An Ultrawideband Digital Signal Processing System for the Green Bank Telescope

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Project Description

I Overview

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

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

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

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

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

Figure 1: A block diagram representation of the existing GBT intermediate frequency system. Components in the "receiver room" are located next to the radio receivers on the GBT. Signals are transported via IF-over-fiber to the "equipment room", which houses additional analog and digital instruments.

II Intellectual Merit

A A Review of Existing Technology and Equipment

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

B Motivation

Several developments make this project especially timely.

- New commercial ADCs allow high dynamic range sampling of ultra-wide bandwidths, either at RF or after a single down-conversion.
- Advanced FPGAs provide the resources needed to implement real-time RFI excision side-by-side with other DSP procedures.
- The expanding presence of wireless devices and the increasing sensitivity and bandwidth of radio receivers make it essential to *share the spectrum* by using instrumentation that is robust and produces high-quality scientific data in the presence of RFI.
- GBO is actively developing a revolutionary new 0.7–4 GHz UWB radio receiver for the GBT that will serve as the perfect platform for applying the outcomes of this project. This receiver will be optimized to study gravitational waves and fundamental physics, as well as radio transients and regions rich in molecular line emission.

B.1 Next Generation Hardware

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

Table 1: Comparison of ADCs

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

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 trx Speed	6.6 Gbps	32.75 Gbps

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 spurs that are inherent in pipelined ADC technologies (considerable work was required by GBO and CASPER to properly calibrate the ADCs used in VEGAS). *The fast sampling rate, high bit-depth, and* 6 *GHz full-power bandwidth provided by the AD9213 make it feasible to directly sample RF up to* 5 *GHz.*
2. We are in need of a successor to the CASPER ROACH2 boards that were the core of many 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's (allowing larger, more computationally intense designs), significantly smaller feature size (simplifying timing closure), and significantly faster transceivers (allowing higher I/O bandwidth). Table 2 provides a side-by-side comparison to the ROACH2. *These new FPGAs will provide the critical resources needed to implement real-time UWB RFI excision alongside standard DSP procedures (e.g. channelization).*

B.2 Sharing the Radio Spectrum

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).

B.2.1. RFI Resistance: RFI resistance is a perpetual concern for radio observatories. GBO is afforded unique interference protection through its location at the center of the 13,000 square-mile National Radio Quiet Zone and smaller West Virginia Radio Astronomy Zone (for more information on these interference protection zones see Facilities, Equipment, and Other Resources). However, the relevant regulations only apply to fixed, ground-based transmitters, not to mobile ground, air, or space-based transmitters, of which there are many. Other US observatories lack any regulatory protection.

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

[1] ADS-B is used for air traffic control as part of the Next Generation Air Transportation System and is intended to replace secondary

second frequency mixer. *We thus have empirical evidence that illustrates the need to minimize the number of analog components in the GBT's IF system.*

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

B.2.2. RFI Excision: As part of our normal operational activities, 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 that is in its early stages. However, the limitations of our existing ROACH2-based hardware prevents us from fully implementing, testing, and deploying these RFI excision techniques. Specifically, the 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.

The UltraScale+ 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. *We will take advantage of these new technologies to integrate real-time RFI excision into standard data-processing pipelines.*

B.3 Developing a Back-end System for New UWB Receivers

Several observatories and research labs are building UWB (4:1 and 6:1 bandwidth ratio) radio receivers with system noise and efficiency that is competitive with traditional octave (2:1) receivers. One example is a 0.7–4 GHz UWB receiver that is under active, independent development at GBO. This and similar receivers will be exposed to a multitude of RFI sources including cellular communication towers, digital television transmitters, Global Positioning System satellites, ADS-B, Iridium communication satellites, and Sirius XM Satellite Radio. UWB receivers thus require a digital system that is robust against RFI. The GBO UWB receiver will be the perfect development platform and front-end complement for the digital technology and RFI excision techniques that we will produce as part of this work. This will maximize scientific return in the following key areas:

The Low-Frequency Gravitational Wave Universe: The primary science driver of the GBO UWB receiver is the direct detection of nanohertz-frequency GWs via pulsar timing, which is the focus of the NSF-supported North American Nanohertz Observatory for Gravitational Waves Physics Frontier Center (NANOGrav PFC; [28]). 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 other GW observatories (see Figure 2). The NANOGrav PFC is on-track to detect a stochastic GW background within the next 3–5 years [38], 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 to observe a pulsar timing array (PTA) of millisecond pulsars (MSPs) distributed across the sky. The extremely high rotational stability of MSPs allows them to be used as clocks whose "ticks" are pulse times of arrival (TOAs) that can be measured *and predicted* with accuracies of $\lesssim 100$ ns over time scales of decades. The influence of GWs at the Earth will cause a 10–100 ns deviation in the TOAs because of the changing path-length between the observer and the pulsars, with a unique angular correlation pattern [17]. This process of pulsar timing demands a complete characterization of the MSPs themselves, including their rotational,

surveillance RADAR. It will be required on all aircraft operating in the United States by 2020. See `https://www.faa.gov/nextgen/programs/adsb/`

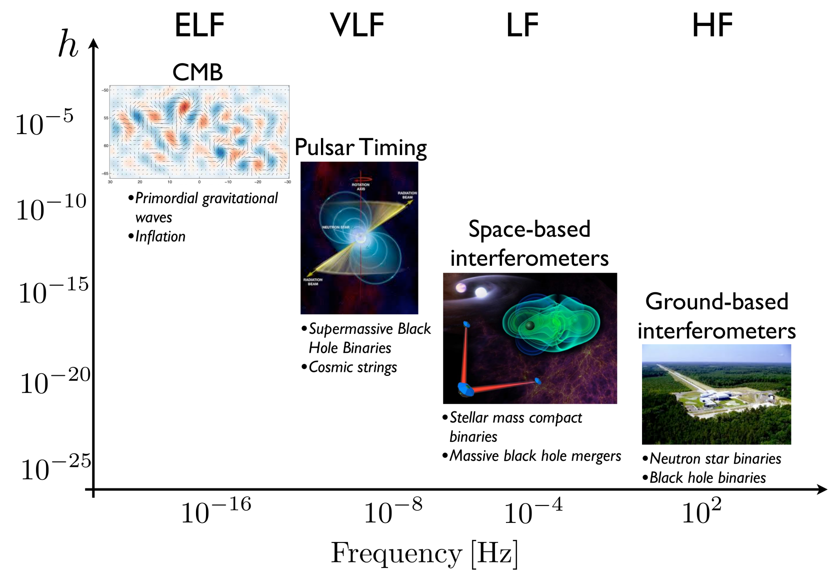

Figure 2: *Left:* Like the electromagnetic spectrum, the GW spectrum spans orders of magnitude and a variety of source-classes that can only be fully studied using complementary techniques. PTAs probe lower GW frequencies than ground- and space-based interferometers, and higher frequencies than cosmic microwave background polarization experiments (Figure courtesy of the NANOGrav PFC). *Right:* A selection of bursts from FRB 121102 showing dramatic spectro-temporal variation. These data were mostly taken between 1–2 GHz and most bursts show features broader than the available observing bandwidth [33].

astrometric, and binary properties. Thus, other high-impact science emerges from this project, such as pulsar mass measurements [14], tests of general relativity [43], and novel constraints on Solar system planetary ephemerides [1].

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

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

where $k_{\rm DM}$ is a physical constant, f is the radio frequency, and ${\rm DM}(t,f)$ is the dispersion measure, i.e. column density of free electrons between the pulsar and the Earth [e.g. 21], which must be measured with a fractional uncertainty of $\sim 10^{-5}$ at each observing epoch. In practice, this requires measuring TOAs at widely spaced frequencies. The NANOGrav PFC currently employs a two-receiver strategy at the GBT and Arecibo to measure DM with the necessary precision, but 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. *An UWB observing system will double the observational efficiency of high-precision pulsar timing programs while improving measurements of DM. When coupled with higher pulsar signal-to-noise from the wider instantaneous 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.

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 (FRBs) — millisecond duration radio-frequency pulses that originate in distant galaxies [20, 40]. 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; [36, 37]), a fact which has enabled the only precise interferometric localization of an FRB to a host galaxy [8, 39], as well as long-duration study of the changing characteristics of the bursts (e.g. DM, Faraday rotation measure (RM), and burst morphology; [29]). With telescopes like the Australian SKA Pathfinder and the Canadian HI Intensity Mapping Experiment poised to discover dozens (if not hundreds) of new FRBs [35, 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 within the larger burst envelope [34]. 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, 24]. There is also some evidence for secular changes in DM and RM [29, 15]. 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 FBR 121102 (and presumably at least some class of FRBs more generally) must explain these wide-band properties, so they serve as a powerful diagnostic tool for understanding FRBs' physical origins. However, most burst detections are limited by the 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[2] magnetars that emit X-rays and gamma-rays [5, 4, 19, 12]. Their sporadic emission and variable power-law spectral index, polarization fraction, polarization position angle, and burst morphology stand in stark contrast to rotation-powered radio pulsars [e.g. 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. 25], 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 system will thus be a powerful tool for expanding our knowledge of radio transients.

Molecular Line Surveys: Survey speeds of regions that are especially rich in molecular lines are often limited by the available instantaneous bandwidth. One example is observations of HII regions using Hydrogen radio recombination lines (RRLs). These act as extinction-free tracers of the ionized gas surrounding high-mass stars. The sensitivity of the GBT allows for individual RRLs to be detected toward star-forming regions across the entire Galactic disk with only minutes of on-source time. However, no current receiver/back-end combination can cover nearly as many simultaneous RRLs as the 0.7–4 GHz UWB system, which will be able to simultaneously observe 93 Hn_α, 117 Hn_β, 134 Hn_γ, and 146 Hn_δ lines. All RRLs of the same type can be combined to drastically increase signal-to-noise, offering unprecedented sensitivity to Galactic ionized gas. Because of the coarse spatial resolution in this frequency range (from $3'$ to $18'$ for the GBT), these lower frequency transitions are especially well suited for studying diffuse, low density plasmas, including ionized outflows from star formation regions and the ambient diffuse ionized gas present throughout much of the plane of the Galaxy [22].

The study of complex chemical species offers another application of UWB technology. Many observations have focused on frequencies of 10's of GHz, but the 0.7–4 GHz band is a promising discovery space [e.g. 27, 13, 41]. Astrochemistry is a unique probe of species not easily studied in a laboratory and has implications for astrobiology and the nature of life on Earth [26]. The bandwidth of the UWB system will allow for serendipitous, discovery-based science in this area.

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

Figure 3: A block diagram representing one possible approach for deploying an UWB DSP system on the GBT sampling up to 5 GHz baseband with a single ADC (in practice two independent paths would exist for each polarization channel, though only one is shown here). We identify those components that would be housed in the GBT receiver room and the equipment room, and refer to these designations throughout this proposal. .

C Innovation

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

C.1 Finding Optimal Sampling Strategies

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

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

C.2 Integrating New ADCs and FPGAs

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

Since our plan calls for installing digitally noisy ADCs and FPGAs very close to radio receivers, minimal power consumption and a low-level of self-generated RFI is absolutely essential. These requirements will be incorporated into all designs from the beginning. The VCU118 is equipped with an FPGA Mezzanine Card

(FMC/FMC+) slot, which will be used to connect our chosen ADC. One challenge is that the AD9213 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. 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).

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 US is only required to be 47 C.F.R. 15 Class A compliant. Functionally, this equates to an additional ~ 100 dBm of isotropic radiated power suppression on any commercial-off-the-shelf (COTS) unintentional radiators that we wish to install close to the focal point of the GBT.

To meet these strict requirements we will likely have to make considerable adjustments and/or add shielding to any COTS boards. This is an area where we have considerable expertise and experience. Previously used suppression methods 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 compute racks used by the Breakthrough Listen project [23], and water-cooling has been used on the GBT as part of a revolutionary new L-Band phased array feed [32]. *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.*

C.3 Developing Firmware for Emerging Technology

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

We will build a variety of new firmware "blocks" (sets of low-level FPGA code abstracted to a higher level for easier use by firmware system designers) for interfacing with various FPGA-facing peripherals as well as for executing advanced DSP techniques. In addition, new firmware tools will need to be developed to allow our CASPER-based designs to take advantage of the 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. The specific blocks that we will develop are outlined below.

Peripheral Interfacing: To take advantage of the possibilities enabled by the newest generation of data-transmission technologies, we will create CASPER 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 ADC via FMC/FMC+. The 100-GbE blocks and ADC card block can be considered improvements upon existing capabilities, while the PCIe interface (and especially the M&C aspect) will be groundbreaking in the CASPER community.

DSP Capabilities: We will create additional basic EDK blocks to improve DSP capabilities. For example, we will develop blocks implementing new RFI-mitigation methods (discussed in more detail in the §C.6) 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 existing software (e.g. Python and C++) to hardware descriptive languages. We will also take advantage of development occurring elsewhere within CASPER (e.g. new floating point FFT blocks).

Heterogeneous Computing: The two preceding tasks are needed to harvest the fruits of Moore's law (higher-speed data transmission, higher-density FPGA chips), but Xilinx has also made great developments in other directions. In recent years, their focus has widened to include heterogeneous computing architectures such as the Manycore Processor System on Chip, RF System on Chip, 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 application (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.

C.4 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 at the receiver itself. This approach will quintuple the bit-rate compared with previous instruments and will require the use of 100-GbE fiber down-links to the equipment room as the backbone of our signal sampling/transmission pipeline. We will thus need to develop solutions to mitigate several challenges.

The total maximum bit-rate for the AD9213 at maximum frequency will be $12 \text{ bits} \times 10.25\text{Gsps} = 123 \text{ Gbps}$. 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 also require us to integrate PCIe-based M&C functionality, and to measure how different bi-directional M&C data-rates between a control computer and the FPGA over the PCIe bus effect the main, uni-directional data-transfer rates from the FPGA to downstream computing clusters.

C.5 Standardized Procedures for Validating RFI Excision Algorithms

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

While being able to accurately and precisely detect and 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. We will create a testing procedure consisting 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.

Placeholder

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

- Carefully curated data sets created using the above set-ups, in common formats and containing a variety of RFI sources, that can be used for off-line testing and validation.
- Synthetic data sets, both free of RFI and with synthetic RFI that matches the characteristics of common sources, to be used for additional, carefully controlled offline verification.
- Procedures for applying and quantifying the efficacy of RFI excision algorithms and assessing their impact on the measurable astrophysical quantities of interest.
- Best practices for applying the above to real-time data acquisition systems (e.g. techniques for parallel capture of RFI-mitigated and unmitigated data streams).
- Side-by-side comparison of the relevant parameters for mitigated and unmitigated data.

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

Test procedures and data sets will be developed openly and collaboratively, allowing for contributions from other researchers and observatories. *We will 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.*

C.6 Active RFI Excision

We will implement complementary real-time techniques that can operate in series for actively identifying and excising RFI.

Real-time RFI excision will be a critical component of UWB systems. Below we describe two techniques that can be most easily deployed as part of this project. Other techniques will explored as appropriate.

Robust Recursive Power Estimator: GBO has built upon work started at the Nançay Radio Observatory [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 ROACH-based firmware, and have successfully conducted initial validation of its efficacy on multiple back-end systems currently being used at GBO. To the best of our knowledge, GBO currently possesses the only CASPER-implemented real-time RFI-excision enabled back-end systems.* We will generalize this method to other sources of RFI and deploy it in the UWB DSP system.

Spectral Kurtosis: Initially conceived at the Center for Solar-Terrestrial Research at the New Jersey Institute of Technology as a robust statistical RFI detector [30, 31], the simple sum/sum-squared algorithm lends itself naturally to implementation in FPGAs. As kurtosis measurements are more affected by a few, extreme outliers rather than many, moderate outliers, we can assume that any high-kurtosis samples (above user-adjustable thresholds) are contaminated with RFI and mitigate them.

Over the past year, a collaboration between the GBO digital engineering group and West Virginia University Physics department have created a Python-based implementation of the generalized spectral kurtosis estimator [30], and its overall effectiveness has been proven (Figure 4). However, our current implementation is not real-time, and has been tested 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 FPGAs to allow an implementation to co-exist with existing channelization firmware. The FPGAs on the VCU118 will let us create and test a real-time implementation of this method that could then be shared with the wider community.

III Broader Impacts

A Commitment to the Public

All of the hardware designs, firmware, and software produced in the course of this work will be made available to the wider astronomical and radio science communities for use at other facilities. Firmware blocks will be included in the CASPER library. We will use a mix of technical memos, presentations at conferences, and refereed publications to document and communicate the results of the work to the broadest possible audiences. 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 Enhancing Infrastructure for Research and Education

B.1 Towards a Complete Next-Generation Observing System

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

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 IF-over-fiber links which are subject to instabilities as discussed in §B.2.
- 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.

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

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 *** 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).

This would be a transformational modernization of the GBT, analogous to the upgrades of the "extended" Jansky Very Large Array (VLA), and would revolutionize all areas of GBT science. The UWB DSP system is a pathfinder that will allow us to determine the most effective and affordable solutions for these future upgrades.

B.3 Relevance for Other Facilities

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

C Broadening Participation for a Diverse, Globally Competitive STEM Workforce

C.1 First-Generation Student Internship Program

GBO is a partnering institution in an NSF-INCLUDES Alliance called the First 2 Network. The First 2

Network aims to improve the persistence of STEM undergraduates during the first two years of their college education and targets first generation college students who face obstacles over and above their non-first generation peers [e.g. 7]. The Alliance focuses on the first two years of college because it is within these years that more than 50% of STEM students leave their majors [9].

Leveraging our participation in the NSF-INCLUDES program, our plan for broadening participation in this proposal is to offer a two-week internship experience to rising college freshmen and sophomores, engaging them in authentic participation in the development of the RFI excision and validation procedures. It is well known that engaging students in research early in their college careers can have a potent impact on their persistence as STEM majors [e.g. 18, 16]. However, most student research experiences including our own Research Experienced for Undergraduates (REU) program generally targets rising juniors and seniors. Through this internship we will be providing a first research experience, and preparing younger students for future success in programs like REU, including our own.

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

- High levels of STEM efficacy at both pre- and post-test, and even higher by post-test.
- Interns tended to be less concerned about barriers to STEM persistence by post-test.
- Interns were somewhat more likely to report that professors lecturing a lot in their STEM courses would be a potential challenge.
- Interns were significantly less likely to be concerned that they would be intimidated by professors.
- Interns were significantly less likely to be concerned that they wouldnt know where to get help when they felt depressed or worried.

A two-week internship is also practical as a first experience. The two-week duration allows students to work summer jobs, which is a necessary enterprise for many first generation students. The key is finding the right research project that is amendable to team work and where real progress can be made in the available time frame.

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

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

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

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

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

Evaluation: We will employ the Undergraduate Research Student Self-Assessment Survey to measure student outcomes related to internship participation including acquisition of STEM skills, leadership, confidence, and STEM identity [42]. We will also participate in evaluation measures designed by the First 2 Network and provide data to the Network to add to the growing knowledge base of successful strategies and interventions.

C.2 Summer Research Experience

This grant will also support one undergraduate student that will work with astronomers and engineers at GBO and UCB on a 10–12 week research project. The focus of the students' work will likely be on developing RFI excision algorithms and the verification plan described in §C.5 & C.6, though we will devise specific projects with the strengths and interests of the individual student in mind. GBO already has a successful track record of involving summer undergraduate students in similar work, with four students having worked over the previous two summers on Python implementations of median absolute deviation and spectral kurtosis excision techniques. The student will be selected from UCB so that they can take advantage of local expertise and mentoring, 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 student will learn skills including 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.

IV Project Management Plan

A Project Scope

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

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

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

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

B Project Governance and Resources

B.1 Project Team

- PI Ryan Lynch (GBO) will provide scientific leadership. He will define the scientific goals and requirements for all work, lead the collection and generation of test data sets for the RFI excision validation procedures, and assist in scientific commissioning and validation of RFI excision algorithms. He is an expert in pulsar and radio transient science and project scientist for VEGAS.
- Co-Is Luke Hawkins, Randy McCullough, and Jason Ray (GBO) will serve as the technical project leads. They will design and develop integrated ADC/FPGA boards, Basic and CASPER EDK blocks

for M&C of FPGA boards, heterogeneous computing systems, and implementations of RFI excision algorithms. They will work with Lynch to asses and meet the scientific requirements. With a combined *** years of experience, they are experts in DSP, Xilinx and CASPER tool flows, and RFI compliance and excision.

- Laura Jensen and Marty Bloss (GBO) will act as project managers, ensuring that systems engineering best practices are used to allocate resources, set and meet milestones, and deliver on all project goals within budget. They will also assist Lynch with review and reporting requirements.
- Jack Hickish and Dan Wertheimer (UCB) will be unfunded collaborators on this project. Hickish will develop CASPER EDK blocks for interfacing with peripherals through 100-GbE and PCIe. Wertheimer will provide local mentoring to a UCB undergraduate student. Both will act as technical advisers to the GBO digital engineering team.
- Sue Ann Heatherly (GBO) will be an unfunded collaborator and will oversee the two-week summer internship program. She is the education officer for GBO and a PI on the NSF-INCLUDES First 2 Network.
- A UCB undergraduate student will be funded for a summer research experience, and will work with the full team with a likely focus on implementing the RFI excision algorithms.

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 NSF requirements as per its Large Facilities Manual (NSF 17-066, March 2017). Experienced GBO program managers will coordinate, track, and report on activities from a project and programmatic view. Scope, schedule, costs, and risks will be managed by GBO program managers.

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

C Risk Management

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

D Schedule Management

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

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

E Performance Measures

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

- Analysis and monitoring of the project baseline (cost, schedule, scope) and controlling the baseline. Changes to the baseline will follow GBOs Change Management Process.

Table 4: Compressed View of Risk Register

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

Table 5: Project Milestones

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

- Measuring project activities through the appropriate allocation of iterative verification and validation of results against hypothesis.
- Communications and stakeholder management through notifications, project reports, presentations, feedback, correspondence, meeting minutes, and other actions indicating transparency in the management of the project.
- Meaningful undergraduate summer student engagement and an organized summer student internship in year two. Undergraduate summer students will receive assessments based on validated evaluation instruments and NSF-INCLUDES requirements.
- Controlling risks through active management of the risk register and the prioritization of highest risks through iterative research, development, and testing.

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

V Results from Prior NSF Support

The PIs and co-PIs have not received support from a current or previous NSF award with an end date in the past five years.

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