Hydrogen Line Telescope

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CONCEPT OF OPERATIONS

FINAL REVISION
27th April 2022

CONCEPT OF OPERATIONS
FOR
Hydrogen Line Telescope

TEAM 10

APPROVED BY:

Project Member	Date	Project Member	Date

Prof. Lusher Date

T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	9/16/21	Team 10		Draft Release
1st	11/30/21	Team 10		Final Report 403 – Revision
Final	4/27/22	Team 10		Final Report 404 - Revision

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1. Executive Summary

Hydrogen line astronomy is a relatively unexplored and inaccessible aspect of astronomy. Many educators and scientists would benefit from this branch of astronomy if they were given the opportunity to use a reliable hydrogen line telescope. This portion of radio astronomy explores the 1420 MHz spectrum. This spectrum allows for views of the arms of the Milky Way galaxy and glimpses into the wider universe. This wavelength can penetrate many of the gas and dust clouds that block smaller wavelengths used in visual astronomy making hydrogen line telescopes an excellent source of galaxy imaging. This project will allow much more accessibility to educators and scientists by providing a high-fidelity hydrogen line telescope featuring several modes of operation and an intuitive graphical user interface.

2. Introduction

The purpose of this document is to introduce the characteristics behind the Hydrogen Line Telescope (HLT) project and discuss a brief history of radio wave telescopes. This type of telescope detects emissions from neutral hydrogen atoms in the Milky Way galaxy. This hydrogen line telescope will feature several modes of operation to give the user flexibility when selecting imaging areas. The telescope will rotate as needed to scan the selected area or point and send a clarified version of the data to an image processing software. This software will create an image of the hydrogen emissions detected by the telescope and output the results as an overlay of the corresponding sky map of that area. The HLT will have an intuitive graphical user interface to make running the telescope and interpreting the results straightforward for educators and researchers.

2.1. Background

Radio astronomy began in the early 1900's when Karl Jansky discovered that the antenna used for testing a thunderstorm static experiment was also detecting a source of static from outer space. Grote Reber, a radio engineer, later took Jansky's ideas a step further and created a telescope that could detect a specific frequency of 160 MHz from the sky giving data that showed the location of different celestial objects.[1] However, this technique was further narrowed by Hendrik van de Hulst who proposed neutral hydrogen as a reliable source of frequency for radio astronomy. Hulst's suggestion eventually brought about the hydrogen line telescope which detects frequencies of 1420.405 MHz or a wavelength of 21 cm and was first used in 1951 by Harold Ewen and Edward Purcell.[2]

The radio waves emitted by neutral hydrogen atoms occur during a rare spin-flip transition.[3] Since neutral hydrogen is such a commonly found substance in outer space with concentrations mainly in the Milky Way galaxy, these emissions make this element a good source for frequency detection. Additionally, radio waves can be observed despite obstructions such as cosmic dust, weather, or the atmosphere giving an ideal way of observing the shape of the galaxy. A hydrogen line telescope can also identify Doppler shifts in the detected frequency giving the rotational direction and consequently velocity of the observed celestial object.[4]

The hydrogen line telescope built during this project will provide several unique features to make it easy for the user to clearly view sections of the galaxy. The user will be able to select an area of emission detection, let the telescope move to retrieve that data, and see the output of the image processing software. This output will show the user where the hydrogen emissions were detected in that area as well as any areas where the software found Doppler shifted frequencies. These results will be shown overlaying a sky map image of the selected area.

2.2. Overview

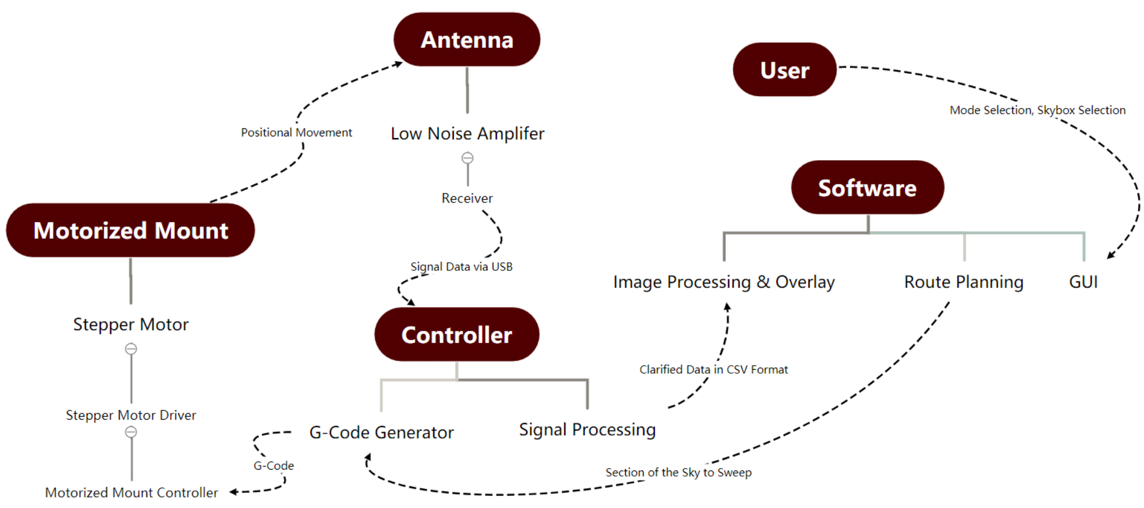

Figure 1: Hydrogen Line Telescope Block Diagram

Johanna: GUI, Image & Signal Processing
Warren: Route Planning, Antenna & Motorized Mount

The HLT project will simplify and make hydrogen line astronomy more accessible to researchers and educators. First, using the graphical user interface, a user will select a section of sky to examine with the HLT. The software will then take that selection, account for the rotation of the earth, and plan a route for the antenna to scan that area. The positional instructions are passed to the controller, a Raspberry Pi, which calculates the current angle the mount is at and then tells the linear actuators to move it to the new position. The system takes the voltage induced in the antenna by neutral hydrogen emissions and passes it through a low noise amplifier into the receiver of the antenna. The receiver, a Software Defined Radio (SDR), takes this signal and separates it into its distinct frequencies and magnitudes. The Raspberry Pi takes the data from the SDR and calculates the frequency from the neutral hydrogen and its peak magnitude for the subsection of sky the beam is pointed at. The Raspberry Pi constructs a CSV file from this data which is sent via USB back to the software running on the laptop. The software takes this CSV file, calculates Doppler shift, and uses this information to create an image with corresponding color and brightness. This image is finally overlaid onto a sky map and the result is displayed to the user.

2.3. Referenced Documents and Standards

1. History of Radio Astronomy (upenn.edu)
2. 21-centimeter radiation | Definition, Importance, & Facts | Britannica
3. Spin-flip Transition | COSMOS (swin.edu.au)
4. Hydrogen Line Radio Observations (spaceacademy.net.au)
5. IEEE 802.11 – Local Area Network Technical Standards
6. USB 2.0 – USB 2.0 Specification
7. TIA-568-C.4 – Broadband Coaxial Cabling and Components Standard
8. IEEE 149-1977 – IEEE Standard Test Procedures for Antennas

3. Operating Concept

3.1. Scope

The Hydrogen Line Telescope project will enable the user to view neutral hydrogen atom emissions from celestial objects in the galaxy. The HLT will be portable and can be placed in any open area. The mounting system for the HLT can then be leveled automatically during a setup process run through the GUI. The user will be able to select an area of detection through the GUI and instruct the telescope to begin collecting data. The HLT will automatically rotate using positional software and a parallel robot to scan the selected area while feeding the data through a low noise amplifier, signal processing system, and finally an image processing system. The results will give the user a cohesive image of the hydrogen emissions detected in that selected area as well as the direction that each object is moving (towards, static, or away) given the frequency detected. These outputs will be shown overlaying a sky map of the area.

3.2. Operational Description and Constraints

The Hydrogen Line Telescope is designed to be used by more entry level researchers and students to look at desired sections of the sky. The antenna mounted on a motorized base will make analyzing sections of the sky easy and intuitive.

The constraints from this operational goal are as follows:

- Must be portable by car and two people, this limits the antenna size
- Must be placed on level enough ground to point where necessary.
- Must be robust enough to repeatedly measure the same section of sky and get similar results.
- Must be able to operate fast enough or be able to be left alone for periods of time as to not inconvenience users.

3.3. System Description

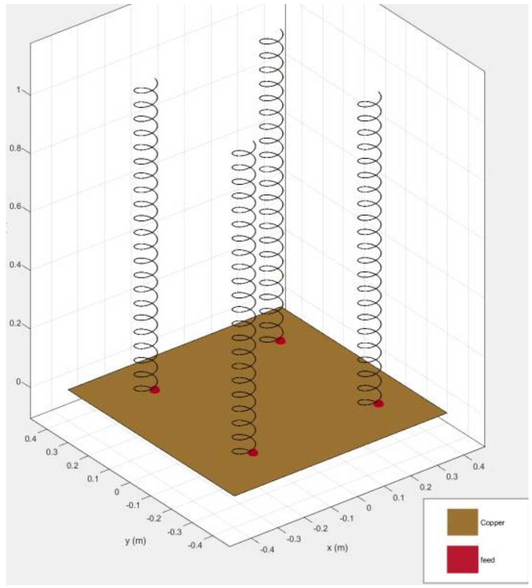

Figure 2: Helical Antenna Design

Signal Acquisition – Using a helical antenna array allows the system to have a much denser package while still maintaining a high gain and narrow beamwidth. The helical antenna array is also a robust design that will not be adversely affected during transit or movement in the field (see Figure 2 above). This antenna will output a signal to a Low Noise Amplifier (LNA) that will be positioned as close to the antenna as possible to avoid signal loss. The output of the LNA will then feed into the SDR which will give the signal data to the Raspberry Pi.

Positioning – Positioning will be accomplished by linear actuators arranged in a parallel robotic configuration. This will allow for any self-leveling needed as well as the high level of precision needed for accurate positioning and measurements. These linear actuators will be controlled using a relay board and accelerometer to control the position of the mount.

Image Processing – This piece of software takes in the data from the Raspberry Pi to calculate the color and intensity of each section of the image based on its Doppler shift and relative magnitude. The image processing software will then overlay data on the corresponding visual image of the night sky and display the combined images as the result.

Usability – The intuitive GUI will allow the user to select the section of sky to be scanned. The user can select from four different modes of operation. The HLT will then collect the appropriate data and return the overlaid image to the user.

Power – The HLT will be powered by the user's vehicle power source that will give off the necessary voltages for the linear actuators, controller, and other components.

3.4. Modes of Operations

The HLT project will have four modes of operation that the user will be able to select. The first mode, "2-dimensional selection", will construct a 2-dimensional image of an area. The user will be able to determine the dimensions of the area in the graphical user interface using a sky map. The second mode of operation will perform "repeated point analysis". In this mode the user will select one point in the sky and an analysis duration. The telescope will observe that selected point over the duration of the analysis and output a detailed GIF of that point in the galaxy over time. Performing repeated point analysis will give a much more accurate representation of that area in space since different hydrogen atoms will be emitting during different times. The third mode of operation, "2-dimensional terrestrial sweep", will sweep a section of the sky vertically while the earth rotates. This mode will allow the user to view more area in the sky than they could during the 2-dimensional selection viewing mode. The final mode, "1-dimensional terrestrial sweep", will simply view a selected point in space while the earth rotates giving a series of detected hydrogen emissions as output.

3.5. Users

This telescope will be used by engineers and researchers to observe the hydrogen emissions of the galaxy for scientific purposes. However, this project will also be simple to run, given the intuitive graphical user interface, meaning that any non-scientific individual could easily run this tool and study the output. This feature makes the HLT a good candidate for use as an educational tool in a classroom setting.

3.6. Support

The resulting hydrogen line telescope will be accompanied by detailed documentation. Some of these documents will cover the technical construction and reasoning behind the different features of this telescope so that the user can fully understand the inner mechanical workings of this project. The HLT will also come with documentation describing the graphical user interface and the software that connects and controls sections of the telescope and manages data processing. These manuals will also include information about antenna calibration and data results and interpretation to ensure that future users can easily run, collect, understand, and use accurate hydrogen line data from the galaxy.

4. Scenarios

4.1. 2-Dimensional Selection

The user would select a box in the sky using the GUI. The HLT would then automatically rotate to gather data from any hydrogen emissions in that area of the sky. Using the data it collected, the HLT would create a 2-dimensional heat map that showed intensity and doppler shift using brightness and color. The software would output this heat map to the user as an overlay of the sky map image of that selected area.

4.2. Repeated Point Analysis

The user would select a single point in the sky. At set intervals the HLT would remeasure the data emitted from that point while tracking it through the sky as long as that point remained in range of the telescope. This data would then be developed and displayed in GIF format to show how the point changed over time.

4.3. 2-Dimensional Terrestrial Sweep

The user would select a point in the sky map. The antenna would then scan a line at this point orthogonal to the earth's rotation. The antenna collects this data over a user-selected range of time to build a series of heatmaps that the software will overlay over sky map photos and display as a GIF to the user.

4.4. 1-Dimensional Terrestrial Sweep

The user would select a single point in the sky and the antenna would gather data points at specified time intervals as the earth rotates. Over time the data gathered would form a 1-dimensional heat map GIF that would be displayed to the user.

5. Analysis

5.1. Summary of Proposed Improvements

The Hydrogen Line Telescope will have several improvements that include:

- Intuitive graphical user interface
- Four imaging modes
  - 2-dimensional selection
  - Repeated point analysis
  - 2-dimensional terrestrial sweep
  - 1-dimensional terrestrial sweep
- Portable power supply and antenna
- Hydrogen line image overlaying a sky map
- Doppler shift analysis

5.2. Disadvantages and Limitations

The Hydrogen Line Telescope may have a few limitations that could include:

- Larger beam width
    - Less precise than telescopes with smaller beam widths
    - Size constraints with this project produce a telescope with a larger beam width
- Frequency range
    - The HLT can only see one frequency range and is not easily customizable for viewing of different wavelengths from the galaxy

5.3. Alternatives

There are some alternatives to the hydrogen line telescope built in this project including:

- The PICTOR telescope - an open-source hydrogen line telescope that can be used to output data and some graphs at a static position for the user
- DIY hydrogen line horn feed telescopes - telescopes that have no specific imaging software to show Doppler shifted frequencies or automated rotational abilities for emission viewing
- Telescopes that detect other frequencies emitted from space - other frequencies that may not be prevalent enough to give accurate images of the galaxy

5.4. Impact

The HLT project involves building a telescope that detects emissions from neutral hydrogen atoms in the atmosphere. These waves, emitting at a frequency of 1420 MHz, provide an accurate method of outer space imaging given the large amount of neutral hydrogen atoms present in the Milky Way galaxy. The telescope built in this project will provide several modes of galaxy imaging through automatic telescope positioning as well as an intuitive graphical user interface. Once complete, this highly scientific project will provide researchers and students with a reliable, easy to use telescope that will advance hydrogen emission imaging of the galaxy.

As this telescope is simply receiving radio waves, not transmitting waves, this project has minimal to no negative impacts on the environment. This project will take up minimal space, the antenna is projected to take up about one meter cubed of space and can be placed in any open, unused, area such as a rooftop. The HLT project will have a positive impact on society as it will provide a way for interested individuals to view sections of space in order to better understand and appreciate the Milky Way galaxy. This instrument could also be a useful tool for educational purposes. As the waves detected by this telescope are naturally occurring and analysis done on these emissions is purely for scientific appreciation and educational purposes, this project poses no ethical concerns.

Hydrogen Line Telescope

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Johanna Hein

FUNCTIONAL SYSTEM REQUIREMENTS

FINAL REVISION
27th April 2022

FUNCTIONAL SYSTEM REQUIREMENTS
FOR
Hydrogen Line Telescope

PREPARED BY:

Author Date

APPROVED BY:

Project Leader Date

John Lusher, P.E. Date

T/A Date

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1. Introduction

1.1. Purpose and Scope

Currently, hydrogen line telescopes are not easily accessible. Educators and students who are interested in viewing hydrogen emissions from the galaxy typically rely on building a DIY version of a hydrogen line telescope. The purpose of the Hydrogen Line Telescope (HLT) project is to provide an intuitive and reliable tool that educators and students can use to view hydrogen line emissions from the galaxy. The HLT will provide users with a graphical interface that enables them to choose from four different modes of data collection. When the user selects the desired option, the telescope will rotate as needed to collect the appropriate data. This data will be analyzed and cleaned before being sent to the image processing software. Finally, an image of the hydrogen emissions will be displayed to the user overlaying a sky map image of that same area. The HLT will make it easy for any interested user to easily view and study hydrogen emissions from the galaxy.

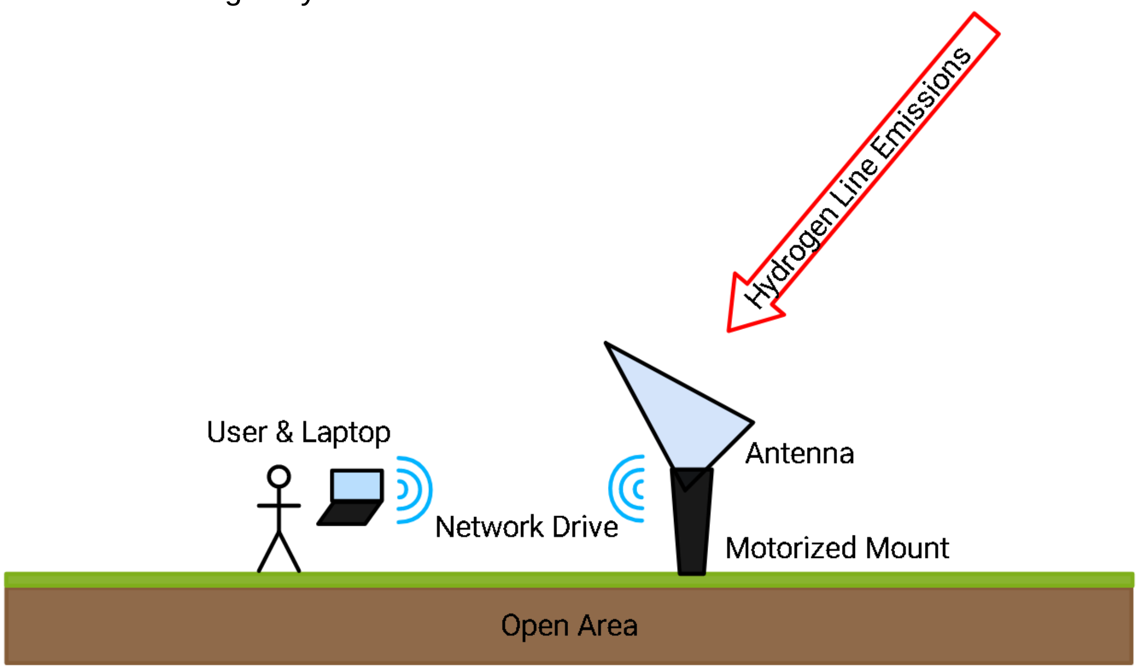

Figure 1: Project Conceptual Image

1.2. Responsibility and Change Authority

Both team members, Warren and Johanna, will be responsible for verifying that all requirements for this project are met. The requirements outlined in this document can only be changed with the approval of both team members and Professor John Lusher.

Subsystem	Responsibility
Antenna	Warren Herrington

Motorized Mount	Warren Herrington
Route Planning	Warren Herrington
Graphical User Interface	Johanna Hein
Image Processing	Johanna Hein
Signal Processing	Johana Hein

Table 1: Subsystem Responsibilities

2. Applicable and Reference Documents

2.1. Applicable Documents

The following documents, of the exact issue and revision shown, form a part of this specification to the extent specified herein:

Document Number	Revision / Release Date	Document Title
IEEE 802.11	2020	Local Area Network Technical Standards
USB 2.0	07/01/2021	USB 2.0 Specification
TIA-568-C.4	07/01/2011	Broadband Coaxial Cabling and Components Standard
IEEE 149-1977	10/12/2008	IEEE Standard Test Procedures for Antennas

Table 2: Applicable Documents

2.2. Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification and are not controlled by their reference herein.

Document Author(s)	Revision / Release Date	Document Title
Lulu Liu Chris Chronopoulos	09/03/2008	The Hydrogen 21-cm Line and Its Applications to Radio Astrophysics
Kamal M. Abood Anmar M. Kitas	2018	Background Radio emissions observation at 1.42 GHz

V. Wongpaibool	2008	Impedance Matching for 2.4-GHz Axial Mode PVC-Pipe Helix by Thin Triangular Copper Strip
Kameron LaCalli	2018	Phased Helical Antenna Array Design for CubeSat Application
K. Jimisha Santhosh Kumar	2012	Optimum Design of Exponentially Varying Helical Antenna with Non Uniform Pitch Profile
Prof. Girish Kumar	2019	Week 9 Helical Antenna Final

Table 3: Reference Documents

2.3. Order of Precedence

In the event of a conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence without any exceptions.

All specifications, standards, exhibits, drawings, or other documents that are invoked as “applicable” in this specification are incorporated as cited. All documents that are referred to within an applicable report are considered to be for guidance and information only, except ICDs that have their relevant documents considered to be incorporated as cited.

3. Requirements

3.1. System Definition

Neutral hydrogen line emissions are a very useful tool for astronomy and can be a more accessible way to look at fascinating parts of the universe. This hydrogen line telescope will take what is normally a fringe and unintuitive process and streamline it for the user. The user will be able to select from four different modes allowing them to choose areas of the night sky. The system will then return intuitive and useful photos and data to the user. The Hydrogen Line Telescope has six subsystems: Antenna Design, Motorized Mount, Image & Signal Processing, Route Planning, and Graphical User Interface.

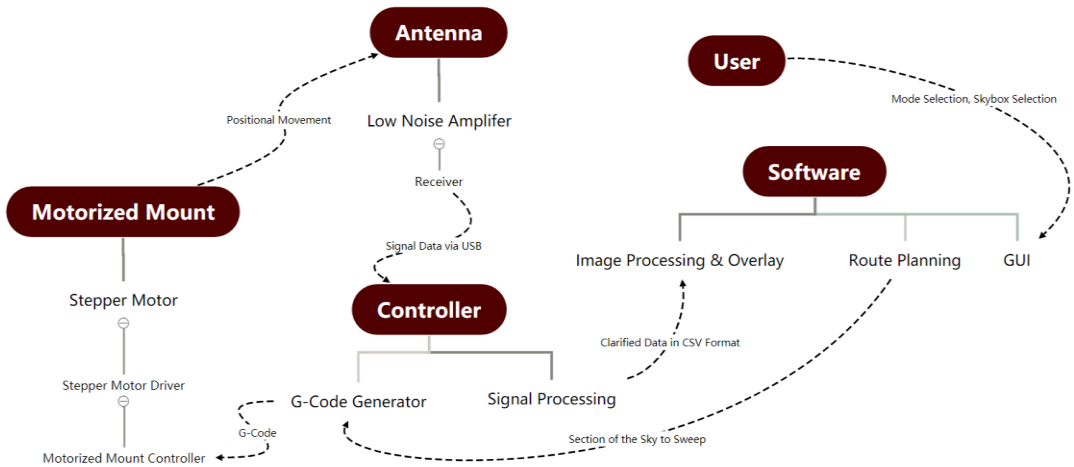

Figure 2: Block Diagram of System

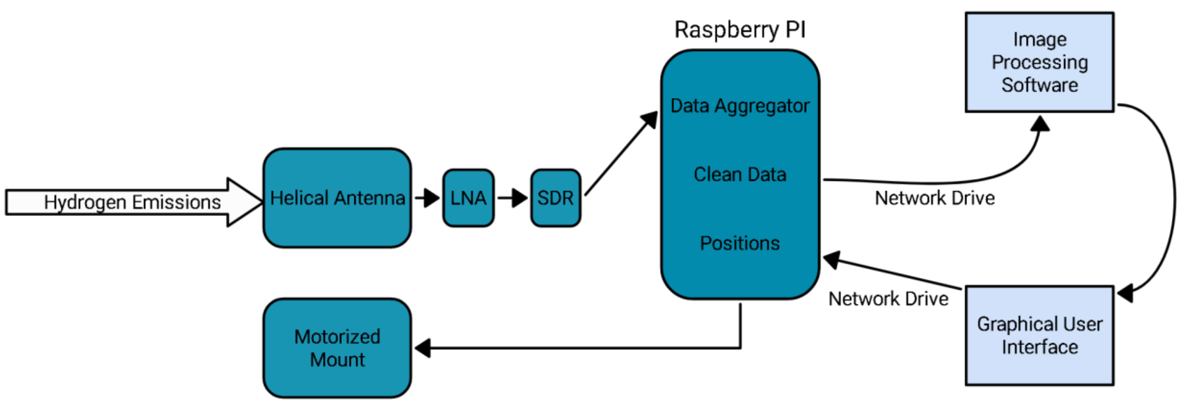

Figure 3: HLT Data Flowchart

The dataflow starts at the graphical user interface. The user selects a mode of operation and runs the program sending the positional information and scanning path to the Raspberry PI. The Raspberry PI then sends the scanning data to the linear actuators in the motorized mount. This antenna position would then be held until the controller had received enough data at which point the motorized mount would move to the next position.

When the helical antenna receives the hydrogen emissions, it passes the data through a low noise amplifier to a software-defined radio. The Raspberry PI takes the SDR output, calculates the magnitude and frequency of that area, and compiles that data into a csv file. This process is repeated until the entire selected section of sky is scanned by the antenna. The csv file is then sent to the image processing software on the user's laptop via a network drive connection. Finally, the image processing software creates a heatmap type image of the hydrogen line emissions to display to the user.

3.2. Characteristics

3.2.1. Functional / Performance Requirements

3.2.1.1. Antenna Beam Width

The HPBW of the antenna shall be equal to or less than 10 degrees.

Rationale: This is to make sure the resolution of the image the telescope outputs is sufficiently high to form an image where the arms of the galaxy are distinguishable

3.2.1.2. Accurate Antenna Positioning

The motorized mount will position the antenna to within 5 degrees of the desired scanning location.

Rationale: The HPBW of the antenna is 10 degrees and in order to get an image that matches what the user desired, it will need to be within 5 degrees of the desired projection.

3.2.1.3. Data Processing Accuracy

The data processing shall have less than a 30% inaccuracy rate when outputting the frequencies and magnitudes calculated from the SDR output.

Rationale: This tolerance ensures that most data received by the image processing software accurately represents the raw data detected by the helical hydrogen line antenna.

3.2.1.4. Graphical User Interface

The graphical user interface shall be intuitive and user friendly. All HLT modes of operation and data results shall be easy to view and understand.

Rationale: The system needs to be able to be run by a student or educator. Using the tool should be relatively straightforward for someone with minimal technical knowledge. To interpret the results, the user will need to have a small amount of technical knowledge.

3.2.1.5. Antenna Routing

The positional system shall be able to correctly route the antenna at least 90% of the time.

Rationale: The system must consider incorrect boundary selection from the user through the GUI as well as the possible inability to track an area of sky given that area's current location and the location in the sky at the end of the scan time given the rotation of the earth.

3.2.1.6. System Run Time

The system shall be able to position the antenna and collect data for up to 6 hours.

Rationale: By looking at the maximum area the user could select which would be 360 degrees around and 80 degrees from vertical. This would have a maximum of 288 "pixels". If the HLT can move *between positions and take data at each pixel at a rate of 1 per minute, it will take 4.9 hours to complete the whole image. One hour of power was added for calibration and setup.*

3.2.2. Physical Characteristics

3.2.2.1. Mass

The system shall be made up of separable parts that are less than or equal to 25 kg per component.

Rationale: The system needs to be transportable by two average adults. The entire system shall be separated into parts for transportation, each of the parts shall be less than the defined mass for ease of transportation.

3.2.2.2. Volume Envelope

The antenna and motorized stand shall each stand less than or equal to 1 meter cubed.

Rationale: Each part of this system must be able to be transported by two adults and a vehicle.

3.2.2.3. Mounting

The antenna shall be mounted on a motorized stand that may rest on any stable, relatively level surface.

Rationale: The antenna will be movable to the user's desired location. The antenna and motorized mount will be connected and can rest on any stable surface for celestial viewing.

3.2.3. Electrical Characteristics

3.2.3.1. Inputs

a. The presence or absence of any combination of the input signals in accordance with ICD specifications applied in any sequence shall not damage the Search and Rescue System, reduce its life expectancy, or cause any malfunction, either when the unit is powered or when it is not.

b. No sequence of command shall damage the Search and Rescue System, reduce its life expectancy, or cause any malfunction.

Rationale: By design, should limit the chance of damage or malfunction by user/technician error.

3.2.3.1.1 Power Consumption

The maximum peak power of the system shall not exceed 45 watts.

Rationale: This requirement is to ensure the proper operation of all subsystems within the Hydrogen Line Telescope.

3.2.3.1.2 Input Voltage Level

The input voltage level for the Raspberry Pi 4 shall be 5V, the input voltage level for the DC linear actuators shall be less than or equal to 13 volts.

Rationale: The Raspberry PI 4 is designed to run off 5V while the DC linear actuators are designed to run off a voltage less than 13V.

3.2.3.1.3 External Commands

The Hydrogen Line Telescope shall document all external commands in the appropriate ICD.

Rationale: The ICD will capture all interface details from the low-level electrical to the high-level packet format.

3.2.3.2. Outputs

3.2.3.2.1 Data Output

The Hydrogen Line Telescope will include a graphical user interface (GUI) for the user to view the telescope's progress and resulting image.

Rationale: The Hydrogen Line Telescope data will be readily available to the user through a GUI.

3.2.3.2.2 Diagnostic Output

The Hydrogen Line Telescope may include a diagnostic interface for control and data logging.

Rationale: Provides the user with a tool for manual debugging.

3.2.4. Environmental Requirements

The Hydrogen Line Telescope shall be designed to withstand and operate in the environments and laboratory tests specified in the following section.

Rationale: The Hydrogen Line Telescope shall be able to function properly in an outdoor setting similar to the Bryan, TX / College Station, TX area.

3.2.4.1. Pressure (Altitude)

The Hydrogen Line Telescope may be able to function properly at altitudes ranging from sea level to 500 feet above sea level.

Rationale: The Hydrogen Line Telescope shall be able to function properly in an outdoor setting similar to the Bryan, TX / College Station, TX area.

3.2.4.2. Thermal

The Hydrogen Line Telescope may be able to function properly in an environment with temperatures ranging from 32°F to 120°F.

Rationale: The system may be able to operate in temperatures reasonable for extended outdoor exposure by the system and the user(s).

3.2.4.3. Humidity

The Hydrogen Line Telescope may be able to function properly in relative humidity ranging from 0% to 70%.

Rationale: The system may be able to operate in moderately humid conditions.

3.2.4.4. Wind

The Hydrogen Line Telescope may be able to function properly in wind conditions with gusts less than 30 mph.

Rationale: The system may be able to operate in moderately windy conditions.

3.2.5. Failure Propagation

The Hydrogen Line Telescope shall not allow propagation of faults beyond the Hydrogen Line Telescope interface.

3.2.5.1. Failure Detection, Isolation, and Recovery (FDIR)

The Hydrogen Line Telescope may have failure detection in the calibration that is run at startup. The calibration process, which levels and positions the system appropriately, may detect any faults in the motorized mount, antenna, or Raspberry PI. If any faults are detected, the system will send an alert to the user and shut down the appropriate subsystems. The system will recover after the user receives the alert informing them of the issue(s) allowing the user to fix the problem and proceed to calibrate and setup the system as usual.

4. Support Requirements

The Hydrogen Line Telescope requires a laptop with Wi-Fi capability in order to connect to the network drive hosted by the Raspberry Pi for data transfer. The user must provide power to the laptop as needed and have the capability to set up a Wi-Fi connection with the Raspberry Pi and laptop. The user must have access to a vehicle to transport and power the telescope as well as an open, flat area for hydrogen line emission viewing.

Appendix A: Acronyms and Abbreviations

GUI	Graphical User Interface
ICD	Interface Control Document
MHz	Megahertz (1,000,000 Hz)
W	Watt
V	Volts
A	Amp
mA	Milliamp
HLT	Hydrogen Line Telescope
HPBW	Half Power Beamwidth
dBi	Decibels Compared to Isotropic
SDR	Software-Defined Radio
LNA	Low Noise Amplifier
RPA	Repeated Point Analysis

Appendix B: Definition of Terms

Hydrogen Line Telescope

Warren Herrington
Johanna Hein

INTERFACE CONTROL DOCUMENT

FINAL REVISION
27th April 2022

INTERFACE CONTROL DOCUMENT
FOR
Hydrogen Line Telescope

PREPARED BY:

Author Date

APPROVED BY:

Project Leader Date

John Lusher II, P.E. Date

T/A Date

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1. Overview

This Interface Control Document (ICD) details how the subsystems within the Hydrogen Line Telescope (HLT) interact. This document describes the interfaces between the antenna, motorized mount, control unit, and the graphical user interface (GUI). The ICD includes a physical description of the subsystem's mass and dimensions as well as a description of the electrical interfaces including voltage and hydrogen emission inputs. Finally, this document explains the user's interaction with the telescope through the GUI.

2. References and Definitions

2.1. References

Refer to section 2.2 of the Functional System Requirements document.

2.2. Definitions

HLT	Hydrogen Line Telescope
GUI	Graphical User Interface
MHz	Megahertz (1,000,000 Hz)
W	Watt
V	Volt
A	Amp
mA	Milliamp
TBD	To Be Determined
HPBW	Half Power Beamwidth
dBi	Decibels Compared to Isotropic
SDR	Software-Defined Radio
LNA	Low Noise Amplifier
RPA	Repeated Point Analysis

3. Physical Interface

3.1. Weight

3.1.1. Antenna

Component	Weight	Number of Items	Total Weight
Antenna Element	1.125 kg	4	4.5 kg
Antenna Backplane	1.5 kg	1	1.5 kg
Frame	1.8 kg	1	1.8 kg

Table 1: Antenna Weight

3.1.2. Motorized Mount

Component	Weight	Number of Items	Total Weight
Linear Actuators	1.5 kg	2	3 kg
Frame	1.8 kg	1	1.8 kg
Control Electronics	200 g	1	200 g

Table 2: Motorized Mount Weight

3.1.3. Main Control Unit

Component	Weight	Number of Items	Total Weight
Raspberry PI 4 B+ (with case)	135 g	1	135 g
Airspy Mini SDR	21 g	1	21 g
LNA	14 g	1	14 g

Table 3: Main Control Unit Weight

3.2. Dimensions

3.2.1. Antenna Subsystem

Component	Length [m]	Width [m]	Height [m]
Antenna Element	0.06	0.06	1.06
Antenna Backplane	0.91	0.91	0.0006
Antenna Frame	0.5	0.5	0.02

Table 4: Antenna Dimensions

3.2.2. Motorized Mount Subsystem

Component	Length [m]	Width [m]	Height [m]
Frame	1	1	0.75
Linear Actuators	0.04	0.04	0.75

Table 5: Motorized Mount Dimensions

3.2.3. Main Control Unit Subsystem

Component	Length	Width	Height
Raspberry PI 4 B+ (with case)	9.8 cm	7 cm	3.2 cm
Airspy Mini SDR	7.7 cm	2.6 cm	1 cm
LNA	7.5 cm	2.5 cm	1.5 cm

Table 6: Main Control Unit Dimensions

3.3. Mounting Locations

The HLT will be portable by two average adults and a vehicle. The HLT can be separated into two sections, the antenna and motorized mount for transportation. The HLT will be able to be set up in any open area containing a stable, relatively flat surface for placing the motorized mount. When the user sets up the HLT on a relatively clear, open, area, the set-up process will calibrate the system and will level the antenna at that area preparing it for accurate emission observations.

4. Thermal Interface

The Raspberry PI 4 B+ shall use multiple heatsinks and a fan to keep temperatures within a safe operating range for this device and to prevent from decreased operating efficiency. The LNA and SDR will also use heatsinks as needed to prevent from overheating. The linear actuators shall make use of an aluminum extrusion frame and thermal compound to dissipate heat produced by the working DC motors.

5. Electrical Interface

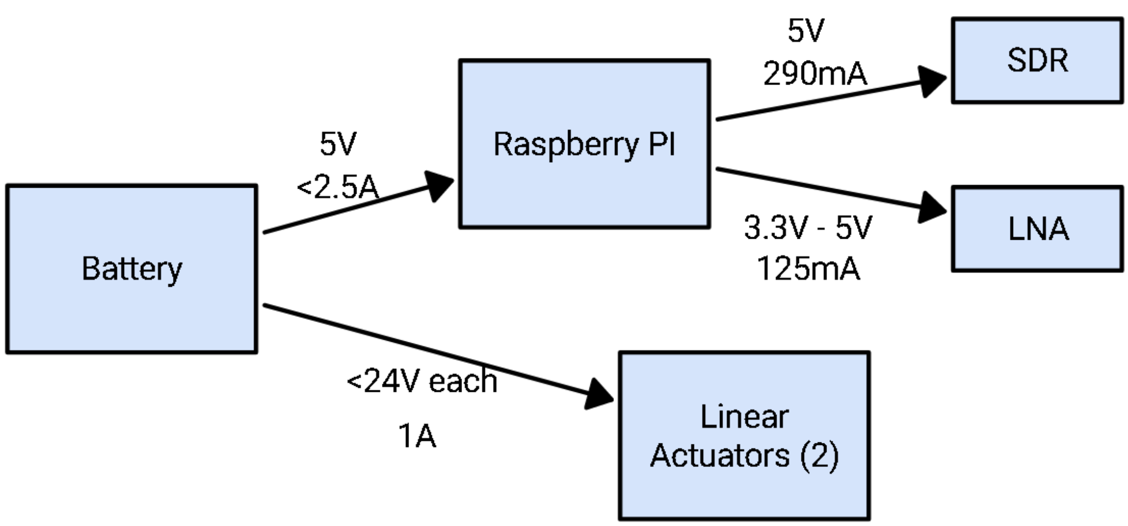


Figure 1: HLT Electrical Interface Diagram

5.1. Primary Input Power

5.1.1. Linear Actuators

The linear actuators shall be powered with a voltage of 12 V ± 20%.

5.1.2. Raspberry PI

The Raspberry PI shall be powered by 5 V from the user's vehicle power source. The Raspberry PI shall power the LNA and SDR.

5.2. Voltage and Current Levels

5.2.1. Maximum Values

Component	Voltage [V]	Current [A]	Power [W]
Raspberry Pi 4B+	5	2.5	12.5
Airspy SDR Mini	5	0.3	1.5
Linear Actuators	12	2	24

Table 7: Voltage & Current Maximum Values

5.2.2. Stand-by Values

Component	Voltage [V]	Current [A]	Power [W]
Raspberry Pi	5.3	1.2	6.2
Airspy SDR Mini	5	100	500
Linear Actuators	10	3	30

Table 8: Voltage & Current Stand-by Values

5.3. Signal Interfaces

5.3.1. Antenna

The antenna will solder to a SMA connector which will then connect to a coaxial cable from a 4-way power combiner. This cable will then feed into the LNA and subsequently the SDR.

5.4. User Control Interface

The user control interface is a graphical user interface that will be run through Python. This GUI will communicate with the Raspberry PI via a network drive connection. The user's input will be used to select the mode of operation, scanning area, scanning time. The GUI will also allow the user to view the resulting hydrogen line images.

6. Communications / Device Interface Protocols

6.1. Wireless Communications

6.1.1. Wi-Fi

The hydrogen line telescope will use Wi-Fi to send data between the user's laptop and the Raspberry Pi via a network drive. The user will be able to setup a hotspot for the network drive connection between the Raspberry Pi and the user's laptop if needed. The user will select from several mode options using the GUI. The Python script will then communicate the route planning for that selection through the network drive to the Raspberry Pi to start the scanning process. Once the scan is complete, the Raspberry PI will send the collected and cleaned data back to the laptop for the final image processing and skymap overlay.

6.2. Device Peripheral Interface

The SDR is controlled through USB from the Raspberry Pi. The Raspberry Pi will interface with the linear actuators.

Hydrogen Line Telescope

Warren Herrington
Johanna Hein

SCHEDULE AND VALIDATION

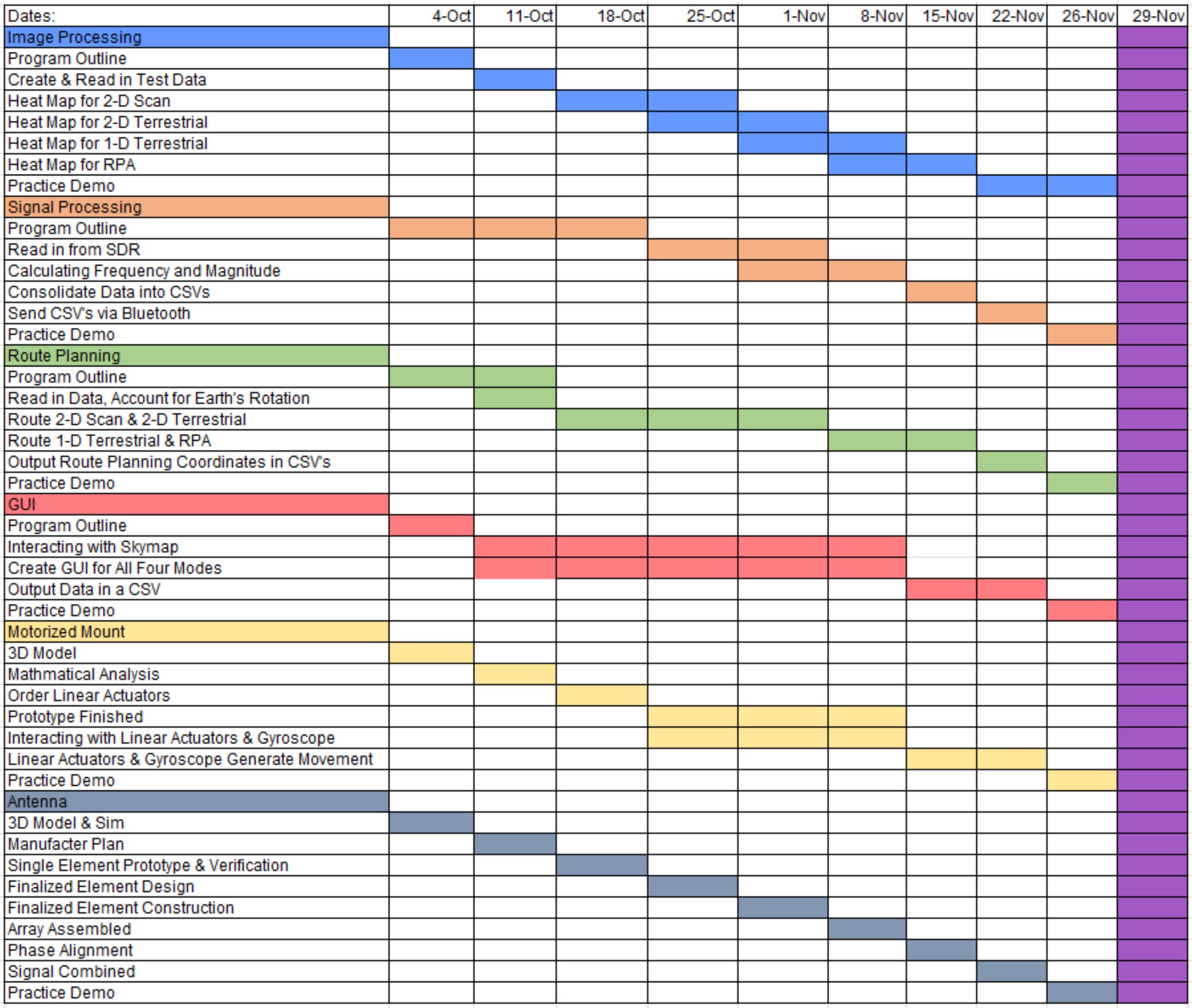
FINAL REVISION
27th April 2022

1st Semester Schedule:

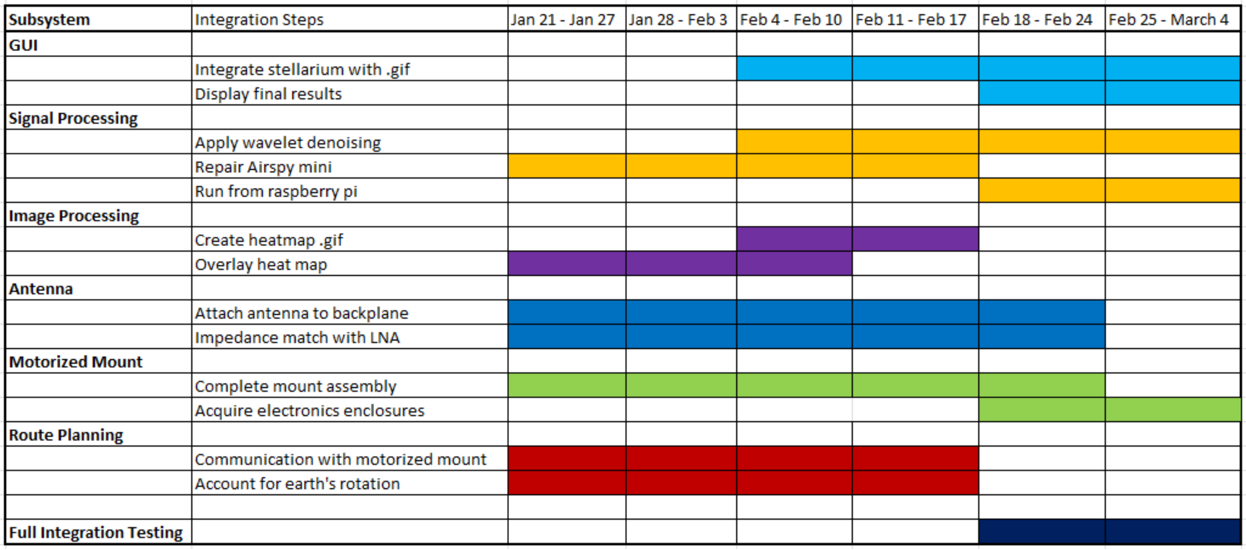
Work	End Date	Owner	Status
Midterm Presentation	6-Oct	All	
Image Processing Program Outline	11-Oct	Johanna Hein	
GUI Program Outline	11-Oct	Johanna Hein	
Motorized Mount 3D Model	11-Oct	Warren Herrington	
Antenna 3D Model and Simulation	11-Oct	Warren Herrington	
Create & Read in Test Data	18-Oct	Johanna Hein	
Route Planning Program Outline	18-Oct	Johanna Hein	
Read in Data, Account for Earth's Rotation	18-Oct	Johanna Hein	
Mathematical Analysis of Motorized Mount	18-Oct	Warren Herrington	
Antenna Manufacturing Plan	18-Oct	Warren Herrington	
Projects Updates	25-Oct	All	
Signal Processing Program Outline	25-Oct	Johanna Hein	
Order Linear Actuators	25-Oct	Warren Herrington	
Single Element Antenna & Design Verification	25-Oct	Warren Herrington	
Heat Map for 2-D Scan	1-Nov	Johanna Hein	
Finalized Element Design	1-Nov	Warren Herrington	
Heat Map for 2-D Terrestrial	8-Nov	Johanna Hein	
Read in from SDR	8-Nov	Johanna Hein	
Route Planning 2-D Scan & 2-D Terrestrial	8-Nov	Warren Herrington	
Finalized Element Construction	8-Nov	Warren Herrington	
Final Presentation	15-Nov	All	
Heat Map for 1-D Terrestrial	15-Nov	Johanna Hein	
Calculating Frequency and Magnitude	15-Nov	Johanna Hein	
Interacting with Skymap	15-Nov	Johanna Hein	
Create GUI for All Four Modes	15-Nov	Johanna Hein	
Motorized Mount Prototype Finished	15-Nov	Warren Herrington	
Interacting with Linear Actuators & Gyroscope	15-Nov	Warren Herrington	
Helical Antenna Array Assembled	15-Nov	Warren Herrington	
Heat Map for RPA	22-Nov	Johanna Hein	
Consolidate Signal Data in CSVs	22-Nov	Johanna Hein	
Route Planning RPA & 1-D Terrestrial	22-Nov	Warren Herrington	

Antenna Phase Alignment	22-Nov	Warren Herrington	
Send CSVs via Network Drive Connection	26-Nov	Johanna Hein	
Output Route Planning Coordinates in CSVs	26-Nov	Johanna Hein	
Output Data from GUI in CSVs	26-Nov	Johanna Hein	
Linear Actuators Generate Movement based off of Gyroscope	26-Nov	Warren Herrington	
Antenna Array Signal Combined	26-Nov	Warren Herrington	
Subsystem Demo	29-Nov	All	
Final Report	5-Dec	All	
System Integration and Full System Testing	28-Feb	All	
System Refinement and Validation	30-Mar	All	
Final Report and Demo	2-May	All	

1st Semester Gantt Chart:



2nd Semester Gantt Chart:



Validation Plan:

Reference	Test Name	Success Criteria	Methodology	Status	Responsible Engineers
3.2.1.1	Antenna Beam Width	The HPBW of the antenna shall be equal to or less than 10 degrees	Antenna to antenna gain mapping in a quiet room.	IN PROGRESS	Warren L. Herrington
3.2.1.2	Antenna Positioning	The motorized mount will position the antenna to within 5 degrees of the desired scanning location.	Use a digital level to measure locations.	COMPLETE	Warren L. Herrington
3.2.1.3	Data Processing	The data processing shall have less than a 30% inaccuracy rate when outputting the frequencies and magnitudes calculated from the SDR output	Compare peak magnitude & frequency output with raw data.	COMPLETE	Johanna K. Hein
3.2.1.4	Graphical User Interface	The graphical user interface shall be intuitive and user friendly. All HLT modes of operation and data results shall be easy to view and understand.	Allowed potential user to interact with & review the GUI.	COMPLETE	Johanna K. Hein
3.2.1.5	Antenna Routing	The positional system shall be able to correctly route the antenna at least 90% of the time	Compare output to desired route path.	COMPLETE	All
3.2.1.6	System Runtime	The system shall be able to position the antenna and collect data for up to 6 hours.	Run full system test for desired time.	COMPLETE	All
3.2.2.1	Mass	The system shall be made up of separable parts that are less than or equal to 25 kg per component.	Weigh each part.	COMPLETE	All
3.2.2.2	Volume Envelope	The antenna and motorized stand shall each stand less than or equal to 1 meter cubed.	Measure each part.	COMPLETE	All
3.2.2.3	Mounting	The antenna shall be mounted on a motorized stand that may rest on any stable, relatively level surface.	Complete mounting construction.	COMPLETE	Warren L. Herrington
3.2.3.1.1	Power Consumption	The maximum peak power of the system shall not exceed 45 watts.	Use a wattmeter to measure peak power consumed	COMPLETE	All
3.2.3.1.2	Input Voltage Level	The input voltage level for the Raspberry Pi 4 shall be 5V, the input voltage level for the DC stepper motors shall be less than or equal to 24V.	Measure input voltages for the Raspberry Pi and motors.	COMPLETE	All
N/A	Full System Demo	A user of the HLT will be able to perform any of the desired modes within 15 minutes of training.	Complete user training and analyze performance.	COMPLETE	All

Performance on Execution Plan:
The execution plan shows completed progress in all electrical and programming sections of the subsystems. Full system integration was competed successfully.

Performance on Validation Plan:
All possible validation was completed on each subsystem and the fully integrated system. Reference 3.2.1.1 was not completed as the anechoic chamber was being remodeled during the 2nd semester of senior design.

Hydrogen Line Telescope

Warren Herrington
Johanna Hein

SUBSYSTEM REPORTS

FINAL REVISION
27th April 2022

SUBSYSTEM REPORTS
FOR
Hydrogen Line Telescope

PREPARED BY:

____

Author Date

APPROVED BY:

____

Project Leader Date

____

John Lusher, P.E. Date

____

T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	11/30/2021	Team 10		Final Report 403 – Report
Final	4/27/22	Team 10		Final Report 404 – Report

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1. Introduction

This report gives an overview of all subsystems within the integrated HLT system. This project has a total of six subsystems. The antenna, motorized mount, and route planning subsystems were completed by Warren Herrington while the signal processing, image processing and GUI subsystems were completed by Johanna Hein. All electrical and physical components have been completed for the six subsystems to create a fully integrated and functional hydrogen line telescope. All validation has been successfully completed with the exception of reference 3.2.1.1 given circumstances outside this teams control. The theory behind each subsystem as well as the outcome and completed validation is detailed in the following sections.

2. Antenna Subsystem

2.1. Subsystem Introduction

This subsystem's purpose is to detect microwave emissions from hydrogen in our galaxy. To complete this task this subsystem will be tuned for 1420 MHz and have a HPBW of 10 degrees. The antenna's data will be read by the SDR in the full system. The antenna subsystem will be positioned by the motorized mount subsystem.

2.2. Subsystem Details

There are many different antenna designs that were looked at, but all had different issues. Parabolic antennas have very narrow beamwidths however manufacturing is difficult at best and probably infeasible with the resources available. A Yagi-Uda antenna can also provide narrow-beam widths however the spacing on the antenna is extremely precise and would take meters of length to get to the required beamwidth. Given the alternatives, a helical design was chosen for this project due to its dense design, forgiving characteristics, and relative ease to achieve narrow beamwidths.

To meet the specifications of this project, a four-element helix array was chosen. Each element has twenty-two turns so that when combined in the array it has a calculated HPBW of 10 degrees. The circumference of the array is equal to the wavelength of light we are trying to measure to put it into axial mode. The spacing is 4.55 centimeters between each turn to maximize gain. Each element is then spaced at 2.236 times the desired wavelength. This design was then modeled and simulated in MATLAB's Antenna Designer.

Once the model met the desired characteristics, the next step involved the development of the building process. To make for easier manufacturing, the design changed from a circular helix to a square helix as this makes very little difference in the final gain. Next, the system was designed in AutoCAD so that the frame for the elements could be laser cut out of acrylic. Once the designs were developed and finalized, the acrylic pieces were cut out and glued together using epoxy. Then 10-gauge copper wire was wrapped around each acrylic skeleton to produce each element. After the copper was wrapped around the frame it had to be impedance matched. This was done using copper triangles which utilized the band as an inductor and the isolation from the backplane as a capacitor to impedance match the antennas.

Once the elements were wrapped around the acrylic frame, the frame was reinforced with 3D printed supports. Using 3D printed element mounts, the antenna elements were secured to the backplane and frame. The frame was made out of 2020 aluminum extrusion to reinforce the back plane and support all of the elements. Everything was secured using nylon M4 bolts and nuts to minimize the amount of metallic support material above the backplane. Mechanically the antenna can support ±90° of travel.

Figure 1: Antenna Validation Design & Construction

Each element was impedance matched to the rest of the radio system using a copper triangle to reduce the 140 Ohm impedance of the antenna to the 50 Ohm impedance used by the rest of the system. An SMA connector is attached at the feed point of every antenna and a coax cable feeds each signal into a 4-way power combiner. The LNA is placed directly at the output of the power combiner to lock in the signal to noise ratio. The output of the LNA will then feed into the SDR which is attached to the Raspberry Pi.

2.3. Subsystem Validation

This subsystem has been fully validated. Testing was done by maneuvering the antenna to different parts of the sky and inspecting how the signal pattern changed. The LNA can add a wave to the signal so a baseline reading was subtracted from the measured signal to make sure the actual hydrogen emission signal could be detected. This validation demonstrated that the antenna had sufficiently narrow beamwidth to meet the requirements of the project. If the project was continued in the future, doing a full antenna beam width measurement in the anechoic chamber would have been desirable however that facility was not available for testing at the time of this project.

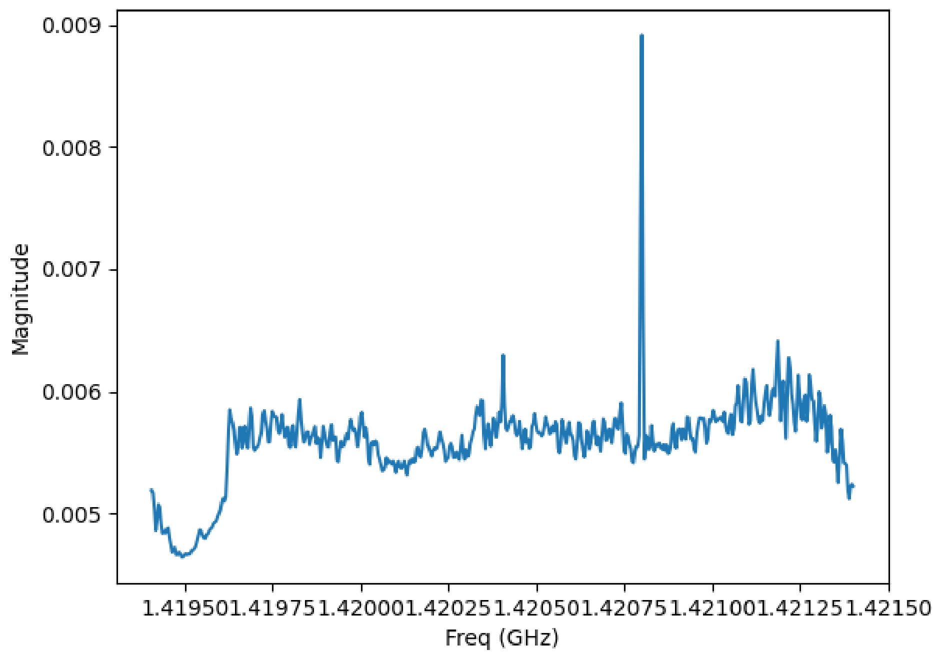


Figure 2: Antenna Validation Baseline Reading

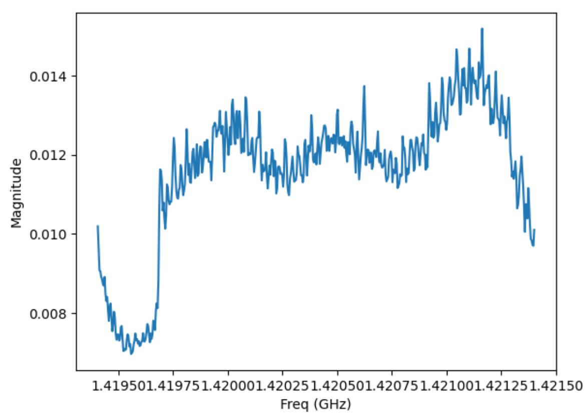


Figure 3: Example Noise from the LNA

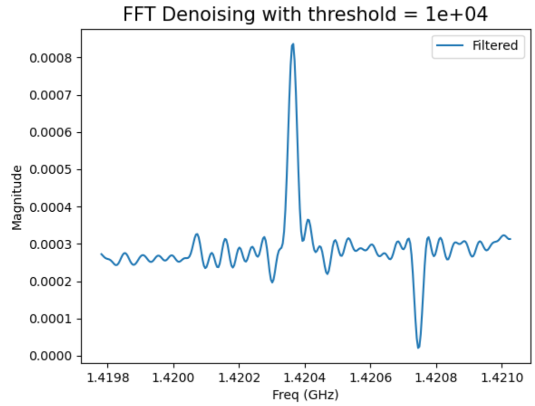


Figure 4: Hydrogen Line Reading

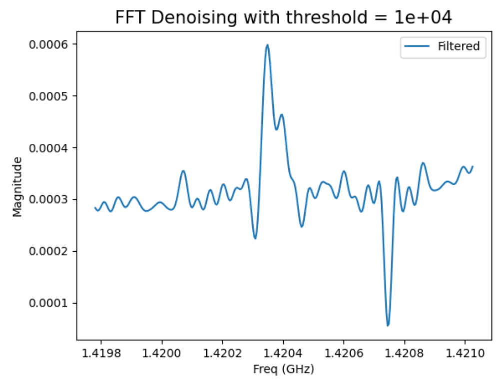


Figure 5: Hydrogen Line Reading

All of these data graphs how the expected change in signal as can be inferred from the sky map and positional data. The graphs show both filtered and unfiltered data. These graphs show that the antenna does receive data as expected. The first graph in figure 3 shows the system reading noise from LNA. This noise looks as expected and was removed during calibration. In figure four, you can see data from possibly a star in the galaxy due to the sharpness of the magnitude peak. In figure five, you can see data from part of an arm of the Milky way as the frequency band of the peak is wider and has a slightly lower magnitude than the star reading. The antenna works as expected and is fully integrated with the system.

2.4. Subsystem Conclusion

The subsystem execution, validation, and integration goals were met this semester. The antenna has been fully combined and works with the full system. Future improvements could involve further reinforcement of the frame and antenna to stop some undesirable wobbling as well as a full radiation pattern mapping.

3. Motorized Mount Subsystem

3.1. Subsystem Introduction

The goal of this subsystem was to position the antenna array accurately and reliably where desired. The motorized mount takes the desired points given to it by the route planning subsystem and then positions itself and the antenna at that point until scans are complete and it is given a new position.

3.2. Subsystem Details

There are several different methods traditionally used for antenna positioning however the design used in this project took a unique approach. Most antenna mounts use two rotational motors in order to position at the correct azimuth and elevation. This design has several issues that would have been difficult to overcome with the HLT project. This system works well with small antenna. However, with a large array, very large motors or sizable counterbalances would be needed to make this system work effectively. Also, true rotation was not needed as the main lobe of the HLT antenna is symmetrical. For the HLT project this team designed a two DOF system inspired by recent progress in parallel robotics. The parallelized motorized mount has a simpler design only needing two linear actuators to achieve its movement as well as a much simpler control system. Initially a stepper motor design relying on positional mathematics and reverse kinematics was envisioned, however a simpler feedback loop was finally decided on due to its robustness and versatility.

The feedback system works by moving one linear axis until the accelerometer communicates that it is at an acceptable value. Then, the system moves the next axis to an accelerometer approved point. The linear actuators and accelerometer move in this way until both axes are at correct values. In order for this system to work, this team had to derive a non-standard spherical coordinate system so that each axis could be individually mapped and confirmed. The route planning subsystem automatically converts to this coordinate system for ease of use.

For assembly a steel and 3d printed U-joint was manufactured. The antenna frame was mounted to the top of the U-joint and the frame holding the electronics and controls was attached to the other side. The linear actuators were attached using a combination of 3D printed parts, T-nuts, steel rods, and cotter pins to hold everything in place and make sure only two degrees of movement would occur. Due to the weakness of 3D printed parts large springs were added in parallel to the linear actuators to help balance the system at larger travel angles. When the whole system moves there is some unintended movement however not enough to jeopardize the system or take it out of the specified angle range.

3.3. Subsystem Validation

The subsystem has been validated by feeding it many points to travel to and measuring the accuracy of the system in getting to those desired points. Throughout the testing the motorized mount had an average deviation of 0.5 degrees of deviation. This was more than accurate enough for the ±5 degrees of accuracy needed.

Instructed X	Instructed Y	Measured X	Measured Y
0	0	0	0
-10	0	-11	0
-10	-10	-11	-9
0	-10	-1	-10
-20	-20	-22	-21
-30	-20	-31	-20
-40	-20	-41	-19
-45	0	-45	0
-50	0	-49	-2
5	5	5	6
10	10	10	10
10	0	10	0
0	10	0	10
0	20	0	20
10	20	10	21
20	20	21	21
20	25	21	25
20	30	21	30
0	30	1	30
0	35	1	35
0	40	0	40
0	45	1	45

Table 1: Motorized Mount Angle Accuracy

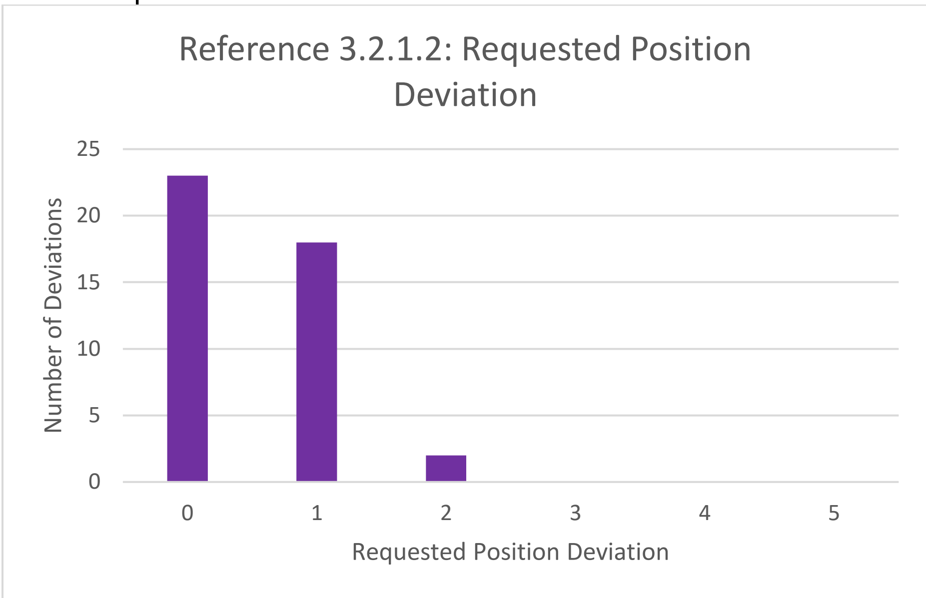


Figure 6: Motorized Mount Angle Deviation

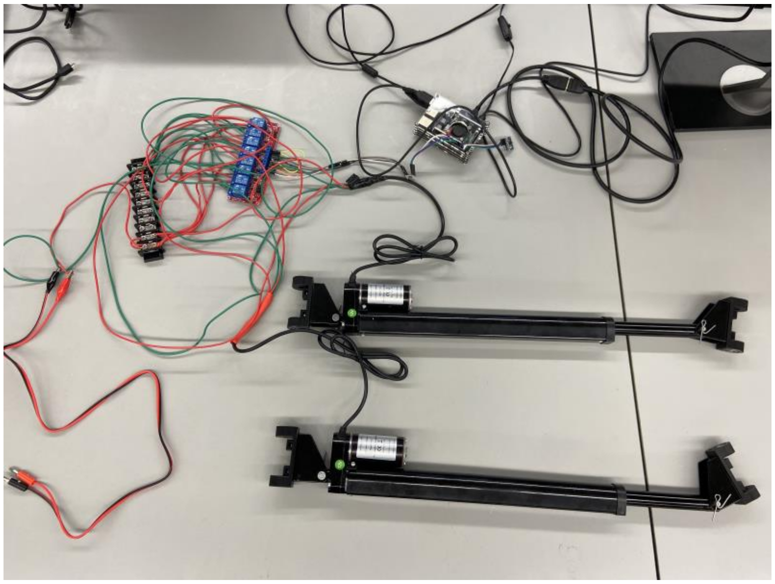


Figure 7: Motorized Mount Electronics

Figure 8: Motorized Mount After Full System Integration

3.4. Subsystem Conclusion

The motorized mount has been finalized and fully integrated. The system has been fully validated and works with the integrated system.

4. Route Planning Subsystem

4.1. Subsystem Introduction

This subsystem's purpose is to plan all the individual points the antenna will scan in order to create the necessary image. It reads in different pixel-based coordinates based on what mode the user selects and then plans all the necessary steps.

4.2. Subsystem Details

The subsystem reads in the pixel radius of the image and the pixel coordinates selected by the user with the center of the skymap photo as the origin. Based on what the program needs for each mode, the script extrapolates and transforms the different positions.

The two-dimensional area scan takes in two inputs containing the coordinates of diagonal rectangle corners. First, the program extrapolates all additional points based on the HPBW and the two input points. The route planner then feeds this list of points to the heart of the program, the projection mapper. The projection mapper converts the given points from the equal area projection to the spherical coordinate system used by the motorized mount. The program starts by normalizing the points according to their maximum radius. It then converts from 2-D Cartesian points to 2-D polar points. Using these polar points, the program converts to spherical coordinates using the standard inverse projection mapping for the equal area projection used in this project. Then the route planner uses a conversion equation to map the spherical projection into one that instead uses two-phi values. These final phi values are then output as a list to be delivered to the Raspberry Pi.

Two-dimensional terrestrial sweep uses a similar method but only generates points for a single axis. Both one dimensional terrestrial sweep and repeated point analysis use the inverse projection to output a single point.

4.3. Subsystem Validation

This subsystem has been validated within the integration of the whole system. The subsystem was integrated with the GUI and fed data from user inputs. Every test the Route Planner was subjected to it flawlessly output the correct points in the correct order to the Motorized Mount. It was tested in every mode and given a variety of inputs. The system worked well and correctly mapped the route during every full unit and full system test. An example of the coordinate selection is shown below.

Phi x	Phi y	Phi x	Phi y	Phi x	Phi y	Phi x	Phi y	Phi x	Phi y	Phi x	Phi y	Phi x	Phi y
-37	-23	-28	-22	-20	-21	-11	-20	-3	-20	5	-20	14	-20
-36	-14	-27	-13	-19	-12	-11	-12	-3	-12	5	-12	13	-12
-35	-5	-27	-4	-19	-4	-11	-4	-3	-4	5	-4	13	-4
-35	5	-27	5	-19	4	-11	4	-3	4	5	4	13	4
-36	14	-27	14	-19	13	-11	13	-3	12	5	12	13	13
-37	24	-28	22	-20	21	-12	21	-3	20	5	20	14	21
-39	33	-30	31	-21	30	-12	29	-3	29	6	29	14	29
-41	43	-32	40	-22	38	-13	37	-4	37	6	37	15	38
-45	52	-35	49	-25	47	-14	46	-4	46	7	46	17	46

Table 2: Route Planning Validation 2-D Area

Phi x	Phi y
-64	73
-54	60
-47	48
-43	37
-41	25
-39	13
-39	2

-39	-10
-40	-21
-42	-33
-46	-45
-51	-56
-60	-69

Table 3: Route Planning Validation 2-D Terrestrial

Phi x	Phi y
31	17

Table 4: Route Planning Validation 1-D Terrestrial & RPA

Test Number	Mode	Completion
1	2D Area	PASSED
2	2D Terrestrial	PASSED
3	1D Terrestrial	PASSED
4	RPA	PASSED
5	2D Area	PASSED
6	2D Area	PASSED

Table 5: Route Planning Validation Data

The validation data above shows how the system performed during the full tests and examples of how the data it would output during each mode. All of the points were read in by the motorized system and the correct order was output.

4.4. Subsystem Conclusion

This subsystem is fully integrated with the system and works for all modes. The system works well and communicates the data to the rest of the system where it is integrated and has been utilized in several full system tests.

5. Signal Processing Subsystem

5.1. Subsystem Introduction

The goal for this subsystem is to successfully pull raw data from the desired SDR at the selected center frequency through Python, apply wavelet denoising to the signal, graph the raw and denoised data to validate results, and output the peak magnitude and frequency of that scan point in CSV files. During full system operation, the antenna pauses movement at each scan point, calls the signal processing software, adds that peak magnitude and frequency value to the data files, and continues movement to the next scan point where it repeats the process. Once the antenna has completed the instructed route and filled the magnitude and frequency files, these files are sent to the image processing software to create heatmaps for the final image overlay.

5.2. Subsystem Details

The signal processing subsystem uses the soapy power library in Python to communicate with an SDR. The soapy power library has a number of settings to customize the signal acquisition. This signal processing script uses several including defining the correct driver, defining the center frequency, outputting the raw data to a specific CSV file, specifying the desired gain, cropping the raw data as needed to remove soapy power artifacts, and averaging several spectra of data to output more accurate results.

The signal processing script also converts the magnitudes output by the soapy power module from dB into linear values. The signal data is then sent through a fast Fourier transform using a function within NumPy. The threshold for this transformation was chosen to best represent the raw data while removing extraneous noise. From the denoised signal data, the script pulls the peak magnitude and the corresponding frequency and outputs these values to separate CSV files within the network drive. Additional peak magnitude and frequency values are appended to these CSV files as the antenna continues its routing path. Once the route is complete these CSV files are saved to the network drive and are read in by the image processing software.

The SDR used in this project is the RTL-SDR as this unit is robust and can withstand long scanning sessions without overheating. Initially, the project was going to use the Airspy Mini SDR, however this device broke as soon as it was plugged into the Raspberry PI. After spending several months trying to get an Airspy Mini replacement, the team decided to move forward with using the RTL-SDR. The RTL-SDR is a much cheaper SDR, and as expected can show additional noise compared to the Airspy Mini. However, with the Fourier transform to smooth out the raw data, the RTL-SDR works well above the specified accuracy requirement listed in the FSR. The python program for signal processing was written to easily pull data from either SDR only requiring a simple change of driver specification in the soapy power function call.

5.3. Subsystem Validation

The validation for this subsystem is fully complete. The signal processing program was tested with the RTL-SDR to confirm successful data pulling, accurate raw data, and correct peak frequency and magnitude values calculated from the denoised data.

The accuracy of the raw data was determined by comparing the signal processing program output to results in SDRSharp which is the program maintained by Airspy for SDR signal viewing.

These tests were completed with the RTL-SDR and the first test antenna with a center frequency of 1.2Ghz. The series of five tests was taken over a period of 30 minutes in the FEDC. The validation requirements show that the system must have an inaccuracy rate less than 30%. These test results show an accuracy rate of 100% or an inaccuracy rate of 0%.

Test Number	Successfully Pulled Data	Confirm Data Accuracy	Output Correct Magnitude	Output Correct Frequency
Test #1	PASS	PASS	PASS	PASS
Test #2	PASS	PASS	PASS	PASS
Test #3	PASS	PASS	PASS	PASS
Test #4	PASS	PASS	PASS	PASS
Test #5	PASS	PASS	PASS	PASS

Table 6: Signal Processing Validation

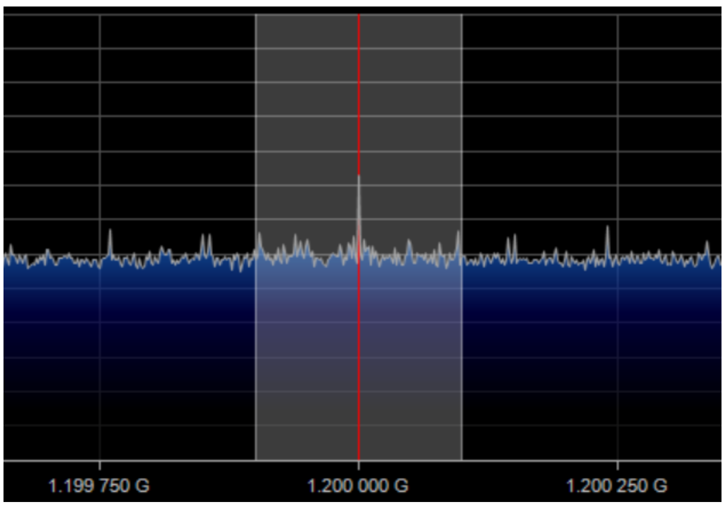


Figure 9: SDRSharp Signal, 1.2GHz Center Frequency

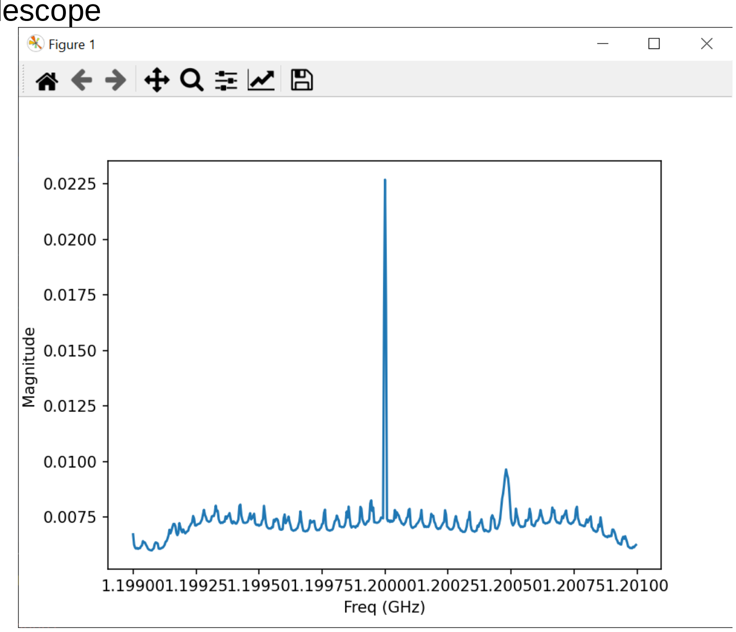


Figure 10: Signal Validation Test

Magnitude: 0.02269, Frequency: 1.2 GHz

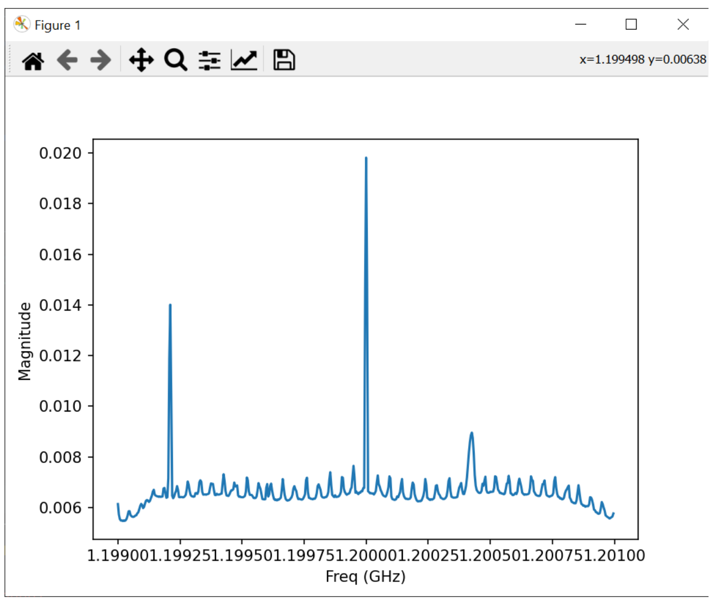


Figure 11: Signal Validation Test #2

Magnitude: 0.01981, Frequency: 1.2 GHz

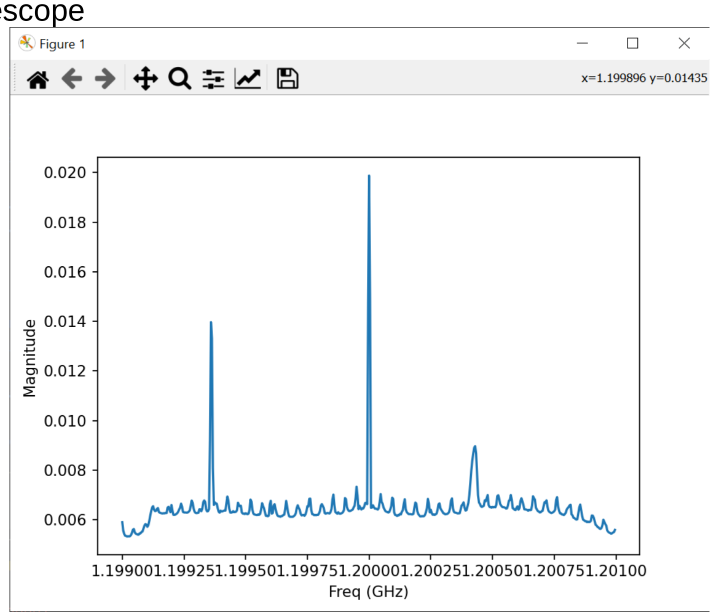


Figure 12: Signal Validation Test #3

Magnitude: 0.01988, Frequency: 1.2 GHz

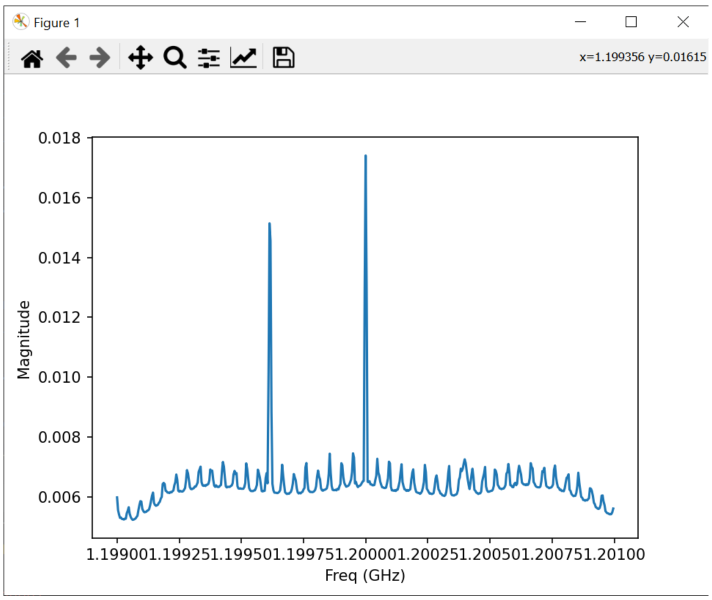


Figure 13: Signal Validation Test #4

Magnitude: 0.01740, Frequency: 1.2 GHz

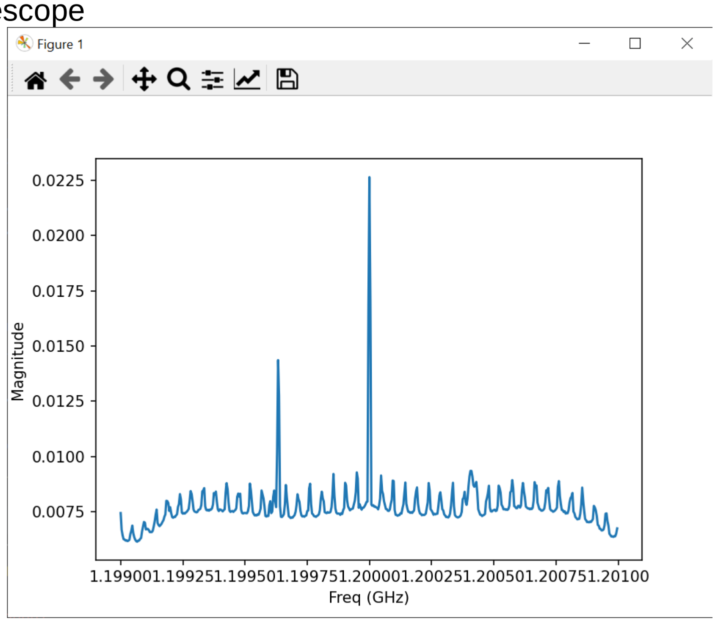


Figure 14: Signal Validation Test

Magnitude: 0.02264, Frequency: 1.2 GHz

Once the antenna array was assembled the four antenna elements were connected through the power combiner and LNA via coaxial cables. In order to clean up the noise added to the signal due to the LNA, the signal processing program took a reading from the RTL-SDR with just the LNA attached. This data set was then used as a reference signal and was subtracted from all data sets taken with the antenna elements attached to the SDR. Subtracting the reference signal from the antenna signals removed the noise from the LNA and increases the accuracy of the program output peak magnitude and frequency values.

The graph below displays a reference signal, a new signal taken with the antenna array attached to the RTL-SDR, and the output signal which is the difference between these two signals. The calibrated data graph clearly shows the removal of the three waves that are present in the reference and new signals.

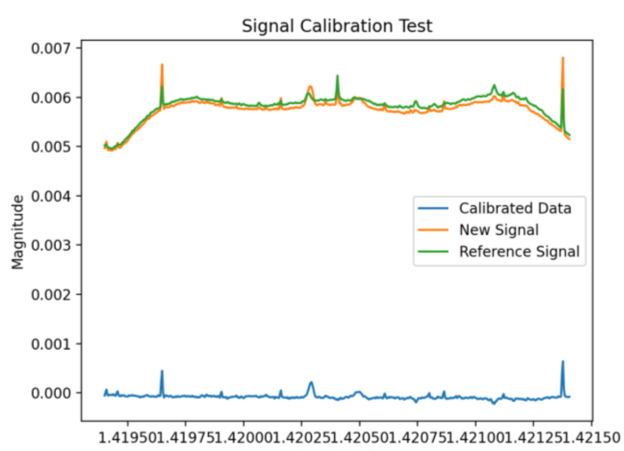


Figure 15: Signal Calibration

Further data processing accuracy tests were completed with the assembled antenna array to fulfill reference 3.2.1.3. In order to complete this validation, the antenna was run through several routes where it called the signal processing functions at each specified scanning point. The filtered signal data for each point was saved as a graph with the program output peak magnitude and frequency as the graph label. Each graph was visually assessed to determine the filtered data's peak magnitude and frequency values and these values were compared to the program's output peak magnitude and frequency. The table below shows the results of the tester determined values versus the program determined values.

Program Determined Magnitude	Program Determined Frequency	Tester Determined Magnitude	Tester Determined Frequency	Deviation of Magnitude	Deviation of Frequency
0.000108241	1420.305	0.00011	1420.305	1.75909E-06	0.000
0.000854071	1420.309	0.00085	1420.305	4.07107E-06	0.004
0.00085974	1420.301	0.00085	1420.3	9.74002E-06	0.001
0.000763548	1420.305	0.00076	1420.305	3.54759E-06	1.00044E-11
0.000479774	1421.377	0.00048	1421.38	2.26155E-07	0.003
9.05E-05	1420.305	0.00009	1420.305	4.68141E-07	1.00044E-11
0.000790101	1420.305	0.00079	1420.305	1.01089E-07	1.00044E-11
0.000815437	1420.301	0.00081	1420.3	5.4374E-06	0.001
0.000725207	1421.377	0.00073	1421.38	4.7931E-06	0.003
0.000301505	1419.401	0.0003	1419.4	1.50521E-06	0.001
4.67E-05	1421.121	0.000047	1421.12	3.17018E-07	0.001
0.000560788	1421.121	0.00056	1421.12	7.87906E-07	0.001

Table 7: Signal Validation

The graphs below display histograms of the magnitude and frequency deviations between tester and program determined values. The magnitude values below were divided by 1E-6 while the frequency values below were divided by 1E-2 to display the graphs in a concise manner.

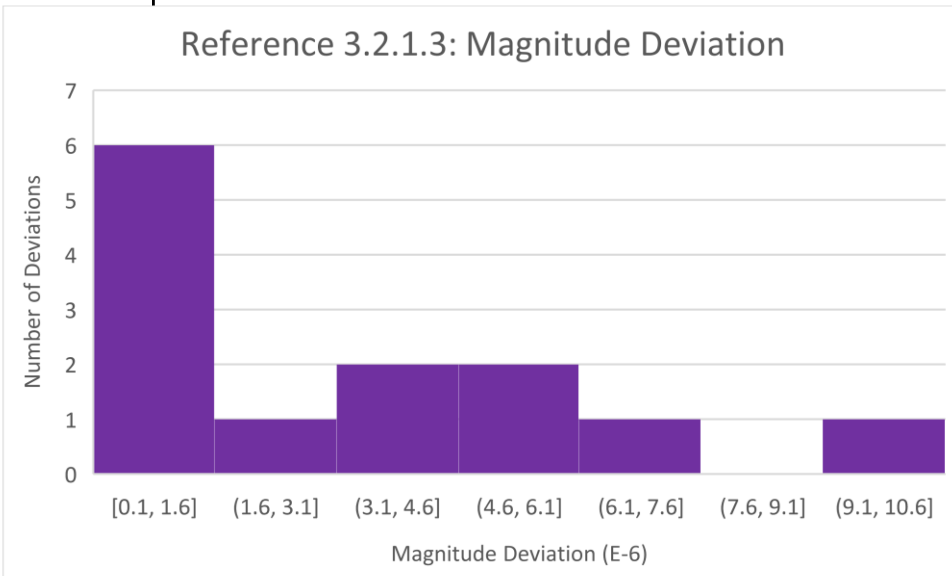


Figure 16: Magnitude Deviation

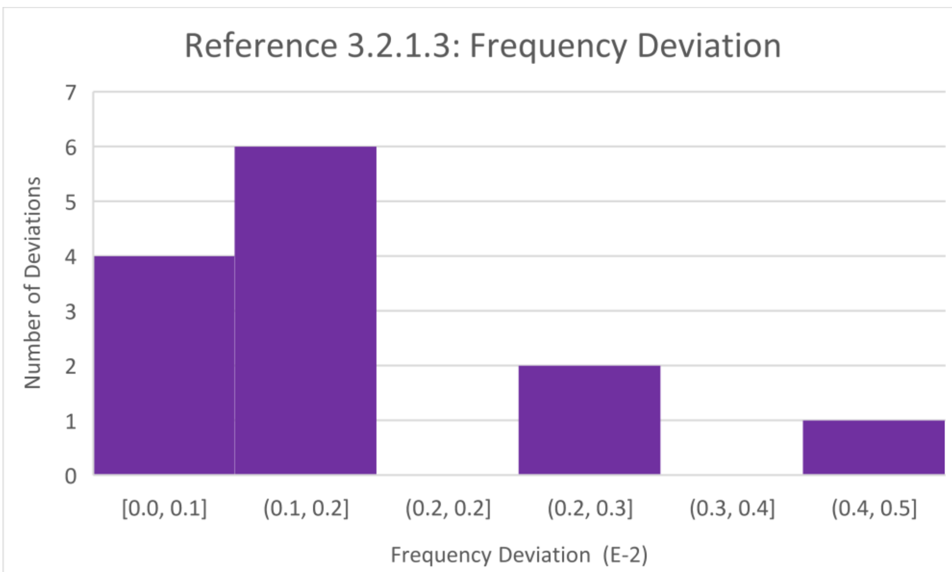


Figure 17: Frequency Deviation

As seen by the table and graphs above, the signal processing subsystem completed the validation for reference 3.2.1.3 with 100% data processing accuracy.

5.4. Subsystem Conclusion

All execution and validation goals for this subsystem are completed. This subsystem was successfully integrated with the rest of the HLT subsystems and works well within the specifications listed in the FSR.

6. Image Processing Subsystem

6.1. Subsystem Introduction

This subsystem takes in CSV files containing the peak magnitude and frequency data values found at each scan point output by the signal processing subsystem. After the image processing subsystem reads in the CSV files from the Raspberry PI, it then converts those CSV files into heatmaps that display the doppler shift and intensity of each scan point. These heatmap images are interpolated and overlaid on skymap photos of the scanned area so that the user can visualize the scan data and see the elements of the galaxy in the skymap behind the semi-transparent heatmap image. The final overlaid image is output to the user via the results GUI window along with a legend of the heatmap to facilitate data comprehension for the user.

6.2. Subsystem Details

The image processing subsystem was written in Python and primarily makes use of the pandas, matplotlib pyplot, and pillow libraries. The heatmaps are created based on a color scheme consisting of three colors, red, blue, and purple to make up the gradient displayed in the image below.

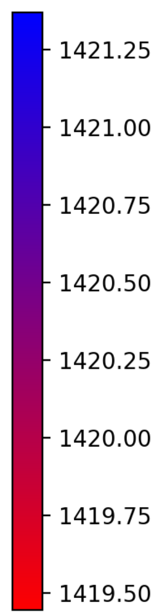


Figure 18: Heatmap Legend

These colors were chosen to represent the doppler shift of the object the antenna is scanning as well as the center frequency. In the heatmaps, any frequency values around the center frequency are assigned the color purple while values less than the center frequency values shift towards the color red and any values greater than the center frequency values shift towards the color blue. The red values indicate objects that are moving away from the antenna, the blue values indicate objects that are moving towards the antenna, and the purple values indicate objects that are remaining stationary in relation to the antenna.

Once each frequency value in the heatmap is assigned to either a red, blue, or purple gradient color, the intensity of each pixel is adjusted using the magnitude of the signal at each data point. The magnitude data received by the signal processing subsystem is normalized between a defined maximum and minimum magnitude in Python for use in a heatmap opacity function through pillow. Defining these static maximum and minimum magnitude values allows the user to accurately compare data and heatmaps between different system runs. The largest magnitude values receive the highest intensity in color while the smallest magnitude values fade towards white. Finally, the individual pixels are interpolated to create a cohesive heatmap image ready for overlay.

Once the heatmap is correctly interpolated, the program fetches the corresponding skymap image and user selected coordinates for the image overlay function. The heatmap is adjusted to fit the area originally selected by the user and is overlaid on top of that area with an opacity of 30%. This opacity value allows the user to see the heatmap colors and intensities while also being able to determine any objects behind the heatmap that are present in the skymap photo. Displaying the results in this manner allows the user to identify stars, planets, and sections of the Milky Way galaxy via the skymap photo and the hydrogen emissions.

The image below shows a sample heatmap of a 2D area selection using generated data. The data to heatmap accuracy was validated in the first semester of Senior Design.

Figure 19: 2D Area Heatmap

The image below shows sample heatmaps for a 2D terrestrial sweep selection using generated data. This data would be displayed to the user via a gif where each frame contains a skymap and heatmap at one scan time.

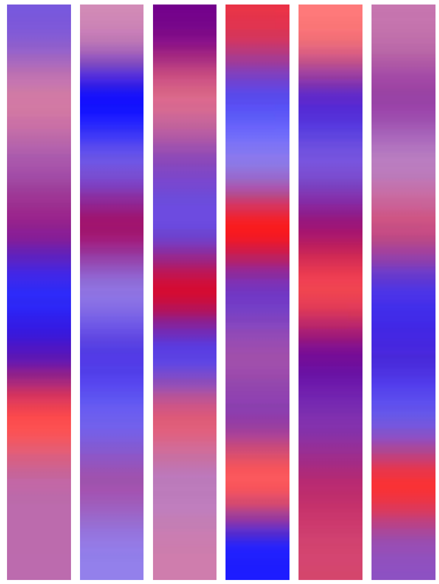


Figure 20: 2D Terrestrial Heatmaps

The images below display the heatmaps for the 1D terrestrial sweep and repeated point analysis (RPA) modes. Like the 2D terrestrial, these images will also be displayed as a gif to the user overlaid on a skymap image at each timestamp.

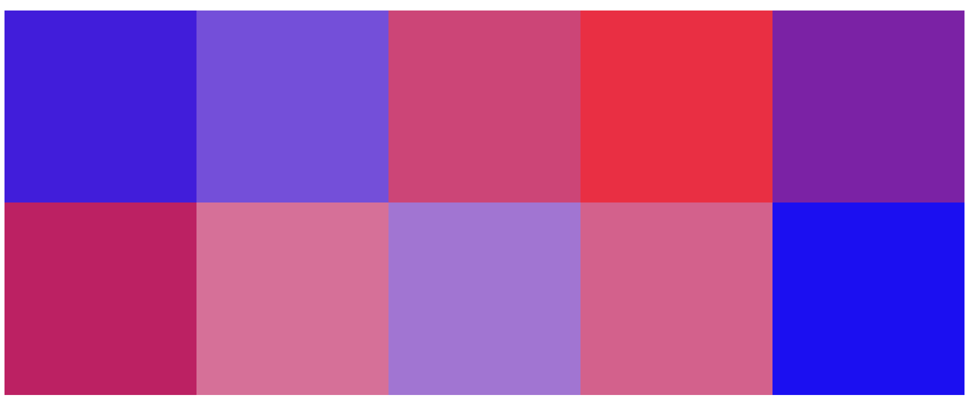


Figure 21: 1D Terrestrial & RPA Heatmaps

6.3. Subsystem Validation

This subsystem was tested and validated by creating randomized data for each mode of telescope operation. This data containing peak magnitudes and the corresponding frequencies, was saved in CSV files to emulate the input files identical to the files that will be input to this subsystem during full system operation. These CSV data files were then fed into the appropriate function in the image processing script to produce heatmaps for each mode of operation.

The modes of operation output for testing and validation consist of 2-dimensional area selection, 2-dimensional terrestrial sweep, 1-dimensional terrestrial sweep, and repeated point analysis. A total of five tests were completed to determine image processing accuracy with different randomized data created for each test. The tests passed if the raw data input to the image processing software matched the corresponding heatmap output.

Test Number	Successfully Imported Data	Output Correct Doppler Shift	Output Correct Intensity
Test #1	PASS	PASS	PASS
Test #2	PASS	PASS	PASS
Test #3	PASS	PASS	PASS
Test #4	PASS	PASS	PASS
Test #5	PASS	PASS	PASS

Table 8: Image Processing Validation

To validate the image overlay function, the coordinate selection GUI was used to select scanning areas and set specified durations as needed. Once the scan area coordinates were selected, the program took the necessary Stellarium images for the gif overlays and the image overlay function was called with synthetic data. A total of five tests were recorded for the validation, however, many more tests were successfully completed throughout full system demonstrations. After the image overlay function output its results, the placement, opacity, and readability of each overlay was graded and entered into the table below as either a pass or fail.

Test Number	Correctly Overlaid Heatmap	Skymap Details are Visible	Heatmap Details are Visible
Test #1	PASS	PASS	PASS
Test #2	PASS	PASS	PASS
Test #3	PASS	PASS	PASS
Test #4	PASS	PASS	PASS
Test #5	PASS	PASS	PASS

Table 9: Image Overlay Validation

A sample 2D area overlay is shown below, this image was taken from a full system demo and utilizes real data.

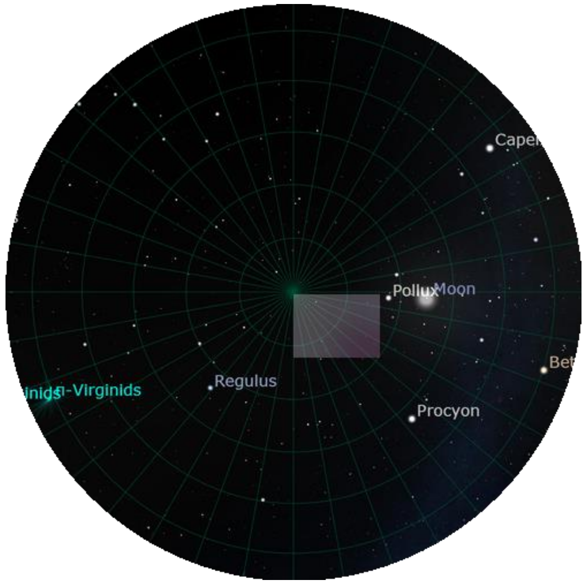


Figure 22: 2D Area Overlay Validation

A sample 2D terrestrial sweep overlay is shown below, this image utilizes synthetic data to validate the image overlay functions.

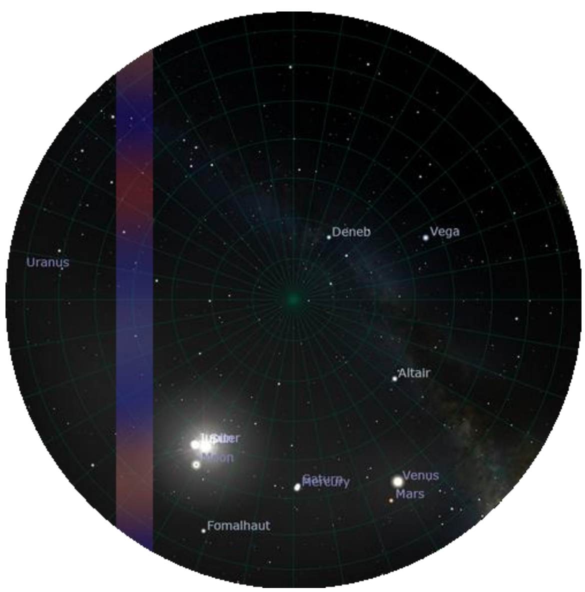


Figure 23: 2D Terrestrial Overlay Validation

A sample 1D terrestrial sweep and repeated point analysis overlay is shown below, this image utilizes synthetic data to validate the image overlay functions.

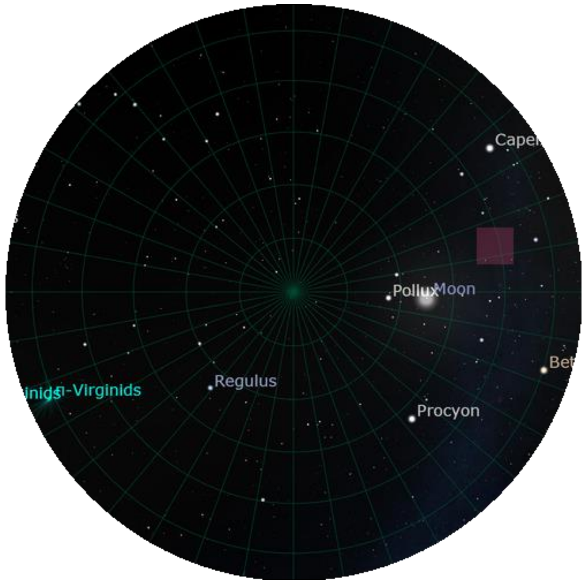
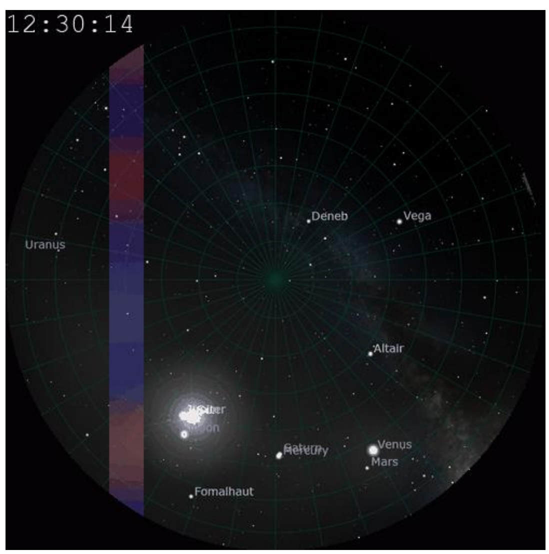


Figure 24: 1D Terrestrial / RPA Overlay Validation

A sample gif frame is shown below for the 2D terrestrial sweep mode using synthetic data. Each gif frame is labeled with the corresponding timestamp.



6.4. Subsystem Conclusion

The validation and execution for the image processing subsystem is complete. This subsystem has been successfully integrated with the signal processing subsystem in order to output heatmaps for real time data and merge the heatmaps with skymap screenshots from Stellarium.

7. Graphical User Interface Subsystem

7.1. Subsystem Introduction

The graphical user interface (GUI) subsystem allows the user to select their desired scanning mode and determine the scanning coordinates and duration that will be sent to the route planning subsystem and antenna. The goal for this subsystem was to create a simple and easy to understand design with clear use instructions included for each mode of operation.

7.2. Subsystem Details

This subsystem makes use of the tkinter Python library for GUI development. The subsystem also accesses Stellarium's API to take a current screenshot of the galaxy each time the GUI starts running. The Stellarium screenshot is customized for the purpose of this project by adjusting Stellarium's field of view, showing the azimuthal grid, adjusting the view to the current date, time, and location, and setting the zoom level to show a complete image of the sky. The projection method chosen in Stellarium is the Lambert Azimuthal Equal-Area projection as this projection style fits well with the scope of this project and the needs of the route planning subsystem.

After the real-time skymap screenshot is procured from Stellarium, this screenshot is sent through a few cropping functions. These functions crop the image to specific image dimensions and create a circular image that is adjusted so that the user can only select within the range of the antenna. This final circular image is displayed in each GUI coordinate selection window and is used in the final image overlay in the image processing subsystem.

The skymap coordinates are chosen by the user after they click the "Select Corners" or "Select Point" button within each mode. As stated in each mode's instructions, after this button is selected, the program will start recording mouse click coordinates within the Skymap image. These coordinates are normalized to an x-y coordinate system with the origin at the center of the Skymap and display below the Skymap after selection. The program only allows the user to select the proper number of coordinates based off of the chosen mode.

Several error handling and visualization features were added to the coordinate selection of the GUI during the second semester of Senior Design. For the 2D area mode, the user can select any diagonal rectangle corners and the GUI will draw a gray rectangle depicting the total area selected. For the 2D terrestrial mode, the user can select any single point on the skymap, and the GUI will draw two vertical parallel lines depicting the scan path of the antenna. For the 1D terrestrial and repeated point analysis modes, the user can select any single point on the skymap and the GUI will depict a gray square showing the beamwidth of the antenna at that point. The user can also enter in a duration between one and five hours for the 2D terrestrial, 1D terrestrial, and repeated point analysis modes as these modes scan the selected area periodically over the specified duration. If the user does not enter in a duration, the duration field is automatically set to one hour.

If the user incorrectly selects any points or would like to change the scanning area, they will be prompted to click a circular “R” button in the upper left corner to reset the coordinate selection and area visualization drawing. The user can then reselect points as desired and visualize the scan area upon selection. In the 2D area mode, the GUI also catches any selections that are too small for the antenna to scan (less than ten degrees width or height). When the program detects this error, it displays an error message to the user detailing the issue and prompts the user to reselect the scan points.

When the user selects the “Initiate Scan” button, the GUI sends the selected coordinate(s) directly to the route planning subsystem. Once the route information is received by the Raspberry Pi, the user’s laptop waits until the completed signal data information is ready to be read and transformed into a heatmap. After the image processing subsystem completes the heatmap generation and image overlay, the GUI subsystem displays the overlayed skymap and heatmap as a static image for the 2D area mode or a GIF for the 2D terrestrial, 1D terrestrial, and repeated point analysis modes.

The GUI subsystem flow begins by displaying a window briefly describing each of the antenna scan mode options and allowing the user to select their preferred mode. This window is shown below.

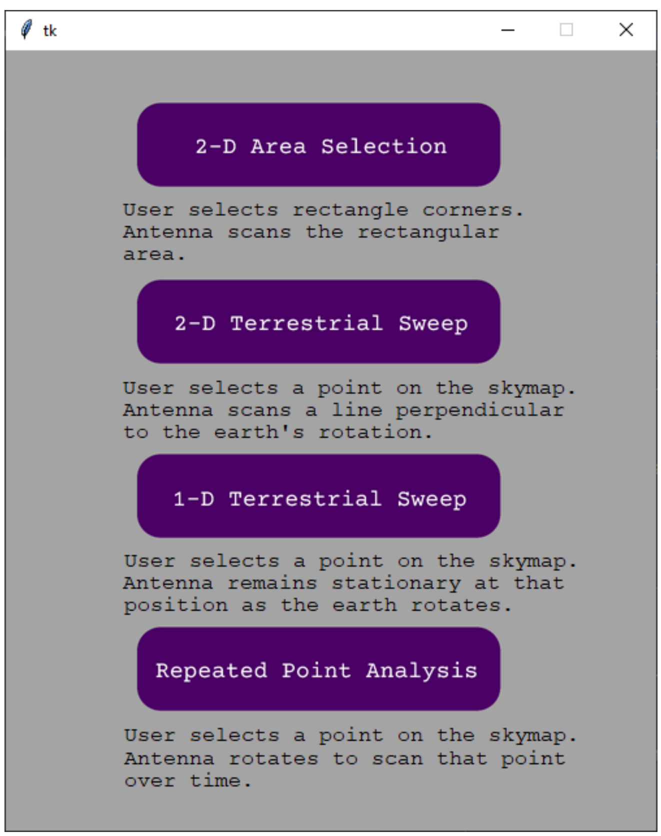


Figure 25: GUI Mode Selection

Once the user chooses their desired scan mode, the GUI displays the corresponding coordinate selection window. Each area selection window displays the current skymap image as well as a set of more detailed area selection instructions customized for each mode. This window also features visual selection aids in the form of a gray rectangle, square, or set of parallel lines to depict the scan pattern of the antenna for the user's selection as well as displaying the selected numerical coordinates below the skymap image. The area selection window also contains a reset button that will remove the current visual selection aid and numerical coordinates allowing the user to start a new area selection. In the 2D terrestrial, 2D terrestrial, and repeated point analysis modes, the user can also select a scan duration in hours. The coordinate selection windows are shown below with sample area and duration selections.

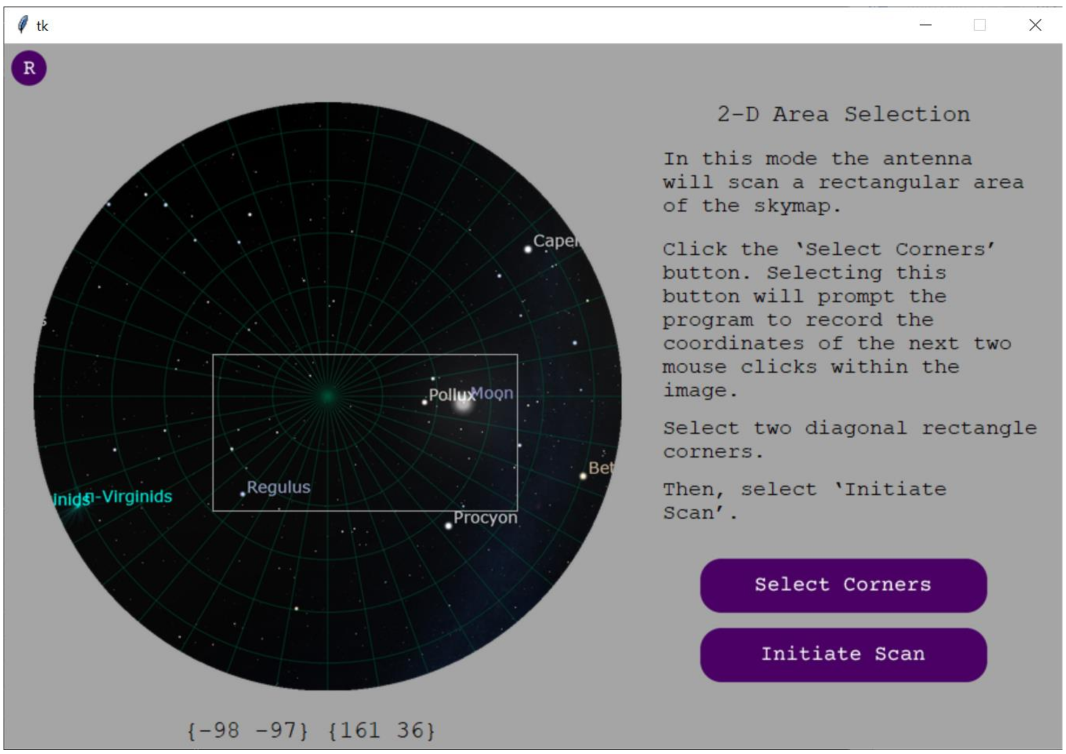


Figure 26: GUI 2-D Area Selection

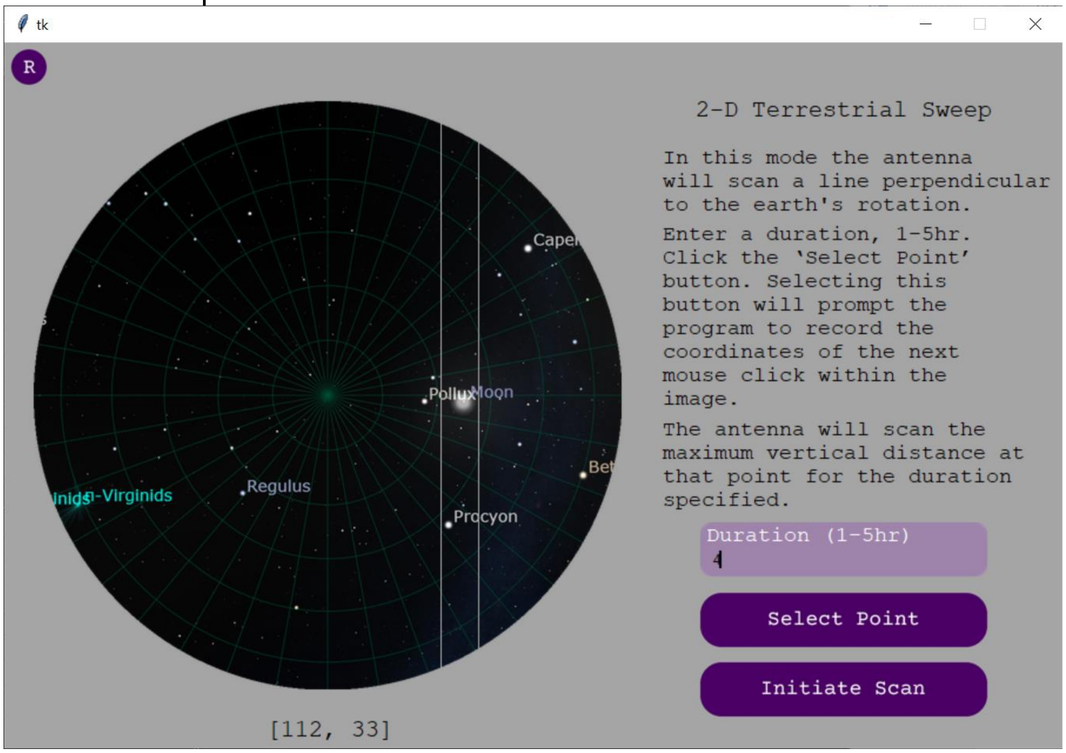


Figure 27: GUI 2-D Terrestrial Sweep

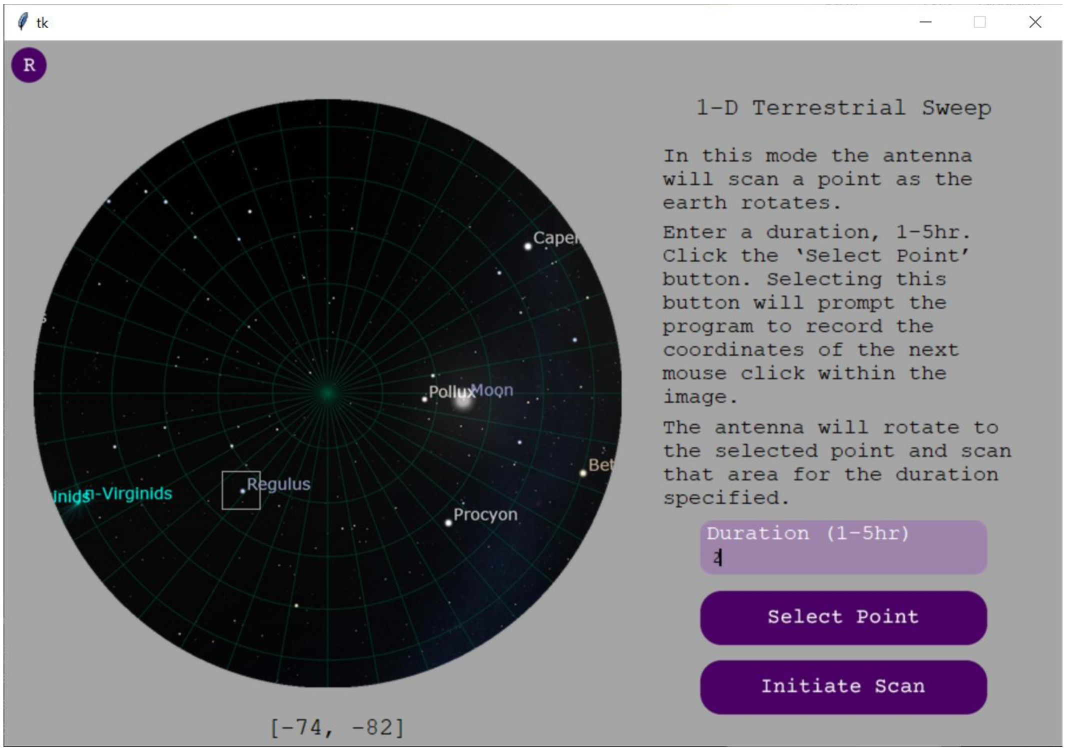


Figure 28: GUI 1-D Terrestrial Sweep

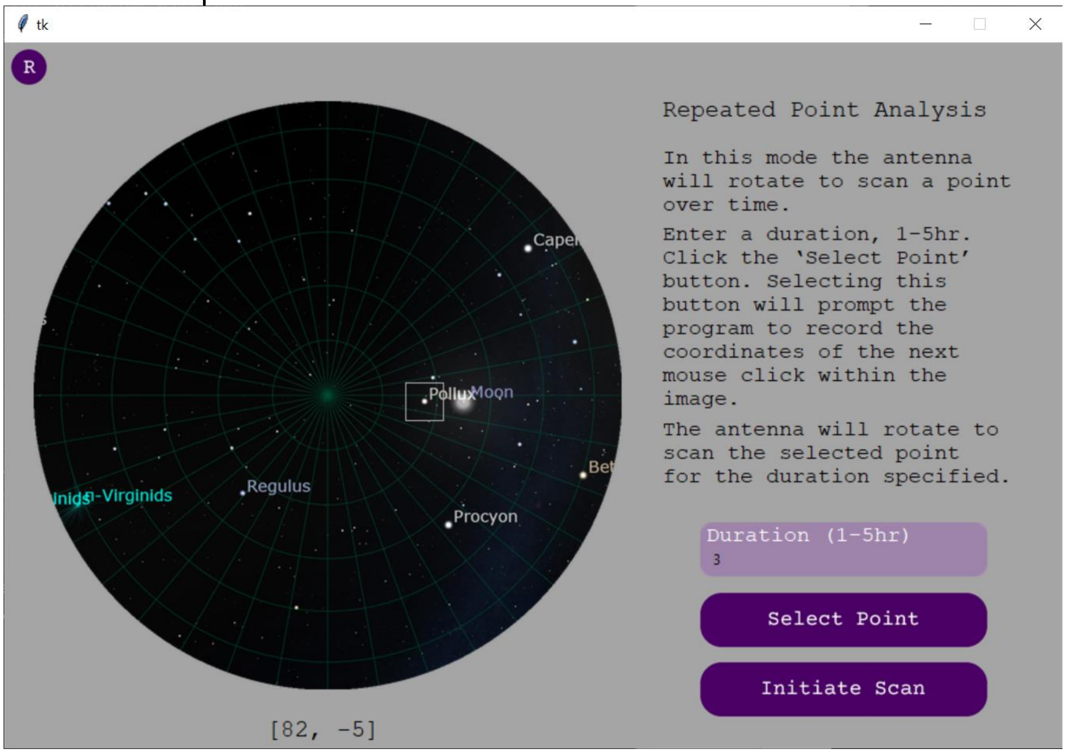


Figure 29: GUI 1-D Terrestrial Sweep

Once the system completes scanning, signal processing, and image processing, the GUI will display the results in a clear and concise manner to the user. The results GUI window contains a legend for the heatmap and an explanation of the results so that the user can easily understand the visualized data. The user can also press the "Open Results Folder" button to open up a folder stamped with the scan date and time containing all of the raw data, heatmaps, and image overlays for further study. The user can also navigate through previous scan data using the timestamped folders in order to compare scan results as desired.

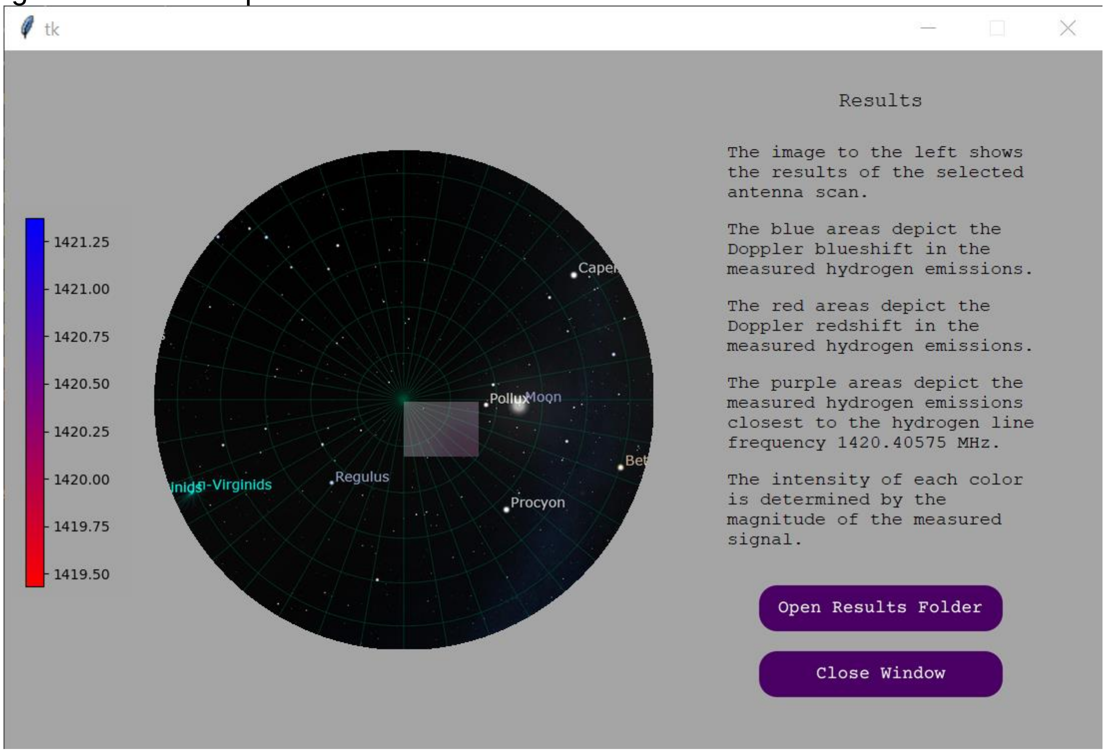


Figure 30: GUI Results Window

7.3. Subsystem Validation

This validation for this subsystem included interacting with a potential user of this product to complete reference 3.2.1.4. The user interacted with the GUI after 3 minutes of instruction during which the general project concept and flow was explained briefly. The user then rated each category of the GUI based off of their experience. The rating categories included design, instruction clarity, and ease of use.

The user chosen for this review was a sophomore electrical engineering student and fits the profile for future users of this product. The three minutes of instruction involved explaining the project concept to the user so that they could understand the reasoning behind the mode, coordinates, and duration selections. After the user interacted freely with the GUI, they were left to fill out the review form shown below. A rating of 1 indicates a need for significant improvement while a rating of 10 indicates that no improvements are needed. The GUI received an overall grade of 97.5% for this validation reference.

Category:	Rating:	Comments:
Design	10	Design is basic but straightforward and fulfills its requirement.
Instruction Clarity	9	Instructions were clear and concise, but some required inputs weren't clearly marked

		such as the time and could use additional surrounding explanation.
Ease of Use	10	Easy to use and navigate
Cool Factor	10	Very cool Kanye
Total	39	
Max possible score	40	

Table 10: GUI Validation

Given the above user's feedback, several changes were made to the GUI to improve the user experience. The first change involved adding a description of the duration textbox for three of the scanning modes. The second change added a display to show the coordinate values to the user after selection from the Skymap. These changes were completed during the first semester of Senior Design.

This subsystem also underwent full system demo validation during the second semester of Senior Design which required a user to be able to be able to perform any of the desired modes within 15 minutes of training. Two users were asked to participate in this validation. The first user was a senior electrical engineering student while the second user was an electrical engineering teaching assistant.

The users were given less than 15 minutes of training, just enough to familiarize them with the project concept, function, and general GUI flow. After this training, they were allowed to interact freely with the GUI, watch the antenna move to their selected scan area, and view the GUI results display window as well as the raw data folder. After experiencing the full system demonstration, the users were asked to fill out the review form shown below.

Category:	Rating:	Comments:
Design	10	
Instruction Clarity	10	
Ease of Use	10	
Intuitive Results	10	
Cool Factor	10	
Total	50	
Max possible score	50	

Table 11: GUI Full System Validation, User #1

Category:	Rating:	Comments:
Design	10	Very cool structure, looks very pleasing to use
Instruction Clarity	9	GUI is mostly intuitive. Reset / false coordinate entry takes a second to figure out, but clear instructions are given on the screen.
Ease of Use	9	GUI is mostly intuitive; some buttons take a minute to get used to.

Intuitive Results	10	Image display is clear and intuitive, all data presented well
Cool Factor	10	YES!
Total	48	
Max possible score	50	

Table 12: GUI Full System Validation, User #2

7.4. Subsystem Conclusion

The GUI subsystem is an integral part of this project as it links all of the other subsystems together for full system integration. With the GUI completed and functioning as a reliable system and at an intuitive level as determined by the user feedback, the entire system has a strong functioning base. All execution and validation goals were completed for the GUI subsystem.

8. Appendix

The Python scripts for all software subsystems are in the GitHub link for this project below.

johannahein/Hydrogen-Line-Telescope at final-project-code (tamu.edu)

Hydrogen Line Telescope

Warren Herrington
Johanna Hein

SYSTEM DESCRIPTION AND DEVELOPMENT

FINAL REVISION
13th April 2022

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1. Overview

The Hydrogen Line Telescope (HLT) is a reliable and intuitive way for users to view sections of the Milky Way galaxy using hydrogen emissions. The HLT consists of six subsystems: Antenna, Motorized Mount, Route Planning, Signal Processing, Image Processing, and GUI. These six subsystems work together to create a smoothly integrated Hydrogen Line Telescope that meets the specifications and requirements outlined in the FSR. Upon completion of these six subsystems and a successful integration, this team was able to provide users with an intuitive, automated, portable, and accessible Hydrogen Line Telescope for use as an educational tool that will further the understanding of radio telescopes and the Milky Way galaxy.

2. Development Plan and Execution

The six individual subsystems were completed during the first semester of Senior Design. The second semester of Senior Design focused on integrated these six subsystems to create a fully working Hydrogen Line Telescope. After integration was completed, the remainder of the second semester was spent validating the full system as well as completing some fine tuning with the software and hardware. This report will focus on the execution and validation completed during the second semester of Senior Design.

2.1. Design Plan

The design plan for the Hydrogen Line Telescope began with several conversations with the project sponsor, Max Lesser. Lesser communicated a very broad idea of the project to this team with a few specific necessary elements including showing the doppler shift and displaying a resulting hydrogen overlay on an image of the scanned area. Lesser also stated that the full system did not have to be fully electronic or hands-off and could include extensive documentation that the user would have to read and understand before being able to use this radio telescope. The type of antenna, mount, and system function were left completely up to the HLT team.

Having this amount of creative freedom inspired the HLT team to go above and beyond with the HLT project goals. The team completed extensive research into different types of antennas, talking with several professors and acquiring a retired antenna specialist as a very invested mentor figure. The team also decided to make the entire system fully hands-off and electronic, requiring the user to only press a few buttons on a GUI in order to instruct the antenna to scan any selected area, this decision dramatically increased the amount of software required for the project. The team also defined four separate modes of operation for the user to select depending on their scanning purpose. The team's goal was to make this hydrogen line telescope extremely intuitive for the user so that any individual, regardless of radio telescope knowledge, could open up the GUI, select a mode and scanning area, and interpret the results correctly. As most hydrogen line telescopes are very primitive, having a telescope that can scan and display results in a very intuitive manner is unique and promotes the use of this telescope as an educational tool.

Once the general design plan was determined, the project was split into six subsystems. These subsystems include the antenna, motorized mount, route planning, signal processing, image processing, and graphical user interface. These six subsystems were clearly defined and split between the two team members according to each person’s skill sets and interests. Herrington was assigned to the antenna, motorized mount, and route planning subsystems, focusing on the more mechanical parts of the project. Hein was assigned to the signal processing, image processing, and graphical user interface subsystems, focusing on the more software-based parts of the project.

The individual subsystems were competed during the first semester of Senior Design after which the team moved on to subsystem finalization and integration.

2.2. Execution Plan

The execution plan for the second semester of Senior Design is shown below. This execution plan covers mainly the first half of the semester as the second half was spent focusing on competed validation and fine tuning the software and hardware to get the fully integrated system working together seamlessly. The focus during the first half of the semester was to build the physical parts of the system, the antenna and motorized mount subsystems. The electrical parts of these subsystems were completed and partially validated during the first semester of Senior Design, but the physical elements were simply designed and not yet fabricated.

The software execution plans focused on finalizing a few details within the subsystems to prepare for integration. The signal processing added a fast Fourier transform on the raw signal data to clean up the signal and find more accurate peak magnitudes and frequencies. The image processing subsystem completed image overlay for the results. The GUI completed integrating with Stellarium and displaying the final results to the user in an understandable manner.

Once the items in the below execution plan were completed, the focus was switched to completing full system integration as soon as possible. Given this team’s thorough work on finalizing and testing each subsystem, integration went fairly smoothly with only a few minor issues to fix for the subsystems to work together. The main integration issues were related to the mechanical parts of the project as a few of the 3D printed parts were not strong enough to hold all four antenna elements and the backplane during system routing at certain angles. These mechanical issues were resolved by acquiring stronger 3D printed parts and supporting these parts even more with strategically placed springs to reduce the load at critical points.

There were very few software issues present during final integration, these errors were easily solved, and the entire system was fully integrated and working correctly within several weeks after the end of the execution plan below. The last few weeks of March were spent completing validation and preparing for the final presentation and demonstration. Full system integration was completed and validated by April 8th before the team gave their final presentation.

Subsystem	Integration Steps	Jan 21 - Jan 27	Jan 28 - Feb 3	Feb 4 - Feb 10	Feb 11 - Feb 17	Feb 18 - Feb 24	Feb 25 - March 4
GUI							
	Integrate stellarium with .gif						
	Display final results						
Signal Processing							
	Apply wavelet denoising						
	Repair Airspy mini						
	Run from raspberry pi						
Image Processing							
	Create heatmap .gif						
	Overlay heat map						
Antenna							
	Attach antenna to backplane						
	Impedance match with LNA						
Motorized Mount							
	Complete mount assembly						
	Acquire electronics enclosures						
Route Planning							
	Communication with motorized mount						
	Account for earth's rotation						
Full Integration Testing							

Table 1: Execution Plan

2.3. Validation Plan

The validation plan for the second semester of Senior Design is shown in the table below. This validation plan follows the validation requirements listed in the FSR for subsystem and full system functionalities. As seen in the table below, all validation requirements were successfully completed with the exception of reference 3.2.1.1 which could not be validated before the submission of this report due to remodeling of the anechoic chamber on the Texas A&M campus. The validation process, results, and data are listed and described in the full system data section of this report.

Reference	Test Name	Success Criteria	Methodology	Status	Responsible Engineers
3.2.1.1	Antenna Beam Width	The HPBW of the antenna shall be equal to or less than 10 degrees	Antenna to antenna gain mapping in a quiet room.	IN PROGRESS	Warren L. Herrington
3.2.1.2	Antenna Positioning	The motorized mount will position the antenna to within 5 degrees of the desired scanning location.	Use a digital level to measure locations.	COMPLETE	Warren L. Herrington
3.2.1.3	Data Processing	The data processing shall have less than a 30% inaccuracy rate when outputting the frequencies and magnitudes calculated from the SDR output	Compare peak magnitude & frequency output with raw data.	COMPLETE	Johanna K. Hein
3.2.1.4	Graphical User Interface	The graphical user interface shall be intuitive and user friendly. All HLT modes of operation and data results shall be easy to view and understand.	Allowed potential user to interact with & review the GUI.	COMPLETE	Johanna K. Hein
3.2.1.5	Antenna Routing	The positional system shall be able to correctly route the antenna at least 90% of the time	Compare output to desired route path.	COMPLETE	All
3.2.1.6	System Runtime	The system shall be able to position the antenna and collect data for up to 6 hours.	Run full system test for desired time.	COMPLETE	All
3.2.2.1	Mass	The system shall be made up of separable parts that are less than or equal to 25 kg per component.	Weigh each part.	COMPLETE	All
3.2.2.2	Volume Envelope	The antenna and motorized stand shall each stand less than or equal to 1 meter cubed.	Measure each part.	COMPLETE	All
3.2.2.3	Mounting	The antenna shall be mounted on a motorized stand that may rest on any stable, relatively level surface.	Complete mounting construction.	COMPLETE	Warren L. Herrington
3.2.3.1.1	Power Consumption	The maximum peak power of the system shall not exceed 45 watts.	Use a wattmeter to measure peak power consumed	COMPLETE	All
3.2.3.1.2	Input Voltage Level	The input voltage level for the Raspberry Pi 4 shall be 5V, the input voltage level for the DC stepper motors shall be less than or equal to 24V.	Measure input voltages for the Raspberry Pi and motors.	COMPLETE	All
N/A	Full System Demo	A user of the HLT will be able to perform any of the desired modes within 15 minutes of training.	Complete user training and analyze performance.	COMPLETE	All

Table 2: Validation Plan

3. Full System Data

3.1. Reference 3.2.1.1

The antenna beam width validation has not been completed for this project due to the inability to access the anechoic chamber on the Texas A&M campus. The chamber is currently being remodeled and cannot be used until completion of the construction.

3.2. Reference 3.2.1.6

The system runtime validation was completed in the FEDC. The integrated system was left powered and running for several consecutive days. The LNA, SDR, Raspberry Pi, and other electronics remained functional throughout the test.

3.3. Reference 3.2.2.1

The validation for reference 3.2.2.1 was competed by weighing each part of the integrated hydrogen line telescope using a large digital scale provided by the FEDC. Each separable part weighed less than the stated limit of 25 kg as seen in the table below. In fact, the entire system ended up being extremely lightweight with a total mass of 15.1 kg. The completion of this validation ensures that the system components will be easily moved between scanning locations given their low weight.

Item	Weight (kg)
Antenna Elements (4)	4.4
Antenna Frame	6.2
Mount Base	4.5

Table 3: Reference 3.2.2.1

3.4. Reference 3.2.2.2

The validation for reference 3.2.2.2 was completed by measuring each component of the hydrogen line telescope using a tape measure provided by the FEDC. Each separable part was less than the stated limit of one meter cubed as seen in the table below. The completion of this validation ensures that the system components can be easily moved between scanning locations given their dimensions so that the user can easily carry and fit each element into a vehicle for transportation.

Item	Height (m)	Width (m)	Depth (m)	Volume (m^3)
Antenna Elements	1.0668	0.4826	0.4826	0.248460664
Antenna Frame	0.1778	0.9144	0.9144	0.148663445
Mount Base	0.6223	1.016	1.016	0.642372909

Table 4: Reference 3.2.2.2

3.5. Reference 3.2.2.3

The validation for reference 3.2.2.3 was completed by finishing and testing the construction of the motorized mount with attached antenna elements. The requirements for this validation include a system containing a mount that can hold all four antenna elements and rest on a relatively stable and level surface.

An image of the completed motorized mount is shown below. The mount is able to rest on a relatively level surface and will level the backplane and antennas automatically upon system start with the accelerometer feedback loop. The mount fully supports the weight of the four antenna elements and the copper backplane throughout routing paths and movement tests within ±45º.

Figure 1: Reference 3.2.2.3

To supplement the strength of the aluminum extrusion and 3D printed parts used to construct the mount, the team used springs to support movement away from the side of the mount containing the linear actuators. An image of the springs attached to the motorized mount is shown below.

Figure 2: Support Springs

The team also utilized metal braces to support the points of connection between pieces of aluminum extrusion and hold the springs securely. These metal braces can be seen in the image below.

Figure 3: Motorized Mount Braces

3.6. Reference 3.2.3.1.1

The power consumption requirements in reference 3.2.3.1.1 were completed using the USB power meter and power supply shown below. The meter was used to measure the power consumption of the Raspberry Pi. The power consumed by the linear actuators was found by reading the voltage and current from the display on the power supply unit.

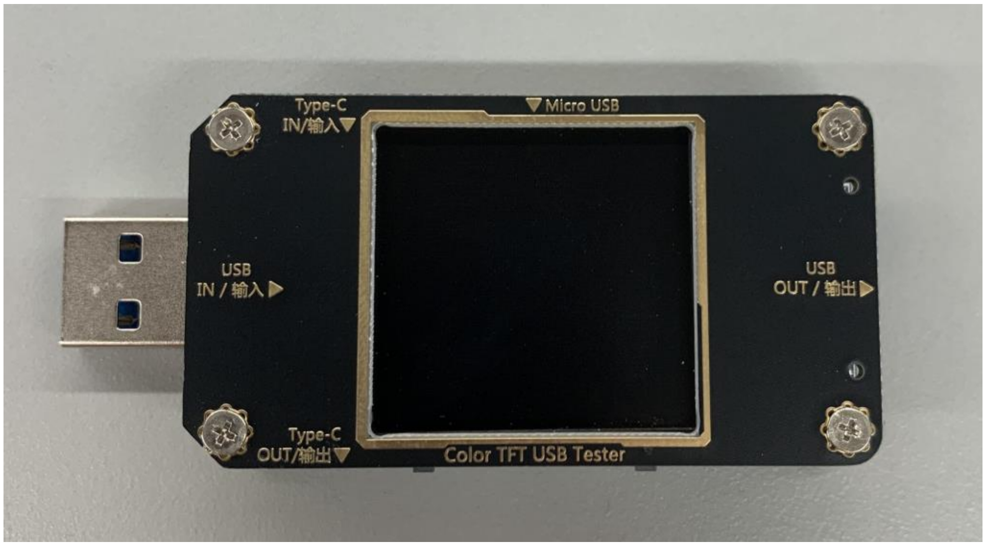

Figure 4: USB Power Meter

Figure 5: Power Supply

The table below shows the power consumption measured for the linear actuators and Raspberry Pi during an antenna scan. The total power consumption was 36.2 W which is much lower than the limit of 45 W defined in the FSR.

Peak Power Consumption	
Linear Actuators	30 W
Raspberry PI	6.2 W

Table 5: Reference 3.2.3.1.1

3.7. Reference 3.2.3.1.2

The input voltage level requirements for reference 3.2.3.1.2 were completed using the USB power meter and power supply shown in the above reference section. The input voltage level limit for the Raspberry Pi defined in the FSR was 5V and the USB power meter measured a maximum voltage of 5.3V during system operation which is slightly higher than the 5V limit but still within a reasonable range. The maximum limit for the linear actuators' voltage was listed as 24V in the FSR. The linear actuators were found to operate reliably at 10V, this value was found via the power supply display during system operation.

Input Voltage Level	
Linear Actuators	10V
Raspberry PI	5.3V

Table 6: Reference 3.2.3.1.2

3.8. Full System Demo

The full system demo was completed after integration and fine tuning. The team selected two individuals to operate the system from start to finish. The users interacted with the GUI to select a scan area, observed the antenna complete it's scanning route, and viewed the antenna output as an image overlay via the results GUI page. After system operation completion, the users were asked to fill out a form rating several different aspects of the full system operation with an optional section for comments. Both users gave very high ratings. The feedback from each user is shown in the tables below.

Category:	Rating:	Comments:
Design	10	
Instruction Clarity	10	
Ease of Use	10	
Intuitive Results	10	
Cool Factor	10	
Total	50/50	

Table 7: GUI Full System Demo, User #1

Category:	Rating:	Comments:
Design	10	Very cool structure, looks very pleasing to use
Instruction Clarity	9	GUI is mostly intuitive. Reset / false coordinate entry takes a second to figure out, but clear instructions are given on the screen.
Ease of Use	9	GUI is mostly intuitive; some buttons take a minute to get used to.
Intuitive Results	10	Image display is clear and intuitive, all data presented well
Cool Factor	10	YES!
Total	48/50	

Table 8: GUI Full System Demo, User #2

3.9. Full System Results

The images below are from full system operation with a 2D area selection. The first image below shows in the initial selection of the scan path by the user. After selecting an area, the user can select the “Initiate Scan” button to send the route path to the motorized mount via a network drive connection.

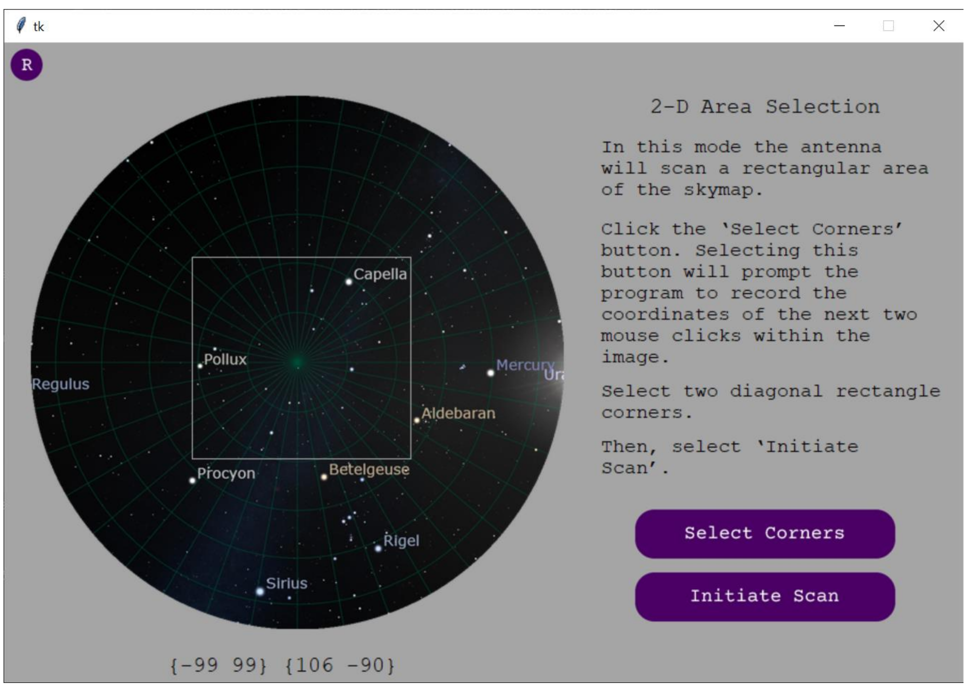

Figure 6: 2D Area Selection Visual

Once the route path is placed in the network drive, the motorized mount will read in the coordinates and move the antenna to the first scan point. The image below shows the antenna at it’s first scan point. Once the accelerometer detects the correct angles for that point, the antenna will then read in a signal and the software will calculate the peak magnitude and frequency. These values are appended to a csv file in the network drive and the motorized mount moves on to the next point.

Figure 7: Antenna and Motorized Mount Mid-Scan

Once the motorized mount and antenna complete the route path, the software on the user's laptop will read in the csv files containing the peak magnitude and frequency values. These values are converted into an interpolated heatmap image and overlaid on the skymap as seen in the images below.

Figure 8: Resulting Heatmap

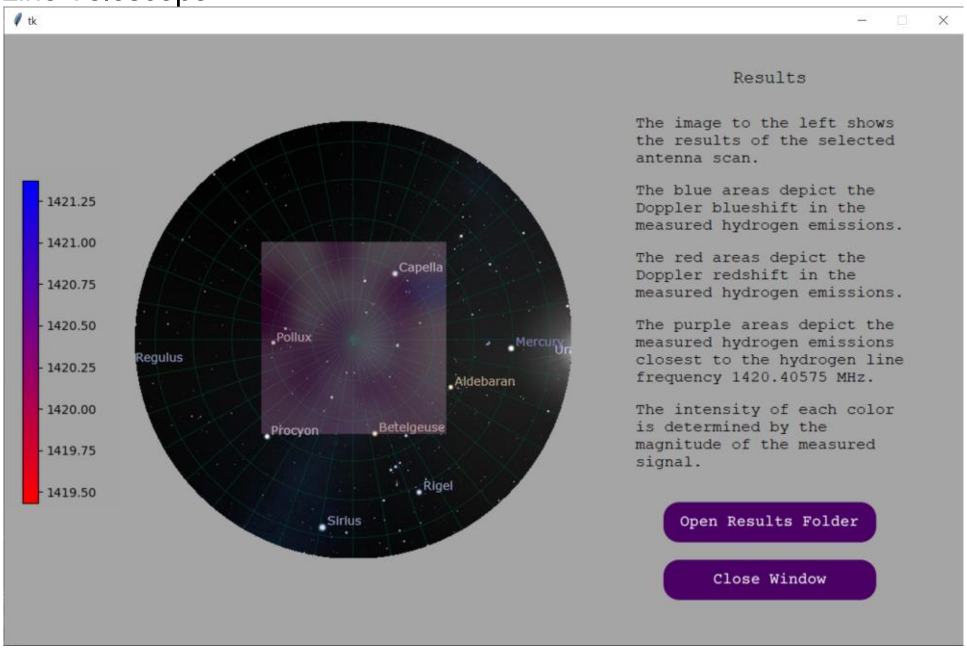

Figure 9: 2D Area Scan Results

The results in the images above show that the antenna is reading in hydrogen data. The scan area contains an arm of the milky way galaxy in the upper right and lower left corners. The heatmap contains areas of purple in those regions. There is also a dark area near Pollux and a dark area near Capella showing a higher magnitude in those areas. The results still show some noise and possible reflections from buildings in the area as this scan was taken in the equad.

4. Conclusion

4.1. Learnings

During these past two semesters the hydrogen line telescope team learned numerous valuable skills. The experience of designing, planning, and developing a complicated technical project from scratch was rewarding and educational.

The hardware and software building process for this project introduced several new tools in order to complete all of the subsystems. The signal processing system required the use of software defined radio applications as well as specialized python libraries to pull in and visualize raw signal data. The image processing subsystem needed the creation of high-quality GIFs that could be displayed via the tkinter GUI, the use of the pillow and matplotlib python libraries to create customized heatmaps, and the ability to access and customize the Stellarium API for skymap photos. The GUI subsystem required extensive use of tkinter to create a visually pleasing and intuitive application for this project. The route planning utilized projection and inverse projection mapping techniques as well as the study of different projections used by Stellarium to determine the best match. To complete the antenna subsystem, this team had to learn how to use antenna modeling software to design an antenna with the desired half power beam width and dimensions as well as performing laser cutting, impedance matching, and soldering on each antenna element. The motorized mount construction involved learning several skills including milling, mount design, accelerometer feedback loops, relay controlled linear actuators, and 3D modeling. The entire project also required the use of GitHub and this team had to learn how to create an efficient wireless file transfer method between the Raspberry Pi and the user's laptop.

The team also learned how to solve and recover from significant setbacks. A few days before the fourth bi-weekly presentation, the team was completing several antenna routes with the softly integrated motorized mount and antennas to validate the subsystem connections. During one of the movement tests, the center piece of the motorized mount flexed causing the antennas to fall to one side of the mount. One of the antenna elements broke at a middle connection point.

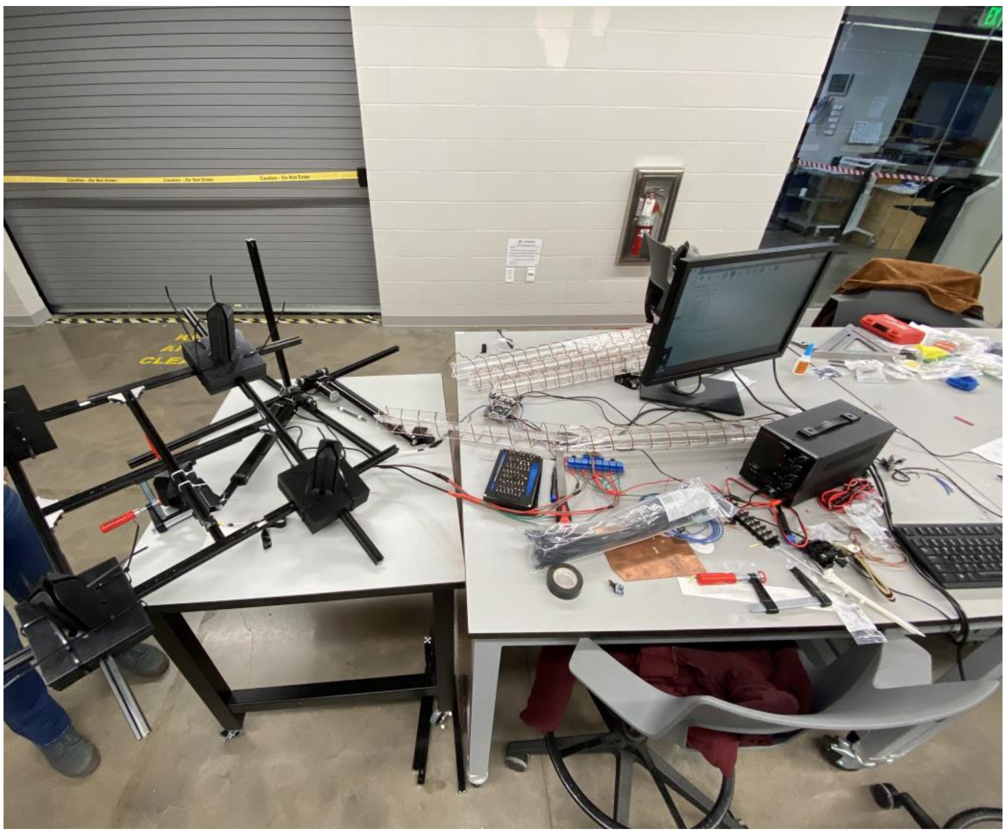

Figure 10: Broken Antenna Element

To recover from this setback, the team designed a 3D printed element to strengthen the acrylic connection points on all antenna elements. This change required unwinding the copper wire from all four elements and spending a large number of additional hours in lab reapplying epoxy to strengthen and attach the new pieces before rewinding the antennas. The team also strengthened the motorized mount, removing all flex in the center piece to prevent a repeat of the fall.

Figure 11: Completed & Strengthened HLT

This project also required the use of several soft skills. The most important of these was the process of choosing a team and maintaining constructive team communication throughout both semesters. The team also had to communicate well with the sponsor of the project and the lab TA, giving them weekly updates and progress reports throughout the semesters. The team also gave bi-weekly presentations as well as a final presentation and learned how to present well as a group, covering information in a clear, concise manner within a time limit.

4.2. Future Work

This project could benefit from a few future improvements to increase the strength and accuracy of this Hydrogen Line Telescope. A few of these improvement ideas are listed below:

- Decreasing the antenna beam width by designing a more complicated, precise, and expensive radio telescope
- Building the motorized mount with steel milled parts to increase stability and strength of the mount while also increasing the scanning range of the antenna
- Designing a project power supply subsystem
- Implementing more sophisticated movement logic
- Remote access and scan capabilities via a website

5. Appendix

The Python scripts for all software subsystems are in the GitHub link for this project below.

johannahein/Hydrogen-Line-Telescope at final-project-code (tamu.edu)