

# Precision Telescope Control System

## PTCS/SN/2: Overview of the GBT

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### Abstract

The GBT, with its unblocked 100 m aperture, is potentially the world's largest millimeter-wave telescope, with sensitivity  $1 \text{ Jy} \approx 1 \text{ K}$  and resolution  $\approx 7''$  at  $\lambda \approx 3 \text{ mm}$ . The GBT is so big in wavelengths that, in important ways, it behaves more like an optical telescope than a radio telescope. This overview of the GBT emphasizes those features that affect the PTCS goal of making astronomically useful observations in benign conditions at frequencies up to the atmospheric cutoff at 117 GHz.

### 1. Introduction

The Robert C. Byrd Green Bank Telescope (GBT) is the successor to the old 300-foot telescope that collapsed in 1988. It is a 100 m general-purpose radio telescope operated by the NRAO for use by the worldwide astronomical community, and observing time is granted for projects of the highest scientific merit as judged by external referees. The GBT (Fig. 1) has an unblocked aperture which increases the effective collecting area and reduces system noise, standing waves, and sidelobe levels (Lockman 1998). The primary reflector surface consists of 2004 precision ( $\approx 70 \mu\text{m}$  rms error) solid aluminum panels. The heights of these panels can be adjusted by 2209 computer-controlled actuators to maintain the desired surface shape under changing environmental conditions and gravitational loading. The actuators are currently used to correct the primary mirror only for the gravitational deformations predicted by the GBT finite-element model (FEM). Recent aperture-efficiency measurements made at 20 and 43 GHz indicate that the rms deviation from the best-fit paraboloid is less than  $470 \mu\text{m}$  over a wide range of elevations. The rms absolute pointing error in two dimensions is  $\sigma_2 \approx 10''$ , and the offset pointing accuracy is  $\sigma_2 \approx 3''$ . Thus the GBT is already usable up to about 40 GHz (Condon 2003b).

The science goals of the GBT require observations spanning the entire frequency range accessible through the atmosphere at Green Bank (Fig. 2). At low frequencies, radio frequency interference (RFI) degrades many astronomical observations. Green Bank is located in the National Radio Quiet Zone and is naturally shielded from ground-based RFI by the surrounding mountains. Finally, the exceptionally clean GBT beam helps to suppress interference from all unwanted directions. Atmospheric absorption and the associated thermal emission naturally limit astronomical observations at the highest frequencies. Oxygen absorption blocks the frequency ranges  $52 \lesssim \nu \text{ (GHz)} \lesssim 68$  and  $\nu \gtrsim 117 \text{ GHz}$ . Tropospheric water vapor can affect observations at all frequencies  $\nu \gtrsim 15 \text{ GHz}$  to varying degrees. Although the elevation of Green Bank is only 800 m, the sky is cold enough in late autumn and winter that the column density of precipitable water vapor is low. The 86 GHz zenith opacity measured with a tipping radiometer located near the Jansky lab is  $\tau_z < 0.1$  for significant periods (Fig. 3). Since the subreflector, feeds, and receivers do not block the beam, the GBT receiver cabin can be large enough to hold all of the millimeter-wavelength receivers ready for use in changing weather conditions. Thus the GBT is potentially the world's largest and most sensitive millimeter-wave telescope. The purpose of the High Frequency Observing System (HFOS) (Prestage 2003) and its principal component, the Precision Telescope Control System (see <http://www.gb.nrao.edu/ptcs/index.shtml>), is to realize this potential.

Receivers covering most frequencies below 52 GHz already exist. The main gap is the 26–40 GHz band, which is a good band for observing continuum sources and hence characterizing the GBT performance. A continuum receiver covering the 1 cm band is under construction: see

<http://www.gb.nrao.edu/electronics/projects/1cmRx/>

No 3 mm receiver exists yet, but a pseudocorrelation receiver suitable for observations of continuum sources is under construction. The first “module” will cover 68–95 GHz and be ready by the end of 2004. The second module will cover 90–116 GHz. See

<http://www.gb.nrao.edu/electronics/projects/3mmRx/>

for details on this receiver.

## 2. The GBT structure

The GBT is an azimuth-elevation telescope with a traditional wheel and track design. In azimuth, 16 wheels ride on a 64 m diameter rail and allow tracking over  $\pm 270^\circ$  from due South at a maximum rate of  $40^\circ$  per minute. The tipping structure turns about a 46 m axle driven by a bull gear of radius 30 m. The telescope beam can move at rates up to  $20^\circ$  per minute between elevations  $+5^\circ$  and  $+95^\circ$ . These slew rates were chosen to match those of other large telescopes (e.g., the VLA and the Bonn 100 m) for efficient very long baseline interferometry (VLBI). The lower elevation limit is well matched to the local horizon and allows the longest possible  $(u, v)$ -plane tracks when the GBT is used for VLBI. However, the GBT alidade structure must be unusually tall (and massive) to reach such low elevations. The moving structure, weighing approximately 7700 metric tons, is believed to be the largest on land. The azimuth track has been damaged by this weight, and options for replacing or modifying the wear strip are currently being explored and tested. Changes in gravitational loading with elevation cause small deformations of the reflector backup structure and the feed support arm. The primary mirror panel heights can be adjusted to compensate for deformations in the backup structure. The Gregorian subreflector can be translated, tilted, and rotated about its axis to maintain accurate focus tracking.

The primary reflector is an asymmetrical offset  $100\text{ m} \times 110\text{ m}$  section cut from a symmetric parent paraboloid whose diameter is 208 m and whose focal length is 60 m. The unblocked GBT aperture has no scattering sidelobes, sees very little ground radiation, and has few locations for standing waves to develop. A single, cantilevered feed arm is attached behind the main reflector. It extends about 90m from below the the surface to its termination almost 10m above the primary focal point. Since the feed arm, subreflector, and receiver cabin are all outside the main beam, they can be unusually large and robust. The receiver cabin is big enough to hold 10 receivers simultaneously, ready for dynamic scheduling to exploit the best weather conditions for high-frequency observations. The feed arm has a large cross section for stiffness, in contrast to the slender feed-support legs found on conventional telescopes. Even so, jerks applied by wind or by the telescope drive system can excite high-Q oscillations with frequencies  $\nu \approx 1\text{ Hz}$  (Balsler 2000).

Unlike most millimeter-wave telescopes, the GBT is not protected by a radome. All of the major structural members are made of steel and have a thermal expansion coefficient  $\alpha \approx 1.2 \times 10^{-5}\text{ K}^{-1}$ . Temperature differences across the GBT might be as high as  $\Delta T \approx 5\text{ K}$  on a sunny day and as low as  $\Delta T \approx 1\text{ K}$  at night. The resulting thermal distortions are large enough to cause unacceptable pointing errors at  $\lambda = 3\text{ mm}$  and so must be corrected. High winds will also degrade performance at short wavelengths. We expect that the GBT will be usable at 3 mm only under benign environmental conditions.

### 3. Telescope Optics

The GBT has both a prime focus and a Gregorian secondary focus. For prime focus operation, a retractable boom holding a receiver is placed in front of the Gregorian subreflector. The prime focus is used only for the low frequency bands between 300 and 1200 MHz and is therefore not a concern for the PTCS. The Gregorian subreflector is an 8 m ellipsoidal mirror positioned by a Stewart platform having 6 degrees of freedom (three translations, two tilts, and rotation about the mirror axis). The Gregorian focal ratio is  $f/D = 1.9$  referred to the  $D = 100$  m effective aperture, so the field-of-view in the focal plane is wide enough to permit imaging with many simultaneous beams at short wavelengths (Norrod & Srikanth 1999a, 1999b). The Gregorian receivers are mounted on a rotating turret enclosed in a large receiver room. The secondary focus lies 11 m below the primary focus at an angle of 5.6 deg with respect to the vertex line. This geometry, which includes a predetermined tilt of the subreflector, cancels the beam squint between the two circular polarizations otherwise produced by an offset paraboloid. All receivers operating at the Gregorian focus should thus have excellent polarization properties. See Norrod & Srikanth (1996) for a more detailed summary of the GBT optics.

The offset clear aperture and huge size of the GBT have several consequences for the PTCS:

(1) The focal axis is tilted about  $37^\circ$  from the axis of the parent paraboloid (Srikanth 1990b). Here, the focal axis is defined as the direction of subreflector motion that causes no change in pointing. Motions of the subreflector perpendicular to the axis of the parent paraboloid, caused by gravitational bending of the feed arm with elevation for example, will axially defocus the telescope as well as produce pointing shifts (Srikanth 1990a). This interaction complicates the problem of collimating and pointing the GBT.

(2) The beamwidth of the 100 m GBT is only

$$\left( \frac{\theta}{740 \text{ arcsec}} \right) \approx \left( \frac{\text{GHz}}{\nu} \right), \quad (1)$$

where  $\theta$  is the full width between half-power points and  $\nu$  is the observing frequency. The beamwidth can be as small as  $\theta \approx 7''$ . Since the two-dimensional tracking error must not exceed  $\sigma_2 \approx 0.2\theta$  for usable astronomical observations (Condon 2003a), the GBT pointing requirements are exceptionally severe:  $\sigma_2 \approx 1''.3$  at  $\nu = 115$  GHz. The GBT must be collimated and pointed with a precision normally associated with optical, infrared, and submm telescopes, and we anticipate adopting techniques developed for adjusting such telescopes.

For example, the angular pointing error caused by differential thermal expansion is nearly independent of telescope size, so the error in beamwidths is proportional to the telescope diameter in wavelengths. Among several “natural limits” to telescope pointing accuracy, the thermal limit usually dominates gravity and wind for large telescopes ( $D > 45$  m) constructed of steel (von Hoerner 1967). The shortest usable wavelength for a 100 m steel telescope exposed to a 1 C temperature differential is  $\lambda_t \approx 5$  mm (von Hoerner 1987). In sunshine, temperature differentials as large as 5 C can be expected, resulting in  $\lambda_t \approx 25$  mm. Consequently, the GBT tracking accuracy at  $\lambda = 3$  mm is a major concern for the PTCS project. There are several ways we might avoid the natural thermal limit of the GBT:

- (1) Accept large absolute pointing errors and correct the pointing frequently by using nearby pointing calibration sources to estimate the current azimuth and elevation offsets. This is the usual method for pointing optical telescopes but is often not needed for radio telescopes.

(2) Measure temperatures at critical locations on the structure with errors  $< (3 \text{ mm}/5 \text{ mm}) \times 1 \text{ C} = 0.6 \text{ C}$  and use a thermal model of the GBT to correct the absolute pointing.

(3) Measure accurate distances between critical members of the GBT using the laser range finding (LRF) system and use a geometrical model of the GBT to correct the absolute pointing.

Wind also affects GBT pointing, although wind is usually not the most important natural limit for large telescopes (von Hoerner 1967). Gawronski & Parvin (1995) applied a quadratic wind model (that is, the wind pressure and the resulting strains are proportional to the square of the wind speed) to the GBT FEM and concluded that a  $7 \text{ m s}^{-1} \approx 16 \text{ mph}$  wind would cause absolute pointing errors up to  $13''$ , primarily in the cross-elevation direction. Quadratic scaling yields a maximum wind speed of  $2.2 \text{ m s}^{-1} = 5 \text{ mph}$  for  $1''/3$  absolute pointing errors. Wind speeds near the GBT have been monitored at heights of 90 feet and 158 feet, and the mean wind speed during the night is just under 5 mph even at 158 feet (McKinnon 1995). Furthermore, gusts normally contribute only 20% of the wind force (Gawronski & Parvin 1995), so the pointing errors might be reduced with the aid of wind velocity data and observations of offset pointing calibrators. Given the benign prevailing conditions, particularly on cold nights, wind should not preclude observations at  $\lambda = 3 \text{ mm}$  with the GBT.

Even if the GBT structure is positioned exactly, tropospheric turbulence (Olmi 2001) can shift the apparent position of an astronomical source by several arcsec on time scales of seconds. Treating this “anomalous refraction” is not part of the core PTCS but remains a concern for the HFOS.

(3) The GBT is exceptionally sensitive:  $1 \text{ Jy} \approx 2 \text{ K}$  at low frequencies and  $\approx 1 \text{ K}$  at the highest usable frequencies. Switching between two highly overlapping beams of 100 m diameter separated by several beamwidths (separations less than 1 m at the tropospheric altitude of about 2 km for mm-wavelength observations with the GBT) should be extremely effective at canceling noise caused by tropospheric water-vapor fluctuations. Thus the GBT will be a very fast continuum telescope at short wavelengths, and even relatively faint sources ( $S \lesssim 0.1 \text{ Jy}$ ) can be used as offset pointing calibrators. The sky is covered with astronomical sources that can be observed with high signal-to-noise ratios ( $\text{SNR} = 10^3$  to  $10^4$ ) in seconds, so we can use astronomical calibrators to measure and correct many telescope errors. Furthermore, such observations can be made at relatively low frequencies (e.g., 5 GHz) where the atmosphere is transparent throughout the year. For example, noise contributes only

$$\sigma_1 \approx \frac{\theta}{2 \times \text{SNR}} \quad (2)$$

to the rms uncertainty in the coordinate measured by fitting a Gaussian (Condon 1997) to a calibrator scan. There are literally thousands of sources that the GBT can use to measure sub-arcsec pointing offsets quickly (Condon & Yin 2001).

There are even a number of unresolved sources strong enough ( $S \gtrsim 10 \text{ Jy}$ ) to dominate the receiver noise at centimeter wavelengths. Out-of-focus beam maps of strong point sources can be used to map the distribution of phase errors across the aperture (Nikolic et al. 2002) over a wide range of elevations. The low natural sidelobe level of the clear GBT aperture should allow large beam maps and hence high spatial resolution in the aperture plane. Traditional holography using coherent transmissions from geostationary satellites also benefits from high sensitivity, but it can only characterize the telescope at a single elevation.



#### 4. The Active Surface

The GBT primary reflector is composed of 2004 panels, each with a solid aluminum surface. The panels are arranged in rings concentric with the vertex of the 208 m parent parabola. The panels are mounted at their corners on 2209 motor-driven actuators which can be positioned in increments of  $25\ \mu\text{m}$  over a total travel range of 5 cm. The actuators are intended to minimize the deviations from the best-fit paraboloid at each elevation, not maintain a rigid surface shape. Consequently, the lateral position of the prime focus and the primary focal length both vary with elevation. The Stewart platform of the Gregorian subreflector must be adjusted continuously to track the prime focus and relay it to the phase center of the feed in use.

The rms surface accuracy of a single panel is about  $70\ \mu\text{m}$ . The overall surface error of the primary is its deviation from the “best fit” paraboloid at each telescope elevation. The construction contract specified an overall surface error  $\epsilon \leq 1.2\ \text{mm}$  rms at the rigging angle. The current actuator zero-points were determined via photogrammetry of the surface at the rigging angle and the actuators were set under NRAO supervision. Aperture efficiency measurements made at 20 and 43 GHz suggest that an rss (root sum square) error including the subreflector surface and collimation errors  $\epsilon \approx 0.47\ \text{mm}$  has been achieved. At elevations other than the rigging angle, gravitational bending distorts the surface. These deviations are currently compensated for in an open-loop fashion using the predictions of the telescope FEM. At least up to 20 GHz, these are sufficient to maintain the telescope gain and low near-in sidelobe level over a wide elevation range.

#### 5. GBT Metrology Systems

The GBT Metrology Systems were described in detail by Hall et al. (1998). The objectives of the metrology system include:

- (1) check critical alignments
- (2) check and refine the FEM
- (3) identify structural anomalies and fault conditions
- (4) provide useful data for optimization of servo algorithms
- (5) allow independent measurements of acceptance criteria
- (6) aid in expediting outfitting and commissioning operations
- (7) improve surface setting accuracy, servo performance and pointing accuracy
- (8) provide a basis for ongoing trend analysis and
- (9) be of service in development of a GBT maintenance program.

The core of the measurement program is the laser range-finder (LRF) system. Twelve ground-based rangefinders mounted on monuments surrounding the telescope will be used to perform non-invasive measurements of alignment errors, thermal deformations, and gravitationally induced bending of the structure, ultimately at the  $\approx 100\ \mu\text{m}$  accuracy level. A number of additional rangefinders will be

installed on the telescope tipping structure to measure the surface panel setting and alignment of the telescope optical elements.

Closure tests indicate that distances measured between the stationary ground LRF stations are at least self-consistent at the 100  $\mu\text{m}$  level. However, the LRF has not yet been used to measure or correct dimensions on the GBT itself, we do not know how often the LRF will be unusable for making real-time corrections during astronomical observations at 3 mm (owing to frost on the retroreflectors, for example). Thus the ultimate utility of the LRF system is quite uncertain. Ideally, the LRF would operate during most 3 mm observations and allow us to correct pointing and reflector surface errors in real time.

Additional metrology systems are available or planned. These include the “quadrant detector” for measuring the position of the tip of the feed arm with respect to the elevation axle, accelerometers, strain gauges, theodolites, inclinometers, etc. An array of temperature sensors for the feed arm, backup structure, and alidade is being designed. First we plan to use these engineering instruments to understand the GBT structure. For example, thermal maps of the GBT made during observations of astronomical calibrators can be combined with predictions of the FEM to show how various temperature gradients affect pointing. Once the correlations between engineering data and astronomical performance are understood, we hope to use real-time measurements from these metrology systems to improve GBT performance during astronomical observations.

Completing these metrology systems, using them as engineering tools, and finally integrating them into the GBT control system during astronomical observing are clearly important parts of the PTCS.

Not all metrology systems needed for high-frequency observing measure the GBT directly. There is an 86 GHz tipping radiometer to measure atmospheric emission and opacity. It will be used for dynamic scheduling of high-frequency observations. There is also a 12 GHz interferometer with a 100 m baseline to measure tropospheric phase fluctuations in case anomalous refraction is a problem in Green Bank.

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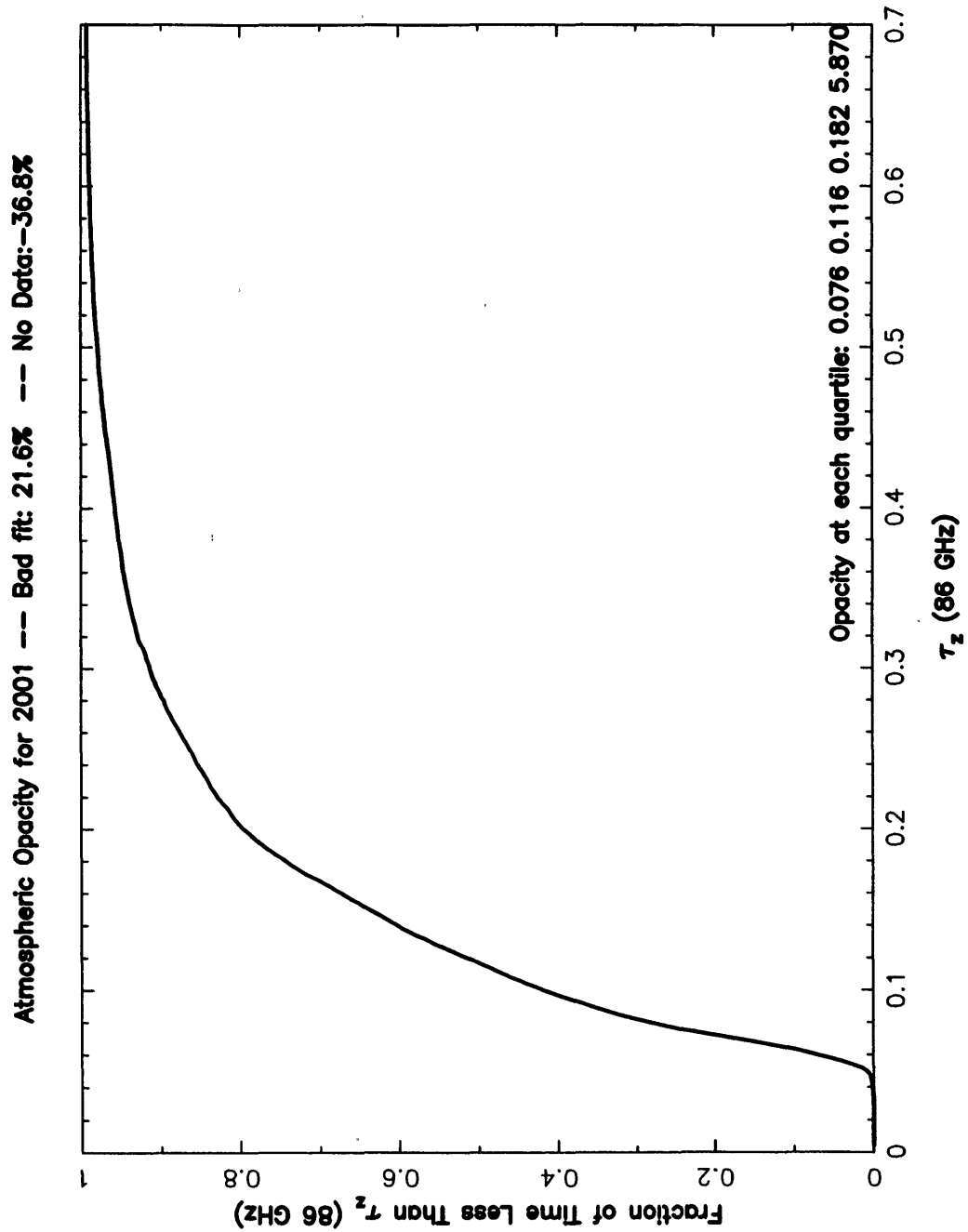


Fig. 3.— The cumulative distribution of 86 GHz zenith opacities measured throughout the year 2000 shows that  $\lambda = 3$  mm observations are possible ( $\tau_z < 0.1$ ) for significant periods, primarily in cold weather. Abscissa: Zenith optical depth  $\tau_z$ . Ordinate: Fraction of time with opacity  $\leq \tau_z$ .