A Short Guide to Current and Future High-Frequency Capabilities of the GBT

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1. Introduction

This document is intended to familiarize the participants of the GBT High Frequency Workshop with the current performance and capabilities of the GBT, and the planned capabilities for high frequency observing in the future. For the purposes of this document, "high frequency" will be defined as $\sim$ 20 GHz up to the 115 GHz CO transition; this scientific target, as well as the 118.75 GHz O_2 line make this a natural cutoff. Presently one receiver is in routine use for science in this range (K-band: 18 – 26 GHz). The Q-band receiver (40 – 50 GHz) is built and ready for final commissioning in Fall 2003. Efficient GBT observing can currently be achieved at K-band and, to a lesser extent, Q-band. To meet the scientific requirements for higher frequency observing will require innovative engineering techniques. The program to achieve effective 3mm operation of the antenna is referred to as the Precision Telescope Control System (PTCS) Project.

An overview of the requirements and goals for 3mm operation of the GBT is presented in § 2; this section includes a description of the PTCS project and pointers to extensive additional reference material. § 3 summarizes telescope performance. § 4 describes current high frequency instrumentation, including those instruments which are under active development. A brief list of instrumentation under consideration is provided in § 5. More information on the GBT and its current instrumentation can be found at

`http://www.nrao.edu//GBT/proposals/short_guide.shtml`

2. Operation of the Antenna at 3mm

A major design goal of the Green Bank Telescope (GBT) is the ability to work effectively at frequencies up to $\nu \simeq$ 115 GHz (wavelengths as short as $\lambda \simeq$ 2.7 mm). Currently, using largely conventional techniques, the high frequency limit of the GBT is $\simeq$ 40 GHz. The Precision Telescope Control System (PTCS) project aims to bridge the gap between the current and target performance, with a delivery timescale for prototype 3mm operation by Winter 2004/05. This entails a factor of $\sim 2\frac{1}{2}$ improvement in the two prime figures of merit for the physical antenna: pointing accuracy and RMS surface accuracy. These are discussed below. The PTCS project is the key component of a more broadly-scoped initiative known as the "High Frequency Observing System" (HFOS). HFOS will implement ancillary operational infrastructure necessary to fully harness the GBT as a millimeter wave instrument (*e.g.*, realtime site monitoring, dynamic scheduling, improved antenna control strategies, *etc.*).

The PTCS Project underwent a major reorganization in November 2002, followed by a Conceptual Design Review in April 2003. Information on the current status of the project, and the Conceptual Design Review material, are available from the PTCS web pages at:

`http://www.gb.nrao.edu/ptcs`.

The review material contains extensive details about the current GBT performance, the required performance for 3mm operation, and the strategy we will use to achieve this. The major components of the PTCS are summarized in PTCS System Note 1 "Overview of the PTCS Project", while the key features of the GBT for high-frequency operation are summarized in PTCS System Note 2 "Overview of the GBT". In July 2003 the PTCS project achieved a major milestone by outfitting the antenna with a network of temperature sensors. These instruments are operational, and will be used to refine our understanding of the structure's behavior (in particular, the dependence of pointing and focus on the structure's thermal state).

The science requirements of the PTCS have been established by Jim Condon (PTCS System Note 4). The PTCS aims to have full Q-band (52 GHz) capability by Winter of 03/04; this implies a two-dimensional rms tracking error of $2''.8$ and a surface RMS of $360\,\mu$m. Prototype 3mm capability is scheduled for winter 04/05, with full 3mm operation by late fall 2005. Ultimately the PTCS aims to deliver a $1''.3$ rms tracking error and a $210\,\mu$m surface RMS. The "blind pointing" target for 3mm operations is somewhat looser ($\sim 3''$) and periodic pointing references are likely to be needed. The $210\,\mu$m RMS goal corresponds to surface efficiencies of 93%, 53%, and 36% at frequencies of 30 GHz, 90 GHz, and 115 GHz. These efficiencies imply gains from $\sim 2\,$K/Jy at 30 GHz to $0.72\,$K/Jy at the upper frequency limit. These goals, and the current status, are summarized in Table 1 at the end of § 3. A brief summary of the relation between surface efficiency, the RMS surface error, and aperture efficiency is given in Appendix B.

Preliminary analysis of Green Bank site data indicates that roughly 50% of the time from October through March is suitable for 3mm observations ($\tau_{3mm} < 0.12$), however this is based on one years' data which may not be typical. It is likely that the PTCS will only be able to effectively deliver a 3mm capability under fairly benign environmental conditions also (*e.g.*, winds of less than 5 to 10 mph), and these constraints also need to be factored in to establish a realistic expectation. Further evaluation of the environmental envelope for 3mm GBT operations will be undertaken in the near future. Further characterization of the Green Bank site falls into the scope of the High Frequency Observing System effort rather than the PTCS as such. In any case we believe that the GBT's sensitivity will be sufficient to deliver world-class science even if only a small fraction of the year is suitable for observations in the 3mm band.

3. Current Telescope Performance

Commissioning of the K-band system is essentially complete; several K-band science projects were observed and completed in the winter and spring of 2003. Our discussion of current performance thus relates only to observations at K-band or lower frequencies. Preliminary engineering measurements with the Q-band receiver were made in the early 2003; these measurements indicated an aperture efficiency of $\eta_A \sim 35\%$ at 43 GHz. Astronomical commissioning of the Q-band system begins during Fall 2003.

The telescope pointing can be broken down into blind pointing accuracy, offset pointing accuracy, and tracking accuracy. The blind pointing accuracy measures the pointing precision after a substantial slew, and is important to allow easy acquisition of a pointing calibrator; offset pointing accuracy measures the precision after a local pointing correction has been applied by observing a nearby pointing calibration source; and the tracking error measures how accurately a given source can be tracked. The latter two are most crucial for GBT high frequency operations. The GBT's blind pointing accuracy has been measured to be $\sim 10''$ RMS (see Figure 1). The offset pointing accuracy has been measured at $3.2''$RMS, after the removal of some systematic residual effects which we believe are due to correctable inadequacies in our current pointing and focus tracking models (Fig. 2). A recent experiment to measure pointing accuracy while tracking a source indicated a one-dimensional RMS tracking error of $\sim 1''$-2 $''$. While improvements are needed, these are impressive results for a 100-meter telescope.

When observing at 20 GHz or above, it is currently necessary to focus the telescope every hour or so or when slewing to a new position in the sky. Focus corrections can be as large as 20 mm (appoximately 25% in gain at 20GHz). Work is underway to improve both the pointing and focus-tracking performance of the GBT. The PTCS temperature sensor network is a cornerstone of these efforts.

Figure 3 shows a measurement of aperture efficiency at 20 GHz measured as a function of elevation. The active surface was turned on to correct for gravitational flexure as predicted by the Finite Element Model (FEM), and the measurement was repeated. Near the rigging angle ($\sim 50^\circ$) the efficiencies are identical, as expected. With the active surface on, efficiencies are near $\sim 60\%$ between elevations of 15° and 80°. Turning the active surface on also reduces sidelobes to a nearly negligible level. By way of comparison the GBT aperture efficiency at long wavelengths is $\eta_A \simeq 0.70$, consistent with the expectation from the standard illumination taper; a panel RMS of $\epsilon \sim 470\,\mu$m is suggested by the comparison. Again, improvements are needed for mm operations, but the early results are encouraging. Improvement in the focus tracking model, and adjustments on the basis of "out-of-focus" and traditional holography, may yield modest improvements in aperture efficiencies. The mechanism for achieving further improvements after this is currently perhaps the least well defined aspect of the PTCS Project.

In the best weather conditions, system temperature at K-band has been measured as low as 35 K. The current sensitivity is 1 Jy $\simeq$ 1.6 K at 20 GHz, and this value is expected to improve by another $\sim$ 15% following full implementation of the PTCS. A typical sensitivity achieved in K-band spectral line observations during Spring 2003 was 4 mJy per 24 kHz channel over a 30 minute integration.

In summary, the current performance of the GBT with offset pointing, occasional focus corrections, and active surface corrections made according to the Finite Element Model predictions make the system usable up to frequencies of ~ 43 GHz. The PTCS project is currently working to correct the structure for temperature-dependent deformities to achieve effective Q-band operation up to 50GHz. Experiments over Winter 2003/4 will demonstrate the current potential of the GBT to achieve 3 mm operation under the most ideal conditions, and will provide data to allow us to decide upon the most effective strategy to both improve this performance, and extend it to a wider range of environmental conditions, with the goal of prototype 3mm operation by Winter 2004/05.

Figure of Merit	Current	PTCS Target
Panel RMS	$\sim 470\,\mu$m	$210\,\mu$m
Blind Pointing	$10''$	$3''$
Referenced Pointing	$3''.2$	$1''.3$
Tracking	$\sim 2''$	$1''.3$

Table 1: Current antenna characteristics, and the required values for 3mm operations.

4. High Frequency Instrumentation

Table 2 summarizes current and planned GBT high frequency capabilities. Further discussion is in the subsections below.

4.1. Backends

The backends currently available and under development are discussed in detail in Appendix A; here we only summarize. The two workhorse backends are the Digital Continuum Receiver (DCR) and the Spectrometer. The DCR accepts up to 16 input channels with IF bandwidths of up to 3 GHz each; the Spectrometer accepts up to 8 inputs of 4 GHz IF bandwidth each. They both support electronic switching at rates of up to about 20 Hz. The switching cycles are highly configurable and allow injection of noisecals, as well as electronic beam switching to suppress the effect of relative gain fluctuations in the electronics. The maximum resolution available with the spectrometer is 48 Hz in a 12.5 MHz mode with 256k total channels. In addition a fast-switching continuum backend (the Caltech Continuum Backend) is being constructed for the Ka and W band receivers. The Caltech backend will make optimal use of the pseudo-correlation receiver architectures to achieve a noise level close to the theoretical minimum implied by the radiometer equation. A wideband spectrometer is under consideration; this is discussed in § 5. It would be intended for use with the Ka and W band receivers.

Receiver	T_{sys}	Receiver Band	$\Delta\nu_{IF}$	Continuum Sensitivity $[\mu Jy\sqrt{sec}]$	N_{feed}	status
K-band	$40\,K$	18 - 26 GHz	4 GHz	380	4	commissioned Q1 2001
Ka-band	$45\,K$	26 - 40 GHz	4 [14] GHz	200	2	commissioning Q1 2004
Q-band	$50\,K$	40 - 52 GHz	4 GHz	530	4	Astronomy Q1 2004
W-band(1)	$85\,K$	68 - 92 GHz	4 [24] GHz	510	2	commissioning Q1 2005
W-band(2)	$100\,K$	90 - 115 GHz	4 [25] GHz	$2,100$	1	planned
Penn Array	N/A	86 - 94 GHz	N/A	350	64	commissioning Q1 2005

NOTES:

- T_{sys} estimated under good weather conditions at zenith.
- $\Delta\nu_{IF}$ values in brackets indicate bandwidth instantaneously available for spectrometry.
- A filterwheel upgrade to the Penn Array is possible to allow greater sensitivity under benign conditions.
- Continuum sensitivities computed over full available continuum band, with both polarization, but assuming one feed.
- Continuum sensitivity for K, Q, and W2 will be worse due to $1/f$ receiver gain flucutations.
- Assumed gains correspond to $210\,\mu$m RMS surface errors

Table 2: Summary of planned high frequency receiver properties.

4.2. K (commissioned)

The K-band receiver has four beams, each with dual circular polarization. One pair of beams cover the 18 – 22.4 GHz band with fixed separation of $3'$ on the sky, and the other two beams cover the 22 – 26.5 GHz frequency range, with a similar fixed separation. The two beams in each frequency pair are positioned with a common elevation. The feeds are corrugated horns with cooled polarizers producing circular polarizations. Internal switching modes are frequency and beam switching. Receiver temperatures are typically 20 to 25 K. A seperate diode in each feed injects noise for calibration. System temperatures on the sky measured during science runs in the Spring 2003 were recorded at $\sim 40\,$K under good weather conditions. Commissioning of the K-band receiver was essentially completed by the Spring of 2003, but upgraded amplifiers were installed during Summer 2003.

4.3. Q (partially commissioned)

The Q-band receiver has four beams with fixed separation, each with dual circular polarization operating over 40-52 GHz. The four feeds are arranged in a square with one side oriented parallel to azimuth. The internal switching modes are frequency switching and beam switching. The IF Bandwidth is 4000 MHz. Calibration is by noise injection. A tertiary beam chopper is planned for this receiver. The Q-band receiver was mounted on the GBT in Spring 2003 and went through initial engineering tests successfully, but astronomical commissioning of this receiver will not begin until Fall 2003.

4.4. Ka (under development)

A dual-beam, dual circular polarization receiver covering the 26 to 40 GHz band is currently under development at Green Bank. In order to maximize continuum sensitivity this receiver has a pseudo-correlation architecture and supports rapid electronic beam switching to limit the impact of $1/f$ gain fluctuations in the electronics; this will also offer advantages for spectral line observing. The receiver should have system temperature between 40 and 50 K in good conditions, which translates into a point source sensitivity of $\sim 410\,\mu$Jy sec$^{\frac{1}{2}}$ across a single 3.5 GHz band. Calibration will be via internal noise diodes, as is the current practice for cm receivers on the GBT.

The Caltech Continuum Backend (§ A.4) will be used to detect the four 3.5 GHz continuum bands (in both polarizations, and for both horns) which this receiver provides. The full receiver bandwidth will also be available for future backends. The initial plan is to deliver a 4 GHz IF to the existing GBT IF system.

The Ka band receiver and Caltech Continuum Backend are expected to be commissioned in the first Quarter of 2004.

4.5. W (under development)

The 3mm heterodyne capabilities of the GBT have been divided into two sub-bands, W1 ($68 \rightarrow 92$ GHz) and W2 ($90 \rightarrow 115$ GHz). A dual-beam pseudo-correlation receiver much like the Ka band receiver described above is under development for the W1 sub-band.

The W-band receiver will present three 8 GHz continuum bands to the CCB (§ A.4) for each beam in each polarization. Like the Ka-band receiver, the full bandwidth of 24 GHz will be available for future wideband backends. The W1 receiver is expected to be commissioned in the first quarter of 2005.

A W2 band receiver, covering from 90 GHz up to the $J = 1 - 0$ line of CO, will be constructed in the future. This is notionally a single beam receiver optimized for spectroscopy.

4.6. Penn Array (under development)

The Penn Array is an array of 64 Transition-Edge Superconductor (TES) bolometers operating at a wavelength of 3mm; it is being developed under the Universities Instrumentation Program by the University of Pennsylvania, NASA GSFC, NIST, Cardiff University, and NRAO-Green Bank. It will initially have a bandpass of 86 to 94 GHz, with the possibility of installing a filterwheel in the future which would permit bands up to 20 GHz wide to be used under the best observing conditions. The Penn Array on the GBT will have significantly greater point source mapping speed at millimeter wavelengths than is currently available. With the expected $350\,\mu\mathrm{Jy\,sec}^{\frac{1}{2}}$ per detector sensitivity it should be possible to map one square degree to $120\,\mu$Jy RMS in six hours. The Penn Array on the GBT will also have better resolution than existing millimeter and submillimeter wave single dishes ($\sim 8''$ FWHM).

The Penn Array/GBT combination is a revolutionary instrument. Since the GBT focal plane can easily accommadate thousands of 3mm detectors, the Penn Array is a pathfinder for a much larger TES array.

Field Size	Penn Array [μJy]	80×80 array [μJy]
$30'' \times 30''$	1	—
$5' \times 5'$	10	1
$1^\circ \times 1^\circ$	120	12
$8^\circ \times 8^\circ$	980	100
$25^\circ \times 25^\circ$	—	310

Table 3: Continuum sensitivity for large-area maps with bolometer arrays on the GBT. An integration time of 6 hours is assumed in each case.

5. Possible Future High Frequency Instrumentation

- Chopping Tertiary: initially planned for the Q-band receiver, a tertiary will improve the spectral baselines for high frequency observations.
- Wideband Spectrometer: We are considering the construction of a wideband (up to 24 GHz) spectrometer. The primary scientific application of such an instrument would be to measure redshifted CO emission from known sources in the range $1\,\mathrm{cm} < \lambda < 3\,\mathrm{mm}$.
- Large Format Bolometer Array: Using TES technology, it is feasible to construct 3mm bolometer arrays with many thousands of pixels. Such an array on the GBT would offer unprecedented continuum point source sensitivity in the millimeter regime.
- Heterodyne FPAs: MMIC technology will soon enable the construction of heterodyne focal plane arrays with hundreds of elements. With the apropriate electronics, these could be used for continuum work; for large-area, high-resolution maps of molecular transitions in the Milky Way; or for large-area, blind surveys for redshifted CO.

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A. Appendix: Backends

The GBT currently has three observatory-supported backends for astronomical use: the Digital Continuum Receiver (DCR), the Spectrometer, and the Spectral Processor. In addition a fast-switching, broadband continuum backend is under development (the Caltech Continuum Backend) for use with the Ka and W band receivers (see §§ 4.4 and 4.5). There are also a number of backends— two pulsar backends, a VLBI backend, and a radar backend— which are not discussed here.

A.1. DCR

The Digital Continuum Receiver (DCR) is a general purpose backend used for continuum-mode observation. The DCR is used for utility observations such as pointing and focus checks as well as continuum astronomical observations such as continuum mapping and point source flux determination. The GBT IF system will allow the DCR to be supplied with a continuum band up to 3 GHz wide. 16 channels can be detected simultaneously.

A.2. Spectrometer

The GBT spectrometer is a versatile and powerful backend designed as a modular system, with each of the modules, or quadrants, independently configurable or capable of being grouped into banks for added resolution. The spectrometer can be configured at bandwidths of 800, 200, 50, and 12.5 MHz, with either 3- or 9-level sampling in the latter two modes and 3-level sampling in the wideband modes. By configuring 8 contiguous samplers in the 800 MHz mode, the spectrometer can achieve a maximum bandwidth of 6.4 GHz, at which the channel spacing is 391 kHz. The GBT IF system permits at most 4 GHz IF bandwidth. The narrowest channel spacing available is 48 Hz, in a 12.5 MHz bandwidth, 1 sampler mode that records a total of 256k channels.

The spectrometer can perform auto and cross correlations of the input signals, but cross correlation observations are not yet supported in software. The signals may be a) dual polarization inputs in a selected frequency range, b) a number of inputs at different frequency ranges in a single polarization, c) inputs from different feeds of multi-feed receivers, or d) combinations of the preceding options.

A.3. Spectral Processor

The Spectral Processor is an FFT spectrometer primarily designed for high time resolution pulsar observations. Because of its wide dynamic range it is also useful for spectral line observations at low frequencies where strong interference is a problem. It contains two FFT engines, each with 1024 channels over a maximum bandwidth of 40 MHz which may be divided into 1, 2, or 4 separate passbands. The two FFT engines are synchronous and their outputs may be cross-multiplied to measure polarization. The most commonly used types of observing with the spectral processor are pulsar timing and either total power or frequency switched spectral line.

A.4. Caltech Continuum Backend (under development)

The Caltech Continuum Backend (CCB) is a backend for the 1cm and 3mm pseudo-correlation receivers, intended to maximize their continuum sensitivity by detecting the continuum over a very wide band (up to 24 GHz) and implementing rapid phase switching ($> 1\,\mathrm{kHz}$). It is being constructed by Tony Readhead's group at Caltech under the Universities Instrumentation Program.

B. Surface Efficiency

We define the surface efficiency η_s as the fraction of power an aperture, viewed as a transmitter, emits in the direction of maximum gain in comparison to the case that the aperture is geometrically perfect. In the case that imperfections have a correlation length much smaller than the aperture size, and an RMS deviation from the perfect geometry of ϵ, this is

$$\eta_s = exp\left[-\left(\frac{4\pi\epsilon}{\lambda}\right)^2\right] \tag{B1}$$

In the long-wavelength limit $\eta_s = 1$. The aperture efficiency η_A is the overall efficiency of the antenna in comparison to the geometrical cross section, including for example the illumination taper and blockage. This can be taken to comprise two factors such that $\eta_A = \eta_s(\lambda)\,\eta_0$. For the GBT $\eta_0 \sim 70\%$ assuming the standard edge taper used by GBT receivers. The GBT gain at low frequencies is $\Gamma \sim 2\,\mathrm{K/Jy}$, and in general $\Gamma = 2\,\mathrm{K/Jy} \times \eta_s(\lambda)$.

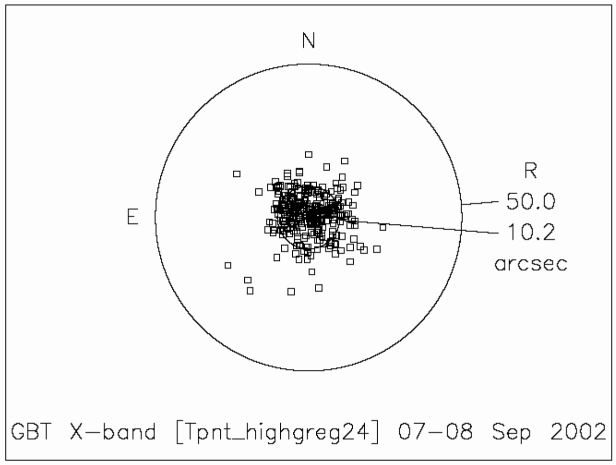

Fig. 1.— The distribution of "blind" pointing errors taken from the all-sky pointing observations made by Balser et al (2002) at 9.6 GHz.

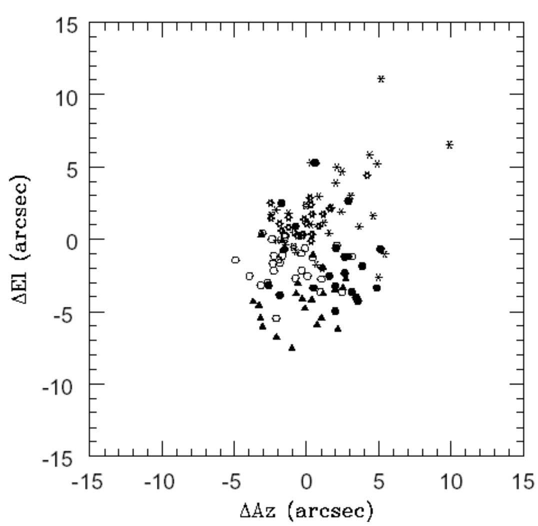

Fig. 2.— The distribution of "offset" pointing errors for five different sources, each shown with a different symbol. Correcting for systematic differences between reference sources, the RMS is about $3''.2$.

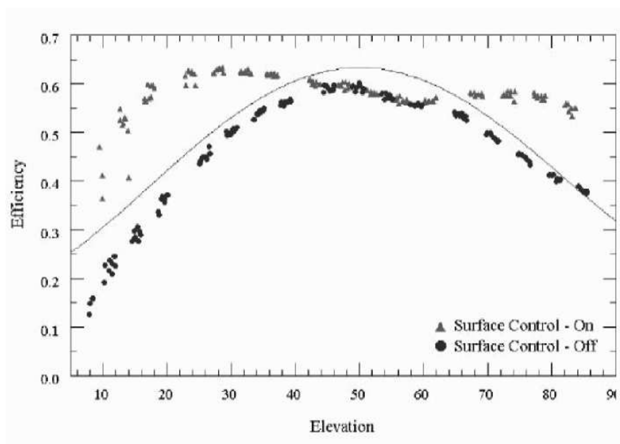

Fig. 3.— The GBT aperture efficiency at 20 GHz with the active surface off (circles) and on (triangles). In this data, the active surface is responding to predicted gravitational deformations according to the Finite Element Model. The cause of the apparent dip at mid elevations is unknown, although this data is the result of a single night's observations, and the experiment needs to be repeated.