

An Ultrawideband Digital Signal Processing System for the Green Bank Telescope

October 28, 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**

I Overview

We propose to use state-of-the-art technologies to build an ultra-wideband 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 bit-depth analog-to-digital converters (ADCs) that will directly sample the entire 0.7–4 GHz radio frequency (RF) bandwidth of the new ultra-wideband 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 implement 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 front-end 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 experiences of a similar UWB system that has been deployed on the Effelsberg Radio Telescope that was 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 UWB-DSP system will use cutting edge digital hardware, innovative RFI excision techniques not in use at any other observatories, and pioneering methods for handling very high data rates using 100-gigabit Ethernet (GbE) protocols. These will complement the UWBR, which will deliver a combination of wider instantaneous bandwidth and lower system noise temperature than was possible with previous generation technology. 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 facility 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 the RFI excision project by creating training data sets for machine learning algorithms. The students will also be exposed to a wide range of engineering and scientific disciplines that contribute to the success of 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.

II Intellectual Merit

A Motivation

Our objective is to enable a diverse range of high-impact astronomical science benefiting from ultra-wide bandwidths at radio frequencies, particularly the study of pulsars and transients, and of rich molecular line regions. We will also develop technical solutions for sharing the radio spectrum with civil and commercial users. We describe the science and technical motivations for this project in more detail below.

A.1 Scientific Motivation

A.1.1. The Low-Frequency GW Universe: The primary science driver of the UWB-DSP 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; [22]). 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 and similar experiments are highly complementary to ground- and space-based laser interferometers that probe higher GW frequencies, and cosmic microwave background experiments that probe lower frequencies. The NANOGrav PFC is on-track to detect a stochastic GW background within the next 3–5 years [30], 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 [3, 2]. 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 [2].

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 quadrupolar nature of GWs will specifically cause a quadrupolar angular correlation between pulsars distributed across the sky, which makes it possible to distinguish between GWs and other 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; [15]). 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 [13], tests of general relativity [35], and novel constraints on Solar system planetary ephemerides [2].

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 dispersive delay given by

$$\Delta t_{\text{DM}} = k_{\text{DM}} \text{DM}(t, f) (f_l^{-2} - f_h^{-2}), \quad (1)$$

where k_{DM} is a physical constant, f is the radio frequency and the subscripts denote a lower and higher frequency, and $\text{DM}(t, f)$ is the dispersion measure, i.e. column density of free electrons between the pulsar and the Earth [e.g. 19]. We emphasize that DM is both time and frequency dependent [9], and thus represents a noise term *that must be measured at each observing epoch with a fractional precision of $\sim 10^{-5}$* .

The NANOGrav PFC currently employs a two-receiver strategy at the GBT to precisely measure DM, observing from 0.72–0.92 GHz and 1.1–1.9 GHz. This approach is sub-optimal 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 NANOGrav PFC is sensitive to individual SMBBHs—analogue to the improvement between the first phase of the Laser Interferometric Observatory for Gravitational Waves (LIGO) and Advanced LIGO.

A.1.2. Radio Transients: Wide instantaneous bandwidth is essential for characterizing the spectro-temporal behavior of highly variable radio transients. One such population are fast radio bursts — millisecond duration radio-frequency pulses that originate in distant galaxies [18, 32]. 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; [28, 29]), a fact which has enabled the only precise interferometric localization of an FRB to a host galaxy [8, 31], as well as long-duration study of the changing characteristics of the bursts (e.g. DM, Faraday rotation measure (RM), and burst morphology; [23]). With telescope like the Australian SKA Pathfinder and the Canadian HI Intensity Mapping Experiment poised to discover dozens (if not hundreds) of new FRBs [27, 4], more repeaters are sure to follow.

FRB 121102 exhibits dramatic burst-to-burst spectro-temporal variation including a) a highly variable power-law spectral index; b) non-power-law spectral shapes including band-limited bursts with characteristic bandwidths of ~ 100 MHz; c) changing peak frequency; d) changing burst morphology; and e) distinct sub-bursts that drift towards lower peak frequencies with time in the larger burst envelope [26]. These features may be intrinsic, extrinsic, or both — the sub-burst structure in particular may be a sign of plasma lenses in the local environment of FRB121102 [10, 20]. There is also some evidence for secular changes in DM and RM [23, 14]. 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 properties, so they serve as a powerful diagnostic tool for understanding FRBs’ physical origins. However, most burst detections are limited by the bandwidth of the receiver, so the only way thus far to investigate the behavior of FRB 121102 over ultra-wide bandwidths has been through simultaneous observations using multiple telescopes. This is obviously logistically complicated and sub-optimal. 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 bandwidth 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 bandwidths? e) is the apparent ~ 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, such as the aforementioned plasma-lensing model.

A second class of variables are radio magnetars — a sub-class of 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 of 29^{1} magnetars that emit X-rays and gamma-rays [6, 5, 17, 12]. 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 [e.g. 7], and the physical processes giving rise to their radio emission remains a mystery. As with FRB 121102, spectro-temporal studies have been limited by the relatively small bandwidth provided by most receivers. 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. 21], and the extremely high RM observed in FRB 121102 has only one known analog: the radio magnetar near the center of the Milky Way [12]. Thus, studies of magnetars may improve our understanding of FRBs, and vice versa. The UWB-DSP system will thus be a powerful tool for expanding our knowledge of radio transients.

A.1.3. Molecular Line Surveys: TODO

A.2 Technical Motivation

The ultra-wide bandwidth observations needed to realize the above scientific potential come with a number of technical challenges. One of the most pressing is the ability to *share the spectrum* with man-made transmitters, producing scientifically usable data at frequencies where there is significant, strong RFI. GBO’s location

¹See <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html> for an up-to-date list.

at the center of the 13,000 square-mile National Radio Quiet Zone and smaller West Virginia Radio Astronomy Zone gives it unique interference protection, but many sources of RFI, such as satellite transmitters, are unavoidable (for more information on these interference protection zones see Facilities, Equipment, and Other Resources). The ability to effectively coexist with other spectrum users is made all the more important by the expanding presence of wireless devices in our lives, and the inevitable pervasiveness of self-driving cars relying on RADAR or similar active-RF methods for guidance, as well as the increasing sensitivity and bandwidth of astronomy receiver systems (and thus the total number of RFI detections per-second).

We broadly classify techniques for sharing the spectrum into RFI resistance (i.e., a high linear dynamic range in every component of the front-end and back-end) and RFI excision (i.e. removal of RFI at the lowest-possible level of data to improve data quality). We note that GBO is taking extreme care to ensure that the front-end UWBR is sufficiently resistant to RFI as part of a separate research and development effort, so here we concern ourselves only with the UWB-DSP system.

A.2.1. RFI Resistance: The GBT currently uses the Versatile Green Bank Astronomical Spectrometer (VEGAS, developed in part with support from NSF-***²) as its primary digital back-end 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 780 graphical processing unit (GPU). A relatively straightforward expansion of the HPC system will be sufficient to process the full bandwidth provided by the UWBR for pulsar and FRB observations, but this approach comes with significant drawbacks. Most notably, VEGAS makes use of the GBTs IF system before digital sampling, which will expose the UWB system to potential saturation of numerous components including the RF-over-fiber transceivers, 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 back-end systems in addition to VEGAS. growing use of automatic dependent surveillance-broadcast (ADS-B) technology² transmitting at 1.09 GHz; the instability itself has been isolated to analog components between the RF-over-fiber transceivers and second frequency mixer. The UWB system will be exposed to an even worse RFI environment that includes cellular communication towers, digital television transmitters, Global Positioning System satellites, airport radar and aircraft positioning systems, Iridium communication satellites, and Sirius XM Satellite Radio. *We thus have empirical evidence that illustrates the need to minimize the analog components in the UWB signal path and to digitally sample with sufficient dynamic range to maintain linearity across 0.7–4 GHz.*

The UWB-DSP system will accomplish this goal by completely bypassing the existing GBT IF system, sampling at RF with a minimum of 12-bits per polarization channel. This will also provide better spectral baseline stability.

A.2.2. 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, and a new project using machine learning (ML) algorithms. The latter is, to our knowledge, unique among major radio astronomy observatories. As part of normal operations the GBT regularly conducts RFI scans that have resulted in a database of over 20 million instances of narrow-band RFI, resulting in a rich data set that can be used to train deep neural networks. However, the limitations of our existing ROACH2-based DSP hardware prevents us from fully implementing, testing, and deploying these RFI excision techniques. Specifically, this previous generation 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 bandwidth I/O transceivers. We have also struggled to meet timing closure using the Virtex-6 technology for complex firmware designs.

Luckily, new developments in field programmable gate arrays (FPGAs) and associated tool flows fundamentally change the paradigm for realizing sophisticated RFI excision techniques. New FPGAs have factors of several more memory, logic density, and I/O bandwidth. Improvements in development tools make it easier to achieve timing closure and to build complex programs, leading to faster prototyping. The upcoming Xilinx Versal series artificial intelligence accelerator chips are also optimized for ML algorithms. *Our development of an UWB-DSP system is perfectly timed to take advantage of these new technologies.*

²ADS-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/>

B Innovation

To realize the above scientific and technical goals we will make use of cutting-edge hardware and innovative DSP techniques. *We emphasize that we will use modular designs that abstract away lower-level components. This will make it easier to rapidly take advantage of new technologies as they emerge, so that the impact of our efforts will last much longer than a single generation of specific technology.*

B.1 Next-Generation Hardware

We will use acquire and deploy the latest generation of digital hardware, far surpassing the DSP capabilities of currently deployed instruments.

B.1.1. New FPGA Boards: GBO’s current digital back-end is based on CASPER ROACH2 boards, which used Xilinx Virtex-6 series FPGAs. As part of the UWB-DSP system we will develop a next-generation successor to the ROACH2. We have identified the Xilinx Virtex UltraScale+ FPGA VCU118 evaluation kit as a promising platform. The VCU118s FPGA has significantly more resources than the ROACH2 (allowing larger, more computationally intense designs), significantly smaller feature size (simplifying timing-closure), and significantly faster transceivers (allowing higher I/O bandwidth). Table 1 provides a side-by-side comparison.

Table 1: 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	$8 \times 10\text{--GbE}$	$3 \times 100\text{--GbE}$
FPGA Silicon Feature Size	40 nm	16 nm
Expansion Bus	$2 \times \text{ZDOK}$	$1 \times \text{FMC}, 1 \times \text{FMC+}$
Max FPGA transceiver speed	6.6 Gbps	32.75 Gbps

One benefit of the ROACH2 over the VCU118 is that the ROACH2 was specifically designed by a radio astronomy research and instrumentation organization with radio astronomy applications in mind, whereas the VCU118 is a development board developed by Xilinx whose purpose is to exhibit the full range of the possibilities created by the Virtex UltraScale+ series chips. Functionally, the one area of the boards where this discrepancy is made obvious is the high-speed transceivers — on the ROACH2 all of the transceivers are connected to expansion bus connectors, whereas many transceivers on the VCU118 are connected to “exhibition” technologies (PCIe, Samtec FireFly) that we do not intend to use on our deployed VCU118s. Nevertheless, the overall “useable” I/O bandwidth of the VCU118 far exceeds that of the ROACH2.

B.1.2. High-Speed ADCs: Table 2 compares the current EV8AQ160 ADC standard with our prospective for use in the UWB-DSP system (AD9213). The specifications for the AD9213 are representative of the upcoming generation of high-speed ADCs. As the electronics industry advances, so do ADC technologies — the AD9213 is faster, more precise, and has lower-noise than our current deployed technology. One large driver behind the lower spur-free dynamic range is the 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 our existing ADCs).

B.2 Firmware Development

We will develop firmware designs for the next-generation hardware and communication protocols deployed in the UWB-DSP system. These designs will be shared widely with the scientific and engineering communities.

In light of the variety of new hardware that we will use in the UWB-DSP system, a variety of new firmware “blocks” (sets of low-level FPGA code abstracted to a higher level for easier use by firmware system designers) will need to be developed for interfacing with various FPGA-facing peripherals as well as for executing advanced DSP techniques. In addition, new firmware tools may need to be developed to allow

Table 2: Comparison of ADC Standards

Feature/Spec	E2V EV8AQ160	AD AD9213
Max. Sampling Rate	5 GHz	10.25 GHz
Bit-depth	8	12
Spur-free Dynamic Range (@max. rate)	56 dBc	68 dBc
Power Consumption (@max. rate)	4.2 W	5.1 W
Effective Number of Bits (@ max. rate)	7.1	8.7

our CASPER-based designs to take advantage of the totality of hardware advancements that are provided by Xilinx Ultrascale+ and later technologies. Much of this new firmware development can be broken into functional blocks within Xilinx Embedded Developer's Kit (EDK) architecture. "Basic EDK blocks" are primarily dedicated to data processing with no use of peripheral components (e.g. BRAM, transceivers, Microblaze access, etc.), whereas "CASPER EDK blocks" interface with peripherals. Many of the CASPER EDK blocks exist for earlier generations of hardware, but considerable work is required to prepare them for the newest generations. A discussion of prospective developments is provided below.

B.2.1. Peripheral Interfacing: To take advantage of the possibilities enabled by the newest generation of data-transmission technologies, GBO intends to create CASPER EDK 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 our custom ADC cards via the FPGA Mezzanine Card (FMC/FMC+) slots on the VCU118. 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.

B.2.2. DSP Capabilities: In addition to the new functional blocks listed above, GBO will create additional blocks (basic EDK) to improve our DSP capabilities. For example, we intend to develop blocks implementing new RFI-mitigation methods (discussed in more detail in the §B.4) that are too computationally expensive to run in real-time on our current hardware. These developments can largely be considered (with the exception of ML) translations of algorithmic implementations from Python notebooks to hardware descriptive languages (HDL).

B.2.3. Heterogeneous Computing: The two preceding sections address what we must do to harvest the expected fruits of Moore's law (higher-speed data transmission, higher-density FPGA chips), but Xilinx has also made great developments in some less obvious directions. In recent years, their focus has widened to include heterogeneous computing architectures such as the Manycore Processor System on Chip (MPSoC), RF System on Chip (RFSoc), and the Adaptive Compute Acceleration Platform (ACAP).

While all of these advancements open up new, exciting horizons of system and DSP design, the most exciting possibilities are enabled by the ACAP architecture (the upcoming chip series is named Versal). These chips are heterogeneous devices, combining the generality and accessibility of CPUs, the vector processing power of GPUs/DSPs, the I/O and memory bandwidth, and adaptability of FPGAs, and integrated ADCs and digital-to-analog converters (DACs) suitable for commercial 5G applications. Subsets of these chips were developed with the deployment of real-time neural-network based ML as the target applications (upcoming native integration between the Xilinx chips and common ML suites such as Caffe or TensorFlow via an application overlay through Xilinx Vivado has been announced). A broader discussion of ML possibilities is provided in the §B.4.

With such a wide variety of advancements being exhibited in the Versal series, the depth and breadth of possible firmware developments required to take advantage of the full suite of improvements is quite large. CASPER EDK blocks could (**Could or will?**) be developed to interface the scalar processing, vector processing and programmable logic portions of the chip, which will enable acceleration of our DSP algorithms and a faster and less intrusive M&C methodology compared to the current CASPER standard of interfacing via a soft-core Microblaze processor.

Additionally, while the ADCs that are integrated with the ACAP may be too slow for the high-bandwidth, high time-resolution requirements of many upcoming radio astronomy instruments, possessing integrated,

high-speed DACs (Xilinx integrated DACs have so far been significantly faster than their ADCs) will allow us to improve on our ability to perform full-system tests. This will not only accelerate our design-to-deployment cycle, but would also allow more robust, realistic, and real-time evaluation of future algorithms. **(How?).** Thus, creating CASPER EDK blocks that interface the ADCs/DACs with the tool flow will enable improved test methodologies, and the use of the ADCs (lowering the system-cost for systems where the speed is acceptable).

Finally, developing a methodology for tying together Xilinx upcoming ML application overlay with the CASPER tool flow will enable the implementation of real-time ML algorithms for applications such as transient detection and RFI-mitigation.

B.3 Data Transmission Methods and Topology

Our plan for the UWB-DSP system calls for a move from IF-over-fiber with sampling in the GBO equipment room (over 1 km from the GBT) to sampling the receiver itself. This approach will quintuple the bit-rate compared with previous instruments and will require the use of 100-GbE fiber downlinks to the equipment room as the backbone of our signal sampling/transmission pipeline. We will thus need to develop solutions to mitigate a several challenges.

For example, the AD9213 analog-to-digital converter's power dissipation is 5.1W, compared to the 10W maximum power dissipation allowed per the VME International Trade Association (VITA) 57 specification for the FMC/FMC+ daughter card specification. Since each VCU118 contains only a single VITA 57-compliant connector with high-speed transceivers, we will likely need to either develop power-mitigation methods that would allow us to safely contravene the standards (allowing multiple ADCs per VCU118), or we would need to develop robust methods of cross-board ADC clock synchronization (single ADC per VCU118) to ensure that our dual-polarized samples are coherent. We will also then have to develop custom ADC boards that complies with our preferred method.

Continuing with the AD9213 as an archetype of the upcoming generation of ADCs, the total maximum bit-rate will be $12 \text{ bits} \times 10 \text{ GSPS} = 120 \text{ Gbps}$. This is more than a single 100-GbE port is capable of handling. With the majority of new Xilinx FPGA boards having only $2 \times 100\text{-GbE}$ ports (the VCU118 is an outlier with $2 \times 100\text{-GbE}$ QSFP28 ports and $1 \times 100\text{-GbE}$ FireFly port), we are in an age of technological development where the ADC bit-rates are growing faster than the I/O bandwidth of FPGA boards. This will spur examinations of optimal network topologies (one or two polarizations per receiver-room board? one or two polarizations per 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 bandwidth while minimizing system cost and complexity.

A new trend among FPGA board designers is to include a PCIe edge-connector while also eliminating the 1-GbE port that we have used for FPGA-related M&C functions in previous designs. This trend will require us to integrate PCIe-based M&C functionality, and to measure how different bi-directional M&C data-rates between the host computer and the FPGA over the PCIe bus effect the main, uni-directional data-transfer rates from the FPGA to the host computer.

(This section could use a punch line statement summarizing what we plan to do to investigate/solve these issues.)

B.4 Active RFI excision

We will implement real-time techniques for actively identifying and excising RFI, along with standard acceptance procedures.

Real-time RFI excision is a critical component of the UWB-DSP system that is broadly applicable to other observatories and instruments. Below we describe the techniques that we plan to deploy as part of this project. In addition, we will develop a generalized test methodology for validating the efficacy of these techniques while preserving scientific data quality — such a methodology does not exist in the public domain, but would be a great boon to the future of the larger community and is critical to building confidence in the new techniques among scientific users.

B.4.1. Robust Recursive Power Estimator: GBO has built upon work started at the Nançay Radio Observatory [11] 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 (detection is based both on power and duration of the pulse). *Members of our team have now implemented this functionality in 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.

B.4.2. Spectral Kurtosis: Initially conceived at the Center for Solar-Terrestrial Research at New Jersey Institute of Technology as a robust statistical RFI detector [24, 25], the simple sum/sum-squared algorithm lends itself naturally to implementations 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 are mitigated.

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 [24], and its overall effectiveness has been proven. However, our current implementation is not real-time, and has been designed specifically using archived complex voltage data gathered as part of GBT pulsar observation. None of our extant back-end systems have enough logic/DSP cores and RAM resources available in the FPGA chips to allow an implementation to co-exist with the existing channelization firmware that currently occupies ever-growing percentages of the available resources on our current hardware. Acquisition of newer FPGAs with three to five times more logic/DSP cores and RAM resources would enable us to create and test a real-time implementation of this method that could then be shared with the wider community. SpectralKurtosis has also been identified as a promising method for the detection and classification of astrophysical transients [25]. *Our UWB-DSP system will thus enable real-time detection of FRBs and other scientifically interesting transients.*

B.4.3. Machine Learning: ML is subset of artificial intelligence whose applicability and accessibility has increased dramatically in recent years. In response to industry trends, Xilinx has recently taken steps to optimize their hardware (see §B.2) and software for easier development and faster run-time of ML algorithms. The Xilinx ML-suite is also compatible with the Alveo-series chips, but the Versal series is advertised as being intentionally optimized for such applications.

While there have been some promising investigations into Machine Learnings applications to the astronomical community in areas such as RFI-detection [16], source classification [34, 1], and transient-detection [33], a concerted effort to create a validated, real-time algorithm, or to even publish an open-source dataset for training and testing a model to our specifications has yet to come to fruition. GBO intends to utilize the Xilinx’s new hardware and software advances in concert with the datasets outlined below to bring real-time ML applications to life in the astronomical community.

(For Luke: I think we need to discuss the specific techniques we might use in more detail)

B.4.4. Standardized Verification and Qualification Procedures: While being able to accurately and precisely detect/remove RFI is an important and difficult problem to solve, it is not necessarily more difficult or important than defining a methodology for ensuring the efficacy of specific removal techniques while preserving the underlying scientific data of interest. This will also be essential to convincing scientific users that the procedures preserve the integrity of the data. We will create just such a procedure that 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, bandwidth, duration, and frequency sweep.

- Carefully curated datasets 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 datasets, both free of RFI and with RFI injected that matches 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 thus 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.5 Interference Compliance and Cooling

As an inherent feature of transitioning toward receiver-room signal sampling, we will need to install relatively large, digitally noisy electronics in an environment that mandates minimal power consumption and a low-level of emitted radio-frequency emissions.

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), whereas equipment in typical commercial applications in the United States is only required to be 47 C.F.R. 15 Class A compliant. Functionally, this equates to GBO being responsible for providing an additional ~ 100 dBm of isotropic radiated power suppression to 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 (and limit unwanted perturbations of the yet-to-be sampled data), we will likely have to make considerable adjustments and/or add shielding to any COTS boards (such as the VCU118) that are used in the UWB-DSP system. This is an area where we have considerable expertise and experience. Suppression methods that we have used previously on COTS equipment include component-level shielding of “noisy” components (chip cage) and equipment-level shielding (metal box, in-case RF absorbent foam). We have also designed 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 HPC racks used by the Breakthrough Listen project (***citation***), and water-cooling has been used on the GBT as part of a revolutionary new L-Band phased array feed (***citation***). *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.*

III Broader Impacts

A Commitment to the Public

The UWB-DSP system will be deployed on the 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 §A.1, and it will also be valuable to Breakthrough Listen, as it will allow for faster surveys for extraterrestrial techno-signatures. Both NANOGrav and Breakthrough Listen have committed to making data publicly available.

All of the hardware designs, firmware, and software produced in the course of this work will be made freely available to the wider astronomical and radio science communities for use at other facilities. 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. GBO also hosts thousands of visitors each year through its education and outreach programs. Visitors participate in public tours (some of which are specialized for a technical audience), short educational courses, and weekend and week-long student camps. The co-investigators all participate in these programs and will use these opportunities to educate the broader public about the UWB system and radio astronomy more generally.

B Enhanced Infrastructure for Research and Education

B.1 Maximizing Return from the UWB Receiver

The UWB-DSP system will be fully integrated into the UWB front-end receiver. This will allow us to bypass the existing GBT IF system, mitigating the risk of non-linear response in the analog components caused by strong RFI. By digitizing as close as possible to the receiver we will also minimize gain fluctuations that can lead to unstable spectral baselines. These benefits taken together with the active RFI identification and excision algorithms will ensure that the UWB system results in the highest quality science data products under all observing conditions.

B.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 12 GHz could provide > 8 GHz of instantaneous bandwidth but are limited by various bandpass filters to no more than 8 GHz bandwidth, and in many cases only 4–6 GHz (see Table 3 for details).
- Multiple spectral windows (up to 64) are formed via a complex set of secondary and tertiary mixers and bandpass filters before the signal is finally sampled at base-band frequencies. Once again, bandpass filters are a limiting factor, setting a maximum separation between spectral windows. The number of converters also limits the maximum number of spectral windows.
- The secondary and tertiary converters are housed in a building over 1-km from the GBT. The signals are transported via RF-over-fiber links which are subject to saturation.
- All of the above analog components can undergo gain variation due to changing environmental conditions. For very deep observations of faint sources the resulting spectral baseline changes can be limiting.
- Doppler broadening of spectral lines 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 (e.g. to account for source motion in a binary system) is not possible.

The digital technology that we propose to use in the UWB-DSP system has the potential to eliminate nearly all of these restrictions. Multiple fast ADCs could be employed to sample the full available bandwidth for single-pixel receivers, and would provide maximum flexibility when trading bandwidth for pixels in multi-pixel receivers. *This could lead to as much as a factor of 20 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, drastically lowering the risk of saturation from RFI while providing much better spectral

Table 3: Bandwidth of GBT Receivers

Receiver	Frequency Coverage (GHz)	Max. Instantaneous Bandwidth (GHz)
PF1 342 MHz	0.29–0.395	0.24
PF1 450 MHz	0.385–0.520	0.24
PF1 600 MHz	0.510–0.690	0.24
PF1 800 MHz	0.680–0.920	0.24
PF2	0.910–1.23	0.24
L-Band	1.15–1.73	0.65
S-Band	1.73–2.60	0.97
C-Band	3.95–8.0	3.8
X-Band	8.0–11.6	2.4
Ku-Band	12.0–15.4	3.5
KFPA	18.0–27.5	1.8 (multi-feed); 8 (single-feed)
Ka-Band MM-F1	26.0–31.0	4.0
Ka-Band MM-F2	30.5–37.0	4.0
Ka-Band MM-F3	36.0–39.5	4.0
Q-Band	39.2–49.8	4.0
W-Band MM-F1	67.0–74.0	6.0
W-Band MM-F2	73.0–80.0	4.0
W-Band MM-F3	79.0–86.0	4.0
W-Band MM-F4	85.0–93.3	4.0
ARGUS	80.0–115.3	1.5

baselines. Doppler tracking and windowing would be accomplished digitally. Active RFI mitigation would also be incorporated into all GBT observing. This will become increasingly important as more of the super high and extremely high frequency portions of the spectrum are used for new technologies (e.g. collision avoidance car RADARs that operate in the 76–81 GHz band).

(TODO: A paragraph on scientific impact)

This would be a transformational modernization of the GBT, analogous to the upgrades of the “extended” Jansky Very Large Array, 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.

B.3 Relevance for Other Facilities

The radio astronomy community is planning for major new facilities that will begin construction and operation in the 2020s, such as the SKA and ngVLA, in addition to a myriad of experiment-class instruments. These next generation telescopes should use next generation technology, including integrated wideband digitization and RFI excision. We emphasize once again that all products supported by this ATI proposal will be made freely available to the wider community, including communication protocols, firmware designs, RFI excision implementations, and tool flows. Our standardized procedure for testing RFI-excision algorithms will be of especially long-lasting impact for existing and future observatories around the world. 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 Broadening Participation

- **Section lead(s):** Sue Ann Heatherly
- **Target length:** 2 pages
- Describe the two week annual summer camp and activities related to RFI excision, professional development, and STEM retention

- Tie into INCLUDES program

IV Project Management Plan

- **Section lead(s):** Laura Jensen
- **Target length:** 2 pages
- Should align with activities identified in §B
- Should also include metrics for success and a plan for evaluation
- Can we talk about modular design and future upgrade strategies here?

A Work to Be Undertaken

(Include roles of all personnel)

B Evaluation

C Timeline

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

V 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)

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