The Proposer's Guide for the Green Bank Telescope

GBT Support Staff

June 23, 2015

This guide provides essential information for the preparation of observing proposals on the Green Bank Telescope (GBT). The information covers the facilities that will be offered in **Semester 16A**.

Important News for Proposers

Deadline Proposals must be received by 5:00 P.M. EST (21:00 UTC) on Monday, 2 February 2015.

Limited Time for ”Fixed” and ”Windowed” Observations Due to varied pressures on the GBT’s schedule, the amount of time that can be accepted for fixed time observations (e.g. VLBI, pulsar transit observations, etc.) and windowed observations (e.g. monitoring observations) will be limited for the proposal call.

Technical Justification is Required All GBT proposals must include a Technical Justification section (see Section 9.2)). Any proposal that does not include a technical justification may be rejected without consideration.

ARGUS A 16 pixel W-band array receiver is being built by a collaboration of Standford, Cal Tech, Maryland and NRAO. This receiver will operate from 75-115.3 GHz. Proposals for this receiver will be accepted for the 16A semester. However, the instrument development team must be members of the proposal team. For further information contact the NRAO helpdesk at https://help.nrao.edu/.

JPL Radar Backend This is a new radar system that is an improvement over the old ”PFS radar” system. The new system has more options for bandwidths and sample rates. The new radar backend is available for anyone to use. For further information contact the NRAO helpdesk at https://help.nrao.edu/.

Mustang 1.5 not available The Mustang bolometer array has been returned to UPenn do diagnose problems with the detector readouts. We will not accept any proposals requesting Mustang as a part of the 16A proposal call.

Mapping Limitations If you are considering mapping with the GBT such that there are major turns or moves (end of rows in raster map, change in position for pointed maps, etc.) that occur with a cadence faster than every 30 seconds, you will need to consult with a GBT support scientist to ensure that the GBT can safely withstand the stresses induced by the mapping motions.

PF1/450 Feed RFI Digital TV signals at frequencies above 470 MHz will make observing very difficult with this receiver. Available RFI plots do not show the strength of these signals very well as they overpower the system. Observers should consult the support scientists before submitting a proposal for this feed.

PF1/600 Feed RFI Digital TV signals at frequencies covering most of this feed will make observing very difficult with this receiver. Available RFI plots do not show the strength of these signals very well as they overpower the system. Observers should consult the support scientists before submitting a proposal for this feed.

C-band Receiver and VLBI The C-band receiver has been upgraded to cover the 4-8 GHz frequency range. Due to the design of the receiver there is a large amount of cross-talk between LCP and RCP for VLBI observations. The amount of cross talk is thought to be stable on hour to one day timescales. We will only accept proposals for VLBI using this receiver that will measure only Stokes I which will also require measuring the ”D-terms” during the observational time.

The Dynamic Scheduling System (DSS) The GBT will be scheduled by the DSS during the 16A semester. Further information on the GBT DSS can be found at: http://www.gb.nrao.edu/DSS

Large Proposals Large Proposals (more than 200 hours) will be accepted for the 16A semester. Large proposals will be accepted for the fully commissioned hardware only. You should also review the NRAO Large Proposal Policy.

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1 Introduction to the GBT

Location	Green Bank, West Virginia, USA
Coordinates	Longitude: 79°50′23.406″ West (NAD83) Latitude: 38°25′59.236″ North (NAD83) Track Elevation: 807.43 m (NAVD88)
Optics	110 m x 100 m unblocked section of a 208 m parent paraboloid Offaxis feed arm
Telescope Diameter	100 m (effective)
Available Foci	Prime and Gregorian f/D (prime) = 0.29 (referred to 208 m parent parabola) f/D (prime) = 0.6 (referred to 100 m effective parabola) f/D (Gregorian) = 1.9 (referred to 100 m effective aperture)
Receiver mounts	Prime: Retractable boom with Focus-Rotation Mount Gregorian: Rotating turret with 8 receiver bays
Subreflector	8-m reflector with Stewart Platform (6 degrees of freedom)
Main reflector	2004 actuated panels (2209 actuators) Average intra-panel RMS 68 μm
FWHM Beamwidth	Gregorian Feed: $\sim 12.60/f_{GHz}$ arcmin Prime Focus: $\sim 13.01/f_{GHz}$ arcmin (see Section 4.1.1)
Elevation Limits	Lower limit: 5 degrees Upper limit: $\sim$ 90 degrees
Declination Range	Lower limit: ~ -46 degrees Upper limit: 90 degrees
Slew Rates	Azimuth: 35.2 degrees/min Elevation: 17.6 degrees/min
Surface RMS	Passive surface: 450 μm at 45° elevation, worse elsewhere Active surface: $\sim$ 250 μm, under benign night-time conditions
Pointing accuracy	1σ values from 2-D data 5″ blind 2.7″ offset

Table 1: GBT Telescope Specifications.

The Green Bank Telescope is a 100-m diameter single dish radio telescope. The telescope has several advanced design characteristics that, together with its large aperture, make it unique:

- **Fully-steerable antenna** 5–90 degrees elevation range and 85% coverage of the celestial sphere [1]
- **Unblocked aperture** reduces sidelobes, Radio Frequency Interference (RFI), and spectral standing waves
- **Active surface** allows for compensation for gravity and thermal distortions, and includes near real-time adjustments to optics and pointing.
- **Frequency coverage of 290 MHz to 115.3 GHz** provides nearly 3 decades of frequency coverage for maximum scientific flexibility

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[1] Because the GBT is an alt-az mounted telescope it cannot track sources that are near the zenith.

- **Location in the National Radio Quiet Zone** ensures a comparatively low RFI environment

The GBT is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities Incorporated. The GBT is intended to address a very broad range of astronomical problems at radio wavelengths, and is available to qualified observers on a peer-reviewed proposal basis. It is run primarily as a facility for visiting observers, and the NRAO provides extensive support services including round-the-clock operators.

Technical specifications for the telescope are given in Table 1.

Source rising and setting times can be estimated using Figure 1.

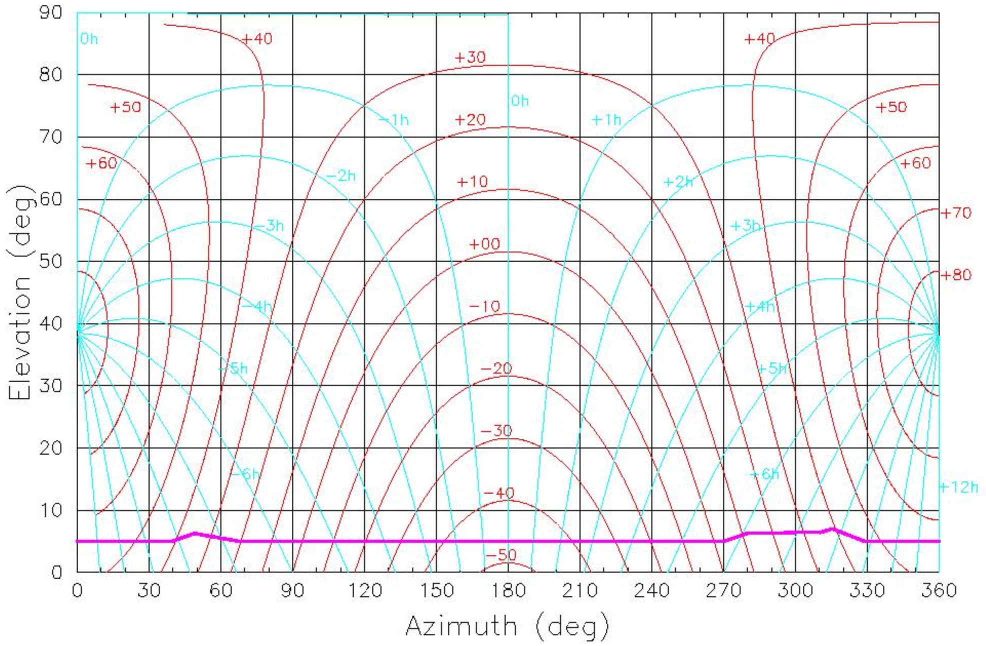

Figure 1: Plot of elevation vs azimuth, with lines of constant Hour Angle (HA; cyan lines) and Declination (DEC; brown lines) for the GBT. The horizon (magenta line) is shown at 5 degrees elevation, except for the mountains in the west and the 140–foot (43-m) telescope at azimuth = 48°. The lines of constant DEC are shown in increments of ± 10°, while the lines of constant HA are in increments of ± 1 hour.

2 Submitting a proposal

General proposal information is available at https://science.nrao.edu/observing. The NRAO proposal submission tool (https://my.nrao.edu/) should be used to submit all GBT proposals.

2.1 Latest Call for Proposals

The latest call for proposals can be found at https://science.nrao.edu/observing.

2.2 Joint Proposals

If you are submitting a joint proposal, you must explicitly state this in your proposal abstract. Proposals requiring GBT participation in VLBA or global VLBI observations should be submitted to the VLBA only, not to the GBT. Proposals for joint GBT and VLA observations must be submitted for each instrument separately.

If you are planning to use the GBT as part of a co-ordinated program with other observatories, you should follow these links:

For FERMI joint proposals see http://fermi.gsfc.nasa.gov/ssc/proposals/cycle4/ .

For CHANDRA joint proposals see http://cxc.harvard.edu/proposer/.

For SPITZER joint proposals see http://ssc.spitzer.caltech.edu/propkit/currentcp.html .

For SWIFT joint proposals see http://swift.gsfc.nasa.gov/proposals .

For HST joint proposals see http://www.stsci.edu/hst/proposing/documents/cp/cp_cover.html .

2.3 Travel Support

Some travel support for observing and data reduction is available for U.S. investigators on successful proposals. Information can be found at
http://www.nrao.edu/administration/directors_office/nonemployee_observing_travel.shtml.

2.4 Student Financial Support

Due to funding pressures the NRAO is unable to support its Student Observing Support (SOS) program for the VLA, VLBA, and GBT in fiscal year 2016.

2.5 Observing Policies

The policy for observing with the GBT, including a description of the restrictions concerning remote observing, can be found at https://science.nrao.edu/facilities/gbt/observing/policies.

2.6 Page Charge Support

NRAO is able to partially support page charges for U.S. authors for any paper that presents original data obtained with any NRAO telescope. See http://library.nrao.edu/pubsup.shtml for more details.

3 GBT Availability

3.1 Summer Maintenance

During the months of June through August the GBT has 10.5 hour maintenance days every Monday through Thursday except in the case of Holidays (typically onlyu July 4). The GBT remains shutdown overnight between these maintenance days to aid in painting the telescope structure and to aid structural inspections.

3.2 Winter Maintenance

From September through May the GBT has one or two 8.5 hours mainetenance days per week. These are scheduled dynamically on the Monday (or first non-Holiday business day) of each week.

3.3 Thanksgiving and Christmas Shutdowns

The GBT is shutdown for 36 hours between at midnight UTC at the beginning of Thanksgiving day and Christmas day.

3.4 Non open skies time

The GBT is moving into an operational regime in which the NSF funded ”open skies” time will not constitute all observing time granted on the GBT. The non ”open skies” observing times will be determined from contractual obligations. The requirements for the non ”open skies” time may severely reduce (over even eliminate) the amount of time that can be accepted for fixed time observations (e.g. VLBI, pulsar transit observations, etc.) and will reduce time available for windowed observations (e.g. monitoring observations).

4 GBT Instruments

4.1 Antenna

4.1.1 Resolution

The resolution of the GBT is given by

$$\mathrm{FWHM} = (1.02 + 0.0135 * \mathrm{Te(Db)})\,\frac{\lambda}{100\ \mathrm{m}}\ \mathrm{rad} \tag{1}$$

where FWHM is the Full-Width at Half-Maximum of the symmetric, two-dimensional Gaussian shaped beam and Te(Db) is the edge taper of the feed’s illumination of the dish in decibels. The edge taper varies with frequency and polarization for all of the GBT feeds. For the Gregorian feed the edge taper is typically $14 \pm 2\,\mathrm{Db}$ which results in

$$FWHM_{>1GHz} = \frac{12.46 \rightarrow 12.73'}{f_{GHz}} = \frac{747.6 \rightarrow 763.8''}{f_{GHz}} \tag{2}$$

For the prime focus receivers the edge taper is typically $18 \pm 2\,\mathrm{Db}$ which results in

$$FWHM_{<1GHz} = \frac{12.73 \rightarrow 13.29'}{f_{GHz}} = \frac{763.8 \rightarrow 797.4''}{f_{GHz}} \tag{3}$$

4.1.2 Surface

The GBT surface consists of 2004 panels mounted on 2209 computer-controlled actuators. Below 4 GHz, use of the active surface makes a negligible change to the telescope efficiency, and it is disabled to avoid unnecessary wear on the actuators.

Above 4 GHz, the active surface is automatically adjusted to compensate for residual non-homologous deformations as the gravity vector changes with changing elevation. The corrections are a combination of predictions from a Finite Element Model (FEM) of the GBT structure plus additional empirical corrections derived from Out-of-focus (OOF) holography measurements. The OOF measurements are parametrized as low-order Zernike polynomials. The FEM plus OOF corrections are automatically calculated for the elevation of the mid-point of a scan, and are applied prior to the start of the scan.

4.1.3 Efficiency and Gain

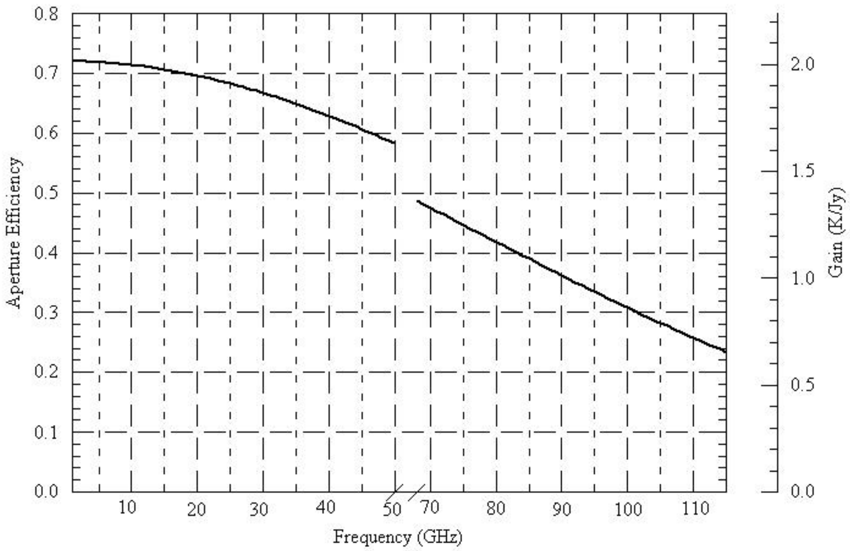

Figure 2: Predicted aperture efficiencies for the GBT. Values below 5 GHz are based on a surface RMS of 450 μm and 300 μm for frequencies above 5 GHz. The beam efficiencies are 1.37 times the aperture efficiency.

A graph of the anticipated and measured aperture efficiencies for the GBT appears in Figure 2.

The proposer should also read the memo
http://www.gb.nrao.edu/~rmaddale/GBT/ReceiverPerformance/PlaningObservations.htm
by Ron Maddalena for more details on the characteristics and performance of the GBT.

4.2 Receivers

GBT receivers cover frequency bands from 0.290-49.8 GHz and 67-115.3 GHz. Table 3 summarizes the receivers and their properties (nominal frequency ranges, efficiencies, etc.). If you would like to know about any receiver's performance outside of the nominal frequency ranges you should contact one of the GBT Observational Support Scientists (see Table 10).

4.2.1 Prime Focus Receivers

The prime focus receiver is mounted in a focus-rotation mount (FRM) on a retractable boom. The boom is moved to the prime focus position when prime focus receiver is in use, and retracted when Gregorian receivers are required. The FRM has three degrees of freedom: Z-axis radial focus, Y-axis translation (in the direction of the dish plane of symmetry), and rotation. It can be extended or retracted at any elevation. This usually takes about 10 minutes.

As the FRM holds one receiver box at a time, a change from PF1 to PF2 receivers requires a box exchange. Additionally, changing frequency bands within PF1 requires a change in the PF1 feed. Changes of or in prime focus receivers are usually made during routine maintenance time preceding a dedicated campaign using that receiver.

Prime Focus 1 (PF1)

The PF1 receiver is divided into 4 frequency bands within the same receiver box. The frequency ranges are (see Table 3) 290 - 395 MHz, 385 - 520 MHz, 510 - 690 MHz and 680 - 920 MHz. Each frequency band requires its specific feed to be attached to the receiver before that band can be used.

The receivers are cooled FET amplifiers. The feeds for the first three bands are short-backfire dipoles. The feed for the fourth is a corrugated feed horn with an Orthomode transducer (OMT) polarization splitter.

A feed change is required to move between bands. This takes 2-4 hours, and is done during routine maintenance days (see above).

The user can select one of four IF filters in the PF1 receiver. These have bandwidths of 20, 40, 80 and 240 MHz.

Prime Focus 2 (PF2) (0.910 - 1.23 GHz)

PF2 uses a cooled FET and a corrugated feed horn with an OMT. The user can select one of four IF filters in the PF2 receiver. These have bandwidths of 20, 40, 80 and 240 MHz.

4.2.2 Gregorian Receivers

The receiver room located at the Gregorian Focus contains a rotating turret in which the Gregorian receivers are mounted. There are 8 portals for receiver boxes in the turret. All 8 receivers can be kept cold and active at all times.

More information on individual Gregorian receivers follows, which includes design types and internal switching modes, i.e., those switching modes activated inside the receiver (e.g., frequency, beam, or polarization). External switching such as antenna position switching is always available. The Gregorian subreflector can be used for slow chopping.

The Gregorian receivers all have the following components unless explicitly stated below. Each of the Gregorian receivers is a cooled HFET amplifier and every feed/beam has a corrugated horn wave-guide. All calibration for the Gregorian receivers are done via injection of a signal from a noise diode.

For information on how T_{sys} varies with weather conditions and telescope elevation, please see http://www.gb.nrao.edu/~rmaddale/GBT/ReceiverPerformance/PlaningObservations.htm.

L-Band (1.15 – 1.73 GHz)

This receiver has one beam on the sky, with dual polarizations. The feed has a cooled OMT producing linear polarizations. The user can select circular polarization which is synthesized using a hybrid (after the first amplifiers) in the front-end. Allowed internal switching modes are frequency and/or polarization switching. The user can select one of four RF filters: 1.1-1.8 GHz, 1.1-1.45 GHz, 1.3-1.45 GHz, 1.6-1.75 GHz. A notch filter between 1.2 and 1.34 GHz is available to suppress interference from a nearby Air

Surveillance Radar. There is choice between two noise diodes with different levels ($\sim 10\%$ or $\sim 100\%$ of the system temperature) for flux calibration.

S-Band (1.73 – 2.60 GHz)

This receiver has one beam with dual polarizations. The feed has a cooled OMT producing linear polarizations. The user can select circular polarization synthesized using a hybrid (after the first amplifiers) in the front-end. Internal switching modes include frequency switching. The user can select one of two RF filters: 1.68-2.65 GHz, 2.1-2.4 GHz. There is choice between two noise diodes with different levels ($\sim 10\%$ or $\sim 100\%$ of the system temperature) for flux calibration.

A superconducting notch filter is permanently installed immediately after the first amplifiers and covers the range 2300–2360 MHz. This filter suppresses interference from the Sirius and XMM satellite radio transmissions.

C-Band (3.95 – 8 GHz)

This receiver has one beam, with dual polarizations. The feed has a cooled OMT producing linear polarizations. The user can select circular polarization synthesized using a hybrid (after the first amplifiers) in the front-end. The allowed internal switching mode is frequency switching. The full instantaneous bandwidth will be 4.0 GHz. There is choice between two noise diodes with different levels ($\sim 10\%$ or $\sim 100\%$ of the system temperature) for flux calibration.

Due to the wide bandwidth of the receiver and the hybrid being after the first amplifiers, there is a large amount of cross-talk between the LCP and RCP channels when circular polarization is used. The stability of the amplifiers control the time over which the cross-talk between LCP and RCP will remain stable. All observations using circular polarization (mainly VLBI) will need to make calibration observations during their observing period in order to correct for the cross-talk.

X-Band (8.0 – 11.6 GHz)

This receiver has one beam, with dual circular polarizations. The feed has a cooled polarizer producing circular polarizations. The internal switching modes are frequency switching and polarization switching. The user can select IF Bandwidths of 500 or 2400 MHz. There is a single noise diode ($\sim 10\%$ of the system temperature) for flux calibration.

The frequency range of the X-band receiver has been extended from 8.0 – 10.0 GHz to 8.0 – 11.6 GHz. However, users are cautioned that above 10 GHz, the polarization purity degrades, and the low level noise-diode strength drops off.

Ku-Band (12.0 – 15.4 GHz)

This receiver has two beams on the sky with fixed separation, each with dual circular polarization. The feeds have cooled polarizers producing circular polarizations. Internal switching modes are frequency and/or IF switching (the switch is after the first amplifiers). The user can select IF Bandwidths of 500 or 3500 MHz. The two Ku-band feeds are separated by $330''$ in the cross-elevation direction. There is a noise diode for each beam ($\sim 10\%$ of the system temperature) for flux calibration.

K-Band Focal Plane Array (18.0 – 27.5 GHz)

The K-band Focal Plane Array has seven beams total, each with dual circular polarization. Each beam covers the 18-27.5 GHz frequency range with fixed separations on the sky. The feeds have cooled polarizers producing circular polarization. The only internal switching modes is frequency switching. The seven feeds are laid out in a hexagon with one central feed. The hexagon is oriented such that the central feed is not at the same cross-elevation or the same elevation as any of the other beams. There is a noise diode for each beam ($\sim 10\%$ of the system temperature) for flux calibration. The maximum instantaneous bandwidth for the receiver is currently 1.8 GHz.

Ka-Band (26.0– 39.5 GHz)

This receiver has two beams, each with a single linear polarization. The polarizations of the two beams are orthogonal and are aligned at $\pm 45^\circ$ angles to the elevation (and cross-elevation) direction.

The receiver is built according to a pseudo-correlation design intended to minimize the effect of 1/f gain fluctuations for continuum and broadband spectral line observation. 180° waveguide hybrids precede and follow the low noise amplifiers. Phase switches between the amplifiers and the second hybrid allow true beam switching to be used with this receiver.

The CCB uses the full 26–40 GHz range of the Ka-band receiver. For other backends, the receiver is broken into three separate bands: 26.0-31.0 GHz, 30.5-37.0 GHz, and 36.0-39.50 GHz. You can only use one of these bands at a time, except for the CCB which can use the full frequency range of the receiver. For backends other than the CCB, the maximum instantaneous bandwidth achievable with this receiver is limited to 4 GHz. There is a noise diode for each beam ($\sim$ 10% of the system temperature) for flux calibration. The feeds are separated by $78''$ in the cross-elevation direction.

Q-Band (38.2–49.8 GHz)

This receiver has two beams with fixed separation, each dual circular polarization. The feeds have cooled polarizers producing circular polarizations. The internal switching mode available is frequency switching. The IF Bandwidth is 4000 MHz. Calibration is by noise injection and/or ambient load. The feeds are separated by $57.8''$ in the cross-elevation direction.

W-band 4mm (67–93 GHz)

The receiver has two beams, each dual linear polarization. The feeds are separated by $286''$ in the cross-elevation direction. The IF system for the 4mm system is broken into four separate bands: 67-74 GHz, 73-80 GHz, 79-86 GHz, and 85-93.3 GHz, and you can only use one of these bands at a time. Please see http://www.gb.nrao.edu/4mm/ for the latest information.

ARGUS (75-115.3 GHz 16 Pixel Array) ARGUS will be a 16 pixel W-band array receiver with each receiver having a singular polarization. Eight receivers will have LCP and the other eight receivers will have RCP. ARGUS is being built by a collaboration of Standford, Cal Tech, Maryland and NRAO. This receiver will operate from 75-115.3 GHz. For further information contact the NRAO helpdesk at https://help.nrao.edu/.

4.2.3 Receiver Resonances

The GBT receivers are known to have resonances within their respected band-passes. These are frequencies where the receiver response is non-linear. The resonances arise in the ortho-mode transducers (OMTs) which separate the two polarizations of the incoming signal. Although valid data can be obtained within the receiver resonances, the observer should be aware that this might not always be the case. As a general rule, polarization observations will be affected much more strongly than total intensity observations in the regions of the resonances.

The receiver resonances have been measured in the lab and are listed in Table 2. However, these data should not be taken as complete as there may be resonances that could not be detected in the lab due to sensitivity limits. The center frequencies of the resonances are determined with an accuracy of only a few MHz at best. The widths of the resonances are typically less than 5 MHz.

Receiver	Frequency MHz	FWHM MHz
PF1	796.6	2.09
PF1	817.4	3.29
PF2	925.9	0.17
PF2	1056.0	–
PF2	1169.9	3.28
L	1263.0	0.60
L	1447.0	0.68
L	1607.0	0.90
L	1720.0	–
S	1844.0	2.00
S	2118.0	0.96
S	2315.0	–
S	2561.0	0.91
X	9742.0	6.7
X	10504.0	118.0
X	11415.0	46.4
Ku	12875.0	8.1
Ku	12885.0	7.1

Table 2: GBT Receivers resonances. This list is not necessarily complete. The FWHMs are from Gaussian fits. Typical resonances have wings that are broader than Gaussian profiles. Resonances with FWHM listed as "–" were not seen in the astronomical data.

Receiver	Band	Frequency Range (GHz)	Focus	Polarization	Beams	Polarizations per Beam	Beam Separation	FWHM	Gain (K/Jy)	Aperture Efficiency	Maximum Instantaneous Bandwidth (MHz)
PF1	342 MHz	.290-.395	Prime	Lin/Circ	1	2	——	$36'$	2.0	72%	240
	450 MHz	.385-.520	Prime	Lin/Circ	1	2	——	$27'$	2.0	72%	
	600 MHz	.510-.690	Prime	Lin/Circ	1	2	——	$21'$	2.0	72%	
	800 MHz	.680-.920	Prime	Lin/Circ	1	2	——	$15'$	2.0	72%	
PF2	——	.910-1.23	Prime	Lin/Circ	1	2	——	$12'$	2.0	72%	240
L-Band	——	1.15-1.73	Greg.	Lin/Circ	1	2	——	$9'$	2.0	72%	650
S-Band	——	1.73-2.60	Greg.	Lin/Circ	1	2	——	$5.8'$	2.0	72%	970
C-Band	——	3.95-8.0	Greg.	Lin/Circ	1	2	——	$2.5'$	2.0	72%	4000
X-Band	——	8.00-11.6	Greg.	Circ	1	2	——	$1.4'$	2.0	71%	2400
Ku-Band	——	12.0-15.4	Greg.	Circ	2	2	$330''$	$54''$	1.9	70%	3500
KFPA	——	18.0-27.5	Greg.	Circ	7	2	$96''$	$32''$	1.9	68%	1800
Ka-Band	MM-F1	26.0-31.0	Greg.	Circ	2	1	$78''$	$26.8''$	1.8	63-67%	4000
	MM-F2	30.5-37.0						$22.6''$			
	MM-F3	36.0-39.5						$19.5''$			
Q-Band	—–	38.2-49.8	Greg.	Circ	2	2	$58''$	$16''$	1.7	58-64%	4000
W-Band 4mm	MM-F1	67-74	Greg.	Circ	2	2	TBD	$10''$	1.0	35-47%	1280
	MM-F2	73-80	Greg.	Circ	2	2					
	MM-F3	79-86	Greg.	Circ	2	2					
	MM-F4	85-93.3	Greg.	Circ	2	2					
ARGUS	—–	75-115.3	Greg.	Circ	16	1	TDB	TBD	—-	TBD	TBD

Table 3: GBT Receivers' parameters. Beam efficiency is 1.37 times the aperture efficiency. See Figure 3 for information on how T_{sys} varies with frequency. See Figure 4 for information on how the System Equivalent Flux Density (SEFD) varies with frequency. Note that for lower frequencies the observer will have to add an estimate for the Galactic background emission, $\mathrm{T_{bg}}$ to the system temperatures in order to get realistic values for sensitivity and noise limits.

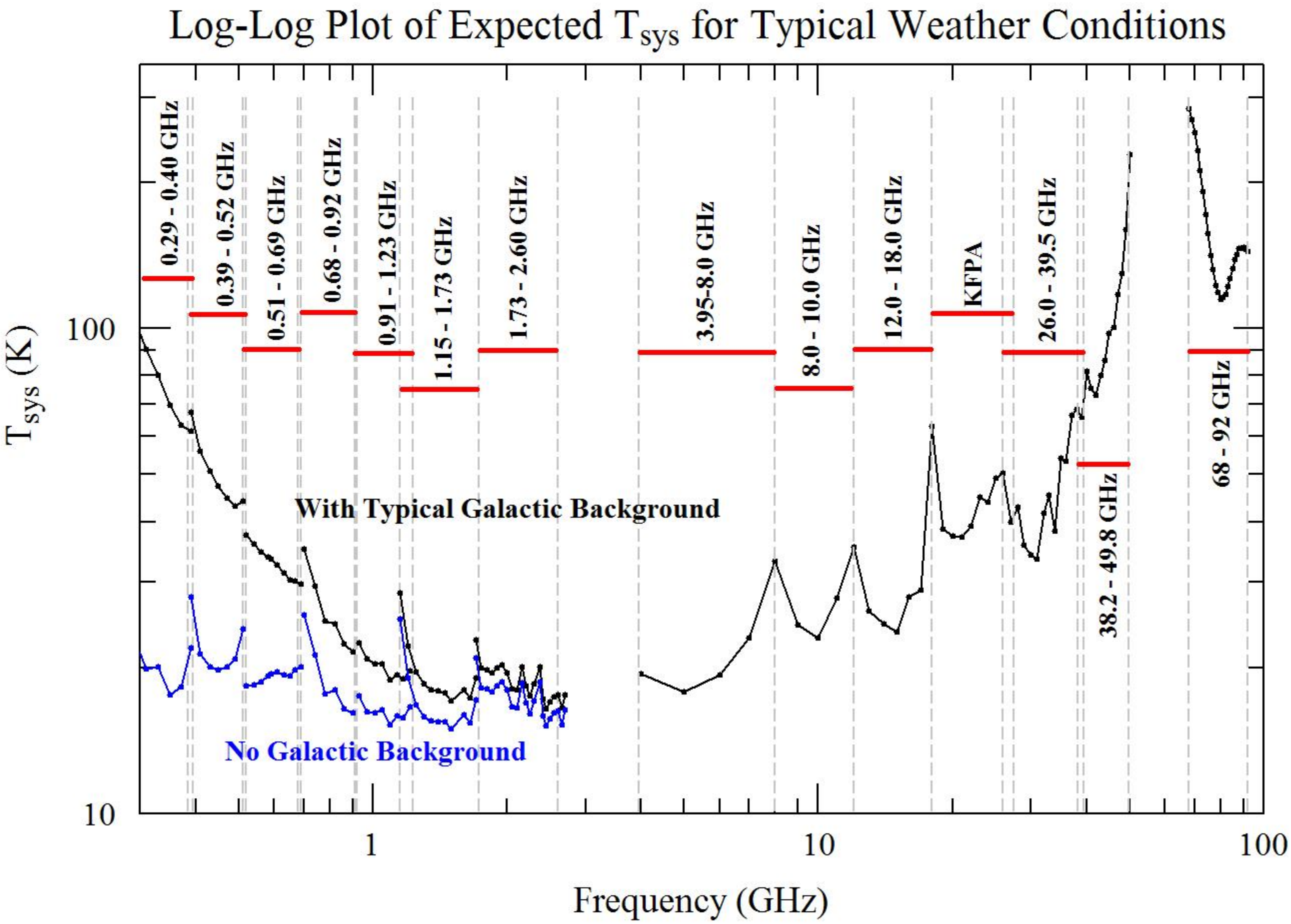

Figure 3: Expected Tsys the GBT for typical weather conditions.

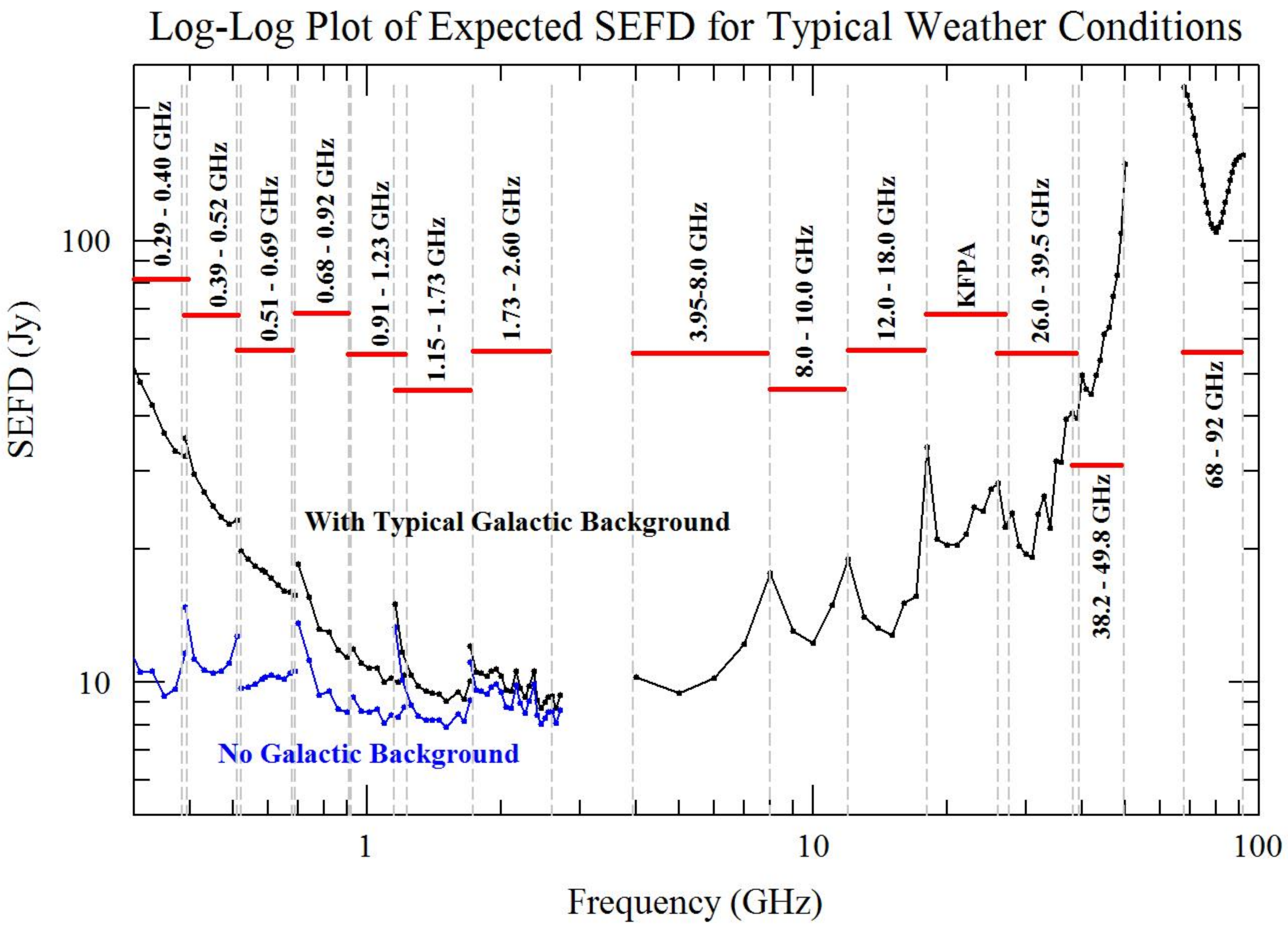

Figure 4: System Equivalent Flux densities the GBT for typical weather conditions.

4.3 Backends

4.3.1 VErsatile GBT Astronomical Spectrometer (VEGAS)

VEGAS is a new FPGA-based spectrometer built by NRAO and UC Berkeley that can be used with any receiver.It consists of eight independent spectrometers that can be used simultaneously. An overview of the capabilities of VEGAS is given in Table 4. For details on the design of VEGAS, please consult `http://www.gb.nrao.edu/vegas/report/URSI2011.pdf`.

Observers can use between one and eight spectrometers (or "banks") at the same time. Each bank within VEGAS can be configured with a different spectral resolution, bandwidth, and number of spectral windows. However, the integration time, switching period, and the frequency switch **must** be the same for all banks and all spectral from a single VEGAS bank must be identical apart from the center frequency and offset, which may be changed betwee windows. The available VEGAS modes for each bank are given in Table 4. The banks can produce spectra with full polarization products (e.g., XX, YY, XY, and YX) without reducing the number of channels in a particular mode. Finally, VEGAS has a large dynamic range and retains a linear response in the presence of strong RFI.

The GBT IF system introduces some constraints on routing signals from the receivers to VEGAS. All single beam receivers (see Table 3) and KFPA beam 1 can be routed to all eight spectrometers (see Figure 5). For all dual beam receivers (see Table 3), including the two-beam mode of the KFPA, the signal from one beam can only be routed to a maximum of four spectrometers (see Figure 6). For the KFPA in four beam mode, each beam can be routed to no more than two VEGAS spectrometers (see Figure 7). When using all seven beams of the KFPA, each beam can map to a single spectrometer with an optional second copy of beam 1 being routed to the eighth VEGAS spectrometer (see Figure 8). Spectral resolution is not gained with VEGAS by using only one beam of a multi-beam receiver.

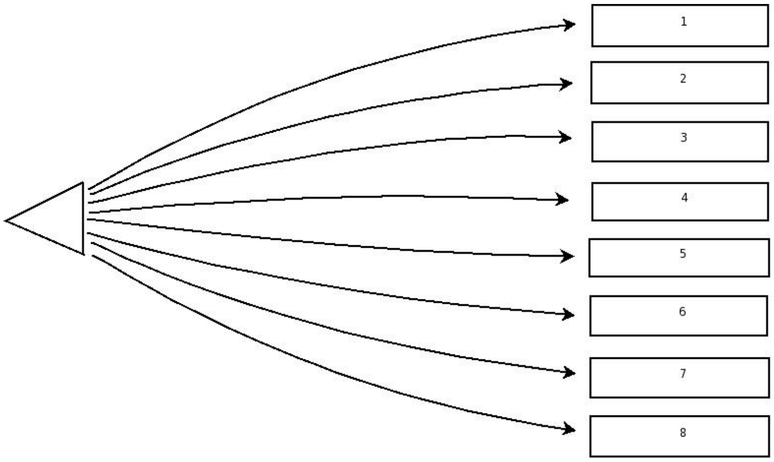

Figure 5: A graphic demonstration of how single beam receivers and beam 1 of the KFPA can be routed to the VEGAS spectrometers. The routing can be to 1, 2, 3, 4, 5, 6, 7 or 8 different VEGAS spectrometers. This routing is not applicable to a single beam of a dual beam receiver.

Although VEGAS is extraordinarily flexible, there are some restrictions on frequency coverage and spectral window placement. The maximum useable bandwidth is 1250 MHz for modes 1 and 2 and 850 MHz for mode 3. For the VEGAS modes with multiple spectral windows (i.e., modes 20 through 29), the spectral windows from a single spectrometer must be within 1500 MHz (modes 20 through 24) and 1000 MHz (modes 25 through 29). The useable bandwidth in these cases is 150 to 1400 MHz and 150 to 950 MHz, respectively. Although the individual spectrometers can be placed up to 10 GHz apart, filters in the GBT system for the most part limit the maximum frequency range to less than 4 GHz. The exceptions are the W-band and KFPA receivers. For the former, the W-band MM1 filter has a

Table 4: VEGAS modes.

Mode	Spectral Windows per Spectrometer	Bandwidth per Spectrometer (MHz)	Number of Channels per Spectrometer	Approximate Spectral Resolution (kHz)
1	1	1500[a]	1024	1465
2	1	1500[a]	16384	92
3	1	1080[b]	16384	66
4	1	187.5	32768	5.7
5	1	187.5	65536	2.9
6	1	187.5	131072	1.4
7	1	100	32768	3.1
8	1	100	65536	1.5
9	1	100	131072	0.8
10	1	23.44	32768	0.7
11	1	23.44	65536	0.4
12	1	23.44	131072	0.2
13	1	23.44	262144	0.1
14	1	23.44	524288	0.05
15	1	11.72	32768	0.4
16	1	11.72	65536	0.2
17	1	11.72	131072	0.1
18	1	11.72	262144	0.05
19	1	11.72	524288	0.02
20	8 [c]	23.44	4096	5.7
21	8 [c]	23.44	8192	2.9
22	8 [c]	23.44	16384	1.4
23	8 [c]	23.44	32768	0.7
24	8 [c]	23.44	65536	0.4
25	8 [c]	16.875	4096	4.1
26	8 [c]	16.875	8192	2.0
27	8 [c]	16.875	16384	1.0
28	8 [c]	16.875	32768	0.5
29	8 [c]	16.875	65536	0.26

[a] The useable bandwidth for this mode is 1250 MHz.

[b] The useable bandwidth for this mode is 850 MHz.

[c] For modes 20-24, the spectral windows must be placed within 1500 MHz with a useable frequency range of 150 to 1400 MHz. For modes 25-29, the spectral windows must be placed within 1000 MHz with a useable frequency range of 150 to 950 MHz.

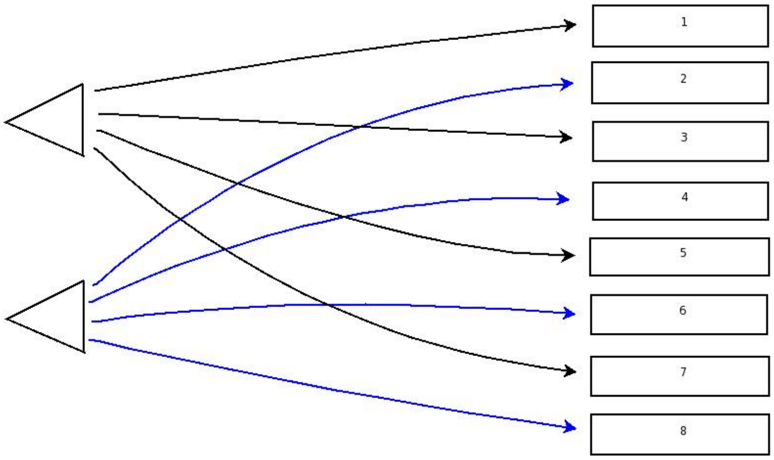

Figure 6: A graphic demonstration of how dual beam receivers, including two beams of the KFPA, can be routed to the VEGAS spectrometers. Each beam can be routed to 1, 2, 3, or 4 different VEGAS spectrometers.

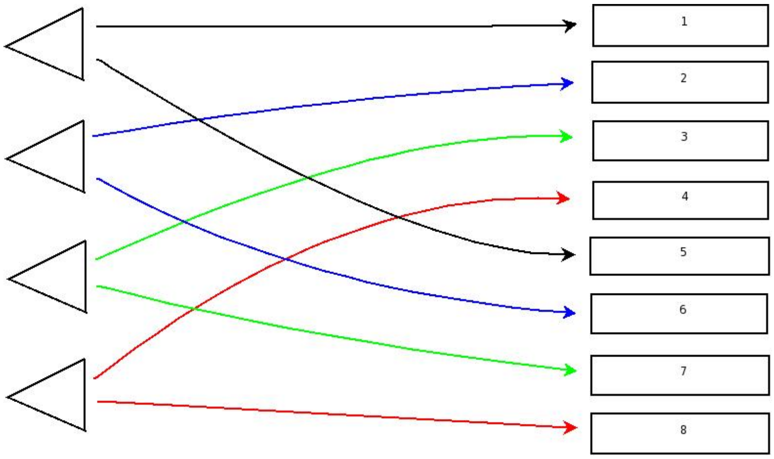

Figure 7: A graphic demonstration of how KFPA four beam mode can be routed to the VEGAS spectrometers. Each beam can be routed to 1 or 2 different VEGAS spectrometers.

maximum bandwidth of 6 GHz. For the latter, the maximum range varies depending on how many beams are desired. In broadband mode, the KFPA can process 7.5 GHz from a single beam. For KFPA observations with more than two beams, the spectral windows must be less than 1.8 GHz apart.

VEGAS is capable of extremely short switching periods. In some cases, these periods are shorter than the blanking introduced by the GBT system associated with noise diode state changes, frequency switching, and Doppler tracking. Tables 5, 6, and 7 give recommended minimum switching periods for different observing modes that will result in less than 10% blanking. If shorter switching periods are necessary, Doppler tracking can be turned off and the user, with some additional effort, can correct for the Doppler motion of their source offline. Improved methods for offline Doppler corrections are currently under development. Please contact the GBT helpdesk if you need more information.

When selecting integration times, a good rule of thumb is that one wants at least four switching periods per integration time to avoid artifacts when on-the-fly mapping, although one can trade off oversampling in the scanning direction with the number of switching periods per integration time. OnOff or Track observations can tolerate having the switching period equal to the integration time, although more

Table 5: Minimum Recommended Switching Periods for Observations Without Doppler Tracking

	Total Power No Noise Diode	Total Power Noise Diode	Frequency Switched No Noise Diode	Frequency Switched Noise Diode
	`tp_nocal`	`tp`	`sp_nocal`	`sp`
Mode	(s)	(s)	(s)	(s)
(1)	(2)	(3)	(4)	(5)
1	0.0005	0.0100	0.3200	0.3300
2	0.0014	0.0280	0.3200	0.3480
3	0.0020	0.0400	0.3200	0.3600
4	0.0100	0.0280	0.3200	0.3480
5	0.0199	0.0559	0.3200	0.3759
6	0.0301	0.1118	0.3200	0.4318
7	0.0102	0.0524	0.3200	0.3724
8	0.0203	0.1049	0.3200	0.4249
9	0.0301	0.2097	0.3200	0.5297
10	0.0056	0.2237	0.3200	0.5437
11	0.0112	0.4474	0.4474	0.8948
12	0.0280	0.8948	0.8948	1.7896
13	0.0447	1.7896	1.7896	3.5791
14	0.0671	3.5791	3.5791	7.1583
15	0.0056	0.4474	0.4474	0.8948
16	0.0112	0.8948	0.8948	1.7896
17	0.0336	1.7896	1.7896	3.5791
18	0.0447	3.5791	3.5791	7.1583
19	0.0895	7.1583	7.1583	14.3166
20	0.0051	0.0280	0.3200	0.3480
21	0.0101	0.0559	0.3200	0.3759
22	0.0301	0.1118	0.3200	0.4318
23	0.0405	0.2237	0.3200	0.5437
24	0.0755	0.4474	0.4474	0.8948
25	0.0070	0.0388	0.3200	0.3588
26	0.0141	0.0777	0.3200	0.3977
27	0.0398	0.1553	0.3200	0.4753
28	0.0544	0.3107	0.3200	0.6307
29	0.1010	0.6214	0.6214	1.2428

Col (1): VEGAS mode
Col (2): Recommended minimum switching period for total power observations without the noise diode (`tp_nocal`) and without Doppler tracking. This value is equivalent to the hardware exposure value for VEGAS.
Col (3): Recommmended minimum switching period (`swper`) for total power observations with the noise diode (`tp`) and without Doppler tracking. This switching period will result in less than 10% of your data being blanked.
Col (4): Recommended minimum switching period (`swper`) for frequency switched observations without the noise diode (`sp_nocal`) and without Doppler tracking. This switching period will result in less than 10% of your data being blanked.
Col (5): Recommended minimum switching period (`swper`) for frequency switched observations with the noise diode (`sp`) and without Doppler tracking. This switching period will result in less than 10% of your data being blanked.

Table 6: Minimum Recommended Switching Periods for Mapping Observations with Doppler Tracking

	Total Power No Noise Diode	Total Power Noise Diode	Frequency Switched No Noise Diode	Frequency Switched Noise Diode
	`tp_nocal`	`tp`	`sp_nocal`	`sp`
Mode	(s)	(s)	(s)	(s)
(1)	(2)	(3)	(4)	(5)
1	0.0010	0.0100	0.3200	0.3300
2	0.0028	0.0280	0.3200	0.3480
3	0.0040	0.0400	0.3200	0.3600
4	0.0114	0.0280	0.3200	0.3480
5	0.0227	0.0559	0.3200	0.3759
6	0.0357	0.1118	0.7600	1.5200
7	0.0128	0.0524	0.3200	0.3724
8	0.0256	0.1049	0.7600	1.5200
9	0.0406	0.2097	0.7600	1.5200
10	0.0168	0.2237	0.7600	1.5200
11	0.0336	0.4474	0.7600	1.5200
12	0.0727	0.8948	0.8948	1.7896
13	0.1342	1.7896	1.7896	3.5791
14	0.2461	3.5791	3.5791	7.1583
15	0.0280	0.4474	0.7600	1.5200
16	0.0559	0.8948	0.8948	1.7896
17	0.1230	1.7896	1.7896	3.5791
18	0.2237	3.5791	3.5791	7.1583
19	0.4474	7.5383	7.1583	14.3166
20	0.0065	0.0280	0.3200	0.3480
21	0.0129	0.0559	0.3200	0.3759
22	0.0357	0.1118	0.7600	1.5200
23	0.0517	0.2237	0.7600	1.5200
24	0.0979	0.4474	0.7600	1.5200
25	0.0090	0.0388	0.3200	0.3588
26	0.0180	0.0777	0.7600	1.5200
27	0.0476	0.1553	0.7600	1.5200
28	0.0699	0.3107	0.7600	1.5200
29	0.1320	0.6214	0.7600	1.5200

Col (1): VEGAS mode
Col (2): Recommended minimum switching period (`swper`) for Doppler-tracked, total power on-the-fly maps with no noise diode (`tp_nocal`). These values will yield less than 10% blanking overall. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.
Col (3): Recommmended minimum switching period (`swper`) for Doppler-tracked, total power on-the-fly maps with the noise diode (`tp`). These values will yield less than 10% blanking overall. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.
Col (4): Recommended minimum switching period (`swper`) for Doppler-tracked, frequency switch observations with the noise diode turned off (`sp_nocal`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall. This switching period will result in less than 10% of your data being blanked. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.
Col (5): Recommended minimum switching period (`swper`) for Doppler-tracked, frequency switch observations with the noise diode turned on (`sp`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.

Table 7: Minimum Recommended Switching Periods for Pointed Observations with Doppler Tracking

	Total Power No Noise Diode		Total Power Noise Diode		Frequency Switched No Noise Diode		Frequency Switched Noise Diode	
	`tp_nocal`		`tp`		`sp_nocal`		`sp`	
	ν_{min}	swper	ν_{min}	swper	ν_{min}	swper	ν_{min}	swper
Mode	GHz	(s)	GHz	(s)	GHz	(s)	GHz	(s)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	> 115	0.0005	> 115	0.0100	> 115	0.7600	> 115	1.5200
2	> 115	0.0014	> 115	0.0280	> 115	0.7600	> 115	1.5200
3	> 115	0.0020	> 115	0.0400	> 115	0.7600	> 115	1.5200
4	> 115	0.0100	> 115	0.0280	> 115	0.7600	> 115	1.5200
5	> 115	0.0199	> 115	0.0559	> 115	0.7600	> 115	1.5200
6	> 115	0.0301	> 115	0.1118	> 115	0.7600	> 115	1.5200
7	> 115	0.0102	> 115	0.0524	> 115	0.7600	> 115	1.5200
8	> 115	0.0203	> 115	0.1049	> 115	0.7600	> 115	1.5200
9	> 115	0.0301	> 115	0.2097	> 115	0.7600	59.6	1.5200
10	> 115	0.0056	> 115	0.2237	> 115	0.7600	54.4	1.5200
11	> 115	0.0112	33.1	0.4474	33.1	0.7600	16.5	1.5200
12	> 115	0.0280	8.3	0.8948	8.3	0.8948	4.1	1.7896
13	82.7	0.0447	2.1	1.7896	2.1	1.7896	1.0	3.5791
14	27.6	0.0671	0.5	3.5791	0.5	3.5791	0.3	7.1583
15	> 115	0.0056	33.1	0.4474	33.1	0.7600	16.5	1.5200
16	> 115	0.0112	8.3	0.8948	8.3	0.8948	4.1	1.7896
17	110.3	0.0336	2.1	1.7896	2.1	1.7896	1.0	3.5791
18	41.3	0.0447	0.5	3.5791	0.5	3.5791	0.3	7.1583
19	10.3	0.3800	0.1	7.5383	0.1	7.1583	0.1	14.3166
20	> 115	0.0051	> 115	0.0280	> 115	0.7600	> 115	1.5200
21	> 115	0.0101	> 115	0.0559	> 115	0.7600	> 115	1.5200
22	> 115	0.0301	> 115	0.1118	> 115	0.7600	> 115	1.5200
23	> 115	0.0405	> 115	0.2237	> 115	0.7600	54.4	1.5200
24	> 115	0.0755	33.1	0.4474	33.1	0.7600	16.5	1.5200
25	> 115	0.0070	> 115	0.0388	> 115	0.7600	> 115	1.5200
26	> 115	0.0141	> 115	0.0777	> 115	0.7600	> 115	1.5200
27	> 115	0.0398	> 115	0.1553	> 115	0.7600	89.7	1.5200
28	> 115	0.0544	68.6	0.3107	68.6	0.7600	33.8	1.5200
29	105.5	0.1010	17.1	0.6214	17.1	0.7600	8.6	1.5200

Col (1): VEGAS mode

Col (2, 4, 6, 8): Frequency above which you should use the minimum recommended switching period values in this table. Below this the values in Table 5 are appropriate.

Col (3): Recommended minimum switching period for pointed, Doppler-tracked, total power observations without the noise diode (`tp_nocal`). These values will yield less than 10% blanking overall.

Col (5): Recommended minimum switching period for pointed, Doppler-tracked, total power observations with the noise diode (`tp`). These values will yield less than 10% blanking overall.

Col (7): Recommended minimum switching period for pointed, Doppler-tracked, frequency-switched observations without the noise diode (`sp_nocal`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall.

Col (9): Recommended minimum switching period for pointed, Doppler-tracked, frequency-switched observations with the noise diode (`sp`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall.

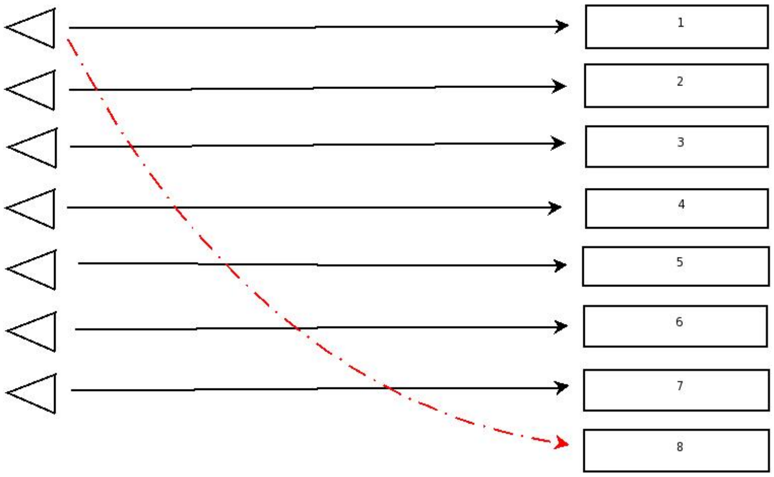

Figure 8: A graphic demonstration of how all seven beams of KFPA can be routed to the VEGAS spectrometers. The routing of a second spectral window from beam 1 to spectrometer eight (7+1 mode of the KFPA) is optional.

switching periods per integration time is encouraged. Typical integration times for normal observations are $\sim 1-10$s. The exact integration time will depend on your observations, e.g., on-the-fly mapping, frequency switching, etc.

Lines that are much narrower than the selected channel width will need to be corrected for the channel filter response. Please contact the GBT helpdesk if you need more information.

The data rates for VEGAS can be very high ($>$ 25 GB/hr), so care should be taken to minimize the data rate while still producing acceptable science data. High data rates must be scientifically justified. The data rate for an individual banks can be calculated using

$$\mathrm{rate[GB/hr]} = 1.34 \times 10^{-5} * \mathrm{n_{channels}} * \mathrm{n_{spw}} * \mathrm{n_{stokes}} * \mathrm{n_{states}}/(\mathrm{t_{int}[s]}) \tag{4}$$

where $n_{channels}$ is the number of channels per spectral window, n_{spw} is the number of spectral windows, n_{stokes} is the number of stokes parameters (2 for dual polarization, 4 for full polarization), n_{states} is the number of switching states (4 for frequency switching and 2 for total power), and t_{int} is the integration time. The total data rate for a project can be calculated by adding the data rates for each bank together. Here we calculate some example data rates for a frequency switched HI observation, a full polarization continuum observation, and a frequency switched 7+1-beam KFPA map. For the frequency switched HI observation, we use mode 10 with 32768 channels, 1 spectral window, 2 stokes parameters (XX and YY), 4 switching states (two for the frequency switch and two for the noise diode switch) and an integration time of 5s. These parameters give a data rate of 0.70 GB/hr. For the continuum polarization observation, we will use mode 1 with 1024 channels, 1 spectral window, 4 stokes parameters, 2 switching states (noise diode switch) and an integration time of 0.04s. The corresponding data rate is 2.7 GB/hr. For the 7+1 beam KFPA map, we use all eight spectrometers in mode 24 with 65536 channels, eight spectral windows per spectrometer, 2 stokes parameters, 4 switching states, and an integration time of 8s. This setup produces a whopping 56.2 GB/hr data rate.

4.3.2 Digital Continuum Receiver (DCR)

The digital continuum receiver is the GBT's general purpose continuum backend. It is used both for utility observations such as pointing, focus, and beam-map calibrations, as well such as for continuum astronomical observations including point-source on/offs and extended source mapping. It has the following specifications and characteristics:

- **Number of input channels:** 32 in two banks of 16, only one bank usable at a time.
- **Switching modes:** A user defined mode and Four pre-defined modes: total power with and without continuous calibration and switched power, with and without continuous calibration.
- **Maximum number of switching phases:** 10 (determined by software).
- **Minimum phase time:** 1 millisecond. Switching frequency is the reciprocal of the sum of the phase times in use.
- **Phase time resolution:** 100 nanoseconds
- **Minimum integration time:** 100 milliseconds.
- **Maximum integration time per switch phase:** 250 seconds at nominal input level and 25 seconds at maximum input level.
- **Blanking:** At the beginning of each switching phase, 100 nanosecond resolution. Blanking time may be different for each switch phase, but the current user interface software assumes the same blanking time on each phase.
- **Integrator type:** Voltage-to-frequency converters into 28-bit counters.

Table 8: Bandwidths for the DCR for different receivers.

Signal From	Receiver	Possible Bandwidths (MHz)
IF Rack	Prime Focus	20, 40, 80, 240
IF Rack	Rcvr1_2, Rcvr4_6, Rcvr8_10, Rcvr12_18	20, 80, 320, 1280
IF Rack	Rcvr2_3, Rcvr18_26, Rcvr40_52	80, 320, 1280
Analog Filter Rack	Any	12.5, 50, 200, 800

4.3.3 Green Bank Ultimate Pulsar Processing Instrument (GUPPI)

Guppi has one hardware mode and many software modes. Guppi can be used with any receiver.Only one polarization would be available for the Ka-band receiver.

GUPPI currently has the following specifications and characteristics:

- **8-bit sampling:** Provides dramatically increased RFI resistance, a high dynamic range and accurate pulse shapes
- **Polarizations:** 2 polarizations and full stokes parameters are available
- **Bandwidths:** 800, 200 and 100 MHz
- **Number of spectral channels:** 2048 / 4096
- **Minimum integration time:** 40.96 μs using an 800 MHz bandwidth. (20.48 μs is possible when on-line folding)

Details of the this backend are available at
https://safe.nrao.edu/wiki/bin/view/CICADA/GUPPiUsersGuide.

4.3.4 Caltech Continuum Backend (CCB)

The Caltech Continuum Backend (CCB) is a sensitive, wideband backend designed exclusively for use with the GBT Ka-band receiver over the frequency range of 26–40 GHz. It provides carefully optimized RF (not IF) detector circuits and the capability to beam-switch the receiver rapidly to suppress instrumental gain fluctuations. There are 16 input ports (only 8 can be used at present with the Ka-band receiver), hard-wired to the receiver's 2 feeds x 2 polarizations x 4 frequency sub-bands (26-29.5 , 29.5-33.0; 33.0-36.5; and 36.5 - 40 GHz). The CCB allows the left and right noise-diodes to be controlled individually to allow for differential or total power calibration. Unlike other GBT backends, the noise-diodes are either on or off for an entire integration (there is no concept of "phase within an integration"). The minimum practical integration period is 5 milliseconds; integration periods longer than 0.1 seconds are not recommended. The maximum practical beam-switching period is about 4 kHz, limited by the needed 250 micro-second beam-switch blanking time (work is underway to reduce the needed blanking time). Switching slower than 1 kHz is not recommended.

Under the best observing conditions (clear, stable, and few or no clouds) the combination of the Ka-band receiver and the CCB deliver a photometric sensitivity of roughly 0.2 mJy for a single one-minute, targeted nod observation. The median sensitivity is 0.4 mJy RMS. These numbers apply to the most sensitive (33-36 GHz) of the four frequency channels; averaging all channels together will slightly, but not significantly, improve performance because of noise correlations and variations in the receiver sensitivity between channels. The analogous noise performance figures for sensitive mapping projects are still to be determined.

4.3.5 Mark5 VLBA Disk Recorder

VLBI/VLBA observing with the GBT is supported with a VLBA backend using the Mark5 recording system.

4.3.6 User Provided Backends

JPL Radar Backend

This is a new radar system that is an improvement over the old "PFS radar" system. The new system has more options for bandwidths and sample rates. The new radar backend is available for anyone to use. For further information contact the NRAO helpdesk at https://help.nrao.edu/.

PFS Radar

The PFS Radar backend is a private user backend used primarily, but not exclusively, for bi-static radar observations. Information on this backend is available at http://mel.epss.ucla.edu/jlm/research/pfs/. If you would like to use this backend please contact Jean-Luc Margot at the University of California, Los Angeles (UCLA).

5 GBT Observing Modes

5.1 Utility modes

Several observing modes are available to the user to characterize the pointing, focus, and efficiency of the telescope. Calibrations of the GBT pointing model, focus curves and telescope efficiencies are made by the GBT staff, but observers should consider repeating these, particularly at higher frequencies as they can be weather, time, etc. dependent.

The observing procedures are described and executed in the GBT observing interface, ASTRID (to learn more about ASTRID go to the GBT Observer's Guide).

Pointing

Global pointing solutions are determined regularly by the observatory staff. Currently the pointing accuracy is 5″ for blind pointing and 2.7″ for offset pointing. For higher frequencies it is necessary to perform periodic pointing observations to determine local pointing corrections (LPCs). The observing procedures "Peak", "AutoPeak" or "AutoPeakFocus" should be used to measure the LPCs. These procedures perform continuous scans in four directions (e.g. two sweeps in Azimuth then two sweeps in Elevation). The data are automatically processed and the LPCs produced are applied to subsequent observations.

Temperature sensors have been placed on the support structure of the GBT. Data from these sensors are used to correct the pointing model for thermal flexing of the telescope. (These corrections are the so-called dynamic corrections.) This procedure allows the observer to take data for about one hour between pointing and focus observations at high frequencies under most night-time weather conditions and for about one half-hour during daytime. At lower wavelengths, data acquisition intervals between pointing calibrations may be longer.

Information on how often to point and focus, parameters to use, and time required for the procedure can be found in the GBT Observer's Guide).

Focus

A focus tracking algorithm will continuously update the focus as the telescope changes elevation. The prime focus has three degrees of freedom while the Gregorian focus has six degrees of freedom. The focus tracking model is pre-calibrated by the staff, and this should be sufficient for low frequency observing. Additionally,a focus tracking algorithm continuously updates the focus as the telescope changes elevation.

There are also several procedures available to check the focus. The observing procedures "Focus" or "AutoPeakFocus" scan the prime focus receiver in its feed's axial direction. This determines the receiver's maximum gain focus position. For Gregorian receivers these same procedures move the sub-reflector in the radial direction to determine the maximum gain focus position of the sub-reflector.

The dynamic-corrections described above also correct the focus for differential-heating-induced focus travel from the GBT back-up structure and feed-arm flexure.

AutoOOF

AutoOOF reduces surface RMS of the GBT resulting in a significant improvement to the efficiency of high frequency observations. The use of AutoOOF now makes it possible to schedule Ka and Q band projects during the day. This procedure measures the current surface deformation of the GBT in the form of Zernike polynomials which can then be sent to the active surface to counteract the deformation and restore good performance.

The AutoOOF procedure is only necessary for observations at frequencies higher than 28 GHz.

Telescope Efficiency and Side Lobe Response

The GBT surface is accurate to within an RMS of 300 microns (i.e. the standard deviation is 300 microns) with the Active Surface turned on and with benign nighttime conditions. The side lobes are greatly reduced compared with traditional single-dish telescopes because of the GBT's unique off-axis design.

Although the telescope efficiency as a function of frequency has been determined by the observatory staff, beam maps can be made by the observer to independently determine the telescope efficiency and side lobe response. The continuum procedures for mapping listed in § 5.5 can be used for this purpose.

Atmospheric Opacity

At higher frequencies the atmospheric opacity has to be taken into account when calibrating your data. Predictions of atmospheric opacity are routinely compiled and archived (for the current predictions for the next 7 days see http://www.gb.nrao.edu/~rmaddale/Weather/). In all tests the numbers from 60 hour forecasts match the measured opacities. The results of the 60 hour forecasts can be used for the initial calibration of high frequency data.

5.2 Standard Observing Modes

The five standard observing modes are:

Track Tracking a sky position (or at a constant velocity across the sky) in any standard or user-defined coordinate system for a specified length of time.

PointMap [Grid Mapping] Tracking positions located within a rectangular grid of positions for a specified length of time. The user specifies the coordinate system, the two overall dimensions of the grid, the step sizes between grid positions, and how long to observe each grid position.

OnOff This type of observation is position switching in which an equal length of time is spent on and off source. The off source observation is then used to remove most of the effects arising from the IF system.

Nod This is a version of position switching for receivers with multiple beams, e.g. two beams A and B. When A is on source, B is off source (on blank sky). Then the telescope is moved so that B is on source and A is on blank sky for an equal time. This allows position switching with no lost time while performing the off-source observations.

SubBeamNod For dual-beam receivers, SubBeamNod causes the subreflector to tilt about the x-axis between the two feeds at a given periodicity. This method is capable of faster switching than the standard telescope nod, giving better baselines. However, a higher proportion of data will be blanked as the subreflector moves between beams, increasing the overall overhead time.

RaLongMap and DecLatMap [On-the-Fly (OTF) Mapping] In this mode, the telescope is slewed within a rectangular area of the sky while taking data. The observer specifies the coordinate system, dimensions of the rectangular area, which of the two dimensions the telescope will slew in, the telescope slew rate, and the step size between rows in the map. Note that OTF mapping is more advantageous (less overhead time) than grid mapping in cases where there is significant signal-to-noise (e.g. Galactic HI mapping) or at high frequencies where atmospheric fluctuations predominate.

A utility to help plan on-the-fly mapping observations is available at
http://www.gb.nrao.edu/ rmaddale/GBT/GBTMappingCalculator.html.

User defined procedures Procedures defined by the observer, tailored for specific observations, may also be written and installed into the GBT observer interface. This will require knowledge of the GBT software system and should be done with the help of one of the GBT support staff.

5.3 Switching Methods

The observer must specify which of five switching methods to use.

Position Switching Before or after an on-source observation, the telescope will move off source and observe a position thought to be devoid of emission. Usually, the 'off' position will be a few beam widths away from the 'on' position and either at the same elevation or declination as the 'on'. For every 'on' observation there is one 'off' observation of equal duration. Nodding is a form of position switching. **Position switching is done via an observing routine and is not setup in hardware unlike the following switching schemes.**

Frequency Switching During an observation, at a rate of about once per second, the center frequency of the observation is alternated between two values. In this way, part of the observation is taken 'on' the frequency of interest and part is taken 'off' frequency. In most cases, the user will spend half of the observing time 'off' and half 'on' frequency.

The difference between 'on' and 'off' frequencies is usually a few times the expected width of the spectral line. If the difference is smaller than about one half the observing bandwidth (called in-band frequency switching), it is in many cases possible to increase the signal-to-noise of the observation by a factor of $\sqrt{2}$ by averaging the 'on' and 'off' frequency measurements.

Beam Switching The Ka-band receiver is the only receiver that can perform beam switching. The switching can route the inputs of each feed to one of two "first amplifiers" which allows the short time-scale gain fluctuations to be removed from the data.

IF Switching This mode of observing is not recommended. For the Ku-band receiver it is possible to switch IF paths between two beams. This is the same as a beam-switching except that the switch comes after the first amplifiers. So IF switching cannot remove short time-scale gain fluctuations.

Polarization Switching This is only available for the L- and X-band receivers. During an observation and at a rate of about once per second, the polarization of the observation is switched between two orthogonal linear polarizations or the two circular polarizations. This switching method is used almost exclusively for Zeeman measurements.

5.4 Spectral Line Modes

Spectral line observations with the GBT can be performed with all currently-available receivers.

5.4.1 Sensitivity and Integration Times

Backend	K_1
VEGAS	1.0

Table 9: K_1 values.

The noise level of an observation is given by:

$$\sigma = \frac{K_1 T_{sys}}{\sqrt{K_2 t_{eff} N_{pol} BW / N_{chan}}} \tag{5}$$

Here, K_1 depends upon the backend sampling efficiency as defined in Table 9; T_{sys} is the total system temperature in Kelvins (see § 4.2)) and includes the expected contributions from the atmosphere (opacity), spillover, etc; K_2 is the auto-correlator channel weighting function (typically 1.21); N_{pol} is the number of independent polarization channels to be averaged (either 1 or 2); BW is the spectrum bandwidth in Hz; N_{chan} is the total number of spectral-line channels across the bandwidth; and

$$t_{eff} = \frac{t_{on} t_{off}}{t_{on} + t_{off}} \tag{6}$$

is the effective integration time in seconds and which is determined from the observing time spent 'on' source or frequency and the time spent 'off' source or frequency.

In equation 5 the following apply:

- $\mathbf{t_{eff}}$ is dependent upon the switching mode, number of 'on's per 'off,' etc.
- **Both** BW **and** N depend upon the configuration of the backend (see § **??** and § **??** for configuration details).

- σ is decreased by $\sqrt{2}$ for in-band frequency switching only if the 'on' and 'off' frequency measurements are averaged.
- σ is not corrected for antenna or beam efficiencies (see Table 3) at the observing frequency.
- σ is not corrected for atmospheric attenuation which is weather dependent at frequencies above about 5 GHz and independent of weather, but not zero, below about 5 GHz.
- **Confusion** from weak background sources can act as a noise-floor for some observations (see § 5.5).
- **The GBT Sensitivity Calculator** is available at https://dss.gb.nrao.edu/calculator-ui/war/Calculator_ui.html.

5.5 Continuum Modes

The GBT supports several types of continuum observations, including OnOff, PointMap, RaLongMap and DecLatMap (see § 5.2). For each of these procedures there are several switching modes which can be selected. In general a noise tube diode (called the CAL) is turned on to inject a known level of noise into the system for flux calibration. Also, in some modes the total power is switched between a "signal" and "reference" to remove instabilities caused by the system and/or atmosphere.

There is a total of four defined switching modes plus a user defined mode. The two most common modes are total power with and without CAL. In total power mode a reference can be obtained by moving the antenna discretely on and off the source (e.g. position switching) or by continuously scanning through a source and using the ends of the raster to define the reference level. The receivers operating above 12 GHz are dual-beam systems (i.e., two feeds); hence there are always two beams on the sky. Nodding is usually used for these systems (see § 5.2).

The continuum point-source sensitivity depends on three factors. These are the thermal noise floor, the $1/f$ gain fluctuations of the receiver, and the astronomical confusion limit. The thermal noise floor can be calculated using the relation

$$S_{rms}(\mu Jy) = \frac{22.6}{\eta_A} \frac{T_{sys}(K)}{\sqrt{BW(GHz) t_{eff}(sec)}} e^{\tau \cdot A} \tag{7}$$

where η_A is the aperture efficiency (see Figure 2), T_{sys} is the system temperature in K (see Table 3), BW is the bandwidth in GHz, t_{eff} is the effective integration time in seconds (see equation 6), τ is the atmospheric opacity, and A is the air mass ($\sim 1/sin(el)$).

For receivers other than the Ka-band receiver, $1/f$ gain fluctuations typically set a lower limit for observations of about $10 - 100$ times the thermal noise limit (see eq 7). $1/f$ gain fluctuations can also affect wide-bandwidth high frequency observations. An approximate expression of when $1/f$ noise will be relavent is when the bandwidth exceeds 8 $MHz/\tau(sec)$ where τ is the integration time in seconds.

The astronomical rms confusion noise limit is given by

$$\sigma_c = 50 \text{ mJy } \cdot \nu^{-2.7} \text{ GHz} \tag{8}$$

where ν is the observing frequency in GHz. For a believable detection, source intensity typically must be stronger than five times the astronomical rms confusion limit, ie. $S_{src} > 5\sigma_c$.

N.B. **Proposers should be aware that 1/f gain fluctuations and/or the astronomical confusion limit may result in a continuum point-source sensitivity well above the theoretical value predicted by the radiometer equation. Note that the predicted RMS confusion assumes no knowledge of the confusing sources. However, for most regions of the sky there is NVSS and/or FIRST information which can be applied to better quantify the confusing signal. Proposers who are uncertain as to how to apply these limits should seek the advice of a GBT staff scientist.**

5.6 Polarization

The devices that can support polarization observations are GUPPI and VEGAS.

5.7 VLBI / VLBA

VLBI observing with the GBT is supported with a VLBA backend using the Mark5 recording system. A total recording bandwidth of 512 MHz is supported. The maximum recording data rate is 2048 Mbits/sec.

Proposals requesting the GBT as part of the VLBA should be submitted to the VLBA. In contrast, proposals requesting the GBT as part of the EVN or other non-NRAO antennas should be submitted simultaneously to the GBT and EVN and other appropriate telescopes.

GBT VLBI observing can only support schedules written in the VLBA "Sched" format.

Move times for the GBT can be estimated by using 17 degrees per minute in elevation, 35 degrees per minute in azimuth, plus about 15 seconds settling time. When the ambient temperature is below 17 Farenheit (-8.3 Celcius) the azimuth slew rate is limited to 17.5 degrees per minute. Changing receiver bands takes 6-12 minutes. Time must also be allotted for pointing and focusing observations at higher frequencies.

All proposals that request the GBT for VLBI observations must include all overhead time in the full time request for the proposal.

More information can be found at http://www.gb.nrao.edu/~fghigo/gbtdoc/vlbinfo.html.

The GBT C-band receiver has a large amount of cross-talk between LCP and RCP for VLBI observations. The amount of cross talk is thought to be stable on hour to one day timescales. We will only accept proposals for VLBI using this receiver that will measure only Stokes I which will also require measuring the "D-terms" during the observational time.

6 Defining Sessions

A session defines how we will schedule the observations on the telescope if the proposal is accepted. It is important to create your sessions very carefully so that you can ensure that you will be able to observe all sources. The session should not be overly restricting such that it can never be scheduled.

A typicall time period for a single epoch of observing on the GBT is 3 to 6 hours long. It is possible to have longer sessions but the consequence is that the session becomes more difficult to schedule. Shorter sessions may also be justified but the proposer must be fully aware of the amount of overhead time.

The GBT Dynamic Scheduling System uses the average RA and Dec of the sources within a session to determine if the observations can be scheduled. If you have sources that are too far apart on the sky you can be scheduled such that you will never get a chance to observe one or more of these sources. Another possibility is that you can restrict the LST range so severley that you greatly reduce the chances of being scheduled.

There are no stringent rules that can be given on how you should create the sessions for your proposed observations. However, if you use the following suggestions then you will create sessions that should help maximize your chances of being scheduled on the GBT if your proposal is accepted.

- Only include receivers and backends that must be used together in a single observation in the same session.
- Typical telescope observing periods are 3 to 6 hours long.

- Sources in a session should be within 2 or 3 hours of each other in Right Ascension.
- Sources in a session should be visible at the same time for at least 1 to 2 hours
- Sources with Declinations less than the latitude of the GBT should not be in the same session as sources with Declinations greater than the latitude of the GBT. This reduces the potential for a large number of lengthy slews between sources.
- The more flexible a session is with regards to when it can be scheduled, the better chance that it can be scheduled.

7 Estimating Overhead Time

Overhead time is defined as time not spend observing your target sources. It consists of:

- **Setup time at the start of your observations:** required to change receivers, reconfigure the GBT IF system, and slew to your target source (about 15 minutes on average)
- **Time spent on pointing and calibration:** allow about 5-10 minutes for each pointing/focus measurement. A pointing (and focus for Gregorian receivers) should be performed at the beginning of each observation. You should use the recommended pointing and focusing time intervals from the GBT Observer's Guide.

- **Slew times** The GBT slew rate is 35.2 deg/min in Azimuth and 17.6 deg/min in elevation during warm weather. When the temperature is below 17 Farenheit (-8.3 Celcius) the slew rates are half of the warm values.
- **A minimum time between scans:** typically 15-20 seconds
- **AutoOOF for high frequency observations:** This procedure takes approximately 25 minutes including a necessary AutoPeakFocus after corrections have been sent to the active surface. These corrections can remain valid for 1-5 hours depending on how the surface deformations are changing with respect to the Sun, cloud cover changes, etc.

8 Radio Frequency Interference (RFI)

Information about RFI at the GBT can be found at http://www.gb.nrao.edu/IPG/.

9 Tips for Writing Your Proposal

In this section, we have listed briefly information that all proposers should consider when writing proposals. We have also mentioned some common errors. We urge proposers to read http://www.naic.edu/~astro/School/Talks/salter_prop.pdf by Chris Salter.

An excellent reference is the Conference Proceedings of the NRAO/NAIC Single Dish Summer School: *Single-Dish Radio Astronomy: Techniques and Applications*, **ASP Conference Proceedings, Vol. 278**, 2002, eds. Snezana Stanimirovic, Daniel Altschuler, Paul Goldsmith, and Chris Salter, ISBN: 1-58381-120-6, San Francisco: Astronomical Society of the Pacific).

9.1 Items To Consider

Pointing You should use the recommended pointing and focusing time intervals from the GBT Observer's Guide.
About 10 minutes should be allowed for each pointing and focusing that is performed.

Overhead Time Estimates of overhead time (see § 7) should be included in the total amount of requested time within the proposal.

Sensitivity Calculations Details of your sensitivity calculations should be included in the proposal. They should give strong preference to the values and equations given in this document.

Confusion Limit You should be aware of the confusion limits, especially at low frequencies (see § 5.5) and their resultant limitations on your observations.

RFI You should be aware of and mention in your proposal, any RFI that may affect your observations. You should state how you propose to deal with RFI during your data reduction. More information on RFI can be found at http://www.gb.nrao.edu/IPG/.

Technical Considerations You should describe your observing plan, how you derived your noise estimates, and any other technical issues that may affect your observations.

Source Right Ascension For observations at frequencies higher than 50 GHz the GBT is only effective from 3 hours after sunset until sunrise.

9.2 Advice For Writing Your Technical Justification

So you have finished writing a brilliant scientific justification that is sure to result in a ground-breaking result and you are ready to submit, but have you written a clear, detailed technical justification? Failure to address technical issues in your proposal could result in not getting all of your requested time or discovering that your simple one hour observation really required 100 hours to get the desired signal-to-noise or learning that you are requesting an unavailable observing configuration. Here are a few simple suggestions for writing a clear technical justification:

Assumptions Clearly state all assumptions including observing frequency, observing mode (the most common are position-switching, frequency-switching, nodding for dual-beam receivers, and mapping), the desired bandwidth and frequency resolution, and the total observing time required to reach your desired sensitivity. When giving sensitivities, it is easier to confirm the values if you present the rms noise per channel for a default configuration of the telescope before smoothing. Then you state how much smoothing is desired to reach your final sensitivity. The technical justification should state the resulting signal-to-noise of the observation and whether it is a peak or integrated value. If it is integrated a linewidth should be provided. If these values are presented for each source and each frequency to be observed, then it will be much easier to confirm the calculations in your proposal and you may even catch some mistakes before submission.

Receiver and Backend Availability Make sure that you are requesting an available receiver and backend configuration.

Overhead Be sure to clearly state what your overhead request is. Overheads can range from 10% at low frequencies up to 50% at high frequencies where frequent pointing and focus observations are needed.

If you follow these simple suggestions, then you are much more likely to get the proper amount of observing time for your project.

9.3 Common Errors in GBT Proposals

Here are some commonly made errors that you should avoid:

RFI The proposer does not investigate the RFI environment of the GBT before writing the proposal. See § 8.

Mapping Rate The proposer does not use realistic mapping rates. See the map planning tool at http://www.gb.nrao.edu/ rmaddale/GBT/GBTMappingCalculator.html.

Scanning too fast during map If there are large changes in motion that occurr on timescales less than 30 seconds apart, you can excessivley stress the GBT structure. Check with a GBT support scientist if you wish to see if you can have large motions on timescales less than 30 seconds apart without affecting the telescope.

Too many IF Signals The proposer asks for too many IF inputs into a backend.

Single polarizations The proposer asks for single polarization.

Incorrect Signal-to-Noise Estimate Did you perform the sensitivity calculations correctly? Many continuum observers forget to consider 1/f noise and source confusion.

Overhead not estimated The proposer does not include an estimate of the overhead time in their proposal.

Full Stokes The proposer asks for full Stokes parameters from backends that can't do this. Currently GUPPI and VEGAS can be used for polarization observations.

Bad Sessions Did you accidently create bad sessions by including all sources in all sessions or including all receiver in all sessions?

10 Further information

10.1 Additional Documentation

Additional documentation on the GBT can be found at
https://science.nrao.edu/facilities/gbt/practical-information-for-astronomers

10.2 Collaborations

Should you wish to collaborate with a GBT staff member for your proposed GBT observations, please contact the staff member before submitting your proposal. Scientific support staff contact details are listed in Table 10.

10.3 Contact people

For questions that may arise about specific GBT capabilities or other issues not addressed by this document, please contact contact one of the staff members listed in Table 10.

Topic	Staff Member and Contact Details	
General Questions on Capabilities	Toney Minter	tminter@nrao.edu
Proposal submission and scheduling	Toney Minter	tminter@nrao.edu
Pointing, focus calibrations	Frank Ghigo	fghigo@nrao.edu
Receivers	Ron Maddalena	rmaddale@nrao.edu
4mm Receiver	David Frayer	dfrayer@nrao.edu
VEGAS	Adam Kobelski	akobelsk@nrao.edu
Spectral Line Observing	Ron Maddalena	rmaddale@nrao.edu
Continuum Observing	Toney Minter	tminter@nrao.edu
VLBA/VLBI Observing	Frank Ghigo	fghigo@nrao.edu
Pulsar Observing	Ryan Lynch	rlynch@nrao.edu
Radar Observing	Frank Ghigo	fghigo@nrao.edu
General software issues	Mark Whitehead	mwhitehe@nrao.edu
GBT/ Green Bank policy	Toney Minter Karen O'Neil	tminter@nrao.edu koneil@nrao.edu
RFI Management	Toney Minter	tminter@nrao.edu
Observational Support	Toney Minter Frank Ghigo Ron Maddalena Dan Perera Dave Frayer Alyson Ford Adam Kobelski Ryan Lynch	tminter@nrao.edu fghigo@nrao.edu rmaddale@nrao.edu dperera@nrao.edu dfrayer@nrao.edu aford@nrao.edu akobelsk@nrao.edu rlynch@nrao.edu

Table 10: GBT Contacts

A GBT Sensitivity to Extragalactic 21 cm HI

If the HI emission from an object is optically thin, its mass is

$$\frac{M_{HI}}{M_\odot} = 2.4 \times 10^5 D^2 \int S(v)\ dv \tag{9}$$

where D is the distance in Mpc, and S is the flux density in the HI line in Jy as a function of velocity in $\mathrm{km\,s^{-1}}$. For an object much smaller than the GBT beam at 21 cm, the antenna temperature of the line in Kelvin is twice the flux density in Janskys: $T_L(K) = 2S(Jy)$.
In practice, the integral is actually a sum over channels:

$$\frac{M_{HI}}{M_\odot} = [1.2 \times 10^5 D^2]\ \sum_{i=1}^{n} T_L(i)\ \Delta v, \tag{10}$$

where Δv is the channel spacing in $\mathrm{km\,s^{-1}}$.

If the noise in each channel is identical, the 1σ error in the mass estimate is the error in the area of a channel, $\sigma(T_L \Delta v)$, times the square root of the number of channels in the sum:

$$\sigma_{M_{HI}} = [1.2 \times 10^5 D^2]\ \ \sigma(T_L\ \Delta v)\ \sqrt{n}. \tag{11}$$

In this notation the total velocity over which the sum is performed is $W \equiv n\ \Delta v$.

For the GBT in the 21cm line, with position-switching or frequency switching 'out-of-band', with equal times on signal and reference, and combining both receiver polarizations, the noise in a 1 $\mathrm{km\,s^{-1}}$ channel is

$$\frac{\sigma(T_L)}{K} = 0.32\ t_{tot}^{-\frac{1}{2}}\ \Delta v^{-\frac{1}{2}}\ \left(\frac{T_{sys}}{18\ K}\right), \tag{12}$$

where t_{tot} it the total integration time, including both signal and reference observations, in seconds. Thus, for the GBT,

$$\frac{\sigma_{M_{HI}}}{M_\odot} = [3.9 \times 10^4 D^2_{Mpc}]\ \ t_{tot}^{-\frac{1}{2}}\ \left(\frac{T_{sys}}{18\ K}\right)\sqrt{W_{\mathrm{km\,s^{-1}}}}. \tag{13}$$

The noise in an HI mass estimate is independent of Δv provided $W >> \Delta v$. The final sensitivity depends only on the total integration time and the velocity range.

This equation must be modified for in-band frequency switching, if $t_{on} \neq t_{tot}/2$, etc. In this case, there will also be an elevation dependence of T_{sys} and some frequency dependence, especially at large redshifts. RFI can affect observations at some frequencies.

B Useful Web Links

Description	Link
Green Bank Web Page	https://science.nrao.edu/facilities/gbt
GBT Astronomers Web Page	https://science.nrao.edu/facilities/gbt/practical-information-for-astronomers
Proposal Writing Tips	http://www.naic.edu/~astro/School/Talks/salter_prop.pdf
GBT General Proposal Information	https://science.nrao.edu/observing/proposal-types
GBT Latest Call For Proposals	https://science.nrao.edu/facilities/calls-for-proposals
GBT Observation Planning	http://www.gb.nrao.edu/~rmaddale/GBT/ReceiverPerformance/PlaningObservations.htm
NRAO Proposal Submission Tool	https://my.nrao.edu/
GBT Sensitivity Calculator	https://dss.gb.nrao.edu/calculator-ui/war/Calculator_ui.html
GBT Spectral Line Wizard	http://wwwlocal.gb.nrao.edu/GBT/setups/configwiz.html
GBT Pointing Strategies	GBT Observer's Guide
GBT 60 Hour Weather Forecasts	http://www.gb.nrao.edu/~rmaddale/Weather/
GBT Mapping Planner	http://www.gb.nrao.edu/ rmaddale/GBT/GBTMappingCalculator.html
GBT VLBA Recorder	https://safe.nrao.edu/wiki/pub/GB/Knowledge/GBTMemos/GBT_Mark5A_S2.pdf
VLBI Information	http://www.gb.nrao.edu/~fghigo/gbtdoc/vlbinfo.html
Mark5 Single Dish Mode	https://safe.nrao.edu/wiki/bin/view/GB/Data/HowToObserveReduceMark5AandS2Data
Astrid	GBT Observer's Guide
GBTIDL	http://gbtidl.nrao.edu
RFI	http://www.gb.nrao.edu/IPG/
Guppi	https://safe.nrao.edu/wiki/bin/view/CICADA/GUPPiUsersGuide
VEGAS	http://www.gb.nrao.edu/vegas/

Table 11: Useful Web Sites for Proposal Writers.