An Ultrawideband Digital Signal Processing System for the Green Bank Telescope

November 8, 2018

Project Description

I Overview

We propose to build a state-of-the-art ultra-wideband digital signal processing (UWB-DSP) system for the Robert C. Byrd Green Bank Telescope that will sample wide radio frequency (RF) bandwidths and protect scientific data quality in the presence of strong radio frequency interference (RFI). The UWB-DSP system will ultimately be deployed to directly sample the entire 0.7–4 GHz radio frequency (RF) bandwidth of a new ultra-wideband radio receiver (UWB-R) that is being developed in parallel for the GBT. This strategy will bypass 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 algorithms to identify and remove RFI in the presence of astronomical signals. The combination of real-time RFI removal and high dynamic range digital sampling as close as possible to the front-end receiver will make this complete UWB system significantly 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 the 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).

This project will be broken into two phases, *the first of which will be supported by this ATI:*

- **Phase I:** Research and develop the next generation of digital signal processing hardware, firmware, data transmission protocols, and RFI removal techniques.
- **Phase II:** Integrate the technologies and techniques developed in phase one into the UWB-R, which will then be deployed as a complete, facility instrument.

The UWB-DSP system will use fast, high dynamic range analog to digital converters, powerful field programmable gate arrays (FPGAs), 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 open for use by the full astronomical community via NSF-funded open skies programs. 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. An additional full-time summer undergraduate student will work directly with experts at GBO and the University of California-Berkeley on digital engineering for the UWB-DSP project. 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.

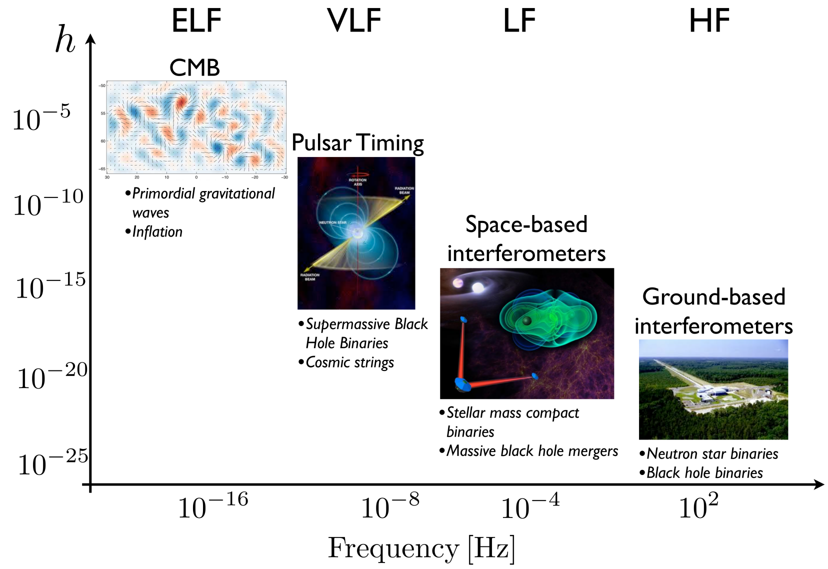

Figure 1: Like the electromagnetic spectrum, the GW spectrum spans orders of magnitude and a variety of source-classes that can only be fully studied using complementary techniques. PTAs probe lower GW frequencies than ground- and space-based interferometers, and higher frequencies than cosmic microwave background polarization experiments (Figure courtesy of the NANOGrav PFC).

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. New DSP hardware makes both goals feasible and especially timely. 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; [20]). 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 (see Figure 1). The NANOGrav PFC is on-track to detect a stochastic GW background within the next 3–5 years [28], 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 [2, 1]. 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 [1].

The NANOGrav PFC uses the GBT and the William E. Gordon telescope at the Arecibo Observatory (AO) to observe a pulsar timing array (PTA) of millisecond pulsars (MSPs) distributed across the sky. The extremely high rotational stability of MSPs allows them to be used as clocks whose "ticks" are pulse times of arrival (TOAs) that can be accurately measured *and predicted* with accuracies of $\lesssim 100$ ns over time scales of decades. The influence of GWs at the Earth will cause a 10–100 ns deviation in the TOAs because of the changing path-length between the observer and the pulsars. The quadripolar nature of GWs will specifically cause a quadripolar angular correlation between pulsars distributed across the sky, which makes it possible to distinguish between GWs and 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; [14]). 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 [12], tests of general relativity [31], and novel constraints on Solar system planetary ephemerides [1].

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

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

where k_{DM} is a physical constant, f is the radio frequency, and $\mathrm{DM}(t,f)$ is the dispersion measure, i.e. column density of free electrons between the pulsar and the Earth [e.g. 17]. We emphasize that DM is both time and frequency dependent [8], 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 employees 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 improving 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—analogous 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 [16, 30]. 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; [26, 27]), a fact which has enabled the only precise interferometric localization of an FRB to a host galaxy [7, 29], as well as long-duration study of the changing characteristics of the bursts (e.g. DM, Faraday rotation measure (RM), and burst morphology; [21]). With telescopes like the Australian SKA Pathfinder and the Canadian HI Intensity Mapping Experiment poised to discover dozens (if not hundreds) of new FRBs [25, 3], 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; 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 [24]. 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 [9, 18]. There is also some evidence for secular changes in DM and RM [21, 13]. All bursts thus far have been detected between $\sim$ 1–8 GHz despite significant observing campaigns at lower and higher frequencies.

Any theory regarding the nature of FBR 121102 (and presumably at least some class of FRBs more generally) must explain these wideband 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 — 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 [5, 4, 15, 11]. 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. 6], and the details of the radio emission mechanism 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. 19], and the extremely high RM observed in FRB 121102 has only one known analog: the radio magnetar near the center of the Milky Way [11]. 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. The primary technical motivation for the UWB-DSP system is also one of the most pressing: the ability to *share the spectrum* with man-made transmitters while producing scientifically usable data at frequencies where there is significant, strong RFI. GBO's location at the center of the 13,0000 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 (such as 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 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). 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 award AST-1006509) 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. These concerns are not esoteric —- in recent months GBO staff have become aware of total power instabilities that are present in the 1–2 GHz band. 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[2] transmitting at 1.09 GHz; the instability itself has been isolated to non-linear response of analog components between the RF-over-fiber transcievers and second frequency mixer. The UWB system will be exposed to an even worse RFI environment that includes cellular communication towers, digital

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

[2] 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/`

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, robust recursive power estimation, and a new project using machine learning (ML) algorithms. 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 FPGAs and associated tool flows fundamentally change the paradigm for realizing sophisticated RFI excision techniques. New FPGAs have improved memory capacity, 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, testing, and deployment. *Our development of an UWB-DSP system is perfectly timed to take advantage of these new technologies to integrate real-time RFI excision into standard data-processing pipelines.*

A.2.3. 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 generation of hardware used in VEGAS.

1. The **Analog Devices AD9213** is a 10.25 Gsps 12-bit ADC which is representative of the upcoming generation of high-speed ADCs. The AD9213 is faster, more precise, and has lower noise than our current EV8AQ160 (see Table 1). One large driver behind the lower spur-free dynamic range is the improved manufacturer-provided calibration techniques for the suppression of multi-core interleaved suprs that are inherent in pipelined ADC technologies (considerable work was required by GBO and CASPER to properly calibrate our existing ADCs). *The fast sampling rate, bit-depth, and* 6 *GHz full-power bandwidth provided by the AD9213 will allow us to directly sample the UWB-R at RF.*

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

This ATI proposal is thus perfectly timed to take advantage of cutting-edge technology in the service of our scientific and technical goals.

Table 1: Comparison of ADC Standards

Feature/Spec	E2V EV8AQ160	AD AD9213
Max. Sampliing 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

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 Innovation

Our use of emerging technology in the UWB-DSP system means that there is no turn-key solution available. Instead, we will develop new procedures for integrating various hardware components, as well as new firmware, data transmission methods, and network topologies for very high data rates. We will also begin 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. In the following sections we detail the specific tasks that will be accomplished as part of Phase I of the UWB-DSP project that is supported by this ATI.

B.1 Integrating New ADCs and FPGA Boards

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.

We will experiment with two techniques for direct RF sampling over the bandwidth of the UWB-R. The first, most straightforward approach is to clock the ADCs near their maximum rate, digitizing the entire 0.7–4 GHz with one sampler. This would simplify downstream processing by avoiding the need to stitch together different sub-bands, but does come at the cost of a lower effective number of bits (ENOB; the pre-release specifications for the AD9213 quote 8.7 bits at the maximum sampling rate of 10.25 Gsps). The second approach would use a simple signal-splitter to produce two or three copies of the UWB-R signal, which would each be sent to a seperate pair of ADCs (one for each polarization) clocked at slower speeds. The first copy would be low-pass filtered and sampled at base band (i.e. the first Nyquist zone), while higher frequencies would be bandpass filtered to prevent alisasing and sampled in higher Nyquist zones. This would still bypass the existing GBT IF system and would have the advantage of offering a higher ENOB, at the expense of additional processing steps. We will determine if the better dynamic range in the second approach is needed and select the most appropriate path forward for the final, production system.

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 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's 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, we will 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, we will create additional basic EDK blocks 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 translations of algorithmic implementations from Python notebooks to hardware descriptive languages.

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, 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 Xilinxs Vivado has been announced).

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 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 (Xilinxs 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 will also allow more robust, realistic, and real-time evaluation of future algorithms. 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 Xilinxs 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 several challenges.

For example, the AD9213 ADC'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 develop power-mitigation methods that would allow us to safely contravene the standards (allowing multiple ADCs per VCU118).

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 2×100-GbE ports (the VCU118 is an outlier with 2×100-GbE QSFP28 ports and 1×100-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. We will thus examine optimal network topologies (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 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.

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 Nanc̈ay Radio Observatory [10] 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 [22, 23], 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 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 [22], 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 observations rather than more general data products. 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. Spectralk kurtosis has also been identified as a promising method for the detection and classification of astrophysical transients [23]. *Our UWB-DSP system will thus enable real-time detection of FRBs and other scientifically interesting transients.*

B.4.3. 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 latter step is, however, essential for convincing scientific users to adopt real-time RFI excision. We will create a testing 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 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 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.*

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 $\gg 8$ 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 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 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).

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

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

D Developing a Diverse, Globally Competitive STEM Workforce

This grant will support two undergraduate students that will work with astronomers and engineers at GBO and the University of California-Berkeley. The focus of the students' work will likely be on developing RFI excision algorithms and the verification plan described in §B.4, though we will devise specific projects and the strengths and interests of the individual students 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 Python implementations of median absolute deviation and spectral kurtosis excision techniques. The students will be selected from UC-Berkeley so that they can take advantage of local expertise and mentoring, and will also spend time during the summer at GBO. While at the observatory 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 skills that the students participating in the UWB-DSP project learn will include advanced programming in languages such as Python and CUDA, 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. This project will thus help build a competitive, 21st century American workforce.

IV Project Management Plan

A Project Scope

Development and implementation of the UWB-DSP system will occur in two phases. The scope of work planned and budgeted under this proposal is for Phase I only. Phase I will 1) explore the technical feasibility of new, innovative technologies to enable the digitization of signals from the telescope at RF; and 2) develop and assess RFI excision techniques enabled by this technology. This will be pioneering work into the use of technologies having only recently been released.

Phase I includes basic and applied research into newly available technologies including FPGAs and new high-speed ADCs. The project team will design and build printed circuit boards to interface the ADC evaluation boards and the Xilinx VCU118 FGPA.

Developing RFI excision algorithms is crucial to the success the UWB-R being developed by GBO, and will also be directly relevant to other observatories. Evaluating potential RFI excision algorithms independently across different sub-bands will isolate efficacy tests for various types of RFI within the different bands (i.e. impulsive RFI at low frequencies vs digital RFI that is more common above 2 GHz). This will enable the project team to assess the efficacy of excision techniques in a very systematic way. We anticipate that algorithms developed for RFI excision could be packaged into core modules that ultimately could be made available and merged into other DSP system designs.

During Phase I, GBO will work collaboratively with UC-Berkeleys SETI Research Center and CASPER teams, who will serve as advisors 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. An undergraduate summer student from UC-Berkeley will assist in the RFI excision research during both years of the project. A shared strategic goal for both GBO and UC-Berkeley is to transition from current ROACH2 based architectures as that technology is becoming obsolete.

From a systems engineering perspective, Phase I 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 I will also enable GBO to develop a more detailed plan and cost for Phase II.

Phase II of the project (out of scope for this proposal) will build upon the preliminary design to enter into a detailed design phase. Phase II may build out additional digitization frontends for use across different sub-bands of the UWB-R (see §B.1). Phase II will include software and backend development, integration verification and validation, and commissioning. Significant outreach to the US and international astronomy community will be required to validate that the RFI excision techniques do not have any adverse impacts on the science data products. The goal of Phase II is to deliver a GBO user instrument to the Observatory as well as innovative digital signal processing hardware and software designs and RFI excision techniques that can be made available to the US science community.

B Project Governance and Resources

B.1 Project Team

PI Ryan Lynch will provide scientific leadership to the Ultra-wideband Digital Signal Processing project. The research and development for the project will take place at GBO, where the staff have 60 years' experience in building and maintaining facility instruments for the scientific community. GBO digital engineers will work collaboratively with Lynch and project management resources.

Research and development for the ultra-wideband digital signal processing system will require expertise in digital signal processing algorithms, RFI mitigation, and FPGA and GPU firmware development. Assessment and testing of the new technologies will also require extensive experience in operating wideband frequencies GBT, and detailed knowledge of the science requirements.

As a Federally-Funded Research and Development Center (FFRDC), GBO has been granted an exemption by NSF to submit this proposal since the technical innovations developed through this project will make unique contributions to the needs of researchers across the international scientific community. GBO staff have proven expertise in taking research projects from concept through design and construction with a goal of repeatable, reliable, maintainable, and scalable production use. Through its operation of the GBT and other site telescopes and its work within the radio quiet zone, GBO staff have unique experience in how to identify, assess, and mitigate RFI emissions. System design requirements will need to consider weather factors and performance specifications for real-world application. This GBO-led project, developed in collaboration with UC-Berkeley, ensures that rigorous systems engineering approaches will be employed to enable the technical proof-of-concept developed under this proposal to move forward into a future, production-ready implementation stage.

B.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 the NSFs 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 Berkeley 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.

C Risk Management

Our risk management plan identifies uncertainties in the project and mitigations to reduce loss, while identifying and realizing opportunities. As a research and development effort using newly released technologies, there are a number of risks related to uncertainties that will be mitigated through systematic basic and applied research. These uncertainties are to be expected in the development of innovative techniques.

To address these risks associated with a research and development effort, the highest risk items will be tackled and tested first, in order to identify subsequent approaches. If testing validates the assumptions, performance, and hypothesis, then risks are reduced as the project progresses. If testing does not validate assumptions, then the risks are not reduced and reassessment will be required. Iterative project management techniques will be applied to ensure the project moves forward as outcomes are progressively elaborated.

D Schedule Management

The project outcome for Phase I is a technical feasibility assessment and proof-of-concept. Research and development projects undergo iterative design, experimentation, test, verification, and validation phases. GBO's schedule management will provide measurement of the R&D progress towards outcomes. The planned period of performance for Phase I is two years from the date of award. GBO plans to conduct preliminary evaluation of the new Xilinx VCU118 FGPA boards in collaboration with UC-Berkeley SETI Research in advance of project award. This pre-work will address risks early on and enable the project to commence immediately upon award.

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

Table 4: Compressed View of UWB-DSP Risk Register

Item	Risk	Rating	Mitigation Strategy
1	The integration of planned technologies has never been done before; therefore expected outcomes cannot be guaranteed	High	A systematic approach to the basic and applied research, with multiple iterations to assess outcomes and refine assumptions. The planned phased approach takes incremental steps which reduces risk.
2	Specifications for technologies to be used are still in development. For example, specifications for the 12-bit AD9213 chip have net yet been released.	High	Current hypothesis are based on expected performance specifications for the chips. These assumptions will need to be validated through iterative testing of the technologies as they are integrated.
3	ROACH2 technology currently used by CASPER and GBO is reaching end of life.	High	This is an opportunity risk that will be realized if the research into new technologies for digitization is not undertaken in a timely basis.
4	Potential impacts of RFI excision on data products	Medium	RFI excision algorithms will be systematically tested against individual subbands. Detailed comparisons to pre-excised data will be conducted.
5	Alignment of GBO digitization efforts with CASPER	Medium	The CASPER team at UC-Berkeley is a collaborator on the project. GBO and UC-Berkeley have a good history of working collaboratively on projects.
6	Availability of new digitization technology to support GBO UWBR.	Low	GBO has decoupled this digitization project from its development of an UWBR. The UWBR will be released using existing GBO systems until new digitization technologies are available.

E Performance Measures

Program Management performance measures throughout the Phase I project lifecycle will include:

- Analysis and monitoring of the project baseline (cost, schedule, scope) and controlling the baseline. Changes to the baseline will follow GBOs 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 camp in year 2. Undergraduate summer students will receive assessments based on University requirements and are required to submit a project report.
- 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.

Table 5: Project Milestones

Item	Milestone	Target Completion (FY Quarter)
1	GBO electronics printed circuit board design; hardware procurements; RFI characterization and preliminary RFI excision algorithm design in collaboration with GBO REU and UC-Berkelely summer undergraduate students.	FY2019 - Q4
2	Development of new FPGA firmware	FY2020 - Q2
3	Iterative FPGA firmware testing (simulations)	FY2020 - Q3
4	FPGA firmware/hardware integration; RFI excision algorithm testing in collaboration with GBO REU and UC-Berkeley summer undergraduate students; GBO summer student camp; Document standards and best practices for assessing RFI excision techniques	FY2020 - Q4
5	Iterative independent instrument testing with RFI excision techniques; Develop plan, schedule, and budget for phase two	FY2021 - Q1
6	Iterative integration testing with VCU118	FY2021 - Q3
6	Document outcomes and final report	FY2021 - Q4

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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