Controlling the Green Bank Telescope

Joseph J. Brandt[a]

[a]National Radio Astronomy Observatory, Green Bank, West Virginia USA

ABSTRACT

The Green Bank Telescope (GBT) is a 100-meter clear aperture radio telescope of unique design. It features off-axis optics, an active surface primary, and both Gregorian and prime focus feed mounts. The GBT also includes an assortment of accelerometers, tilt meters and laser metrology units for measurement of structural deflections. The GBT will begin commission tests in mid 2000.

Controlling an instrument of the scale of the GBT is a complex challenge. Motions of the GBT primary will require the acceleration and deceleration of more than 8 million kilograms of steel, while maintaining a high degree of positioning accuracy. Vibration induced by the servo drive systems will be significant when observing at higher frequencies unless special care is taken when generating servo commands. The Gregorian secondary is capable of six degrees of freedom and must be periodically reoriented to maintain proper optics alignment. The GBT primary active surface must be adjusted to compensate for thermal effects and gravitational forces.

This paper presents the GBT antenna control system architecture, describes the tracking options available to the observer, and details the GBT pointing, focus tracking and active surface control systems, as well as approaches to vibration reduction by use of minimal jerk trajectory generation. A description of the phased approach to improve telescope performance through the use of laser metrology range finders is given.

Keywords: Pointing,Software,Distributed Systems

1. INTRODUCTION

"Here was the K-band radiometer just on his desktop....All of us who saw it then knew that this would be an important instrument."[*]

"The telescope radically altered man's view of his position in the universe. No longer was he the center of things..."[†]

The Green Bank Telescope (GBT) is a 100-meter radio telescope, located in Green Bank, West Virginia USA, and is operated by the National Radio Astronomy Observatory. [‡] The GBT is an off-axis design, resulting in a clear aperture. The GBT is equipped with receivers ranging from 100MHz to 100GHz (planned), an advanced laser metrology system, a wide-band spectrometer, and digital continuum backends. The GBT stands approximately 150 meters tall, and can be seen from quite a distance.

1.1. Main Axes

The GBT mount is an elevation over azimuth design, with approximately 8 million kilograms of moving weight. The elevation axle is 46 meters long, and carries the entire 4.3 million-kilogram tipping structure.

The primary surface is comprised of 2004 aluminum panels. Each panel corner is mounted upon linear actuators to provide a mechanism to compensate for gravitational and thermal deflection of the main reflector structure. The GBT primary reflector structure has been designed to be *homologous*,which means that the primary backup structure will deform with gravity into shapes that are parabolic in shape, but differ in focal length.

(Send correspondence to P.O. Box 2, Green Bank, WV 24944 USA): E-mail: jbrandt@nrao.edu

[*]Edward Purcell of Robert Dicke's invention

[†]James Burke, *Connections*

[‡]The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

1.1.1. Servo Instrumentation

The most of the GBT servomechanisms are provided by Precision Controls, of Richardson, Texas. § The servo loops are of PID type design, with velocity feed forward to improve tracking characteristics. The loops are closed by two VME based computers, one located in a 400 square foot room at the alidade base, and the other in the Gregorian receiver room at the feedarm tip. The alidade also carries a 600 kW generator, which is used in case of commercial power failure.

The azimuth axis is driven on a 64 meter diameter rail by sixteen 30 HP motors distributed on four trucks. On each four-wheel truck, dual motors power the two outer drive wheels. An additional eight motors can be mounted on the inner wheels of each truck. At low speeds, the outside wheels are driven against each other in such a way as to present a preload in order to minimize backlash. The azimuth axis is capable of rotating at speeds up to 40 degrees per minute, with a maximum acceleration of 0.2 $\frac{deg}{sec^2}$. Each motor is driven with a Baldor-SWEO drive amplifier.

The eight elevation drives are mounted on a carriage, designed to keep them in constant contact with the 30-meter radius bull gear. The elevation axis is capable of speeds of up to 20 degrees per minute, with a maximum acceleration of 0.2 $\frac{deg}{sec^2}$. A 203-mm x 381-mm x 1.8 meter solid steel stow pin can be inserted in any of four positions, to lock the tipping structure in place.

1.1.2. Primary Surface Actuators

The primary surface is mounted upon 2209 linear actuators. Each actuator can be adjusted with a positioning resolution of 25 microns, and has a total travel of 53-mm. The expected travel required to compensate for gravitational deformation¶ is estimated to be 6-mm peak-to-peak.[1,2]

1.2. Secondary Optics

The GBT can operate either in prime focus or Gregorian optics configuration. A 9 meter long feed boom can be deployed to position a receiver at the prime focus, or retracted to allow servicing and illumination of a Gregorian subreflector.

1.2.1. Prime Focus

In prime focus mode, the receiver box can be moved 1100-mm axially for focusing, rotated ± 208 degrees to maintain constant parallactic angle, and translated 890-mm to compensate for gravitational deflection (approximately 225-mm) of the 90 meter vertical feed arm. A permanent magnet motor, via a Kollmorgen drive amplifier drives each axis. Two prime focus packages hold either a 290-920 MHz or a 910-1230 MHz receiver. Only one prime focus receiver package is available at a time.

1.2.2. Gregorian Subreflector

The 8-meter Gregorian subreflector is mounted on a Steward platform.[3] The Steward platform uses three linear actuators in the (Y) direction, parallel to the vertical feedarm; two in the (X) direction (perpendicular to the vertical feedarm, and parallel to the plane of symmetry) and one in the (Z) (cross-elevation) direction. These six actuators allow the subreflector to be moved with six degrees of freedom to compensate for feed arm deflection, and also allow flexible optics control. Approximate subreflector travel ranges are: 850-mm in Y; 475-mm in X; and 42-mm in Z. The actuator servo loops are closed independently, except for delta position limit criteria.

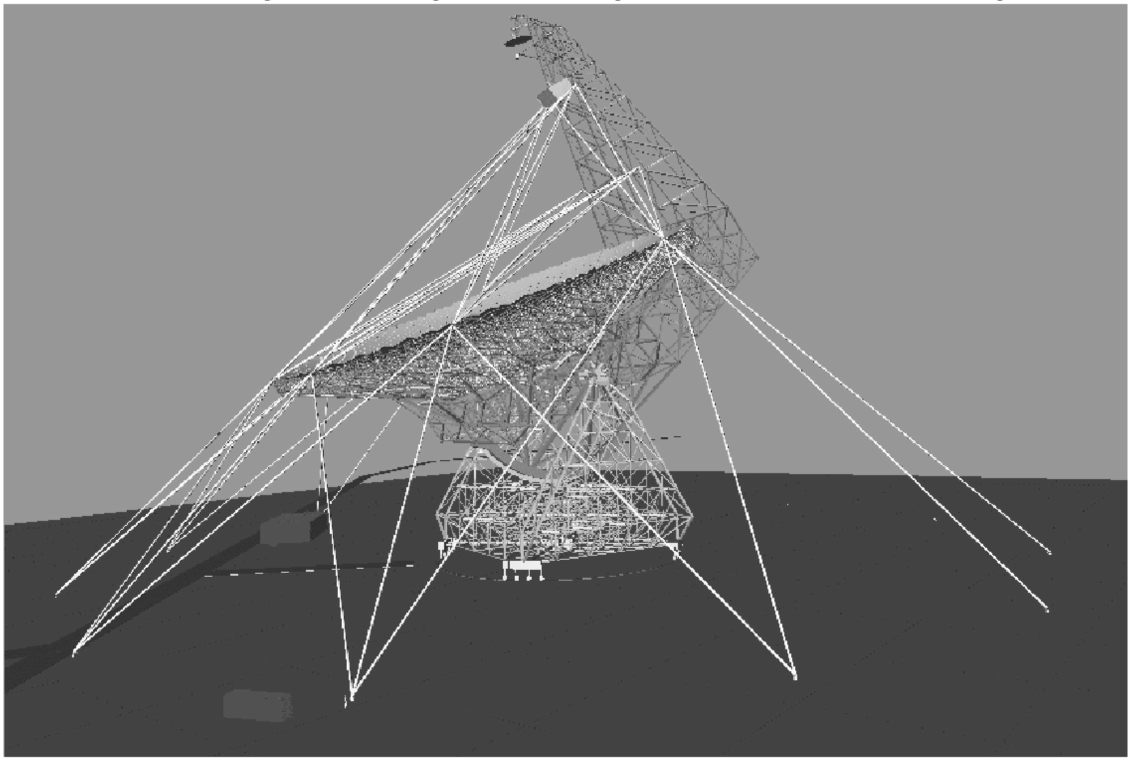
1.2.3. Gregorian Receiver Turret

The Gregorian receivers are mounted in a 4.3-meter diameter turret, which can be rotated to bring one of eight receiver packages into position. Gregorian receivers ranging from 230 MHz to 26.5 GHz are currently available. A multiple feed Q band receiver is currently under construction. Some of the turret receiver positions contain a feed rotator to track apparent parallactic angle.

§Precision Controls is a TriPoint Global Company and a business unit of Radiation Systems Inc., Richardson, Texas

¶With respect to the nearly homologous paraboloid.

Figure 1. Range-finder to edge retro-sphere geometry with elevation at 45 degrees



1.3. Metrology Instrumentation

Operating the GBT at the higher frequencies will be a challenging task. In order to realize the operation of the GBT at the higher frequencies, continuous characterization of the structure by means of precision metrology is necessary. NRAO has developed laser-ranging units to meet this challenge.[4,5] Twelve ranging units surround the GBT in a 120 meter diameter circle on stable monuments for the purpose of referencing cardinal structure points to a ground based coordinate system. Six range finders are mounted on the vertical feedarm, to survey the 2209 active surface retro-reflectors, special edge reference retro-spheres, the Gregorian subreflector, and ground based reference targets. A conceptual example of the range finders measuring to the edge-reference retro-spheres is shown in figure 1.

2. CONTROL SOFTWARE ARCHITECTURE

"I can never pick a thing up without wishing to improve it."[‖]

A radio telescope is made up of a heterogeneous conglomeration of instruments, and bears more resemblance to a laboratory than a single instrument. Computer programs are used – among their other functions – to setup, synchronize, and monitor these instruments, record data, and notify the operator of extraordinary conditions.Though the instruments vary widely in their design, implementation, use, and complexity, the software engineering is simplified significantly to the extent a common interface can be defined for all instruments and sub-systems.

Niels Bohr once stated "Prediction is extremely difficult. Especially about the future." It is nearly impossible to predict how an instrument, or even what combination of instruments will be used years from now. It is therefore necessary to define interfaces that are general enough for use on any type of device, yet exposes the capabilities of each specific device to the user.

The GBT monitor and control system[6,7] can be categorized into two parts, a generic portion that may be applicable to any telescope, and a GBT specific portion. Software is intangible, so we often create names for it.

[‖]Thomas Edison

Ygor** is the name selected for the generic portion of the GBT monitor and control software. Things almost never turn out as expected. Although Ygor was written for use on the GBT, it has been already been used to control the spectral processor and receivers on the 140 foot telescope; the 140 foot itself; and is soon to be in use by the Green Bank Interferometer (GBI); and the 85-3. Therefore, the GBT will not be the first, but rather the fifth telescope to use Ygor.

As with any monitor and control system, Ygor must be able to command (i.e. setup system parameters) and control (i.e. make an observation happen) these devices in an efficient manner. Ygor also must provide monitoring for logging purposes, and an alarm/messaging system for those un-expected failures.

The Ygor system provides three major interfaces to all devices:

- Command and Control
- Messages and Alarms
- Data Monitoring and Logging

These interfaces and much of the supporting code for communications and state machines are provided in code modules called libraries. These modules are common to each device, which reduces the total number of lines of code.

Ygor also has some standard daemons to support various functions. They are: (a) a message multiplexing daemon, (b) a logging program, which writes monitor data in FITS[8] format files, (c) a coordinated logger, which logs monitor data into FITS files during scans, and (d) a scan coordination daemon, which controls the start/stop timing of scans, selects which devices are to be controlled, and writes information about each device into a scan log, for use by AIPS++[9] data analysis processes. ††

2.1. Command and Control

The Control library defines a common interface for setup, synchronization, and access through the use of a generic finite state machine and a single mechanism for handling setup information. Device settings are represented as a set of inter-dependent parameters. The term "parameter" in this document is used in the context of a C++ object. Hence, a "parameter" is permitted to be anything from a simple data type, to a complex record structure. Parameters for a given device often have relationships, much like the cells of a spreadsheet. That is, a change in the value of a parameter may cause other *dependent* parameters to be changed, recalculated, or interpreted differently.

In order for a telescope to perform an observation, many systems must be controlled and *coordinated.* This coordination is done by a process called the ScanCoordinator, which resides at the very top of the control hierarchy. In order to minimize real-time dependencies, a three phased approach to scan control has been chosen.

When a scan has been specified (by setting parameters), a signal to all systems to report a start-time estimate is issued. When all systems have reported back, a second command *activate/arm* is issued, to command the systems to start at the agreed upon time. Once this is done, each device performs its function, relative to the start time. For the antenna, this means to follow a precise trajectory, for a backend, it means to start integration etc. Where high synchronization rates are needed (switching signals for example) hardware signals are used.

2.2. Message/Alarms

The Message library provides a common state-based exception reporting system, with message severity divided into two major categories and six error severity levels. The message categories are either state-based or transient. Message severity levels are info, notice, warning, error, fault and fatal. State based messages report only when the error state changes, thereby inhibiting a flood of repetitive messages to the operator's screen. Transient messages report on every occurrence, and are used only where the error condition is not expected to recover spontaneously. Two examples of these might be antenna in limit, (a state based condition), or lightning strike detected (transient).

**Who is Ygor? Ygor (pronounced ē-gor) was Dr Frankenstein's faithful servant. As a bit of trivia, I found that neither the original text by Shelly nor the first Frankenstein movies had an Ygor. The 1931 version of Frankenstein had a character named Fritz. The Ygor character first appeared in 1939, when Lugosi teamed with Karloff in Son of Frankenstein.

††AIPS++ is the primary data analysis system for the GBT.

All messages are sent to a message-multiplex, which logs the condition, and broadcasts the event to all active message viewers. Optionally, a script may be run when a message is received, to trigger a logging process, send email, or perform some other action.

Classification of the significance a condition is often difficult, but we have decided upon the following definitions:

- **Fatal** - The most severe error condition. A problem-causing event which the system took some action as a result of, or requires some action by telescope personnel, i.e., equipment or personnel are in danger; or an event from which the software cannot recover and must be restarted. Examples of a Fatal condition are: (a) an emergency stop was initiated; (b) a power supply has shut down; or (c) a limit condition has been reached.
- **Fault** - This level describes events which will cause the system to – at least in part – generate bad observational data or prevents the completion of actions. Example: The tracking LO has gotten out of sync with the sig/ref signal.
- **Error** - An event has occurred which requires a specific action by the operator. Example: A cryogenic compressor has failed and a spare should be connected.
- **Warning** - This level provides a description of an unexpected or possible problem-causing event, which requires more careful monitoring or investigation by the operator. Data integrity may be in question. Example: The receiver cryogenic temperatures have climbed beyond a specified threshold.
- **Notice** - The least significant "error" condition. This level indicates such conditions as illegal actions from users. Example: The user enters an illegal value for a control parameter.
- **Info** - Merely provides parenthetical text for indicating expected events or for debugging purposes.

2.3. Monitor and Logging

The Monitor library provides a common data transport and delivery mechanism for both on-demand and long term logging applications. Closest to the data source is the `Sampler`, which consumes data samples, time tags the data, and makes the data optionally available to the monitor system. These sampling points are analogous to hardware test points, and can be inserted in code for test and debugging or long term statistical analysis, as well as normal data recording. Using this system allows any sampling point to be selected as additional user data, archived as FITS formatted files.

Two data writing daemons perform this function. The first is called the Archivist, which communicates with the ScanCoordinator to record auxiliary data during each scan. The second daemon is called sampler2log, which simply logs the data for long-term analysis.

Each sampler maintains a ring buffer, so that for data not logged continuously, a history is maintained. Messages can trigger the monitor system into dumping this history buffer, so that data leading up to an event may be recorded for further analysis, without intervention from the operator.

2.4. User Interfaces

Graphical User Interface (GUI) development can be one of the most costly tasks on a project, especially when the user interface is specific to a piece of equipment. Often implementers blur the line between code specific to a single device, and code which is specific to the user interface itself. User interfaces are often difficult to implement because of differing and evolving requirements with respect to screen design and behavior.

The Ygor interfaces make the distinction between device, and GUI clear and consistent across all devices. Devices differ only by the parameter set which represents them. I would like to have included example operator and observer screens, however space limitations dictate their omission. Example screens are available on the Green Bank web site, at http://www.gb.nrao.edu/Ygor.

2.4.1. GBT Observe

GBT Observe[10] is a Glish-Tk[11] [‡‡] application, primarily for use by astronomers. It contains screens for common observing modes, as well as detailed device setup. A scripting mechanism is available for batch runs.

[‡‡] Glish is scripting language in use and supported by the AIPS++ project.

2.4.2. Control Library for Engineers and Operators

Control Library for Engineers and Operators (CLEO)[12] is a tcl/Tk based set of applications, which are designed to work with anywhere from a single piece of hardware, to the entire telescope itself. Some of the applications provide summary information and gross control for a large group of devices. Almost all interactive monitoring is displayed via CLEO screens. CLEO is written in tcl/Tk, and integrates with the Ygor system via an interpreter called Segeste.

2.4.3. Glish Scripting Language

Although not intended for inexperienced or casual users, Ygor provides an interface for using the Glish language directly. This has been extremely useful for device testing and integrating with AIPS++.

2.4.4. Perl Module

A Perl interface module is planned in the near future.

2.4.5. OVRO Java Displays

The Steve Scott demonstrated his novel Java-based monitoring windows at the 1998 SPIE conference.[13] Currently Ygor supports the use of this display system for monitoring any of the GBT systems.

3. ANTENNA CONTROL SYSTEM SOFTWARE ARCHITECTURE

*"Astronomy compels the soul to look upwards and leads us from this world to another."**

The GBT antenna control system is built using Ygor libraries, and therefore supports the control interface for command and coordination functions. Indicated position data and other metrics are recorded and logged via the Ygor monitoring interface. Alarms and messages are sent to the operator via the Ygor messaging system. The antenna control system is distributed, and is comprised of several parts: (a) Antenna coordinator; (b) Active surface servo; (c) Precision pointing; (d) Main axis servo monitor; (e) Antenna manager; (f) Main axis and secondary optics servos (supplied by contractor); Each system is described in more detail below.

3.1. Antenna Coordinator

The coordinating entity that negotiates scan start times for each of the antenna systems and performs parameter cross checks to verify inter-system parameter settings. The antenna coordinator can also act much like the ScanCoordinator, allowing the antenna to be run synchronously with other devices (the most common case) or asynchronously for maintenance purposes and testing.

This program executes on a Sun Ultra-sparc, located in the alidade room, running Solaris for an operating system. Typically, all user control interaction takes place with this module. It contains a superset of the control parameters available at the antenna manager, and includes parameters for the active surface, servo monitor and metrology pointing systems.

3.2. Active Surface Servo

The active surface servo system consists of 3 MV-167 single board computers which communicate with 7 intelligent input output processors to close 2209 servo loops. The surface actuator command positions are sent via a RPC protocol, from the antenna manager. The antenna manager also retrieves actuator position data and status information.

3.3. Precision Pointing System

The precision pointing system is currently still under development. Pointing synchronization data[14] is sent at a 2Hz rate, to convey the indicated axis position, and profile future demand positions. This allows the metrology systems to acquire retro-reflector targets, and perform measurement task scheduling, based on projected retro-reflector visibility criteria.

*Plato, *The Republic*

3.4. Main Axis Servo Monitor

The servo monitor system performs essential monitoring of the antenna health and performance parameters of the 24 main axes drive systems. Encoder outputs are continuously monitored for inconsistencies. Up to 192 analog inputs are available to monitor field and armature currents, tachometer feedback, rate commands, etc. Environmental conditions such as wind speed are continuously monitored. This system is able to trigger an automatic stow procedure, during periods of excessive wind, or loss of commercial power.

3.5. Antenna Manager

The antenna manager is responsible for the generation of real-time commands for the main axes, secondary optics, and active surface servo systems. High level commands are processed into periodic servo system commands, and instantaneous indicated positions are retrieved. Once a second, status information is retrieved, and the overall system status is analyzed. The program executes on a Motorola MV167 single board computer, using VxWorks as an operating system. System tasks are synchronized to an IRIG clock.

The main and secondary optics servos are updated at a 10Hz rate, with commands in the form of a position, with first and second derivatives. The servo systems operate at a 50Hz rate, and use the two derivatives to update the position and velocity loops between commands.

The antenna manager consists of 7 modules, and approximately 20 VxWorks tasks. The sections below summarize the operation of each antenna manager module.

3.5.1. Manager

The manager module provides a standard interface for Ygor user interfaces and control, performs input parameter checking, and implements a finite state machine, to track the various stages of an observation.

3.5.2. Executive

As the name suggests, the executive provides a real-time supervisory function for all axes. This module initiates new commands every 100ms from user input. The executive also communicates with the metrology systems to convey current encoder indicated position, static pointing offsets, and future demand positions.[14]

3.5.3. Primary Axes Control

The primary axes control module performs the coordinate transformations necessary to map user demand positions into an azimuth-elevation based system, using the Starlink SLALIB.[15] Refraction correction based on current weather data, pointing corrections, and local offsets, are handled by this module. The resulting commands are sent to the main axis servo computer.

3.5.4. Secondary Optics Control

The GBT can be used in either Gregorian or prime focus configurations. Prime focus mode offers three degrees of freedom, axial focusing, rotation, and translation.

Several control options are available in Gregorian optics mode. The subreflector can be controlled by specification of the individual actuator lengths, or by movement with respect to a locally defined XYZ system, or by specification of focal point offsets with respect to nominal values. When this mode is selected, the offsets are given as additional input into the Gregorian focus tracking module.

In both configurations, command processing is similar to that of the main axes. At 100 ms intervals, the trajectory specification is interpolated for the given instant in time. If focus tracking is enabled, then corrections for deflection of the vertical feedarm are calculated, using the currently indicated elevation.

If selected, apparent parallactic angle is maintained by rotation of the Gregorian feed rotator ring, or prime focus polarization mount.

3.5.5. Active Surface Control

Initially the GBT active surface will be used to reposition the surface based on a finite element model of the tipping structure. As elevation changes, the difference between the intended surface and the indicated surface is monitored. When a threshold is reached, the actuators are updated with a new position. This threshold is controlled by two factors: the highest observing frequency in use, and the requested surface tolerance, in wavelengths.

3.5.6. Position Monitor

The primary responsibility of the position monitor is to retrieve position data, transform portions of the data into a user reference system, and make the data available to the monitor system.

3.5.7. Status Processor

The status processor monitors the state of both the hardware and software of the main axis, secondary optics and active surface systems. Actions to disable an axis based on an error condition, and alarm messages originate in this module.

4. COMMAND PROCESSING

This section describes a portion of the internal operation of the Antenna Manager, with respect to command generation. Commands are generated at 100 millisecond intervals. Trajectory specification from an observer takes the form of a list of piecewise parabolic curves, each valid over a limited interval of time. These curved line segments are referred to as *scan segments*. Lists of scan segments are referred to as a *track* or *scan*. Algebraically a scan has the definition:

$$track(t) \equiv \sum_{i=1}^{n} f(s_i, \dot{s}_i, \ddot{s}_i, t) \Big|_{t=t_i}^{t=t_{(i+1)}} \tag{1}$$

where

$$f(s_i, \dot{s}_i, \ddot{s}_i, t) = \begin{cases} s_i + \dot{s}_i(t - t_i) + \ddot{s}_i \frac{(t-t_i)^2}{2}, & \text{if } t_i \le t < t_{(i+1)}; \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Scans are used to specify motions for each of the GBT axes. The primary axes also include an additional term $offset(t)$. In some circumstances, $track(t)$ may be approximately constant. For example, the user may be observing a quasar, which is essentially fixed to the celestial coordinate system (e.g., right ascension and declination of a mean catalog date). In other cases, the user may choose to map a source fixed to the celestial coordinates and thus $track(t)$ will substantially change in time. In both of these examples, $offset(t)$ is set to zero. An example of a constant offset might be when a user has $track(t)$ set to a cardinal position in some source (e.g., the center of a galaxy) and uses offset to measure an object displaced from the center. Moreover, there may be instances where it is desirable to have both $track$ and $offset$ be functions of time. Mapping the Moon is one example. The $track(t)$ coordinates would be set to the center of the Moon, which is not fixed to the celestial coordinates, while $offset(t)$ could be used to specify the mapping scans across the Moon relative to the center.

Using these facilities, arbitrary scan patterns may be realized. For example, performing a circular trajectory about a source, or complex Lissajous patterns are all possible. The astronomical conversions are achieved using the Starlink SLALIB library. Seven common coordinate systems are supported: right-ascension declination of J2000, B1950 or a user-specified epoch; Galactic; hour-angle declination; azimuth elevation, or cable wrap. A time varying user-defined transformation can also be specified with respect to any of the base coordinate systems.

5. POINTING

"The un-aimed arrow never misses."[†]

The ability for an instrument to track a specified object is what is usually referred as *pointing*. The angular position readout of the GBT encoders, however, does not reflect the actual direction of maximum gain of the primary reflector. This is due to many effects, such as structure deformations, encoder non-linearity and offset, axis collimation, track irregularities, foundation shift, etc. The drive systems attempt to position the antenna axes, based upon the encoder readouts, so *corrections* must be made to transform the ideal commands into the imperfect reference system of the encoders. This is the task often referred to as *pointing correction*.

[†]From the Maui Rules tee shirt.

The offset design of the GBT makes the pointing a particularly complex task. Pointing errors for offset design telescopes such as the GBT are larger due to (a) poorer dynamics from the large feed support structure; (b) a coupling of pointing variation with changes in focal length; and (c) a large deviation in feed arm position, due to gravitational forces.

5.1. Pointing errors

In general, pointing errors can be classified as being repeatable or non-repeatable. Repeatable errors are those which remain constant over a period of days, and may be functions of physical parameters, such as elevation angle. Non-repeatable errors are often due to parameters either too complex to model such as thermal variations, or other completely random processes such as wind forces.

The GBT pointing systems make a further distinction between *pointing errors* and *focus tracking errors*. In the GBT context, pointing errors are defined to be errors which effect the location of the prime-focal point, as imaged by the main reflector surface, while focus tracking errors are caused by the misalignment of the secondary optics foci, with the prime-focal point. Therefore, the pointing system is concerned solely with controlling the azimuth and elevation drives so that the desired refracted target is imaged onto the point of peak gain for the primary mirror.

Using these terms, variations in *pointing* are caused by az-el encoder offset and non-linearity, axis misalignment, track irregularities, main reflector surface shape etc., but not by feedarm sag due to gravity. It is interesting to note that although a single pointing equation can be used, two distinct focus tracking algorithms are required for Gregorian and prime-focus.[16]

5.2. Repeatable Pointing Error Correction

The most significant pointing errors are presumably due to structure deflections due to gravity, track irregularities, encoder offset, imperfections in axes alignment, bearing run-out and the like. These errors are typically repeatable, and can be modeled as a function of azimuth and elevation angle.

On the GBT, repeatable pointing errors are modeled using a two dimensional Fourier series. Condon[17] has shown that certain terms of the series correspond to the basic geometric defects of a telescope. Track irregularities can be modeled, by the higher order terms. An implementation of the algorithm by Wells[18] has been incorporated in the antenna control system.

Traditionally, pointing models have been determined solely from a statistical reduction of all sky pointing runs. Physical defects of the telescope can often be inferred from such pointing data. The GBT however, is outfitted with laser ranging units that can in many cases directly measure these defects. Work is already underway to determine initial values of some of the model coefficients through methods proposed by Balser, Goldman and Wells.[19]

5.3. Focus Tracking

As mentioned previously, focus tracking corrections are primarily concerned with maintaining the secondary optics foci, in alignment with point of peak gain. Most of the correction required is due to the (repeatable) deflection of the vertical feedarm, as a function of elevation. There is another variable however, which results from the primary reflector as it deforms homologously, changing the focal length of the primary reflector. These two effects must be properly coordinated. Don Wells has provided a complete analysis of the technical details of both the prime focus and Gregorian focus tracking algorithms in several technical reports.[20–22]

5.4. Refraction

As with any ground-based telescope, the GBT must deal with refractive effects of the earth's atmosphere. Two weather stations are used, one located to the North and the other to the Southwest of the antenna. Each station is mounted on a 45-meter tower, (approximately at the height of the main reflector) and carries instruments for measuring temperature, barometric pressure, and dew-point. A refraction model has been implemented, using techniques described by Maddalena.[23]

5.5. Local Pointing Offsets

Like many other telescopes, the GBT control system provides the ability for the user to define a set of local offsets, in azimuth and elevation. This could be used for example to zero out residual pointing errors based on observations of a nearby reference source.

5.6. Metrology Development and Integration

The metrology system development and integration will be accomplished in three phases as described by Hall.[24] In phase I ‡, telescope pointing corrections will be achieved using traditional methods, in the sense that repeatable errors are modeled mathematically, and corrections are derived from these models. The active surface will be shaped through the use of a finite element structural model, developed by Wells.[25] This is most commonly referred to as the "open loop active surface", where the antenna control system computes a displacement matrix for the best fitting paraboloid, relative to the (nearly) homologously deformed paraboloid. The active surface control system is periodically updated with a new matrix. The update rate is dependent upon the highest frequency in use, and the requested surface tolerance. Phase II will incorporate a second displacement matrix, for the active surface formed through the use of laser ranging measurements to further improve the surface figure. This phase will also improve subreflector positioning, since the feedarm location with respect to the prime focal point will be more precisely monitored. Phase III adds an additional dynamic correction loop for main axis pointing.

5.7. Dynamic Corrections

The second set of pointing errors are due to dynamic effects such as differential heating of the structure, static wind loading, and other random effects, and by definition are not repeatable. When observing at the higher frequencies, feedback from the metrology instruments will be used to refine the static model corrections. The techniques used to perform ranging measurements, reduce the data and provide updates to the static model is work in progress by the GBT metrology group, and would require a paper devoted to that subject alone. With apologies to the persons performing this work, I will attempt to summarize the process below, however, Goldman[26] and Wells[27] describe it more rigorously.

The main responsibility of the feedarm based range finders is to monitor the feedarm, and subreflector location with respect to the surface, and survey the 2209 surface retro-reflector targets. The ground range finders must work in concert with the feedarm units, to tie the measurements to a ground based reference system. Operation proceeds along the following lines: (a) the antenna manager broadcasts information about the current state of the antenna, including current and future demand position; (b) the range finder scheduler tabulates a series of measurements to be made with the consideration that coordination may be required between units, and targets may have visibility criteria; (c) the individual ranging requests are sent each range finder unit; (d) measurements are performed; (e) the measurements are incorporated into a regression model; (f) positioning errors are analyzed, and residual corrections are sent to the antenna manager.

6. IMPULSIVE TRAJECTORY FILTERING

"You cannot really appreciate Dilbert unless you've read it in the original Klingon."§

For mapping applications, the telescope must be driven at a rate several times the sidereal tracking rate, across the source, reversing direction as rapidly as possible, at the end of each raster. Beam switching applications require the telescope to move quickly from one position to another. Normally these motions would result in high values of error signal and impulsive application of acceleration forces. Resonant vibrations are excited by the rapid changes in acceleration forces rather than by the periods of constant acceleration. ¶ These vibrations would both interfere with tracking accuracy and cause lengthy settling times. A simulation of the dynamics of the GBT, which analyzed performance during a one-degree step, showed residual vibrations that were significant even after thirty seconds. Reacting to this result, Lacasse and Weadon asserted: *"..moving 16 million pounds of steel with a high degree of accuracy is going to take a bit more time than people are used to."*[28]

This prompted further investigations of how to reduce settling times, including the possible application of an active mass-driven damper,[29] alternate control algorithms,[30] and trajectory preprocessing.

Wells gives an account of the events which led to his investigations of preprocessors: "In response to [LW93[28]], Mellstrom [Mel93[31]] argued for use of trajectories generated by a preprocessor which will keep servo systems operating in their linear regime with reduced vibration levels, and he mentioned the preprocessor work by Tyler which appeared

‡I should note that for acceptance tests, the active surface actuators will not be used to correct the surface.

§Klingon Programming Proverb

¶This is best illustrated with using a crane model, fishing pole, etc. Sudden movements excite oscillations, but gentle, precisely timed motions do not.

in a report about a year later.[32] Simulations by Gawronski and Parvin showed that Tyler's technique which uses $sin^2 t$ profiles ... will achieve substantial reductions in the vibration induced by step motions."[33] Von Hoener suggested two additional profiles be considered for the GBT.[34,35]

This led to the decision to implement trajectory preprocessing in the GBT antenna control system. Don Wells has recently addressed these proposals and provided a general solution in GBT memo 203, along with implementations in C code of both the Tyler, and Von Hoener profiles. In addition, Wells proposed using a technique first described by Smith[36] called Posicast control. These algorithms have been incorporated into the GBT antenna control system.

Initially the GBT antenna control system will use acceleration profiles that are shaped in the form of $sin^2 t$. As we learn about the as-built structure through the measurement program,[4] historical analysis of laser metrology, and accelerometer data, Posicast techniques suggested by Smith will be applied to minimize or cancel modal vibrations.

It should be noted that although pre-processors can reduce the amplitude of servo induced vibration, however, as Smith states "Any transient which enters a resonant system and does not pass through an element like (1+P) [the Posicast control section] will excite oscillations. This is particularly true of load disturbances...".[36] Stated another way, trajectory preprocessing reduces the vibration input into the structure caused by control, but does little to reduce vibrations caused by wind forces and stiction/friction cycling.

Sidereal tracking in some regions of the sky requires slow speed tracking in azimuth will cause stiction/friction cycling. Some approaches to this problem have been discussed, including the addition of a high frequency dither signal into the servo amplifiers.[37] Cancellation of vibration excited by wind forces would likely require some type of active damping system. In order to make the best use of inclement weather conditions, dynamic scheduling concepts are being considered.

7. CURRENT STATUS

The GBT antenna control system is ready to begin commissioning. Basic traditional pointing (phase I) is implemented, with algorithms for both prime focus and Gregorian focus tracking. Motions of the GBT are performed with impulsive acceleration limiting and trajectory preprocessing.

8. CONCLUSION

It is hoped that many of the pointing coefficients will be determined directly through metrology, possibly even prior to first light. The proof of the GBT systems will of course be in stability and accuracy of the pointing with reference to the sky.

I have presented the status of the GBT antenna control system, and I am anxious to begin commissioning tests. It is hoped that the aggressive strategies being pursued by the measurement program and scientific staff will aid in exploiting the full capabilities of the GBT. The algorithms and strategies will certainly need modification and improvement as we learn more about the as-built structure. Perhaps by the next conference, I can report our actual successes and document any pitfalls.

9. ACKNOWLEDGEMENTS

I would like to thank: Don Wells for his work in pointing, active surface control, and focus tracking development; the GBT metrology group for the enabling technology of the laser range finder; Mark Clark for much of the Ygor architecture design; Ron Maddalena for the CLEO display system; and Rick Fisher for the GBT Observe user-interface. Others significant contributors and advisors include: Dana Balser, Ramon Creager, John Ford, M. Goldman, Arno Granados, Bob Hall, Dave Hogg, Gareth Hunt, Rich Lacasse, Mark McKinnon, Roger Norrod, Dave Parker, Amy Shelton, and Tim Weadon.

REFERENCES

1. R. Norrod, *GBT Surface Accuracy*, Technical Report 119, GBT Memo Series, NRAO, 1995.
2. R. Lacasse, *The Green Bank Telescope Active Surface System*, Technical Report 184, GBT Memo Series, NRAO, 1998.
3. D. Steward, *A platform with six degrees of freedom.*, Proc. Inst. Mech. Engrs., Part I, 180(15):371-386, 1965-66.
4. B. Hall, *Measurement Program for the Green Bank Telescope*, Technical Report 191, GBT Memo Series, NRAO, 1998.
5. D. Parker, *The Green Bank Telescope Laser Metrology R&D Project*, Technical Report 166, GBT Memo Series, NRAO, 1997.
6. M. Clark, *The Control Software Architecture for the Green Bank Telescope*, Technical Report 180, GBT Memo Series, NRAO Green Bank, 1998.
7. R. Fisher, *Object Oriented Experiences with GBT Monitor and Conrol*, Astronomical Data Analysis Software and Systems VII, A.S.P. Conf. Ser., 1997.
8. W. Cotton, D. Tody, and W. Pence, *Binary Table Extension to FITS*, Astronomy and Astrophysics Supplement Series 113, pp. 159-166, October 1995.
9. *AIPS++ Project Website*, http://aips2.nrao.edu/.
10. R. Fisher, *GBT Observe Prototype*, http://www.gb.nrao.edu/ rfisher/Glish/gbt_gui_proto.html, 2000.
11. D. Schiebel and V. Paxson, *The Glish 2.6 User Manual*, National Radio Astronomy Observatory, June 1996.
12. R. Maddalena, *Control Library for Engineers and Operators*, http://www.gb.nrao.edu/ rmaddale/GBT/CLEOManual/index.html, 2000.
13. S. Scott, *Remove Observing with the Caltech Millimeter Wave Array*, Telescope Control Systems III, SPIE Conf., pp.118-126, Owens Valley Radio Observatory, 1998.
14. J. Brandt, *A Protocol for Pointing Synchronization Messages*, Technical Report 197, GBT Memo Series, NRAO, 1999.
15. P. T. Wallace, *SLALIB – Positional Astronomy Library*, Tech Rep. Starlink User Note 67.34, CCLRC Rutherford Appleton Laboratory, February 1996.
16. D. Hogg and R. Fisher, *A Revised Description of the Green Bank Telescope Pointing System*, Technical Report 122, GBT Memo Series, NRAO, 1995.
17. J. Condon, *GBT Pointing Equations*, Technical Report 75, GBT Memo Series, NRAO, 1992.
18. D. Wells, *The Condon Series Pointing Model in C*, Technical Report 173, GBT Memo Series, NRAO, 1998.
19. M. Goldman, D. Balser, and D. Wells, *GBT Pointing Coefficient Estimates for Phase I From Metrology Instruments*, Technical Report 195, GBT Memo Series, NRAO, 1999.
20. D. Wells, *GBT Gregorian Focus Tracking in C*, Technical Report 183, GBT Memo Series, NRAO, 1998.
21. D. Wells, *Imaging Properties of the GBT Subreflector in C*, Technical Report 179, GBT Memo Series, NRAO, 1998.
22. D. Wells, *The "Ray" Ray Tracing Package*, Technical Report 178, GBT Memo Series, NRAO, 1998.
23. R. Maddalina, *Refraction, Weather Station Components, and Other Details for Pointing the GBT*, Technical Report 112, GBT Memo Series, NRAO, 1994.
24. B. Hall, *GBT Phases*, Technical Report 113, GBT Memo Series, NRAO, 1994.
25. D. Wells and L. King, *GBT Best-Fitting Parabolid in C*, Technical Report 131b, GBT Memo Series, NRAO, 1995.
26. M. A. Goldman, *Dynamical Rangefinder Measurements*, Technical Report 188, GBT Memo Series, NRAO, 1998.
27. D. Wells, *Fitting Models to Simulated Rangefinder Data*, Technical Report 196, GBT Memo Series, NRAO, 1999.
28. R. Lacasse and T. Weadon, *GBT Dynamics*, Technical Report 104, GBT Memo Series, NRAO, 1993.
29. J. Payne and D. Emerson, *Active Damping for the GBT Arm*, Technical Report 133, GBT Memo Series, NRAO, 1995.
30. W. Gawronski and B. Parvin, *Simulations of the GBT Antenna with LQG Controller*, Technical Report 136, GBT Memo Series, NRAO, 1995.
31. J. Mellstrom, *Comments on Lacasse Memorandum*, JPL interoffice memorandum 3324-93-040, April 1993.

32. S. Tyler, *A Trajectory Preprocessor for Antenna Pointing*, TDA Progress Report 42-118, JPL Ground Antennas and Facilities Engineering Section, 1994.
33. D. Wells, *Jerk-Minimizing Trajectory Generator in C*, Technical Report 203, GBT Memo Series, NRAO, 1999.
34. S. von Hoerner, *Fast Pointing Change and Small Oscillation*, Technical Report 132, GBT Memo Series, NRAO, 1995.
35. S. von Hoerner, *Preventing Oscillations of Large Radio Telescopes After a Fast Stop*, Technical Report 152, GBT Memo Series, NRAO, 1996.
36. O. J. M. Smith, *Feedback Control Systems*, McGraw-Hill,pp.331-346, N.Y., 1958.
37. O. J. M. Smith, *Feedback Control Systems*, McGraw-Hill,pp.481-483, N.Y., 1958.

¶GBT technical reports may be accessed via the web at http://www.gb.nrao.edu/