Project Description: New Wide-band Digital Technology and Interference Excision for Radio Astronomy

A Overview

Advances in radio frequency (RF) analog and digital devices are opening new possibilities for ultra-wide bandwidth (UWB) radio astronomy science. However, a complete UWB digital signal processing (DSP) system that takes advantage of these advances is not yet available. UWB instrumentation also poses new challenges for sharing the spectrum with other users. We therefore propose to research and develop new technologies and techniques for UWB radio astronomy, and for maintaining the highest data quality in the presence of terrestrial radio frequency interference (RFI). Our project consists of four main activities:

1. Develop the hardware, firmware, and tool flows needed to integrate cutting-edge analog to digital converters (ADCs) and field programmable gate arrays (FPGAs) for radio astronomy applications. *The primary outcome of this activity will be the next generation of UWB DSP boards and a prototype system for the Robert C. Byrd Green Bank Telescope (GBT).*
2. Create standard, quantitative, and well-tested procedures for validating real-time RFI excision techniques and ensuring that they preserve scientific data quality, for use in this project and as a service to the community. *The primary outcome of this activity will be tools and best practices that are necessary for testing the efficacy of RFI excision algorithms and building confidence in their use among scientists.*
3. Develop new algorithms for identifying and removing RFI in real-time, validate them using the procedures created in activity two, and implement them in our UWB DSP system. *The primary outcome of this activity will be innovative RFI excision techniques, ready to be used by radio astronomy observatories in the US and around the world.*
4. Engage first-generation college students in STEM fields through a two-week summer internship at the Green Bank Observatory (GBO), during which they will directly contribute to the RFI excision work by helping to create a public database of common RFI. This internship will leverage GBO's partnership in the NSF-INCLUDES program. *The primary outcome of this activity will be a cohort of students that are better prepared for STEM careers.*

The majority of this work will be conducted at GBO, in close collaboration with the University of California, Berkeley (UCB) and as part of the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER). Through CASPER, we will ensure that the outcomes of our work are shared broadly. *As a Federally-Funded Research and Development Center, GBO has been granted an exemption by NSF to submit this proposal since the resulting technical innovations will make unique contributions to the needs of researchers across the scientific community.* GBO staff have proven expertise in taking research projects from concept to design and construction with a goal of repeatable, reliable, maintainable, and scalable production use. By operating the GBT and other site telescopes, and working within the National Radio Quiet Zone (see Facilities, Equipment, and other Resources), GBO staff have gained unique experience in how to identify, assess, and mitigate RFI.

This project is the first step in a longer-term effort to build a next generation, end-to-end DSP system and flexible digital back-end for the GBT that employs active RFI mitigation. Such a system would be used to maximize scientific return of a new UWB radio receiver under independent development by GBO, and could also be adapted for use at other observatories. We will also lay the ground-work for revolutionary upgrades to the GBT that will expand its available bandwidth (BW) and enhance performance across all areas of radio astronomy science.

We describe the motivation for this project in more detail in §B.2, and specify the innovative work that we will carry out in §B.3. In §C.1 we affirm our commitment to making the results of this project of broad use, and in §C.2 we explain how the outcomes of our work can be applied to enhance research at GBO, and at other US and world observatories. We describe our two-week STEM student internship program in §C.3. We explain our timeline and how the project will be managed to ensure success in §D.

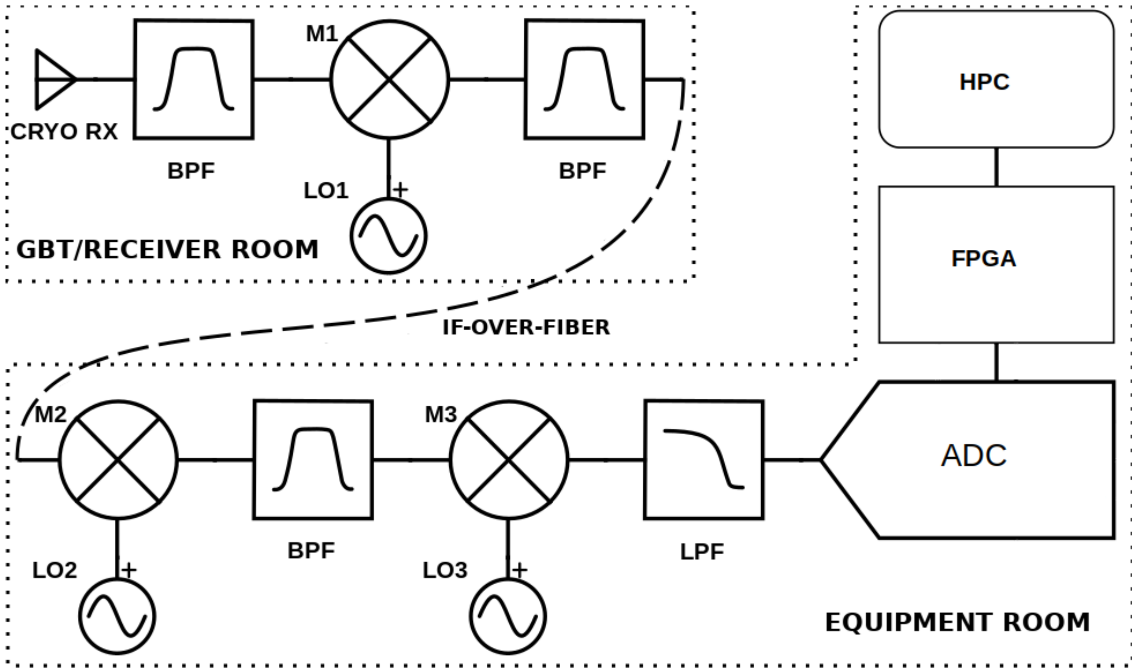

Figure 1: A simplified block diagram representation of the existing GBT intermediate frequency system. Components in the "receiver room" are located next to the radio receivers on the GBT. Signals are transported via IF-over-fiber (dashed line) to the "equipment room", which houses additional analog and digital instruments. Only one polarization channel is shown. Individual receivers will have slightly different configurations.

B Intellectual Merit

B.1 A Review of Existing Technology and Equipment

We begin by reviewing the existing instrumentation for wide-bandwidth radio astronomy using the GBT as an example. The GBT is the world's largest fully-steerable telescope and offers nearly continuous coverage from 0.3–116 GHz (excepting the 50–67 GHz oxygen absorption band). The Versatile Green Bank Astronomical Spectrometer (VEGAS, developed with support from NSF award AST-1006509) is the current primary digital back-end instrument. VEGAS employs eight CASPER ROACH2 boards, each equipped with two 8-bit ADCs clocked at 3 Gsps (one for each polarization). Before reaching VEGAS, all signals pass through the GBT's analog intermediate frequency (IF) system. The IF system consists of a first tunable local oscillator (LO) located in the "receiver room" on the GBT, which is used to convert RF to an IF that can be transferred over fiber to the "equipment room", located over 1 km from the telescope. The IF is then transported over coaxial cable through additional banks of bandpass filters and mixers before being converted to baseband and fed into the VEGAS ADCs (see Figure 1). This set-up is extremely flexible, but has several drawbacks (discussed in §B.2.2 and §C.2.2)that can be overcome using new technology and DSP techniques.

B.2 Motivation

Several developments make this project especially timely.

- New commercial ADCs allow high dynamic range sampling of ultra-wide BWs, either at RF or after a single down-conversion.
- Advanced FPGAs provide the resources needed to implement real-time RFI excision side-by-side with other DSP procedures.
- The expanding presence of wireless devices and the increasing sensitivity and BW of radio receivers make it essential to *share the spectrum* by using instrumentation that is robust and produces high-quality scientific data in the presence of RFI.

- GBO is actively developing a revolutionary new 0.7–4 GHz UWB radio receiver for the GBT that will serve as the perfect platform for applying the outcomes of this project. This receiver will be optimized to study gravitational waves and fundamental physics, as well as radio transients and regions rich in molecular line emission.

B.2.1 Next Generation Hardware

In only the last few months, industry leaders have started to offer a number of exciting and powerful new ADCs and FPGAs. We have identified two products in particular that improve by factors of several over the previous generation.

1. The **Analog Devices AD9213** is a 10.25 Gsps 12-bit ADC that is representative of the upcoming generation. The AD9213 is faster, more precise, and has lower noise than our current EV8AQ160 (see Table 1). One large driver behind the better spur-free dynamic range is improved manufacturer-provided calibration techniques for the suppression of multi-core interleaved spurs that are inherent in pipelined ADC technologies (considerable work was required by GBO and CASPER to properly calibrate the ADCs used in VEGAS). *The fast sampling rate, high bit-depth, and 6 GHz full-power BW provided by the AD9213 make it feasible to directly sample RF up to 5 GHz.*

Table 1: Comparison of ADCs

Feature/Spec	EV8AQ160	AD9213
Max. Sampling Rate	5 Gsps	10.25 Gsps
Bit-depth	8	12
Spur-free Dynamic Range*	56 dBc	68 dBc
Power Consumption*	4.2 W	5.1 W
Effective Number of Bits*	7.1	7.7

* @ max. rate

2. A promising successor to the CASPER ROACH2 boards that were the core of many previous generation DSP systems is the **Xilinx Virtex UltraScale+ FPGA VCU118 evaluation kit**. The VCU118's FGPA has significantly more resources than the ROACH2's (allowing larger, more computationally intense designs), significantly smaller feature size (simplifying timing closure), and significantly faster transceivers (allowing higher I/O BW). Table 2 provides a side-by-side comparison to the ROACH2. *These new FPGAs will provide the critical resources needed to implement real-time UWB RFI excision alongside standard DSP procedures (e.g. channelization).*

Table 2: Comparison of ROACH2 and VCU118

Resource	ROACH2	VCU118
FPGA System Logic Cells	476K	2586K
FPGA DSP Slice	2016	6840
FPGA BRAM	38 Mb	6840 Mb
Board DDR4	2 GB	8 GB
High-Speed Ethernet	$8 \times$ 10-GbE	$3 \times$ 100-GbE
FPGA Silicon Feature Size	40 nm	16 nm
Expansion Bus	$2 \times$ ZDOK	$1\times$ FMC, $1\times$ FMC+
Max FPGA Transceiver Speed	6.6 Gbps	32.75 Gbps

B.2.2 Sharing the Radio Spectrum

Radio receivers are exposed to a multitude of RFI sources such as ground- and space-based communications channels. Emerging technologies such as collision avoidance car RADARs that operate from 76–81 GHz will start to affect regions of the spectrum that had been comparatively free of RFI. Digital systems that effectively share the spectrum with other users are therefore critically important. We broadly classify techniques for sharing the spectrum into RFI resistance (i.e., a high linear dynamic range in every analog and digital component of the signal processing chain) and RFI excision (i.e. removal of RFI at the lowest-possible level of data to improve data quality).

RFI Resistance: RFI resistance is a perpetual concern for radio observatories. GBO is afforded unique interference protection through its location at the center of the 13,000 square-mile National Radio Quiet Zone and smaller West Virginia Radio Astronomy Zone (for more information on these interference protection zones see Facilities, Equipment, and Other Resources). However, the relevant regulations only apply to fixed, ground-based transmitters, not to mobile ground, air, or space-based transmitters, of which there are many. Other US observatories lack any regulatory protection.

The consequences of a worsening RFI environment are best illustrated by the recent discovery by GBO staff of total power instabilities present in the 1–2 GHz band of the GBT. These instabilities are seen in a variety of digital back-end systems, including VEGAS, and have been traced to the growing use of automatic dependent surveillance-broadcast (ADS-B) technology[1] transmitting at 1.09 GHz; the instability itself has been isolated to non-linear response of analog components between the GBT's IF-over-fiber transcievers and second frequency mixer. *We thus have empirical evidence that illustrates the need to minimize the number of analog components in the GBT's IF system.*

The technology that we will develop as part of this project will enable direct, high-dynamic range sampling up to 5 GHz. *This will allow us to completely bypass the usual analog IF system for many existing and future receivers.*

RFI Excision: 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, robust recursive power estimation, and a new exploration of machine learning (ML) algorithms that is in its early stages. However, the limitations of our existing ROACH2-based hardware prevents us from fully implementing, testing, and deploying these RFI excision techniques. Specifically, ROACH2 hardware has a comparatively low number of on-board resources such as block random access memory (BRAM), DSP cores, and logic cells, as well as low BW I/O transceivers. We have also struggled to meet timing closure using the Virtex-6 technology for complex firmware designs. As detailed above, the UltraScale+ FPGAs and associated tool flows fundamentally change the paradigm for realizing sophisticated RFI excision techniques. *We will take advantage of these new technologies to integrate real-time RFI excision into standard data-processing pipelines.*

B.2.3 Developing a Back-end System for New UWB Receivers

Several observatories and research labs are building UWB (4:1 and 6:1 BW ratio) radio receivers with system noise and efficiency that is competitive with traditional octave (2:1) receivers. One example is a 0.7–4 GHz UWB receiver that is under active, independent development at GBO. The GBO UWB receiver will be the perfect development platform and front-end complement for the digital technology and RFI excision techniques that we will produce as part of this work. This will maximize scientific return in the following key areas:

The Low-Frequency Gravitational Wave Universe: The primary science driver of the GBO UWB receiver is the direct detection of nanohertz-frequency gravitational waves (GWs) via pulsar timing, which is the focus of the NSF-supported North American Nanohertz Observatory for Gravitational Waves Physics Frontier Center (NANOGrav PFC; [31]). Pulsar timing is highly complementary to other GW observatories (see Figure 2). The NANOGrav PFC is on-track to detect a stochastic GW background from supermassive binary black holes (SMBBH) within the next 3–5 years [41], 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 [4, 3]. The detection of individual binaries 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 [3].

The NANOGrav PFC uses the GBT and the William E. Gordon telescope at the Arecibo Observatory 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 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, with a unique angular correlation pattern [19]. This process of pulsar timing demands a complete characterization of the MSPs themselves, including their rotational, astrometric, and binary properties. Thus, other high-impact science emerges from this project, such as pulsar mass measurements [16], tests of general relativity [46], and novel constraints on Solar system planetary ephemerides [3].

[1] ADS-B is used for air traffic control as part of the Next Generation Air Transportation System and is intended to replace secondary surveillance RADAR. It will be required on all aircraft operating in the United States by 2020. See `https://www.faa.gov/nextgen/programs/adsb/`

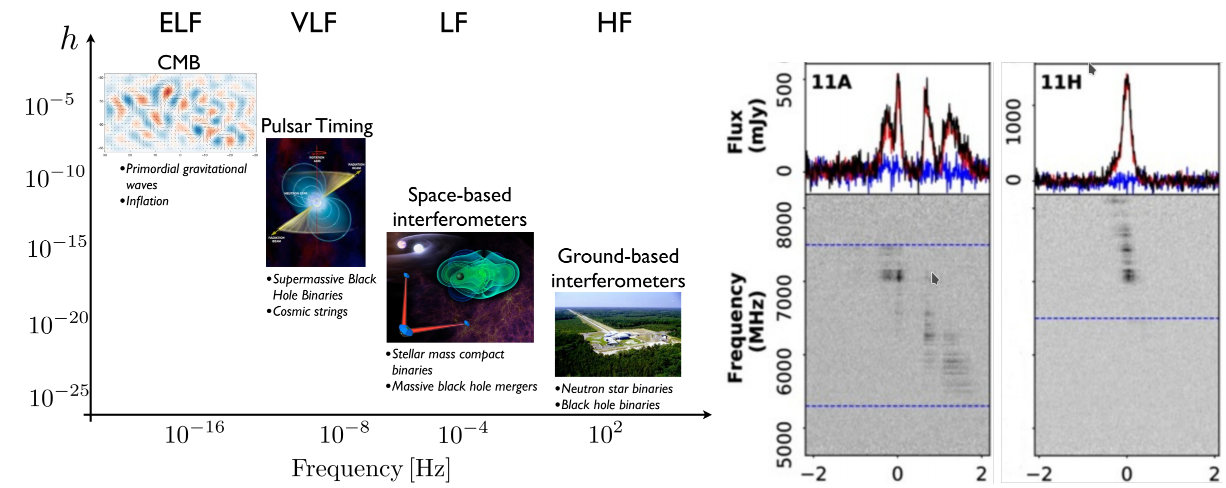

Figure 2: *Left:* Like the electromagnetic spectrum, the GW spectrum spans orders of magnitude and a variety of source-classes that can only be fully studied using complementary techniques. PTAs probe lower GW frequencies than ground- and space-based interferometers, and higher frequencies than cosmic microwave background polarization experiments (Figure courtesy of the NANOGrav PFC). *Right:* A selection of bursts from FRB 121102 showing dramatic spectro-temporal variation. The red and blue traces represent linearly and circularly polarized flux, respectively. These data were taken between 4–8 GHz and the second burst clearly extends beyond the available observing BW [17].

One of the biggest noise-terms for PTAs is a time and frequency dependent delay in pulse arrival times given by

$$\Delta t_{\rm DM} = \frac{k_{\rm DM}\,{\rm DM}(t,f)}{f^{-2}} \tag{1}$$

where $k_{\rm DM}$ is a physical constant, f is the radio frequency, and ${\rm DM}(t,f)$ is the dispersion measure, i.e. column density of free electrons between the pulsar and the Earth [e.g. 24], which must be measured with a fractional uncertainty of $\sim 10^{-5}$ at each observing epoch. In practice, this requires measuring TOAs at widely spaced frequencies. The NANOGrav PFC currently employs a two-receiver strategy to measure DM with the necessary precision, but this approach effectively doubles the observing time needed to obtain a single TOA and makes it difficult to resolve DM variations on intra-day timescales. *An UWB observing system will double the observational efficiency of high-precision pulsar timing programs while improving measurements of DM. When coupled with higher pulsar signal-to-noise from the wider instantaneous BW, the NANOGrav PFC's pulsar timing precision has the potential to improve by as much as a factor of two.*

Radio Transients: The UWB system will be a powerful tool for expanding our knowledge of radio transients with variable spectro-temporal behavior. One such population are fast radio bursts (FRBs) — millisecond duration radio-frequency pulses that originate in distant galaxies [23, 43]. Their physical 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; [39, 40]), a fact which has enabled the only precise interferometric localization of an FRB to a host galaxy [10, 42], as well as long-duration study of the changing characteristics of the bursts (e.g. DM, Faraday rotation measure (RM), and burst morphology; [32]). With telescopes like the Australian SKA Pathfinder and the Canadian HI Intensity Mapping Experiment poised to discover hundreds (if not thousands) of new FRBs [38, 5], more repeaters are sure to follow.

FRB 121102 exhibits dramatic burst-to-burst spectro-temporal variation (see Figure 2) including a) a highly variable power-law spectral index; b) non-power-law spectral shapes including band-limited bursts; c) changing peak frequency; d) changing burst morphology; and e) distinct sub-bursts that drift towards lower peak frequencies with time within the larger burst envelope [40, 37, 17]. It is not yet clear if these features are intrinsic or related to the local environment [e.g. 12, 27]. There is also some evidence for secular changes in

DM and RM [32, 17]. All bursts thus far have been detected between 1–8 GHz despite significant observing campaigns at lower and higher frequencies.

Any theory regarding the nature of FRB 121102 (and presumably at least some class of FRBs more generally) must explain these wide-band properties, so they serve as a powerful diagnostic tool for understanding FRBs' physical origins. However, most burst detections are limited by the BW of the receiver, so the only way thus far to investigate the behavior of FRB 121102 over ultra-wide BWs has been through limited simultaneous observations using multiple telescopes. Our new UWB system will enable spectro-temporal studies of FRB 121102 and future repeating FRBs, answering critical questions such as a) does the characteristic BW of bursts change with frequency, and if so, with what form? b) do band-limited bursts appear simultaneously in widely separated sub-bands? c) do sub-bursts cluster in frequency and time, or can the peak frequency change on burst-to-burst timescales? d) what is the burst morphology over ultra-wide BWs? e) is the apparent $\sim$ 1 GHz lower limit real or an artifact of under-sampling at lower frequencies? and f) does DM vary as a function of frequency in broad-band bursts? The answers to these questions can then be quantitatively compared with physical models for FRB emission.

A second class of variables are radio magnetars — neutron stars whose emission is powered by the decay of extremely strong magnetic fields. To-date only four radio magnetars have been discovered out of a larger population[2] that emit X-rays and gamma-rays [7, 6, 22, 14]. Their sporadic emission and variable power-law spectral index, polarization fraction, polarization position angle, and burst morphology stand in stark contrast to rotation-powered radio pulsars [e.g. 8], and the details of the radio emission mechanism remains a mystery. Interestingly, there may be a connection between magnetars and FRBs. A young, powerful magnetar is one of the leading candidates for the source of FRB 121102 [e.g. 28], and the extremely high RM observed in FRB 121102 has only one known analog: the radio magnetar near the center of the Milky Way [14]. Thus, studies of magnetars may improve our understanding of FRBs, and vice versa.

Molecular Line Surveys: Survey speeds of regions that are especially rich in molecular lines are often limited by the available instantaneous BW. One example is observations of HII regions using Hydrogen radio recombination lines (RRLs). These act as extinction-free tracers of the ionized gas surrounding high-mass stars. The sensitivity of the GBT allows for individual RRLs to be detected toward star-forming regions across the entire Galactic disk with only minutes of on-source time. However, no current receiver/back-end combination can cover nearly as many simultaneous RRLs as the 0.7–4 GHz UWB system, which will be able to simultaneously observe 93 Hn_α, 117 Hn_β, 134 Hn_γ, and 146 Hn_δ lines. All RRLs of the same type can be combined to drastically increase signal-to-noise, offering unprecedented sensitivity to Galactic ionized gas. Because of the coarse spatial resolution in this frequency range (from $3'$ to $18'$ for the GBT), these lower frequency transitions are especially well suited for studying diffuse, low-density plasmas, including ionized outflows from star formation regions and the ambient diffuse ionized gas present throughout much of the plane of the Galaxy [25].

The study of complex chemical species offers another application of UWB technology. Many observations have focused on frequencies of 10's of GHz, but the 0.7–4 GHz band is a promising discovery space [e.g. 30, 15, 44]. Astrochemistry is a unique probe of species not easily studied in a laboratory and has implications for astrobiology and the nature of life on Earth [29]. The BW of the UWB system will allow for serendipitous, discovery-based science in this area.

B.3 Innovation

To realize the technical and scientific potential offered by UWB technology, we will integrate new cutting-edge hardware components and develop new firmware, data transmission methods, and network topologies for very high data rates. We will also implement and test various RFI excision strategies. To the extent possible we will use modular designs that abstract away lower-level components. This will make it easier to rapidly take advantage of future technologies as they emerge, so that the impact of our efforts will last much longer than a single generation or specific architecture. All of our work will be conducted in an open and collaborative framework for use by other observatories and interested parties. Figure 3 shows one possible high-level configuration of the system that we will build. The specific tasks that we will carry out are detailed below.

[2]See `http://www.physics.mcgill.ca/~pulsar/magnetar/main.html` for an up-to-date list.

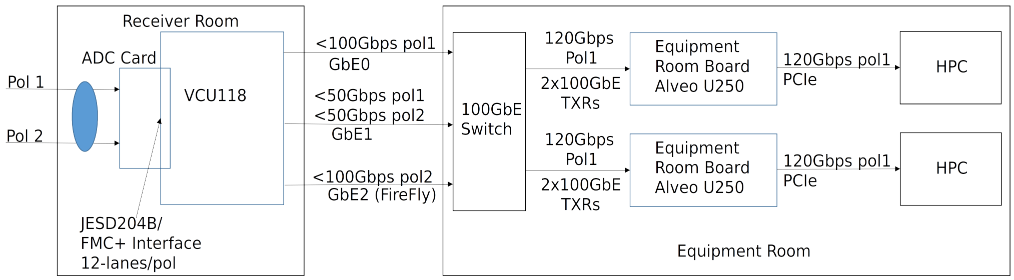

Figure 3: A block diagram representing one possible approach for deploying an UWB DSP system on the GBT sampling up to 5 GHz baseband with a single ADC. We identify those components that would be housed in the GBT receiver room and the equipment room, and refer to these designations throughout this proposal. Other configurations are possible.

B.3.1 Finding Optimal Sampling Strategies

We will determine the optimal approach for digitizing very wide RF BWs.

The AD9213 ADC has the ability to digitally sample baseband BWs up to approximately 5 GHz with a single sampler. Thus, the most straightforward approach is to clock the ADCs near their maximum rate, which would simplify downstream processing by avoiding the need to stitch together various smaller sub-bands to achieve the same BW while eliminating most analog components. However, this comes at the cost of a lower effective number of bits (ENOB) — the pre-release specifications for the AD9213 quote 7.7 bits at the maximum sampling rate of 10.25 Gsps. A second approach would use a simple signal-splitter to produce two or three copies of the desired UWB signal, which would each be sent to a separate pair of ADCs (one for each polarization) clocked at slower speeds. The first copy could be low-pass filtered and sampled at base band (i.e. the first Nyquist zone), while higher frequencies would be bandpass filtered to prevent aliasing and sampled in higher Nyquist zones. This would still eliminate the need for an analog IF mixing stage and would have the advantage of offering a higher ENOB (for example, pre-release specifications quote 8.3–9.1 ENOB when sampling at 6 Gsps), though at the expense of additional processing steps and analog RF conditioning. We will determine if the better dynamic range in the second approach is needed, using the UWB receiver as the test platform. This will inform the design of additional UWB systems at GBO and other observatories.

B.3.2 Integrating New ADCs and FPGAs

We will design and build custom printed circuit boards that will interface new ADCs and FPGAs.

Since our plan calls for installing digitally noisy ADCs and FPGAs very close to radio receivers, minimal power consumption and a low level of self-generated RFI is absolutely essential. These requirements will be incorporated into all designs from the beginning.

The VCU118 is equipped with an FPGA Mezzanine Card (FMC/FMC+) slot, which will be used to connect our chosen ADC. We prefer to use two ADCs per VCU118 (one for each polarization channel) to simplify design. However, each AD9213 dissipates 5.1 W, so two would exceed the maximum power allowed for the FMC/FMC+ daughter card (10 W). We will develop power-mitigation methods that would allow us to safely contravene the standards, allowing two ADCs per board. However, if unsuccessful we can fall back on using two VCU118's, each with a single ADC.

GBO requires that all installed electrical equipment in the GBT receiver room be ITU-R RA.769 compliant (protection criteria used for radio astronomical measurements). Functionally, this equates to an additional ~ 100 dBm of isotropic radiated power suppression on any commercial-off-the-shelf (COTS) unintentional radiators that we wish to install close to the focal point of the GBT. To meet these strict requirements we will likely have to make considerable adjustments and/or add shielding to any COTS boards, which will include component-level shielding of noisy components (chip cage) and equipment-level shielding (metal box, in-case RF absorbent foam). We have substantial experience designing low-radiation electronics, and have an excellent RF anechoic chamber to validate our modifications (see Facilities, Equipment, and Other Resources).

However, many RFI-shielding techniques, such as encasing boards within metal boxes, works at cross-purposes with effective cooling techniques. As such, we will also be developing efficient and simple cooling methods. Air-cooling is preferred due to its simplicity, but water-cooling will be considered if necessary. Members of our team have already deployed water-cooling on compute racks used by the Breakthrough Listen project [26], and water-cooling has been used on the GBT as part of a revolutionary new L-Band phased array feed [35]. *All RFI-shielding and cooling techniques used at GBO will be broadly applicable to any observatory interested in using noisy COTS hardware near sensitive RF receivers.*

B.3.3 Developing Firmware for Emerging Technology

We will design firmware for next-generation hardware and communication protocols. These designs will be shared widely with the scientific and engineering communities.

We will build a variety of new firmware "blocks" (sets of low-level FPGA code abstracted to a higher level for easier use by firmware system designers) for interfacing with various FPGA-facing peripherals as well as for executing advanced DSP techniques. In addition, new firmware tools will need to be developed to allow our CASPER-based designs to take advantage of the advancements that are provided by new technologies. Much of this new firmware development can be broken into functional blocks within Xilinx's System Generator for DSP architecture (SGDSP). Basic SGDSP blocks are primarily dedicated to data processing with no use of peripheral components (e.g. BRAM, transceivers, Microblaze access, etc.), whereas CASPER blocks interface with peripherals. Many of the CASPER blocks exist for earlier generations of hardware, but considerable work is required to prepare them for the newest generations. The specific blocks that we will develop are outlined below.

Peripheral Interfacing: To take advantage of the possibilities enabled by the newest generation of data-transmission technologies, we will create CASPER blocks that interface with the 100-GbE core (both single-direction and duplex flavors), PCIe (generations 3×16 and 4×8, including monitor and control (M&C) of the FPGA board over the PCIe), as well as a block to interface the FPGA with ADC via FMC/FMC+. The 100-GbE blocks and ADC card block can be considered improvements upon existing capabilities, while the PCIe interface (and especially the M&C aspect) will be groundbreaking in the CASPER community.

DSP Capabilities: We will create additional basic SDGP blocks to improve DSP capabilities. For example, we will develop blocks implementing new RFI-mitigation methods (discussed in more detail in the §B.3.6) that are too computationally expensive to run in real-time on our current hardware. We will also take advantage of development occurring elsewhere within CASPER (e.g. new floating point FFT blocks).

B.3.4 Data Transmission Methods and Network Topology

We will find optimal strategies for managing the extremely high data rates produced by fast sampling with high bit-depth.

New ADCs will quintuple the bit-rate compared with previous instruments and will require the use of 100-GbE fiber down-links as the backbone of our signal sampling/transmission pipeline. We will develop solutions to mitigate several challenges.

The total maximum bit-rate for the AD9213 at maximum frequency will be $123\ \mathrm{Gbps}$. The VCU118 is an outlier among Xilinx FPGA boards with 2×100-GbE QSFP28 ports and 1×100-GbE FireFly port. We will examine optimal network topologies to deal with these data rates (one or two polarizations per receiver-room board? 100-GbE duplex? how comparatively large is the 100-GbE duplex logic to single-direction logic?), and other related questions that will allow us to maximize our system's throughput BW while minimizing cost and complexity. The move to PCIe edge connectors instead of a 1-GbE port will also require us to integrate PCIe-based M&C functionality, and to measure how different bi-directional M&C data-rates between a control computer and the FPGA over the PCIe bus effect the main, uni-directional data-transfer rates from the FPGA to downstream computing clusters. These topologies will be compared by scalability, I/O BW, processing power, cost, rack-space, and ease of maintenance. Factors that could impact the comparisons include cost of future 100-GbE network switches, ease of heterogeneous computing solutions, and the eventual computing requirements imposed by the final system.

B.3.5 Standardized Procedures for Validating RFI Excision Algorithms

We will develop a generalized test methodology for validating the efficacy of RFI excision techniques while preserving scientific data quality. This is crucial for building confidence in these techniques among scientific users.

This will consist of:

- Well defined observing modes (e.g. pulsar timing and HI spectroscopy), astrophysical sources, and quantifiable parameters that can be measured from each observation, that will serve as standards against which different observatories and instruments can test RFI excision techniques.
- A database of common RFI characteristics such as frequency, amplitude, BW, duration, and frequency sweep.
- Carefully curated data sets created using the above set-ups, in common formats and containing a variety of RFI sources, that can be used for off-line testing and validation.
- Synthetic data sets, both free of RFI and with synthetic RFI that matches the characteristics of common sources, to be used for additional, carefully controlled offline verification.
- Procedures for applying and quantifying the efficacy of RFI excision algorithms and assessing their impact on the measurable astrophysical quantities of interest.
- Best practices for applying the above to real-time data acquisition systems (e.g. techniques for parallel capture of RFI-mitigated and unmitigated data streams).
- Side-by-side comparison of the relevant parameters for mitigated and unmitigated data.

The limits for acceptable amounts of RFI non-detections, false-positives, and data perturbations are likely to be specific to the scientific requirements of a given observation, so we will focus on *how* to measure the impact of RFI excision in ways that are reliable *and replicable*. Observers and other facilities can then choose the most appropriate procedures for applying these algorithms as needed.

Test procedures and data sets will be developed openly and collaboratively, allowing for contributions from other researchers and observatories. *We will create a community-oriented, self-sustaining resource that will be vitally important for ensuring the integrity of scientific data as new instruments and telescopes are developed alongside increasing use of the radio spectrum.*

B.3.6 Active RFI Excision

We will implement complementary real-time techniques that can operate together to actively identify and excise RFI.

Below we describe two techniques that can be most easily deployed as part of this project. Other techniques will explored as appropriate.

Robust Recursive Power Estimator: GBO has built upon work started at the Nançay Radio Observatory [13] that detects and excises interference from ground-based RADAR sources, and which should be applicable to other impulsive sources of RFI. It functions by measuring the frequency-domain mean power level and flags or replaces sets of samples that exceed a given threshold for a given amount of time. *Members of our team have now implemented this functionality in ROACH-based firmware, and have successfully conducted initial validation of its efficacy on multiple back-end systems currently being used at GBO. To the best of our knowledge, GBO currently possesses the only CASPER-implemented real-time RFI-excision enabled back-end systems.* We will generalize this method to other sources of RFI and deploy it in the UWB DSP system.

Spectral Kurtosis: Initially conceived as a robust statistical RFI detector [33, 34], the simple sum/sum-squared algorithm lends itself naturally to implementation in FPGAs. As kurtosis measurements are more affected by a few, extreme outliers rather than many, moderate outliers, we can assume that any high-kurtosis samples (above user-adjustable thresholds) are contaminated with RFI and mitigate them.

Over the past year, a collaboration between the GBO digital engineering group and West Virginia University Physics department have created a Python-based implementation of the generalized spectral kurtosis estimator [33], and its overall effectiveness has been proven (Figure 4). However, none of our extant back-end

Figure 4: Pre- and post-mitigation data demonstrating the efficacy of our spectral kurtosis excision algorithm. Test data are from archived raw-voltage pulsar observations.

systems have enough logic/DSP cores and RAM resources available in the FPGAs to allow an implementation to co-exist with existing channelization firmware. *The FPGAs on the VCU118 will let us create and test a real-time implementation of this method that could then be shared with the wider community*.

C Broader Impacts

C.1 Commitment to the Public

All of the hardware designs, firmware, and software produced in the course of this work will be made available to the wider astronomical and radio science communities for use at other facilities. Firmware blocks will be included in the CASPER library. We will use a mix of technical memos, presentations at conferences, and refereed publications to document and communicate the results of the work to the broadest possible audiences. The co-investigators also participate in public facing programs at the Green Bank Observatory to educate the broader public about the UWB system and radio astronomy more generally.

C.2 Enhancing Infrastructure for Research and Education

C.2.1 Towards a Complete Next-Generation Observing System

We view this project as the first in a two-phase effort that will ultimately result in a complete next-generation digital back-end system and flexible UWB spectrometer. This first R&D phase will produce the foundational hardware and firmware, ending in a functional prototype that can then be scaled up into a full, production system. This final system will be integrated into the GBT's new UWB receiver and released as a facility-supported instrument for use by the entire scientific community.

C.2.2 A Pilot Program for Future GBT Upgrades

The GBT has a flexible IF system that has enabled ground-breaking discoveries in all areas of astronomy, but it is now over 20 years old and has several limitations.

- Receivers operating above 18 GHz could provide $\gg 8$ GHz of instantaneous BW but are limited by existing IF filters to 4–6 GHz in most cases (see Table 3 for details).
- Up to 64 spectral windows can be formed through a bank of secondary and tertiary mixers and filters, as well as DSP in VEGAS, but filters limit the maximum BW and separation between spectral windows and the number of banks limits the number of windows.
- The secondary and tertiary converters are located over 1 km from the GBT, with signals transported via IF-over-fiber links that are subject to instabilities as discussed in §B.2.2.
- The above analog components can undergo gain variation due to changing environmental conditions, leading to spectral baseline changes that can be limiting.

Table 3: High Frequency GBT Receiver BW

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	5.28
Ka-Band MM1	26.0–31.0	4.0	13.5	3.375
Ka-Band MM2	30.5–37.0	4.0		
Ka-Band MM3	36.0–39.5	4.0		
Q-Band	39.2–49.8	4.0	10.6	2.65
W-Band MM1	67.0–74.0	6.0	26.3	4.38–6.575
W-Band MM2	73.0–80.0	4.0		
W-Band MM3	79.0–86.0	4.0		
W-Band MM4	85.0–92.0	4.0		
16-pixel Argus	75.0–115.3	1.5	8	5.3

Note — The full BW of receivers operating below 18 GHz can be processed by the existing IF system, so only higher-frequency receivers are shown. A wide-band 8 GHz mode exists for KFPA but can only use one pixel. MM refers to different millimeter converter rack filters, which are required by the existing IF system, but could be bypassed. The maximum BW of Argus is determined by integrated receiver components.

- Doppler broadening caused by the Earth's motion can be removed by a tunable first-stage frequency mixer, but only for a single rest frequency. More complex Doppler tracking is not possible.

The proposed UWB-DSP technology has the potential to eliminate nearly all of these restrictions. Multiple fast ADCs could be employed to sample the full available BW for single-pixel receivers, and would provide maximum flexibility when trading BW for pixels in multi-pixel receivers. *This could lead to as much as a factor of 6.575 increase in survey speed when observing widely spaced spectral lines (see Table 3).* Digitization would occur at RF for low-frequency receivers and either in higher Nyquist zones or after a single down-conversion at higher frequencies. This would eliminate most analog components, reducing saturation from RFI while providing much better spectral baselines. More flexible Doppler tracking and windowing would be accomplished digitally. Active RFI mitigation would also be incorporated into all GBT observing. *This would be a transformational modernization of the GBT, analogous to the upgrades of the "extended" Jansky Very Large Array (VLA), and would revolutionize all areas of GBT science.* The UWB DSP system is a pathfinder that will allow us to determine the most effective and affordable solutions for these future upgrades.

C.2.3 Relevance for Other Facilities

As part of the Astro2020 Decadal Survey, the radio astronomy community is planning for major new facilities that could begin construction and operation in the 2020s, such as the Next Generation VLA, in addition to a myriad of experiment-class instruments. Our efforts, especially the RFI excision validation procedures and algorithms, would be an invaluable resource for many new facilities. Because of our focus on modular design enabling rapid development, our efforts will also serve as a pathfinder for technologies that will be deployed on these future facilities. *The GBT, and single-dish telescopes more broadly, are perfect test-beds for new techniques and technologies because of their simpler design and signal paths (compared to multi-dish arrays).*

C.3 Broadening Participation for a Diverse, Globally Competitive STEM Workforce

C.3.1 First-Generation Student Internship Program

GBO is a partnering institution in an NSF-INCLUDES Alliance called the First 2 Network. The First 2 Network aims to improve the persistence of STEM undergraduates during the first two years of their college education and targets first generation college students who face obstacles over and above their non-first generation peers [e.g. 9]. The Alliance focuses on the first two years of college because it is within these years that more than 50% of STEM students leave their majors [11].

Leveraging our participation in the NSF-INCLUDES program, our plan for broadening participation in this proposal is to offer a two-week internship experience to rising college freshmen and sophomores, engaging them in authentic participation in the development of the RFI excision and validation procedures. It is well known that engaging students in research early in their college careers can have a potent impact on their persistence as STEM majors [e.g. 21, 18]. However, most student research experiences including our own Research Experience for Undergraduates (REU) program generally targets rising juniors and seniors. Through this internship we will be providing a first research experience, and preparing younger students for future success in programs like REU, including our own.

GBO piloted a 2-week internship for early first generation undergraduates in 2017 with clear success. Pre- and post-survey results revealed:

- High levels of STEM efficacy at both pre- and post-test, and even higher by post-test.
- Interns tended to be less concerned about barriers to STEM persistence by post-test.
- Interns were somewhat more likely to report that professors lecturing a lot in their STEM courses would be a potential challenge.
- Interns were significantly less likely to be concerned that they would be intimidated by professors.
- Interns were significantly less likely to be concerned that they wouldn't know where to get help when they felt depressed or worried.

Internship Activities: Twenty student interns will participate in the research and development effort in year two of the project. They will work in teams to analyze archived RFI data to curate a categorized and searchable database that includes common RFI features. They will test sources of RFI in our anechoic chamber to develop RFI exemplars. This work is important for testing RFI removal algorithms in a controlled manner.

Their research will be scaffolded with "just in time" learning through hands-on activities and talks by the PI and other GBO staff on radio astronomy science and instrumentation, and DSP. Additionally, interns will be completely immersed in the GBO academic culture during their residence, participating in regular activities such as colloquia and organized REU summer student activities.

We will also offer an opportunity for students in our existing REU program to act as near-peer mentors. Working with GBO educational staff, they will hold workshops to prepare our participants for college success and for future internship experiences. Sessions will include: "What I wish someone had told me when I started college", time management, study tips, and applying for internships.

At the end of the two-week internship student teams will present the results of their work in a student colloquium for GBO staff.

Participant Recruitment and Selection: First generation (which generally includes under-represented minority students) STEM undergraduate students will be targeted for participation in the internship. Rising freshmen and sophomores will be eligible to apply. We will advertise through the First 2 Network and other NSF-INCLUDES Alliances and Launch Pilot projects via the NSF-INCLUDES National Hub website.

Evaluation: We will employ the Undergraduate Research Student Self-Assessment Survey to measure student outcomes related to internship participation including acquisition of STEM skills, leadership, confidence, and STEM identity [45]. We will also participate in evaluation measures designed by the First 2 Network and provide data to the Network to add to the growing knowledge base of successful strategies and interventions.

C.3.2 Summer Research Experience

This grant will also support one undergraduate student that will work with astronomers and engineers at GBO and UCB on a 10–12 week research project. The focus of the students' work will likely be on developing RFI excision algorithms and the verification plan described in §B.3.5 & B.3.6, though we will devise specific projects with the strengths and interests of the individual student in mind. GBO already has a successful track record of involving summer undergraduate students in similar work, with four students having worked over the previous two summers on implementations of median absolute deviation and spectral kurtosis excision techniques. The student will be selected from UCB so that they can take advantage of local expertise and mentoring. While at GBO they will be fully integrated into the GBO/NRAO summer student activities (which includes the NSF-funded REU program). This will include living in observatory housing with other summer students, participating in scientific, technical, and career development seminars, and opportunities to engage in education and public outreach and local community events. The student will learn skills including advanced programming languages, fundamentals of DSP, and firmware and hardware design using the latest technology and tools. These skills are in extremely high demand within astronomy and other fields of basic research, as well as in applied fields and private industry.

D Project Management Plan

D.1 Project Scope

The scope of work planned and budgeted under this proposal will 1) design and prototype innovative technologies to enable the digitization of signals from the telescope at RF, resulting in the first stage of a deployable instrument; 2) create standardized procedures for testing RFI excision algorithms; and 3) develop and assess new RFI excision techniques enabled by this technology.

GBO will work collaboratively with UCB's SETI Research Center and CASPER teams, who will serve as advisers to the project to ensure that the efforts are synchronized, and knowledge is shared across multiple interested groups. In parallel, the CASPER team will be evaluating and integrating new technologies into the CASPER open-source platform. A shared strategic goal for both GBO and UCB is to transition from current ROACH2 based architectures as that technology is becoming obsolete.

We foresee this work leading into a second phase that will result in a final, production system. From a systems engineering perspective, phase one (this proposal) will encompass basic and applied research into new digitization technologies and RFI excision techniques, include a preliminary design for a new system, and conclude with a technical proof of concept. The preliminary design work in phase one will also enable GBO to develop a more detailed plan and cost for phase two.

Phase two of the project (out of scope for this proposal) will build upon the preliminary design to enter into a detailed design phase. This will include integration into the existing GBT M&C system, digital spectrometer development, engineering integration verification and validation, and scientific commissioning. The goal of the second phase will be to deliver a GBO user instrument to the Observatory.

D.2 Project Governance and Resources

D.2.1 Project Team

- PI Ryan Lynch (GBO) will provide scientific leadership. He will define the scientific goals and requirements for all work, lead the collection and generation of test data sets for the RFI excision validation procedures, and assist in scientific commissioning and validation of RFI excision algorithms. He is an expert in pulsar and radio transient science and project scientist for VEGAS.
- Co-Is Luke Hawkins, Randy McCullough, and Jason Ray (GBO) will serve as the technical project experts. They will design and develop integrated ADC/FPGA boards, Basic and CASPER blocks for M&C of FPGA boards and implementations of RFI excision algorithms. They will work with Lynch to asses and meet the scientific requirements. With over 40 years of combined experience, they are experts in DSP, Xilinx and CASPER tool flows, and RFI compliance and excision.
- Laura Jensen and Marty Bloss (GBO) will act as project managers, ensuring that project management and systems engineering best practices are used to allocate resources, set and meet milestones, and deliver on all project goals within budget. They will also assist Lynch with review and reporting requirements.
- Jack Hickish and Dan Werthimer (UCB) will be unfunded collaborators on this project. Hickish will develop CASPER blocks for interfacing with peripherals through 100-GbE and PCIe. Werthimer will provide local mentoring to a UCB undergraduate student. Both will act as technical advisers to the GBO digital engineering team.

Table 4: Compressed View of Risk Register

Risk	Rating	Mitigation Strategy
The integration of planned technologies has never been done before, so expected outcomes cannot be guaranteed.	High	A systematic approach with multiple iterations to assess outcomes and refine assumptions, with incremental steps that reduce risk.
Specifications for some technologies are still in development (e.g AD9213).	High	Current assumptions will be iteratively tested as new technologies are integrated.
ROACH2 technology currently used by CASPER and GBO is reaching end of life.	High	This is an **opportunity risk** that will be realized if research into new technologies is not undertaken in a timely basis.
Potential impacts of RFI excision on data products.	Medium	RFI excision algorithms will be systematically tested. Detailed comparisons to pre-excised data will be conducted.
Alignment of GBO digitization efforts with CASPER.	Medium	The CASPER team at UCB is a collaborator on the project, building on past collaborations.

- Sue Ann Heatherly (GBO) will oversee the two-week summer internship program. She is the education officer for GBO and a PI on the NSF-INCLUDES First 2 Network.
- A UCB undergraduate student will be funded for a summer research experience, and will work with the full team with a likely focus on implementing the RFI excision algorithms.

D.2.2 Project Organization

The UWB DSP project will be managed using documented GBO budget management, project management, and systems engineering processes developed in adherence with NSF requirements as per its Large Facilities Manual (NSF 17-066, March 2017). Experienced GBO program managers will coordinate, track, and report on activities from a project and programmatic view. Scope, schedule, costs, and risks will be managed by GBO program managers.

GBO and UCB have collaborated successfully on many projects over a number of years, and the project will benefit from established coordination mechanisms. Full project team teleconferences will be held monthly, and face-to-face meetings and short working sessions will be scheduled as required.

D.3 Risk Management

Our risk management plan identifies uncertainties in the project and mitigations to reduce loss, while identifying and realizing opportunities. As an R&D effort using newly released technologies, there are a number of risks related to uncertainties that we will mitigate through systematic basic and applied research. We will apply iterative project management techniques, testing the highest risk items first. If these tests are successful we will move on to next steps; otherwise we will reassess our approach and develop new strategies. Table 4 summarizes the risks we have identified thus far.

D.4 Schedule Management

The project will undergo iterative design, experimentation, test, verification, and validation phases. GBO's schedule management will measure progress towards the ultimate outcome of a prototype UWB DSP system. The planned period of performance is two years from the date of award. We will conduct preliminary evaluation of the new Xilinx VCU118 FGPA boards in collaboration with the UCB SETI Research Center in advance of the project award. This pre-work will address risks early on and enable the project to commence immediately upon award.

Table 5 summarizes target milestones by quarter based on the project schedule and an assumed start date in Q3 of Fiscal Year 2019.

Table 5: Project Milestones

Milestone	Target Completion
GBO electronics printed circuit board design; hardware procurements; RFI characterization and preliminary RFI excision algorithm design in collaboration with GBO REU and UCB summer undergraduate students.	FY2019 - Q4
Development of new FPGA firmware	FY2020 - Q2
Iterative FPGA firmware testing (simulations)	FY2020 - Q3
FPGA firmware/hardware integration; RFI excision algorithm testing in collaboration with summer student; Two-week student internship; Document standards and best practices for assessing RFI excision techniques.	FY2020 - Q4
Iterative independent instrument testing with RFI excision techniques; Develop plan, schedule, and budget for phase two.	FY2021 - Q1
Iterative integration testing with VCU118.	FY2021 - Q3
Document outcomes and final report.	FY2021 - Q4

D.5 Performance Measures

Program management performance measures throughout the project life-cycle will include:

- Analysis and monitoring of the project baseline (cost, schedule, scope) and controlling the baseline. Changes to the baseline will follow GBO's Change Management Process.
- Measuring project activities through the appropriate allocation of iterative verification and validation of results against hypothesis.
- Communications and stakeholder management through notifications, project reports, presentations, feedback, correspondence, meeting minutes, and other actions indicating transparency in the management of the project.
- Meaningful undergraduate summer student engagement and an organized summer student internship in year two. Undergraduate summer students will receive assessments based on validated evaluation instruments and NSF-INCLUDES requirements.
- Controlling risks through active management of the risk register and the prioritization of highest risks through iterative research, development, and testing.

The GBO Program Manager will prepare and submit quarterly status reports for review by the project team, GBO Management, and collaborators. Annual, Final, and Outcomes reports will be submitted in accordance with NSF requirements.

E Results from Prior NSF Support

The PI was an unfunded co-I on "Radio telescope computer software for detecting exotic astronomical sources that change with time" (PI: N. Schmid; Award number AAG-1615884; 09/01/2016–08/31/2019; $119,131).

Intellectual Merit: The project developed detection algorithms for astrophysical pulses such as FRBs. Algorithms were tested using single pixel telescope data (e.g. the GBT). These techniques differ from the traditional approach by detecting pulses in transform spaces, (spatial Fourier transforms (SFT) or Radon transform). After the application of the SFT, the signature of a dispersed astrophysical pulse is concentrated in a very small area around the origin. The compactness of the pulse signature in the SFT space yields extremely efficient blind detection statistics. Four papers have been published as a result of this work [2, 20, 36, 1].

Broader Impacts: To-date this work has supported three MS/PhD students at West Virginia University (WVU). An additional undergraduate student at WVU was sponsored through the Summer Research Experience for Undergraduate program, and two REU students worked on this project at the GBO during the summer of 2017 (co-advised by Lynch).

References Cited

[1] M. Alkhweldi and N. A. Schmid. Spatial Fourier Transform for Detection and Analysis of Periodic Astrophysical Pulses. In *2018 6th IEEE Global Conference on Signal and Information Processing*, page 1, November 2018.

[2] M. Alkhweldi, N. A. Schmid, and R. M. Prestage. A blind transform based approach for the detection of isolated astrophysical pulses. In *2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), March 2017, id.1*, page 1, June 2017.

[3] Z. Arzoumanian, P. T. Baker, A. Brazier, S. Burke-Spolaor, S. J. Chamberlin, S. Chatterjee, B. Christy, J. M. Cordes, N. J. Cornish, F. Crawford, H. Thankful Cromartie, K. Crowter, M. DeCesar, P. B. Demorest, T. Dolch, J. A. Ellis, R. D. Ferdman, E. Ferrara, W. M. Folkner, E. Fonseca, N. Garver-Daniels, P. A. Gentile, R. Haas, J. S. Hazboun, E. A. Huerta, K. Islo, G. Jones, M. L. Jones, D. L. Kaplan, V. M. Kaspi, M. T. Lam, T. J. W. Lazio, L. Levin, A. N. Lommen, D. R. Lorimer, J. Luo, R. S. Lynch, D. R. Madison, M. A. McLaughlin, S. T. McWilliams, C. M. F. Mingarelli, C. Ng, D. J. Nice, R. S. Park, T. T. Pennucci, N. S. Pol, S. M. Ransom, P. S. Ray, A. Rasskazov, X. Siemens, J. Simon, R. Spiewak, I. H. Stairs, D. R. Stinebring, K. Stovall, J. Swiggum, S. R. Taylor, M. Vallisneri, R. van Haasteren, S. Vigeland, W. W. Zhu, and NANOGrav Collaboration. The NANOGrav 11 Year Data Set: Pulsar-timing Constraints on the Stochastic Gravitational-wave Background. ApJ, 859:47, May 2018.

[4] Z. Arzoumanian, A. Brazier, S. Burke-Spolaor, S. J. Chamberlin, S. Chatterjee, B. Christy, J. M. Cordes, N. J. Cornish, K. Crowter, P. B. Demorest, X. Deng, T. Dolch, J. A. Ellis, R. D. Ferdman, E. Fonseca, N. Garver-Daniels, M. E. Gonzalez, F. Jenet, G. Jones, M. L. Jones, V. M. Kaspi, M. Koop, M. T. Lam, T. J. W. Lazio, L. Levin, A. N. Lommen, D. R. Lorimer, J. Luo, R. S. Lynch, D. R. Madison, M. A. McLaughlin, S. T. McWilliams, C. M. F. Mingarelli, D. J. Nice, N. Palliyaguru, T. T. Pennucci, S. M. Ransom, L. Sampson, S. A. Sanidas, A. Sesana, X. Siemens, J. Simon, I. H. Stairs, D. R. Stinebring, K. Stovall, J. Swiggum, S. R. Taylor, M. Vallisneri, R. van Haasteren, Y. Wang, W. W. Zhu, and NANOGrav Collaboration. The NANOGrav Nine-year Data Set: Limits on the Isotropic Stochastic Gravitational Wave Background. ApJ, 821:13, April 2016.

[5] P. C. Boyle and Chime/Frb Collaboration. First detection of fast radio bursts between 400 and 800 MHz by CHIME/FRB. *The Astronomer's Telegram*, 11901, August 2018.

[6] F. Camilo, S. M. Ransom, J. P. Halpern, and J. Reynolds. 1E 1547.0-5408: A Radio-emitting Magnetar with a Rotation Period of 2 Seconds. ApJ, 666:L93–L96, September 2007.

[7] F. Camilo, S. M. Ransom, J. P. Halpern, J. Reynolds, D. J. Helfand, N. Zimmerman, and J. Sarkissian. Transient pulsed radio emission from a magnetar. Nature, 442:892–895, August 2006.

[8] F. Camilo, S. M. Ransom, J. Peñalver, A. Karastergiou, M. H. van Kerkwijk, M. Durant, J. P. Halpern, J. Reynolds, C. Thum, D. J. Helfand, N. Zimmerman, and I. Cognard. The Variable Radio-to-X-Ray Spectrum of the Magnetar XTE J1810-197. ApJ, 669:561–569, November 2007.

[9] E. F. Cataldi, C. T. Bennett, X. Chen, and S. A. Simone. First-Generation Students: College Access, Persistence, and Postbachelors Outcomes. Technical Report 2018421, U.S. Department of Education, Institute of Education Sciences, National Center for Education Statistics, February 2018.

[10] S. Chatterjee, C. J. Law, R. S. Wharton, S. Burke-Spolaor, J. W. T. Hessels, G. C. Bower, J. M. Cordes, S. P. Tendulkar, C. G. Bassa, P. Demorest, B. J. Butler, A. Seymour, P. Scholz, M. W. Abruzzo, S. Bogdanov, V. M. Kaspi, A. Keimpema, T. J. W. Lazio, B. Marcote, M. A. McLaughlin, Z. Paragi, S. M. Ransom, M. Rupen, L. G. Spitler, and H. J. van Langevelde. A direct localization of a fast radio burst and its host. Nature, 541:58–61, January 2017.

[11] X. Chen. STEM Attrition: College Students' Paths into and out of STEM Fields. Technical Report 2014001, U.S. Department of Education, Institute of Education Sciences, National Center for Education Statistics, November 2013.

[12] J. M. Cordes, I. Wasserman, J. W. T. Hessels, T. J. W. Lazio, S. Chatterjee, and R. S. Wharton. Lensing of Fast Radio Bursts by Plasma Structures in Host Galaxies. ApJ, 842:35, June 2017.

[13] C. Dumez-Viou, R. Weber, and P. Ravier. Multi-Level Pre-Correlation RFI Flagging for Real-Time Implementation on UniBoard. *Journal of Astronomical Instrumentation*, 5:1641019–408, December 2016.

[14] R. P. Eatough, H. Falcke, R. Karuppusamy, K. J. Lee, D. J. Champion, E. F. Keane, G. Desvignes, D. H. F. M. Schnitzeler, L. G. Spitler, M. Kramer, B. Klein, C. Bassa, G. C. Bower, A. Brunthaler, I. Cognard, A. T. Deller, P. B. Demorest, P. C. C. Freire, A. Kraus, A. G. Lyne, A. Noutsos, B. Stappers, and N. Wex. A strong magnetic field around the supermassive black hole at the centre of the Galaxy. Nature, 501:391–394, September 2013.

[15] A. Faure, A. J. Remijan, K. Szalewicz, and L. Wiesenfeld. Weak Maser Emission of Methyl Formate toward Sagittarius B2(N) in the Green Bank Telescope PRIMOS Survey. ApJ, 783:72, March 2014.

[16] E. Fonseca, T. T. Pennucci, J. A. Ellis, I. H. Stairs, D. J. Nice, S. M. Ransom, P. B. Demorest, Z. Arzoumanian, K. Crowter, T. Dolch, R. D. Ferdman, M. E. Gonzalez, G. Jones, M. L. Jones, M. T. Lam, L. Levin, M. A. McLaughlin, K. Stovall, J. K. Swiggum, and W. Zhu. The NANOGrav Nine-year Data Set: Mass and Geometric Measurements of Binary Millisecond Pulsars. ApJ, 832:167, December 2016.

[17] V. Gajjar, A. P. V. Siemion, D. C. Price, C. J. Law, D. Michilli, J. W. T. Hessels, S. Chatterjee, A. M. Archibald, G. C. Bower, C. Brinkman, S. Burke-Spolaor, J. M. Cordes, S. Croft, J. E. Enriquez, G. Foster, N. Gizani, G. Hellbourg, H. Isaacson, V. M. Kaspi, T. J. W. Lazio, M. Lebofsky, R. S. Lynch, D. MacMahon, M. A. McLaughlin, S. M. Ransom, P. Scholz, A. Seymour, L. G. Spitler, S. P. Tendulkar, D. Werthimer, and Y. G. Zhang. Highest Frequency Detection of FRB 121102 at 4-8 GHz Using the Breakthrough Listen Digital Backend at the Green Bank Telescope. ApJ, 863:2, August 2018.

[18] M. J. Graham, J. Frederick, A. Byars-Winston, A. Hunter, and J. Handelsman. Increasing persistence of college students in STEM. *Science*, 341:1455–1456, September 2013.

[19] R. W. Hellings and G. S. Downs. Upper limits on the isotropic gravitational radiation background from pulsar timing analysis. ApJ, 265:L39–L42, February 1983.

[20] M. Jiang, B.-Y. Cui, N. A. Schmid, M. A. McLaughlin, and Z.-C. Cao. Wavelet Denoising of Radio Observations of Rotating Radio Transients (RRATs): Improved Timing Parameters for Eight RRATs. ApJ, 847:75, September 2017.

[21] J. Lave and E. Wenger. *Situated Learning: Legitimate Peripheral Participation*. Learning in Doing: Social, Cognitive and Computational Perspectives. Cambridge University Press, 1991.

[22] L. Levin, M. Bailes, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, N. D'Amico, S. Johnston, M. Keith, M. Kramer, S. Milia, A. Possenti, N. Rea, B. Stappers, and W. van Straten. A Radio-loud Magnetar in X-ray Quiescence. ApJ, 721:L33–L37, September 2010.

[23] D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, and F. Crawford. A Bright Millisecond Radio Burst of Extragalactic Origin. *Science*, 318:777, November 2007.

[24] D. R. Lorimer and M. Kramer. *Handbook of Pulsar Astronomy*. Cambridge University Press, October 2012.

[25] M. Luisi, L. D. Anderson, D. S. Balser, T. V. Wenger, and T. M. Bania. Diffuse Ionized Gas in the Milky Way Disk. ApJ, 849:117, November 2017.

[26] D. H. E. MacMahon, D. C. Price, M. Lebofsky, A. P. V. Siemion, S. Croft, D. DeBoer, J. E. Enriquez, V. Gajjar, G. Hellbourg, H. Isaacson, D. Werthimer, Z. Abdurashidova, M. Bloss, J. Brandt, R. Creager, J. Ford, R. S. Lynch, R. J. Maddalena, R. McCullough, J. Ray, M. Whitehead, and D. Woody. The Breakthrough Listen Search for Intelligent Life: A Wideband Data Recorder System for the Robert C. Byrd Green Bank Telescope. PASP, 130(4):044502, April 2018.

[27] R. Main, I.-S. Yang, V. Chan, D. Li, F. X. Lin, N. Mahajan, U.-L. Pen, K. Vanderlinde, and M. H. van Kerkwijk. Pulsar emission amplified and resolved by plasma lensing in an eclipsing binary. Nature, 557:522–525, May 2018.

[28] B. Margalit and B. D. Metzger. A concordance picture of FRB 121102 as a flaring magnetar embedded in a magnetized ion-electron wind nebula. *ArXiv e-prints*, August 2018.

[29] B. A. McGuire, P. B. Carroll, R. A. Loomis, I. A. Finneran, P. R. Jewell, A. J. Remijan, and G. A. Blake. Discovery of the interstellar chiral molecule propylene oxide (CH_3CHCH_2O). *Science*, 352:1449–1452, June 2016.

[30] Brett A. McGuire, Ryan A. Loomis, Cameron M. Charness, Joanna F. Corby, Geoffrey A. Blake, Jan M. Hollis, Frank J. Lovas, Philip R. Jewell, and Anthony J. Remijan. Interstellar Carbodiimide (HNCNH): A New Astronomical Detection from the GBT PRIMOS Survey via Maser Emission Features. ApJ, 758:L33, October 2012.

[31] M. A. McLaughlin. The North American Nanohertz Observatory for Gravitational Waves. *Classical and Quantum Gravity*, 30(22):224008, November 2013.

[32] D. Michilli, A. Seymour, J. W. T. Hessels, L. G. Spitler, V. Gajjar, A. M. Archibald, G. C. Bower, S. Chatterjee, J. M. Cordes, K. Gourdji, G. H. Heald, V. M. Kaspi, C. J. Law, C. Sobey, E. A. K. Adams, C. G. Bassa, S. Bogdanov, C. Brinkman, P. Demorest, F. Fernandez, G. Hellbourg, T. J. W. Lazio, R. S. Lynch, N. Maddox, B. Marcote, M. A. McLaughlin, Z. Paragi, S. M. Ransom, P. Scholz, A. P. V. Siemion, S. P. Tendulkar, P. van Rooy, R. S. Wharton, and D. Whitlow. An extreme magneto-ionic environment associated with the fast radio burst source FRB 121102. Nature, 553:182–185, January 2018.

[33] G. M. Nita and D. E. Gary. The generalized spectral kurtosis estimator. MNRAS, 406:L60–L64, July 2010.

[34] G. M. Nita, J. Hickish, D. MacMahon, and D. E. Gary. EOVSA Implementation of a Spectral Kurtosis Correlator for Transient Detection and Classification. *Journal of Astronomical Instrumentation*, 5:1641009–7366, December 2016.

[35] K. M. Rajwade, N. M. Pingel, R. A. Black, M. Ruzindana, M. Burnett, B. Jeffs, K. Warnick, D. J. Pisano, D. R. Lorimer, R. M. Prestage, L. Hawkins, J. Ray, P. Marganian, T. Chamberlin, J. Ford, W. Shillue, and D. A. Roshi. Commissioning of FLAG: A phased array feed for the GBT. In P. Weltevrede, B. B. P. Perera, L. L. Preston, and S. Sanidas, editors, *Pulsar Astrophysics the Next Fifty Years*, volume 337 of *IAU Symposium*, pages 398–399, August 2018.

[36] N. A. Schmid and R. M. Prestage. Blind detection of isolated astrophysical pulses in the spatial Fourier transform domain. MNRAS, 477:4052–4062, July 2018.

[37] P. Scholz, L. G. Spitler, J. W. T. Hessels, S. Chatterjee, J. M. Cordes, V. M. Kaspi, R. S. Wharton, C. G. Bassa, S. Bogdanov, F. Camilo, F. Crawford, J. Deneva, J. van Leeuwen, R. Lynch, E. C. Madsen, M. A. McLaughlin, M. Mickaliger, E. Parent, C. Patel, S. M. Ransom, A. Seymour, I. H. Stairs, B. W. Stappers, and S. P. Tendulkar. The Repeating Fast Radio Burst FRB 121102: Multi-wavelength Observations and Additional Bursts. ApJ, 833:177, December 2016.

[38] R. M. Shannon, J.-P. Macquart, K. W. Bannister, R. D. Ekers, C. W. James, S. Oslowski, H. Qiu, M. Sammons, A. W. Hotan, M. A. Voronkov, R. J. Beresford, M. Brothers, A. J. Brown, J. D. Bunton, A. P. Chippendale, C. Haskins, M. Leach, M. Marquarding, D. McConnell, M. A. Pilawa, E. M. Sadler, E. R. Troup, J. Tuthill, M. T. Whiting, J. R. Allison, C. S. Anderson, M. E. Bell, J. D. Collier, G. Gurkan, G. Heald, and C. J. Riseley. The dispersion-brightness relation for fast radio bursts from a wide-field survey. Nature, 562:386–390, October 2018.

[39] L. G. Spitler, J. M. Cordes, J. W. T. Hessels, D. R. Lorimer, M. A. McLaughlin, S. Chatterjee, F. Crawford, J. S. Deneva, V. M. Kaspi, R. S. Wharton, B. Allen, S. Bogdanov, A. Brazier, F. Camilo, P. C. C. Freire, F. A. Jenet, C. Karako-Argaman, B. Knispel, P. Lazarus, K. J. Lee, J. van Leeuwen, R. Lynch, S. M. Ransom,

P. Scholz, X. Siemens, I. H. Stairs, K. Stovall, J. K. Swiggum, A. Venkataraman, W. W. Zhu, C. Aulbert, and H. Fehrmann. Fast Radio Burst Discovered in the Arecibo Pulsar ALFA Survey. ApJ, 790:101, August 2014.

[40] L. G. Spitler, P. Scholz, J. W. T. Hessels, S. Bogdanov, A. Brazier, F. Camilo, S. Chatterjee, J. M. Cordes, F. Crawford, J. Deneva, R. D. Ferdman, P. C. C. Freire, V. M. Kaspi, P. Lazarus, R. Lynch, E. C. Madsen, M. A. McLaughlin, C. Patel, S. M. Ransom, A. Seymour, I. H. Stairs, B. W. Stappers, J. van Leeuwen, and W. W. Zhu. A repeating fast radio burst. Nature, 531:202–205, March 2016.

[41] S. R. Taylor, M. Vallisneri, J. A. Ellis, C. M. F. Mingarelli, T. J. W. Lazio, and R. van Haasteren. Are We There Yet? Time to Detection of Nanohertz Gravitational Waves Based on Pulsar-timing Array Limits. ApJ, 819:L6, March 2016.

[42] S. P. Tendulkar, C. G. Bassa, J. M. Cordes, G. C. Bower, C. J. Law, S. Chatterjee, E. A. K. Adams, S. Bogdanov, S. Burke-Spolaor, B. J. Butler, P. Demorest, J. W. T. Hessels, V. M. Kaspi, T. J. W. Lazio, N. Maddox, B. Marcote, M. A. McLaughlin, Z. Paragi, S. M. Ransom, P. Scholz, A. Seymour, L. G. Spitler, H. J. van Langevelde, and R. S. Wharton. The Host Galaxy and Redshift of the Repeating Fast Radio Burst FRB 121102. ApJ, 834:L7, January 2017.

[43] D. Thornton, B. Stappers, M. Bailes, B. Barsdell, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, D. J. Champion, P. Coster, N. D'Amico, A. Jameson, S. Johnston, M. Keith, M. Kramer, L. Levin, S. Milia, C. Ng, A. Possenti, and W. van Straten. A Population of Fast Radio Bursts at Cosmological Distances. *Science*, 341:53–56, July 2013.

[44] Chenoa D. Tremblay, Natasha Hurley-Walker, Maria Cunningham, Paul A. Jones, Paul J. Hancock, Randall Wayth, and Christopher H. Jordan. A first look for molecules between 103 and 133 MHz using the Murchison Widefield Array. MNRAS, 471:4144–4154, November 2017.

[45] T. J. Weston, S. L. Laursen, and E. Dolan. The Undergraduate Research Student Self-Assessment (URSSA): Validation for Use in Program Evaluation. *CBELife Sciences Education*, 14(3):ar33, 2015.

[46] W. W. Zhu, I. H. Stairs, P. B. Demorest, D. J. Nice, J. A. Ellis, S. M. Ransom, Z. Arzoumanian, K. Crowter, T. Dolch, R. D. Ferdman, E. Fonseca, M. E. Gonzalez, G. Jones, M. L. Jones, M. T. Lam, L. Levin, M. A. McLaughlin, T. Pennucci, K. Stovall, and J. Swiggum. Testing Theories of Gravitation Using 21-Year Timing of Pulsar Binary J1713+0747. ApJ, 809:41, August 2015.