Radio Telescope

Project Proposal

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Executive Summary

The Rose City Astronomers (RCA) Radio Telescope System is RCA's first educational project related to radio astronomy. It integrates a 3-meter parabolic dish antenna with a 1/4 wave-in-horn waveguide feed, a low-noise amplifier (LNA), and a software-defined radio (SDR) for signal processing. It connects to a laptop or PC running amateur radio astronomy software, enabling users to detect and analyze weak celestial signals in the 1 GHz to 2 GHz frequency range, specifically intended to view the 1.42 GHz hydrogen line (also referred to as the 21 centimeter line). The system is designed for amateur radio astronomers, educators, and the general public outreach.

Users manually adjust the antenna to optimize signal reception. The LNA amplifies weak signals, and the SDR digitizes and processes them for real-time analysis. A connected laptop or PC displays the processed data, allowing users to explore celestial phenomena such as the hydrogen 21-cm line at 1.42 GHz in the Milky Way, OH masers, and pulsars in the UHF L Band.

The system will operate at RCA's SkyLark site, supporting both private observations and educational events. It offers hands-on experience with radio astronomy, making the field accessible to both enthusiasts and learners.

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Background and Research

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Background and Research

Background

The sponsor of our capstone is Rose City Astronomers (RCA), an organization of amateur astronomers in Portland, Oregon, dedicated to promoting education and enjoyment of astronomy to its members and the general public [1]. As a 501(C3) non-profit public benefit organization, RCA sponsors affordable activities, with members volunteering their time, personal equipment, and covering their own personal expenses to support various activities. The proposed project is RCA's first educational project related to radio astronomy. It will initiate exploring suitable equipment for amateur radio astronomy observations and equip RCA with assets to use at its dark sky site and for educational outreach in Greater Portland and other locations [2].

With a one-meter-dish radio telescope system previously built by Michael Caba, an amateur radio astronomer and co-leader of RCA's Radio Astronomy SIG, the project aims to produce a 3-meter-dish radio telescope system operating in the 1-2 GHz range able to observe: 1. Hydrogen 21-cm line in the Milky Way that would allow to plot the galaxy's rotation curve and show dark matter's impact. 2. OH masers. 3. Pulsars in the UHF L Band. The system will include a 3-meter parabolic dish antenna with 1/4 wave-in-horn waveguide feed, a low-noise amplifier (LNA) and a software-defined radio (SDR) for signal processing and interfacing with a laptop or PC running amateur radio astronomy software. Based on the videos provided by the sponsors [3 and 4], the system will resemble those shown in **Figure 1**.

Figure 1: 3-meter-dish radio telescope systems from the sponsors' videos.

Research

The research for our capstone includes LNAs, antenna receiver designs, filters, SDRs and software to design a radio telescope with the required characteristics. The videos provided by the sponsors make a good contribution to the research. The 3-meter-dish radio telescope described by Dr. Wolfgang Herrmann [3] has a "Kumar" type feed horn made from galvanized steel, which he considers not an ideal but workable solution. For LNA, it uses Triquint (or QORVO) TOPM9037 as the first stage and SPF5189Z as the second stage for extra gain, which does not affect the noise figure coming from the first stage, thus getting the noise figure of 0.4 dB. A weatherproof standard aluminum die cast housing holds the LNA with N-connectors to the feed horn. The telescope includes a home-built cavity filter made from standard aluminum profile and standard aluminum rods, which Dr. Wolfgang Herrmann recommends as easy to make and good at filtering out the frequency range of interest (1420 MHz for the hydrogen line) when mounted reasonably precisely. For SDRs, to analyze the signal, it uses standard ADALM Pluto, which Dr. Wolfgang Herrmann recommends as fairly gain-stable, though Lime SDR, HackRF, RTL-SDR, SDRPlay, and Airspy are other SDR options to use. The telescope uses the in-house developed software based on Soapy-SDR abstraction layer: "Spectrometer_II" for spectral measurements, and "Continuum_II" for continuum measurements, both reading pointing information from telescope control. The controller feature is not relevant for our project, since our 3-meter-dish radio telescope is going to be manually controlled. For the mechanical design, Dr. Wolfgang Herrmann puts special emphasis on the support structure to be rigid.

Commercial Off-the-Shelf Products

While researching any commercial off-the-shelf projects that can help with our project, we found an offer for SPIDER 300A MarkII advanced radio telescope, a fully built 3-meter diameter radio telescope for 1420 MHz radio astronomy [5]. It is equipped with all the features desired by our sponsors, including a 3-meter diameter prime focus antenna with specially designed front and rear supports, 1420 MHz optimized feed and 2 LNAs for LHCP and RHCP circular polarization, C106-HEAVY high load capacity pier for concrete base designed to keep the radio telescope permanently installed in the field, and RadioUniversePRO control and acquisition software for Windows 10/11, designed to control all devices of SPIDER radio telescope and to collect radio astronomy data. Described as powerful but affordable, SPIDER 300A MarkII in **Figure 2** has the price starting at 39,350.00 Euro, VAT excluded, while the system budget provided by the sponsors should not exceed $1,000.

Figure 2: SPIDER 300A MarkII, commercial off-the-shelf 3-meter-dish radio telescope system.

As for SDR options that are commercially available, there are several SDR vendors we mentioned like HackRF, Airspy, RTLSDR, and SDRPlay. From these vendors, there are 3 products suitable for this project: the Analog Devices ADALM-Pluto, the SDRPlay RSP1B, and the HackRF One. These SDR products are capable of providing the necessary 1-2 GHz frequency range and also are powered directly from USB. The Pluto is an SDR that contains a 12-bit ADC that can provide a sampling rate up to 61.44 MSPS. Also, the Pluto provides a 20 MHz viewable bandwidth, and it is housed in a plastic construction [6]. The SDRPlay RSP1B provides up to 10 MHz bandwidth, a 14-bit ADC that can sample 2 - 6.048 MSPS, and uses a metal construction. The RSP1B performs IQ sampling of the input signal which is first driven through several filters and then passed to the ADC [7]. The HackRF One is an open-source SDR that provides both TX/RX capability from 1 MHz to 6 GHz, a sampling rate up to 20 MSPS at 8-bit resolution, and also uses a metal construction simlar to the RSP1B [8]. The trade-off of the smaller resolution of the HackRF One is that it can sample a much larger frequency range compared to the other 2 SDRs. The HackRF One and the Pluto also include transmission capabilities which is not necessary for the type of application in this project. The price range of these 3 products is from $100 to $350, which is around the $200 budget for the SDR.

Open Source Projects

While searching for any appropriately licensed open-source projects that can help with our capstone, we found PICTOR, a free-to-use Radio Telescope [9]. Unfortunately, it has a 1.5-meter parabolic dish, not a 3-meter one, but there are schematics and PCB designs, code libraries, and other information that might be useful while designing our radio telescope. This open source has a GNU General Public License, which allows us to use their designs and distribute copies if we are an open source as well and act under the same license, which we do.

To complement the SDR we will use in the project, we found several open-source SDR softwares to choose from: SDR++, Virgo, SDRAngel, GQRS, and CubicSDR. A majority of these SDR softwares are GUI-based and have similar functionality of providing the user visual data of SDR readings. The main three softwares to consider in the project will be SDR++, SDRAngel, and GQRS since their releases are recent as of 2024 and are GUI-based. SDR++ is a popular open-source SDR software that provides an easy-to-use GUI, quick connect menu for SDRs, and simple navigation across the RF FFT graph [10]. SDRAngel is the most complex software out of the three, but it includes many additional radio astronomy features such as sky maps, rotator controls, star trackers, and a radio astronomy plugin [11]. GQRX is the simplest software of the three which provides an RF FFT display, draggable window navigation, and the ability to save settings into files for easy configuration [12].

Patents, Papers, White Papers, Articles, Conference Proceedings

We conducted extensive research across multiple sources, including patent databases, scholarly articles, commercial white papers, and conference proceedings. While we did not find any patents applicable to our project, we identified a few publications that are useful for it.

Chapters 4 and 6 of *The Physical Processes and Observing Techniques of Radio Astronomy: An Introduction* (Pannuti, 2020), a collection of lecture notes from an undergraduate course at Morehead State University, provide several key insights that directly support the design and implementation of our radio telescope project [13]. The explanation of the hydrogen 21-cm line details its emission mechanism, signal characteristics, and significance in studying galactic rotation and dark matter. This ensures the telescope's design parameters, such as frequency range and sensitivity, align with established scientific principles. The chapters cover critical antenna design considerations, including dish size, feed horn configurations, and beamwidth calculations, essential for optimizing signal reception. The overview of various SDR architectures, digital signal processing techniques, and the impact of sampling rates and bit-depth on data quality directly informs component selection and system integration in the telescope's signal processing chain. Noise reduction and calibration techniques from the book have practical applications in the project. The described methods for mitigating thermal noise, atmospheric interference, and radio frequency interference (RFI) are key challenges in ensuring high signal-to-noise ratio (SNR) observations. Techniques such as LNA selection, shielding strategies, and filtering approaches can improve the telescope's ability to detect weak celestial signals.

The article "Techniques of Radio Astronomy" by T. L. Wilson provides a technical overview of radio astronomy methodologies relevant to our radio telescope project [14]. It covers key aspects of signal detection, data processing, and analysis, offering insights that inform design choices for the telescope's signal acquisition chain, including LNA selection and SDR-based signal digitization. The project's goal of detecting weak celestial signals aligns with the article's discussion of spectral line observations and receiver calibration techniques, ensuring that the system can achieve the necessary sensitivity and frequency resolution for accurate data collection. The discussion of aperture synthesis and interferometric techniques provides valuable context for improving angular resolution and signal processing. The principles of phase-coherent observations and correlation techniques can be adapted to enhance signal extraction and noise reduction. The article explains how interferometric arrays achieve high-resolution imaging, and the use of Fourier transforms to analyze visibility data and reconstruct radio images informs the software implementation of the telescope's

SDR processing pipeline, particularly for spectral analysis and source detection. It also addresses the impact of atmospheric and instrumental noise on radio astronomical observations, critical for system performance and calibration. Techniques such as hot-cold load calibration, phase correction, and atmospheric modeling, detailed in the text, provide strategies to improve measurement accuracy. Furthermore, the importance of site selection and environmental considerations, such as shielding the receiver from terrestrial interference, aligns with the project's goal of operating the telescope at an optimal dark-sky location.

The document "Interactive Lab to Learn Radio Astronomy, Microwave & Antenna Engineering" presents an initiative at the Technical University of Cartagena (UPCT) to develop a small radio telescope (SRT) and an associated laboratory, emphasizing student involvement in designing, constructing, and operating a 3-meter parabolic dish antenna system [15]. It integrates a Low Noise Block (LNB) to amplify and filter received signals, which are transmitted via high-quality coaxial cable for further processing. The SRT follows common design principles in amateur and educational radio telescope development, particularly in capturing and analyzing celestial signals such as the hydrogen line at 1.42 GHz. It addresses key technical challenges, including minimizing noise in amplification stages and ensuring precise signal transmission. The setup includes software-controlled antenna positioning and real-time data acquisition, with remotely controlled engines adjusting azimuth and elevation for accurate celestial tracking. The software interface processes received signals and provides visualization tools for analysis. SDR technology enhances flexibility in signal processing, improving the system's capability to detect and interpret weak astronomical signals. A dual-receiver setup supports both commercial and student-designed analog RF receivers: the commercial receiver provides reliability and baseline performance, while the student-designed system functions as a hands-on learning tool. Multiple test points allow students to analyze RF signals using spectrum analyzers and oscilloscopes, reinforcing key principles of high-frequency signal processing. The system's modular design enables iterative improvements, ensuring that the system remains adaptable for future modifications. The focus on student-led development aligns with best practices in engineering education, combining theoretical coursework with practical implementation, which is directly applicable to our project.

Product Design Specification

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Product Design Specification

Product Overview

The RCA Radio Telescope System combines a 3-meter parabolic dish with feed horn waveguide, provided by the sponsor, followed by a quarter wave monopole antenna with a low-noise amplifier (LNA) and a software-defined radio (SDR) for signal processing and interfacing with a laptop or PC running amateur radio astronomy software to detect and analyze weak celestial signals in the 1 GHz to 2 GHz frequency range, designed by the capstone team. We create the radio telescope system for amateur radio astronomers, educators, and the general public outreach. Users manually adjust the antenna for optimal signal reception. The LNA amplifies weak signals, which are then digitized and processed by the SDR for real-time analysis. The data is displayed on a laptop or PC for visualization and analysis, enabling users to explore phenomena like the hydrogen 21-cm line in the Milky Way at 1.42 GHz, OH masers, and pulsars in the UHF L Band. The system will work for both private observations at RCA's SkyLark site and for educational events, offering hands-on experience with radio astronomy. The final product will resemble the one described by Dr. Wolfgang Herrmann [3] in **Figure 3**.

Figure 3: Dr. Wolfgang Herrmann's 3-meter-dish radio telescope system.

Stakeholders

Industry sponsor:

- Rose City Astronomers represented by Art Koehler and Michael Caba

Users of the product:

- Rose City Astronomers members
- The general public

Faculty advisors:

- Andrew Greenberg
- Joshua Mendez
- Mark Martin

Project team members:

- Brad Glaubitz
- Davyd Gamza
- Daniyil Kashkan
- Truong Le
- Paul Nguyen

Requirements

Must:

- Must display real-time signal data on a laptop or PC interface.
- Must generate data for weak celestial signals with sufficient signal-to-noise ratio (SNR $\geq$ 20:1).
- Must be able to interface with a software-defined radio (SDR) for signal acquisition.
- Must have a low-noise amplifier (LNA) with a noise figure $\leq$ 0.7 dB at 1 GHz to 2 GHz.
- Must provide an intuitive software interface for real-time data visualization and analysis.
- Must consume $\leq$ 50 watts per hour, with a total power consumption of $\leq$ 600 watts over 12 hours of continuous use.

Should:

- Should have a low-noise amplifier (LNA) with a gain of at least $\geq$ 30 dB for the 1 GHz to 2 GHz frequency range.
- Should not exceed the total project budget of $1000 in component costs.
- Should utilize a 12 V DC power system for compatibility with on-site solar power and battery backups.
- Should use cross-compatible SDR software to support multiple platforms (Windows, Linux, macOS).

May:

- May operate in various environmental conditions, with a temperature range of -25°C to +60°C, with appropriate passive cooling.
- May utilize solar power available on-site at SkyLark for extended functionality.
- May run off of a car battery for portability at dark-sky sites.

Specifications

The design specifications for the Radio Telescope come from a few major goals. Technical specifications will be further elaborated once selection is finalized by the design team and the industry sponsors.

Initial Product Design

Hardware Architecture

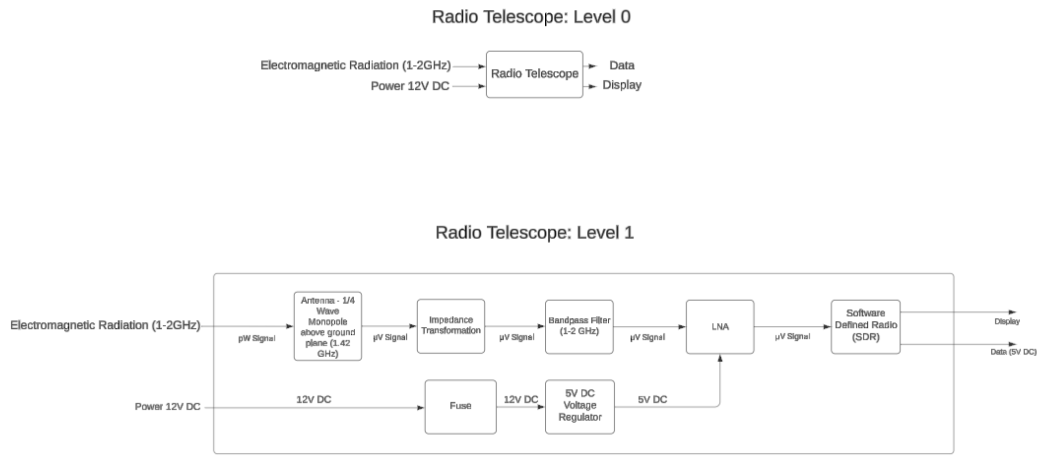

Figure 4: Level 0 and 1 block diagrams of the Radio Telescope System.

Software Architecture

For the development environment, we will use LaTeX to create the user manual documentation and manage its version control with GitHub.

User Interface / Experience

The user interacts with the SDR's sample data through SDR software. When the user opens the software on their computer, it prompts them to select the source device to begin sampling. The user connects the SDR device to the computer using a USB interface. During the initial setup, the software may require the user to install additional drivers to recognize the device. The software displays an FFT graph that visualizes the signals across a frequency spectrum and shows their strength on a decibel scale. It also allows the user to select a tuning frequency for detailed analysis. The user can record and capture screenshots of their sampling data for future reference.

Verification Plans

A testing procedure for the RCA Radio Telescope System should ensure the functionality and accuracy of all components, as well as the system's ability to detect and process celestial signals. Here's an outline of a potential testing procedure.

Testing Procedure for the RCA Radio Telescope System:

- **Visual Inspection**: Check the parabolic dish for physical damage, misalignment, or debris. Inspect the waveguide feed, low-noise amplifier (LNA), and software-defined radio (SDR) for proper connections and secure mounting. Verify the integrity of all cables and connectors, ensuring there are no breaks or loose connections.

- **Power and Signal Flow Check**: Power on the system components (LNA, SDR, laptop/PC). Verify the LNA receives power and amplifies signals by checking voltage levels or using a signal generator and oscilloscope. Confirm the SDR initializes correctly and interfaces with the laptop or PC without errors.

- **Calibration**: Use a known signal source (e.g., a calibrated signal generator) to simulate a weak signal within the 1 GHz to 2 GHz range. Adjust the system to ensure the detected signal matches the input frequency, amplitude, and characteristics. Record and verify the system's response to signals of varying strengths and frequencies to confirm linearity and sensitivity.

- **Antenna Alignment Test**: Point the antenna at an orbital source, such as a geostationary satellite, with a known signal (e.g., weather satellites or communication satellites within the system's L Band frequency range). Measure the signal strength and adjust the antenna manually to verify the alignment process and optimize reception.

- **Celestial Signal Detection**: Point the telescope toward a strong celestial source, such as the Sun, to confirm it detects expected signals. Test the system's ability to observe the hydrogen 21-cm line at 1.42 GHz by pointing it toward the Milky Way's plane. Log signal strength, frequency spectrum, and any detected features.

- **Software and Data Analysis Verification**: Open the SDR software on the laptop or PC. Confirm that the software processes and displays the signal data in real-time (e.g., frequency spectrum, time-domain signals). Analyze the displayed data to ensure accurate representation of input signals.

- **Long-Term Stability Test**: Operate the system continuously for a set period (e.g., 24–48 hours) to monitor stability and detect any thermal drift or noise issues. Evaluate signal consistency and identify potential interference or environmental factors affecting performance.

- **Outreach and Educational Simulation**: Simulate an educational event by guiding users through the setup, alignment, and signal analysis process. Verify the ease of use and the ability to detect and interpret meaningful signals.

- **Documentation and Reporting**: Record all test results, including screenshots of the software interface and any measured values. Identify any issues or inconsistencies, and propose solutions or adjustments.

- **Final Performance Verification**: Revisit all critical tests (e.g., signal detection, software processing, and alignment) to confirm optimal performance before operational use.

Risks

Technical Risks:

- Ensuring the LNA noise figure is maintained at ≤ 0.7 dB.
- Ensuring SNR $\geq$ 20:1

Budget Constraints:

- Components such as the LNA and SDR must be sourced cost-effectively to stay within the given budget limit from Sponsors.

Environmental Constraints:

- Wind and temperature stability of the dish system, ensuring robustness in the field.

Design Constraints:

- No cryogenic cooling or extreme temperature control systems will be incorporated into the system other than components such as heat sinks if it is necessary for design.
- The system should be modular and scalable for future upgrades or integration into other radio astronomy systems utilizing screw together connectors.
- Reducing any external noise interference.
- Anticipate that the final project report will be submitted to the "Radio Astronomy, Journal of the Society of Amateur Radio Astronomy."
- Anticipate presenting the design, prototype performance, and project lessons learned at a General Meeting of the Rose City Astronomers. This is to be scheduled with Mark Martin, Teaching Assistant Professor, PSU.
- The design shall be documented, open source, accessible via arXiv, GitHub, or another reputable open-source server.

Expected Challenges and Risk Mitigation:

- Component Availability: Limited availability of specialized components might affect the timeline. Mitigation: Identify alternative components and commercial off the shelf subsystems early in the design process.
- Prototype Performance: Achieving the target performance metrics (gain, noise figure, etc.) within the specified cost may be challenging. Mitigation: Extensive simulation and design optimization will help reduce the number of prototype iterations required.
- Budget Constraints: Ensuring the BOM stays under the given Sponsor budget could require strategic selection of components. Mitigation: Focus on cost-effective transistors and minimize the use of expensive specialized components.

Deliverables

By the end of our capstone, we are going to deliver to our industry sponsor:

- Project Proposal
- Weekly Progress Reports
- Final Report
- ECE Capstone Poster Session poster
- Detailed design documentation, explaining what our design does, how it works, and why we've made such decisions
- Simulations, including both the simulation inputs and outputs
- Bill of materials and pricing
- Version control, including checked in previous revisions of our design (GitHub repo)
- A working prototype

The deliverables can be accessed via our GitHub repo and Google Drive.

Project Management Plan

Project Management Plan

Timeline, with Milestones

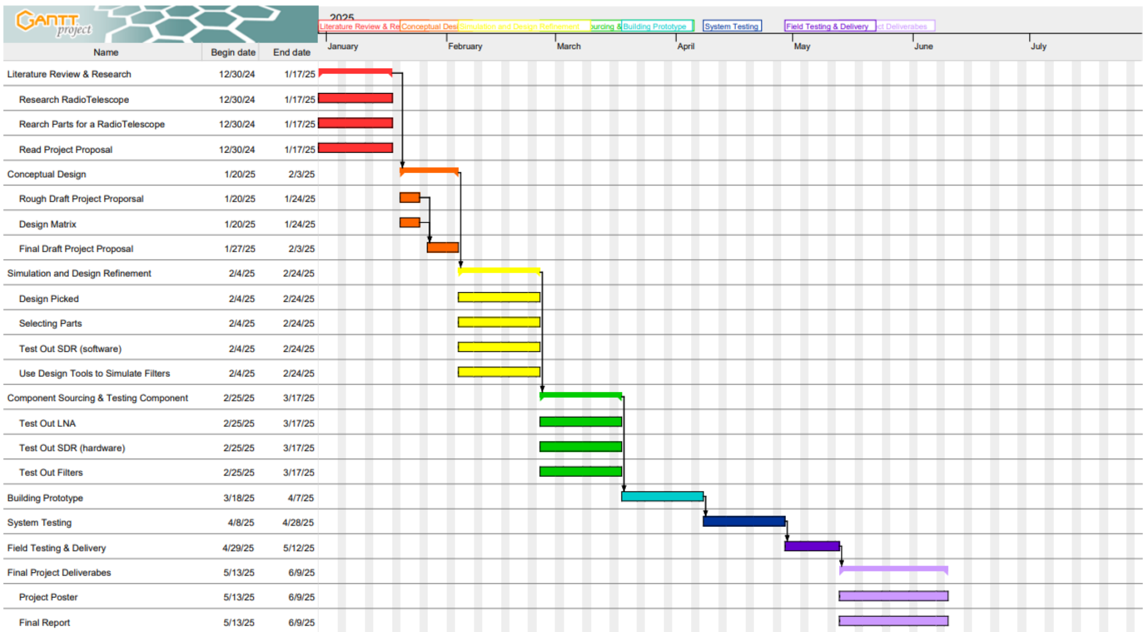

Figure 5: Gantt Chart Project Timeline.

Note: Gantt Chart to be updated throughout the term to represent the timeline better. The timeline can be shifted from 1 to 2 weeks due to unforeseen problems that can occur.

Budget and Resources

Total Estimated BOM Cost: $750

Component	Estimated Cost (USD)
Low-Noise Amplifier (COTS components)	$150
Filtering	$150
$\frac{1}{4}\lambda$ Monopole Antenna	$100
Software-Defined Radio (SDR)	$250
Shielded Coaxial Cables and Connectors	$100

Table 1: Component Costs for Radio Telescope Setup

Resources:

- EPL (PSU)
- Capstone Lab (PSU)
- Locker (PSU)

Intellectual Property Discussion

The Radio Telescope capstone project will use an open-source framework for its design and implementation. This approach aligns with the values of RCA and the goals of the project by promoting transparency, accessibility, and collaboration. The team shares all designs, schematics, software, and documentation publicly on GitHub under suitable open-source licenses. This ensures that the project becomes a valuable educational tool for the amateur astronomy community while allowing others to build on or adapt it for their own use. Keeping the project open-source empowers amateur radio astronomers and educators and encourages innovation in radio astronomy. RCA representatives have shown support for this approach because it simplifies collaboration and increases the project's impact.

Team

Project team members:

- Brad Glaubitz (Main Communicator)
- Davyd Gamza
- Daniyil Kashkan
- Truong Le
- Paul Nguyen

Name	**Strengths**
Brad	Analog & Radio Frequency Design, Antenna Design, Optics, Python, C, MatLab, Soldering, Fabrication, PCB Layout and design, Schematics
Davyd	Power systems, linguistics, soldering, welding, metal-working, general handiwork
Daniyil	Documentation, formatting, organization, presentation, proofreading, communication (email, Discord, calls, etc.), programming (Python, MATLAB), soldering
Truong	Programming (C/Assembly/Probably Python), read/make documentation, review other people's work, microsoldering/soldering, 3D modeling (Fusion 360) and 3D printing, schematic layout/planning
Paul	Documentation, Soldering, PCB Layout and Design, Schematics

Table 2: Project Team Members and Their Strengths

Development Tools and Process

To get the project done, it is likely the following tools will be used:

- Agile Method using Sprints
  - We plan to gather research, calculations, and simulations to serve as a basis for the selection of parts. This data will be provided in a separate document to show the team's conclusions on what specifications are needed in the part-selection process.
  - Once components are selected, the parts are integrated into a complete system as the initial sprint. This system will be tested to see if it coincides with our prior data. If any issues arise from the assessment, we will proceed with another sprint to resolve those issues.
- Discord for regular team meetings and for meetings with the Faculty Advisor
- Microsoft Teams for weekly meetings with the Industry Sponsor
- Google Drive for sharing all project-related documentation
- GitHub as a repo for files and code
- Virtual Network Analyzer (VNA)
- Function Generators
- Python
- Keysight ADS
- KiCad

Appendix

LNA				
Criteria	Weight	SAWbird+ H1	ZRL-2400LN+	ZX60
Gain	4	5	4	3
Power Consumption	2	4	1	5
Noise Figure	5	4	3	5
Bandwidth	4	2	5	5
Cost	3	5	2	3
Power Supply	1	2	5	2
Score		73	64	78

Table 3: LNA Decision Matrix

Criterias	SAWbird+ H1	ZRL-2400LN+	ZX60
Gain	42 (dB)	24 (dB)	12.4 (dB)
Power Consumption	0.75 Watts	5.64 Watts	0.5 Watts
Noise Figure	0.9 (dB)	2.0 dB	0.7 (dB)
Bandwidth	1376MHz - 1441MHz	1GHz - 2 GHz	400 MHz - 3GHz
Power Supply	5V	12-17V	3V-5V
Noise Temperature	NA	NA	NA
Cost	$44.95	$177.03	$145.41

Table 4: LNA Criteria with Worst Case Analysis

SDR				
Criteria	Weight	HackRF One	SDRPlay RSP1B	ADALM-Pluto
Signal Resolution	5	3	5	4
Sampling Rate	5	4	3	5
Frequency Coverage	2	5	3	4
Viewable Bandwidth	3	5	3	5
Open Source / Software	2	5	3	4
Construction	2	5	5	3
Cost	3	1	5	3
Score		83	86	91

Table 5: SDR Decision Matrix

Criteria	HackRF One	SDRPlay RSP1B	ADALM-Pluto
Signal Resolution	8 bit ADC	14 bit ADC	12-bit ADC
Sampling Rate	2 Msps - 20 Msps	2 – 6.048MSPS (Native)	65.2 kSPS to 61.44 MSPS
Frequency Coverage	1 MHz to 6 GHz	1 kHz to 2 GHz	325 MHz to 3.8 GHz
Viewable Bandwidth	20 MHz	10 MHz	20 MHz
Construction	Metal	Metal	Plastic
Compatibility with Software	Mostly compatible	Requires additional libraries	Mostly compatible
Cost	$340	$133	$233

Table 6: SDR Analysis Table

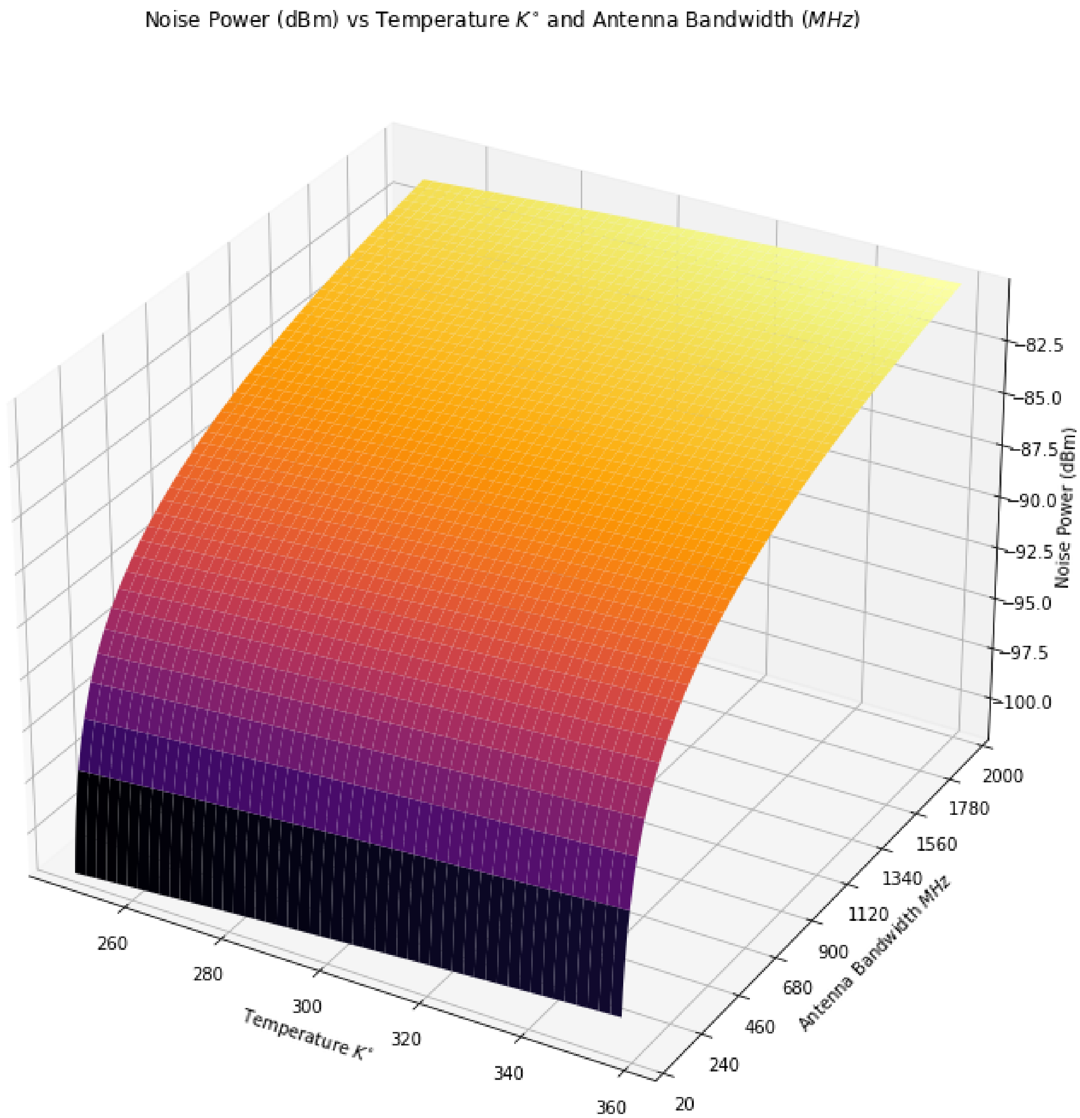

Figure 6: Plot of half-wave dipole antenna S11 (dB) vs Frequency (GHz).

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