

The National Science Foundation's AST Portfolio Review of 2012 is Not Relevant to the Green Bank Telescope of 2017: A White Paper

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Summary

The National Science Foundation (NSF) Astronomy Division's Portfolio Review of 2012 [21] is no longer relevant to the Green Bank Telescope (GBT) of 2017 for two principal reasons, one instrumental and the other astrophysical: 1) The GBT has begun significant operations in the 3mm band, giving it unrivaled capabilities for spectroscopy and continuum studies over 67-116 GHz. It is now an instrument that is unique worldwide and is a critical complement to ALMA for the U.S. scientific community. These capabilities had not been implemented at the time of the review. 2) The detection of gravitational radiation by LIGO in 2015 places the GBT's work on pulsar observations of nano-Hz gravitational radiation at the forefront of modern astrophysics.

The Green Bank Telescope of 2017 is not the GBT that was reviewed by the Eisenstein-Miller committee in 2012, a review that was specific to the NSF Astronomy portfolio [21]. The GBT serves a wide spectrum of science areas including physics, chemistry, and planetary studies as well as astronomy. Besides its well-documented intellectual merit, it thus has a significant broader impact. The GBT is making significance advances in our understanding of gravitational waves, the equation-of-state of nuclear matter, the mass of supermassive black holes, the value of H_0 , and the physics of star-formation, all key science goals for astronomy identified in a recent National Academy study *New Worlds, New Horizons: A Midterm Assessment* [54]. In the era of ALMA and LIGO, other countries have bolstered their mm-wave and cm-wave facilities; it is critical that U.S. scientists have ready access to a large filled aperture to remain at the forefront of research.

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1. BEFORE THE PORTFOLIO REVIEW: 2001 – 2011

1.1. GBT Instrumental Capabilities

The Green Bank Telescope (GBT) is one of the newest facilities of the Division of Astronomical Sciences (AST) of the National Science Foundation (NSF). At the beginning of its scientific operations in 2001, the GBT was unique in having an active surface that could be used to remove gravitational and thermal distortions in real time [60]. A surface correction of this type had never before been attempted on a radio telescope [32], so its implementation was not part of the construction contract but was left for the NRAO staff to achieve sometime within the first decade of GBT operations [30]. With a passive surface the GBT has acceptable performance at frequencies up to 15 GHz, but it was understood that use of the active surface would allow operations in the 3mm atmospheric window up to 116 GHz [32], where the Green Bank site has good atmospheric conditions for more than 2000 hours a year [40]. Because the style in the United States is to fund telescope construction fully while underfunding the transition to operations [80], it was not until 2010 that the GBT surface panels were adjusted precisely and the active surface was completely operational [33]. At that time the telescope pointing and tracking were also improved.

The GBT construction budget included funding for a suite of receivers covering 0.2 - 50 GHz based on designs from the 1990's [5, 6], and a spectrometer whose design was established at the same time [39, 37, 23]. In 2010, when it finally became possible to use the telescope at 3mm with good efficiency, there was no funding for receivers to operate in this band, so by the start of 2012, GBT operations in the 3mm band were limited to the pathfinder MUSTANG instrument, a 64-pixel bolometer array built by a group at the University of Pennsylvania [19]. It confirmed the GBT's performance at 90 GHz and produced significant results on the formation of galaxy clusters [45], but had a relatively small field of view that limited its general utility, and no spectroscopic capabilities.

It was at this time that the NSF's Eisenstein-Miller Portfolio Review occurred [21].

1.2. The State of Gravitational Wave Astronomy Back in 2012

Gravitational Waves (GW) can be created by a number of sources, and the GW spectrum spans many orders of magnitude in frequency, much like the electromagnetic spectrum. GWs in the nanohertz (nHz) frequency range are expected to arise from supermassive binary black holes in the early stages of inspiral, and potentially exotic sources such as

cosmic strings. They can be detected through variations in the arrival time of pulses from millisecond radio pulsars [42, 68].

Because of its large collecting area, broad sky coverage, sensitive receivers, and location in the National Radio Quiet Zone, the GBT is the world’s premier telescope for the study of pulsars and other compact objects (see §4). Together with the Arecibo Observatory, the GBT is crucial to the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), an NSF-funded North American collaboration working towards a direct detection of nHz GWs [64]. This complements ground-based GW interferometers in the kilohertz window and possible future space-based interferometers in the millihertz window. Pulsar timing arrays are also sensitive to GW bursts with memory, a key but unproven prediction of general relativity [16].

In 2012, at the time of the NSF’s Eisenstein-Miller Portfolio review, direct detection of the GW universe was not possible (see Figure 1). The upper limits on GW amplitude being set by pulsar timing measurements were higher than the amplitude predicted by most theoretical models [15], and initial LIGO operations had concluded without a detection. Advanced LIGO was only beginning to be installed [38].

2. SINCE THE PORTFOLIO REVIEW: 2012 – 2017

2.1. The GBT High-frequency Receiver Development

In early 2012 a 7-pixel receiver for spectroscopy in the 18–26 GHz band (built primarily using non-Federal funds) was put into regular service, and in the spring of 2012 a receiver was also installed to work at the lower end of the 3mm window from 67–92 GHz. This latter “W-band” receiver has only two pixels, too widely spaced for efficient mapping, and was built from existing parts with a modest upgrade in late 2012.

Because of the lack of funding for GBT receiver development in the NRAO operations budget, it is only now, in 2016, that receivers have become available to exploit some of the GBT’s new capabilities. The new receivers are Argus and MUSTANG-2.

Argus is a 16-pixel array for spectroscopy at 75–116 GHz built by a consortium led by Sarah Church at Stanford [71]. MUSTANG-2 is a 211 pixel bolometer array with a 30 GHz bandwidth around 90 GHz, built by a consortium led by Mark Devlin at the University of Pennsylvania [20]. Both were funded through separate competitions in the NSF AST-ATI program. Argus is a testbed for new scalable receiver technologies, while MUSTANG-2 builds on the experience with the earlier bolometer array, MUSTANG, with a significantly

improved design. In support of Argus and other GBT receivers there is a new spectrometer, VEGAS, built by a consortium led by Dan Wertheimer at University of California, Berkeley [13], again funded through a successful competition in the NSF AST-ATI program.

Argus gives the GBT spectroscopic capabilities in the molecule-rich upper frequencies of the 3mm band. Figure 2 shows the first Argus map from the complete 16-pixel array. This ^{13}CO map was made in only 40 minutes in September 2016 in poor weather (zenith $\tau = 0.42$ at 110 GHz). Nonetheless, it demonstrates the unique power of the GBT for high angular resolution wide-field mapping. Argus is heavily oversubscribed and will be in regular use during the 2016–2017 winter season for projects described in §3.1.

MUSTANG-2 has about 4 times more pixels than the original MUSTANG, each with a greater sensitivity. With its wide field of view and better stability, it should be at least 30 times faster. It will be commissioned in the 2016-2017 winter observing season.

The GBT has not yet reached its full potential in the 3mm band. Daytime thermal distortions of the surface and pointing degradation from wind currently limit 3mm operations to calm nights (Appendix A). However, there are straightforward solutions to these limitations that can be achieved at relatively modest cost (\lesssim \$1M). If such funding became available the useable observing time at 3mm could be increased by a factor ~ 2 [61].

2.2. The Changing Landscape of Gravitational Wave Astronomy

The spectacular discovery by LIGO of multiple GW sources in the ~ 100 Hz frequency band has officially ushered in the era of GW astronomy [1], and pulsar timing still continues to be the only tool available for studying the GWs from the evolution of super massive Binary Black Holes (SMBBHs). The NANOGrav collaboration has been achieving its predicted sensitivity and is probing interesting GW phase space, placing severe constraints on the simplest models of SMBBH mergers [3]. The latest NANOGrav results are also beginning to provide independent constraints on parameters such as the eccentricity distribution of SMBBHs or the coupling between SMBBHs and their local galactic environments [3].

While the amplitude of the stochastic nHz GW background now appears less than predicted by the early models, unlike the GW events at ~ 100 Hz probed by LIGO which are appearing at expected levels (Fig. 1), newer models predict that a direct detection of nHz GWs is likely within 5 years and almost certain in 10 years, if the GBT (and Arecibo) continue at their current levels of sensitivity [75]. The GBT is especially important because of its extensive sky coverage which is necessary to detect the correlated signals expected

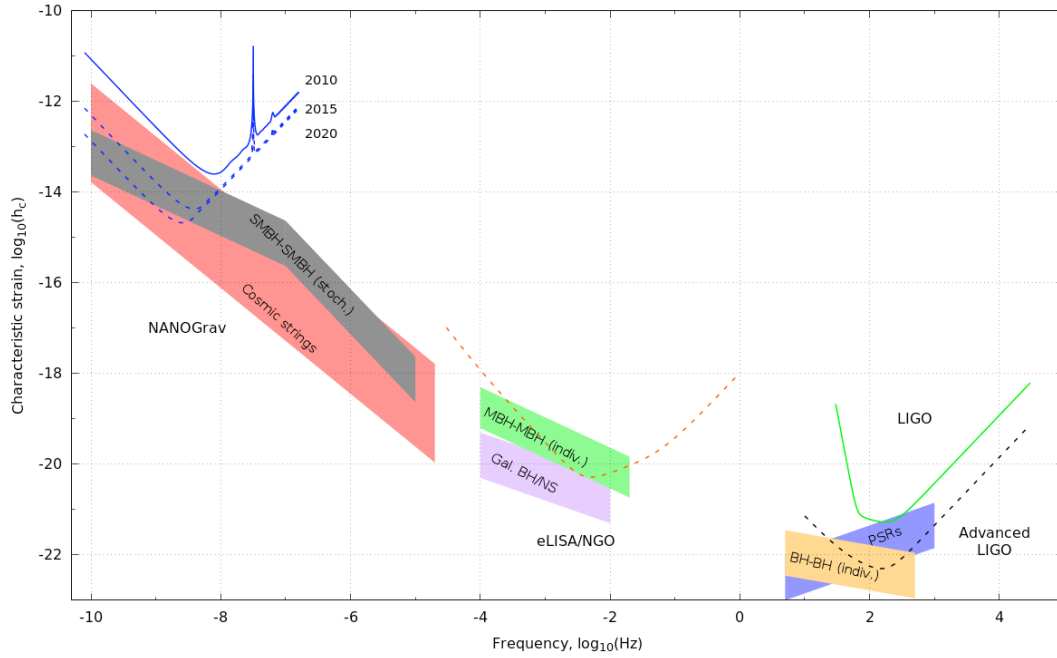


Fig. 1.— This figure, from 2012, shows the state of gravitational wave astronomy at that time. The colored areas show theoretical expectations, and the solid and dashed lines the predicted sensitivity of various experiments. Both Advanced LIGO and NANOGrav have achieved their predicted sensitivities, but in the case of LIGO the theoretical expectations were correct, while for NANOGrav they were not [1, 3]. Newer models predict that a direct detection of nHz gravitational waves is likely within 5 years [75]. eLISA/NGO is not operational. *Figure courtesy of Paul Demorest.*

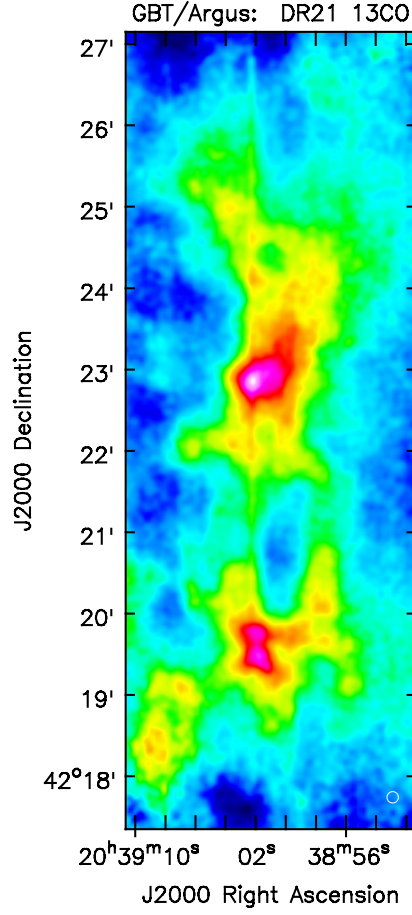


Fig. 2.— Argus map of ^{13}CO around DR 21 made during instrument commissioning in September 2016. Emission is integrated over 10 km s^{-1} . The angular resolution is shown by the small circle at the lower right. The map was made in 40 minutes on the GBT, in poor weather, with a zenith opacity at 110 GHz of $\tau = 0.42$.

from the GW background. The high aperture efficiency of the GBT, its very sensitive receivers, and relative freedom from interfering signals make it 2 to 4 times faster for pulsar timing than the JVLA [64] (see also §3.3).

3. THE ROLE OF THE GBT IN US SCIENCE: 2017 ONWARDS

3.1. Spectroscopy at 3mm: A Critical Complement to ALMA

The new Argus camera is demonstrating the unique capabilities of the GBT in the 3mm atmospheric window, which contains a very large number of important spectral lines including the ground-state transitions of CO and its isotopologues, as well as HCO⁺, SiO, HNC, N₂H⁺, CS and HCN. The scientific significance of this band has been documented exhaustively (e.g., [26, 49]). The GBT now offers the high sensitivity of a filled aperture with an angular resolution of 6''-10'', well-matched to the mid- and far-infrared observations from the Spitzer, SOFIA, and Herschel telescopes. The GBT is ideal for resolving cold cores within local star-forming regions, tracing the dynamics of molecular filaments, and for mapping giant molecular clouds in nearby galaxies. Its powerful wide-field mapping capabilities for 3mm spectroscopy are unique, and unrivaled worldwide. The GBT provides a wide-field complement to ALMA and can supply critical short-spacing data [9] for 3mm synthesis observations.

Table 1 compares the time it would take to reach a Ta* noise limit of 20 mK in a 3' × 3' field for the current single-pixel receiver on the GBT, for the 16-pixel Argus, and for a 50-pixel receiver that could be built with existing technology, in comparison with ALMA and the proposed ngVLA [11]. Green Bank has acceptable observing conditions for 3mm

Table 1. Time to map spectra at 86 GHz over a 3' × 3' field to 20 mK rms^a

GBT 2015	Argus 2015	GBT 2020	ALMA	ALMA	ALMA	ngVLA
1 Pixel	16 Pixels	50 Pixels	50x12m	50x12m	10x7m	300x18m
8''	8''	8''	3''	1''	23''	1''
21h	3.3h	< 1h	19h	1,500h	0.5h	17,500h

^aFor $\delta = 0^\circ$, 1 km s⁻¹ channels, GBT Ta* 2000 h/yr opacity, ngVLA tapered to 1'' resolution at 80 GHz for the Clark/Conway configuration [11]. GBT2020 has dual polarization. ALMA numbers from the ALMA sensitivity calculator on 10 July 2016. No allowances for overhead.

spectroscopy for more than 2000 hours each year [40], during which the GBT’s 86 GHz receiver has a system temperature at zenith about equal to that of ALMA (Appendix A). It is clear that the GBT occupies a critical place in U.S. 3mm instrumental capabilities.

The GBT at 3mm is now making contributions to areas as diverse as the distribution of dense molecular gas in nearby galaxies and the structure of the jet of M87 [35, 29]. General science areas where it will contribute in coming years include interstellar chemistry, comets, the context of star formation, stellar outflows, Galactic molecular clouds and complexes, molecules in nearby galaxies, and molecules in galaxy clusters.

Approved Argus projects for the GBT winter observing of 2016–2017 include:

- Measurement of the physical conditions and kinematics in star-forming filaments;
- Surveys of the infall and fragmentation in dense pre-stellar cores;
- Study of the transition between atomic and molecular gas in the Galactic halo;
- Tests of theories of fragmentation in interstellar filaments;
- Investigation into the formation paths of organic molecules in protostars;
- Characterization of the distribution of dense molecular gas in nearby galaxies.

The technical path to a 50 pixel camera for the GBT at 3mm is straightforward and follows from existing technology and precursors like Argus. Such an instrument would transform our understanding of many fields, open up new areas of research, and, at relatively modest cost, add significant capability to the ensemble of U.S. astronomical facilities (Table 1). The focal plane of the GBT can support 3mm cameras with many hundreds of pixels without significant coma or gain loss [41]. Phased-array-feed technology, though still in engineering tests at this time, may lead to multi-pixel receivers for highly efficient spectral line mapping in this band [22].

3.2. Ultra-sensitive 3mm Continuum Studies: Dust and the SZE

The pathfinder MUSTANG showed that the GBT was a unique instrument for 90 GHz continuum studies which include high angular-resolution mapping of the Sunyaev-Zel’dovich Effect (SZE) in galaxy clusters [45, 36, 53] and measuring the physical properties of interstellar dust [69]. MUSTANG-2 is expected to have a factor of 30 improvement in speed as well as increased stability. Table 2 compares the wide-field continuum mapping capabilities of MUSTANG-2 with ALMA and the ngVLA. Note that neither Table 1 nor Table 2

accounts for the time needed to obtain the short-spacing data that must be added to the interferometer observations to restore all the flux in the field.

MUSTANG-2 will produce a high-resolution ($9''$) $62 \mu\text{K}$ rms image of the SZE in a galaxy cluster in just one hour. In the course of a winter observing season it could image hundreds of massive clusters. In 2 hours it will measure the pressure profiles in the inter-cluster medium to a radius of $3'$ in systems as small as $4.5 \times 10^{14} M_{\odot}$. It can image the cavities found in X-ray emission from clusters much faster than ALMA while recovering emission on scales larger than ALMA's $\sim 1'$ field of view at 3mm.

MUSTANG-2 will be a science pathfinder for ALMA and JWST, mapping large areas to identify sources for studies of galaxy formation in the high-redshift Universe. Its can detect ~ 5000 sources per square degree down to the confusion limit, providing constraints on star formation rates at $z > 5$. For Galactic studies, in just a few hundred hours on the GBT MUSTANG-2 can make a $10,000 \text{ deg}^2$ survey of the Galaxy to a 5σ completeness limit of 8 mJy , complementing surveys from Herschel, Bolocam, and Planck. As Table 2 shows, the GBT is a powerful and unique instrument for continuum studies at 3mm.

3.3. Gravitational Radiation and Fundamental Physics: 2017 Onwards

The GBT will continue to be the premier telescope for pulsar astronomy because of its sensitivity, sky coverage, and relative freedom from RFI afforded by the unique National Radio Quiet Zone. In a direct comparison, the GBT proved to be from 2 to 4 times

Table 2. 3mm Continuum rms noise over a $5' \times 5'$ field in 1 hour^a

GBT MUSTANG-2 $9''$	ALMA 50x12m $3''$	ALMA 50x12m $1''$	ALMA 10x7m $23''$	ngVLA 300x18m $1''$
$62 \mu\text{Jy}$ $0.062 \text{ mK}^{\text{b}}$	$49 \mu\text{Jy}$ 0.9 mK	$49 \mu\text{Jy}$ 8.0 mK	1.35 mJy 0.12 mK	$65 \mu\text{Jy}$ 13.0 mK

^angVLA values for a 30 GHz bandwidth at 80 GHz tapered to $1''$ resolution [11]; ALMA for 7.5 GHz band around 86 GHz; MUSTANG-2 for 75-105 GHz [20]. No allowances for overhead.

^bThis is T_{a}^* . To convert to T_{mb} use a factor 1.25 (including stable error beam) or 1.74 (main beam only).

faster than the JVL A for pulsar timing despite the larger collecting area of the JVL A [64]. Searching for new pulsars using the JVL A is not practical because of extreme computational complexity.

Ongoing surveys and follow-up of unidentified Fermi sources are discovering ~ 4 new millisecond pulsars a year that are being added to the NANOGrav sample [64]. As the sensitivity to GWs is proportional to the number of pulsars in the timing array, the steady rate of discovery is one of the main reasons that NANOGrav is achieving its predicted improvements in sensitivity. A new ultra-wideband receiver ($\sim 0.7 - 4$ GHz) could improve NANOGrav sensitivity on the GBT by as much as a factor of two by reducing the uncertainties arising from interstellar scattering. This receiver would also be extremely useful for studies of transient sources such as Fast Radio Bursts and other pulsar timing experiments that probe extreme physics, an area where the GBT is beginning to contribute [46].

GW astronomy was unproven in 2012, but in 2017 is a fully realized observational window with demonstrable results and paths for improvements in sensitivity. The GBT is at the forefront of the direct detection of nHz GWs in the next decade, but detection is only the first step. Pulsar timing arrays like NANOGrav are informing our knowledge of SMBBH mergers including the solution to the “final parsec” problem [51, 67], and will continue to do so. As the sensitivity of NANOGrav improves, it could measure the properties of individual SMBBH systems and anisotropies in the GW background [52]. These measurements are also the best way of testing the existence of cosmic strings [68]; the latest constraints significantly surpass the limits from the Planck satellite [3].

4. COMPLEMENTARY CURRENT GBT SCIENCE

In addition to the science described above, the GBT continues to be significantly oversubscribed [73, 74] for a broad range of research that takes advantage of its unique capabilities at frequencies below 50 GHz. The following list gives a representative sample of recent GBT research that cuts across many disciplines:

Chemistry — With its high sensitivity to low surface-brightness, the GBT has been used to discover ≈ 20 new interstellar organic molecules including C_6H^- , the first interstellar anion [47], and Propylene Oxide, the first interstellar chiral molecule [48].

Solar System — The GBT is used regularly as the receiving element of bi-static radar programs to study Lunar geology [10], the rotation state of planets and their satellites [44], and the structure and orbit of near-Earth objects [4]. One program reported conclusive

evidence for a liquid core in the planet Mercury [43]

Star formation — GBT observations often serve as the pathfinder for higher-frequency or higher-resolution observations with the JVLA and ALMA. The GBT has studied the evolution of dense cores in filamentary clouds [70], and determined their evolutionary state through abundance changes in long carbon-chain molecules [25]. Wide-area mapping in transitions of NH_3 has measured the gas dynamics, temperature, and chemistry in star-forming regions [66], and identified areas where turbulence dissipates prior to star formation [59]. More than 1,000 new Galactic HII regions have been discovered [2].

Stars — The GBT provided the critical sensitivity for VLBI parallax measurements that determined an accurate distance to the Pleiades [50]. A companion star to a pulsar studied with the GBT is the coolest known white dwarf, with an implied age ~ 10 Gyr [34].

Galaxies — The GBT has made extremely sensitive observations of HI in dwarf galaxies [72], measured very faint neutral circumgalactic gas [78], and detected H_2O masers in the disk of M31 [17]. GBT surveys of HI in galaxies revealed the structure of the local Universe [76]. The GBT has discovered H_2O megamasers around galactic nuclear accretion disks [27], probed the physics of accretion disks [58], and measured the mass of numerous supermassive black holes with errors below one percent [27, 28]. Megamasers give an independent measurement of the Hubble constant from simple geometry [7].

Fundamental physics — The GBT is used to place limits on violations of the equivalence principle [63], to limit variations in the gravitational constant G outside the Solar System [79], and to measure general relativistic effects in the strong field approximation [8]. Discovery of a $2M_\odot$ pulsar with the GBT limits the equation of state of matter in its densest form [18, 57]. The importance of the GBT to the nuclear astrophysics community was emphasized in a recent white paper [77].

5. THE GBT AND THE U.S. SCIENTIFIC COMMUNITY

The GBT serves a large and diverse scientific community who work in astronomy, chemistry, planetary science, physics, STEM education, and related fields [14].

The GBT provides critical capabilities not otherwise available to U.S. scientists, and is in high demand [73, 74]. In the three years 2013–2015 the telescope was used by more than 950 individual scientists and their students. A typical GBT proposal in that period had five investigators, one of whom was a student, and one of whom was from an institution outside the U.S. The user community is growing. Nearly 750 individuals proposed to use the GBT

in 2016, 337 of whom had not used the GBT in 2013–2015. This is a substantial increase from the 600 individuals who proposed to use the GBT in 2012. Its new capabilities at 3mm ensure a continued growth in the GBT user community.

The GBT is a unique facility available to scientists for developing new instrumentation [13, 19, 20, 22, 31, 71] and new astronomical techniques (e.g., HI intensity mapping [12]). It also offers opportunities for hands-on training in astronomical observing methods [e.g., NRAO eNews 5, 7], an increasingly rare resource at all wavelengths [56]. While other nations are bolstering their mm-wave and cm-wave facilities in response to ALMA and LIGO [55, 24], the U.S. is closing or reducing access to its facilities.

The GBT is integrated into a broad program of Education and Public Outreach to the more than 40,000 visitors who come to the Green Bank Observatory each year. Programs include science teacher training, hands-on use of radio telescopes by K-12 students and their teachers, programs for amateur astronomers, visiting college professors and tourists, among others. The Pulsar Search Collaboratory has involved more than 2,000 high school students and more than 100 teachers in the analysis of GBT data resulting in the discovery of seven new pulsars [62, 65]. The GBT is a rare public showcase for NSF-funded science.

6. CONCLUSION

The National Academies study *New Worlds, New Horizons: A Midterm Assessment* [54] highlighted the importance of measuring gravitational waves, constraining the equation-of-state of nuclear matter, determining the mass of supermassive black holes, determining H_0 , and understanding the physics of star-formation, as key science goals for astronomy. All of these key areas are currently being advanced using the GBT, e.g., [3, 18, 28, 27, 7, 59, 25, 70].

The NSF’s Astronomical Sciences Portfolio Review of 2012 has been overtaken by subsequent events, both scientific and instrumental. Its conclusions with respect to the Green Bank Telescope are no longer relevant to the needs of the U.S. scientific community in 2017.

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Appendix A: Atmospheric Conditions at Green Bank for 3mm Observations

Atmospheric opacity is the fundamental limit on use of the GBT in the 3mm band, and results from many years of monitoring are presented in GBT memo 267 [40]. In summary, at 86 GHz there are extensive periods of acceptable atmospheric opacity ($\tau < 0.2$) throughout the entire year, but especially in the winter observing season between 1 October and 1 May. During this time there are typically 1300 hours for which $\tau < 0.1$, and 2000 hours for which $\tau < 0.14$. These periods are predictable several days in advance. GBT data in Table 1 are for $\tau = 0.14$. (GBT data in Table 2 are derived from experience at the GBT with MUSTANG.) The opacity rises rapidly toward the lower and higher frequency edges of the 3mm band because of absorption by Oxygen.

There are also considerations of wind. Most nights during the winter season have a mean wind speed low enough to permit accurate GBT measurements throughout the 3mm band with the current GBT optics and control systems. All in all, there are currently ~ 1000 hours of “photometric” quality conditions ($\tau < 0.1$ at 86 GHz) during each winter season that also have low wind-induced pointing errors. Wind-induced errors could be reduced by improvements to the GBT optics and servo systems.

At 86 GHz the current single-pixel GBT receiver has a receiver temperature ~ 50 K, and an atmosphere with a zenith opacity $\tau = 0.1$ adds 27 K of noise, so counting all contributions, the zenith Tsys is ~ 85 K for > 1000 hours each year, a Tsys comparable to that of ALMA at this frequency.

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