Precision Telescope Control System

PTCS/SN/8: Critical Experiments

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Abstract

The GBT is already a high-precision radio telescope having fractional errors $\lesssim 10^{-5}$ in critical dimensions, and they must be reduced by a factor of three for astronomical observations up to 117 GHz. No doubt these small errors have multiple causes, some of which depend on variable environmental conditions. The PTCS team should make coordinated engineering and astronomical measurements of the GBT to identify, understand, model, and correct these errors. We cannot just "set and forget" the GBT—some of these measurements and corrections will have to be updated during high-frequency observing programs. New observing and data-reduction scripts will be needed to make these measurements efficiently and reduce them in nearly real time.

The largest nonrepeatable focus-tracking and pointing errors are probably caused by thermal expansion and contraction of GBT structural members. Our highest priority is to install an array of thermometers at critical locations on the GBT by 2003 June. Only then can we usefully make astronomical observations of strong calibration sources (1) to model the largest thermal distortions using the temperature map and the GBT finite-element model (FEM), (2) to isolate and measure the effects of gravity on focus tracking at all elevations, and (3) to determine the gravitationally induced pointing errors as functions of both azimuth and elevation. Fortunately, the GBT is sensitive enough that we can quickly measure position offsets with sub-arcsec accuracy even at relatively long wavelengths ($\lambda \lesssim 6$ cm), so these observations can be made even during mediocre summer observing conditions. Incorporating quadrant-detector data will help tie all of these measurements together.

Errors in the reflector surfaces can be imaged accurately at moderate spatial resolution via out-of-focus (OOF) beam maps of strong, compact radio sources and by traditional holography using a geostationary satellite at $\nu \approx 12$ GHz. The main OOF advantage is its ability to map the GBT surface over a wide range of elevation angles. Since small-scale surface errors are relatively insensitive to small thermal distortions, OOF tests can proceed immediately and are scheduled to begin in 2003 April. Since the GBT is so sensitive, we have a wide range of potential sources: Galactic methanol masers at $\nu \approx 6.7$ GHz, Galactic water masers at $\nu \approx 22$ GHz and, extragalactic continuum sources at almost any frequency. The holography receiver was recently modified to reduce overloading by the strong satellite signal, and new holographic measurements will be attempted during the summer. The largest contributor to errors in the OOF and holographic images of the GBT surface is likely to be GBT pointing errors, not noise, so it will be necessary to observe in very benign conditions (e.g., overcast night with no wind) and to make frequent pointing corrections.

The laser rangefinder (LRF) system is potentially the single most powerful tool for GBT metrology, but it is still in the engineering development stage. Closure experiments have shown that distances between LRFs in the "ring of fire" surrounding the GBT foundation can be measured with $< 100\,\mu$m rms repeatablity over time scales of hours. The engineering measurement system (EMS) will systematically expolore the ability of the LRF system to make the passive "Phase II" measurements on the GBT itself. Until we have results from the EMS, we can only speculate about the prospects for "Phase III" control of the GBT incorporating near real-time data from the LRFs.

1. Introduction

The goals of the PTCS are to make the GBT astronomically usable up to 52 GHz by 2003 October and up to 117 GHz a year later. The consequent requirements are an rms tracking accuracy $\sigma_2 \approx 2''.8$ and an rss (root sum square) surface error $\epsilon \approx 0.36$ mm at 52 GHz, and $\sigma_2 \approx 1''.3$, $\epsilon \approx 0.21$ mm are needed to reach 117 GHz (Condon 2003a). The GBT is currently usable up to $\nu \approx 40$ GHz (Condon 2003b) in benign conditions when the active surface is used to correct only for the gravitational deformations predicted by the GBT finite-element model (FEM).

From the PTCS perspective, the GBT is already a high-precision radio telescope having fractional errors $\lesssim 10^{-5}$ in critical dimensions, and these small errors must be further reduced by a factor of three. No doubt multiple problems contribute to the remaining errors, some of which depend on time-variable environmental conditions. The PTCS team must make both engineering and astronomical measurements of the GBT to identify, understand, and correct these errors. Furthermore, the "set it and forget it" policy that works for many radio telescopes will not do—like large optical telescopes, the acceptable GBT errors are so small that the primary surface, pointing, and focus tracking will have to be monitored and readjusted during high-frequency observing programs.

The GBT commissioning staff have done an excellent job of characterizing and adjusting the antenna to yield outstanding performance up to 20 GHz and astronomically usable performance to about 40 GHz. However, the pressure to deliver a working telescope rapidly and the lack of PTCS instrumentation required some empirical approaches (Condon 2003b) that leave room for some comparatively straightforward improvements which can be made in the next few months. At the same time, as we approach our long-term goals of 1.3 arcsecond performance, it will be vital that all factors which contribute to that performance are rigorously understood and controlled.

We have therefore designed a series of critical experiments which will continue the work started by the commissioners, but take us to the next stage in system performance. Our approach to developing these is guided by several assumptions:

(1) Independent error components add quadratically, so that only the largest can be clearly identified. Not until it has been corrected can the second-largest problem be addressed, and so on. This suggests an incremental approach that also has the advantage of yielding useful performance improvements quickly.

(2) Coordinated engineering and astronomical measurements will be essential. Astronomical measurements *define* our performance goals, and it is easy to measure pointing errors, beam maps, etc. quickly and accurately with the large and sensitive GBT. However, astronomical measurements combine the contributions of many error components, and additional engineering measurements are needed isolate and identify these sources of error. For example, astronomical observations of calibration sources can quickly determine GBT pointing errors with arcsecond accuracy over the whole sky. A major cause of these pointing errors will be structural deformations produced temperature gradients in the telescope. Understanding the pointing results and making better pointing corrections will require simultaneous temperature measurements of critical structural members and would be aided by metrology (quadrant detector, LRFs, etc.).

(3) The GBT is so complex that telescope errors must be understood before they can be corrected reliably. Empirical corrections are the fastest way to improve telescope performance during commissioning, but they might not correspond to the best solution and may introduce errors that actually impede progress toward finding the best solution. For example, the current "empirical" GBT focus-tracking corrections are entangled with pointing errors of the primary mirror. Errors in both may be caused by unmeasured thermal deformations. The consequences are avoidable aberrations and pointing errors that cannot be removed by terms in the "traditional" pointing model. Since the PTCS project is not under pressure to commission the GBT and deliver astronomical improvements immediately, we should aim for the best long-term result, not short-term gains.

In principle, accurate real-time distance measurements with the laser range-finder (LRF) system may ultimately be used to set the primary surface as well as control pointing and focus tracking on the GBT. Such a feedback system automatically corrects all errors measured by the LRF, even those that we cannot identify and understand, and so it might let us evade assumption (3). Having this deus ex machina solution would be nice, but we cannot count on it. The risk of failure is too high, and the LRF may be unusable during many observations at 3 mm (owing to uncertainties in the refractive index or frost on the retroreflectors, for example).

The experiments described here are intended to tackle the largest sources of error as described in (1) above, with a goal of making significant performance improvements for 2003 October. Additional experiments, such as half-power tracking whilst simultaneously acquiring quadrant detector, accelerometer, servo current and other data, will be required to probe the feasibility of 100GHz operation, and assist in PTCS system design. These experiments are unlikely to commence before 2003 October, and will be elaborated more fully at a later time.

2. Structural Temperatures

The largest nonrepeatable GBT focus, collimation, and pointing errors are probably caused by thermal expansion and contraction. It is quite likely that the current "empirical" focus-tracking model was affected by temperature changes that occurred during the focus observations, and that errors in the focus-tracking model affect the pointing model in term. Our first priority should be outfitting the GBT with thermometers so that the effects of thermal distortions on astronomical measurements can be modeled and corrected.

Almost all GBT structural members are made of steel, which has a thermal expansion coefficient

$$\alpha \equiv \frac{1}{l}\frac{dl}{dT} \approx 1.2 \times 10^{-5}\ \mathrm{K}^{-1} \tag{1}$$

Here l is the length of any structural member and T is its temperature. Since $1\ \mathrm{rad} \approx 2 \times 10^5$ arcsec, we anticipate that temperature differences dT across the telescope will cause pointing errors of order $2dT$ arcsec. Thermal pointing errors in unfavorable environmental conditions ($dT \gtrsim 5$ K) often dominate all other time-dependent pointing errors. For example, pointing errors having amplitudes $\approx 20''$

near solar noon were measured during the 4.85 GHz sky surveys made with the Green Bank 300-foot telescope (Condon et al. 1989) and the Parkes 210-foot telescope (Condon et al. 1993). Both telescopes acted like "reverse sunflowers," bending away from the direction of solar heating. At other times, the rms pointing errors were $< 7''$.

The effects of differential heating also depend on telescope geometry. Most of the GBT support structure (Fig. 1) consists of triangles. Figure 2 shows an isosceles triangle with base b and side members of length l. If the right leg is heated and the left leg is cooled such that their temperature difference is dT, the right leg will lengthen by

$$\frac{dl}{l} = \alpha \frac{dT}{2} \tag{2}$$

and the left leg will shrink by the same amount. The vertex will shift dx to the left, tilting the line between the vertex and the midpoint of the base by an angle ϵ. Plane geometry implies

$$dx \approx \alpha dT \left(\frac{l^2}{b} \right) \tag{3}$$

and

$$\epsilon \approx \alpha dT \operatorname{cosec} \theta \;, \tag{4}$$

where θ is the vertex angle between the two sides. Equations 3 and 4 show that thin triangles ($b \ll l$ or $\theta \ll 1$) are much more sensitive to thermal deformation than wide triangles ($b \approx l$ or $\theta \approx 1$) for a given α and dT. Thermally induced pointing errors at the 140-foot telescope (von Hoerner 1975) illustrate this effect: the largest single contributor was bending of the thin yoke arms in the declination direction.

The GBT feed arm is a thin triangle ($b \approx l/5$) in the elevation plane, and it is exposed to solar heating during the day and radiative cooling into the cold sky at night. It will be a major source of thermal pointing errors in the elevation direction. The cantilevered dish backup structure is also much thinner than the dish diameter, so the dish surface may flatten when heated by the Sun during the day and curl up by radiative cooling on clear nights. Note that a temperature difference between the feed arm and reflector surface can cause pointing errors because the GBT is not rotationally symmetric. Lengthening the feed arm or changing the reflector curvature doesn't just defocus the GBT, it shifts the pointing because the subreflector axial focusing direction Y_s is tilted by about 37 deg from the axis of the parent paraboloid (Norrod & Srikanth 1996).

The GBT alidade structure is made of wide triangles and is shielded by the main reflector from both solar heating and radiative cooling into the sky, so it will be a smaller contributor to thermal pointing errors.

Figure 3 shows possible locations for a set of 25 thermometers to be placed on the GBT. We hope to have them running by 2003 June. They should be used during the focus-tracking and pointing measurements described in the next two sections.

3. Focus Tracking

The Gregorian subreflector is used for all high-frequency ($\nu \gtrsim 1$ GHz) observations relevant to the PTCS. The subreflector is cut from an ellipsoid having eccentricity $e = 0.528$ and separation $c = 11$ m between its two focal points (Norrod & Srikanth 1996). The near focus must track the focal point of the primary mirror and the far focus should coincide with the phase center of the feed horn in use. If the GBT is viewed as a transmitting antenna, small focus-tracking errors cause small phase errors across the aperture and degrade the beam. The distribution of these phase errors determines the type of degradation. The linear ph resulting from a transverse focusing error causes a pointing error but does not otherwise affect the beam. To first order, a small phase error proportional to the square of the distance from the center of the aperture corresponds to axial defocussing, reducing the peak gain and filling in the nulls between sidelobes. The cubic phase error caused by a transverse focusing error broadens one side of the beam and generates a coma sidelobe on the other, etc. The asymmetry of the GBT complicates this picture somewhat. The "axial" focus direction Y_s is tilted by $\approx$ 37° from the axis of the 208 m parent paraboloid. Apparently transverse displacements of the subreflector, caused by swaying of the feed arm for example, will yield symptoms of both axial and transverse focusing errors. Apparently axial displacements, caused by the feed arm length changing as its temperature changes for example, will also yield symptoms of both axial and transverse focusing errors. Thus pointing and focus tracking are entangled on the GBT.

We plan to separate pointing and focus-tracking errors by making azimuth-elevation cross scans to peak up on strong point sources over a range of offsets $\pm dX_s$, $\pm dY_s$, and $\pm dZ_s$ from the optimum subreflector coordinates and rotations predicted by the FEM. These measurements will be repeated over the full range of elevation, and we will assume that changing azimuth has no effect. Fitting for maximum gain and/or minimum sidelobe level should yield the optimum focus offsets. Only after the focus tracking terms have been measured accurately, and their dependences on elevation and temperature understood, will we concentrate on pointing. Both the focus-tracking and pointing observations can be made at relatively long wavelengths ($\lambda \lesssim 6$ cm) during summertime observing conditions because the sky is full of calibration sources that the GBT can observe with high (10^3 to 10^4) signal-to-noise ratios.

New observing and analysis scripts will be needed for us to make focus-tracking measurements easily and efficiently, and to analyze the data in nearly real time.

4. Pointing

The astronomical pointing requirements for the GBT are two-dimensional rms pointing errors $\sigma_2 \leq 2''.8$ at 52 GHz and $\sigma_2 \leq 1''.3$ up to 117 GHz. It would be convenient, but it is not necessary, for the GBT absolute pointing errors to satisfy these requirements. It is sufficient for the GBT to meet these targets with offset pointing based on observations made every hour or half-hour of nearby astronomical sources having accurately known positions. Because the GBT is so sensitive, the nearest calibrator is never more than $d\theta \sim 0.1$ rad away (Condon & Yin 2001), so offset pointing may remove up to 90% of the slowly varying absolute pointing error at the source position.

The largest pointing errors are repeatable errors caused by fixed instrumental offsets and by gravitational deformations depending only on elevation. They have been measured and can be largely removed by "traditional" pointing models (Balser et al. 2001) that depend only on azimuth and elevation. The uncertainty in the position offset measured from a single cross scan on a calibrator is $< 1''$ even at relatively long wavelengths ($\lambda \lesssim 6$ cm) because the signal-to-noise ratio is so high with the GBT (Condon 1997). It is therefore straightforward to measure accurate pointing offsets over the full range of azimuths and elevations, and these offsets determine the coefficients of the pointing model. The uncertainties in these coefficients are completely dominated by time-dependent pointing errors.

The largest time-dependent pointing errors are probably thermal in origin. For this reason, significant improvements in GBT pointing can be made only after we can add thermal corrections to the traditional pointing model as described in Section 2. Unmodeled temperature-dependent pointing errors degrade the absolute pointing accuracy (currently $\sigma_2 \approx 10''$) directly. They also induce gradients in pointing errors that degrade the offset pointing accuracy (currently $\sigma_2 \approx 3''$). We anticipate that straightforward extensions of the current focus-tracking and pointing programs used during commissioning to include thermal effects will meet the 52 GHz pointing goals of the GBT within six months. It would be premature to predict a time scale for reaching the 117 GHz goal before we have carefully sorted out the thermal pointing errors,

5. Holography

Traditional holography can image the GBT surface with $\epsilon \approx 100\,\mu$m accuracy and with spatial resolution $dx \approx 0.5$ m needed to distinguish individual panels on the primary (Maddalena et al. 1991). The best source is a 12 GHz geostationary satellite at elevation angle $\approx 45°$, so these excellent results would be obtained at only one elevation. Since the GBT is so sensitive, the largest contributor to errors in the map is pointing, not noise. A $1''$ random offset pointing error causes $\epsilon \approx 60\,mu$m image noise, and systematic offset pointing errors cause systematic image errors. This means that useful observations can be made only under optimum conditions—no wind, at night under clouds to minimize radiative heating and cooling.

The dynamic range of the receiver used on the GBT must be very high. The first attempt to make a holographic image of the GBT surface did not succeed because the receiver dynamic range was inadequate. That receiver has since been modified, and a new attempt is planned for 2003 June.

6. Out-of-focus Beam Maps

Out-of-focus (OOF) beam mapping (Nikolic et al. 2002), or phase-retrieval holography, complements traditional holography for measuring the GBT surface. The spatial resolution is not as high, but astronomical sources (Galactic methanol masers at $nu \approx 6.7$ GHz and water masers at $\nu \approx 22$ GHz plus extragalactic continuum sources at any convenient frequency) can be used to image the GBT surface over a wide elevation range.

Nikolic et al. (2002) have already tested OOF beam mapping on the GBT (see `http://www.mrao.cam.ac.uk/ bn204/gbtoof/oofgbt.html`), and that team will help NRAO staff to make OOF beam maps during 2003 April. As with traditional holography, offset pointing errors must be minimized to reduce noise on the surface image.

7. Laser Ranging Experiments

Astronomical observations at $\lambda \approx 3$ mm require that critical dimensions of the GBT (e.g., surface panel heights, subreflector position) be controlled within $\approx 200\,\mu$m rms. Such strict requirements are unprecedented for a telescope as large as the GBT, which is directly exposed to environmental temperature changes and wind loading. To measure distances of order 100 m to targets on the GBT and in a ring of piers on the ground with $\lesssim 100\,\mu$m accuracy, the NRAO proposed and developed the LRF metrology system. The metrology program plan as summarized by Hall et al. (1998) incorporates the LRFs in two stages:

> Phase II: For operation at 43 GHz, the LRF system would be used "open loop" to measure GBT dimensions passively. The results would be used to check critical alignments, test the FEM of the structure, identify structural anomalies and fault conditions, provide data for optimizing servo algorithms, improve pointing, improve surface setting accuracy, etc.
>
> Phase III: For operation at $\lambda \approx 3$ mm, "closed loop" operation of the LRF system would be incorporated into telescope control to make nearly real-time pointing corrections and primary surface adjustments.

The current GBT already approaches the Phase II performance goals, and we anticipate that improvements made by 2003 October will reach them without the use of LRF metrology. The "ring of fire" LRFs on fixed piers surrounding the GBT has has been operated, and a range closure test indicates that distances of order 100 m can be measured with $\approx 100\,\mu$m repeatability over time scales of hours. However, the closure test had to determine a large number of free parameters (e.g., a range zero offset for each LRF) so significant systematic range errors might remain. Moving individual LRFs to different piers and repeating the closure test would show whether or not their offsets were indeed measured accurately and remain constant.

While these results are promising, additional tests will be needed before we can evaluate the ability of the LRFs to meet even the Phase II metrology goals. For example, range measurements on slanted paths from the ground to targets on the GBT tipping structure are needed to answer questions such as: How accurately can the LRF beams point to those targets? How do vertical gradients in atmospheric refraction affect the beam pointing and distances measured? The engineering measurement system (EMS) is intended to approach these metrology questions systematically. Until we have those answers, we can only speculate about the ability of the LRF system to reach the Phase III goals.

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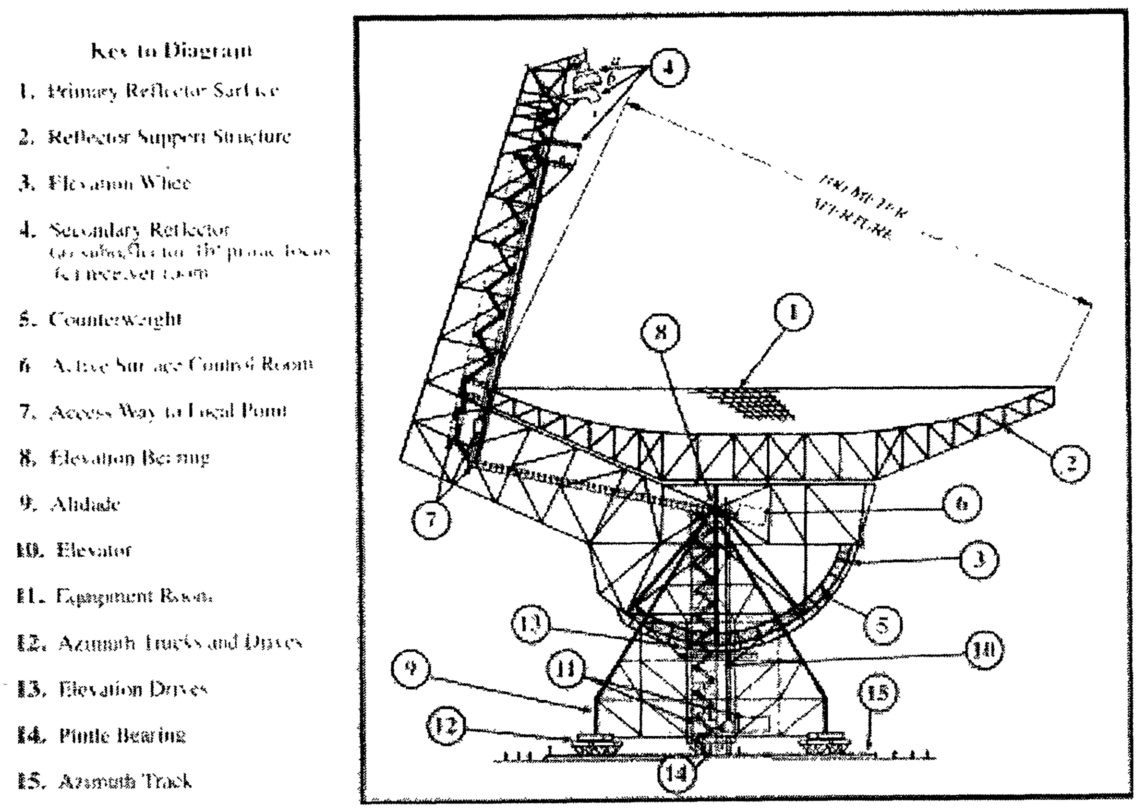

Fig. 1.— Outline of the GBT.

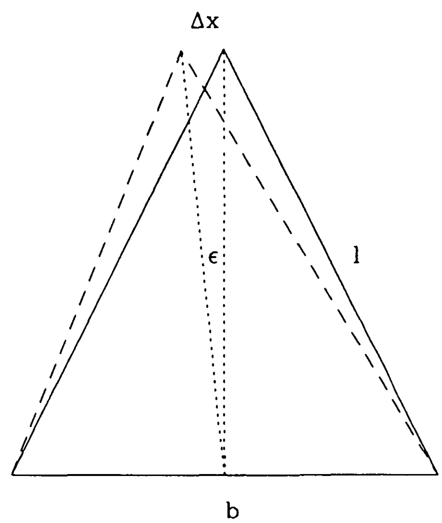

Fig. 2.— An isosceles triangle having sides l and base b deforms as shown if the right side is heated and the left side cooled. The vertex moves left by dx, tilting the line between the vertex and the middle of the base by an angle ϵ.