An Ultrawideband Digital Signal Processing System for the Green Bank Telescope

October 7, 2018

Project Description

- **Note: 15-page limit**
- **Note: A separate, 2-page data management plan can include details on standards used for data and metadata, and policies for accessing, sharing, and re-using data**
- **Note: A separate resources and facilities section can include a "description of the internal and external resources (both physical and personnel)", and this may be a good place to discuss local expertise. We must also include biographical sketches that list education, professional preparation, and related "products", somewhat akin to a CV**

1 Overview

We propose to use state-of-the-art technologies to build an ultrawideband digital signal processing (UWB-DSP) system that will be integrated into a new radio receiver under development for the Robert C. Byrd Green Bank Telescope (GBT) at the Green Bank Observatory (GBO). Our UWB-DSP system will consist of fast, **high** **(is this the right word?)** bit-depth analog-to-digital converters (ADCs) that will directly sample the entire 0.7–4 GHz radio frequency (RF) bandwidth of the new ultrawideband receiver (UWBR), bypassing the GBT's usual system of analog mixers and filters that convert the RF signal to an intermediate frequency (IF). The UWB-DSP system will also make use of new system-on-chip (SOC) architectures to enable advanced, real-time radio frequency interference (RFI) excision using statistical and new machine learning (ML) algorithms to identify RFI in the presence of astronomical signals. The combination of real-time RFI removal and high dynamic range digitization as close as possible to the frontend receiver will make this complete UWB system **significantly** **(better word choice?)** more resistant to RFI than is currently possible with existing technology on the GBT. This is crucially important given the experience of a similar UWB system that have been deployed on the Effelsberg Radio Telescope that were crippled by strong interference.

The primary science motivation for our UWB system is the direct detection of low-frequency gravitational waves (GWs) via pulsar timing. The system will also allow for new, wideband spectral studies of fast radio bursts (FRBs), magnetars, and other radio transients, as well as faster surveys of regions rich in molecular lines at these frequencies (e.g. HII radio recombination lines and complex chemical species). The UWBR itself will deliver a combination of wider instantaneous bandwidth and lower system noise temperature than was possible with previous generation technology. The UWB-DSP system will use cutting edge ADCs, innovative RFI excision techniques not in use at any other observatories, and pioneering methods for handling very high data rates using 100-gigabet ethernet (GbE) protocols. Our project will thus pair advanced digital and analog technologies for the world's largest single-dish radio telescope to enable transformative scientific advances in cutting edge fields of astronomy and astrophysics.

The UWB system will be deployed on the GBT as a facilty instrument open to the full astronomical community via the NSF-funded open skies program. This project will also serve as a pilot program for upgrades to the GBT's existing receivers and IF system. All of the hardware design, firmware, and software developed through our efforts will be made publicly available for use at other observatories, and will be directly relevant for possible future telescopes such as the Next Generation Very Large Array (ngVLA) and Square Kilometer Array (SKA). We will also leverage GBO's leadership in the NSF INCLUDES program to broaden participation in digital engineering and radio astronomy via an annual summer camp for undergraduate students. During this camp students will directly participate in developing our new RFI excision project by creating training data sets for machine learning algorithms. The students will also be exposed to all wide range of engineering and scientific disciplines that contribute to the success of the GBO, and will receive interventions that will increase retention in STEM fields **(among rural/first generation college students?)**. This will create a pipeline of students for GBO's successful summer student programs (including our NSF-funded REU program), alumni of which have already contributed to the RFI excision project. The UWB-DSP project will thus have an extremely broad impact on the wider scientific community and the next generation of STEM professionals.

2 Intellectual Merit

2.1 Motivation

2.2 Scientific Motivation

2.2.1. The Low-Frequency GW Universe: The primary science driver of the UWB system is the direct detection of nanohertz frequency GWs via pulsar timing, which is the focus of the NSF-supported North American Nanohertz Observatory for Gravitational Waves Physics Frontier Center (NANOGrav PFC). At these GW frequencies the dominant source class is expected to be supermassive binary black holes (SMBBH) in the early stages of inspiral at the centers of galaxies; exotic sources of GWs such as cosmic strings may also emit in the nHz-regime. The NANOGrav PFC is on-track to detect a stochastic GW background within the next 3–5 years, and is already placing important constraints on the amplitude of this background that informs models of SMBBH evolution and coupling to the surrounding galactic environments. The detection of individual continuous wave sources is expected to follow in the coming decade, which will enable multi-messenger studies of SMBBH systems. The NANOGrav PFC also places the most stringent existing limits on the energy density of cosmic strings. Other science is obtained "for free" as part of this project, such as pulsar mass measurements, tests of general relativity, and novel constraints on Solar system planetary ephemerides.

The NANOGrav PFC uses the GBT and the William E. Gordon telescope at the Arecibo Observatory (AO) to observe a pulsar timing array (PTA) of millisecond pulsars (MSPs) distributed across the sky. The extremely high rotational stability of MSPs allows them to be used as clocks whose "ticks" are pulse times of arrival (TOAs) that can be accurately measured *and predicted* with accuracies of $\lesssim 100$ ns over time scales of decades. The influence of GWs at the Earth will cause a 10–100 ns deviation in the TOAs because of the changing path-length between the observer and the pulsars. The quadripolar nature of GWs will specifically cause a quadripolar angular correlation between pulsars distributed across the sky, which makes it possible to distinguish between GWs and sources of TOA deviations (e.g. uncorrelated effects on individual pulsars, or observatory clock errors or Solar System effects that will have a monopolar and dipolar angular correlation, respectively).

One of the most important steps in obtaining TOAs with the required accuracy is measuring and correcting for the effects of the ionized interstellar medium (ISM) on pulsar signals. One of these effects is a dispersirve delay given by

$$\Delta t_{\rm DM} = k_{\rm DM}\,{\rm DM}(t,f)\,\left(f_{\rm l}^{-2} - f_{\rm h}^{-2}\right), \tag{1}$$

where $k_{\rm DM}$ is a physical constant, f is the radio freqnuency and the subscripts denote a lower and higher frequency, and ${\rm DM}(t,f)$ is the dispersion measure, i.e. column density of free electrons between the pulsar and the Earth. We emphasize that DMis both time and frequency dependent (see ***), and thus represents a noise term *that must be measured at each observing epoch with fractional precision of* $\sim ***$.

The NANOGrav PFC currently employees a two-receiver strategy at the GBT to precisely meausure DM, observing from 0.72–0.92 GHz and 1.1–1.9 GHz. This approach is suboptimal for several reasons. First, it effectively doubles the observing time needed to obtain a single TOA. Second, for operational reasons these observations are typically scheduled with a separation of a few days, making it impossible to resolve DM variations on shorter timescales. *The UWB system will double the observational efficiency of high-precision pulsar timing programs while providing a factor of *** improvement in measurements of DM. When coupled with higher pulsar signal-to-noise from the wider instantaneous bandwidth, the NANOGrav PFC's sensitivity to GWs will increase at twice the rate as without an UWB system.* This in turn will effectively double the volume over which the PTA is sensitive to individual SMBBHs.

2.2.2. Radio Transients: Fast radio bursts are millisecond duration radio-frequency pulses that originate beyond the Milky Way. Their phyiscal origin is one of the most pressing mysteries in astronomy and will be a major area of research in the coming decade. To-date, only one FRB has been observed to repeat (FRB 121102), a fact which has enabled the only precisise interferometric localization of an FRB to a host galaxy, as well as long-duration study of the changing characteristics of the bursts (e.g. DM, Faraday rotation measure, and burst morphology). With telescope like the Australian SKA Pathfinder and the Canadian HI Intensity

Mapping Experiment poised to discover dozens (if not hundreds) of new FRBs, more repeaters are sure to follow.

FRB 121102 shows dramatic variation in spectral shape and burst morphology from pulse to pulse which may be due to intrinsic or extrinsic effects. Any theory regarding the nature of FBR 121102 (and presumably at least some class of FRBs more generally) must explain these properties, so they serve as a powerful diagnostic tool. Bursts are to be band-limited with variable center frequency and bandwidth and have been detected at frequencies as high as 8 GHz. Most observations are limited by the bandwidth of the receiver, however, so the only way thus far to investigate the behavior of FRB 121102 over ultrawide bandwidths has been through simultaneous observations with multiple telescopes. This is obviously logistically complicated and suboptimal. Our new UWB system will enable spectral studies of FRB 121102 and future repeating FRBs, and will give us a better understanding of the characteristic bandwidth of the bursts and their low-frequency cutoff (so far FRB 121102 has not been detected below 1 GHz). These will have important implications for the theory of FRBs.

Radio magnetars — a sub-class of neutron stars whose emission is powered by the decay of extremely strong magnetic fields — represent another broadband and highly variable radio transient. To-date only four radio magnetars have been discovered (out of a larger population of *** magnetars that emit X-rays and gamma-rays). Their sporadic emission and variable power-law spectral index, polarization fraction and position angle, and burst morphology stand in stark contrast to rotation-powered radio pulsars, and the physical processes giving rise to their radio emission remains a mystery. A young, energetic magnetar are one of the leading explanations for the origin of FRB 121102, and as with this FRBs studies of radio magnetars over ultrawide bandwidths have been difficult. The UWB system will thus be a unique resource for learning more about multiple populations of radio transients.

2.2.3. Molecular Line Surveys: TODO

2.3 Technical Motivation

The observations over an ultrawide instantaneous bandwidth needed to realize the above scientific potential come with a number of technical challenges. The frontend receiver must achieve a high aperture effiency and polarization purity while maintaining a low system noise temperature. The entire system from the receiver's low noise amplifiers through the ADCs must also *share the spectrum*, producing scienticically usable data at frequencies where there is significant, strong RFI. GBO's location in the National Radio Quiet Zone and West Virginia Radio Astronomy Zone gives it unique interference protection, but many source of RFI, such as satellite transmitters, are unavoidable (for more inforation on these interference protection zones see Facilities, Equipment, and Other Resources).

The frontend receiver is being developed as a research project by GBO **with additional support provided by the Gordon and Betty Moore Foundation via a grant to the NANOGrav PFC**. The work supported by this ATI proposal will focus on the DSP system after the front-end receiver.

2.3.1. RFI Resistance: The GBT currently uses the Versatile Green Bank Astronomical Spectrometer (VEGAS, developed in part with support from **NSF-*****) as its primary digital backend system. VEGAS uses eight spectrometer banks each consisting of 2×3 Gsps 8-bit ADCs (one for each polarization channel) paired with a high-performance computer (HPC) equipped with an nVidia **GTX 1080** graphical processing units (GPUs). A relatively straightforward expansion of the HPC system will be sufficient to process the full bandwidth provided by the UWBR for pulsar observations, but this approach comes with significant drawbacks. Most notably, VEGAS makes use of the GBTs IF system before sampling, which exposes the UWB system to potential saturation of analog components including and the RF-over-fiber system, two additional frequency mixers and bandpass filters, and the VEGAS 8-bit ADCs. In recent months GBO staff have become aware of total power instabilities that are present at a variety of observing bands (most notably L-Band, i.e. 1–2 GHz) and digital backend systems in addition to VEGAS. These instabilities correlate with the presence of strong RFI and have been isolated to somewhere between the RF-over-fiber system and second frequency mixer. The UWB system will be exposed to the same RFI environment as the L-Band receiver and more. This band includes cellular communications, digital television, Global Positioning System, airport radar and aircraft positioning systems, Iridium, and Sirius XM Satellite Radio. *We thus have empirical evidence that* *illustrates the need to minimize the analog components in the UWB signal path, sampling RF with sufficient dynamic range to maintain linearity across* 0.7–4 *GHz.*

2.3.2. RFI Exscision:

- **Section lead(s):** Ryan Lynch, digital group
- **Target length:** 3 pages
- **Note: Highlight "expected significance" here**
- **Note: Highlight "objectives" here**
- Scientific Motivation (Ryan Lynch and Scott Ransom)
  - Additional science drivers (scientific staff; radio recombination lines? astrochemistry?)
- Technical Motivation (Digital group (+ BTL/CASPER?))
  - **Randy: please provide your thoughts on what best goes under this section**
  - Importance of digitizing at RF
    - RFI resistance (i.e. high dynamic range, reducing analog components)
      - Talk about limitations of existing IF system and VEGAS here
    - Improved stability, reliability?
  - "Sharing the spectrum" (i.e. RFI excision)

2.4 Innovation

- **Section lead(s):** Digital group (+ BTL/CASPER?)
- **Target length:** 4 pages
- **Note: Highlight "relationship to present state of knowledge" here**
- **Note: To the extent possible, explicitly describe work to be undertaken and/or major activities (can expand in §4 as needed)**
- **Randy: please provide your thoughts on what best goes under this section**
- New hardware?
- Firmware development
  - Fast sampling
  - Increased bit-depth/dynamic range
  - Dealing with bandpass slope/selecting significant bits?
- Protocols/formats for high data rates
  - Packetization
  - 10 $\rightarrow$ 40 $\rightarrow$ 100 GbE
  - **Question for digital group: How would we break up band (i.e. subband the way GUPPI and VEGAS do in coherent DD modes) and transmit to HPCs?**
  - **Note: We should talk to Chris and computing group about network infrastructure**
- Active RFI excision
  - MAD and SK algorithms

- Machine learning algorithms
    - Talk about new chips/architecture here?

- Interference compliance
  - Design of low-power, non-interfering electronics
  - Shielding (w/ input from Carla?)

- Cooling? (w/ input from mechanical/works divisions?)

- Commensal/multi-backend/multi-mode observing?
  - **Note: We should talk with software group about software backends**

- **Note: We could include impact on key science drivers here**

3 Broader Impacts

Note: We should decide if we want to support a postdoc, intern, or grad student. This would most likely be in engineering. If so, we can place this under sections for "Development of a Competitive Workforce"

Note: Ryan will talk to Sue Ann about whether we can naturally include any EPO components (within budget)

3.1 Commitment to the Public

The UWB-DSP system will be deployed on GBT as a facility-supported, general purpose instrument available to all GBT users. A majority of GBT time is allocated through the NSF-funded open-skies program, and is thus open to astronomers anywhere in the world. The other primary users of the GBT are the Breakthrough Listen project and the NANOGrav PFC. The importance of the UWB system to the NANOGrav PFC has been explained in §2.2, and it will also be valuable to Breakthrough Listen, as it will allow for faster surveys for extraterrestrial technosignatures. Both NANOGrav and Breakthrough Listen have committed to making data publicly available. (**(How much should we go into detail on this?)**

All of the hardware designs, firmware, and software produces through this ATI will be made publicly available to the wider astronomical and radio science communities for use at other facilities. These products will also be documented and spread through the wider community through publicatoin in peer-reviewed journals and presentations at meetings such as AAS and URSI.

- **Section lead(s):** Ryan Lynch
- **Target length**: 3/4 page
- Facility-supported, general-user, open-skies instrumentation
- Make all designs, firmware, software, and RFI excision algorithms publicly available

3.2 Enhanced Infrastructure for Research and Education

- **Section lead(s):** Ryan Lynch + scientific staff, digital group
- **Target length:** 2pages
- Reiterate importance to UWB Rx project
  - Include impact metrics for NANOGrav, pulsar, transient, and other science areas
- "Pilot program" for GBT IF system upgrades

  - Enable instantaneous use of full bandwidth for all existing (single-feed?) receivers
    - Focus on the science this would enable (e.g. astrochemistry, extragalactic surveys)
  - Provide maximum flexibility when balancing bandwidth vs number of pixels for camera program
    - Mention Argus+ and any other camera programs?
  - Incorporate active RFI excision at all frequencies
    - Mention car radar and any other new, high-frequency sources of RFI (w/ input from IPG)
  - Provide greater resistance to RFI through increased bit depth and by minimizing analog components
  - Improve reliability and reduce operational complexity by minimizing components in signal path
  - Update IF system with state-of-the-art technology
  - Create a model for fast, modular upgrades as new technology emerges
- Relevance for other instruments
  - Highlight ngVLA, SKA, and emphasize that all products of research will be shared freely
    - See if Jay and/or BTL/CASPER know of any existing plans for RF digitization at these or other observatories

3.3 Broadening Participation

- **Section lead(s):** Sue Ann Heatherly
- **Target length:** 2 pages
- Describe the two week anual summer camp and activities related to RFI exscision, professional development, and STEM retention
- Tie into INCLUDES program

4 Project Plan and Timeline

- **Section lead(s):** Laura Jensen
- **Target length:** 2 pages

4.1 Work to be Undertaken OR Key Milestones and Evaluation

- Should align with activities identified in §2.4
- Should also include metrics for success and a plan for evaluation

4.2 Proposed Timeline

- A graphical timeline, organized by year and work type
- A narrative description of the timeline

5 Results from Prior NSF Support

- **Section lead(s):** All (as needed)
- **Target length:** ? (must be < 5 pages)
- **Note: Only needed for PIs or co-PIs with a current NSF award or one with an end date in the past five years.**
- For each award:
  - NSF Award number, amount, and period of support
  - Title of project
  - Summary of completed/proposed work
    - Intellectual Merit
    - Broader Impacts
  - List of publications
  - Evidence of research projects and their availability
  - Relation of completed work to proposed work (for renewals only)