Astro2020 APC White Paper

Advanced Capabilities for the Green Bank Telescope

Type of Activity:
■ Ground Based Project ☐ Space Based Project ☐ Infrastructure Activity
☐ Technology Development Activity ☐ State of the Profession Consideration ☐ Other

Summary: We describe projects to advance the capabilities of the GBT in survey speed, bandwidth, interference mitigation, preservation of legacy data, and community access. These upgrades will impact the study of GW and MM astronomy, fundamental physics, FRBs, cosmology, star formation, astrochemistry, distant galaxies, and searches for technosignatures.

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1 Overview

The Robert C. Byrd Green Bank Telescope (GBT) is a unique resource for the US and global astronomical communities. The combination of its fully steerable 100-m unblocked aperture, active surface, 0.29–116 GHz nearly continuous frequency coverage, flexible instrumentation, and location in two different interference protection zones are not found in any other single telescope. This makes it one of the world's premier telescopes for studying low-frequency gravitational waves, multi-messenger astronomy, fundamental physics, fast radio transients, cosmology, star formation, astrochemistry, gas in galaxies, and in the search for technosignatures.

The GBT was built to be flexible and continuously upgraded to meet the needs of the astronomical community (e.g. opening the 3-mm band over the past decade). In this white paper, we present several projects that would expand the GBT's performance in four key areas of survey speed, point source sensitivity, radio frequency interference (RFI) protection, and accessibility and preservation of legacy data. These projects are:

A. Expanding the instantaneous field of view (FoV) of the GBT with advanced **radio cameras**.
B. Increasing the instantaneous bandwidth of the GBT by developing **ultrawideband analog and digital instruments**.
C. Preserving scientific data quality while **sharing the radio spectrum** with a growing number of private, commercial, and civil users through better identification and excision of RFI.
D. Ensuring long-lasting public access to GBT data through a **multi-petabyte data archive and high-performance processing tools**.
E. Providing **increased funding for peer-reviewed use of the GBT** for the U.S. astronomy community.

Each of these projects are categorized as small (<\$20M), can be carried out independently, and would have significant scientific impact. Taken together, however, they would have a transformative impact on a broad range of GBT science, and will continue the GBT's role as a key single-dish complement to existing and upcoming radio arrays, at the level of a medium-scale project (\$20–\$70M). We refer to this collected package of upgrades as the *advanced GBT* (A-GBT)[1].

2 Key Science Goals and Objectives

2.1 The Low Frequency Gravitational Wave Universe and Multi-messenger Astronomy

Detecting Gravitational Waves via Pulsar Timing Arrays: The coming decade will witness the detection and characterization of the nanohertz-frequency gravitational wave (GW) universe via observations of radio millisecond pulsars [1, 2]. In North America this effort is being led by the NANOGrav Physics Frontiers Center (PFC), primarily using the GBT and the William E. Gordon Telescope at the Arecibo Observatory [2]. Pulsar timing arrays (PTAs) are on-track to detect a stochastic GW background from supermassive binary black holes (SMBBH) early in the

[1] Additional details about each project and a full list of relevant science white papers can be found at https://greenbankobservatory.org/science/astro2020/

next decade [1, 2], and are already placing important constraints on models of SMBBH evolution and coupling to the surrounding galactic environments [3, 4, 5, 6, 7, 8]. The detection of individual SMBBHs will follow later in the decade [9, 10], enabling multi-messenger (MM) studies of SMBBH systems [11, 12]. Pulsar timing will provide orbital periods and chirp masses for SMBBHs that will inform time-domain searches for EM counterparts [13]; alternatively, candidate SMBHHs found in the EM band will enable sensitive searches for GW signatures via pulsar timing. MM observations will elucidate BH spins, eccentricity, coupling to the surrounding environment, and will allow the systems to be used as "standard sirens" [11]. PTAs also places the most stringent existing limits on the energy density of cosmic strings [6] and other physics beyond the standard model [14]. The larger instantaneous bandwidth of the A-GBT will help reduce systematic TOA errors arising from time-variable dispersive delays caused by the ionized interstellar medium [15]. This has the potential to increase pulsar timing precision by a factor of two [2]. Further increases in GW sensitivity come from finding new pulsars, which requires access to the GBT for large-area surveys. Better RFI detection and excision will also improve TOA measurements and greatly simplify post-processing. The optimal observing frequencies for most pulsars are from a few hundred MHz to few GHz [16], which is heavily populated by sources of RFI.

EM Follow-up of GW Events: LIGO (and eventually LISA) will detect many individual GW events per year, representing a vast discovery space [17]. Resolved imaging of these mergers using VLBI is the only direct way of mapping the kinematic distribution of the ejecta [18]. The GBT plays a critical role in VLBI follow-up: it is typically the first or second most sensitive telescope in the array and contributes to the highest angular-resolution measurements along with telescopes in the Southwest and Europe [19, 20]. While EM studies of GW events have been confined thusfar to cm-wavelengths, the A-GBT will excel at exploring EM counterparts at mm-wavelengths. The combination of the current GBT and ALMA is already more sensitive by >20x than any other instrumental combination for high-resolution imaging at 3-mm [21, also see Fig. 1]. Straightforward receiver upgrades will improve point-source sensitivity even further.

2.2 Fundamental Physics

Tests of gravity and ultra-dense matter: Pulsars can be used to test theories of gravity and compact matter at otherwise inaccessible energy scales. Binary pulsars have been used to measure high-order relativistic effects [22, 23, 24], to place limits on tensor-scalar-vector gravity theories [25] and to test the strong equivalence principle [26]. Neutron star masses measured through pulsar timing have substantially constrained quark-matter models for the equation of state (EoS) of dense matter [27, 28]. Pulsar surveys are still sensitivity limited and there are no doubt other excellent physical laboratories waiting to be discovered. Among these may be pulsar-black hole binaries, sub-millisecond pulsars, and ever more massive neutron stars that can definitively determine the dense matter EoS. New pulsars can also be found in archival data by applying more computationally intensive analyses that only become feasible at large scale with better computing resources [e.g 29]. The A-GBT will provide more precise pulsar timing measurements that will in turn lead to more precise tests of fundamental physics. Effectively removing RFI is especially important in blind searches for new pulsars, as many sources of RFI can mimic pulsar signals. Public access to existing and future survey data will allow the community to experiment with and apply innovative new algorithms for finding pulsars [e.g 30].

Changes of fundamental constants: The frequencies of atomic and molecular lines arising from different physical processes (e.g. Lambda-doubling, hyperfine structure, etc.) depend differently on combinations of physical constants. Accurate measurements of multiple transitions in the same galaxy can thus be used to derive the value of these constants at different cosmological epochs and locations. Major progress in this field awaits a large sample of appropriate transitions spanning a wide range of redshift. The A-GBT's upgraded receivers will greatly enhance searches for transitions of HI, OH, NH_3, CH_3OH, CO, and HCO^+.The next decade will see significant progress in astronomical studies of fundamental constant evolution [31].

2.3 Fast Radio Bursts

Fast radio bursts (FRBs) are millisecond duration radio-frequency pulses that originate in distant galaxies [32, 33]. Their physical origin is one of the most pressing mysteries in astronomy and will be a major area of research in the coming decade [34]. Hundreds of FRBs are being discovered by wide-field survey telescopes such as CHIME [35] and ASKAP [36], but to-date, only two repeating FRBs appear in the literature [37, 38]. The first and best-studied repeater is FRB 121102, which exhibits dramatic burst-to-burst spectro-temporal variation [39]. Any theory regarding the nature of repeating FRBs must explain these wide-band properties, so they serve as a powerful diagnostic tool for understanding FRBs' physical origins. A better understanding of FRBs will require both statistical analyses of a large population and more intensive follow-up of a small number of individual objects. The wider bandwidth of the A-GBT will make it an excellent instrument for carrying out detailed follow-up of repeating FRBs. A public data archive of high time resolution snapshots of the sky will also enable archival searches for FRBs and other novel phenomenon as new processing techniques arise.

2.4 Cosmology

The Sunyaev-Zel'dovich (SZ) effect has only recently become a mature tool for performing high resolution studies of the warm and hot ionized gas in and between galaxies, groups, and clusters. Galaxy groups and clusters are powerful probes of cosmology, and they also serve as hosts for roughly half of the galaxies in the Universe. In the next decade, the A-GBT will allow for advances in our understanding of thermodynamic and kinematic properties of the warm-hot universe through spatially and spectroscopically resolved measurements of the SZ effects at $10''$ resolution [40].

Sehgal et al. [41] propose an extremely deep (0.5 μK), high resolution ($10''$) sky survey to provide major advances in a number of areas, including gravitational lensing of the primordial microwave background to map out the distribution of matter on small scales (k $\sim$ 10 hMpc^{-1}) and the measurement of the thermal and kinetic SZ effects on small scales to map the gas density and gas pressure profiles of galaxy clusters and groups. The GBT is currently capable of such maps, and planned improvements will simply enhance its ability in this area.

2.5 Star Formation

A fundamental question in astronomy is how stars form, and how this impacts the formation of planetary systems and the evolution of galaxies over time. The mechanisms that regulate star formation span a huge range of spatial scales, from the sub-parsec scales on which individual stars form to the the kiloparsec scales of galactic encounters. Molecular transitions of NH_3, CO, HCN,

N_2H^+, and HCO^+ are important tracers of gas at different temperatures and densities. While telescopes like ALMA provide excellent sensitivity to dense, compact structures, single-dish telescopes like the GBT are essential for mid-sized to large spatial scales.

Radio cameras on the A-GBT operating in the 18–26 and 74–116 GHz ranges will significantly increase survey speeds of star forming regions, complementing ALMA and future telescopes like the ngVLA. Such cameras have FoVs comparable to those of interferometers and are thus well-suited to use as short-spacing complements to those observations, as well as standalone instruments.

2.6 Astrochemistry

In the last several years, significant advances in our knowledge of complex chemical inventories have suggested that there may be a substantial reservoir of undetected interstellar carbon that influences the star and planet-formation process from its earliest stages. These carbon sinks as well as other topics in astrochemistry such as the formation and transport of complex molecules from the ISM to star and planet-forming cores, and their connection to molecules of biological interest, will be studied intensely with the GBT [42, 43, 44, 45]. The important instruments will be interferometers working in the 100+ GHz range, and the GBT covering frequencies from 20–116 GHz with wide bandwidth, high spectral resolution, angular resolution of $< 10''$–$20''$, and a large FoV.

2.7 Gas in Galaxies

The GBT has the unique ability to study both extremely low surface brightness HI [e.g. 46] and CO(1-0) at 2.6-mm [47] in nearby galaxies. Tracing the flow of faint, diffuse gas from the circumgalactic medium (CGM) into galaxies in the local universe is a major goal of the next decade [e.g. 48], and L-Band cameras on the GBT will extend previous surveys of extremely low surface brightness HI throughout the virial radius of numerous galaxies. This has the potential to complete the census of HI in the CGM. Observations of fainter dense gas tracers, such as HCN and HCO^+ provide a better understanding of the physical processes connecting dense molecular gas with ongoing star-formation activity [49]. The GBT has played an important role in studying the evolution of gas in the early universe by using CO(1-0) to measure redshifts and the molecular gas content of systems uncovered by *Herschel* [e.g. 50] and *Planck* [e.g 51]. The GBT can also provide the required wide-area imaging of extended CO and [CI] emission that is needed to study the cold gas supply fueling the formation of massive galaxies from the surrounding CGM within young proto-cluster environments at high redshift [52].

2.8 Search for Technosignatures

In [53], the question is asked "How can future searches [for technosignatures] be optimized to enhance the probability of detection?" The clear answer is the need for continued sensitive searches within the radio realm. Radio SETI has so far managed to continue its efforts by appealing primarily to the private sector for funding, such as the Breakthrough Listen initiative [54, 55, 56]. The next decade will see the completion of the largest ever technosignatures search [54, 55, 56] and the potential of even more sensitive surveys of larger areas of the sky through the use of wide band feeds and radio cameras ([57]; also see "Searches for Technosignatures: The State of the Profession" white paper by J. Wright).

3 Technical Overview

Telescope and Observatory Architecture: The A-GBT will take advantage of site and telescope infrastructure that is already in place, well tested, and well understood. The GBT has a 100-m diameter unblocked primary reflector with an active surface that can maintain an RMS surface accuracy of 230 μm under stable thermal conditions. This surface accuracy yields good observing efficiency at frequencies as high as 116 GHz. The unblocked aperture results in an extremely clean point spread function allowing high dynamic range observations of diffuse emission. The GBT can observe declinations as low as $-47°$, covering 85% of the entire celestial sphere. Green Bank Observatory (GBO) experiences approximately 2,000 hours per year with atmospheric opacity suitable for observing in the 70–116 GHz and near the 22 GHz water line, and the GBT is scheduled dynamically to take full advantage of these conditions [58].

The GBT's suite of low-noise radio receivers provides nearly continuous frequency coverage from 0.29–116 GHz, and its spectrometer can process up to 4–8 GHz of instantaneous bandwidth (exact limits depend on receiver). The GBT has four multi-pixel receivers: the K-Band Focal Plane Array (KFPA; developed by GBO), the Argus 3-mm receiver (a facility instrument developed via University partnership), the MUSTANG2 90 GHz bolometer (an open-use PI instrument), and the Focal L-Band Array for the GBT (FLAG, a PI instrument developed via University partnership), a pathfinder cryogenically cooled phased array feed (PAF) receiver that currently holds the sensitivity record for a PAF.

GBO is surrounded by the National Radio Quiet Zone and West Virginia Radio Astronomy Zone, which provide regulatory protection against fixed transmitters that may adversely impact the GBT. The radio quiet zones are invaluable resources but they do not protect against mobile ground or space-based transmitters. Satellite communications and the prevalence of always-on wireless devices cause significant RFI. While this has historically had the greatest impact at frequencies below 3 GHz, the rise of automotive radar, 5G, and new wireless bands will result in significant RFI at higher frequencies, especially from 20–30 GHz.

GBO operates a state-of-the-art electronics and digital development lab, specializing in the design of low-noise cryogenic receivers and FPGA-based wideband digital backend systems. The GBO machine shop builds nearly all feed horns, dewars, RFI enclosures, and other components.

The A-GBT will leverage all of the above infrastructure and capabilities. We describe each of the A-GBT projects in more detail below.

3.1 Ultrawideband Analog and Digital Systems

Recent advances in feed design and broadband low noise amplifiers (LNAs) have led to the deployment and scientific validation of so-called ultrawideband (UWB) receivers with bandwidth ratios approaching 6:1 or greater [59]. GBO is actively developing a 0.7–4 GHz UWB receiver for the GBT with the primary science goal of improving sensitivity to low-frequency GWs and broad-band fast transients (see §2.1–2.3). Secondary science goals include the study of radio recombination lines and molecular spectroscopy.

The first phase of operations with the UWB receiver will make use of existing signal transport

Table 1: Expansion of GBT Receiver Bandwidth

Receiver	Frequency Range (GHz)	Current Max. BW (GHz)	Potential Max. BW (GHz)	Factor Increase
7-pixel KFPA	18.0–27.5	1.8	9.5	5.3
Ka-Band	26.0–31.0	4.0	13.5	3.4
Q-Band	39.2–49.8	4.0	10.6	2.6
W-Band	67.0–74.0	6.0	26.3	4.4–6.6
W-Band	73.0–92.0	4.0		
16-pixel Argus	74.0–116	1.5	8	5.3

Note — GBT receivers operating below 18 GHz are not bandwidth limited. A wide-band 8 GHz mode exists for KFPA but can only use one pixel. The maximum BW of Argus is determined by integrated receiver components.

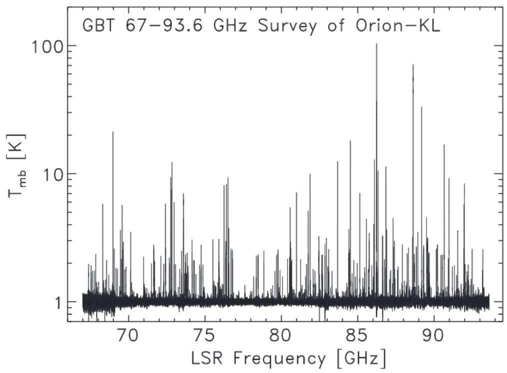
infrastructure and back-end instruments. However, RFI is prevalent at these frequencies, and there is already evidence that some of these sources of RFI can cause non-linear behavior in the GBT's analog signal path (see §3.3). GBO has started R&D on new high-speed and high-dynamic range analog-to-digital converters (ADCs) that can sample up to 5 GHz of bandwidth at 12-bits, along with related technologies. This will enable direct digitization of the entire bandwidth provided by the UWB receiver with a minimum of analog components, creating a much more robust and stable system in the presence of strong RFI.

The UWB receiver and accompanying digital upgrades will serve as a pilot program for future A-GBT upgrades. Receivers operating above 18 GHz could provide $\gg 8$ GHz of instantaneous BW but are limited by existing analog filters to 4–6 GHz in most cases. The analog signal transport system is also susceptible to environmental changes that can be a limiting factor for very deep observations. The proposed digital technology has the potential to eliminate nearly all of these restrictions. Bypassing the analog restrictions on bandwidth and digitally sampling the full available frequency range of the GBT's receivers could lead to as much as *a factor of 6.6 increase in survey speed when observing widely spaced spectral lines* (see Table 1 and Fig. 1) and improve spectral baselines. This would be a transformational modernization of the GBT, analogous to the upgrades of the Jansky Very Large Array, and would revolutionize all areas of GBT science.

Key Performance Requirements: *For the UWB receiver:* Measurements of pulsar dispersive delays with fractional uncertainty $\leq 10^{-5}$; sensitivity over frequencies of interest for FRBs (anywhere from 0.3–8 GHz). *For UWB digital upgrades:* digital sampling of up to 26 GHz bandwidth (in multiple subbands) with high dynamic range.

Technical Requirements: *For the UWB receiver:* $T_{\rm sys} \leq 30$ K and total efficiency $\eta = 0.5$–0.7 from 0.7–4 GHz. *For the UWB digital upgrades:* Sampling rates up to 10 Gsps with up to 12-bit precision, support for data rates up to 500 Gbps.

Public/Private Partnerships: The GBO UWB receiver is funded in part by the Gordon and Betty Moore Foundation through Grant GBMF7576 to Associated Universities Inc. to support the work of the GBO and the NANOGrav PFC. GBO was recently awarded an NSF ATI grant to support the



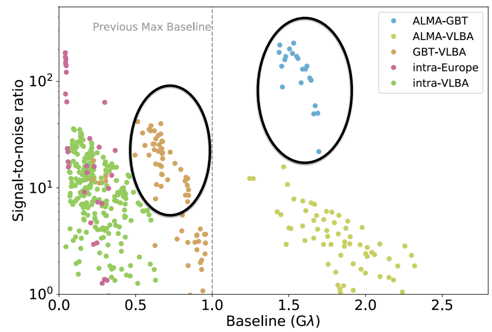


Figure 1: *Left:* A spectrum of Orion-KL observed with the GBT's W-Band receiver. These observations required ten spectrometer set-ups. The proposed wideband upgrades would allow it to be done with one [60]. *Right:* The S/N of 3-mm VLBI observations of Sgr A* vs. baseline. Antenna pairs including the GBT are circled (note the logarithmic scale). Data including the GBT is 20x the S/N of other instrumental pairs [21]

first phase of development of wideband digital hardware (as well as new RFI excision techniques).

Technology Drivers: The UWB receiver is made possible by new quad-ridge feed designs with excellent performance over the frequencies of interest, as well as wide-band LNAs such as Low Noise Factory LNF-LNC0.2_3A. The Analog Devices AD9213 and Xilinx Vertex UltrScale+ FPGA VCU118 kit are representative of the next generation of technology that will enable digital sampling closer to the output of the receivers.

Current Status and Schedule: The UWB receiver is finishing preliminary design and a prototype will be built and tested by the end of 2019. Scientific commissioning will begin in late 2020 or early 2021. GBO has started the first phase of R&D with the VCU118 development kit. Development will begin with the AD9213 starting in Q4 of FY2019. The second and third phases (not yet funded) would integrate a digital signal transport system with the UWB receiver, followed by additional GBT receivers.

Cost Category: Small (<$20M)

3.2 The Radio Camera Program and Upgraded Receivers

FLAG2: FLAG is the first operational cryogenically cooled PAF receiver and the most sensitive PAF receiver in the world. It samples the focal plane of the GBT using 19 dipole elements, and its digital beamformer produces seven Nyquist-sampled beams on the sky with a bandwidth of 150 MHz. FLAG2 will have four times the survey speed of the original FLAG and more bandwidth, providing a powerful survey instrument for pulsars, FRBs, and HI. FLAG2 will be an excellent all-sky complement to the NSF-funded ALPACA PAF being developed for the Arecibo Observatory.

Key Performance Requirements: 40–50′ FoV; 300 MHz bandwidth tunable within a 440 MHz window; flexible data products appropriate for both pulsar and FRB surveys (high time and moderate frequency resolution) and spectral line surveys (moderate time and high frequency resolution).

Technical Requirements: 80 dipole elements providing dual polarizations; $T_{\rm sys}/\eta \approx 35$ K; 40

formed beams on-sky; 2.4 Gsamp/s direct sampling with 12-bits

Partnerships: FLAG2 is a collaboration between GBO, Brigham Young University, and West Virginia University

Technology Drivers: New LNAs developed by S. Weinreb (Caltech) achieve 12-15 K noise temperature without cryogenic cooling, vastly simplifying the design and operation of the receiver. The digital signal transport system will also be more robust than the current FLAG receiver by taking advantage of Xilinx RF system on chip FPGAs.

Current Status and Schedule: A detailed design has been developed for FLAG2, and the core technologies have been demonstrated on FLAG and other PAFs built by the same team. The project will take three years to complete and deploy on the GBT.

Cost Estimate or Category: Small (<$20M)

Radio cameras operating at 18–26 and 74–116 GHz are the topic of two separate APC white papers, so we provide only a brief overview here. For details, see "A Beam-Forming Array for the GBT at K-Band" by L. Morgan et al., and "Argus+: Wide-field, High Resolution 3-mm Molecular Imaging" by D. Frayer et al.

A Beam-Forming Array at 18–26 GHz: The K-Band PAF receiver will be capable of forming 225 independent, Nyquist-sampled beams which will dramatically increase the mapping capability of the GBT from 18–26 GHz. This instrument will be ideally suited to the size scales found in star-forming regions and will complement continuum studies such as *Herschel's* SPIRE program with kinematic and accurate temperature measurements. It will provide $\lesssim$0.1 K RMS noise in 0.1 km s^{-1} channels, with a system temperature $\leq$50 K and formed beam efficiency of 0.61. The project is in the preliminary design phase but builds off of experience with the existing FLAG instrument on the GBT, and is categorized as a small project (<$20M).

Argus+: Argus+ is a proposed 144 feed-horn camera operating within the 74–116 GHz band that would provide wide-field imaging of key molecular transitions for the study of star formation and astrochemistry. It will include a dedicated spectrometer providing a total velocity coverage of 2000 km s^{-1} with 0.015 km s^{-1} resolution at 90 GHz. Argus+ is a natural extension of the existing Argus receiver and has a total cost of $12.7M.

Receiver Upgrades: The GBT is already one of the world's most sensitive radio telescopes [see Fig. 10 of 61], and straightforward upgrades of the existing GBT receivers would lead to a 30–50% improvement in survey speed, even without adding additional pixels. This can be achieved by replacing older LNAs and other receiver components. The total cost of upgrading all existing receivers is ~$1M, and is thus categorized as a small project.

3.3 Sharing the Radio Spectrum

Spectrum occupancy will continue to grow for the foreseeable future, including at frequencies that were once comparatively free of RFI. Digital systems that effectively share the spectrum for scientific, civil, and commercial use are therefore critically important. GBO has been actively testing several techniques for automated RFI detection and excision. These include the use of median absolute deviation of complex voltage samples, spectral kurtosis [62, 63], robust recursive power estimation [64], and a new exploration of machine learning algorithms that is in its early stages. However, existing digital signal processing (DSP) hardware lacks the on-board memory and processing power to implement most of these techniques in real-time along side channelization, detection, and data formatting functions. The newest generation of hardware overcome these limitations. They offer significantly more on-board resources, processors specialized for machine learning, and support for high data rates. RFI excision methods can also be included in processing that occurs on GPUs. The next generation of wideband digital backends will be built using these technologies, and RFI mitigation will be included in DSP designs.

Key Performance Requirements: The ability to automatically identify and remove data affected by RFI in individual frequency and time samples, without any compromise of data quality.

Public/Private Partnerships: GBO was recently awarded an NSF ATI grant to develop and verify new RFI excision techniques (as well as the development of wideband digital hardware). The Breakthrough Listen project donated a Xilinx VCU118 development kit to GBO.

Technology Drivers: FPGAs and GPUs with the processing power needed to include different RFI mitigation strategies in traditional DSP chains.

Current Status and Schedule: GBO has developed offline implementations of median absolute deviation and spectral kurtosis methods of identifying RFI in voltage data, and demonstrated their efficacy using archival pulsar data. A proof-of-concept real-time robust recursive power estimation algorithm has been implemented on the GBO 20-m telescope, and its impact on astrophysically relevant data products is being evaluated in detail. A machine learning approach is currently underway, beginning with carefully curating a training data set. The second phase (not yet funded) would focus on deploying these techniques as part of the real-time signal processing system.

Cost Category: Small (<$20M)

3.4 Data Archive and High-performance Processing Tools

Large area surveys provide extremely valuable legacy data sets. The discovery of FRBs is an excellent example of unexpected phenomena that can be uncovered with new and improved analysis techniques applied to old data [32, 33]. This requires archiving low-level data products that can easily grow to PB scales. These data must be easily accessible in a well documented and commonly used format, and come with tools that allow for easy reprocessing. High-level data products should also be available for researchers who are exploring the data in different ways. Finally, an archive must contain complete meta-data and processing pipelines to ensure reproducibility.

While GBO and NRAO archive spectral line and low-data-rate pulsar data, they have not archived high-time-resolution pulsar data because of the associated data volumes. A multi-PB data archive will ensure that *all* A-GBT data resulting from open-skies projects will be preserved.

The scientific value of the archive will be further enhanced by developing a new suite of data reduction software. GBO currently supports `gbtidl` for spectral line data reduction, and a Python-based pipeline for creating maps and spectral cubes. We will port `gbtidl` to Python and optimize the mapping pipeline for large, multi-pixel maps.

Technical Requirements: A 2-PB filestore that can be expanded as needs arise and storage costs decrease. Access to subsets of the data over internet, and computational resources sufficient to support local processing of full data sets.

Technology Drivers: Low-power, fast I/O, affordable solid state storage; open-source data processing packages upon which processing pipelines can be collaboratively built.

Current Status and Schedule: GBO is completing an evaluation of current and future requirements for. Construction of a complete data center could be completed in less than five years.

Cost Category: Small (<$20M)

4 Increased Funding for Peer-reviewed Use of the GBT

The GBT is a facility of the National Science Foundation (NSF) operated by the GBO, which was separated from the NRAO in October 2017 and now operates as an independent observatory. In FY2018 6,500 hours were used for scientific observing (the remainder is almost entirely taken up by planned maintenance activities). Under the current cooperative agreement, the NSF funds approximately 60% of these available hours for peer-reviewed astronomy. The remaining 40% is allocated to paid use of the telescope by private parties and institutions[2]. For many research areas this simply reduces the peer-reviewed scientific output of the telescope since fewer projects can be scheduled. However, projects requiring coordination with other observatories, observations at specific dates/times and cadences, and the best weather conditions are disproportionately impacted by the now-fragmented and tightly constrained telescope schedule. These include high-impact areas such as VLBI follow-up of GW events [19, 20, 21] and 3-mm imaging of AGN [65], pulsar timing experiments that require regular, fixed-time observations [e.g. 66, 27, 67, 68], bistatic radar observations of planets, the Moon, and near-Earth asteroids, high-frequency observations, and multi-wavelength observations in conjunction with other telescopes. The 40% reduction in peer-reviewed science time has led to a factor of three decrease in the use of the GBT for VLBI (where it provides critical sensitivity; see Fig. 1) and more than a factor of two reduction in the amount of time available under the best weather conditions. The impact of this reduction will be even greater in the era of more opportunities for time-domain astronomy that require flexible scheduling.

While it would be ideal if the GBT was funded 100% for peer-reviewed research, here we propose NSF funding for only an increase of 1,500 hours/year, which would take the research time from 3,900 hours to 5,400 hours, up a factor of 1.38. This would translate into an increase in scientific output of a factor between 1.38 and at least three, depending on the program, supplying critical capabilities to the U.S. community. More information is provided in the APC white paper "The Case for a Fully Funded Green Bank Telescope" by K. O'Neil.

[2] While it is true that some funds used to purchase GBT time for "private" use currently come from peer-reviewed NSF grants to individuals or consortia, these uses of the GBT have not been peer-reviewed relative to other possible uses of the telescope, and are not seen by the GBT TAC. There is also no requirement that private funds be peer-reviewed.

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