Precision Telescope Control System

PTCS/SN/1: Overview of the PTCS Project

Version:	3
Date:	2003 March 31
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Archive:	PR003
File:	PROJECTS
Keys:	PTCS, antenna, precision pointing, management

Revision History

Ver.	Changes	Date	Author
1	Initial Version	5th March 2003	Richard Prestage
2	Major overhaul	26th March 2003	Richard Prestage
3	Add sections 8,9,10; other minor mods	2003 March 31	Richard Prestage

Contents

Abstract

This document provides an introduction to the GBT Precision Telescope Control System Project, for the Conceptual Design Review Meeting to be held on 8/9th April 2003.

1. Introduction

A major design goal of the Green Bank Telescope (GBT) is the ability to work effectively at frequencies up to the atmospheric cutoff at $\nu \approx$ 115GHz (wavelengths as short as $\lambda \approx$ 3mm). Currently, using largely conventional techniques, the high frequency limit of the GBT is $\approx$ 40GHz; the goal of the GBT Precision Telescope Control System (PTCS) Project is to bridge the gap between the current and target performance, with a delivery timescale of approximately two years.

Although 3mm operation has been a design goal since the inception of the telescope, forward progress had become unacceptably slow in the last two years. In November 2002, after a review of GBT priorities, the PTCS Project Team was reconstituted and significantly strengthened. Although considerable technical and scientific progress has already been made — extending the operating range of the telescope from 15 to 40GHz — it is clear that significant work remains to be done. In addition, although some parts of the project are essentially complete, others lag far behind; in particular an overall architecture for tying the component parts together has not been well articulated.

Work since November 2002 has concentrated on developing a conceptual design for the complete system, as well as outlining a specific development strategy which we believe will allow us to meet our goals. These designs and approaches are now sufficiently well developed that a review of the project as a whole is warranted. The fact that we consider this a Conceptual Design Review reflects the early stage in the project for this newly reconstituted team and approach.

The intent of the remainder of this document is to provide a high level overview of the major components of the PTCS project. The majority of this information is expanded in considerably more detail in a series of PTCS System Notes, as summarized in Appendix A.

2. What is the PTCS?

The optical properties of the GBT depend upon the shapes, orientations and locations of its optical elements. The optical and structural design was carefully selected in order to achieve certain scientific (observational) objectives, but this design acknowledged the influence of a variety of repeatable and non-repeatable factors that would degrade performance over the desired operating regime:

- The effect of temperature change over time and location in the structure is to distort the optical alignment. Although the structure was designed to minimize these effects, they can still be substantial. While temperature effects are repeatable, the state of the structure (distribution of temperatures, whether the structure is in thermodynamic equilibrium) is not well known.

- Wind loading can cause structural loads that significantly distort the telescope (i.e. cause the optical properties to change). Again, the effects are repeatable, but the flow field will not be well known.
- Structural vibrations can be excited by wind or servo system drives. These vibrations can be significant, and have modal frequencies from 0.6Hz and up. The largest magnitude motions are in the feedarm assembly.
- Changing gravitational distortions are the most well behaved, as they depend only on the GBT elevation angle. The structure was designed so as to minimize the effect where possible, and the distortions have been modeled to some level of accuracy.

The design of the GBT was intended to ensure that the gross effects of the above would be mitigated well enough to give acceptable performance up to 15GHz without any additional compensation. We must then use active control to correct for the residual effects, and this is the role of the Precision Telescope Control System. Specifically, the PTCS consists of:

- an extensive metrology system, including laser rangefinders, accelerometers and other devices;
- servo systems that can control the shape (i.e. the 2004 panels of the primary mirror) or position and orientation (i.e. the six-degrees of freedom mount for the subreflector) of the GBT optical elements; and
- a control system which can harness these measurement and control capabilities to deliver a wide variety of observing modes with the precision necessary to allow 3mm operation.

The mission of the PTCS project team is to complete the design of the overall control system, and integrate these three components into a coherent whole, which can be used easily and effectively to enable the GBT to perform science at millimeter wavelengths.

3. The Challenges and Advantages of the GBT

The key features of the GBT relevant to the PTCS are described in detail in PTCS/SN/2. The scientific requirements for high-frequency operation are described in PTCS/SN/3, and the current performance in PTCS/SN/4. In this section, we briefly review some of the key challenges that the PTCS will have to overcome, as well as some features of the GBT which work in our favor.

In brief, the GBT is 100m diameter general purpose radio telescope designed to operate at frequencies spanning the whole range accessible through the atmosphere at Green Bank. The GBT has a completely unblocked aperture, which increases the effective collecting area and reduces system noise, standing waves and side-lobe levels. Since the subreflector, feeds and receivers do not block the beam, the GBT receiver cabin is large enough to hold a range of receivers, and can therefore switch to millimeter operation whenever conditions warrant. Thus the GBT is potentially the world's largest and most sensitive millimeter wave telescope.

The two key performance goals the PTCS must deliver are excellent pointing accuracy and minimal rss surface errors. Pointing requirements include a two-dimensional blind pointing error of 3 arcsec, and a tracking error of ≤ 1.5 arcsec. The performance specification for the "raw" telesope (without PTCS control) required non-repeatable pointing errors of less than 7 arcsec without wind and thermal effects; 14 arcsec when wind effects are included. An analysis of the anticipated sources of error (Loral Technical Memo 52) suggested that the design should meet these requirements under almost all normal operating conditions. The current performance of the GBT without the PTCS achieves rms two-dimensional pointing residuals from all sky pointing runs of around 10 arcsec, rms offset pointing errors of around 3 arcsec, and one-dimensional tracking errors of ≤ 2 arcsec under benign conditions. Thus, to meet the most stringent requirements for 3mm operation, we will have to improve the GBT pointing/tracking performance by around a factor of 2-3.

Surface accuracy requirements are similarly challenging. The current GBT performance suggests a total effective rss surface error of around 0.47mm (this is with the active surface working in open-loop mode). The surface error budget is presented in Norrod (1995) - the total contribution allocated to the primary surface is 150 μm for high-frequency operation. Thus again we need to improve our ability to measure and set the active surface panels by a factor of 2-3.

The large size of the GBT does have some advantages, as pointed out in PTCS/SN/2. For example, its exceptional sensitivity means that there will be literally thousands of sources which may be used for offset pointing. The sensitivity and low natural sidelobe level of the GBT should allow us to use out-of-focus beam map and traditional holography techniques to improve the current surface accuracy even in advance of delivery of the complete PTCS.

4. The PTCS and the "High Frequency Observing System"

As noted, the goal of the PTCS Project is to enable effective operation of the antenna at wavelengths down to 3mm. However, the PTCS will not be successful unless this capability can easily be harnessed by observers as part of an integrated observing system. The core PTCS will measure and control the positions of the GBT optical elements well enough to allow 3mm operation; the "High Frequency Observing System" (HFOS) will provide the additional new capabilities of the overal observing system needed to harness that performance. This includes for example the ability to measure and potentially correct for anomalous atmospheric refraction, improved mapping and other observing strategies, dynamic scheduling tools and so on. The HFOS is described in more detail in PTCS/SN/5, including specifically a proposed division of responsibilities between the PTCS team and other NRAO groups.

5. PTCS System Design

The current PTCS design contains two major new components, the Precision Measurement System (PMS) and the Precision Control System (PCS). The PMS harnesses the current (and future) metrology systems of the GBT: it takes a variety of measurements, often sampled irregularly in time and on widely varying timescales, and synthesizes these into a regularly sampled, uniform stream of data which can specifically be used by the PCS for control purposes.

The PCS takes as input a specification for an observing strategy (e.g. have the primary adopt the best fit parabola as a function of elevation), a specific set of position demands provided by the higher level observing system, and the data provided by the PMS to perform the precision control of the various GBT servo systems. This includes an integrated control strategy across all optical elements, so that for example small motions of the subreflector may be used to correct for residual pointing errors not compensated for by the main drives.

The conceptual PTCS System Design is presented in PTCS/SN/6. In order to examine the flexibility and completeness of the PCS, we have started to develop a series of observing scenarios against which to test the PCS behavior, and these are discussed in PTCS/SN/7.

6. The Engineering Measurement System and the Laser Rangefinders

Another key part of the PTCS is the Engineering Measurement System (EMS). This is a tool to allow us to make use of the metrology systems independently of the PMS and normal astronomical observations. It will be available as a GBT surveying tool, allowing us to measure critical dimensions and characterize the antenna with considerably higher accuracy and convenience than is possible with conventional surveying techniques. The EMS will also form an algorithm test bed for the PMS; it will be implemented in a signal flow graph/graphical programming environment to allow rapid prototyping, and easy reconfiguration to perform different experiments. More details of the EMS will be presented at the review meeting.

The laser rangefinders (LRFs) are a key component of the metrology systems, and the EMS is specifically design to allow simple and straighforward LRF data reduction and analysis. This will allow us to perform both in-situ calibration and characterization of the LRFs themselves, and refine our plans for their best operation and deployment. A complete description of the laser rangefinders, and a detailed analysis of their current and predicted performance will be presented at the review.

7. Additional Antenna Instrumentation

As noted, the LRFs are the largest single component of the metrology program. Other important devices are available and in use however, including the so-called “quadrant detector”, which measures the position of the tip of the feed arm with respect to the elevation axle, and accelerometers which have been used for a variety of investigations. We believe it critical that we continue to develop this ancillary instrumentation, and in particular have identified the immediate need to equip the antenna structure with temperature sensors in a variety of locations. Further details will be provided at the review.

8. PTCS Development Strategy

The PTCS development strategy will: pursue a plan of improving our quantitative understanding of the limiting factors for high frequency observation and developing the ability to predict and control the degradations; implementing short term improvements on the basis of this understanding; elaborating the initial system designs and simulating these designs until sufficient confidence is achieved that the design will have the desired properties; and then implementation and test of the new measurement and control systems. We anticipate that the PTCS will undergo modifications and improvements throughout the GBT lifecycle — the PTCS architecture is designed in such a way as to provide flexibility without undue complexity. We believe that this approach gives us the best mix of risk mitigation and early capability, and uses minimum resources.

In order to refine our understanding of the telescope we plan on enhancing our ability to measure relevant structural and servomechanism quantities, primarily structural temperature, gravitational distortion and azimuth and elevation servo performance, and use this information, along with astronomical inferences, to test our ability to predict telescope pointing. We will also attempt to improve telescope efficiency via methods such as out-of-focus beam maps and a Finite Elemement Model (FEM) based parametric panel adjustment, that may provide better adjustment of the primary mirror.

As this experimentation proceeds we will use our increased ability to predict pointing and surface degradations to make short term improvements to telescope performance. For example, we believe that we will be able to deduce refinements to the existing Finite Element Model and develop models of thermal effects on pointing, and then implement enhanced focus tracking and pointing algorithms that will result in substantial improvement to the telescope's astronomical performance.

In parallel with the experimental effort we will develop the Engineering Measurement System described in Section 6. This will allow us to assess and improve rangefinder performance, develop algorithms that measure telescope parameters, and use these algorithms to further characterize telescope alignment and pointing. These further characterizations will be used to develop predictive models of the telescope that are driven by structural temperature, wind and so on.

At this point we will be able to design and simulate the performance of tipping structure rangefinder measurements of the optical alignment, and initiate the installation of the additional rangefinders. We will also have enough design information to begin the elaboration and simulation of our control design (PCS) and the associated measurement system (PMS).

In parallel with this effort a software development will begin implementation and test of the PTCS architecture using our high level system designs. As the simulation of PCS and EMS proceed and we develop confidence in our design, PCS and PMS modules will be implemented in an incremental fashion that provides the earliest and best performance improvements. Modules that have marginal effect will be implemented further into the development cycle.

9. Critical Experiments

As noted in Section 3, the GBT is already a high-precision radio telescope by conventional standards, but to achieve full 3mm operation, the residual errors must be reduced by a factor of three. The errors have multiple causes, some of which depend on variable environmental conditions. The PTCS team will have to make both engineering and astronomical measurements of the GBT to identify, understand, 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 procedures will be needed to make them quickly and efficiently.

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 a network 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 estimate (using the GBT finite-element model) and remove the largest thermal distortions, (2) to improve our measurement of and compensation for the effects of gravity on focus tracking at all elevations, and (3) to determine and remove the repeatable component of the residual 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 (up to 6cm), 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 mapped 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 errors 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 may be able to use both Galactic water masers at $\nu \approx 22$ GHz and extragalactic continuum sources over a wide range of frequencies. 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 will be GBT pointing errors, not noise, so we will have to make frequent pointing corrections.

The laser rangefinder (LRF) system is potentially the most powerful tool for GBT metrology, but it is still in the engineering development stage. It will first be used off-line to make engineering measurements of GBT dimensions on both large and small scales (e.g., for "polishing" the primary surface). Ultimately, it might be used during astronomical observations to make nearly real-time measurements and corrections. Several experiments are needed soon to better characterize the LRF system. The zero-point offsets associated with each LRF must be measured both "in the lab" and via range closure tests. Two-dimensional closure measurements have already been made over paths between piers on the ground. Measurements of slant paths are needed to check the ability of the LRFs to hit target retroreflectors on the GBT and to estimate the importance of systematic range errors caused by atmospheric refraction.

Further details of the PTCS experimentation program will be provided at the review.

10. Project Plan

The PTCS Project as currently conceived received a major boost in priority and resources following the GBT Review held in November 2002. We currently have $\approx$ 6.5 ftes of staff effort available to the project, and hope that this will increase to $\approx$ 7 ftes in the coming months.

For a number of years, the GBT has been advertising that full 3mm operation would be available approximately two years after the start of astronomical commissioning. However, that estimate was not based on any systematic work breakdown or other technique for estimating effort and timescales. We are currently aiming for a target of initial 3mm operation during the winter of 2004/05 (i.e. two years from project reorganization), but that timescale must be considered extremely tentative at this stage. Note that both the Penn Array Receiver (3mm bolometer camera) and our in-house 3mm receiver project are both also working to this deadline. In order to ensure that we remain on schedule, we have developed a series of intermediate project milestones. These include:

Q3, 2003 Ready for 50GHz (Q-band) observing; formal progress review.

Q1, 2004 Demonstrated feasibility of 100GHz (W-band) operation through critical experiments; formal progress review.

Q3, 2004 Ready for prototype 3mm observing.

Q1, 2005 Initial PTCS development complete.

Q3, 2005 PTCS development as separate project complete.

Further details on the PTCS Project Plan, including perceived risk and risk mitigation strategies, are presented in PTCS/SN/11.

11. Summary

The GBT project has planned for 3mm operation since the inception of the telescope. A considerable amount of work, not even touched upon here, has been performed by many NRAO staff, both current PTCS project team members and our predecessors, to enable the GBT to achieve 40GHz operation. The mission of the current PTCS project team is to build upon the existing work, complete the areas which have been less well developed, and integrate existing and new components into a unified system to allow astronomers to perform outstanding science with the GBT at millimeter wavelengths. This is a challenging, but we believe achievable goal.

12. List of Acronyms

EMS Engineering Measurement System

HFOS High Frequency Observing System

LRF Laser Rangefinder

PCS Precision Control System

PMS Precision Measurement System

PTCS Precision Telescope Control System

A. Additional Conceptual Design Review Documentation

The contents of the various PTCS System Notes are briefly summarized as follows. In addition to these documents, an Annotated Bibliography and Glossary will be available from the PTCS web site (www.gb.nrao.edu/ptcs).

Completed Documents:

PTCS/SN/1 "Overview of the PTCS Project". This document.

PTCS/SN/2 "Overview of the GBT". A brief review of the major properties of the GBT, with an emphasis on those most relevant to high frequency operation.

PTCS/SN/3 "Scientific Requirements for the PTCS Project". An explicit statement of the requirements. Includes both fundamental scientific requirements, and resulting system requirements for the various componenents.

PTCS/SN/4 "Current GBT Performance". A brief review of the current performance of the GBT.

PTCS/SN/5 "Overview of the High Frequency Observing System". A general description of the current GBT Observing System, but which specifically includes the relationship of the PTCS to the remainder of the system, and other aspects not covered by the core PTCS but which will be required for 3mm operation.

PTCS/SN/6 "PTCS System Design". A more detailed description of the conceptual design of the PTCS, with particular emphasis on the Precision Control System.

PTCS/SN/7 "PTCS Observing Scenarios". Descriptions of a variety of potential observing modes designed to probe the completeness and flexibility of the PTCS design.

In preparation:

PTCS/SN/8 "The Laser Rangefinders". A description of the current and predicted future performance of the Laser Rangefinders.

PTCS/SN/9 "Critical Experiments". Presents the key experiments which will need to be performed over the course of the PTCS project both to make short-term performance improvements and to demonstrate the feasibility of achieving routine 3mm operation.

PTCS/SN/10 "Antenna Instrumentation". A description of additional instrumentation which will be required to complete the measurement and characterization of the antenna structure.

PTCS/SN/11 "PTCS Project Plan". Includes a discussion of resources, schedule, costs and risk mitigation.