SOCIETY OF PHYSICS STUDENTS
An organization of the American Institute of Physics

SPS Chapter Research Award Interim Report

Project Title	Construction of a radio telescope for the 21 cm hydrogen line
Name of School	Universidad Autónoma de Ciudad Juárez
SPS Chapter Number	3291
Total Amount Awarded	$ 920
Project Leader	Dr. Jesús Saenz

Abstract

The SPS chapter at our university plans to build a relatively small radio telescope capable enough to make detections of the hydrogen emissions occurring in the galactic center. We intend to take the recreational only astronomical observations that already have place in our university to a student-research-level by building and operating a fully functional radio telescope.

Statement of Activity

The entire Statement of Activity should be no more than three pages and organized as follows. Note that some of the information requested may be taken directly from your proposal, but it is anticipated that the research questions, goals, and methods/designs/procedures have evolved for most projects since work has started. The information provided in this interim report should reflect those changes.

Interim Assessment

Research Question

With the research that we are conducting in order to complete this project, we want to answer the following question: *"How can we develop a functional Radiotelescope to help our students and the community of Ciudad Juárez to improve their experiences in Astronomical research?"* With this question in mind, our group is working to achieve our main objective: Develop a simple, but functional and cost-effective Radiotelescope.

Brief description of the project

This project consists in developing a functional Radiotelescope in order to improve and foment Astronomical research in our community. Our aim is very simple: with the equipment we are acquiring using the funds that the SPS is providing us, we will be able to study the hydrogen spectral lines present in our galaxy, the ones wich corresponds to a frequency of about 1420 MHz, and at the same time with the construction, operation and data acquisition, the students involved in the SPS chapter will be able to get into radioastronomical field using the instruments developed in the present project. A side effect of this, will be the raise in the interest that astronomy research have in our community.

The elements which have influenced us to start this project remain the same: We want to make the gap between undergraduate students and astronomical reasearch smaller. At the same time, we want to promote the scientifical research of areas such as radioastronomy or astrophysics in our city.

Progress on research goals

Following the proposed project timeline (presented in our project proposal), we have completed, in a succesful way, the preliminar components and software tests. At this moment, our team is capturing some initial results (see the respective section on this report for this initial results) and testing the whole hardware and software used in a prototype of a radiotelescope. The software and hardware are working well after a few difficulties that we have encountered with.

Changes in the scope of the project

With the COVID-19 pandemic striking our country, the Government have declared a status of quarantine around the republic. Because of that, we have suffered many delays in our project, specifically with the installation and acquisition of equipment. Right now, some SMA Male to Rp-sma Male adaptors required to advance in our project are inside of our university, our team were asking to Dr. Jesús Saenz a way to get back this equipment and continue with the building of the radiotelescope. The plan of the university is to resume activities until september 21, if and only if government declares that it is secure to resume normal activities. At the moment of this report is being written, we are building the radiotelescope with some parts that Sergio Gonzalez and Alan Barraza found in their respectives workshops and open electronic stores around the city. Also, we are looking for a better antenna that will help us to improve our project, the actual antenna that we are using will be used as a secondary attachment to the radiotelescope.

Personnel

Because of the pandemic, our team has been reorganized to be more efficient by assigning specific activities. Five SPS members are involved in this project: Angel Sosa, Dayra Torres, Alan Barraza, Sergio Gonzalez are working together without breaking the quarantine, specifically: two groups have been created to work while the situation is unfavorable to us: Sergio Gonzalez and Alan Barraza are working together with the available hardware to get some data and building a small radiotelescope to get some initial results (those results are exposed in their respective section on this report), Dayra Torres is working on a binnacle and with Angel Sosa doing the reports and writing the achievements of the team in order to report them to SPS; we have lost contact with Fernando Terrazas, so he is not working with us anymore.

Dr. Jesús Saenz is moderating and being aware of everything that happens in the project, also he is working with the writters correcting and supervising the report.

SPS Connection

The work carried out by our team is helping to promote the SPS around our school. At this moment, almost 90 students of our Physics department are hearing about SPS and the chapter reasearch awards. We are using a Facebook page to promote the chapter in our university and the benefits of becoming a SPS member. This means that maybe in the next year, a few new projects and members can be added to the SPS chapter. At a slow but constant rate, the reception of the SPS around our classmates and teachers is growing, there are a few students who are interested in becoming members of the SPS and new ideas about projects were being expressed before the quarantine around the hallways of our school.

Updated Background for Proposed Project

This section should be a supplemental update to the background given in the project proposal. Indicate any new literary sources being used and include a brief summary of relevant research that has been newly published or that has been newly uncovered or applied by the researchers. If appropriate, provide an updated explanation of how the research project will contribute to the scientific discussion.

Radio astronomy was born in the early 1930s when a Bell Laboratories employee found a strange noise source that was showing up in receivers operating in the 20 MHz region of the radio spectrum, this man was Karl Jansky, an American radio engineer and physicist considered the one of the founding figures of radio astronomy; Jansky discovered that this noise he detected was from extraterrestrial sources, at the time, this discovery from Jansky did not have much attention from the scientific community. Nevertheless, there were a few individuals interested enough to continue with Jansky's work. Grote Reber was one of them, electronics engineer, and avid radio amateur speculated that the signals Jansky discovered were from thermal origin and they would be easier to detect at higher frequencies. Reber built a receiver and antenna for a 3000 MHz operation frequency. Although he did not prove his hypothesis, by the late 1930's he accomplished the first radio map of the galactic plane and built the first radio telescope by himself, even though the term had not been coined yet. The development of radio telescopes has been done thanks to the search of noise from the universe, this noise bears witness to the physical characteristics of the universe [1].

Van de Hulst [2] suggested in 1945, in occupied Holland, that the 21 cm line of atomic hydrogen might be detectable in interstellar space. Soon, after the war, searches were initiated in both Holland and U.S. Unfortunately, for the Dutch team, their receiver caught fire and was destroyed, setting their work back by several months.

Finally, the line was first detected in the interstellar medium by Ewan and Purcell [3] at Harvard University. Wishing to allow others the opportunity to confirm the discovery before publication, they immediately informed to their colleagues in Holland and Australia. Both groups made successful detections within a few weeks of difference, with the Dutch paper [4] appearing as a companion to the original Nature discovery paper, and the Australian detection as a footnote. This early history of the 21cm line, which represents an interesting insight into how science was conducted in gentler times, is described, for example, by Kerr [5] and Sullivan [6]. The original horn antenna used by Ewen and Purcell is currently on display at the National Radio Astronomy Observatory, Greenbank, West Virginia.

Just as Dr. Griffiths has explained in his "Introduction to Quantum Mechanics" [7], the magnetic moments in both proton and electron are given by:

$$\overrightarrow{\mu_p} = \frac{g_p e}{2m_p}\overrightarrow{s_p} \quad ; \quad \overrightarrow{\mu_e} = -\frac{e}{m_e}\overrightarrow{s_e}$$

Were e is the electric charge, m_p and m_e are the respective masses of the proton and electron, $\overrightarrow{s_p}$ and $\overrightarrow{s_e}$are their respective spins and g_p is a g-factor which is measured to be 5.59 for protons and 2 for electrons.

The existence of magnetic moments in both proton and electron implies the existence of a magnetic dipole $\vec{\mu}$ which it´s magnetic field is given by:

$$\vec{B} = \frac{\mu_0}{4\pi r^3}[3(\vec{\mu}\cdot\hat{r})\hat{r} - \vec{\mu}] + \frac{2\mu_0}{3}\vec{\mu}\delta^3(\vec{r})$$

Were $\delta^3(\vec{r})$ is the Dirac delta function in three dimensions. This means that the hyperfine splitting in hydrogen is produced by the magnetic field due to proton´s magnetic dipole. The Hamiltonian of the electron perturbation is given by:

$$H_{hf}^1 = \frac{\mu_0 g_p e^2}{8\pi m_p m_e}\frac{[3(\overrightarrow{s_p}\cdot\hat{r})(\overrightarrow{s_e}\cdot\hat{r}) - (\overrightarrow{s_p}\cdot\vec{s}_e)]}{r^3} + \frac{\mu_0 g_p e^2}{3m_p m_e}\overrightarrow{s_p}\cdot\overrightarrow{s_e}\delta^3(\vec{r})$$

According to perturbation theory, the first order correction in an unperturbed system corresponds to the expectation value of the perturbed Hamiltonian [8]. Which is given by:

$$E_{hf}^1 = \frac{\mu_0 g_p e^2}{8\pi m_p m_e}\langle\frac{3(\overrightarrow{s_p}\cdot\hat{r})(\overrightarrow{s_e}\cdot\hat{r}) - (\overrightarrow{s_p}\cdot\vec{s}_e)}{r^3}\rangle + \frac{\mu_0 g_p e^2}{3m_p m_e}\langle\overrightarrow{s_p}\cdot\overrightarrow{s_e}\rangle|\Psi(0)|^2$$

Were the first term vanishes at ground state, also it is the case that:

$$|\Psi(0)|^2 = \frac{1}{(\pi a)^3}$$

Therefore, the first order correction to energy becomes:

$$E_{hf}^1 = \frac{\mu_0 g_p e^2}{3m_p m_e(\pi a)^3}\langle\overrightarrow{s_p}\cdot\overrightarrow{s_e}\rangle$$

Since the total spin is given by the addition of proton´s and electron´s spin, if we square the relation:

$$\vec{S}^2 = \vec{s}_p^{\ 2} + \vec{s}_e^{\ 2} + 2\,(\vec{s}_p \cdot \vec{s}_e)$$

Since the dot product between proton´s and electron´s respective spin is given by:

$$(\vec{s}_p \cdot \vec{s}_e) = \frac{1}{2}(S^2 - s_p^{\ 2} - s_e^{\ 2})$$

And the fact that proton and electron are spin ½ particles:

$$s_e^{\ 2} = s_p^{\ 2} = \frac{3}{4}\hbar^2$$

In the parallel spins state (the triplet state) the total spin 1 and $S^2 = 2\hbar^2$. In the single state the total spin is 0, and $S^2 = 0$.

Therefore, the first order correction to the energy is then:

$$E_{hF}^{\ 1} = \frac{4g_p\hbar^2}{3m_pm_ec^2a^4}\begin{cases} +\frac{1}{4}\ paralelo \\ -\frac{3}{4}\ antiparalelo \end{cases}$$

Where a is the Bohr radius.

In practice, the transition between those states has an energy gap given by:

$$\Delta E = \frac{4g_p\hbar^2}{3m_pm_ec^2a^4} = 5.88 \times 10^{-6}\ eV$$

This energy corresponds to the energy of the emitted photon in a transition between states. We can find the frequency of this photon using:

$$v = \frac{\Delta E}{\hbar} = 1420\ MHz$$

Which corresponds to a wavelength $\lambda = \frac{c}{v} = 21$ cm, this corresponds to the 21-cm hydrogen line produced in the galactic center which can be detected with our proposed radio telescope.

Description of Research - Methods, Design, and Procedures

To build a radio telescope, we needed to do an investigation to buy all the necessary equipment. The principal components that we needed are an antenna, a feedhorn specifically for the hydrogen line, the electrical components to amplifies the signal and reduce the noise, and the converter of the analog signal to a digital one to analyze the data received with a software. The diagram with the general configuration to get signal of the hydrogen line can be found in the Figure 1.

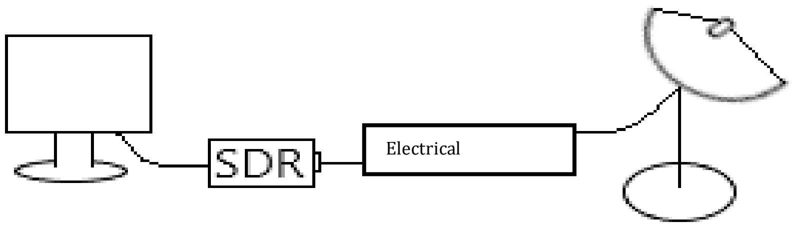

Figure 1. General connection of the components.

1. We have been using two different antennas for the first trials (see Fig. 2). One of them is a cable antenna with 82.5 cm on its major axis and 72.5 cm on the minor axis. The antenna had a Low Noise Block (LNB) of the Ku band (covers from 12 to 18 GHz), so we had to replace it with a feedhorn specifically designed to detect the desired frequency. The other one is a parabolic grid antenna that has a feedhorn with a LO frequency of 2278 MHz.

Figure 2. Parabolic grid antenna at front and cable antenna at back.

2. We also have been using two feedhorns with different design and dimensions. The first feedhorn that we used is a conical feedhorn with the following dimensions: 21 cm high, 23 cm opening diameter and 10.5 cm of minus diameter. This is made with metal and foiled with aluminum to increase the connectivity it is in the Fig. 3.

Figure 3. Cylindrical feedhorn

3. Our other feedhorn was make it according with a base design [9] and it is in Fig. 4. This feedhorn has a rectangular opening whose dimensions are 16.5 cm x 8.25 cm and can receive frequencies between 1.12 GHz and 1.70 GHz. It is made of carton foiled in aluminum and protected for bad weather with Styrofoam and electrical tape.

Figure 4. Rectangular feedhorn.

4. Both feedhorns have a probe that consist of a 2 mm section of cooper wire of ¼ wavelength of 1420 MHz and positioned at ¼ wavelength from the back of the feedhorn [9]. This probe is connected into a coaxial connector to be able to connect the coaxial cable and the rest of the components.
5. For the electrical components we bought a Low Noise Amplifier (LNA) and two Band Pass Filters (BPF), one of 1380 MHz and the other of 1445 MHz; these components are in Figure 5. The first component that we connect is the LNA. This amplifies the central frequency that works with, in this case is 1420 MHz, reducing the noise floor detected from the environment and the coaxial cable. It is important that the LNA is as close as possible from the feedhorn to avoid increasing noise.
6. After the LNA, we connected the BPF of 1445 MHz that works in a range of 1420 to 1470 MHz. Next to this we connected the other BPF with a central frequency of 1380 MHz and a range of 1340 to 1420 MHz. The BPF's are supposed to filtrate the signal received in the range of functionality to reduce the noise.

Figure 5. LNA at left, 1445 MHz BPF at middle, and 1380 MHz BPF at right.

7. To converts the analog signal into a digital one that we can visualize with a software, we needed a Software Defined Radio (SDR), so at the end we can find the RTL-SDR connected at the computer to analyze the signal of the hydrogen line (see Fig. 6).

Figure 6. RTL-SDR to analyze the hydrogen line.

8. The software used to visualize the signal is *Airspy*. This software contains some programs to analyze the signal, but we are only using the program SDR-SHARP. This program only shows the signal in real time, but we need analyze the signal during a lapse time. To achieve this, we installed the *If Average* plugin, a tool used to average the spectrum for a period.
9. Before starting data capture, we need to calibrate the equipment. To do it, we need to adjust the parameter for the averaging, disconnect the antenna of the rest of the components and wait until the software finish the process. Once that it is done, we connect the antenna to start to collect data during periods between 5 to 10 minutes to avoid overheating of the components. The parameters are based in one of the projects investigated [9] and are shown in the Fig. 7.

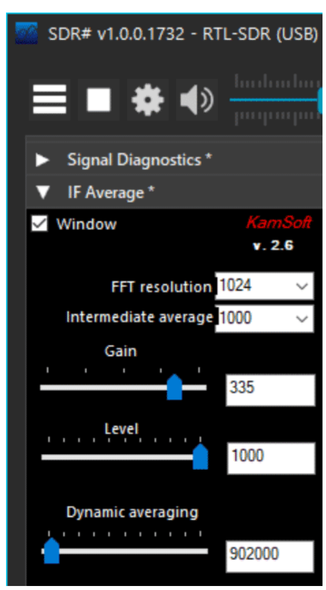

Figure 7. Parameters for the *If Average* plug-in.

We did not have the expected results in our first test, that is the reason why we use different combinations of the equipment to obtain better results. These changes are described with the initial results.

Initial Results

For the first trial, we connected the cable antenna with the cylindrical feedhorn, the LNA, the two BPF's and the RTL-SDR as it is shown in Fig. 8. For this trial, we used the *If average* plug-in and adjust the parameters according with the Figure 7. The results of this trial are in the Fig. 9.

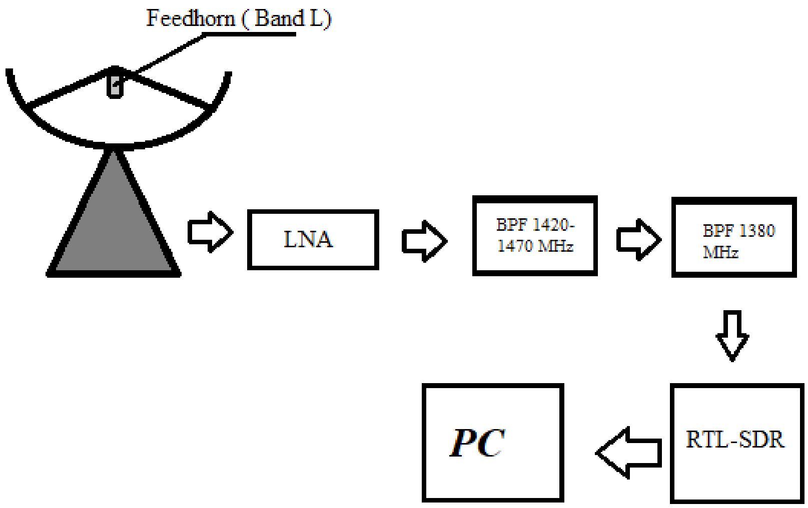

Figure 8. Connection of the components with the cable antenna.

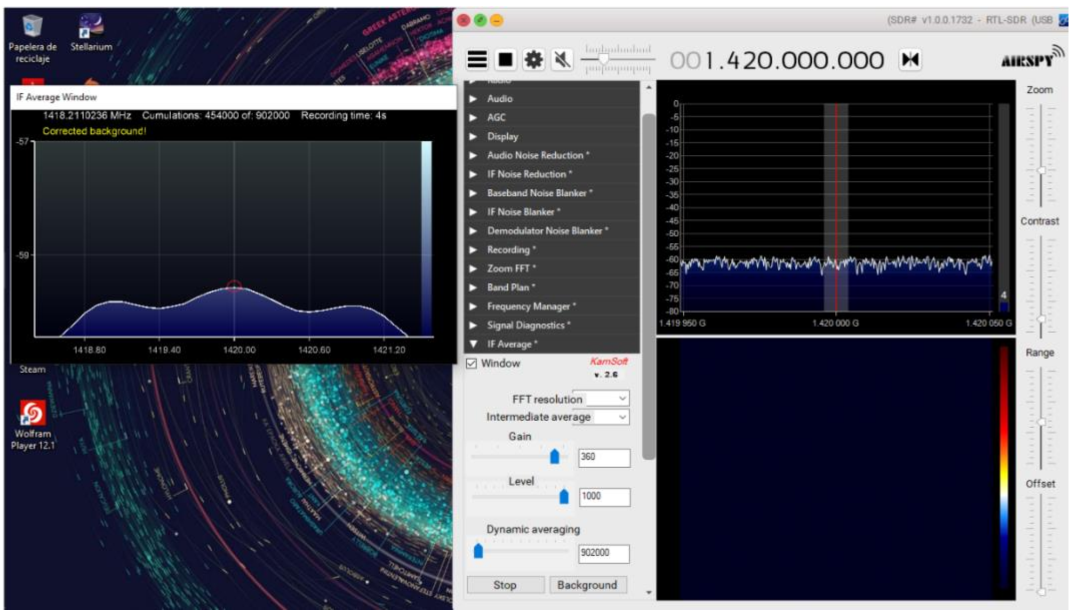

Figure 9. Results with the cable antenna and the cylindrical feedhorn.

With this arrangement of the equipment, we could see only one pixel in the top of the curve located at 1420 MHz. In the image of the right side in the Fig. 9, we can´t see any peak at 1420 MHz, so we thought that the problem was in the feedhorn because we were not sure that the material and dimensions were appropriate for the detection.

We decided to change the feedhorn for the rectangular one and to avoid the previous problem we used a base design for the hydrogen line. The rest of the equipment was connected the same as the previous test (see Fig. 8), as well as the parameters. The results of this test are in Figure 10.

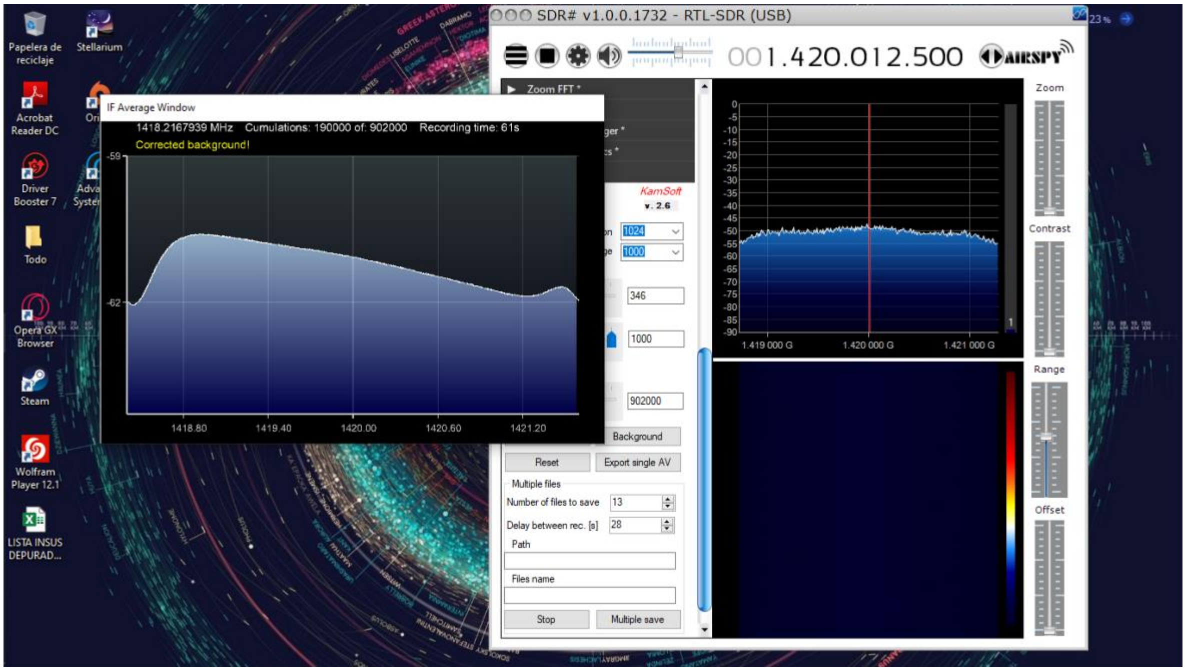

Figure 10. Results with the cable antenna and the rectangular feedhorn.

Of this trial we can observe that the graph of the right side has an improvement from the first trial but is not still enough to achieve that the average graph shows a peak around 1420 MHz. At this moment we were thinking that maybe the problem was the antenna. So, we decided to change it for the next trial.

We changed the cable antenna for a parabolic grid antenna. This antenna has its own feedhorn and we decided to let it to test it and see if we can use it for the following trials. The rest of the components stayed as the previous tests (see Fig. 11)). The average graphs of this test are shown in Fig. 12.

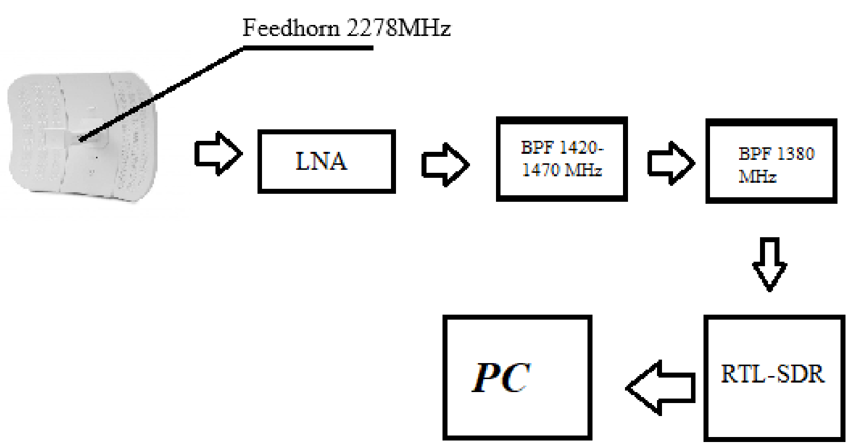

Figure 11. Connection of the components with the parabolic grid antenna.

Figure 12. Result with the parabolic grid antenna and its feedhorn.

We can notice that with the parabolical grid antenna and its feedhorn the noise floor was reduced it if we compare it with the test of the other antenna. Besides this, we can still not see the desire peak at 1420 MHz.

After these trials we conclude that the signal received is not strong enough to generate the expected result. To solve this problem, we need another LNA with a central frequency in 1420 MHz and connect it with the rest of the electrical components.

Statement of Next Steps

The entire Statement of Next Steps should be no more than one page, and organized as follows.

Plan for Carrying Out Remainder of Project (including Timeline)

This section should detail an updated plan for carrying out the remaining components of the project, in bullet or paragraph form. Include, at minimum:

- The key milestones and the dates by which important steps need to be completed in order to finish the project on time (by December 31).
- Personnel - Who will be involved in the remaining research activities and in what way? How many participants are likely to be SPS members? Are there SPS members or others with special expertise that will help to ensure success?

Bibliography

Cite all resources referenced in the interim report here.

[1] Fredsti, S. (2019).*A brief history of Radio Astronomy*. [online] Astronomytoday.com. Available at: http://www.astronomytoday.com/astronomy/radioastro2.html [Accessed 12 Nov. 2019].

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[6] W.T. Sullivan III, *Classics in Radioastronomy*, (D. Reidel, Dortrecht, 1982), pp 299 - 335. This book is a compilation, with commentary, of early radioastronomical papers. It includes refs. 3 - 5, and an English translation of ref. 2.

[7] Griffiths, David J., *Introduction to Quantum Mechanics*, Upper Saddle River, NJ: Pearson Prentice Hall, 2005.

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[9] Morgan, David. Experiments with Software Defined Radio Telescope. 2011.