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# The GBT Precision Telescope Control System

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**Abstract.** The National Radio Astronomy Observatory has undertaken an ambitious project that is intended to control our 100m primary Gregorian telescope, the Green Bank Telescope (GBT), at frequencies up to 115 GHz. In order to ensure adequate efficiency and pointing performance, the net wave front path errors need to be less than 1/16 of a wave and the telescope pointed to 1.2 arc seconds over periods of an hour. The Precision Telescope Control System (PTCS), an architecture that generates control signals for the telescope servomechanisms on the basis of telescope metrology and models, seeks to extend the domain of environments for which high frequency observations can be effectively performed. We will present an overview of the GBT and the PTCS architecture, discuss our algorithmic and computational approaches, and present preliminary results of our characterization of the GBT and inferences about the ultimate potential of the GBT for 3mm observations.

## 1. Introduction

The GBT is an offset-Gregorian radio telescope on a alt-az mount with a design goal of 115 GHz operation. The structure is approximately 150 meters high and masses about 8 million kilograms. The 100 meter aperture, 60 meter focal length paraboliodal primary mirror has 2209 movable panels used to compensate for structural deformations. Prime focus operation is used for low frequency observations, and an eight meter diameter, eleven meter interfocal distance ellipsoidal subreflector is used at high frequencies to image onto receivers located in a receiver cabin attached to the offset feed arm. The subreflector mount has servos with approximately one Hertz bandwidth that can adjust all six degrees of freedom and can be used to adjust for the up to 400 millimeters of relative motion between the feed arm and prime focus as the feed arm bends during elevation changes from five degrees to 95 degrees. The receiver cabin has a turret with eight receiver mounting locations so that receivers can be changed relatively easily. The alt-az mount drives have slew rates of 20 and 40 degrees per minute, respectively, and have encoders with 0.3 arc second resolution. Closed loop control bandwidths are approximately 0.3 Hertz. The natural modes of vibration of the GBT begin at 0.6 Hertz, and the structure is very lightly damped due to its welded steel construction.

Requirements for net wavefront error and pointing accuracy can be derived from observational requirements (Condon 2003). At the design maximum frequency of 115 GHz these requirements are approximately 200 microns net wavefront error, about 3 arc seconds blind pointing, and about 1.2 arc seconds radial pointing error RMS during source tracking[1]. We have added a requirement that we should stabilize pointing (and wavefront error) to these levels for one-half to one hour, and that the environmental domain should be as large as possible, i.e., over as great a range of tracking speeds, temperature changes, and wind loads as possible.

Over the past seven months we have made substantial progress towards our 115 GHz goal, and now believe that we can now achieve the blind and tracking performance requirements for 50 Ghz, with a somewhat less than optimal antenna efficiency.

## 2. Degradations to Pointing and Efficiency

The ideal pointing of the GBT is degraded by a variety of effects that can be divided into mechanical alignments, structural deformations, and servo and drive errors. The first category, mechanical alignments, includes the orthogonality of the elevation and azimuth axis, RF axis and the elevation axis, azimuth axis verticality, and encoder offsets. These effects are compensated for by a traditional pointing model (using TPOINT[2]) and then applying the pointing model to the commanded telescope positions to produce the servo demands for the main drives. A caveat with this procedure is that model generation uses all-sky surveys to produce pointing offsets as a function of elevation and azimuth angles and can be corrupted by systematic wind and thermal effects.

Wind and thermal degradations to pointing are caused by the associated deformations of GBT substructures. Scales of these effects are summarized in Condon 2003 and are attributed to changes in primary focal length and translations and rotations of the primary, the subreflector (in the Gregorian configuration) and feed. Additional pointing perturbations are caused by distortions of the GBT alidade. The expected size of these effects and associated plate scales have been predicted to be as large as 20" in the GBT design studies under 5 C thermal gradients and 6 m/s winds, much higher than our ultimate performance goals.

Even when the GBT primary panels have been adjusted to the required accuracy at a specific elevation angle and hence are producing the desired efficiency, thermal, wind, and gravity deformations can deform the mirror at different elevations and in the presence of thermal gradients and wind loads. At this time there are no definitive predictions of the magnitude of these effects, although we are confident that they need to be measured and corrected.

Finally, the properties of the main drives and subreflector servos can introduce additional pointing errors. For example, the elevation servo system exhibits $\sim 0.8$" periodic errors due to closed-loop servo resonances at $\sim 0.3$ Hz and a limit cycle at $\sim 0.04$ Hz. Structure vibrations can cause significant pointing er-

[1]At 115 GHz anomalous refraction could be a dominant factor in tracking performance. PTCS goals include development of instruments and predictors to compensate for these effects as well, but this paper will only concern itself with the pointing performance of the telescope itself.

[2]`http://www.tpsoft.demon.co.uk/`

rors if they have been excited by main drive angular accelerations or pumped by wind speed variations. The structural vibrations have modal frequencies from $\sim 0.6$ Hz and up, but are likely to be unimportant at frequencies above 2.0 Hz.

## 3. PTCS Instruments

Various instruments are or will be used to directly measure or infer GBT configuration. Static surveys using conventional techniques can be used for initial setting of components (such as initial primary panel positions via photogrammetry), but adjustments of the telescope during observation require additional measurements. These instruments include precision structure temperature sensors, precision air temperature sensors, a fixed angle-angle measuring device to measure feed arm position in the coordinate frame of the tipping structure, one or more star trackers to measure rotations of substructures (e.g., the primary support structure) with respect to the celestial inertial frame, precision inclinometers to measure alidade structure rotation with respect to the azimuth track, and a constellation of laser rangefinders located both on the ground surrounding the telescope as well as on the tipping structure itself. These rangefinders could then used to determine positions of key components on the structure as a function of time. It is the latter system of rangefinders that has the most complicated signal processing requirements to take the measured ranges to structure positions. We have devised a signal processing environment, called the Engineering Measurement System (EMS), to fuse data from various sources including the laser rangefinders and produce position information that could be in turn used to generate control demands to the various GBT control subsystems and correct for the degradations described above. We anticipate further application of the EMS in exploratory algorithm development and perhaps even generation of real-time servo demands via, for example, SOAP interfaces.

## 4. Correcting Pointing and Focus using Structural Temperature Measurements

We have recently had some success in correcting the GBT for minute time-scale thermal distortions using structural temperature sensors. Linear combinations (derived features) of an array of 19 0.1C accurate temperatures are used to characterize deformations of substructures of the GBT, and then these data are used in conjunction with astrometric observations to determine the linear regression of these features with respect to experimentally determined focus and pointing drifts in order to determine linear maps that take features and produce correction signals. These regressions simultaneously estimate tradition gravity pointing terms so that we end up with both a thermally-neutral gravity model and the thermal corrections to the gravity model all at once. Figures 1 and 2 show the improvements we can achieve in nighttime focus and elevation angle.

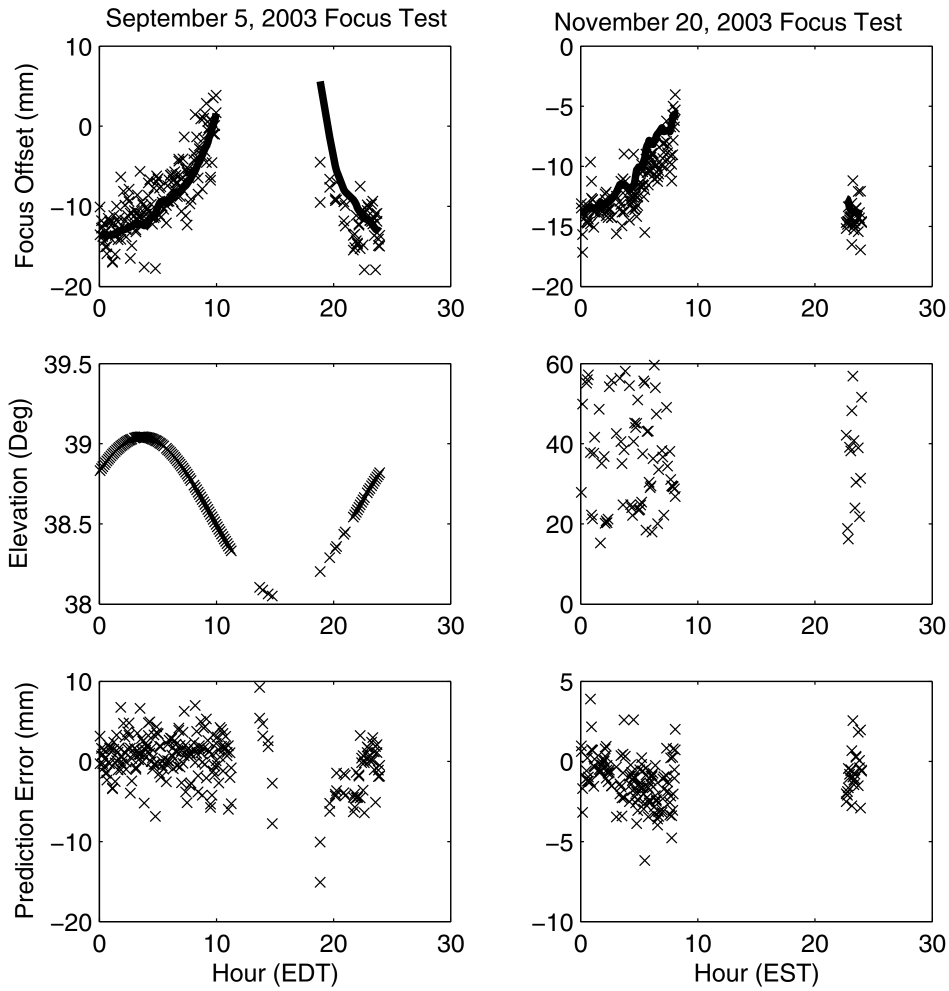


Figure 1. Predicting focus with structural temperatures. The upper graphs show measured (x) and predicted (solid line) focus, the bottom graphs show the prediction error as a function of time. The September experiment tracked a source near the North Celestial Pole. The mean and standard deviation of focus error was 0.1 and 3.0 mm, respectively. The November experiment was an all-sky pointing run. The mean and standard deviation of focus error was -1.1 and 1.5 mm, respectively.

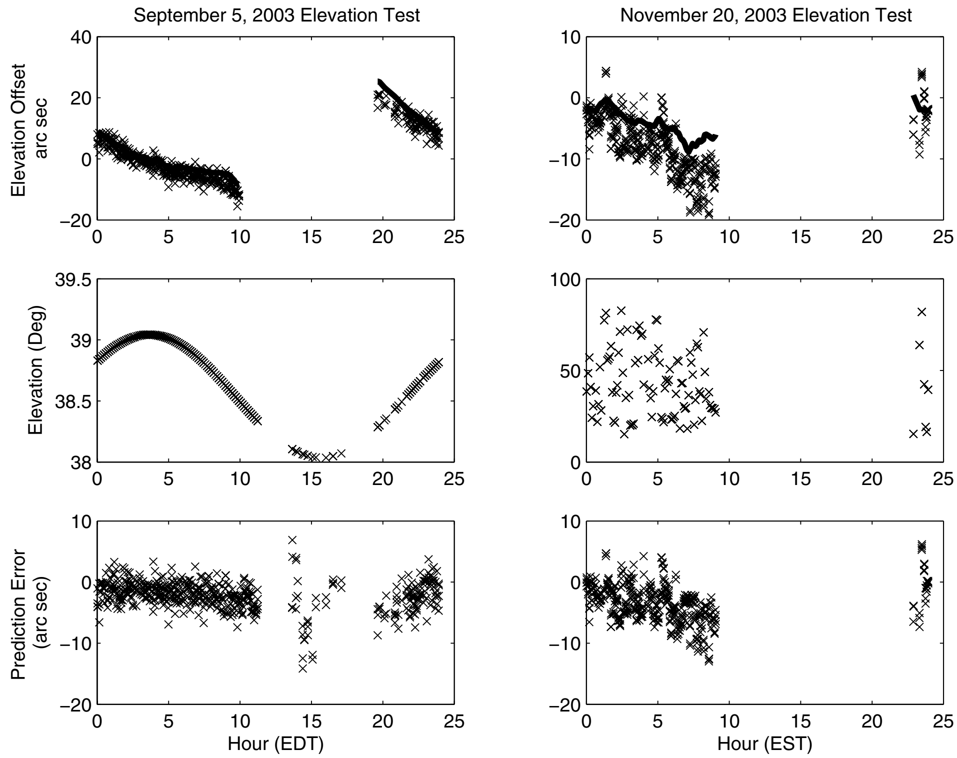


Figure 2. Predicting elevation with structural temperatures. The upper graphs show measured (x) and predicted (solid line) elevation offset, the bottom graphs show the prediction error as a function of time. The September experiment tracked a source near the North Celestial Pole. The mean and standard deviation of elevation error was -1.8 and 2.0 arc seconds, respectively. The November experiment was an all-sky pointing run. The mean and standard deviation of elevation error was -3.4 and 3.2 arc seconds, respectively.

## 5. Laser Rangefinders

The GBT Laser Metrology System currently consists of steerable 780 nm laser rangefinders with 1.5 GHz modulation and phase detection of the returned 1.5 GHz modulations. There are associated glass retroreflectors located on cardinal points of the structure that can be seen from the ground, such as the tip of the feed arm, the elevation bearing housings, etc., and a large number on the primary mirror itself. The former targets could be used to measure the deformations of the optical element supports, i.e., the position and pose of the elements with respect to each other. The latter are solely intended to be used in adjusting the figure of the primary mirror to the nominal 150 micron accuracy required for adequate antenna efficiency at 115 GHz. Twelve rangefinders on a circle around the GBT could be used to trilaterate the positions of the cardinal point retros, while up to six laser rangefinders on the feed arm could be used to measure primary figure and tie the position of the optical elements together into a coordinate system for the purpose of collimation and to tie the optical system coordinates to ground coordinates in order to predict GBT pointing from a geodetic frame.

## 6. The Engineering Measurement System

The calculations required to achieve this goal are extensive and varied. For example, auto-calibration of all rangefinders needs to occur on a frequent basis (approximately once per minute). The positions and orientations of rangefinders with respect to each other must be frequently measured in order to establish the fiducial coordinate systems which may change due to ground monument motions or changes in pose of the GBT that change the position of the feed arm rangefinders with respect to the elevation axle due to feed arm deflection The group refractive index of air is calculated from air temperature, pressure, and dew point. Some data require filtering and smoothing operations to remove blunder points and enhance accuracy. Errors must be propagated through all calculations to get metrics of the final position estimate quality. Databases of persistent calibrations, such as the glass offsets associated with individual retroreflectors, are used and perhaps updated. Finally, nonlinear optimizations solve for position given three or more independent ranges from distinct locations to the target (retroreflector) of interest.

Since the algorithms and methods for achieving these results had been specified in an informal way we decided to implement an algorithm development environment to explore different methods of reducing these data to the quantities of interest: The positions of structural elements on the GBT. Our first objective was simply to be able to perform automated, high accuracy, surveys of the stationary GBT, and hence provide data to structure models, investigate thermal deformations, etc.

There are several main elements to the environment: First, we choose a graphical signal flow graph representation for the high-level signal processing description. Processing tasks are described by a graph where edges in the graph carry data items (as either primitives or user defied structures), and node in the graph represent operators that can be overloaded for different input data. Hence, the top-level description is just a data driven graph. Special node operators were then devised to be able to insert into and query a relational database (though ODBC). These special nodes provided us with a way to consistently represent, e.g., persistent calibration and survey data for each rangefinder. Another special node set provided us with connections to a powerful scripting numerical analysis package, Matlab. This connection (and package) allowed us to leverage existing high-quality numerical algorithms and visualizations without much effort on our part. On important element of the script-level engine is a FEM-based model of the GBT structure that is used to predict total range from rangefinder to target and thus resolve the 10 cm uncertainty distance of the rangefinder ranges. Finally, special nodes were constructed to allow standard transports into and out of the signal flow graph. Initial implementations were TCP/IP transport, and we are extending this to SOAP based transports.

Figure 3 is an example of a real-time trilateration data reduction that involves all of the elements above. Data from rangefinders is asynchronously im-

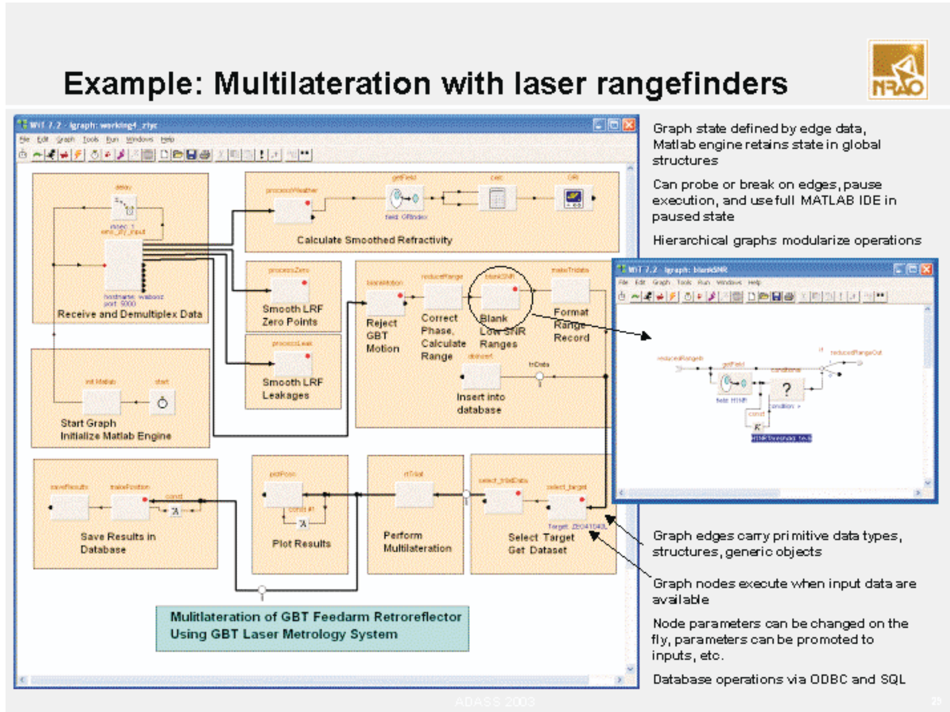


Figure 3. A signal flow graph in Wit demonstrating a trilateration data reduction for the GBT Laser Metrology System

ported into the graph (upper left) and drives the subsequent operations. These data are demultiplexed into weather data (for estimating group refractive index), data for estimating laser rangefinder zero points and coupling of the input and output beams ("leakages"). These data are then processed to predict the total corrected range from rangefinder to target, and construct a data item that includes information such as the FEM predicted range, signal-to-noise qualities, etc. Then these data items are tested for adequate signal to noise, no telescope motion, etc. Qualifying data are then stored in a database. Then the database is again queried for range records that satisfy certain requirements, e.g., all range records within the past 60 seconds that have a specific retro as a target. These data are then provided to a non-linear least squares algorithm and a target position is generated that minimizes the residual range errors from all participating rangefinders to the fitted position solution. Finally, these data are stored in a database for further analysis, and could be used to generate real-time control signals for adjust the GBT azimuth, elevation, etc.

The results of these calculations have been very informative, and have allowed us to identify several problems with instrumentation and laser metrology system design. We are now enhancing the EMS to allow applications to other GBT instrumentation signal processing tasks, such as generating control signals from inclinometers, and are sure that the environment will lets us rapidly explore and determine suitable algorithms and techniques for production improvements of GBT performance.

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