improve the performance of the GBT at high frequency. I thank Jay Lockman for providing useful comments for the memo.

6 References

1. The GBT 4mm Receiver: http://www.gb.nrao.edu/4mm/

2. MUSTANG-2: http://www.gb.nrao.edu/mustang/

3. Argus: http://www.gb.nrao.edu/argus/

4. Condon, J.J. & Balser D.S. 2015, Dynamic Scheduling Algorithms, Metrics, and Simulations, DS Project Note 5.6

5. Maddalena, R.J. & Frayer, D.T., 2014, Recommended Changes to the Constants Used by the DSS for Fall 2014, DS Project Note 18.1

6. Schwab, F.R. & Hunter, T.R. 2010, Distortions of the GBT Beam Pattern Due to Systematic Deformations of the Surface Panels, GBT Memo # 271

7. Sieth, M. 2016, Argus: A 16-pixel Millimeter-wave Spectrometer, Ph.D. Thesis, Stanford University

8. Maddalena, R.J. 2010, Theoretical Ratio of Beam Efficiency to Aperture Efficiency, GBT Memo #276

9. Frayer, D.T., et al. 2015, The GBT 67-93.6 GHz Spectral Line Survey of Orion-KL, AJ, 149, 162

10. Maddalena, R.J., Frayer, D.T., Lashley-Cohirst, N. & Norris, T. 2014, The Updated 2014 Gravity Model, PTCS Project Note 76.1

11. Norrod, R. & Srikanth, S. 1996, A Summary of the GBT Optics Design, GBT Memo #155

12. ALMA Calibrator Source Catalog: https://almascience.eso.org/sc/

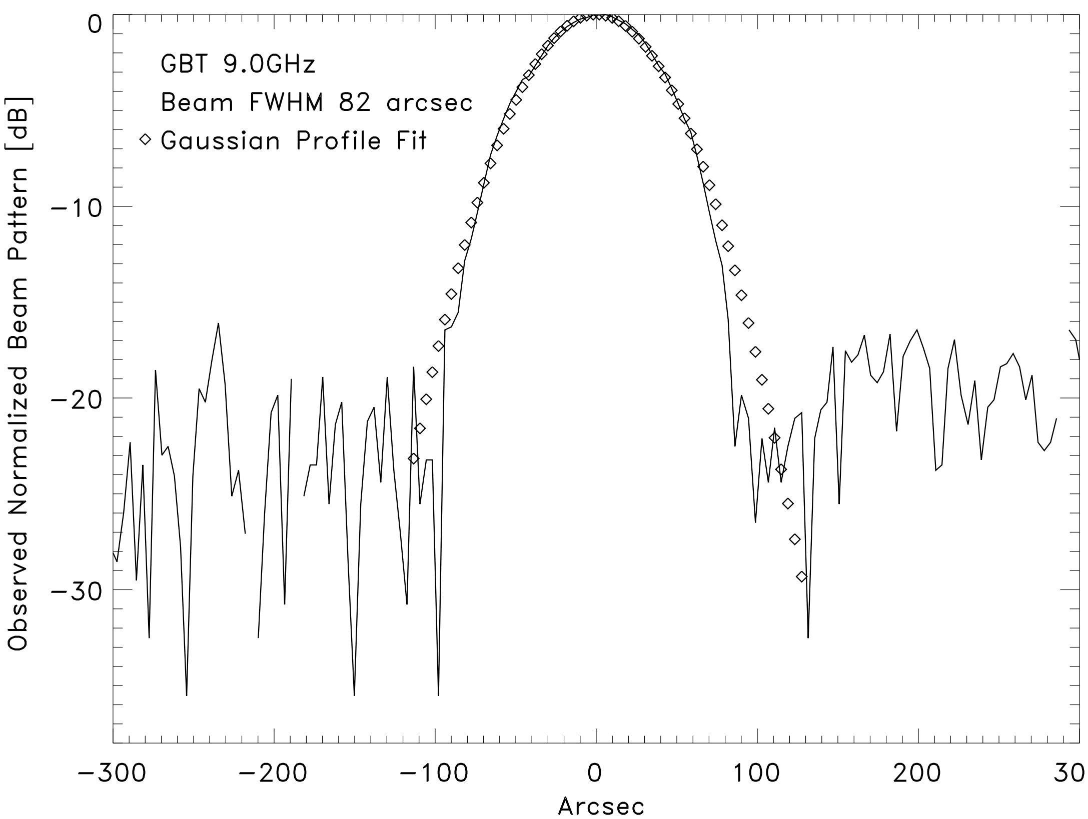

Figure 1: The normalized GBT beam profile in dB observed at 9.0 GHz shown as the solid line as a function of arcsec from 0510+1800 along the elevation axis. The diamonds show a Gaussian fit to the observed profile. The absolute value of the data was used for plotting on a logarithmic scale to show the relative noise level of the observations (−20dB).

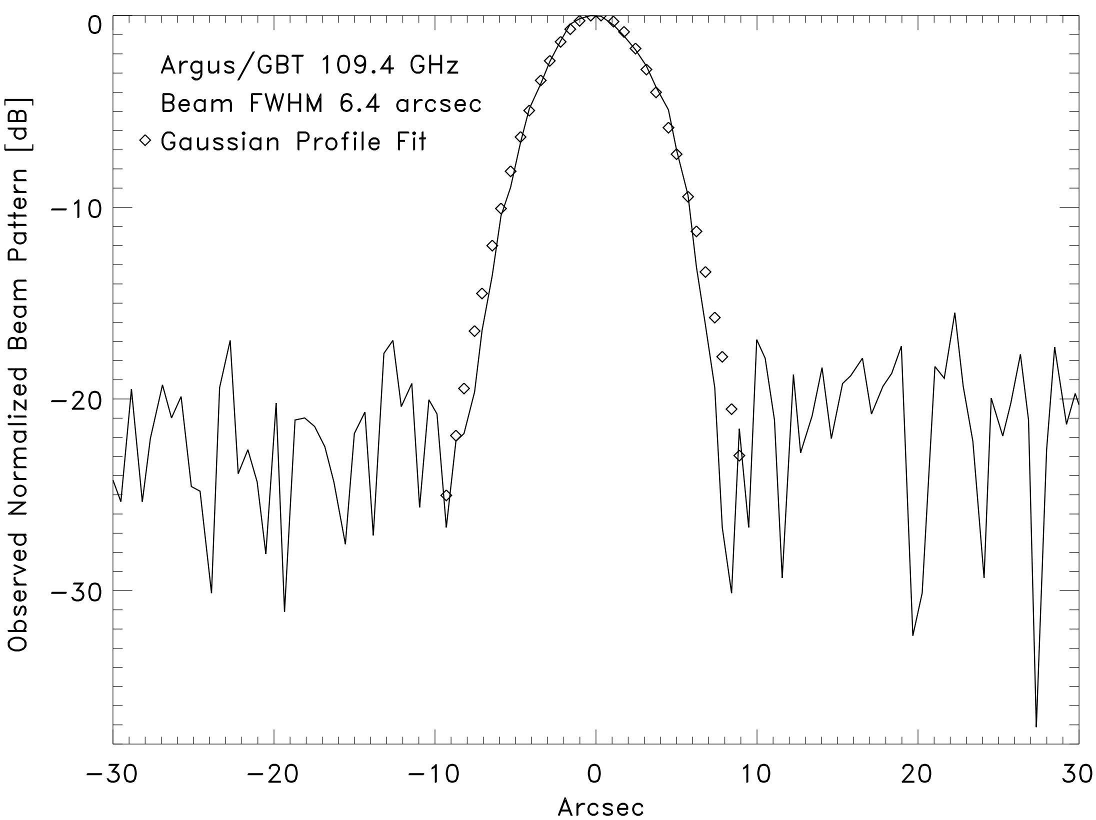

Figure 2: The normalized GBT beam profile in dB observed at 109.4 GHz shown as the solid line as a function of arcsec from 3C273 along the elevation axis. The diamonds show a Gaussian fit to the observed profile. The observed beam of 6.4 arcsec is the smallest beam observed to date with the GBT.