Radio-Frequency Pulsar Observation using Small-Aperture Antennas

Ryan McKnight, Frank van Graas, *Ohio University*

BIOGRAPHY

Ryan McKnight is pursuing his Ph.D. in Electrical Engineering and Computer Science at Ohio University as part of the Avionics Engineering Center. His research interests include GNSS inter-constellation time offset determination and radio-frequency pulsar navigation and timing. He was previously involved with development and operations of the Bobcat-1 CubeSat. He received his B.S. in Electrical Engineering from Ohio University in 2019.

Frank van Graas holds an endowed Fritz J. and Dolores H. Russ Professorship in Electrical Engineering and Computer Science, and is a Principal Investigator with the Avionics Engineering Center at Ohio University. Dr. van Graas is a Past President of The Institute of Navigation (1998–1999) and served as the Institute of Navigation (ION) executive branch fellow at the Space Communications and Navigation Office, National Aeronautics and Space Administration, Washington, DC (2009). He is a fellow of the ION (2001) and received the ION Kepler (1996), Thurlow (2002), and Burka (2010) awards, as well as the American Institute of Aeronautics and Astronautics John Ruth Avionics Award (2010). He has been actively involved with navigation and timing research since 1984.

ABSTRACT

Recent research on pulsar based navigation and timing by organizations such as NASA and ESA has primarily focused on X-ray measurements as opposed to previous research which instead focused primarily on radio-frequency (RF) measurements. X-ray based systems offer the potential for greater accuracy than RF based systems and do not require the large antenna apertures historically considered to be necessary for adequate performance of an RF system. However, recent RF studies have suggested the feasibility of 1-10 microsecond timing performance using an antenna with an effective aperture on the order of 10 square meters, which is more optimistic than many previous results. This level of performance may be sufficient to prove useful for both terrestrial and space applications, particularly in deep space or even cislunar space where navigation and timing performance requirements are typically more relaxed. Such a radio-frequency based solution would not require the large, heavy, complex hardware required to receive X-ray signals and could be particularly advantageous for small spacecraft where size, weight, and cost are of higher concern.

This paper serves as a literature review of radio-frequency pulsar observation, timing, and navigation systems. It examines the theoretical relationship of system parameters such as antenna size, amplifier noise figure, observation time, and processing techniques to overall system signal-to-noise ratio (SNR) and measurement performance. It then details the design of a terrestrial experiment to observe pulsars in the radio-frequency band using two small-aperture observing stations and low-cost hardware with the goal of determining experimentally the minimum practical antenna size for radio-frequency pulsar measurements as a function of signal-to-noise ratio, measurement performance, and observation time. Additionally, experimental results of pulsar observations performed by amateur radio operators are discussed and used to provide context to the theoretical results.

I. INTRODUCTION

Pulsars are highly magnetized rotating neutron stars that emit high-energy beams of electromagnetic radiation [1]. As the pulsar rotates, this beam sweeps through space and can be observed at a large distance as a series of regular, short pulses. Hundreds of pulsars have been observed, each with their own unique rotational period and pulse characteristics. Typically, these rotational periods range from just a few milliseconds to several seconds. The pulses can be observed at a wide range of frequencies ranging from radio-frequency to X-ray bands, although the signal strength can be highly frequency-dependent.

The pulses are highly regular and stable over long periods of time, and certain pulsars have even been known to rival the stability of atomic clocks [2]. These properties have led to the development of many useful applications for pulsars, such as their use as scientific tools to aid the detection of gravitational waves [3]. Many studies have been performed on the use of pulsars as naturally-occurring beacons for timing and navigation purposes. For example, Fuhr [4] proposed the terrestrial use of pulsar signals as an alternative to GNSS for power grid timing purposes. For navigation purposes, most studies conclude that the attainable accuracy of a pulsar-based system would not prove very useful for terrestrial use. However, many authors have proposed the use of pulsars to navigate spacecraft in deep space or even cislunar space [5], where accuracy requirements for a useful system may be more relaxed.

Although pulsars emit very high levels of energy (on the order of 10^{17} J with each pulse [6]), they are typically found at distances of thousands of lightyears from Earth, resulting in very low observed power levels. On Earth, pulsars are primarily observed using large radio telescopes such as the 100 meter diameter Green Bank Telescope at the Green Bank Observatory in West Virginia. These radio telescopes play an important role in the discovery of new pulsars as well as the characterization of their stability and timing variations over time. When using small-aperture antennas, the low signal strength of pulsars requires their signals to be integrated over several hours to retrieve the pulsar timing information [7].

For spacecraft navigation purposes, the size and weight of a practical antenna antenna is highly constrained. While early studies of pulsars as navigation and timing aids focused on radio-frequency time-of-arrival (TOA) measurements [6], recent work by NASA [8] and ESA [9] has focused instead on X-ray measurements, due in large part to their advantages in terms of measurement accuracy using small-aperture antennas. However, recent radio-frequency studies such as those conducted by Tavares et al. [10] and Jessner [11] have shown feasibility of 1-10 microsecond timing performance using a relatively small antenna with an effective area on the order of 10 square meters. These results are more optimistic than previous results such as those given by Becker et al. [12], and support the idea that radio-frequency pulsars may be able to form the basis of a deep-space navigation and timing solution with reasonable antenna size requirements. Such a radio-frequency based solution would not require the large, heavy, complex hardware required to receive X-ray signals [8] and would be particularly advantageous for small spacecraft where size, weight, and cost are of higher concern.

In recent years, many members of the amateur radio community have taken an interest in pulsars. This has resulted in a proliferation of promising amateur observations in the radio-frequency bands using antenna types such as dish, Yagi, or corner reflector antennas with effective apertures as small as 1 square meter or lower and observation times on the order of a few hours. These amateur observations help to support some of the more optimistic results obtained by [10] and [11] and suggest that even relatively simple, low-cost hardware and small-aperture antennas are sufficient to observe pulsars in the radio-frequency bands. The hardware and antenna requirements may even be relaxed enough to enable the design of a pulsar experiment onboard a fast-moving low-Earth orbit satellite such as a CubeSat, where further improvements to navigation and timing performance may be feasible using advanced processing techniques based on space, time, and frequency domain processing.

This paper serves as a literature review of radio-frequency pulsar observation, timing, and navigation systems. It examines the theoretical relationship of system parameters such as antenna size, amplifier noise figure, observation time, and processing techniques to overall system signal-to-noise ratio and measurement performance. It then details the design of a terrestrial experiment to observe pulsars in the radio-frequency band using two small-aperture observing stations and low-cost hardware with the goal of determining experimentally the minimum practical antenna size for radio-frequency pulsar measurements as a function of signal-to-noise ratio, measurement performance, and observation time. Additionally, experimental results of pulsar observations performed by amateur radio operators are discussed and used to provide context to the theoretical results.

II. BACKGROUND

1. The Radiometer Equation for Pulsars

The radiometer equation is found in various forms and relates the minimum flux density that is detectable by a receiver to the parameters of the system. These parameters typically include system noise temperature, pre-detection bandwidth, integration time, and minimum detectable signal-to-noise ratio, among others. A simple form of the radiometer equation for pulsar observations is given by Bhattacharya [13] in terms of the observed signal-to-noise ratio:

$$\text{SNR} = \frac{SG\sqrt{n_\text{p}\Delta f \tau}}{T_\text{sys}}\frac{P}{W} \tag{1}$$

Where:

SNR is the observed signal-to-noise ratio (unitless)

S is the pulsar mean flux density (Jy)

G is the antenna gain (K/Jy)

n_p is the number (1 or 2) of orthogonal polarizations averaged (unitless)

Δf is the pre-detection bandwidth of the receiver (Hz)

τ is the post-detection integration time (s)

T_sys is the total system noise temperature (K)

P is the pulse period (s)

W is the width of a single pulse (s)

Of note is that the "post-detection integration time" τ used in this equation refers to the "boxcar averaging" of consecutive samples over a period of τ seconds, and is unrelated to the process of epoch folding (discussed later). Also of note is the use of the *jansky* (Jy) unit in the definitions of S and G. The jansky is a unit of spectral flux density that is commonly used in radio astronomy, where $1\,\mathrm{Jy} = 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$. The representation of antenna gain in units of $\mathrm{K/Jy}$ is also common to radio astronomy, and is defined as follows: [14, pg. 263]

$$G = A_\mathrm{e}/2k_\mathrm{B} \tag{2}$$

Where:

G is the antenna gain $(\mathrm{K/Jy})$

A_e is the effective aperture of the antenna (m^2)

k_B is the Boltzmann constant: $1.381 \times 10^{-23}\,\mathrm{J/K}$ or $1381\,\mathrm{Jy\,m^2/K}$

It is also important to note that the signal-to-noise ratio specified in Equation 1 is defined as the difference between the mean power level observed during the pulse "on-time" and the mean power level observed during the pulse "off-time" divided by the standard deviation of the observed power level during the "off-time":

$$\mathrm{SNR} = \frac{P_\mathrm{mean}(t = t_\mathrm{on}) - P_\mathrm{mean}(t = t_\mathrm{off})}{P_\mathrm{std}(t = t_\mathrm{off})} \tag{3}$$

Other forms of the radiometer equation sometimes use different methods of defining SNR.

2. Epoch Folding

When observing pulsars with small-aperture antennas, it is necessary to perform signal processing techniques such as *epoch folding* to increase the observed signal-to-noise ratio to a useful level [14]. Epoch folding is a process by which a long time series of observed data at a very low signal-to-noise ratio is processed to obtain a shorter time series with length equal to the pulsar period known as an *integrated pulse profile* which represents the average emission of the pulsar as a function of its pulse phase. The process involves first dividing the original time series of samples into a sequence of *records*, with each record containing the samples representing one pulse period. Each of these records are then further divided into a sequence of n_b equal-length *bins*, which are numbered 0 through $n_b - 1$. Finally, all samples which fall into an equally-numbered bin are averaged together, resulting in a time series containing n_b data points, with the data point in bin b representing the average emission of the pulsar at a pulse phase of $(b + 0.5)/n_b$, where pulse phase varies between 0 and 1.

To determine the effect of epoch folding on the pulsar radiometer equation [13], consider the reason that the signal-to-noise ratio in Equation 1 is proportional to the square root of the product of the integration time with the bandwidth. Integrating over a period of τ seconds is equivalent to taking the average of each set of $\tau\Delta f$ consecutive independent samples in the input series. This has no effect on the mean of the input series, but reduces its standard deviation by a factor of $\sqrt{\tau\Delta f}$, thereby increasing its signal-to-noise ratio by a factor of $\sqrt{\tau\Delta f}$ (see Equation 3). Similarly, the process of epoch folding N periods of data using n_b bins per period is equivalent to taking the average of $N(P/n_b)\Delta f$ independent samples, where P is the pulse period in seconds. Therefore $N(P/n_b)$ serves as the *effective integration time* τ_eff for folded data. This can be written in terms of the total observation time (referred to as t_int by many sources, although it has a different meaning than the integration time τ) by using the relation that $t_\mathrm{int} = NP$ such that $\tau_\mathrm{eff} = t_\mathrm{int}/n_b$.

The pulsar radiometer equation for folded observations can then be written as:

$$\mathrm{SNR} = \frac{SG\sqrt{n_\mathrm{p}\Delta f \tau_\mathrm{eff}}}{T_\mathrm{sys}}\frac{P}{W} = \frac{SG\sqrt{n_\mathrm{p}\Delta f}}{T_\mathrm{sys}}\frac{\sqrt{t_\mathrm{int}}}{\sqrt{n_b}}\frac{P}{W} \tag{4}$$

Where:

t_int is the total observation time (s)

n_b is the number of bins for epoch folding (unitless)

τ_eff is the effective integration time t_int/n_b (s)

Another form of the pulsar radiometer equation for folded observations is given in [14, pg. 265], and cited by many authors:

$$\text{SNR} = \frac{SG\sqrt{n_p \Delta f t_{\text{int}}}}{T_{\text{sys}}}\sqrt{\frac{P-W}{W}} \tag{5}$$

The difference between Equations 4 and 5 can be partially explained by the fact that Equation 5 uses a definition of signal-to-noise ratio [15] that differs slightly from the one given in Equation 3. However the larger difference is caused by the fact that Equation 5 contains the implicit assumption that each pulse period is divided into only two bins: one containing the entire on-pulse and another containing the entire off-pulse [13]. Therefore this equation represents the theoretical minimum limit for n_b resulting in the maximum possible signal-to-noise ratio as a function of bin size. However in actual practice it is difficult to reach this maximum for a variety of reasons, such as the fact that a real pulsar has a pulse shape that does not look like the theoretical "top-hat" pulse with a clearly defined on-pulse and off-pulse time. Additionally, the process of folding effectively reduces the bandwidth of the integrated pulse profile by a factor of $P\Delta f/n_b$. For timing purposes, it is therefore desirable to increase the number of bins in order to obtain better time resolution at the cost of lowering the overall signal-to-noise ratio. Therefore for many use cases Equation 4 is likely to give more realistic results. However, with the use of advanced processing techniques such as those described in [7] it may be possible to approach the signal-to-noise ratio performance of Equation 5 while maintaining adequate bandwidth for timing purposes.

3. System Noise Temperature

As shown by Equation 5, system noise temperature plays a very important role in the observed signal-to-noise ratio of the pulsar. Various methods of estimating this temperature exist, with a common method given by [14, pg. 263]:

$$T_{\text{sys}} = T_{\text{rec}} + T_{\text{spill}} + T_{\text{atm}} + T_{\text{sky}} \tag{6}$$

Where:

T_{sys} is the total system noise temperature (K)

T_{rec} is the receiver noise temperature (K)

T_{spill} is the spillover noise temperature (K)

T_{atm} is the atmospheric noise temperature (K)

T_{sky} is the sky background noise temperature (K)

The sky background noise temperature T_{sky} is a function of both observing frequency and the position of the pulsar on the celestial sphere. At $430\,\text{MHz}$, it can range from around $30\,\text{K}$ to nearly $800\,\text{K}$ depending on the direction of the pulsar in space while at $1400\,\text{MHz}$, its value is typically below 10–20 K. Datasets available from several sources can be used to estimate T_{sky} to varying degrees of accuracy [16]. The spillover noise temperature T_{spill} is a result of antenna side lobes or dish feed spillover and varies as a function of elevation angle, but is typically assumed to be less than $10\,\text{K}$. The atmospheric noise T_{atm} is typically ignored for observing frequencies below $5\,\text{GHz}$.

While T_{spill}, T_{atm}, and T_{sky} are largely fixed by the observing frequency and the direction of the pulsar, large improvements to T_{sys} and therefore signal-to-noise ratio can be realized by improving the receiver noise temperature T_{rec}. This temperature is calculated by the standard Friis formula:

$$T_{\text{rec}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots \tag{7}$$

Where T_1, T_2, $\cdots$ are the noise temperatures and G_1, G_2, $\cdots$ are the gains of each successive component of the receiver, respectively. Assuming the gain G_1 is relatively large, the value of T_{rec} is dominated by T_1, the noise temperature of the first component. Therefore in order to maximize signal-to-noise ratio it is crucial for the receiver to incorporate a high-quality low-noise amplifier (LNA) at the beginning of the signal path with sufficient gain to minimize the noise contributions of the other receiver components.

III. PREVIOUS WORK

1. Literature Review

The idea to navigate spacecraft using RF pulsar observations was proposed as early as 1974 by Downs [6]. This study detailed a system comprising of a receiver with an observation frequency of $200\,\mathrm{MHz}$ and a $200\,\mathrm{MHz}$ bandwidth using a matched filter to measure the incoming pulse. The total system noise temperature was estimated as $515\,\mathrm{K}$, with a contribution of $300\,\mathrm{K}$ from the receiver and $215\,\mathrm{K}$ from galactic sources. The study estimates that the position of a spacecraft could be determined after 24 hours of observation time to an accuracy of $1500\,\mathrm{km}$ using an omnidirectional antenna, or to $150\,\mathrm{km}$ using an antenna with a gain of $10\,\mathrm{dB}$ (equivalent to an effective aperture of $1.8\,\mathrm{m}^2$ at the observation frequency). The topic was later revisited by Sala et al. [17]. This study derives a sophisticated model of pulsar-based timing estimation for single pulsars and further develops this into a model of position estimation using a set of multiple pulsars. The model considers many factors including the properties of the pulsar signal profile such as pulse period, pulse width, and pulse shape, various parameters of the receiver and antenna system, and geometrical factors. According to the model, the TOA estimation error for a pulsar is given by the following equation:

$$\sigma_t = \frac{\gamma T_{\text{sys}}}{2\pi S G \sqrt{\Delta f t_{\text{int}}}} \tag{8}$$

Where:

σ_t is the TOA measurement error (s)

γ is a factor depending on the shape of the pulse

It then derives performance bounds used to analyze the feasibility of both X-ray- and RF-based systems. Using a receiver with a center frequency of $1000\,\mathrm{MHz}$ and a bandwidth of $200\,\mathrm{MHz}$, a system noise temperature of approximately 40–$50\,\mathrm{K}$ (with a contribution of approximately $30\,\mathrm{K}$ from a non-cooled receiver), and an antenna with an effective aperture of $10\,\mathrm{m}^2$, it determines that it is feasible to observe a set of pulsars resulting in a positioning accuracy better than $1000\,\mathrm{km}$ with an observation time of less than 1 hour. The significant improvement in needed observation time given by these results compared to those given by [6] is due the larger antenna aperture and lower system noise temperature used in the analysis. The more sophisticated model used by this study in fact results in a less optimistic prediction than would be obtained by applying the methodology of [6] to these improved receiver parameters.

Publications such as [18–20] began to shift much of the research on pulsar-based navigation systems towards using X-ray pulsars rather than RF, deeming the large antenna apertures and long observation times needed for acceptable RF performance to be impractical for most spacecraft. Becker et al. [12] found that detection of pulsars at an acceptable signal-to-noise ratio at one hour of observation time would require an antenna aperture of $342\,\mathrm{m}^2$, or $171\,\mathrm{m}^2$ for four hours of observation time. However these apertures were computed using by assuming values of $100\,\mathrm{MHz}$ for bandwidth, $100\,\mathrm{K}$ for system noise temperature, $2/10$ for the ratio W/P, and $10\,\mathrm{mJy}$ for average flux density. Aside from the noise temperature, these values are fairly conservative when considering the best available pulsars and modern RF hardware.

The use of advanced signal processing techniques [21] and modern digital and RF hardware featuring increasingly lower noise figures along with higher sampling rates and high-speed data processing capabilities may enable faster and more accurate measurements even with small antenna apertures [22]. Tavares et al. [10] analyzed a receiver system consisting of state-of-the-art RF technology with a bandwidth of $400\,\mathrm{MHz}$, an observation frequency of $1400\,\mathrm{MHz}$, and an uncooled receiver noise temperature of $100\,\mathrm{K}$ coupled to an antenna with an effective aperture of $10\,\mathrm{m}^2$. Following the same methodology as [17], they determined that a position accuracy of $10\,\mathrm{km}$ could be attained after an observation time of one day.

An alternative model of pulsar timing estimation is presented by Jessner [11]. This model states that the TOA estimation error of a pulsar can be determined by the following equation:

$$\sigma_t = \frac{T_{\text{sys}}}{SG\,(2\pi\ln 2)^{1/4}\,\sqrt{\Delta f t_{\text{int}}}}\sqrt{\frac{W^3}{2P}} \tag{9}$$

This equation has a similar structure to Equation 8, considering that both γ and $\sqrt{W^3/(2P)}$ are terms that depend on the properties of the pulse shape. Using this model, the study concludes that using an effective aperture of $90\,\mathrm{m}^2$, a center frequency of $540\,\mathrm{MHz}$, a bandwidth of $270\,\mathrm{MHz}$, and a receiver noise temperature of $100\,\mathrm{K}$, TOA measurements can achieve an accuracy of $3.3\,\mu\mathrm{s}$ (equivalent to $1\,\mathrm{km}$) after 1 hour of observation time. These results assume a typical flux density of $10\,\mathrm{mJy}$ and a W/P of $1/10$, which are fairly conservative estimates when considering the best available pulsars.

It is clear that as of yet there is no general consensus for the positioning or timing accuracy that may be achieved using a radio-frequency pulsar system. This accuracy is affected by a large number of factors including but not limited to effective antenna aperture, observation time, observation frequency, receiver bandwidth, receiver noise temperature, external noise sources, interference, pulse period, pulse shape, geometry of the pulsar set, digital processing techniques, knowledge of error sources, and external constraints such as limited antenna pointing accuracy. Any study theorizing the accuracy of such a system must necessarily make some assumptions about these factors, and the analysis often includes additional simplifying assumptions to reduce its complexity. These assumptions have a large effect on the theoretical accuracy of the system and account for most of the variation in results by different studies. Hecht et al. [23] propose the use of in-space experiments to provide a more concrete idea of the accuracy that may be achieved using a real-world system. Such experiments are necessary to better determine which assumptions about the system parameters are reasonable and demonstrate the validity of the theoretical models.

2. Amateur Observations

The increasing availability and performance of low-cost RF hardware in recent years has resulted in many successful detections of pulsars by amateur radio operators around the world. Amateur operator Steve Olney (VK2XV) maintains a website [24] containing a great deal of useful information for amateur radio astronomers, including a non-exhaustive list of successful amateur pulsar detections ordered by smallest antenna aperture. Most of these amateurs use setups consisting of low-cost commercial off-the-shelf or even homemade hardware and freely available open-source software. Many setups feature antennas with an effective aperture of 5 square meters or less.

Andrea Dell'Immagine (IW5BHY) [25] has been performing pulsar observations for many years with a variety of setups. One setup near Barga, Italy features a 3D corner reflector antenna with an effective aperture of approximately 2.5 square meters at a frequency of $422\,\mathrm{MHz}$ along with an LNA with a noise figure of approximately $0.3\,\mathrm{dB}$ and an RTL-SDR (software-defined radio) with a bandwidth of $2\,\mathrm{MHz}$. The total system noise temperature is estimated to be below $100\,\mathrm{K}$. The setup uses fixed pointing and therefore the total observation time is limited by the time it takes the pulsar under observation to sweep through the beamwidth of the antenna as the Earth rotates on its axis. Using this setup, he was able to detect the pulsar B0329+54 with less than three hours of observation time. Additionally, using an Airspy SDR and a receiver bandwidth of $10\,\mathrm{MHz}$, he was able to detect the pulsar B0950+08 in less than three hours. More recently, he has performed observations using an even smaller antenna, a double bi-quad with an effective aperture of approximately 0.8 square meters, also using fixed pointing. Using the same $0.3\,\mathrm{dB}$ noise figure LNA and the Airspy SDR he was able to again detect B0329+54 in under 3 hours of observation time.

Hannes Fasching (OE5JFL) [26] has detected B0329+54 at a frequency of $422\,\mathrm{MHz}$ with his setup in Austria using a 23-element Yagi antenna. The Yagi has an effective aperture of approximately 2.8 square meters and a fixed mount. Using an RTL-SDR with a bandwidth of $2\,\mathrm{MHz}$, he was easily able detect the pulsar in under 4 hours of observation time.

Amateur observations have also been performed at L-band. One such observation was performed by Wolfgang Herrmann using a 3-meter dish with an effective apertuere of $3.7\,\mathrm{m}^2$ [27]. In this frequency band, it is less practical to use a fixed pointing setup due to the smaller beamwidth of the antenna, and the dish setup is therefore mounted to a rotator system to track the pulsar across the sky. Using $50\,\mathrm{MHz}$ of bandwidth, he was able to detect B0329+54 in less than 3 hours of observation time.

These results, along with many others from the amateur community, are very encouraging. They demonstrate that it is in fact feasible to perform terrestrial pulsar observations using small antennas in a very reasonable time window, on the order of just a few hours. They help to provide credibility to some of the more optimistic results from the literature, such as those given by Tavares et al. [10].

IV. EXPERIMENT DESIGN

1. Motivation and Goals

As discussed in Section III, analysis of experimental data is necessary in order to validate models of the attainable accuracy by a radio pulsar timing and navigation system in real-world scenarios. Hecht et al. [23] propose two in-space experiments with the eventual goal of demonstrating independent position determination using pulsar timing data: an initial experiment using an existing space-based telescope [28] followed by a further experiment using a small satellite equipped with a large-aperture deployable antenna in a cislunar or deep space trajectory. This would allow for an experimental determination of the system specifications necessary to achieve useful timing and navigation performance.

This paper proposes the use of a terrestrial-based setup featuring a small-aperture antenna to demonstrate the observation of pulsars in the radio-frequency bands. The goal of the experiment is to determine the minimum antenna aperture and receiver specifications necessary to perform radio pulsar detections as a function of pulsar parameters, desired measurement performance, and observation time. The terrestrial nature of the experiment greatly simplifies its design and execution compared to an in-space experiment. Additionally, it allows for easy modification and adjustment of the experimental setup to support the development of future terrestrial experiments pertaining to pulsar detection, navigation, and timing. The results will be able to guide the development of these further terrestrial experiments as well as future in-space experiments, particularly for small satellites where constraints on size, weight, cost, and complexity can greatly limit the choice of receiver hardware and maximum practical antenna aperture.

2. Instrumentation

Ohio University maintains two existing stations with antenna setups that could be adapted for the reception of radio pulsars. The first station (Figure 1) is a $1.9\,\mathrm{m}$ diameter parabolic dish antenna with an L-band feed located at the Ohio University Airport in Albany, OH. It is primarily used for characterization and monitoring of GNSS signals. The second station (Figure 2) is the Bobcat-1 ground station, located on the roof of Stocker Center in Athens, OH. It is a dual-polarization setup consisting of two UHF-band $3\,\mathrm{m}$ long Yagi antennas and serves as the primary ground station for command, control, and data downlink of the Bobcat-1 CubeSat. At both stations, the antennas are mounted to SPID BIG-RAS/HR rotors allowing for full azimuth and elevation control via a SPID-MD01 rotator controller. Details about the two stations are found in [29–31]. Some relevant parameters of the antennas are summarized in Table 1.

Figure 1: $1.9\,\mathrm{m}$ diameter parabolic dish located at the Ohio University Airport in Albany, OH

Figure 2: Bobcat-1 ground station located on top of Stocker Center in Athens, OH

Table 1: Antenna specifications for the two receiver stations

Station	Antenna/Feed	Bandwidth	Effective Aperture $A_e = G_i\lambda^2/(4\pi)$	Beamwidth
Dish	RF HAMDESIGN $1.9\,\mathrm{m}$ mesh dish ANTCOM G8 Passive LHCP feed	1100–$1600\,\mathrm{MHz}$	$1.15\,\mathrm{m}^2$	$8°$ at $1400\,\mathrm{MHz}$
Yagi	M2 Antenna Systems 436CP30 (x2) $3\,\mathrm{m}$ long RHCP/LHCP Yagi	432–$440\,\mathrm{MHz}$	$1.33\,\mathrm{m}^2$	$30°$ at $436\,\mathrm{MHz}$

The plan for the initial experiment is to collect data using the setup illustrated in Figure 3. This setup is very similar to many of the setups that have been used for successful pulsar observations by amateur radio operators. After passing through a low-noise amplifier, the incoming signal from the antenna passes through a band-pass filter and is sampled by a software-defined radio. The SDR uses an internal GPS-disciplined oscillator (GPSDO) to provide frequency stability over long observation periods. The rotator controller is commanded by a MATLAB script that continuously computes the current azimuth and elevation angle of the pulsar and commands the rotator controller. A GNU Radio flowgraph is used to collect and process IQ samples from the SDR. The samples are separated into several discrete frequency channels, detected, integrated to reduce the data rate and stored to a file for later analysis. The incoming signal is also routed to a spectrum analyzer used to perform periodic radio-frequency interference (RFI) analysis.

In order to successfully detect pulsars, epoch folding must be performed for a sufficiently long observation time to raise the observed signal-to-noise ratio above a detection threshold, such as $10\,\mathrm{dB}$. Equation 5 is used to provide an upper bound to the observed SNR after folding. The contribution of the antenna and the receiving system to Equation 5 is directly observed in the parameters G, Δf, and T_{rec}. The gain G is fixed by the effective aperture of the antenna (see Table 1) via Equation 2. The maximum usable bandwidth Δf, which should be maximized to improve SNR, is constrained by the maximum bandwidth of the antenna, amplifier, and the SDR. The band-pass filter should be chosen such that it serves as the limiting factor for the bandwidth of the system. A high-selectivity filter with good stopband attenuation, such as a cavity filter, should be used in order

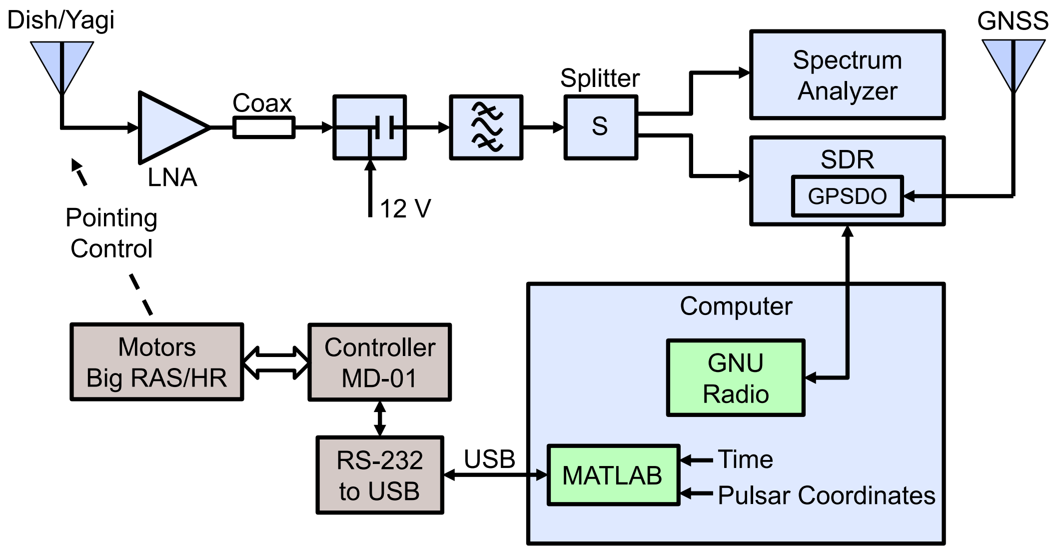

Figure 3: Basic components of a pulsar data collection system

to minimize RFI. By Equation 6, the receiver noise temperature T_{rec} directly contributes to the total system noise temperature T_{sys}. Equation 7 shows that T_{rec} is largely dominated by the noise figure and gain of the LNA. Therefore it is critical to select an LNA with noise figure as low as possible and sufficient gain to negate the noise contributions of the other components.

Table 2 lists some of the expected system specifications for each receiving station. The gain values are directly calculated from the effective aperture of the antennas using Equation 2. The receiver noise temperature has been estimated using specifications from commercially available low-cost hardware at the given observation frequency. The bandwidth is assumed to be equal to the maximum bandwidth of the limiting component of the receiver system. For the dish station, this is the bandwidth of the software defined radio used to sample the data, while for the Yagi station this is the bandwidth of the antenna itself. For both stations, a single polarization is assumed. A factor of $\sqrt{2}$ $(1.5\,\text{dB})$ improvement in SNR could be realized at the Yagi station by utilizing both antennas for dual-polarization measurements, but initial experiments will utilize only a single polarization for the sake of simplicity.

Table 2: Estimated receiver system specifications for each station

Station	f_{obs} (MHz)	A_e (m^2)	G (K/Jy)	T_{rec} (K)	Δf (MHz)
Dish	1420	1.15	4.15×10^{-4}	38.0	50
Yagi	436	1.33	4.83×10^{-4}	24.5	8

3. Pulsar Selection

Selection of pulsars to observe in the experiment is driven by two factors. The first factor to consider is the properties of the pulsar signal. There are four terms in Equation 5 that depend on the specific pulsar being observed: the mean flux density S, the pulse period P, the pulse width W, and the system noise temperature T_{sys} via the sky noise contribution T_{sky}. The values of S, T_{sky}, and to a lesser extent W are affected by the choice of observation frequency. While most pulsars are significantly brighter in the UHF band than in L-Band, the sky noise temperature is typically much higher at UHF. The second factor to consider is the location of the pulsar on the celestial sphere relative to the observing station, in particular its *declination angle* δ relative to the latitude φ of the observing station. Declination is analogous to latitude and is the angle formed between a vector pointing towards the pulsar and the plane of the Earth's equator [32, pg. 2-23]. This angle, along with the *right ascension* angle of the pulsar, which is analogous to longitude, can be used to calculate the elevation angle of the pulsar relative to an observing station located on the surface of the Earth at a given point in time. This elevation angle varies over the course of a day as the Earth rotates around its axis. In order to minimize terrestrial radio-frequency interference and atmospheric noise, observations of a pulsar are conducted only when its elevation relative to the observing station is above a chosen mask angle, such as 30°. It is therefore advantageous to observe pulsars located at a favorable declination angle which results in the pulsar being visible at high elevation angles for a large portion of each day. Published values of pulsar declination angles must be referenced to a specific time epoch, typically the J2000 epoch (January 1, 2000 at 12:00PM TT), since effects such as axial precession and nutation of the Earth's rotational axis result in the true declination angle slowly changing over time. Known equations are available to transform these reference values into values of true declination for the present day [33].

The Australia Telescope National Facility maintains an online pulsar catalog [34] containing various parameters for a large number of known pulsars, along with a website [35] that can be used to generate a list of pulsars matching specific criteria. The parameters available in the catalog include measured values of flux density at various observing frequencies, nominal pulse period, nominal pulse width, and declination angles referenced to the J2000 epoch. Using this data, a visibility analysis was performed to generate a list of all pulsars that can be observed above an elevation angle of 30 degrees from the two observing stations. Further analysis was then performed for all pulsars in this list using Equation 5 to determine the required observation time to detect the pulsar at a signal-to-noise ratio of $10\,\mathrm{dB}$ at each observing station, assuming the parameters listed in Table 2. To calculate T_{sys}, the values of T_{spill} and T_{atm} were assumed to be $10\,\mathrm{K}$ and $0\,\mathrm{K}$, respectively. T_{sky} was individually calculated for each pulsar at both observation frequencies using the global sky model datasets and software developed by De Oliveira-Costa et al. [36], including a $2.725\,\mathrm{K}$ contribution from the cosmic microwave background. Results describing the six best observation candidates at each station are listed in Tables 3 and 4.

Table 3: Best pulsar candidates for observation from the parabolic dish station at $1420\,\mathrm{MHz}$

Pulsar Name (B1950)	S_{1420} (mJy)	P_0 (s)	W_{50} (ms)	T_{sky} (K)	T_{sys} (K)	Daily Visibility at 39°N Latitude (hr)	Observation Time for SNR $= 10\,\mathrm{dB}$ (hr)
B0329+54	198.4	0.715	6.6	4.3	52.3	12.33	2.08
B0950+08	98.2	0.253	8.9	3.2	51.3	7.58	32.01
B1933+16	56.9	0.359	6.0	5.7	53.7	8.58	48.93
B2045-16	21.5	1.962	9.8	3.7	51.7	3.50	93.69
B1133+16	19.6	1.188	5.9	3.4	51.4	8.50	110.69
B1642-03	24.8	0.388	3.4	4.1	52.1	6.25	125.46

Table 4: Best pulsar candidates for observation from the Bobcat-1 ground station at $436\,\mathrm{MHz}$

Pulsar Name (B1950)	S_{436} (mJy)	P_0 (s)	W_{50} (ms)	T_{sky} (K)	T_{sys} (K)	Daily Visibility at 39°N Latitude (hr)	Observation Time for SNR $= 10\,\mathrm{dB}$ (hr)
B0329+54	1306.8	0.715	6.6	41.0	75.5	12.33	0.46
B1133+16	225.8	1.188	5.9	18.5	52.9	8.50	4.08
B1642-03	314.1	0.388	3.4	36.4	70.9	6.25	6.69
B0950+08	357.6	0.253	8.9	15.6	50.1	7.58	10.62
B2045-16	100.2	1.962	9.8	26.4	60.9	3.50	27.53
B2016+28	257.5	0.558	14.9	48.2	82.6	9.67	41.99

It is clear from the analysis that B0329+54 is an ideal candidate for initial experiments, as its high flux density compared to the other pulsars results in much shorter observation times needed to reach the $10\,\mathrm{dB}$ threshold. Additionally, its high declination angle results in large time intervals spent above the 30 degree elevation mask angle. For the Yagi station, there are two additional pulsars that appear to be good candidates: B1133+16 and B1642-03, while at the dish station the second best pulsar would require 32 hours of observation time to reach an SNR of $10\,\mathrm{dB}$. Although the dish station has a much higher bandwidth and lower values of T_{sky} compared to the Yagi station, this is not enough to overcome the low flux densities found in L-Band. The observation of additional pulsars at this station may require the use of a replacement dish feed to lower the observation frequency enough to observe higher flux densities.

V. CONCLUSIONS AND FUTURE WORK

While many authors [6, 10–12, 17–22] have examined the feasibility of radio pulsar navigation and timing systems, there is not yet a clear consensus as to the required system parameters needed to achieve a useful level of performance. Perhaps the most important of these parameters to consider, especially for in-space applications, are effective antenna aperture and receiver noise temperature. By practically any model of performance, both of these parameters have a direct influence on the upper bound for the time of arrival measurement error of a system while often being bound by strict constraints in a realistic system subject to limits on size, weight, complexity, and cost. Despite the considerable variation in estimated system performance found in the literature, there is widespread support for the idea that a radio pulsar system will at a minimum be able to provide some level of useful positioning and timing knowledge. Experimental studies allow for the demonstration and concrete analysis of a real, practical system. While it would be ideal to perform in-space experiments to demonstrate the performance of a positioning and timing system under the same conditions as the most commonly theorized use cases, the inherent cost and complexity of designing such an experiment makes terrestrial experiments an attractive option for initial studies. The results of these terrestrial experiments can then be used to inform the design of future in-space studies.

This paper considers the first steps towards an experimental study of radio-frequency pulsar measurement by a terrestrial system. Further software work is required to implement the algorithms necessary to recover the pulsar signal from below the noise floor. Preliminary analysis, however, appears to show that these observations will be feasible for at least the strongest available pulsars using existing antenna setups at Ohio University. Future modifications to these setups such as improved RF hardware and architecture, new antenna feeds, and improved data processing capabilities may enable the observation of additional pulsars. Although further work is necessary to ensure that the calculated system specifications are actually achieved in practice, existing results from the amateur radio community [24–27] help to provide confidence that the calculated values are reasonable. Validation of the correct characterization of the system performance is an important first step towards the study of system measurement accuracy.

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