Radio Frequency Pulsar Signal Simulator

João Santos, Gonçalo Tavares, Jorge Fernandes, Diogo Brito
INESC-ID / Instituto Superior Técnico - TU Lisbon, Portugal
Email: joao.carlos.palma.santos@gmail.com, {goncalo.tavares,jorge.fernandes,diogo.brito}@inesd-id.pt

***Abstract*—Pulsars are subject of research by agencies such as NASA, ESA, and others, to study gravitational waves, the cosmos itself, deep-space, plane localization methods and other topics. This paper approaches the characteristics of the signals emitted by these objects and implements a prototype that generates a signal resembling the signals emitted by pulsars, a pulsar simulator. This prototype can be used to test pulsar signal receivers in real time, since testing them with real signals is inconvenient given the interferences they are subject until reaching Earth.**

The design and implementation of the electronic system of the prototype, and its results are all reported in this thesis. The pulsar simulator is composed of several blocks, namely, a profile generator, noise generators, mixers and adders, all of which are essential to obtain the desired signal. The constructed prototype simulates three different pulsar signals, in real time, is portable, and is capable of adjusting the Signal to Noise Ratio (SNR) and bandwidth of the generated signals, as desired.

I. Introduction

Pulsar are highly magnetized rotating neutron stars which emit a very wide electromagnetic radiation [1], that scatters throughout the universe, [2]. They have great rotational speed and a very strong magnetic field, thus emitting an electromagnetic beam, thus emitting light in short periods of time, similar to a lighthouse. Fig. 1, from [1], illustrates the basic structure of a pulsar.

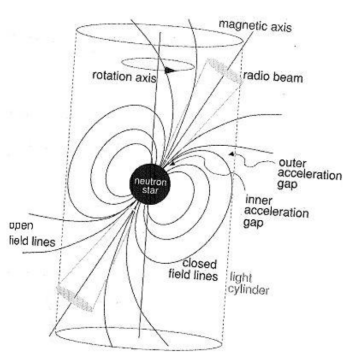

Fig. 1: Basic structure of a pulsar [1]

Space agencies such as ESA, NASA and other institutions have investigated these objects, their characteristics, variety and how they may contribute to humanity. Today, more than a thousand pulsars are known and new ones are being discovered everyday. For instance, pulsars are commonly used to study gravitational waves. Also, the PulsarPlane project investigates the possibility of a navigation system inside the Earth's atmosphere using signals from millisecond radio pulsars [3].

In the PulsarPlane project, the feasibility for a navigation method based in acquiring the signals emitted by a few pulsars, and thus identify a plane's location was evaluated [4]. Even though these receivers are purposely designed to acquire these signals they can't be properly tested with actual pulsar signals while on earth due to several factors, such as distance, Radio-frequency interferences, and the Earth's atmosphere [3].

These receivers could be tested with a source capable of producing a signal with the same characteristics as pulsar signals, in other words, they could be tested by a pulsar simulator, which hasn't been developed so far. This also brings the opportunity to study new tools of simulation based on signal processing, new and improved architectures of generators, a way to test receivers anywhere, and in real time, and even to generate pulsar data without allocating slots in radio telescopes.

The aim of this work is to successfully implement a pulsar simulator prototype that will serve to test pulsar receiver systems. The pulsar simulator must have several adjustable parameters, that will be discussed further. Furthermore, it must be a portable system and perform a real time simulation.

The deployed system is an analogue system, mainly because of the fact that it can output signals with wider ranges of frequency than a digital system since the last one would be dependant of the bandwidth of a converting component, such as a Digital to Analogue Converter (DAC).

This extended abstract is divided in six sections. The first section introduces the pulsar simulator, its background, motivation, objectives and the structure of this paper. Section II formulates the problem, specifying the characteristics of pulsar signals and establishes a bond between these characteristics and the design of the pulsar simulator. Section III approaches the employment of the pulsar simulator system. Section IV approaches the system's results. Section V the conclusions of the work are summarized. And finally, in section VI the acknowledgements are given.

II. Pulsar Signals

The signal emitted by pulsars has a broadband electromagnetic radiation from radio (that can range from a few kHz to a few hundred GHz) to X and γ-ray frequencies (that can range from dozens of PHz to dozens of EHz). Each pulsar has an individual signature, its pulse, which has a particular shape and period [1].

The pulsar signal $s_p(t)$ corresponds to a random signal with time-varying statistics, at the pulsar's location, and can be expressed as Eq. 1.

$$s_p(t) = a(t) \cdot p_{rot}(t) = a(t) \cdot \sum_{n=-\infty}^{\infty} p(t - nT_p) \qquad (1)$$

where $a(t)$ is the pulsar intrinsic random process due to the synchrotron emission, which is wideband, and modeled as a zero-mean real Gaussian, stationary, correlated noise process, with autocorrelation $R_a(\tau)$; $p_{rot}(t)$ is a periodic (deterministic) signal that results from the pulsar rotation with period T_p. Consequently, the process $s_p(t)$ is cyclostationary, i.e., its statistical moments are periodic with period T_p. Signals $s_p(t)$ and $p_{rot}(t)$ are represented in Fig. 2.

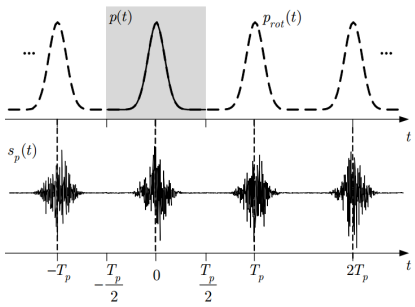

Fig. 2: Graphics of mathematical model of s_p and p_{rot} signals [5]

The power spectrum of the $a(t)$ process is $S_a(f)$, determined by the Fourier transform of $R_a(\tau)$, which presents energy from dozens of MHz to several GHz.

Pulsar profiles have a very precise period. Even though the profile itself may vary slightly from period to period, the actual profile can be obtained by averaging the pulsar signal. Consequently, a pulsar profile can be traced back to its correspondent pulsar, even if the received signal contains noise or a mixture of several pulsar signals, by means of correlation [5].

The Australia Telescope National Facility (ATNF) database contains all the parameters necessary to characterize a pulsar [6], and thus be a tool to simulate and parametrize the signal that will be generated by the pulsar simulator.

In order to do this the pulsar simulator must generate the required data and convert it to an analogue signal.

The received power of a pulsar i is given by Eq. 2.

$$S_r(i) = \alpha A_e 10^{-26} S_p^i \left(\frac{f_{rec}}{f_{ref}}\right)^{\beta_p^i} B \qquad [[W]] \tag{2}$$

where α is the polarization parameter of an antenna ranging between $]0,1[$; A_e (m^2) is the effective area of the receiver antenna; S_p^i (Jy) is the pulsar flux measured for a reference frequency, f_{ref} (GHz); β_p is the pulsar spectral index; f_{rec} (GHz) is the receiver (observation) frequency and B (GHz) is the receiver bandwidth. The quantity $10^{-26} S_p^i \frac{f_{rec}}{f_{ref}}^{\beta_p^i}$ is the pulsar flux at the receiver central frequency f_{rec}, expressed in W / Hz^{-1} / m^2. In any case, for the purpose of simulating a pulsar signal the only parameters that matter are the $10^{-26} S_p^i \frac{f_{rec}}{f_{ref}}^{\beta_p^i}$ and the bandwidth B, which will affect the magnitude and bandwidth of the generated signal.

The pulsar profile was defined by the multiplication of the signals generated in a block that uses the ATNF data to generate the shape of a pulsar profile and in another block that establishes the magnitude and bandwidth of the signal (without affecting the profile).

A pulsar signal is not free of noise. So the total pulsar signal is described as Eq. 3.

$$s_{p_{total}}(t) = s_p(t) + n(t) \tag{3}$$

where $s_p(t)$ is the pulsar signal and $n(t)$ is the added noise. The added noise is Gaussian because no matter how intense the noise is the fact that it is Gaussian makes it possible to always recover the pulsar signal $s_p(t)$.

The power of $n(t)$, which is added to the original pulsar signal and originated from several sources, is given by Eq. 4.

$$N_i = k_B(T_{rec} + T_{back} + T_{gal} + T_{sol})B \qquad [\mathrm{W}] \tag{4}$$

where $k_B = 1.3806488 \cdot 10^{-23}$ J/K is the Boltzmann constant; T_{rec} (K) is the receiver noise temperature. $T_{back} = 2.7$ K is the background cosmic noise temperature; $T_{gal} \approx 6 f_{rec}^{-2.2}$ (K) is the background noise temperature from the galaxy; $T_{sol} = (72 f_{rec} + 0.058) A_e 10^{A_{sl}/10} d^{-2}$ (K) is the solar system noise temperature with the contributions from the Sun and also from Jupiter. The parameter d (au) is the distance from the observation location to the Sun and A_{sl} (dB) is the antenna main side lobe attenuation. A quiet Sun is considered since during solar storms, the solar noise temperature increases dramatically (up to 250 times) and will render pulsar navigation infeasible.

In order to add noise to the pulsar signal a second noise generator is added to the system.

From Eq. 2 and Eq. 4 the SNR formula, when detecting the pulsar i, can be obtained as Eq. 5.

$$SNR_i = \frac{S_r(i)}{N_i} = \frac{\alpha A_e 10^{-26} S_p^i \left(\frac{f_{rec}}{f_{ref}}\right)^{\beta_p^i}}{k_B(T_{rec} + T_{back} + T_{gal} + T_{sol})B} \qquad [\mathrm{dB}] \tag{5}$$

The pulsar simulator should feature a programmable SNR. In order do to this, either the power of the pulsar signal $s_p(t)$ or the added noise power of $n(t)$ must be adjusted, preferably both of them should be adjustable.

III. Implementation

A diagram of the architecture of the pulsar simulator is presented in Fig. 3.

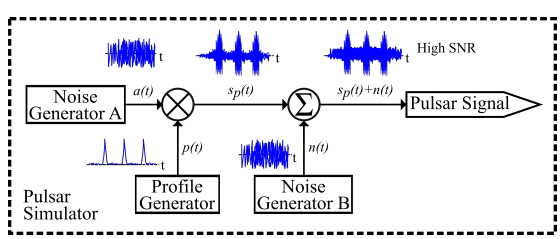

Fig. 3: Diagram of the pulsar simulator's architecture.

As shown in 3, the prototype contains two noise generators, one profile generator, a mixer and an adder.

The noise generators, the mixer and adder blocks were implemented in Printed Circuit Boards (PCB). The profile

generator system was programmed and assembled. In the end, the blocks were all connected accordingly, thus implementing the pulsar simulator system.

To implement the profile generator a PIC16F18855 development board was used. This PIC accommodates an external peripheral, in this case the DAC2Click, where Linear Technologies's LTC2601 is incorporated. This set of components provides storage, processing and conversion, as required. Additionally, a reconstruction low-pass filter was introduced in the profile generator, to smooth the output signal of the DAC. This block generates three different pulsar profiles allowing the user to shift between profiles, by a press of a push button. The final diagram of the implemented profile generator is illustrated in Fig. 4.

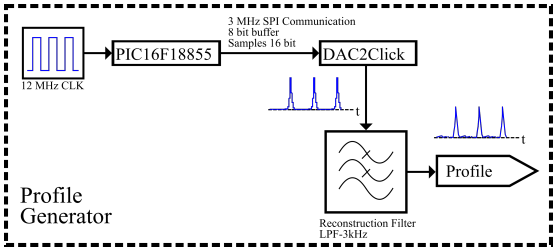

Fig. 4: Diagram of the profile generator

To implement the noise generators an architecture that uses a Zener diode to generate noise wideband Gaussian noise. This block can choose between two different diodes, the 1N756A and the CZRU52C8V2-HF to generate noise. It has an amplification chain consisted of 3 Low Noise Amplifiers (LNA) and a Variable Gain Amplifier (VGA) that controls the magnitude of the generated noise, obtaining a gain of 40 to 80 and a bandwidth of 800 MHz. Finally, it can choose between three different filters, two pass-band filters and a low-pass filter.

A diagram of the noise generator is portrayed in Fig. 5.

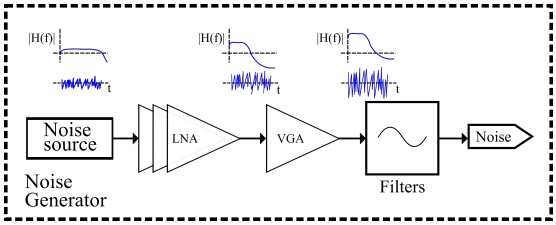

Fig. 5: Diagram of the noise generator.

Once the block's schematic was determined the PCB's layout was designed.

The layout of the noise generator is illustrated in Fig. 6.

The used mixer and adder block was already implemented. It is composed of several components, but most importantly by ADL5391, which performs the required multiplication and addition.

IV. Results

To make sure the profile generator is correctly implemented the generated profiles were observed and measured. Fig. 7 illustrates the profiles generated by the profile generator, profiles of pulsars B0540+23, B1356-60 and B1600-49.

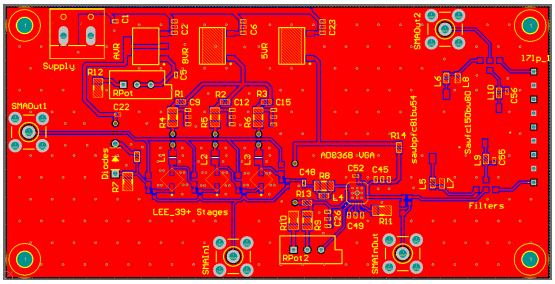

Fig. 6: Layout of the noise generator's PCB.

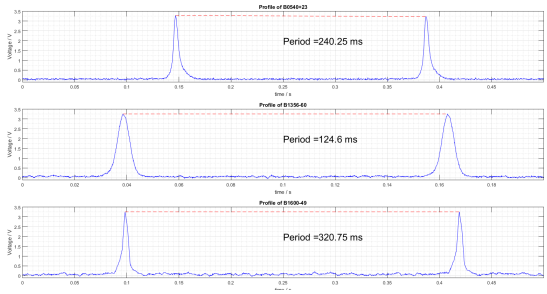

Fig. 7: Generated profiles.

Its possible to obtain the real profiles of the B0540+23, B1356-60 and B1600-49 pulsars thanks to the ATNF database. The actual profiles of these pulsars are represented in Fig. 8.

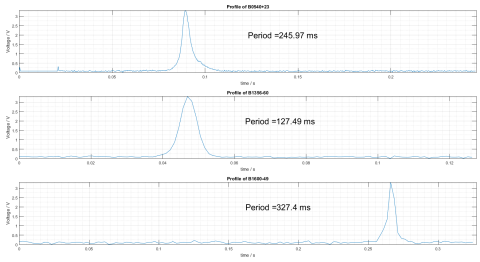

Fig. 8: Real profiles of the generated profiles.

The presented profiles seem to resemble real profiles. Calculating the period's error in percentage, given by $\frac{|P_{Real}-P_{Gen}|}{P_{Real}} \times 100\%$, the obtained period errors are 2.33 %, 2.27 % and 2.03 %, respectively. The actual profiles period are less than 2.5 % larger than the generated profiles which is a very small difference.

The results of the profile generator are solid, since it performs as expected and as intended, thus successfully generating a signal corresponding to the $p(t)$ signal.

Measurements were performed to the noise generators. The measurement of the generated noise, both in time and frequency, for maximum gain, are presented in Fig. 9.

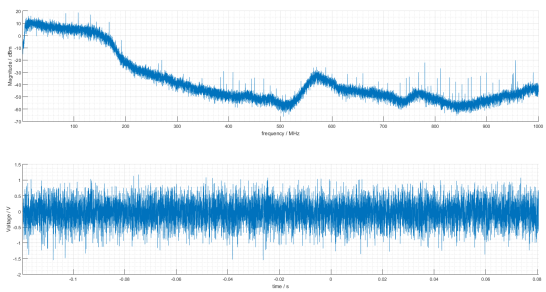

Fig. 9: Generated noise's measurement in time and frequency for maximum gain.

The measurement of the generated noise, both in time and frequency, for minimum gain, are presented in Fig. 10.

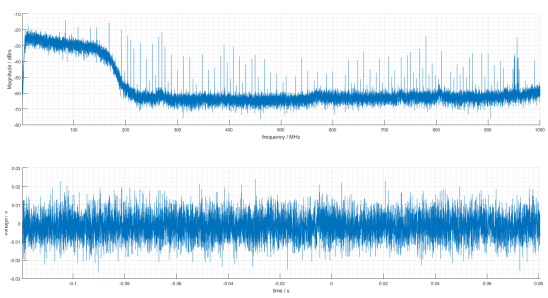

Fig. 10: Generated noise's measurement in time and frequency for minimum gain.

In conclusion, given the obtained results featured in Figs. 9 and 10, the noise has a magnitude ranging between, around, -30 and 10 dBm and a bandwidth of about 170 MHz.

The spectrum of the generated noise when filtered by a low pass filter of of 150 MHz, was measured, and is presented in Fig. 11.

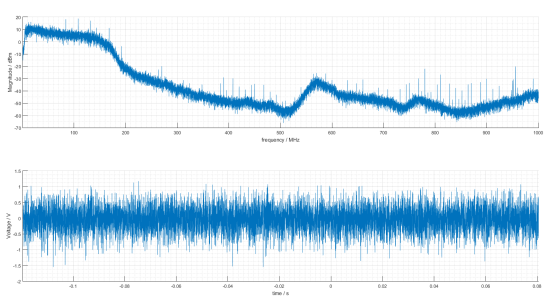

Fig. 11: Generated noise filtered by a LPF of 150 MHz.

As it can be seen there isn't much difference between the unfiltered noise illustrated in Fig. 9 and the filtered noise illustrated in Fig. 11.

The histogram of the previous generated noise was performed and is presented in Fig. 12. The histogram has 21 bins with a 0.3539 width.

The voltage's mean and standard deviation are -0.0328 and 0.38092, respectively. The histogram of the generated noise

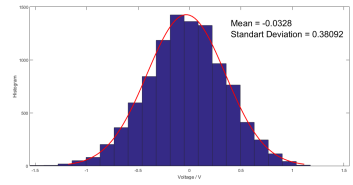

Fig. 12: Histogram of generated noise.

corresponds to a Gaussian distribution, thus proving that the generated noise is Gaussian.

Even though the bandwidth of the generated noise was lower than expected, considering the project's budget and time, overall, the results of the noise generator were satisfactory, and all the goals of the noise generator were met.

The results of the generation of the pulsar signal $s_p(t)$, that resulted from the multiplication of the profile and Gaussian noise are presented in Fig. 13, that illustrates the B0540+23, B1356-60 and B1600-49 pulsars signals.

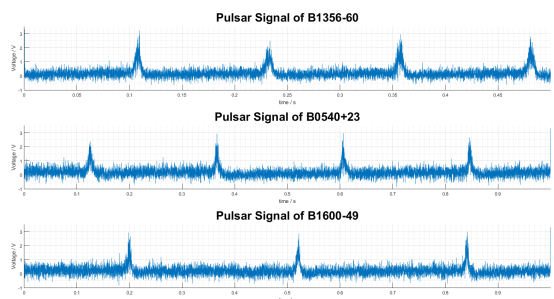

Fig. 13: Generated pulsar signals.

The signals correspond to the expectations, they resemble a peak of noise where the profile's peak used to be.

Now proceeding to the addition of Gaussian noise $n(t)$, Fig. 14 shows the measurement of the output of the mixer and adder block, when adding high magnitude and low magnitude noise, to the pulsar signal of B0540+23. This output also corresponds to the output signal of the pulsar simulator system.

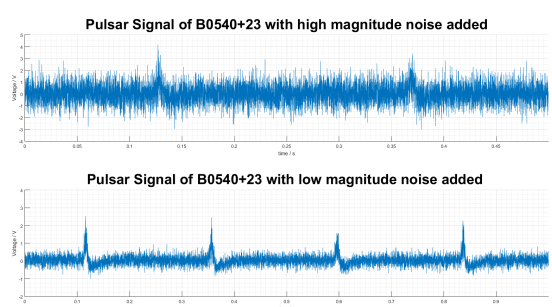

Fig. 14: Generation of B0540+23 pulsar signal with high and low magnitude noises added.

As it can be seen by Fig. 14 the pulsar simulator has a large SNR adjustment. To measure the SNR range, another measurement was performed. Fig. 15 presents the spectrum and power of the pulsar signal $s_p(t)$

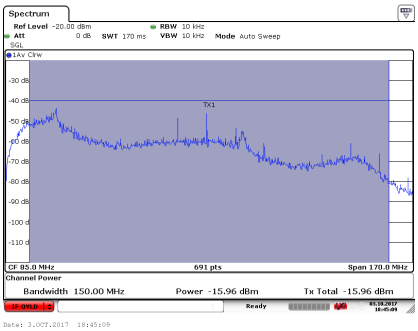

Fig. 15: Spectrum and power of the pulsar signal.

Figs. 16 and 17 present the spectrum and power of the added noise $n(t)$ with maximum and minimum magnitudes, respectively.

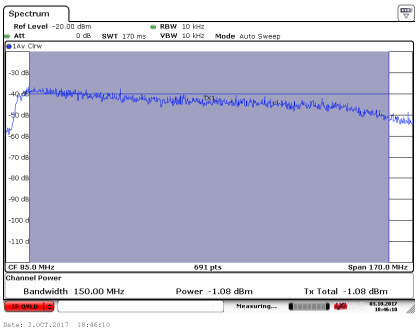

Fig. 16: Spectrum and power of the added noise with maximum magnitude.

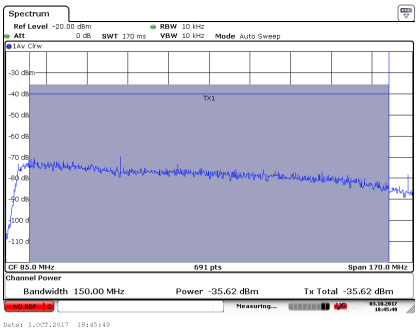

Fig. 17: Spectrum and power of the added noise with minimum magnitude.

From these figures its possible to determine that the SNR ranges between -14.88 and 19.66 dB.

In conclusion, it is safe to say that the obtained results prove that the mixer and adder block performs its job according to the established requirements, and given all the results presented in this Chapter, so does the pulsar simulator.

V. Conclusion

The pulsar simulator is composed of four blocks, a profile generator, two noise generators and a mixer and adder block, connected according to Fig. 3.

The profile generator block generates 3 different profiles, switching between profiles at the press of its push button, with a maximum voltage of 3.3 V, just as expected. This block proved to be well implemented as deduced in section IV It also proved that it is possible to generate analogue signals with very specific characteristics using a PIC and a DAC, being that the only requirement are reliable components and a reliable database, the same way the ATNF was used generate pulsar profiles.

The noise generator blocks produce adjustable Gaussian noise, with a regulable power, since its magnitude and bandwidth are variable. This block presented some difficulties in implementation, especially in the design of its layout. The generated noise bandwidth was greatly affected because of this. It may be due to the layout of the block or the chosen components. Nonetheless, the noise generator still generated a Gaussian noise with a magnitude between -30 and 10 dBm with the capability to regulable the bandwidth, concluding that the noise generator is still viable to generate noise. The adaptability of parameters this generator offers, means this block can be useful to test, or apply in other systems.

The mixer and adder block are responsible for the multiplication and addition of the outputs of the other blocks. They all perform their respective functions, successfully.

This resulted in the development of a working pulsar simulator, which simulates a pulsar signal, anywhere, and in real time, requiring only that its blocks are powered according to its specifications. It's featured with a SNR varying between -14.88 and 19.66 dB, by either changing the signal's magnitude or the magnitude of the added noise, and it can generate 3 different pulsar profiles. Gathering and examining all the results of the blocks intrinsic to the pulsar simulator its safe to say that the accomplished work in this paper resulted in the successful implementation of a pulsar simulator, thus meeting the goals that were set at its beginning.

Given that the goals of this paper were meet and interesting outcomes were obtained, further research would be focused in testing a pulsar signal receiver and improving both the pulsar simulator and the receiver systems. As a starting point the pulsar simulator could be tested supported by a simple acquiring system that connects to a computer and runs an algorithm that retrieves the original pulsar signal based on the signal generated by the pulsar simulator, independently of the SNR level. Later, a real time electronic pulsar signal receiver could be tested using the constructed system.

Even now its possible to think of ways to improve the pulsar simulator, thus developing a more precise, adjustable pulsar simulator, and user friendly system.

The profile generator block could be implemented with a PIC with memory storage capacity and faster clock, or even append a peripheral that interacts with the user, allowing him to generate a wide range of profiles based in a real ones. This block could also benefit from a DAC with more resolution.

Another way the profile generator could be improved is by performing an interpolation similar to what is described in [7], thus obtaining a more precise period.

The noise generator could benefit by being implemented with more care. Use better amplifiers both LNA and VGA. Use a different technique to generate Gaussian noise or, if the same technique is used, choose a diode which generates a higher magnitude and wider bandwidth noise. Have one filter which is adjustable in wide range of bandwidths a and center frequencies, preferably recurring to software.

The mixer and adder block could be substituted by a better system if the established parameters require a mixer or an adder with better characteristics, otherwise, it could same one could be used.

Overall, the pulsar simulator could benefit from better components and designing techniques, which would require more care while designing the whole pulsar simulator and a bigger budget. The ideal pulsar simulator would be a system that provided all its parameters to be adjustable using a software interface, turning it into an easy tool to use to test pulsar signal receivers. Its an application that is at its starting point and that can give fruit to very interesting findings or better applications.

VI. Acknowledgements

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