Searches for Exotic Radio Sources and Intelligent Life on Other Worlds

By

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Professor Geoffrey C. Bower, Co-Chair
Dr. Daniel Werthimer, Co-Chair
Professor Stuart Bale
Professor Eliot Quataert

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Searches for Exotic Radio Sources and Intelligent Life on Other Worlds

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Abstract

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Here I describe several experiments that explore some of the rarest and most intriguing phenomena in the sky: short duration radio transients and possible electromagnetic emission from advanced extraterrestrial technology. Motivated by new discoveries and new technologies, we have performed, and are performing, some of the most thorough searches for these sources ever attempted. Our experiments include a “fly’s eye” search for bright radio pulses at the Allen Telescope Array, commensal searches for extraterrestrial intelligence at the Arecibo Observatory, a targeted search of extrasolar planets for narrow-band radio emission using the Green Bank Telescope and an ongoing effort to discover pulsars in orbit around Sgr A*. Although our experiments explore very different physics, they share common tools and techniques, notably a need for high performance digital signal processing. The experiments described here are prime examples of the synergy that exists between science and technology. Aided by dramatic advances in computing technology and the use of commodity components, we have enabled the processing of heretofore unheard of quantities of observational data. By taking advantage of a reusable design paradigm in which instruments do not have to be built from scratch, we have been able to develop new instruments quickly and efficiently. Our experiments are exploring wavelengths and signal types never before searched with high sensitivity, presenting the exciting chance for serendipitous discovery of unexpected phenomena. With an optimistic spirit, we venture into unexplored territory and expect the unexpected.

This thesis is structured as follows: Chapter 1 presents an introduction to the scientific motivations for our experiments and the tools with which we conduct them, Chapter 2 describes our Fly’s Eye Search for short duration radio transients at the Allen Telescope Array, Chapter 3 discusses our ongoing SETI experiments at radio and optical wavelengths and our plans for the future, Chapter 4 describes a 1.1–1.9 GHz search for narrow-band
emission from planet candidates identified by the *Kepler* mission and Chapter 5 details our ongoing search for pulsars near Sgr A*.
If, like Hamlet, you count yourself king of an infinite space, I do not challenge your sovereignty. I only invite attention to certain disquieting rumours which have arisen as to the state of Your Majesty’s nutshell.

—Sir Arthur S. Eddington
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Chapter 1

Background and Introduction

1.1 Fast Transient Radio Sources

The last decade has seen an explosion of interest in time domain radio astronomy. Driven by new wide field survey instruments, multi-beam receivers and computing advances, exploration of this regime presents opportunities to shed new light on known phenomena and perhaps reveal previously unseen processes as well (Cordes 2007). Investigations in time domain radio astronomy can be conveniently divided into two categories: those that deal with slow transients, events lasting from hours to years, and those that deal with fast transients, shorter duration events lasting from nanoseconds to seconds. Slow transients may originate from a diverse set of phenomena, ranging from the radio counterparts to relatively nearby supernovae or explosive events observed at very high redshift to variation in flux from radio jets associated with accretion disks, as discussed at length in Bower et al. (2007), Ofek et al. (2010), Bower & Saul (2011) and Becker et al. (2010). Fast radio transient phenomena have been observed to arise from only two fundamental physical origins: electrostatic discharge in planetary atmospheres, e.g. Zarka et al. (2008), and non-thermal magnetospheric emission from planets e.g. Zarka (2007) or stars e.g. Lorimer & Kramer (2005); Hallinan et al. (2008). By far the most commonly explored source of fast radio transient emission are pulsars, including their relatively more intermittent flavors: “rotating radio transients” (RRATs), nulling pulsars and those producing giant pulses. A variety of as-yet-unobserved sources of fast transient emission have been proffered, among the more commonly cited are evaporating primordial black holes (Rees 1977) and compact object coalescence (Hansen & Lyutikov 2001). Other more speculative sources include emission from cosmic strings (Vachaspati 2008) and beacons from extraterrestrial intelligence (Benford et al. 2008).

The fast/slow division arises primarily from the different detection techniques employed in each case. Slow transients are identified at radio wavelengths using essentially the same techniques as used at optical wavelengths; images (usually synthesized from interferometric antenna arrays) from multiple epochs are differenced and thresholded, with the period between epochs driven by the parameters of a given experiment. Fast transients are generally identified via a method well established from decades of pulsar searches: high time resolution
1.1. FAST TRANSIENT RADIO SOURCES

Power spectra are corrected for the dispersive effects of the interstellar medium, dedispersed, assuming different integrated column densities of free electrons, dispersion measures or DMS, then collapsed to a time series and thresholded for impulsive events. In the case of periodicity searches a Fourier transform or fast folding algorithm is also applied to the time series. Although the existence of nulling pulsars has been known for some time (Backer 1970), only fairly recently have pulsar searches targeted them specifically. Following the McLaughlin et al. (2006) discovery of the extremely intermittent class of neutron stars dubbed RRATs, several archival data sets were reanalyzed including specific single pulse search algorithms in addition to periodicity searches. Although nearly all RRATs and nulling pulsars have been shown to possess an underlying normal periodicity, the duty cycle of emission can render some pulsars undetectable in a folded profile or Fourier transformed power spectra. For very low duty cycle objects or those with extreme variation in pulse flux, single pulse searches can be much more effective than periodicity searches and sometimes the only viable method of detection. Figure 1.1 depicts the canonical fast transient: a giant pulse from the pulsar at the heart of the Crab Nebula. This extremely intermittent radio source is known to produce the brightest radio pulses in the sky, with temporal structure unresolved at nanosecond scales and brightness temperatures exceeding $10^{32}$ K (Cordes et al. 2004).

![Crab Pulsar: Giant Pulse Detection (sigma = 15.75)](image)

Figure 1.1: The canonical fast radio transient, a giant pulse from the pulsar in the Crab nebula. This pulse was detected in a 60-minute dataset from the Fly’s Eye experiment taken on 22 December 2007. The dispersion of the pulse, correctly corresponding to DM = 56.78 cm$^{-3}$ pc, is clearly visible.

In late 2007, a particularly perplexing radio transient was observed in an archival search of 1.4 GHz pulsar survey data from the Parkes multibeam receiver – the so-called “Lorimer Burst” (Lorimer et al. 2007). This very bright single pulse was detected at a very high signal-to-noise ratio, with a peak flux nearly 100 times the search threshold, in a pointing a few degrees
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south of the Small Magellanic Cloud (SMC). The pulse clearly exhibited the quadratic chirp expected from an astrophysical pulse modified by a cold plasma dispersion relation, with an inferred DM of 375 pc cm$^{-3}$. Even liberal models for the galactic and SMC contribution to the total implied electron column density could account for only a fraction of the DM measured. Assuming the rest of the dispersion was due to a Milky Way-like host interstellar medium (ISM) contribution and traversal of the much more rarified intergalactic medium (IGM), the lower limit on the distance to the source was calculated to be $\sim$600 Mpc. Suffice it to say, the implied energy release of $\sim 10^{40}$ ergs presented a challenge for astrophysical theory, and motivated wide ranging speculation of possible origins. Several subsequent searches (Keane et al. 2010; Deneva et al. 2009) did not detect any similar events, implying that such events must be exceedingly rare. Burke-Spolaor et al. (2010) presented the detection of several additional impulsive events in Parkes survey data with similar dispersive chirps to that seen in the Lorimer Burst but exhibiting clear indications of terrestrial origins. While the Burke-Spolaor et al. (2010) events showed an approximately quadratic frequency evolution, as would be expected for an astrophysical event, the detection of the events in multiple receiver beams simultaneously clearly points to a terrestrial source and the irregularity of received flux across the observing band and large pulse width differentiate them markedly from the Lorimer Burst. Recently, another possibly extragalactic burst was discovered in additional re-analysis of Parkes survey data (Keane et al. 2011), lending some support for the existence of a bonafide population of very bright extragalactic fast transient sources. Regardless of the source of such bursts, a population of extragalactic objects or events producing extraordinarily energetic radio pulses would provide an invaluable probe of the ionized IGM.

1.2 The Search for Extraterrestrial Intelligence

In the last 50 years, evidence has steadily mounted that the constituents and conditions we believe necessary for life are common and perhaps ubiquitous in the nearby galaxy. A plethora of prebiotic molecules have now been detected in molecular clouds, including amino acids and their precursors (Mehringer et al. 1997; Kuan et al. 2003), sugars (Hollis et al. 2004) and a host of other biologically important species (e.g. Lovas et al. (2006); Iglesias-Groth (2011)). Such detections offer an indication that the reactants necessary for building large complex organic structures may be formed readily in proto-planetary environs. Exoplanets themselves, while once relegated to the domain of speculation, now appear to be common and numerous. While strictly Earth-size planets at 1 AU from their parent have so far eluded detection, we have evidence that the conditions necessary to maintain carbon-based life, e.g. liquid water, can exist far away from the traditional “habitable zone” (Carr et al. 1998).

As yet, no evidence exists for the presence of any kind of life outside of the Earth. However, on our own planet, life is known to have arisen early (within 1 Gyr) and flourished (Schopf et al. 2002). And while the propensity for evolution of intelligence from basic forms of life is not currently well understood, it appears that intelligence has imparted a strong evolutionary advantage to our own species. From a Copernican standpoint, the possibility that life has
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arisen elsewhere and perhaps evolved intelligence is plausible and warrants scientific inquiry. “Are we alone as technologically-capable intelligent beings?” is among the most profound questions we can ask as scientists, and observational astronomy represents the best means of determining an answer.

1.2.1 Engineered Radio Emission

For a better part of the last century, human beings have produced radio emissions that could readily be recognized as having come from no known natural source if transmitted at sufficient power from another star and received on Earth. These emissions include spectrally narrow signals, e.g. the sinusoidal carrier waves associated with frequency modulated or amplitude modulated telecommunications, as well as temporally narrow radio pulses used for radar. Natural astrophysical electromagnetic emissions are inherently spectrally broadened by the random processes underlying natural emission physics, with the spectrally narrowest known natural sources having a minimum frequency spread of 500 Hz (Cohen et al. 1987) (astrophysical masers). Emission no more than a few Hz in spectral width is an unmistakable indicator of engineering by an intelligent civilization. While scintillation effects can render an intrinsically amplitude-stable narrow-band signal intermittent (Cordes et al. 1997), narrow-band signals are readily distinguished from background sources of radio emission and are immune to the dispersive effects of the ISM. Although the technologies associated with engineered radio emissions from Earth are developed by humans, similar signal types may be used by extraterrestrial intelligent civilizations if they similarly use electromagnetic radiation for ranging and communication. It is difficult to predict the specific properties of electromagnetic emission from extraterrestrial technologies, but if an extraterrestrial civilization is intentionally indicating its presence via such emission, it would be beneficial to make the signal discriminable. In terms of distinguishability, both pulsed signals and narrow band signals possess merit, and it is prudent to search for both.

Long wavelength radio photons are efficient and effective interstellar information carriers, as they are energetically cheap and the interstellar medium is relatively transparent at radio wavelengths. The frequency band between \(\sim500\) MHz and 10 GHz, the so-called “terrestrial microwave window” (Morrison et al. 1977) (Figure 1.2) is especially attractive for terrestrial transmission or reception, in that it represents a relatively quiet region of spectrum between the Galactic synchrotron-dominated low frequency spectrum and atmospheric H\(_2\)O and O\(_2\) emission and absorption. More fundamentally, electromagnetic waves carry information at the maximum rate possible according to our understanding of the physical universe, and compaction of electromagnetic energy in either time or frequency naturally leads to enhanced detectability. These simple facts, combined with the aforementioned properties of the space between life supporting surfaces, lead to the conclusion that searches for spectrally or temporally confined radio emission represent superb probes of the possible presence of other intelligent communicative civilizations. Extrapolating from humanity’s exploration of space, it is likely that a more advanced civilization having similar proclivities would explore and perhaps colonize multiple planets in their star system. These explorations could very
1.2. THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE

easily include planet-planet communication and radar imaging or radar mapping of orbital debris. Observing planetary systems in which the orbital plane is seen edge-on, such as those identified by transiting exoplanet surveys, thus present a particularly advantageous geometry for eavesdropping on planet-planet electromagnetic signaling by advanced life.

![Diagram of the terrestrial microwave window](image)

Figure 1.2: The “terrestrial microwave window,” a relatively quiet region of spectrum between the synchrotron-dominated low frequency spectrum and atmospheric H$_2$O and O$_2$ emission and absorption at higher frequencies.

1.2.2 Engineered Optical and Infrared Emission

The possibility of detecting optical and infrared emission from extraterrestrial lasers was first suggested in Schwartz & Townes (1961), well before the widespread proliferation of human laser technology in the later 20th century. In the last two decades, both pulsed and spectroscopic optical SETI searches have been widely discussed and conducted (Reines & Marcy 2002; Howard et al. 2004; Wright et al. 2004). The field of pulsed optical SETI rests on the observation that humanity could build a pulsed optical transmitter (using, for example,
1.3. THE TOOLS OF THE TRADE

a National Ignition Facility-like laser and a Keck Telescope-like optical beam former) that would be detectable at interstellar distances. When detected, the nanosecond-long pulses would be a factor of \(~1000\) brighter than the host star of the transmitter during their brief flashes (Howard et al. 2004). Such nanosecond-scale optical pulses are not known to occur naturally from any astronomical source. Spectroscopic laser SETI is discussed in detail in (Reines & Marcy 2002), the conclusion being that terrestrial laser technology could be readily detectable within 100s of ly if properly directed.

Powerful lasers have been developed for a number of applications on Earth and are well within our current technological capabilities. Research groups at Lawrence Livermore National Laboratory are now creating laser pulses with peak power of the order of a petawatt for times lasting many picoseconds\(^1\). Jefferson National Laboratory operates a high power continuous free electron laser program, and have sustained output as high as 15kW\(^2\). A great advantage of these lasers is that they can be narrowly beamed and carry large amounts of information, thus providing high transmitted power flux and information per unit energy. Using such a laser offers a promising means for interstellar communication, and it is possible that an advanced extraterrestrial civilization may choose to communicate in this way.

One major advantage of longer wavelengths for directed interstellar communication is the decrease in interstellar extinction (Mathis 1990), which is of particular importance for communicating close to the plane of the Milky Way. For example, at visual wavelengths (\(~600\) nm) there are 30 magnitudes of extinction looking towards the Galactic Center, whereas at IR wavelengths (\(~1600\) nm) there are only 2 magnitudes of extinction (Nishiyama et al. 2006). The level of extinction between optical and near-infrared wavelengths within the Galactic plane is illustrated in Figure 1.3. Townes (1983) and Betz (1986) discussed the physical reasons why infrared wavelengths might be optimal for interstellar communications, yet this region has remained unexplored territory for SETI.

1.3 The Tools of the Trade

1.3.1 Open Source Hardware Infrastructure

The Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) is a growing community of scientists and engineers interested in developing hardware and software that enables the rapid, efficient and economical implementation of high performance digital signal processing. Although CASPER’s original focus was on astronomical applications, the collaboration has now grown to include researchers tackling a variety of signal processing challenges in biotechnology, quantum computing and other fields.

Figure 1.4 depicts two hardware components developed by the CASPER collaboration that represent fundamental building blocks of the CASPER approach to digital instrument design. Figure 1.4a is the second generation Reconfigurable Open Architecture Computing

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\(^1\)http://lasers.llnl.gov

\(^2\)https://www.jlab.org/free-electron-laser
1.3. THE TOOLS OF THE TRADE

Figure 1.3: The Milky Way Galaxy at optical and near infrared wavelengths. Dark areas in the optical image are regions of the galactic plane heavily obscured by dust. Stars within dark regions are readily seen in the near-infrared image, owing to the dramatically lower extinction of near-infrared radiation compared to optical (See main text).

board (ROACH II), the latest of a series of field programmable gate array (FPGA)-based computing boards developed by CASPER collaborators. Though these boards are custom built, they feature common high-speed hardware interfaces and are programmed using a platform-independent graphical programming language, Simulink. The 2 input analog to digital converter pictured in Figure 1.4b is just one of nearly a dozen ADC and DAC boards ranging from 1 to 64 inputs and 64 megasample/sec to 6 gigasample/sec sampling rates that can be interfaced with CASPER boards. The ADC/DAC hardware interface has remained consistent from generation to generation, allowing digitization components to be reused and upgraded independently.

CASPER advocates a modular and scalable instrument design philosophy in which large instruments, such as the 32-input “FX”-style correlator shown in Figure 1.5, are constructed from smaller generic building blocks. These building blocks can be dynamically programmed for a given task using a set of flexible, platform-independent “gateware” libraries. These libraries can be used as the framework for many common signal processing applications and can be reused with little redevelopment on new generations of hardware. Board-to-board communication is accomplished using industry standard protocols and cross-connect components, such as 10 gigabit Ethernet and commercially available Ethernet switches. Commodity compute components, such as CPUs or graphics processing units (GPUs) can be incorporated into an instrument by simply plugging them into an Ethernet network. Command and control is performed through a standard Linux distribution running on each FPGA board, with FPGA memory mapped to Linux device files.

CASPER FPGA boards can be programmed using the Matlab/Simulink graphical programming environment. Complex signal processing libraries are constructed from primitive digital logic elements and are presented to an instrument developer via a high level parameterized interface. The Simulink environment also provides for clock cycle accurate simulations
of hardware using simulated signal sources and software test instruments. A graphical programming approach abstracts low-level hardware and opens up instrument design to non-specialists. Existing Simulink instrument designs can be shared, modified, recompiled and deployed on hardware in a matter of hours. All CASPER hardware, instrument designs and support software are open source and freely available to the world. All of the digital instruments discussed in the following chapters made great use of the CASPER approach and the community of CASPER collaborators.

The remainder of this work is structured as follows: Chapter 2 describes our Fly’s Eye Search for short duration radio transients at the Allen Telescope Array (Siemion et al. 2012), Chapter 3 discusses our ongoing SETI experiments at radio and optical wavelengths and our plans for the future, Chapter 4 describes a 1.1–1.9 GHz search for narrow-band emission from planet candidates identified by the *Kepler* mission and Chapter 5 details our ongoing search for pulsars near Sgr A*.
Figure 1.5: A cartoon of a 32-input “FX” style correlator assembled from CASPER components. A 10 GbE switch connects sampling and channelization elements (left) with cross-correlation elements (right). Purple elements indicate modular signal processing elements implemented in FPGA gateware.
Chapter 2

The Allen Telescope Array Fly’s Eye Survey for Fast Radio Transients

2.1 Introduction

The relatively unexplored fast radio transient parameter space is known to be home to a variety of interesting sources, including pulsars, pulsar giant pulses and non-thermal emission from planetary magnetospheres. In addition, a variety of hypothesized but as-yet-unobserved phenomena, such as primordial black hole evaporation and prompt emission associated with coalescing massive objects have been suggested. The 2007 announcement by Lorimer et al. of the detection of a bright (30 Jy) radio pulse that was inferred to be of extragalactic origin and the subsequent consternation have demonstrated both the potential utility of bright radio pulses as probes of the interstellar medium and intergalactic medium, as well as the need for wide-field surveys characterizing the fast-transient parameter space. Here we present results from the 450 hour, 150 deg² Fly’s Eye survey for bright dispersed radio pulses at the Allen Telescope Array (ATA). The Fly’s Eye spectrometer produces 128 channel power spectra over a 209 MHz bandwidth, centered at 1430 MHz, on 44 independent signals paths originating with 30 independent ATA antennas. Data were dedispersed between 0 and 2000 pc cm$^{-3}$ and searched for pulses with dispersion measures greater than 50 pc cm$^{-3}$ between 625 µs and 5 s in duration. No pulses were detected in the survey, implying a limiting rate of less than 2 sky$^{-1}$ hour$^{-1}$ for 10 millisecond duration pulses having apparent energy densities greater than 440 kJy µs, or mean flux densities greater than 44 Jy. Here we present a search using the 42-dish Allen Telescope Array for bright dispersed radio pulses, with specific attention paid to those of possible extragalactic origin. Section 2.2 describes the digital spectrometer developed for this experiment, installation, verification and calibration procedures, Sections 2.3 and 2.4 detail observations and analyses and Section 2.5 presents our results and interpretation.
2.2 Instrument and Installation

The single pulse search described here used the Allen Telescope Array (ATA) (Welch et al. 2009) in an unconventional non-interferometric mode. Rather than pointing all 42 dishes in the same direction, each dish was pointed at a unique position, similar to a “fly’s eye.” Such a mode yields a dramatically increased field of view at the expense of sensitivity, well matched to detecting bright, rare events. The primary half-power beam width (HPBW) of the ATA is approximately 2.5 deg at 1.4 GHz, yielding a potential field of view of more than 200 deg$^2$.

In this experiment, each antenna signal path was processed independently using a purpose-built digital spectrometer. This device, dubbed the Fly’s Eye Spectrometer, was constructed using the modular instrumentation infrastructure developed by the Center for Astronomy Signal Processing and Electronics Research (Werthimer et al. 2011). The full system consists of eleven field programmable gate-array (FPGA)-based ‘iBOB’ computing boards, each equipped with two 1024 Msample/sec ‘iADC’ analog-to-digital converter cards. Each ADC board digitizes two independent single-polarization signal paths at 838.8608 Msamples/sec. The Nyquist sampled band is digitally down converted and decimated to a bandwidth of 209.7152 MHz within the FPGA and channelized using a $2^7$ channel complex bipel-pipelined polyphase filterbank. Power spectra are detected and accumulated for 625 $\mu$s, packetized into Ethernet UDP packets on each of the eleven FPGA boards and transmitted to a single Linux PC via an Ethernet switch. The payload of each UDP packet contains a 21 byte header, which specifies a board ID, accumulation number and any error conditions, followed by 512 bytes of spectral data (unsigned byte power measurements $\times$ 128 frequency channels $\times$ 4 inputs). The entire Fly’s Eye digital back end is described in detail in McMahon (2008) and Siemion et al. (2010). Large portions of the hardware design and software are open source and freely available at http://casper.berkeley.edu.

During the course of analyzing our initial observations, a subtle timing error was discovered in the accumulation counter produced by the Fly’s Eye hardware. This error was initially attributed to a flaw in the digital design for the instrument involving the 1 pulse per second synchronization logic. As a result, we disconnected the 1 pulse-per-second input signal from each iBOB board prior to beginning our observation campaign. It was later discovered that the principal cause of the timing error was not the flaw in the digital design, but rather that the sampling clock was not properly locked to the observatory reference. By comparing the unix time stamps applied to each spectra by our data collection computer with the hardware counter applied by the Fly’s Eye spectrometer, we determined that the sampling clock frequency was only absolute to about 1 part in $10^4$. This level of error translates to a center RF frequency and bandwidth ambiguity of about 84 kHz. Because the Fly’s Eye spectrometer derives integration time from counting the sampling clock, the unlocked clock synthesizer also imposes an ambiguity in integration time of about 60 nanoseconds. In total, these effects correspond to an additional $\sim$0.03% temporal smearing at 1430 MHz. Although a small amount of additional temporal smearing has only a small impact on single pulse searches, it renders simple barycentering and folding of known pulsars impossible. We accounted for this effect during operability determination by ‘searching’ for a known pulsar
rather than directly folding on its known ephemeris.

The Fly’s Eye Spectrometer system was installed at the Allen Telescope Array in December of 2007 and connected to the 44 antenna-polarizations exhibiting the lowest system temperature. Galactic HI detection along several lines of sight served as a coarse operability check. To further test the Fly’s Eye Spectrometer, and most importantly to test our ability to detect bright dispersed pulses, we observed several bright pulsars including PSR B0329+54, the brightest known pulsar in the northern celestial sphere in terms of mean flux and also PSR B0531+21 (the Crab pulsar) - a canonical source of bright dispersed radio pulses (Bhat et al. 2008; Cordes et al. 2004). Figure 2.1 shows folded pulse profiles for a 1290s B0329+54 integration as observed in each of the 44 Fly’s Eye inputs. All inputs but one (8B) show some detection, with only 4 others (9D, 6C, 4D, 2C) showing significantly degraded signal-to-noise. Figure 2.2 shows an unweighted incoherent sum of the same data plotted alongside a reference profile.

Figure 2.1: Folded pulse profiles of PSR B0329+54 as observed in individual Fly’s Eye Spectrometer inputs for a 1290s integration at 1430 MHz. Two full turns plotted for clarity.
2.2. INSTRUMENT AND INSTALLATION

The signal-to-noise ratio of a detected pulsar pulse profile can be calculated as (Cordes & Chernoff 1998):

\[ \frac{S}{N} = \frac{S_{\text{mean}}}{S_{\text{sys}}} \sqrt{n_p t_{\text{int}} \Delta f N_h} \]  

(2.1)

where \( \frac{S}{N} \) is the detected signal to noise ratio, \( S_{\text{mean}} \) is the mean flux density of the pulsar, \( S_{\text{sys}} \) is the system equivalent flux density (SEFD) of the observing system, \( n_p \) the number of polarizations summed, \( t_{\text{int}} \) the integration time, \( \Delta f \) the bandwidth observed and \( N_h \) is the number of harmonics used in a harmonic sum, which depends on the pulse period \( P \) and pulse width \( W \) as \( N_h \approx \frac{P}{W} \). For the case of multiple antennas sampled synchronously and detected independently, \( n_p \) is equal to the total number of antenna-polarization signals incoherently summed, \( n_{\text{ant-pol}} \). Applying this equation to the summed profile shown in Figure 2.2 with \( n_{\text{ant-pol}} = 44 \) and the expected mean SEFD for individual ATA antennas (\( \sim 10 \) kJy), we infer a flux density for B0329+54 of \( S_{\text{mean}} \approx 100 \) mJy. This value is in reasonable agreement with a mean value extrapolated from Manchester et al. (2005), \( S_{\text{mean}} = 190 \) mJy, especially considering that the pulsar B0329+54 has a variable mean observed flux density of a factor of \( \sim 3 \) at 1400 MHz (Wang et al. 2005; Liu et al. 2006). PSR B0329+54 is thus a poor flux calibrator, but it is never-the-less a useful diagnostic source for a low sensitivity pulse search.

Observation of giant pulses (GPs) from the Crab pulsar provided the final end-to-end test of the Fly’s Eye observing system. Crab GPs are known to follow a power law brightness distribution, often parameterized in terms of a cumulative probability distribution \( P(E_i > E_0) = K E_0^\alpha \), where \( P \) gives the probability of a pulse having a pulse area \( E_i \) greater than \( E_0 \). Here pulse area is defined as \( E_i = S_i W_i \), where \( S_i \) is the mean intrinsic flux density of the pulse over an intrinsic time \( W_i \). While other authors have referred to the quantity \( E_i \) as “energy”, in later portions of this work we will use the slightly more accurate “energy density.” At 1300 MHz, Bhat et al. (2008) gives \( \alpha \sim -1.9 \) for energy densities greater than 10 kJy \( \mu \)s, with \( K = 4.7 \times 10^{-2} \) and \( E_0 \) in kJy \( \mu \)s. Rearranging equation 3 in Deneva et al. (2009) gives

Figure 2.2: PSR B0329+54 folded pulse profile as detected by the incoherent sum of all 44 inputs to the Fly’s Eye Spectrometer (shown in 2.1) for a 1290s integration at 1430 MHz (left) and a reference profile from Gould & Lyne (1998) taken at 1408 MHz.
an expression for the minimum detectable energy density,

\[ E_i = \frac{mS_{\text{sys}} \sqrt{W}}{\sqrt{n_p \Delta f}} \]  

(2.2)

\( W \) is the observed pulse width, usually taken to be the quadrature sum of the various sources of broadening, both astrophysical and instrumental and \( m \) the signal-to-noise threshold. For a pulse with an observed width limited by our digital hardware and assuming a single polarization SEFD of \( \sim 10 \) kJy, a characteristic \( m = 5\sigma \) minimum detectable energy density for the incoherent sum of 19 inputs is 20 kJy \( \mu s \) or an mean flux density of \( \sim 32 \) Jy for a 625 \( \mu s \) pulse. Based on the expected Crab GP distribution, we should observe a pulse with \( E_i > 20 \) kJy \( \mu s \) about 18 times per hour on average. Figure 2.3 shows the detection of 10 bright GPs at the expected DM of 56.8 pc cm\(^{-3}\) for the Crab pulsar in a 50 minute unweighted incoherently summed observation using the 19 best performing FE inputs, as determined from Figure 2.1.

The set of 44 antenna inputs ultimately used for the FE observing campaign originated with 30 independent antennas, 14 of which included both X and Y polarizations. Figure 2.4 shows antenna performance, described by the system equivalent flux-density (SEFD), for each of the 44 inputs chosen for the Fly’s Eye observing campaign. The values given here were determined by interferometric observation of standard calibrators interleaved with Fly’s Eye observation. Details of the Fly’s Eye instrument parameters are given in Table 2.1.

2.3 Observations

During the period February 2008 to May 2008, we conducted approximately 480 hours of drift-scan observations with the Fly’s Eye Spectrometer (Table 2.2). Data were collected in 60 minute intervals, each consisting of 58 minutes of drift observation followed by 2 minute diagnostic observations used for monitoring the health of the telescope and instrumentation. Fly’s Eye observations produced data at a rate of roughly 36 GB / hour, resulting in approximately 18 TB total collected data for the entire observation period. The data are archived in Berkeley and available for analysis by request to the authors. At the time of these observations, the ATA was undergoing commissioning, and a variety of system performance issues were being actively addressed. The variation in SEFD from antenna to antenna and less-than-complete utilization of the 42 installed antennas are reflective of these issues. To aid in dynamically determining signal path operability, a fixed pointing strip along a constant declination angle of \( +54^\circ \), in which antennae were spaced 1 half-power beam width apart, was chosen for drift scan observations. As the bright pulsar PSR B0329+54 drifted through the beam pattern at the sidereal rate, its detection or non-detection was used to determine whether or not a particular signal path was operable. Declination \( +54^\circ \) is well away from any significant source of galactic electron density confusion, the median maximum galactic DM contribution along this path is \( \sim 68 \) pc cm\(^{-3}\) (from the NE2001 model, Cordes & Lazio (2002)). Figure 2.7 illustrates the overall observing efficiency after applying the B0329+54
Table 2.1: Fly’s Eye Instrument Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency $\nu_0$</td>
<td>1430 MHz</td>
</tr>
<tr>
<td>Number of Channels $N_{\text{chan}}$</td>
<td>128</td>
</tr>
<tr>
<td>Channel Width $\Delta\nu_i$</td>
<td>1.6 MHz</td>
</tr>
<tr>
<td>Bandwidth $\Delta\nu$</td>
<td>210 MHz</td>
</tr>
<tr>
<td>Beam Width $\Theta$</td>
<td>2.5 deg</td>
</tr>
<tr>
<td>Solid Angle $\Omega$</td>
<td>147.3 deg</td>
</tr>
<tr>
<td>System Temperature $T_{\text{sys}}$</td>
<td>50 K</td>
</tr>
<tr>
<td>Gain $G$</td>
<td>$6.25 \times 10^{-3}$ K/Jy</td>
</tr>
<tr>
<td>Dish Diameter $D$</td>
<td>$\sim 6$ m</td>
</tr>
</tbody>
</table>

---

*a* Assuming all signal paths are operable but accounting for some dual-polarization observations, see Section 2.2

*b* Nominal value

detectability metric. Out of a total of 921.1 input-days of observing, 579.9 input-days showed the expected detections of B0329+54, for a total observing efficiency of $\sim$63%. The poor efficiency in Epoch 1 likely reflects an unaccounted for change in our pointing script that directed antennas away from +54°. Although we believe most signal paths were operable, we have conservatively excluded these data. Figures 2.5 and 2.6 show the simulated beam pattern and sky coverage for the ATA Fly’s Eye using all 42 antennas.

## 2.4 Analysis

### 2.4.1 Data Preparation

Power spectra time series for each of the 44 inputs to the Fly’s Eye Spectrometer were extracted as individual “filterbank” format files (Lorimer et al. 2000), broken into analysis chunks of length $2^{20}$ samples (representing 12 minutes). This length was chosen to allow an entire analysis chunk and set of dedispersed time series to be kept in computer memory during analysis. Prior to dedispersion, power spectra were normalized or “equalized” across both frequency channel and time. Equalizing across frequency channels has the primary effect of correcting for the rippled bandpass imposed by both analog filter response and digital
2.4. ANALYSIS

Table 2.2: Fly’s Eye Observations 02/2008–05/2008

<table>
<thead>
<tr>
<th>Epoch</th>
<th>MJD</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>54512.24 - 54515.97</td>
<td>5%</td>
</tr>
<tr>
<td>2</td>
<td>54519.20 - 54521.68</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>54526.13 - 54528.64</td>
<td>86%</td>
</tr>
<tr>
<td>4</td>
<td>54533.04 - 54535.63</td>
<td>73%</td>
</tr>
<tr>
<td>5</td>
<td>54540.17 - 54542.59</td>
<td>75%</td>
</tr>
<tr>
<td>6</td>
<td>54547.18 - 54549.60</td>
<td>86%</td>
</tr>
<tr>
<td>7</td>
<td>54554.18 - 54556.62</td>
<td>93%</td>
</tr>
<tr>
<td>8</td>
<td>54561.26 - 54563.62</td>
<td>66%</td>
</tr>
</tbody>
</table>

down conversion. Equalization of accumulation values mitigates broadband gain changes and broadband impulsive interference. This process was carried out as follows.

We denote the power in channel $i$ at (discrete) time $t$ as $P_i(t) \in [0,255]$, and we computed a mean power per channel

$$\overline{P}_i \equiv \frac{1}{T_0} \sum_{t=0}^{T_0-1} P_i(t) \quad (2.3)$$

over some time period $T_0$. $T_0$ is typically set to the length of an analysis chunk, $2^{20}$ samples. A particular value $P_i(t)$ is then divided by the mean $\overline{P}_i$, i.e. the equalized value $P_i'(t) \equiv P_i(t)/\overline{P}_i$. The mean power in each channel is then unity, since

$$\frac{1}{T_0} \sum_{t=0}^{T_0-1} P_i'(t) = 1 \quad (2.4)$$

Mean power equalization was performed on the frequency spectrum equalized values $P_i'(t)$. The power mean over all frequency channels for a single integration (time sample $t$) is defined as

$$\overline{P}'(t) \equiv \frac{1}{N} \sum_{i=0}^{N-1} P_i'(t) \quad (2.5)$$

$N$ is the number of channels. With the mean powers $\overline{P}'(t)$, we can define the equalization of the powers $P_i'(t)$. The mean power equalized values $P_i''(t) \equiv P_i'(t)/\overline{P}'(t)$. This procedure ensures that the sum of the power samples for any time $T_0$ is normalized such that $\sum_{i=0}^{N-1} P_i''(t) = N$, effectively flattening the DM = 0 time series.
Figure 2.3: A standard single pulse detection plot for a ∼50 minute observation of the Crab pulsar after summing 19 Fly’s Eye inputs. Several giant pulses are apparent at a DM of 56.8 pc cm$^{-3}$. Other features are radio frequency interference. From top, left to right, the panels show a histogram of detection signal-to-noise ratio (SNR) for pulses $> 5\sigma$, a histogram of detection dispersion measure, detection dispersion measure against detection SNR and detection time vs. dispersion measure with detection signal to noise indicated by plot point radius. This plot produced using PRESTO (Ransom 2001).
Figure 2.4: Mean antenna-polarization performance for each input to the Fly’s Eye Spectrometer, as determined by interferometric observation of standard calibrators interleaved with Fly’s Eye observations between 02/2008 and 05/2008. Errors are ± 1σ.
Figure 2.5: From Bower et al. (2008). The beam pattern of the 42 beams at ATA, with the diameters equal to the half-power width. This hexagonal packing is pointing north. A south pointing results in poor interference properties, due to the highly populated areas south of the ATA.
Figure 2.6: From Bower et al. (2008). The sky coverage of the ATA for an observing period of 24 hours. Both the coverages for southern and northern pointings (corresponding to the respective contiguous regions) are shown.
Figure 2.7: Diagram showing operability of each antenna/input as a function of epoch, based on detectability of B0329+54. Filled circles indicate that a given signal path is operable. For an input/epoch pair to be considered operable, B0329+54 must have been detected at every opportunity within the epoch. On the Y axis are each spectrometer input, labeled by their ATA antenna identifier followed by spectrometer input number. The suffix on the antenna identifier indicates which of two dual linear polarization feeds was used.
Figure 2.8: A plot of system sensitivity, described by the system equivalent flux density, vs. total operable observing, described by the observing solid angle \( \cdot \) time product. Plot includes both operable observing, taken from the set of signal paths where PSR B0329+54 was consistently detected, and the final low-RFI analysis set. In cases where two polarizations were observed for a given antenna, the lower SEFD was used.
Prior to the equalization process, individual frequency channels with especially large amounts of interference were identified and logged. Our algorithm used the variance of each frequency channel over an analysis chunk as a measure of the amount of interference in that channel. Using the previously defined quantities, we computed the variance of the values $P_i(t)$ for each channel $i$ over $T_0$, and then fit a polynomial to the resulting curve $\text{Var}(P_i)$ (Figure 2.9). Frequency channels for which the computed variance differed from the polynomial fit by $\text{Var}(P_i) > 2\sigma$ were excluded from subsequent dedispersion. We explicitly excluded 8 frequency channels at the top of the band and 13 frequency channels at the bottom of the band due to analog filter roll off and the presence of bright air route surveillance radar below 1350 MHz.

### 2.4.2 Single Pulse Search

A single pulse search in dedispersed time series for events having a signal-to-noise ratio (SNR) greater than five standard deviations above the mean, $\sigma > 5.0$, was carried out over 744 trial DMs between 0-2002 pc cm$^{-3}$ using the SigProc tools (Lorimer et al. 2000). An approximate matched filtering algorithm was employed to increase sensitivity to broadened pulses in which each dedispersed time series was iteratively smoothed by adding $2^n$ adjacent time samples over the range $n = 0$ to 10, following Cordes & McLaughlin (2003). This results in an effective box car smoothing of maximal window size $2^{10}$ samples or 0.64 to 5.12 s,
depending on the level of time collapse (Table 2.3). The initial DM step size was set such that the time delay associated with the DM step was less than the sampling interval. Spectra were iteratively collapsed in time by a factor of two at DMs 329.0, 658.0, 1314.0 pc cm\(^{-3}\) to speed analysis, as detailed Table 2.3. At these thresholds a pulse would subtend a minimum of 2, 4 or 8 spectra at the top of the band, respectively, and thus halving the effective time resolution imposes no loss in sensitivity. Similarly, the DM step size can be reduced by the same factor and remain less than the new effective time resolution. These search parameter choices were all designed to ensure that the dominant source of temporal smearing was due to the unavoidable (at the time of analysis) integration time smearing and in-band dispersive smearing. Like many problems in radio astronomy, the analysis of multibeam pulse search data is readily parallelizable. Here we distributed 58 minute observations to individual compute nodes, and parallelized inputs over individual CPU cores. In total, our analysis consumed \(\sim\)20,000 CPU-hours.

Table 2.3: Single Pulse Search Parameters

<table>
<thead>
<tr>
<th>Dispersion Measure Range</th>
<th>(\Delta DM)</th>
<th>Time Collapse Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 329.0 pc cm(^{-3})</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>330.0 - 656.0</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>658.0 - 1310.0</td>
<td>4.0</td>
<td>4</td>
</tr>
<tr>
<td>1314.0 - 2002.0</td>
<td>8.0</td>
<td>8</td>
</tr>
</tbody>
</table>

2.4.3 Post Processing RFI Filter

After dedispersion, any strong signal present in a dynamic spectra – be it from interference or a real event – will be detected at multiple DMs, strengths and times. The distribution of these detections depends on the observed properties of the signal, the range of DMs searched and any pre- or post-dispersion processing applied. In the case of quadratically chirped radio pulses, this distribution follows a characteristic functional form (Cordes & McLaughlin 2003). Likewise, certain kinds of interference will exhibit predictable detection distributions. Wideband, temporally narrow RFI will be detected over many DMs with the highest strength detections at low DMs. Narrowband, long duration RFI will also be detected at many DMs but will peak in strength when the dispersion path for a trial dispersion measure optimally overlaps the narrow-band interference. Finally, wideband and long duration interference or rapid gain changes will cause an excess of detections in all DMs for the duration of the event.

As a first cut on the vast number of high SNR candidates detected, we flagged any 1 second input-time region where the highest SNR candidate in that region was \(< 50\) pc cm\(^{-3}\) or \(> 1950\) pc cm\(^{-3}\), or the total number of pulses over 5\(\sigma\) in the same DM regimes exceeded
2.5 DISCUSSION

a factor of 4 times the mean number of pulses in each regime. The DM < 50 pc cm\(^{-3}\) would reject any relatively nearby galactic events, but distinguishing true astrophysical bursts from interference at these low DMs is very difficult because of the correspondingly small quadratic chirp. Further, our focus was primarily on potentially extragalactic events for which the DM contribution from the Milky Way and host ISM should well exceed this threshold. Figure 2.10 shows the results of applying this metric to pulse detections from two observations of the Crab Pulsar. The algorithm was effective at rejecting strong interference and avoided rejecting true astrophysical events. Strong interference dominates Figure 2.10a, but is greatly diminished in 2.10a. Figures 2.10b and 2.10d shows the detection of a bright pulse left untouched after applying our algorithm.

Following RFI rejection, all events with a SNR \(\sigma > 8.0\) detected in \(2^{20}\) sample analysis chunks for which the mean SNR of all detections was \(\bar{\sigma} < 5.5\) were selected for visual analysis. Plots similar to Figure 2.10 were examined for each detection. If an event did not appear to be interference, we extracted and closely examined \(t\) vs. \(\nu\) spectrograms of 1, 2, 4 and 10 seconds around the event. Figure 2.11 shows the SNR distributions for all pulses detected in operable signal paths, all pulses in operable paths after applying the first cut RFI rejection algorithm described above, and (inset) all pulses detected in observations having a mean pulse detection SNR \(\sigma < 5.5\). Upon close inspection, none of the pulse candidates identified appeared to be of astronomical origin. An example of the pathological interference that escaped our interference rejection algorithms is shown in Figure 2.12. Strong pulses were detected in regions where dedispersion curves aligned with the triangle-wave modulation of the interferer, at a DM of \(\sim 80\) pc cm\(^{-3}\). This particular interferer was detected at multiple epochs, and appears to originate with an orbiting satellite.

2.5 Discussion

Our results indicate that the millisecond radio sky is relatively quiescent at the energies probed by our experiment. For a threshold of \(8\sigma\), our minimum detectable energy density is \(E_{\text{min}} = 111\) kJy \(\mu s\) or a mean flux density of \(\sim 178\) Jy for a 625 \(\mu s\) pulse. Based on our non-detection, pulses of these energy densities originating with an isotropic progenitor must occur at a rate less than \(2\) sky\(^{-1}\) day\(^{-1}\). We can determine the limiting rate of occurrence of bursts as a function of antenna sensitivity by computing the rate

\[
\eta(E > E_{\text{min}}) = \frac{1}{\sum \Omega \cdot T_{\text{obs}}(SEFD > SEFD_{\text{min}})}
\]

where \(E_{\text{min}}\) corresponds to the detectable limit for pulses of a given duration in an antenna having \(SEFD_{\text{min}}\). Figure 2.13 shows the event rate limit calculated from these results alongside other recent single pulse searches in Table 2.4. Our rate limit does not yet sample potential coherent radio emission processes from neutron star binary inspirals or gamma ray bursts, but we can place an order of magnitude limit on the luminosity of coherent radio emission from core collapse supernovae (CC SNe). Assuming isotropic emission, our survey
Figure 2.10: Detection of giant pulses from the Crab pulsar for two individual FE inputs before (2.10a, 2.10b) and after (2.10c, 2.10d) application of a post processing RFI filter. Each plot shows events vs. time and trial dispersion measure, here the radii of plot points are proportional to \((\text{signal to noise})^2\).
2.5. DISCUSSION

Figure 2.11: SNR histograms for all pulses detected in operable signal paths, all pulses in operable paths after applying the first cut RFI rejection, and (inset) all pulses detected in $2^{20}$ sample observation chunks having a mean pulse detection SNR $\sigma < 5.5$.

could have detected $\sim 20$ 10 ms events with an intrinsic rate of 1000 sky$^{-1}$ day$^{-1}$ at an apparent energy density limit of $E_{\text{limit}} = 10^4$ kJy µs. Assuming that coherent radio emission from CC SNe is beamed over a solid angle $\Omega$, we can limit the emission cone to $\Omega < 4\pi/20$. Translating this into an upper limit on luminosity using the radius of a spherical volume of 1 Gpc$^3$, we have

$$L \leq E_{\text{limit}} \Delta \nu \frac{4\pi R_{\text{max}}^2}{20} \frac{1}{\Delta t}$$ (2.7)

For emission over a bandwidth $\Delta \nu = 1$ GHz and $\Delta t = 10$ ms we have $L \leq \sim 2 \times 10^{42}$ erg sec$^{-1}$.

As discussed in Lorimer et al. (2007) and Keane et al. (2011), if the two detected pulses inferred to be at cosmological distances are indeed real, they must represent an entirely new source class. The extreme SNR of the two sparse detections is curious, and as previously discussed by several authors, contradicts the assumption of an isotropically distributed population. In the case of this experiment, we would have expected to detect $\sim 15$ events similar to the Lorimer et al. (2007) burst, but $\ll 1$ similar to the Keane et al. (2011) extragalactic event. $^1$ The incompatibility of the implied rates for the two isolated detections is difficult to explain. The galactic latitude of the two events differ significantly, $b = -41.8^\circ$ for the Lorimer et al. (2007) event and $b = -4^\circ$ for the Keane et al. (2011) burst. While one

$^1$ Assuming an Euclidean isotropic distribution and correcting for the Fly’s Eye survey’s lower sensitivity. See, for example, Deneva et al. (2009) for an exposition of this calculation.
might guess that being much closer to the galactic plane would make it easier to explain a large dispersion measure, of the 227 known pulsars between 3° and 5° off the galactic plane, none has a DM > 460 pc cm$^{-3}$, standing in stark contrast with the Keane et al. (2011) event at a DM of 745 pc cm$^{-3}$ However, the increased intragalactic path length of this detection does present more opportunity for an unseen highly ionized nebula to make an aberrant contribution to the total integrated free electron column density.

The 15 Burke-Spolaor et al. (2010) detections also remain puzzling. Assuming the phenomena that generated these bursts is not unique to the Parkes site, we can estimate the number of similar events that the Fly’s Eye survey should have detected. Assuming that these bright events were observed in far out side lobes, a reasonable comparison between the two surveys reduces to simply the ratio of their observing time, thus the Fly’s Eye survey should have detected

$$15 \text{ events} \times \frac{450}{346.1 + 532.4 h} \sim 10 \text{ events}$$

of these events as well. Note that here we assume antenna efficiency and system temperature differences are negligible. We will refrain from speculating on the cause of these events, but note that our observations well sampled the diurnal cycle as well as varying levels of precipitation. We are unaware of any lightning activity in the near vicinity of the ATA during our observations.

It remains perplexing as to why all of these unique transient bursts have been detected only at the Parkes telescope. However, with the aggressiveness with which interference must be excised in such experiments, and the varying means by which it is accomplished, we speculate that it is not wholly out of the question that some processing pipelines could be better tuned to detecting single pulses at extragalactic DMs or other unexpected characteristics. The
2.5. DISCUSSION

Table 2.4: Recent L-band Single Pulse Surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>$T_{\text{obs}}$ (hours)</th>
<th>Total Solid Angle (deg$^2$)</th>
<th>$E_{\text{min}}^a$ (kJy µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edwards et al. (2001), Re-analysis by Burke-Spolaor &amp; Bailes (2010)</td>
<td>346.1</td>
<td>0.556$^b$</td>
<td>0.8</td>
</tr>
<tr>
<td>Manchester et al. (2006), Re-analysis by Lorimer et al. (2007)</td>
<td>480.7</td>
<td>0.556</td>
<td>0.8</td>
</tr>
<tr>
<td>Jacoby et al. (2009), Re-analysis by Burke-Spolaor &amp; Bailes (2010)</td>
<td>532.4</td>
<td>0.556</td>
<td>0.8</td>
</tr>
<tr>
<td>Manchester et al. (2001), Re-analysis by Keane et al. (2010) and Keane et al. (2011)</td>
<td>1864.3</td>
<td>0.556</td>
<td>0.8</td>
</tr>
<tr>
<td>Deneva et al. (2009)</td>
<td>461.0</td>
<td>0.0187$^c$</td>
<td>0.1</td>
</tr>
<tr>
<td>Fly’s Eye (this work)</td>
<td>136</td>
<td>147$^d$</td>
<td>440$^e$</td>
</tr>
</tbody>
</table>

$^a$For a 10 millisecond pulse. Values given here are conservative, see references for details.
$^b$Parkes Multibeam - 14′ HPBW/beam $\times$ 13 beams
$^c$Arecibo ALFA - 3.5′ HPBW/beam $\times$ 7 beams
$^d$2.5° HPBW/beam $\times$ 30 beams
$^e$Using a nominal SEFD of 8 kJy

fact that all of these pulses were themselves discovered in reanalyses of previously mined surveys, with the second extragalactic event discovered in a 3rd reanalysis, indicates that other extant surveys may harbor additional as-yet undetected events. Our own pipeline has been honed by the exercise of this experiment, and a future search would undoubtedly be superior. For instance, summing polarizations would yield an additional $\sqrt{2}$ sensitivity on some antennas. We attempted multi-beam coincidence RFI rejection, excluding pulses found at similar DMs and similar times in multiple antennas, and found it somewhat ineffective. We attribute the poor performance of this algorithm to a number of factors, among them that our algorithm didn’t account for variations in signal path sensitivity and multi-path propagation of interferers led to strong variation in detection signal-to-noise from antenna to antenna.

In previous searches where multi-beam excision has been effective, multiple receivers were co-located in the focal plane of a single telescope. Our results indicate that the interference environment is generally better correlated in these more confined configurations. Even so, applying a multi-beam coincidence metric in the time/frequency plane, prior to baseline subtraction and thresholding, would undoubtedly perform better. We explored these possibilities in parallel with the analysis described here, in anticipation of a future reanalysis,
in Hogden et al. (2011). Of the methods explored on a subset of Fly’s Eye data in Hogden et al. (2011), we find that a combination of Huber filtering and adaptive interference cancellation performs optimally for the types of interference seen in this experiment. Friends-of-friends algorithms, as described in Deneva et al. (2009) or Hough transform-based detection (Fridman 2010) would also improve our ability to detect low SNR events. In any case, additional surveys and analyses will soon detect more examples of isolated radio pulses which will expand the available sample. New wide-field interferometric radio telescopes will be well equipped to not only detect additional events, but also provide much better localization than has so far been possible with single dish facilities. Precise localization would be extremely useful in differentiating between true extragalactic events and those that may appear so because of passage through highly ionized intragalactic regions.

2.6 Summary

We have developed a novel multiple-input digital spectrometer which we have used to conduct a wide field search for bright dispersed radio pulses using the Allen Telescope Array. This wide field search yielded no detections, allowing us to place a limiting rate of less than 2 sky$^{-1}$ hour$^{-1}$ for 10 millisecond duration pulses having mean apparent flux densities greater than 44 Jy. The flux densities probed by this experiment are well above individual pulses from known pulsars and RRATs, just grazing the very brightest of the giant pulse producing pulsars, none of which are present in the field surveyed. We have placed new limits on very bright coherent emission from events similar to the singular event described in Lorimer et al. (2007). Our results indicate that the Lorimer et al. (2007) event must belong to a very rare source class, if it is indeed astrophysical. We did not detect any quadratically dispersed terrestrial interference similar to that seen at the Parkes observatory, e.g. Burke-Spolaor et al. (2010), consistent with other non-Parkes surveys, e.g. Deneva et al. (2009).

The work presented here has shown that sources of bright fast transient radio emission must be relatively rare. We have also shown both the utility, and associated of challenges, of using an interferometric array in a multi-pointing “fly’s eye” mode. The next generation of radio interferometers currently being built in preparation for the Square Kilometer Array (Dewdney et al. 2009) will offer new opportunities to explore the fast transient regime with greater sensitivity over large solid angles. The use of these new instruments for fly’s eye mode surveys will require making individual antenna or station data accessible to sufficient digital hardware, and we encourage this consideration to be taken into account during the design phase. Commensal surveys for fast transient emission with interferometers, using the incoherent sum of antennas pointed in the same direction, could offer an excellent trade-off between sensitivity and solid angle while incurring little additional hardware cost and no additional observing time, see e.g. Macquart (2011). Again, such capabilities will require consideration early in the design process in order to be realized efficiently. The exploration of the fast radio transient parameter space is just beginning, and the contrasting results of this and other experiments clearly indicate we have much yet to learn.
Figure 2.13: Pulse energy density vs. rate limit for the surveys in Table 2.4. Rate limit curves assume a 10 millisecond pulse duration. Shaded bars on the Lorimer Burst and the extragalactic event described in Keane et al. (2011) represent 2 sigma confidence (Gehrels 1986) on the Euclidean isotropic distribution. The point for terrestrial events identified in Burke-Spolaor et al. (2010) assumes off-axis detection. Rates of core collapse supernovae, gamma ray bursts and binary neutron star inspirals in a 1 Gpc$^3$ volume are taken from Madau et al. (1998), Guetta & della Valle (2007) and Kalogera et al. (2004), respectively, via Lorimer et al. (2007). Here we assume flat sensitivity across the HPBW of each receiver beam and do not take into account reduced sensitivity in wide field-of-view sidelobes, except in the case of this work and Deneva et al. (2009). The curved line for the Siemion et al. survey reflects variation in antenna system temperature.
Chapter 3

SETI: Present and Future

3.1 Introduction

For over 50 years, scientists have sought to determine the presence of advanced extraterrestrial life by searching for their electromagnetic communications. These searches were initially confined to targeting narrow-band and pulsed radio signals, but in the last two decades technology has permitted extending these searches into the optical regime and allowed the inclusion of more computationally intensive search algorithms. The radio regime is an especially attractive search space for a number of reasons, among them that the interstellar medium is relatively transparent at these wavelengths, it is energetically inexpensive for a civilization to produce radio photons and the most detectable signatures of our own intelligence are radiated there. Optical communications offer the advantage of potentially much higher information content and much more efficient targeting of individual planetary systems by the transmitting civilization. Our group is engaged in several sky surveys and targeted observation campaigns searching for electromagnetic indicators of extraterrestrial technology. These experiments, both planned and underway, span the electromagnetic spectrum from 100s of MHz to 100s of THz and time scales from nanoseconds to hours, employing the largest and most sensitive telescopes on the planet to conduct the deepest and most exhaustive searches ever performed. Our efforts include “piggy-back” sky surveys with the Green Bank Telescope and Arecibo Radio Observatory, targeted searches of known extrasolar planet systems at radio, infrared and optical wavelengths and the first ever search for pulsed infrared lasers. Here we will discuss our most recent instrumentation design work, observational results and plans for the future.

3.2 Commensal SETI at Arecibo Observatory

The most publicly well known of our group’s searches for extraterrestrial intelligence is our distributed computing effort, SETI@home (Anderson et al. 2002). Launched in 1999, SETI@home has engaged over 5 million people in 226 countries in a commensal sky survey
3.2. COMMENSAL SETI AT ARECIBO OBSERVATORY

Table 3.1: History of SERENDIP

<table>
<thead>
<tr>
<th>Program</th>
<th>Bandwidth (MHz)</th>
<th>Resolution (Hz)</th>
<th>Channels</th>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>SERENDIP I</td>
<td>0.1</td>
<td>1000</td>
<td>100</td>
<td>1979-1982</td>
<td>Hat Creek, Goldstone</td>
</tr>
<tr>
<td>SERENDIP II</td>
<td>0.065</td>
<td>1</td>
<td>64K</td>
<td>1986-1990</td>
<td>Green Bank, Arecibo</td>
</tr>
<tr>
<td>SERENDIP III</td>
<td>12</td>
<td>0.6</td>
<td>4M</td>
<td>1992-1996</td>
<td>Arecibo</td>
</tr>
<tr>
<td>SERENDIP IV</td>
<td>100</td>
<td>0.6</td>
<td>168M</td>
<td>1998-2006</td>
<td>Arecibo</td>
</tr>
<tr>
<td>SERENDIP V.v</td>
<td>300</td>
<td>1.5</td>
<td>2G¹</td>
<td>2009 -</td>
<td>Arecibo</td>
</tr>
</tbody>
</table>

¹SERENDIP V.v is currently multiplexed.

for narrow-band and pulsed radio signals near 1420 MHz using the Arecibo Radio Telescope’s ALFA multi-beam receiver. In 2010, we expanded SETI@home to include searches for dispersed radio pulses, a project called ‘AstroPulse’ (von Korff 2010). Participants in the project are generating the collective equivalent of 200 TeraFLOPs/sec and have performed over $1.4 \times 10^{22}$ FLOPs to date. Another of our radio SETI projects, the Search for Extraterrestrial Radio Emission from Nearby Developed Intelligent Populations (SERENDIP) (Werthimer et al. 1995), is now in its fifth generation and is currently being conducted in a collaboration between UC Berkeley and Cornell University (Table 3.1). In June 2009 we commissioned SERENDIP V.v, the newest iteration of the three-decade old SERENDIP program. This project utilizes a high performance field programmable gate array (FPGA)-based spectrometer attached to the Arecibo ALFA receiver to perform a high sensitivity sky survey for narrow-band signals in a 300 MHz band surrounding 1420 MHz. The SERENDIP V.v spectrometer analyzes time-multiplexed signals from all seven dual-polarization ALFA beams, effectively observing 2 billion channels across seven 3 arc-minute pixels. A copy of this instrument is currently deployed by the Jet Propulsion Laboratory on a 34-m Deep Space Network (DSN) dish, DSS-13, in Barstow, California. Both SETI@home/Astropulse and SERENDIP observe simultaneously and commensally with other ALFA observations.

¹SERENDIP experiment numbering proceeds from IV (four) to V.v (five point five) to accommodate the ambiguous naming of the SERENDIP V computing board, which was in fact never used for searches for extra-terrestrial intelligence.
3.3. OPTICAL SETI

3.2.1 Search for Extraterrestrial Radio Emission from Nearby Developed Intelligent Populations

While both SERENDIP V.v and SETI@home operate simultaneously and commensally on the same RF signal, SERENDIP V.v differs in the key respect that the computationally intensive Fourier Transform is performed internally, rather than through distributed computing. This forces the SERENDIP V.v spectrometer to use a much simpler search algorithm than SETI@home employs. However, since the SERENDIP spectrometer is collocated with the telescope, it has access to a much larger bandwidth. SERENDIP and SETI@home are thus complementary, in that together they can look with both a panoramic gaze across many MHz and with microscopic precision near the 21cm “watering hole.”

The SERENDIP V.v system architecture and dataflow are shown in Figure 3.1. ALFA signals for all 14 beam-polarizations are fed into an RF switch, with a single output fed into a high-speed ADC sampling at 800 Msps. An iBOB board mixes the sampled signal down to baseband, decimates to a 200 MHz bandwidth and transmits the serialized data stream to a BEE2 via a high-speed digital link. Processing on the BEE2 is split into four stages, each of which occupies a separate FPGA on the board. The data stream is 1: coarse channelized via a 4096pt polyphase filter bank (PFB), 2: matrix transposed by a “corner turner” to facilitate a second stage of channelization, 3: fine channelized using a conventional 32768pt Fast Fourier Transform (FFT) and finally 4: “thresholded,” in which each fine frequency “bin” (1.49 Hz wide) is compared against a scaled coarse-bin average to pick out fine bins of interest. Local averages are calculated per PFB channel by averaging the same data being fed to the FFT in parallel with the transform. This way, the total power in each PFB bin can be accumulated while the FFT is being computed (via Parseval’s theorem).

The thresholding process triggers “hits” for fine/FFT bins that are greater than or equal to the threshold power. For practical reasons, the number of hits reported per coarse/PFB bin is capped via a software-adjustable setting, usually set to report fine bins between 15-30 times the average power. The reported hits are assembled into UDP packets on-board the BEE2 and transmitted to a host PC. The host PC combines spectrometer data with meta-information, such as local oscillator settings and pointing information, and writes the complete science data stream to disk. To-date, SERENDIP V.v has commensally observed for approximately 900 hours. Analysis efforts are underway, in parallel, at both UC Berkeley and Cornell.

In the previous 3 years, approximately 8000 hours of observations have been performed, covering a significant fraction of the Arecibo viewable sky (between $\sim -1^\circ$ and $39^\circ$ Dec). Figure 3.2 shows characteristic sky coverage for a four month period, shown here for the period September 2011 to December 2011.

3.3 Optical SETI

Our optical pulse search (Lampton 2000) is based at UC Berkeley’s 30-inch automated telescope at Leuschner Observatory in Lafayette, California. The detector system consists
Figure 3.1: SERENDIP V.v instrument architecture. Analog signals from the ALFA receiver, mixed down to IF, are fed to a computer-controlled switch. One copy of the input is relayed to the SETI@home data recorder and a time-multiplexed beam is sent to the SERENDIP V.v spectrometer. The spectrometer samples the incoming IF signal at 800 Msamples/sec, digitally down converts the data to a complex baseband representation, performs a two-stage channelization (yielding $\sim 1$ Hz spectral resolution) and outputs over-threshold frequency channels to a host PC.

of a custom-built photometer, employing three photomultiplier tubes (PMTs) fed by an optical beamsplitter to detect the concurrent (within $\sim 1$ ns) arrival of incoming photons across a wavelength range $\lambda = 300$–650 nm. This “coincidence” detection technique improves detection sensitivity by reducing the false alarm rate from spurious and infrequent pulses observed in individual PMTs. PMT signals are fed to three high speed amplifiers, three fast discriminators and a coincidence detector (Figure 3.3), where detections are measured by a
3.4. PROSPECTS FOR THE FUTURE

3.4.1 New Instrumentation

Historically, the level of technology and engineering expertise required to implement a SETI instrument was quite high. As a result, SETI programs have been limited to relatively slow (1 MHz) Industry Standard Architecture (ISA) counter card. The photometer features a digitally adjustable threshold level to set the false alarm rate for a particular sky/star brightness.

During a typical observation, the telescope is centered on a star and detection thresholds are adjusted so that the false alarm rate is sufficiently low. Currently we record three types of events: single events, when an individual PMT output is greater than the voltage threshold originally set; double events, when any two of the PMTs output exceeds the threshold in the same nanosecond-scale time period; and triple events, when all three PMTs concurrently exceed threshold. Voltage thresholds are set so that false triple events are very rare and false double events occur only a few times in a 5 minute observation. A duplicate of this instrument is in place at Lick Observatory near San Jose, California (Stone et al. 2005). Figure 3.4 depicts the results of a recent observation using the Lick photometer to observe a *Kepler* planet candidate, the potentially habitable KOI 113.01. Three signal types are shown, individual PMT counts, the three doublet possibilities and triplets.

3.4 Prospects for the Future

Figure 3.2: SERENDIP V.v sky coverage during the period September 2011 to December 2011. Typical integration time per pointing is 15-150 seconds. The overall portion of the sky covered reflects the limited declination range ($\sim -2^\circ < \delta < 38^\circ$) accessible from Arecibo.
Figure 3.3: Schematic diagram for the existing analog electronics and ISA digital counter card used to read out the Lick and Leuschner SETI photometers. An optical telescope feeds three photomultiplier tubes using optical beamsplitters. Analog electronics threshold the signals from three PMTs and coincidence detectors trigger low-speed counters. While this system is effective all detailed data about the event trigger (the digitized light profile) is lost.

just a handful of institutions. Our group is developing two new instruments possessing several advantages over previous generations of SETI instrumentation – an Optical SETI Fast Photometer for optical SETI and the Heterogeneous Radio SETI Spectrometer for observations in the radio. Both are constructed from widely available modular components with relatively simple interconnects. The designer logs into the instrument using Linux and programs in C, obviating the need for cumbersome interfaces (e.g. JTAG) and languages (e.g. VHDL/Verilog). Further, these instruments are scalable and easily upgradable by adding additional copies of commercially available parts (compared with the money and time-consuming upgrades of previous instruments that involved complete redesigns of PC boards and ASICs). Collectively these advances will enable much wider participation in SETI science.

Optical SETI Fast Photometer

The forthcoming Optical SETI Fast Photometer (OSFP) is based on the same front-end optics and photodetectors as the original Berkeley OSETI instrument, but adds a flexible digital back-end based on the CASPER DSP instrument design system. This instrument will significantly improve our sensitivity to pulsed optical signals, and lower some of the barriers to wider engagement in optical SETI searches. The digital back-end for the instrument, Figure 5, will be constructed from modular CASPER components; direct sampling PMT outputs with two dual 8-bit, 1500 Msps ADC boards and using a single ROACH board.
3.4. PROSPECTS FOR THE FUTURE

Figure 3.4: The results of a recent observation using the Lick Optical SETI photometer to observe a *Kepler* planet candidate, the potentially habitable KOI 113.01. Three signal types are shown, individual PMT counts, the three doublet possibilities and triplets.

for DSP. This board features a variety of interfaces for connection to a control computer, accommodating a variety of experiment parameters. For high threshold, low event rate searches, the ROACH’s 100 Mbit Ethernet should be sufficient for data acquisition. For low thresholds, or characterization of instrument PMTs, the ROACH’s 10GbE interfaces can be used for transferring many events and/or large swaths of raw sampled voltages.

The programmable FPGA-based digital back-end will allow us to improve sensitivity by implementing sophisticated real-time detection algorithms. In our existing system at Leuschner observatory, the detection algorithm is very simple – all three PMT signals must be above a programmable threshold to trigger an event. With OSFP, one can implement more sophisticated detection algorithms. For example, a multistage trigger could be implemented that requires the sum of the three digitized PMT outputs to exceed a threshold as well as the requirement that the signal levels in the three streams be similar to each other. The ability to perform significant computations on the data streams in real time is a crucial aspect of this design. We envision searching for multiple signal types simultaneously, including weak pulse trains with repetition times from ns to ms and violations of Poisson statistics in photon arrival times (indicating a non-astrophysical source). False positive signals can also be efficiently rejected based on pulse profiles (a capability sorely lacking in the current threshold-based instrument).

The large amount of DRAM available on the ROACH board will enable buffering of raw PMT waveforms and triggered write-to-disk based on high-confidence events. Such a capability will enable detailed analysis of an event, including precise determination of pulse arrival times using centroiding. Upon detection of a coincidence event, a user-adjustable section of the corresponding waveform, along with microsecond time-tagging provided by a GPS 1 pulse per-second system, will be packetized and transmitted to a host computer over
3.4. PROSPECTS FOR THE FUTURE

Figure 3.5: Schematic diagram for the OSFP digital backend. An optical telescope feeds three photomultiplier tubes (PMTs) using optical beamsplitters. The PMT outputs are digitized directly using 1.5 Gsamp/sec ADCs and transmitted to a ROACH board for processing. Onboard the ROACH, voltage samples are copied into a 4 Gb DRAM ring buffer that feeds a programmable event detection circuit. When triggered, the ring buffer contents are read out to a host computer, capturing raw event data. The digital logic for the instrument is fully compatible with the CASPER open-source instrument design tool flow.

one of the ROACH’s Ethernet interfaces. A parallel, streaming DSP design will enable the instrument to operate at 100% duty with reasonable waveform buffers. Should a significant event be detected, the software system will automatically alert the observer to the possible signal detection, and will optionally automatically cause the telescope to continue observing the same sky coordinates where the telescope was pointed when the reported flash arrived.

In anticipation of the real-time computing capabilities of OSFP, we have performed preliminary simulations of several pulse detection algorithms. These simulations model the entire front-end of the system, including the optical beam splitter, PMTs, and ADCs. In initial work, it appears the optimal algorithm involves thresholding the cross-correlation of each pair of PMT waveforms, but we continue to evaluate tradeoffs in sensitivity and false alarm rate. Future simulations will allow us to improve our algorithms by incorporating more elaborate detection criteria.

Heterogenous Radio SETI Spectrometer

The Heterogeneous Radio SETI Spectrometer (HeRSS) bridges our previous radio SETI programs by connecting open source FPGA-based signal processing hardware to an easily-programmable graphics processing unit (GPU) equipped multicore CPU back-end, thus
achieving an economical student-friendly SETI instrument. HeRSS uses a ROACH board to coarsely channelize from one to four inputs, each digitized at up to 1 Gsps, and transmit them via 10 GbE to GPU-equipped servers for fine channelization and further real-time signal processing. Because 10 Gb ethernet is an industry standard transmission protocol, the HeRSS architecture is agnostic to the device receiving the subbands. Figure 3.6 shows an example configuration of HeRSS with a variety of compute elements attached via a 10GbE switch. The reconfigurability of the HeRSS design makes the required size and computing power of the backend processing cluster elastic, scaling from a single server to a cluster of high powered servers. The flexibility of the CPU/GPU back-end of HeRSS will readily enable arbitrarily sophisticated algorithms in the real-time processing pipeline, including dynamic interference rejection and immediate follow-up.

The number of channels, number of IP addresses, and the packet size can all be easily adjusted in the HeRSS design. This design can support a variety of back-end processing options simply by adjusting these three parameters. The number of channels adjusts the size of the sub-band for each backend processing element. Dividing a 500 MHz band into 16 channels creates large 31.25 MHz sub-bands, which may require more powerful compute elements, but this can be adjusted by increasing the number of channels and thereby reducing the size of the sub-bands and processing demand. The number of IP addresses effectively controls the bandwidth each backend server receives. In a 16-channel design with only 8 IP addresses, each compute server will receive 2 channels. In a compute server with multiple processing elements, these channels can be processed in parallel.

As shown in Table 3.2, HeRSS is extremely cost effective compared to other SETI
3.4. PROSPECTS FOR THE FUTURE

Table 3.2: Comparison of SERENDIP and HeRSS Costs

<table>
<thead>
<tr>
<th>SETI Spectrometer</th>
<th>Bandwidth</th>
<th>Beams</th>
<th>Pol’s</th>
<th>Cost (^a)</th>
<th>Normalized Cost per MHz/beam/pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>SERENDIP V.v</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCB, deployed at</td>
<td>200 MHz</td>
<td>1</td>
<td>1</td>
<td>$40K</td>
<td>$200</td>
</tr>
<tr>
<td>Arecibo &amp; JPL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HeRSS</td>
<td>500 MHz</td>
<td>2</td>
<td>2</td>
<td>$19K</td>
<td>$10</td>
</tr>
</tbody>
</table>

\(^a\)Costs do not include labor.

spectrometers with \(\sim 1\) Hz spectral resolution. HeRSS is less expensive than SERENDIP V.v, primarily because it uses a newer single-FPGA ROACH board paired with commodity computing hardware instead of an iBOB with a 5-FPGA BEE2 board. The HeRSS architecture can be easily scaled up to process a 1.5 GHz dual polarization signal on a single ROACH board using currently available dual 3 Gsps ADCs and multiple fine channelization nodes. HeRSS will enable powerful new surveys for advanced extraterrestrial life, through both upgrades of instruments at facilities already active in SETI and new efforts at observatories not currently conducting SETI research. The Arecibo 305m telescope is the most sensitive telescope on the planet to extraterrestrial radio emission in the terrestrial microwave window, and therefore an obvious choice for deploying a high-performance SETI spectrometer. A commensal GBT survey would sample large swaths of sky and radio spectrum inaccessible from Arecibo, including the source-rich galactic center. An additional exciting capability engendered by simultaneous commensal observation at Arecibo and GBT is the opportunity to incorporate observations at both facilities into high-level scoring algorithms. Candidate databases from both facilities can be compared, and if both facilities detect interesting signals at the same sky coordinates that signal would receive a high score and subsequently be re-observed. GBT and Arecibo have fully overlapping fields of view, and the two facilities have popular receivers overlapping in frequency coverage, notably at L-band.

Table 3.3 compares surveys enabled with HeRSS to other radio SETI sky surveys, either underway or planned. We use the Drake-Gulkis Figure of Merit (FoM)\(^2\) Drake et al. (1984):

\[
\text{FoM} = \text{sky coverage} \times \text{frequency coverage} \times \text{sensitivity}^{-3/2}.
\]  

\(^2\)The Drake-Gulkis FoM does not properly describe targeted searches, Dreher & Cullers (1997), and thus we have only included surveys.
underway. A GBT commensal survey would be between 300-1000 times more powerful than any current or proposed surveys at the GAVRT telescope and 100,000 times more powerful than any current or proposed surveys at the Allen Telescope Array.

The complete instrument system for both HRSS and OSFP, including digitization and packetization hardware, digital signal processing (DSP) algorithms and control software, will be made publicly available for students and researchers worldwide.

3.4.2 New Wavelengths

Infrared Spatial Interferometer

The first SETI searches ever performed at mid-infrared wavelengths will be conducted using the three 1.7 m telescopes of the ISI array at Mt. Wilson, CA (Figure 3.9a), co-developed by Co-Investigator Townes. The mid-IR program will be divided into two areas: continuous wave (CW) detection, based on the Betz (1993) feasibility studies but using modern digital hardware; and a novel coincidence pulse detection system using coincidence between telescopes.

The ISI is currently configured as a three-element interferometer array for stellar size and shape measurements, and it will require little modification for CW OSETI observations. In each telescope, starlight is combined with light from a CO$_2$ laser local oscillator on a HgCdTe mixer diode. The resulting heterodyne signal has a bandwidth from 0.3 to 2.8 GHz. The three RF signals are then amplified and transmitted to a central station for cross-correlation. The likelihood of heterodyne detection of a narrow band CW signal was discussed by Betz (1993), where the mid-IR signal-to-noise using a 10 m telescope was comparable to that in the radio frequency L band using the Arecibo telescope. The new ISI digital spectrometer-correlator (designed in collaboration with the CASPER group) will be programmed for $\sim 500$ kHz channelization, yielding channels having approximately the same fractional bandwidth as our radio searches ($\sim 1$ Hz at 1 GHz sky frequency). All three telescopes will be used simultaneously, incoherently summed for increased signal-to-noise and analyzed for coincidence to reject false-positive detections.

The ISI HgCdTe mixers are valuable for heterodyne detection because they have a large RF bandwidth, and this makes them ideal for fast pulse searches as well. For this search, the ISI digital backend will be reconfigured to threshold the incoming data streams prior to channelization, allowing excellent sensitivity to pulses as short as $\sim 1$ ns. These experiments will use two separated telescopes and determining the proper signal delay will allow coincidence verification as in the Harvard-Princeton visible pulse search (Howard et al. 2004)). It may also be possible to use three-telescope interferometric observations to ensure signals have the proper correlation delay to be of extraterrestrial origin.

Near-Infrared SETI

As discussed in 1.2.2, the near-infrared spectrum offers some distinct advantages over the optical in terms of interstellar extinction. Near-infrared (1000 - 3500 nm) astronomy has
matured rapidly in the last decade, with more advanced infrared detectors offering higher quantum efficiencies and lower detector noise. The Leuschner and Lick Observatories (Figure 3.9d) will soon host new fast photometers and digital electronics (as described in Section 3.4.1), that we will employ to extend the optical SETI search into the near-infrared for the first time. Using dichroic beam splitters, light from meter-class telescopes will be split into optical (350−900nm) and near-infrared (1000−1700nm) signal paths, enabling simultaneous searches in both bands for brief flashes of light indicative of an artificial source. We expect first light with these new instruments in 2013. Targeted observations will be performed with both facilities independently, but we may attempt coordination if we deem it feasible and worthwhile.

3.4.3 ExoPlanet Interplanetary Communication Searches for ExtraTerrestrial Intelligence

The Kepler spacecraft (Borucki et al. 2010) is currently conducting a high precision fast-cadence photometric survey of ~156,000 stars in a 100 sq. degree field to search for Earth-size planets in the habitable zone of Solar-type stars. As of February 2012, the Kepler team has announced 2321 planet candidates, including 896 candidates residing in one of 365 multi-candidate systems Batalha et al. (2012). Notable multi-planet discoveries include the Kepler-11 system of six transiting planets (Lissauer et al. 2011); earth-sized Kepler-20e and 20f (Fressin et al. 2011); KOI-961 b, c, and d – all smaller than earth (Muirhead et al. 2012). Statistical arguments suggest that ~98% of candidates in multi-candidate systems are bona fide planets (Lissauer et al. 2012). These systems present a unique opportunity for performing SETI searches at particularly advantageous times - epochs of conjunction along a line of sight to the Earth (See Figure 3.7). These alignments would allow us to eavesdrop on any planet-to-planet communication or active astronomy, perhaps akin to the manner in which we use the Arecibo Planetary Radar to image other planets in our solar system. The published ephemerides of these known systems readily enable calculation of conjunction times.

Extrapolating from humanity’s exploration of space, it is likely that a more advanced civilization having similar proclivities would explore and perhaps colonize multiple planets in their star system. These explorations could very easily include planet-planet communication, radar imaging or radar mapping of orbital debris. It follows that observing extrasolar multi-planet systems during conjunctions of one or more planets along a line of sight to the Earth, e.g. Figure 3.7, offers a greatly enhanced probability of detecting these signals. Our search will leverage the flood of extrasolar multi-planet ephemerides determined from the Kepler Transiting Planet Survey to conduct the first ever targeted search of multi-planet systems at conjunction for evidence of planet-planet electromagnetic signaling by advanced life. We dub this new observing technique ExoPlanet Interplanetary Communication Searches for ExtraTerrestrial Intelligence, EPIC-SETI.

Due to the shear number of Kepler multi-planet systems, we expect ~25 systems to be in conjunction during any given 30 minute window (see Figure 3.8 and caption). We will
prioritize targets based on equilibrium temperatures ($T_{eq}$), choosing conjunction events in which the more distant planet is closest to the habitable zone. The *Kepler* team defines the habitable zone as $185 < T_{eq} < 303$ K. At this time, there are 12 planets or planet-candidates in multi-planet systems that are in the habitable zone, all of which will be observed. Additional habitable zone candidates will also be observed as they are released by the *Kepler* team.

For calculating conjunction times, we assume all planets to be in perfectly circular and coplanar orbits. We consider two planets to be in conjunction when their angular separation is smaller than the angle subtended by the radius of the host star. We choose stellar radius as the critical angle because one cannot distinguish transits crossing the upper or lower half of the star based on photometry alone. In other words, planets with identical impact parameters could be separated by $\sim$ the stellar radius. Also, the beam width of the radio transmitter is likely significantly wider than the planet radius if it is detectable. In any case, statistical arguments by Fabrycky et al. [2012] suggest that planets in multi-planet systems are nearly coplanar, with typical mutual inclinations of $2^\circ$. Also, if we assume equipartition between mutual inclination and eccentricity, multi-planet systems are also nearly circular. Such small departures from circular, coplanar orbits do not significantly affect our calculation of conjunction.

3.5 Summary

While the basic methodology of most electromagnetic searches for extraterrestrial intelligence have remained the same during the last half century, the speed and sensitivity of current searches are many orders of magnitude greater than their predecessors. Modern digital
3.5. SUMMARY

Figure 3.8: Predicted number of conjunctions per day for 3 months in 2012. The several hour duration of each conjunction event leads to approximately 25 conjunctions in progress for any given 30 minute period.

Electronics and efficient algorithms allow sub-Hz spectroscopy across GHz of bandwidth, with the ability to search the entire terrestrial microwave window for cosmic narrow band signals less than a decade away. The supporting astrophysics and biology underpinning the search for extraterrestrial life has also made great strides, as we are now in an era where we can say with scientific certainty that planets are the rule, rather than the exception, that the galaxy is teeming with biomolecules and water and that life can exist in extraordinarily extreme environments.

The detection of intelligent life outside of the Earth would be one of the most profound discoveries in the history of science. Such a discovery would forever imprint upon our collective psyche a kinship in species that would undoubtedly have far reaching impacts on every aspect of human life, even if nothing more were learned other than that we are not alone as intelligent beings in the universe. It is indeed difficult to imagine an area of science, philosophy or even religion that would not be shaken by such a discovery. The discovery of an independent genesis of life on another world would provide strong evidence that life is common, and its intelligence would suggest that evolution proceeds towards this end easily. Were an information-containing transmission to be received and decoded, we can only conjecture what thoughts and ideas might be contained therein, but surely our human culture would be enriched in unimaginable ways.

Figures 3.9, 3.10 and fig:all ranges summarize the capabilities of our upcoming experiments.
3.5. SUMMARY

Figure 3.9: The five facilities to be used for upcoming SETI observations. From left to right, (a) The Infrared Spatial Interferometer, Mt. Wilson, California, (b) the Green Bank Telescope, Green Bank, West Virginia, (c) The Arecibo Radio Telescope, Arecibo, Puerto Rico and (d) The Leuschner 30”, Lafayette, California (interior left) and The Lick Nickel 40”, Mt. Hamilton, California (interior right).

Figure 3.10: Summary of the wavelength coverage of the 5 facilities to be used (from left to right: Lick-Nickel/Leuschner, the Infrared Spatial Interferometer, the Green Bank Telescope (GBT) and the Arecibo Observatory) are overlaid on a plot of atmospheric opacity. Gaps in coverage for the GBT and Arecibo indicate regions of spectrum not covered by available radio receivers at those facilities.
### Table 3.3: Figure Of Merit (FoM) for Radio SETI Surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sky Coverage (deg$^2$)</th>
<th>Bandwidth (MHz)</th>
<th>Sensitivity (W/m$^2$)</th>
<th>FoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen Telescope Array Galactic Plane Survey$^a$</td>
<td>20</td>
<td>300</td>
<td>$1 \times 10^{-23}$</td>
<td>1.3</td>
</tr>
<tr>
<td>GAVRT Prototype Galactic Plane Survey$^a$</td>
<td>1,560</td>
<td>100</td>
<td>$1 \times 10^{-22}$</td>
<td>1</td>
</tr>
<tr>
<td>GAVRT Planned Galactic Plane Survey$^a$</td>
<td>1,560</td>
<td>13,500</td>
<td>$1 \times 10^{-22}$</td>
<td>130</td>
</tr>
<tr>
<td>SETI@home II (our group)</td>
<td>14,000</td>
<td>2.5</td>
<td>$5 \times 10^{-26}$</td>
<td>20,000</td>
</tr>
<tr>
<td>SERENDIP V.v Commensal Sky Survey</td>
<td>2,000</td>
<td>200</td>
<td>$5 \times 10^{-25}$</td>
<td>7,000</td>
</tr>
<tr>
<td>Arecibo Commensal Sky Survey$^b$</td>
<td>14,000</td>
<td>300</td>
<td>$4 \times 10^{-26}$</td>
<td><strong>76,000</strong></td>
</tr>
<tr>
<td>GBT Commensal Sky Survey$^b$</td>
<td>35,000</td>
<td>500</td>
<td>$1 \times 10^{-24}$</td>
<td><strong>110,000</strong></td>
</tr>
</tbody>
</table>

$^a$Proposed, sensitivity estimates based upon available information  
$^b$Assumes complete sky coverage over 3 years
3.5. SUMMARY

Figure 3.11: The detectable range for an approximately Earth-like technology observed in the discussed experiments. Emissions in the radio assume an Arecibo Planetary Radar-like transmitter, 5MW continuous wave transmitting through an efficient 305m parabolic antenna, integrated coherently for 14 seconds. Optical/infrared emissions assume a Livermore National Ignition Facility-like transmitter, a sub-nanosecond 5MJ pulse focused with a Keck-like 10m mirror, using 3 detectors having a 10% quantum efficiency. Gaps at radio frequencies reflect the available radio receivers at each observatory.
Chapter 4

A 1.1 to 1.9 GHz SETI Survey of the Kepler Field: A Search for Narrow-band Emission from Select Targets

4.1 Introduction

We present a targeted search for narrow-band (< 5 Hz) drifting sinusoidal radio signals from 86 stars in the Kepler field hosting confirmed or candidate exoplanets. Radio emission less than 5 Hz in spectral extent is currently known to only arise from artificial sources. The stars searched were chosen based on the properties of their putative exoplanets, including stars hosting candidates with $T_{eq} > 380$ K, stars with 5 or more detected candidates or stars with a super-Earth ($R_p < 3R_\oplus$) in a > 50 day orbit. Baseband data across the entire band between 1.1 and 1.9 GHz were recorded at the Green Bank Telescope (Figure 4.1) in May 2011 and subsequently searched offline. No signals of extraterrestrial origin were found. We estimate that fewer than $\sim 1\%$ of transiting exoplanet systems are radio loud in narrow-band emission between 1–2 GHz at an equivalent isotropic radiated power of $\sim 1.5 \times 10^{21}$ erg s$^{-1}$, approximately five times the EIRP of the Arecibo Planetary Radar, and limit the the number of 1–2 GHz narrow-band-radio-loud Kardashev type II civilizations in the Milky Way to be $< 10^{-6} M_\odot^{-1}$. The remainder of this chapter is structured as follows; Section 4.2 describes our observing scheme and targets, Section 4.3 details our data reduction procedures, Section 4.4 explains our analysis and in Section 4.5 we review and summarize our results.

4.2 Observations

SETI observations were performed during the period February 2011 - April 2011 using the GBT L-band (1.1 - 1.9 GHz) receiver and the Green Bank Ultimate Pulsar Processor (GUPPI) digital backend (Demorest et al. 2012). The band 1200-1330 MHz was excluded
observations via a bandpass filter to suppress heavy aircraft radar interference contaminating this region. For this experiment, GUPPI was configured in a novel “baseband recording” mode in which an entire 800 MHz band is digitized, channelized to 3.125 MHz with a 256-point polyphase filterbank and written to disk as 2-bit voltage data for both X and Y linear polarizations. The total aggregate data rate in this mode is 800 MBps. In order to obtain the requisite disk recording rates, the data stream was distributed to GUPPI’s eight CPU/GPU computing nodes at 32 channels/node and eight 100 MHz bands were recorded separately. For the purposes of analysis, we have considered each 100 MHz band individually, hereafter Bands 0–7. This is primarily because early technical problems with the GUPPI backend resulted in some computing nodes failing to record data, thus causing some observations to have non-contiguous frequency coverage in 100 MHz increments (see Table 4.5).
performed using a cadence in which each target was observed interleaved with another target separated by $\Theta_{\text{min}} > 1^\circ$ such that each target was effectively observed with an on-source, off-source, on-source sequence with minimal overhead. This technique is crucial to discerning a true astronomical signal from ubiquitous interference from human technologies. Details of the parameters of our observations are presented in Table 4.1. The observations discussed here represent part of a larger 24 hour campaign to search for technologically produced radio emissions in the Kepler field, which included both targeted observations and a raster scan of the entire field. Additional work, in preparation, will discuss a narrow-band search of the raster scan data and pulse searches over both targeted and raster observations.

Table 4.1: Targeted Observation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency</td>
<td>$\nu_o$ 1500 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\Delta \nu$ 800 MHz $^a$</td>
</tr>
<tr>
<td>Beam Width (HPBW)</td>
<td>$\Theta$ 9$'$</td>
</tr>
<tr>
<td>System Temperature$^b$</td>
<td>$T_{\text{sys}}$ 20 K</td>
</tr>
<tr>
<td>Gain$^b$</td>
<td>$G$ 2.0 K/Jy</td>
</tr>
<tr>
<td>SEFD$^b$</td>
<td>$S_{\text{sys}}$ 10 Jy</td>
</tr>
<tr>
<td>Observation Time per Source$^b$</td>
<td>$t_{\text{obs}}$ 300 s</td>
</tr>
</tbody>
</table>

$^a$Excluding the band 1.2 to 1.33 GHz, see Section 4.2  
$^b$Nominal value

4.3 Data Reduction

To maximize the signal-to-noise of the detection of a distant CW transmitter the relative motion between the transmitter and receiver must be accounted for. As we have no a priori knowledge of the specific frequency of emission from an extraterrestrial technology, the overall Doppler shift in the received signal, dominated by the radial velocity of the source, is relatively unimportant for detection. However, the time rate of change of the Doppler shift, dominated by the orbital and rotational motions of the transmitter and receiver, must be considered to integrate $\sim$ Hz spectra over many seconds. The Doppler acceleration is given simply by

$$
\delta f = \frac{dV}{dt} \frac{f_{\text{rest}}}{c}
$$

(4.1)
where $\vec{V}$ is the line of sight relative velocity between receiver and source, $f_{\text{rest}}$ is the rest frequency of the transmitter and $c$ the speed of light. As a point of reference, the maximum contribution from the Earth’s orbital motion at 1 GHz is $\sim \pm 0.02 \text{ Hz s}^{-1}$, and from the Earth’s rotation is $\sim -0.1 \text{ Hz s}^{-1}$. If this effect is corrected for in power spectra, the worst-case minimum achievable spectral resolution for terrestrial observations is thus about $\Delta \nu = 0.3 \text{ Hz}$ (at 1 GHz). Channelization to any finer resolution would be ineffective as the received signal would be smeared over several channels. While the Doppler drift due to the Earth’s motion is known, the drift due to possible motion of the transmitter is largely unknown. For observations where $t_{\text{obs}} \delta f > \Delta \nu$, this necessitates searching various Doppler drift rates to achieve a $\sqrt{t_{\text{obs}}}$ increase in sensitivity. As an aside, an arbitrary Doppler drift can be removed exactly in the voltage domain, with no loss in sensitivity, via multiplication by an appropriate chirp function (Leigh 1998), but this technique is computationally infeasible for most blind searches, an exception being SETI@home (Korpela et al. 2002).

We accomplished a search for narrow-band features drifting at rates up to $\sim \pm 10 \text{ Hz/sec}$ using a modified form of the “tree” dedispersion algorithm, an algorithm originally developed for searching for dispersed pulsar signals (Taylor 1974). In much the same way that dispersed pulse searches seek to find power distributed along a quadratic curve in the time–frequency plane, a search for drifting sinusoids seeks to find approximately linearly drifting features in the same plane. The difference is simply one of the dimensions and orientation of the time–frequency matrix. The tree dedispersion algorithm accelerates these searches by taking advantage of the redundant computations involved in searching similar slopes, reducing the number of additions required from $n^2$ to $n \log_2 n$, where $n$ is equal to both the number of spectra and number of slopes searched. Figure 4.2 shows a diagram of the “tree deDoppler” algorithm implemented for the drifting sinusoid search, shown here for 4 power spectra each having $N$ frequency channels. The tree algorithm has fallen into disuse in the pulsar community due to the fact that it intrinsically sums only linear slopes, and modern broadband pulsar observations require an exact quadratic sum. In the case of Doppler drifting sinusoids, the linear approximation is very good and the algorithm is an excellent fit to the problem.

Our implementation of the “tree deDoppler” algorithm necessitates $2^m$ spectra and searches
2^m doppler drift rates out to a maximum drift rate of:

\[ D_{\text{max}} = (\Delta \nu)^2 \]

where \( \Delta \nu \) is the spectral resolution. The drift rate resolution is constrained to:

\[ \Delta D = \frac{\Delta \nu}{T_{\text{obs}}} \]

where \( T_{\text{obs}} \) is the total observing time. We performed three channelizations at resolutions ranging from 0.75 Hz to 2.98 Hz, giving the maximum drift rates and drift resolutions shown in Table 4.2.

<table>
<thead>
<tr>
<th>Spectral Resolution (Hz)</th>
<th>Drift Resolution (Hz/s)</th>
<th>Maximum Drift Rate (Hz/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.98</td>
<td>0.020</td>
<td>8.88</td>
</tr>
<tr>
<td>1.49</td>
<td>0.010</td>
<td>2.22</td>
</tr>
<tr>
<td>0.75</td>
<td>0.005</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Characteristic value, exact resolution depends on the specific duration of each observation.

Prior to Doppler searching, each 3.125 MHz polyphase channel was further channelized to \( \sim \) Hz resolution, detected and thresholded to search for narrow-band features. After detection, both polarizations were summed to form a single spectrum. Each high resolution spectrum constructed from individual polyphase channels was corrected for the filter response imposed by first stage (GUPPI) channelization by dividing through with a polynomial fit to an average bandpass. This polynomial fit bandpass was constructed a priori by fitting to a sum of many coarsely channelized spectra exhibiting low interference. All \( M \) spectra having length \( N \) from a single observation were then fit into a matrix sized to the nearest larger matrix having dimensions \( 2^m \times N \). Because we can assume that a narrow-band signal transmitted by an extraterrestrial technology will either be drifting due to acceleration in the host system or transmitted uncorrected for the Doppler acceleration at the receiving observatory, any narrow-band signal exhibiting no drift can be ruled out as likely coming from a terrestrial source. This concept is analogous to searches for pulsars in which sources exhibiting no dispersive sweep in their pulse profiles are likely pulsed terrestrial interference. The analogy allows us to again borrow from pulsar search techniques and apply a median filter for sources exhibiting no drift (See e.g. Eatough et al. 2009, Siemion et al. 2012). After dividing each spectral channel by its median value, the tree deDoppler algorithm was applied in-place. Each Doppler corrected spectrum was then collapsed in time and searched for
4.3. DATA REDUCTION

any summed spectral channel exceeding 25 standard deviations above the mean, assuming Gaussian statistics, with results inserted into a database. We use the term “detection” to refer to one measurement of a unique signal or emitter. Depending on source intensity, a single signal or emitter can be detected multiple times at different drift rates and bandwidths. The set of all detections for frequencies $\nu$, standard deviations $\sigma$, drift rates $\omega$ and bandwidths $\Delta \nu$ was searched to identify the detection having the largest $\sigma$ within each spectral window of width $\dot{f}_{\text{max}} T_{\text{obs}}$, and a time–frequency waterfall plot around this detection was extracted and stored with the corresponding database entry. We hereafter characterize each of the highest $\sigma$ detections as “candidate signals.” Ultimately we were left with approximately $3 \times 10^5$ candidate signals.

Although the ISM is relatively unobtrusive to narrow band radio signals, relative to e.g. interstellar dust on optical light, its effects are never-the-less important. The ISM has been considered in the context of SETI for some time, notably in Cordes & Lazio 1991, Cordes et al. 1997 and references therein, with the principal results being as follows. In the strong scattering regime, narrow band sinusoids experience limited spectral broadening due to scattering in the inhomogeneous interstellar plasma, with a bandwidth $\Delta \nu_{\text{broad}}$ equal to:

$$\Delta \nu_{\text{broad}} = 0.097 \text{ Hz } \nu_{\text{GHz}}^{-6/5} \left( \frac{V_\perp}{100} \right) \text{SM}^{3/5} \quad (4.4)$$

Where $V_\perp$ is the transverse velocity of the source in km/sec and SM the scattering measure, a measure of the electron density fluctuations along the line of sight:

$$\text{SM} = \int_0^L C_{ne}(z) dz \quad (4.5)$$

Further, intrinsically steady narrow-band signals can be modulated in intensity up to 100% by strong scattering in the inhomogeneous plasma, with a characteristic time scale $\Delta t_d$ equal to:

$$\Delta t_d = 3.3 \text{ s } \nu_{\text{GHz}}^{6/5} \left( \frac{V_\perp}{100} \right)^{-1} \text{SM}^{-3/5} \quad (4.6)$$

Taking values of the SM from the “NE2001” electron density model (Cordes & Lazio 2002) for a center-field Kepler star at 0.5 kpc and assuming a transverse velocity of 25 km/sec, we calculate $\Delta t_d \approx 3.5$ hrs and $\Delta \nu_{\text{broad}} = 20 \mu\text{Hz}$. For the parameters of this search, we can thus neglect spectral broadening and can assume a steady flux for any received signal over the course of our observing cadence. We note that the transition from strong to weak scattering in our observing band occurs at a distance of about 900 ly, putting many of our targets in the transition or weak scattering regimes. Although the expressions for $\Delta \nu$ and $\Delta t_d$ differ for these cases, the predicted effects are similarly negligible. A key result of Cordes & Lazio (1991) was the suggestion that searches for narrow-band emissions in the strong scattering regime would have an increased likelihood of detecting a source by observing a sky location multiple times spanning many $\Delta t_d$. Although this is an excellent strategy, the extra observing overhead associated with performing multiple on–off–on observation sequences didn’t permit it to be used here.
4.4 Analysis

The principal complication in the otherwise straightforward data reduction involved in a narrow-band SETI experiment is the fact that human radio technology produces copious narrow band emission at \( \sim \) Hz scales. The existence of radio frequency interference is not unique to SETI experiments, of course, and over the years many techniques have been developed to mitigate its effects. It is worth noting, however, that in radio observations of most astrophysical phenomena, narrow-band features in a power spectrum can be immediately flagged and discarded because they are known to originate with technology rather than the target of the observation. Narrow-band radio SETI experiments face the more difficult task of determining whether a narrow-band feature originates with a human technology or distant intelligent life.

Our strategy to mitigate terrestrial interference was to demand that a detected signal be both persistent and isolated on the celestial sphere. By observing in a on−off−on source cadence, we imposed this constraint by requiring that a given candidate signal be detected in both “on” source observations and not in the intervening “off” source observation. Observations in which one of the elements of the on−off−on cadence was not obtained due to technical problems were excluded completely. This technique was very effective, ruling out 99.96% of the candidate signals. Figure 4.3a shows a histogram of the number of detections vs. signal−to−noise ratio for all detections, the detections representing the most significant detection of a single signal and only those candidates passing the on−off−on automated interference excision algorithm. Figure 4.3b shows the number of detected signals as a function of topocentric frequency for the same detection groups. Time−frequency waterfall plots of the remaining 52 candidate signals were examined visually. Of these, 37 were ruled out immediately because candidates detected during pointings at many targets exhibited very similar modulation at nearby frequencies. For the remaining 15 signals, the entire database of detected signals was examined for detections at nearby frequencies, and the associated time−frequency waterfall plots were examined for similarity with the candidates. In all cases, signals detected during pointings at other targets were found that closely resembled the modulation and drift properties of the candidate signals. Figure 4.4 show two candidate signals that passed our initial on−off−on test, but were ruled out as interference based on their similar topocentric frequency and modulation. Figure 4.5 shows two candidate signals detected at different topocentric frequencies, but that were ruled out as interference based on similar bandwidths and modulation.
4.4. ANALYSIS

Figure 4.3: 4.3a Number of detections vs. signal to noise ratio for the set of all detections, the detections representing the most significant detection of a single signal and only those candidates passing an automated interference excision algorithm (See Section 4.4). 4.3b Number of detections vs. topocentric frequency for the same three sets. A region of spectrum between 1200—1330 MHz was excluded due to the presence of a strong interfering radar.
Figure 4.4: Waterfall plots showing narrow band emissions, all of which were determined to be interference based on similar topocentric frequency and modulation. The upper portion of each panel, in blue, shows intensity as a function of topocentric frequency and time and the lower portion of each panel shows a “Doppler-corrected spectrum” – a power spectrum for the entire observation formed by summing consecutive spectra at the drift rate indicated by the red diagonal. Panels 4.4a and 4.4b show detections of the interferer during two pointings on KOI 1192 separated by ∼380 s. Panels 4.4c and 4.4d show detections of a very similar interferer approximately 5 days later during two pointings on Kepler-30.
Figure 4.5: Waterfall plots showing narrow band emissions, all of which were determined to be interference based on similar bandwidth and modulation. See Figure 4.4 caption for plot descriptions. Panels 4.5a and 4.5b show detections of the interferer during two pointings on KOI 1199 separated by \( \sim 360 \) s. Panels 4.5c and 4.5d show detections of a very similar interferer approximately 1 hour later during two pointings on KOI 1372.
4.4. ANALYSIS

4.4.1 Sensitivity

From the radiometer equation, the minimum detectable flux, $F_i$, of a narrow-band signal detected in one polarization is given by\(^1\):

$$F_i = \sigma_{\text{thresh}} S_{\text{sys}} \sqrt{\frac{\Delta b}{t}} \quad (4.7)$$

Where $\sigma_{\text{thresh}}$ is the signal/noise threshold, $S_{\text{sys}}$ is the system equivalent flux density (SEFD) of the receiving telescope, $\Delta b$ is the spectral channel bandwidth and $t$ the integration time. Assuming a flat 10 Jy SEFD for the GBT’s L-band receiver, a characteristic sensitivity for the observations presented here is $\sim 2 \times 10^{-23}$ erg s$^{-1}$cm$^{-2}$ or $\sim 3$ Jy across a 0.75 Hz channel. A useful fiducial for considering the detectability of an extraterrestrial technology at radio wavelengths is the luminosity of the most powerful radio transmitter on Earth, the 5 megaWatt Arecibo Planetary Radar. At a frequency of 1.5 GHz, 5 MW transmitted off an efficient 305m parabolic dish results in an equivalent isotropic radiated power (EIRP) of approximately $L_{\text{AO}} \approx 3 \times 10^{20}$ erg s$^{-1}$. Coincidentally, $L_{\text{AO}}$ is approximately the same as the current average power use by all humans on the planet Earth (Gruenspecht 2010). At 0.5 kpc, such a transmitter beamed in the direction of Earth would have a total flux of about $10^{-24}$ erg s$^{-1}$cm$^{-2}$, placing our detectable limit at $\sim 5 L_{\text{AO}}$. Table 4.5 details total on-source times and sensitivities for all observed sources.

Figure 4.6 shows the range at which a transmitter similar to the Arecibo Planetary Radar ($\sim 5 \times 10^{13}$ erg s$^{-1}$ transmitted through a 305 m parabolic reflector) could be detected using the parameters of this experiment (150 second integrations, 0.75 Hz channelization) applied to all heterodyne receivers at the GBT. These limits also apply to an intrinsically uncertainty-limited broadband pulse having approximately 1000 times the total radiated energy, broadened assuming the “NE2001” ISM model (Cordes and Lazio, 2001) to $t = 0.17 \mu$sec with pulse bandwidth $= 800$ MHz centered on our observing band. Here we have used system temperature and gain values from the GBT Proposer’s Guide (Observatory 2012), neglected galactic synchrotron background and for frequencies above 15 GHz we assume a 50% weather quantile. We have assumed a 25 $\sigma$ detection threshold, as was used in the analysis described here. The approximate median distance to a $Kepler$ catalog star is also indicated. Although Figure 4.6 suggests higher frequencies might be preferred, the additional scheduling difficulties due to weather constraints and pointing correction overhead make lower frequency observations more tractable.

We use the Arecibo Planetary Radar example simply as a point of reference. While this transmitter is highly directional and the probability of interception is thus fairly low, observing systems in which the ecliptic plane is viewed edge-on increases the probability of detecting a radar used for local planetary system ranging and imaging. If we assume that an exo-Arecibo has a duty cycle similar to Earth’s, a characteristic ecliptic ($\pm 5^\circ$) illumination of about 100 hours/year (Perillat 2012), the overall probability of being in the radar beam

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\(^1\) Assuming the intrinsic received signal width is $< \Delta b$, the spectral channel bandwidth
4.5. DISCUSSION AND SUMMARY

Our search of 104 KOIs identified no evidence of advanced technology indicative of intelligent life. If we assume a low false positive rate for KOIs, in the simplest terms this result indicates that fewer than \( \sim 1\% \) of transiting exoplanet systems are radio loud in narrow-band emission between 1−2 GHz at the \( \sim 5 \, L_{\text{AO}} \) level. If we take the orbital inclination requirement for detection to be \( \pm 5^\circ \) and the total planet fraction to be \( \sim 15\% \) (Marcy & Howard 2011), we estimate that fewer than \( \sim 10^{-4} \) FGK stars are detectable via exoplanet orbital plane narrow-band emission in the same band and luminosity. For the GBT, this implies a surface density of \( < \sim 5 \times 10^{-2} \, \text{deg}^{-2} \) detectable sources. For the upcoming Square Kilometer Array, a facility that will be perhaps 100 times more sensitive than the GBT, the similar surface density of detectable sources is \( < \sim 100 \, \text{deg}^{-2} \) \((l = 0, b = 0; \text{ Robin et al. 2003})\).

Although the observations described here were part of a campaign targeting specific KOIs, the size of the telescope beam probed a much larger population of stars at a concomitantly higher luminosity limit. When probing advanced technology luminosities that represent a reasonable extrapolation of terrestrial technology, i.e. \( \approx \) Kardashev type I (Kardashev 1964), describing the target population and quantifying limits based on number of Sun-like stars or number of Earth-like planets is quite logical. However, when we begin to probe luminosities (and energy usage) that are many orders of magnitude larger than the Earth, our uncertainty during an observation is \( \sim 2 \times 10^{-8} \). While this figure is indeed low, it represents an order of magnitude improvement over an isotropic assumption.

4.5 Discussion and Summary

Figure 4.6: The range at which a transmitter similar to the Arecibo Planetary Radar \((\sim 5 \times 10^{13} \, \text{erg} \, \text{s}^{-1} \) transmitted through a 305 m parabolic reflector) could be detected using the parameters of this experiment \((150 \, \text{second integrations, 0.75 Hz channelization})\) applied to all heterodyne receivers at the GBT.
in the bounds of life in general render these measures inadequate. For large luminosities, the total stellar mass is a much more useful measure of the amount of energy-delivering capacity of a surveyed area. Integrating the GBT’s beam out to and encompassing the Milky Way’s halo stars (Gnedin et al. 2010), a characteristic total mass is $\sim 5 \times 10^3 M_\odot$. At 80 kpc, our sensitivity equates to an EIRP limit of $\sim 10^5 L_{AO}$, or approximately an order of magnitude larger than the total solar insolation incident on Earth. A civilization capable of truly isotropic emission at these power levels would likely be capable of harnessing greater amounts of energy from their parent sun than incident on their home planet, and thus would be approaching the Kardashev type II class. Taking our 86 observations as independent samples of a $\sim 5 \times 10^3 M_\odot$ column, we estimate the number of 1–2 GHz narrow-band-radio-loud Kardashev type II civilizations in the Milky Way to be $< 10^{-6} M_\odot^{-1}$.

Ultimately, experiments such as the one described here seek to firmly determine the number of other intelligent, communicative civilizations outside of Earth. However, in placing limits on the presence of intelligent life in the galaxy, we must very carefully qualify our limits with respect to the limitations of our experiment. In particular, we can offer no argument that an advanced, intelligent civilization necessarily produces narrow-band radio signals, either intentional or otherwise. Thus we are probing only a potential subset of such civilizations, where the size of the subset is difficult to estimate. The search for extraterrestrial intelligence is still in its infancy, and there is much parameter space left to explore. The exponential growth in semiconductor technology over the last decades has been an incredible boon to SETI experiments, allowing orders of magnitude improvements in spectral coverage. Within the next decade, we will have the ability to examine significantly larger portions of the electromagnetic spectrum, including instantaneous analysis of the entire 10 GHz of the terrestrial microwave window. In addition to radio searches, new technology will extend SETI into regions of the electromagnetic spectrum never before observed with high sensitivity (Siemion et al. 2011). Extending searches to encompass much larger classes of signals is crucial to producing robust and meaningful limits.
### Objects

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\(^a\)Objects in italic text were observed serendipitously with a primary target, see text. KOI 326, one of our original targets, has been omitted from the table as its single identified planet candidate was determined to be a false positive.

\(^b\)We exclude Band 1 here, as the band 1200-1330 MHz was not searched due to the presence of a bandpass filter used to mitigate heavy aircraft radar interference contaminating this region.

\(^c\)Peak sensitivity quoted for 0.75 Hz channelization

\(^d\) / 10\(^{-23}\)
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Chapter 5

A Search for Pulsars in the Central Parsecs of the Galaxy

5.1 Introduction

Pulsars orbiting near the Galactic Center (GC) could offer unprecedented insights into the properties and surroundings of its super massive black hole, but the nearest few yet discovered are between 10 and 15 arcminutes away, despite the expectation of a large population of neutron stars. This is understandable, as the environs of the GC region present significant challenges to pulsar discovery. Principal among them is the strong scattering due to the high electron densities present, manifested in temporal broadening of pulsar emission. As the broadened pulse length approaches the pulsar period, the periodicity in pulsar emission becomes nearly undetectable (See Figure 5.3). Extending searches to higher frequencies to reduce scattering are hampered by dramatic reductions in intrinsic flux, higher system temperatures and atmospheric opacity. However, recent instrumental advances have enabled some ground to be gained by increasing the bandwidth of pulsar spectrometers. This increase in bandwidth provides both increased sensitivity, as well as an enhanced ability to reject interference based on pulse dispersion. We are opportunistically combining novel digital spectrometer designs with nascent digital hardware, being assembled in support of the Green Bank Telescope’s new K and Ku band receivers, to conduct the most sensitive search for pulsars near the GC ever performed. Our observations consist of a 28 hour campaign, with observing time divided equally between the GBT K-band Focal Plane Array (KFPA) at 18–26 GHz and upgraded Ku receiver at 12–18 GHz. Observing in these two bands provides optimum sensitivity to both normal pulsars and “spun-up” recycled pulsars (Figure 5.5).
5.2 Background

5.2.1 Pulsars in the Galactic Center

Several lines of argument suggest that not only is there a large neutron star (NS) population in the GC, but many NS should be active radio pulsars. Ghez et al. (2008); Gillessen et al. (2009) show that the stellar cluster around Sgr A* consists mainly of early-type stars, whose short lifetimes ($\sim 10^7$ yr) mean that either massive star formation in the region is ongoing or that there was a starburst $\sim 6$ Myr ago. Stars with masses of 10–20 $M_\odot$ are NS progenitors, and the presence of a population of young massive stars near Sgr A* suggests that there must exist numerous NS as well. The time scales also work out for many of these NS to be active radio pulsars: radio emission of canonical $10^{12}$ G objects lasts for $\sim 100$ Myr, the time scale for spindown to lengthen spin periods past the “death line” of a few seconds.

Estimates of the supernova rate within 100 pc of Sgr A* based on the number of young stars in the region and on the heating of X-ray gas range from $10^{-3}$ to $10^{-2}$ yr$^{-1}$ and are consistent, after accounting for the fraction of supernovae that produce pulsars, with the number of point radio sources in the region that could be pulsars (Lazio & Cordes 2008). Such agreement is coarse but suggestive that there are $\sim 10^3$ to $10^4$ active pulsars in the region, of which about 200 to 2000 (20%) would be beamed toward the Earth. This estimate is consistent with recent discoveries of five long-period pulsars with large dispersion measures that place them in the GC region (Johnston et al. 2006; Deneva et al. 2009), most likely on the near side of the plasma-scattering region that angularly broadens Sgr A* and OH/IR masers (van Langevelde et al. 1992).

A population of “recycled” pulsars (i.e. NS spun up to millisecond periods by accretion) is also expected because the stellar density in the GC is large enough so that tidal capture and exchange reactions should occur as they do in globular clusters. Faucher-Giguere & Loeb (2010) posits that MSP–BH systems could be preferentially formed in the GC via 3-body interactions.

5.3 Probing the Galactic Center

The clocklike property of pulsars orbiting Sgr A* will provide unique probes of the spacetime, plasma and dark matter around the massive central BH (Paczynski & Trimble 1979; Wex et al. 1996; Pfahl & Loeb 2003). Together, the classical and relativistic orbital perturbations of pulse arrival times will allow the following:

1. Estimation of the smoothly distributed mass enclosed inside elliptical orbits that cause Newtonian precession; this mass can include stars and dark matter (Weinberg et al. 2005),

2. Strong constraints on the density of stars from two-body perturbations of pulsar orbits (Weinberg et al. 2005; Merritt et al. 2010).
3. Measurement of GR effects on stellar-mass binaries; these include apsidal motion, spin-axis precession, Shapiro delay, and frame dragging (Wex & Kopeikin 1999).

4. Measurement of GR effects on orbits of isolated pulsars (as well as binary pulsars) orbiting Sgr A*.

5. Usage of gravitational lensing to constrain the properties of the black hole in very strong gravity; lensing will produce multiple pulses, whose amplitudes and TOAs will constrain the geometry (e.g. Wang et al. 2009a,b).

6. Measurement of the spin and quadrupole moment of Sgr A* (Merritt et al. 2010). This likely requires finding objects that orbit inside 0.2 pc (Merritt et al. 2010).

7. Testing of the “no-hair” theorem for black holes (e.g. Will 2008; Merritt et al. 2010).

The measureability of these effects may be mutually exclusive in some objects, such as pulsars at distances $\gtrsim 0.5$ pc whose orbits are likely to be perturbed by stellar perturbations (Merritt et al. 2010). While such perturbations may spoil the measurement of GR effects, pulsars on more compact orbits will be cleaner.

5.3.1 Sensitivity

As discussed in Macquart et al. (2010) the optimum observing frequency for pulsars near the galactic center depends on the contrasting pressures of reduced flux from falling power law spectra at high frequencies and increased temporal broadening at lower frequencies. As illustrated in Figures 5.3 and 5.5, our observations are intended to provide maximum sensitivity to a broad range of pulsars, with the shortest observable periods governed by the scattering time in our high frequency band, $\sim 5$ ms at 22 GHz and the lowest luminosity bounded by decreased flux in our lower band, $\sim 7 \mu$Jy at 14 GHz. Our search represents a factor of 2 improvement in sensitivity over Macquart et al. (2010) for “normal” pulsars and is the first search at all sensitive to recycled pulsars in the GC. While a factor of 2 improvement is modest, the nature of the pulsar luminosity function is such that only a small improvement in sensitivity has a disproportionately large effect on increasing the observable fraction of the pulsar population, as pointed out in Macquart et al. (2010).

Based on the previous results of Macquart et al. (2010), who found a conservative upper limit of 500 pulsars in the GC, and assuming the log-normal luminosity function of Faucher-Giguère & Kaspi (2006), we have simulated how many pulsars we might expect to detect in this survey. Depending on the mean spectral index of the GC pulsars, the number could be as high as 13 in the 14 GHz search and 8 in the 22 GHz search. Although there are a number of assumptions implicit in this estimate, it is clear that these observations will improve significantly upon current constraints on the population, even in the event of a non-detection.
5.4 Observations

The first four hours of observations in our campaign were conducted in March of 2012 in parallel with testing of the GBT’s new facility spectrometer – VEGAS. VEGAS employs twenty 3 gigasample/sec 8 bit analog to digital converters (ADCs), 10 CASPER Reconfigurable Open Architecture Computing Hardware (ROACH) boards and 10 compute nodes to provide flexible multi-beam spectroscopy across a 1.25 GHz bandwidth in dual polarization on seven beams. Our group configured VEGAS in a wideband coarse resolution mode (Table 5.1), allowing us to cover an 8 GHz bandwidth on a single KFPA pixel and 3 GHz on a reference pixel. The sixteen available 1.25 GHz bandwidth IFs were apportioned to provide 7.5 GHz of coverage over one KFPA beam for on-source observations and 2.5 GHz of coverage across a second KFPA beam for reference observations.\(^a\) A 1024-channel polyphase filterbank (PFB) FPGA design was used to channelize each 1.25 GHz band and accumulate, packetize and transmit total power spectra to the KFPA spectrometer compute cluster. Total power spectra and observation metadata were incorporated on each compute node and output as a PSRFITS data product.

In low frequency (< ∼5 GHz) pulsar searches, the primary discriminant against terrestrial interference is the presence of quadratic dispersion expected in astronomical signals. However, recent searches for pulsars near Sgr A\(^*\) (Macquart et al. 2010) have specifically noted the difficulty in using this technique, despite the high dispersion measures associated with pulsars near the GC (∼1600 pc cm\(^{-3}\), Cordes & Lazio 2002, Figure 5.4). Even for the relatively larger bandwidths of our search (Table 5.1), a DM of 1600 pc cm\(^{-3}\) corresponds to a total time delay across the observing band of ∼17 ms at 14 GHz and only ∼7 ms at 22 GHz. Comparing these with the expected pulse broadening times for the same bands, ∼20 ms at 14 GHz and ∼5 ms at 22 GHz, it is apparent that dispersion provides much less distinction between broad band interferers and dispersed astronomical signals at high frequencies than at lower frequencies. Thus, an additional method to distinguish between interference and true signals is crucial to effectively identifying real sources. Because we know that a true astronomical signal will be present in only a single beam of a multi-beam receiver, or at the very least at a much higher S/N in one beam for a very bright source, reference beam data serves as an invaluable means of verifying candidate signals in the on-source beam.

Two bright pulsars, B0329+54 and B0355+55 were observed as test sources. These sources are known to be readily detectable at our sensitivities in both Ku and K bands (Kramer et al. 1997). Observations of these sources resulted in strong detections (Figures 5.1 and 5.2, providing a good indication that the VEGAS instrument and our analysis pipeline were operating as expected. The inferred flux densities of these pulsars match (Kramer et al. 1997) to within a factor of ∼2.

\(^a\) Beam 1 (to 4) of the KFPA provide the full 7.5 GHz RF bandwidth.
Figure 5.1: The bright pulsar B0329+54 as detected during VEGAS test observations at the GBT in March 2012. This plot produced by the pulsar search software PRESTO (Ransom 2001)
Figure 5.2: The bright pulsar B0355+54 as detected during VEGAS test observations at the GBT in March 2012. This plot produced by the pulsar search software PRESTO (Ransom 2001)
We also observed a recently discovered pulsar near the galactic center, J1746−2650I (Lazio & Cordes 1998), which has a measured spectral index of $\alpha = -0.3$ and inferred flux density at 14 and 22 GHz of 0.4 and 0.35 mJy, respectively. Based on these flux densities, this pulsar should have been detected at a SNR of around 100 in our observations, but it was not seen either folding on its own ephemeris or in a search. Lazio & Cordes (1998) noted the flat spectral index of this source and discussed the possibility that this very young pulsar could be a magnetar-pulsar transition object. As such, it is quite possible that either the intrinsic radio emission has ceased temporarily.

Figure 5.3: Scattering time versus distance along a line of sight toward Sgr A* and two adjacent lines of sight for 1 GHz (left) and 10 GHz (right).

5.5 Status

Data from our March 2012 observations are currently being searched for pulsed emission using both standard periodicity searches and single pulse techniques, including searching
5.5. STATUS

Figure 5.4: Dispersion measure vs. distance along a line of sight toward Sgr A* and two adjacent lines of sight. Known pulsars in the GC region (Johnston et al. 2006; Deneva et al. 2009) are indicated.

acceleration space for binary systems and pulsars in tight orbits around Sgr A*. In addition to standard pulsar search tools, our team is actively developing new algorithms to match the unique characteristics of our wide-band high-frequency observations. Experimental search techniques, e.g. Hough transform based approaches (Aulbert 2006), and novel RFI rejection strategies, e.g. the use of higher order statistics (Nita & Gary 2010), are being investigated as well. Data from closely spaced observations will be combined coherently for additional sensitivity.

For 14 GHz observations, the same digital hardware will be configured to sample four 3 GHz IF bands from both polarizations of the Ku two-beam receiver.\textsuperscript{b} We note that an effort is underway to upgrade the GBT Ku-band receiver to deliver additional bandwidth. If additional bandwidth becomes available, a tiled system similar to that devised for 22 GHz

\textsuperscript{b}The 3 gigasample/sec ADC boards used for the KFPA spectrometer can be interleaved to sample a single input at 6 gigasamples/sec, giving a 3 GHz Nyquist bandwidth.
Figure 5.5: $10\sigma$ detection limits for a $S_{1400}D^2 = 100$ mJy kpc$^2$ pulsar assuming a 6 hour integration and the survey parameters outlined in Table 5.1, as a function of period and spectral index. The dashed line indicates the $10\sigma$ threshold for a six hour search with a 800 MHz band centered at 14.8 GHz (Macquart et al. 2010). In “preferred” regions, a pulsar is detectable in both bands but a higher S/N is achieved at the indicated frequency.

observations could readily accommodate it. Table 5.1 summarizes spectrometer parameters.
Table 5.1: Survey Parameters

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* aIntra-channel dispersive smearing is negligible even for much larger channel widths, but the data rate for these channel widths is manageable and provides for more exacting interference excision.

* bAssumes 18° elevation, includes GC background (Reich et al. 1990) and atmospheric effects for 50% weather quantile (Maddalena 2011).

* cAssumes 10% duty cycle, 10h integration and summed polarizations.
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