Precision Telescope Control System

PTCS/SN/4:
Current GBT Performance

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Abstract

Many GBT performance parameters relevant to the PTCS (Precision Telescope Control System) have been measured during commissioning, the most important being focus tracking, pointing accuracy, aperture efficiency, and sidelobe levels. The rms differential pointing error in two dimensions is $\sigma_2 \approx 3.1$ arcsec, and the overall rss (root-sum-squared) phase error contributed by the primary surface, the subreflector surface, and decollimation is equivalent to a single surface having rms error $\epsilon \approx 0.47$ mm. Judged by the criteria in the PTCS "Scientific Requirements" system note (Condon 2003), the GBT is already usable at 40 GHz ($\lambda = 7.5$ mm) when the active surface is used to correct errors predicted by the finite-element model and offset-pointing calibrators are used to update the azimuth and elevation offsets.

1. Introduction

The current astronomical performance of the GBT has been measured during commissioning and pointing runs. The focus-tracking errors, pointing errors, aperture efficiency, and sidelobe levels characterize those aspects of the GBT which the PTCS (Precision Telescope Control System) must address immediately.

2. Focus Tracking

Since the GBT is asymmetric in the elevation plane, the "axial" focusing coordinate Y_s along which subreflector translation minimizes pointing shifts is tilted by 36.7° from the axis of the 208 m parent paraboloid (Norrod & Srikanth 1996). The Y_s coordinate for the Gregorian subreflector that maximizes aperture efficiency was measured as a function of source elevation angle E during S-band commissioning (Ghigo et al. 2001). The "transverse" focusing coordinate X_s is normal to Y_s and lies in the elevation plane. The subreflector X_s that maximizes aperture efficiency was also measured as a function of elevation. These best-fit settings were approximated by functions of the form

$$A + B\cos(E) + C\sin(E) \tag{1}$$

Later unpublished measurements of the best Z_s in the horizontal direction as well as subreflector tilts X_t, Y_t, and Z_t constitute the "empirical" focus tracking model currently used on the GBT (Balser et al. 2002a). Errors in this empirical model affect pointing in addition to the telescope parameters traditionally associated with collimation errors (aperture efficiency, beam shape, sidelobe level).

3. Pointing

"All-sky" pointing runs have been made with the GBT at several frequencies during commissioning. A number of strong calibration sources with accurately known positions (Condon & Yin 2001) were observed with cross scans spanning a wide range of azimuth and elevation. The observed azimuth and elevation offsets were used to determine best-fit coefficients for terms in a "traditional" pointing model

(Balser et al. 2001). Since focus tracking and (primary mirror) pointing were treated independently, residual transverse focus-tracking errors appear as pointing errors. The traditional pointing model contains terms corresponding to the dominant zero-point errors and gravitational distortions of the primary reflector, but it is not able to absorb all of the residual focus-tracking errors efficiently.

Results from the X-band (9.6 GHz) pointing run (Balser et al. 2002a) are shown in Figure 1. The best empirical focus-tracking model was applied, and the best-fit traditional pointing coefficients were determined. The rms two-dimensional pointing residual in the data used to generate the model is $\sigma_2 \approx$ 10.2 arcsec. This value is a lower limit to the rms absolute pointing error of the GBT. Subsequent observations at C-band (5 GHz) indicate systematic departures (Figure 2) from the model now in use. Such systematic errors may reflect box offset errors of the X-band and C-band feeds, limitations of the traditional pointing model and the effects of temperature changes on the telescope structure that occurred during and between the focus-tracking measurement, the pointing run, and later observations.

Fortunately, small absolute pointing errors are not required for astronomical observations with the GBT. More important are the differential pointing errors between the program sources and nearby offset-pointing calibration sources. The short-term pointing fluctuations estimated from tracking a strong source at the half-power point are small under benign conditions: $\sigma_2 < 2$ arcsec rms (Balser et al. 2002b). Results from recent observations cycling between pairs of pointing calibrators are displayed in Figure 3 and Table 1. The column labeled "RMS Offset" shows the rms offset pointing errors σ_2. The systematic offsets in Figure 3 are probably caused by systematic errors in the current pointing/focus-tracking model and should be easy to eliminate. Taking away those systematic errors gives the "RMS Scatter" values in Table 1. They suggest that $\sigma_2 \approx 3.1$ arcsec offset pointing accuracy is possible with the current GBT.

4. Aperture Efficiency and Sidelobes

Pointing errors correspond to linear phase gradients across the telescope aperture. Nonlinear phase variations lower the aperture efficiency and raise sidelobe levels. They result from both decollimation and deviations from the optimum shapes of the primary and secondary reflectors. If the correlation

Table 1. Offset Pointing Errors

Reference Source	Test Source	Separation (deg)	RMS Offset (arcsec)	RMS Scatter (arcsec)	Plot Symbol
0204+1514	0141+1353	6.7	3.2	2.4	open hexagon
0534+1927	0603+2159	6.4	5.2	4.2	snowflake
0840+1312	0853+1352	2.0	2.3	2.0	star of David
1120+1420	1143+2206	9.1	4.3	3.5	filled hexagon
1537+1344	1520+2016	8.2	4.9	2.9	filled triangle

length of the deviations is much smaller than the aperture diameter, then a single reflector with rms error ϵ would have a "surface efficiency"

$$\eta_s \approx \exp\left[-\left(\frac{4\pi\epsilon}{\lambda}\right)^2\right] \tag{2}$$

at wavelength λ (Ruze 1966). In the long wavelength limit, the GBT aperture efficiency should be $\eta_a \approx 0.70$. From the decrease of aperture efficiency at short wavelengths we can still use Equation 2 to *define* an effective rss (root sum squared) error ϵ for the GBT. This single parameter is useful because it can be used in Equation 2 to compare estimates of the overall error based on measurements made at different wavelengths, even though the latter contains contributions from two reflectors and decollimation, and the phase correlation lengths are not necessarily small compared with the aperture diameters. The measured aperture efficiency is $\eta_a \approx 0.60$ at 20 GHz ($\lambda = 15$ mm) at most elevations, and $\eta_a \approx 0.35$ at 43 GHz ($\lambda = 7$ mm) near the rigging angle (Maddalena, private communication), so Equation 2 plus the assumption of $\eta_a \approx 0.70$ at long wavelengths (Norrod & Srikanth 1996) give two independent and consistent estimates of the effective rss error: $\epsilon = 0.47$ mm ($\lambda = 15$ mm data) and $\epsilon = 0.46$ mm ($\lambda = 7$ mm data).

With good focus tracking, the largest elevation-dependent loss of efficiency is generally caused by astigmatism, which produces mirror-symmetric near-in sidelobes. GBT beam scans were made at 20 GHz well away from the rigging angle, and Figure 5 shows the beams before and after the finite-element model (FEM) correction was applied to the primary surface. The FEM correction has greatly increased the aperture efficiency and nearly eliminated the near-in sidelobes.

5. Summary

The current performance of the GBT with offset pointing and the active surface correcting for errors predicted by the FEM is $\sigma_2 \approx 3.1$ arcsec and $\epsilon \approx 0.47$ mm. The PTCS scientific requirements (Condon 2003) determine the rms offset pointing error σ_2 and the effective surface error ϵ required for astronomically usable operation at any frequency ν. By those criteria, the GBT is already usable up to $\nu = 40$ GHz ($\lambda = 7.5$ mm), the lower edge of the Q band.

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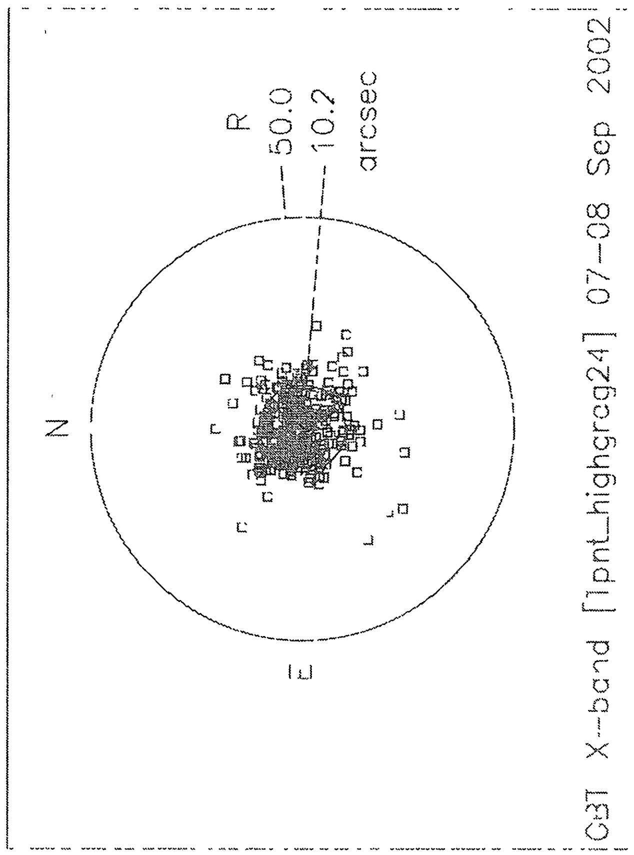

Fig. 1.— The all-sky "blind" pointing error distribution measured at 9.6 GHz (Balser et al. 2002a) has an rms $\sigma_2 \approx 10.2$ arcsec.

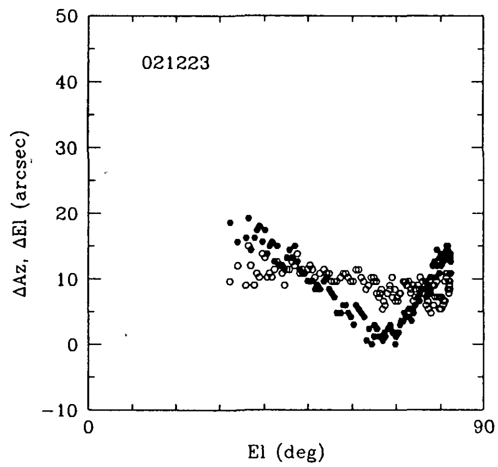

Fig. 2.— The absolute pointing offsets in azimuth (open symbols) and elevation (filled symbols) obtained on 2002 Dec 23 show systematic offsets that were not removed by the current pointing/focus-tracking model. Gradients in the absolute pointing offsets degrade differential pointing based on a calibration source far from the program source. Abscissa: Elevation (deg). Ordinate: Offset (arcsec).

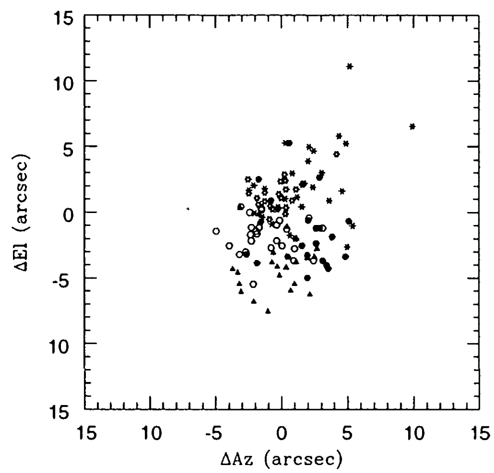

Fig. 3.— The offset pointing residuals obtained on 2003 Jan 5 are shown for five different test sources, indicated by different symbols as listed in the Table. The relatively large systematic residuals result from systematic errors in the current pointing/focus-tracking model and should be easy to eliminate, yielding $\sigma_2 \approx 3.1$ arcsec rms differential pointing. Abscissa: Azimuth residual (arcsec). Ordinate: Elevation residual (arcsec).

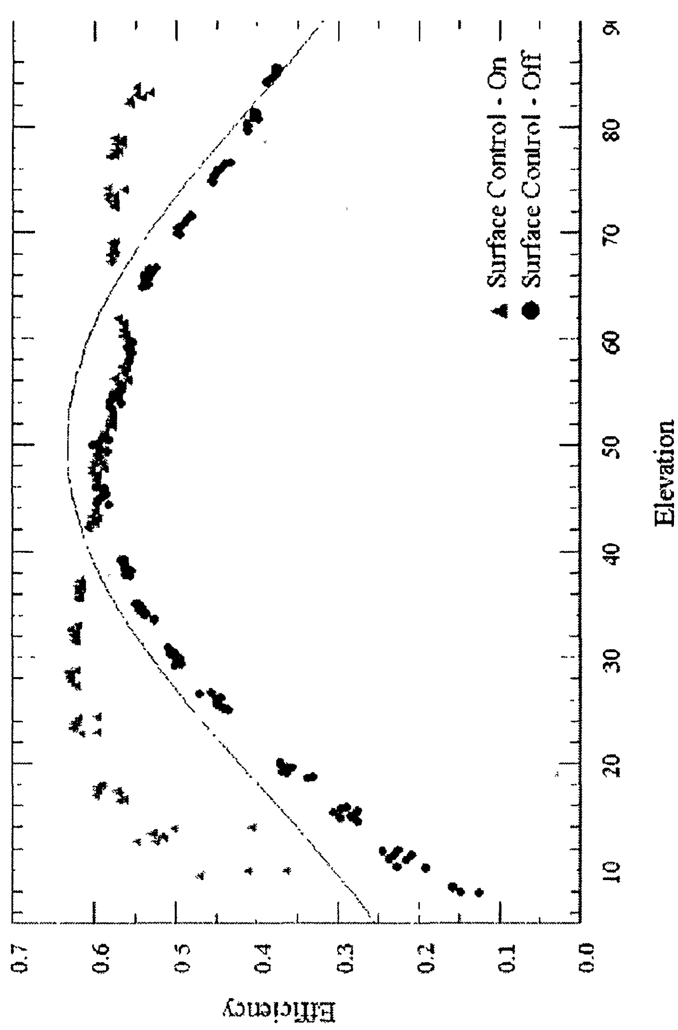

Fig. 4.— The K-band aperture efficiency of the "as built" GBT (filled circles) approaches 60% near the rigging elevation angle $\approx 50°$ but falls off sharply owing to gravitational deformation of the primary surface. With the active surface control correcting for deformations predicted by the finite-element model (FEM), the high aperture efficiency is maintained over a much wider range of elevations (filled triangles). Abscissa: Elevation angle (deg). Ordinate: Aperture efficiency (dimensionless).

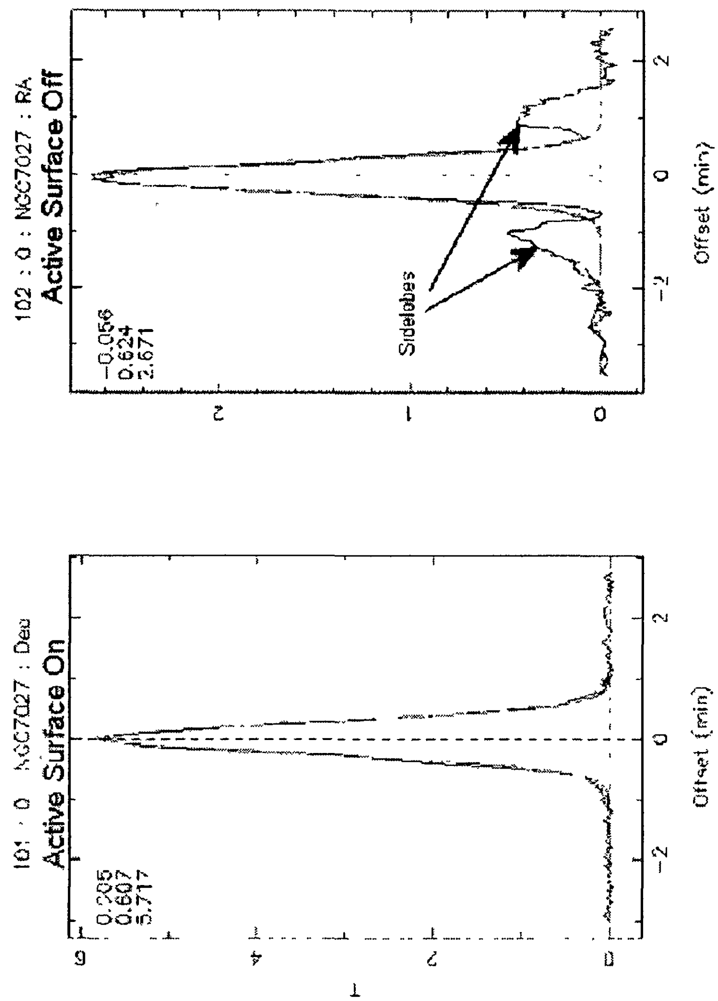

Fig. 5.— Large-scale gravitational deformation of the GBT primary surface tilted far from the rigging angle results in symmetric near-in sidelobes (noisy curve, right panel) that vanish when the active surface is used to compensate for the deformation predicted by the FEM (noisy curve, left panel). The smooth curves are fitted Gaussians. Abscissa: Source offset (arcmin) Ordinate: Antenna temperature (K).