Subject: Gather a Pail of Milky Way
Memo: 32, Revision 5
From: Glen Langston, glangsto@nsf.gov ,dspira-lessons@reply.github.com
Date: 2023 May 2

Summary: Our group continues to work to make discovering our Milky Way Galaxy as easy as possible. Here we present the minimum horn radio telescope to observe the spiral structure of our Milky Way. It's a simple 10 step process! We conclude with pictures of what you'll discover, using the software. You'll find the Cygnus Arm of the Milky Way with your pail..

Overview

We all live in the Milky Way Galaxy and the Milky Way is full of hydrogen! We are so small that we mark our place with a yellow dot for the Sun, shown in the **Figure 1.** We are far from the center of the Milky way. The Milky Way has a concentration of stars at the center and streaks of star formation in clouds of hydrogen gas. These lines of stars are called the Spiral Arms. Our goal is to show you how to build a small Pail of Milky Way Radio Telescope to discover the spiral arms for your self. You will find that we and spiral arms are moving at incredible speeds.

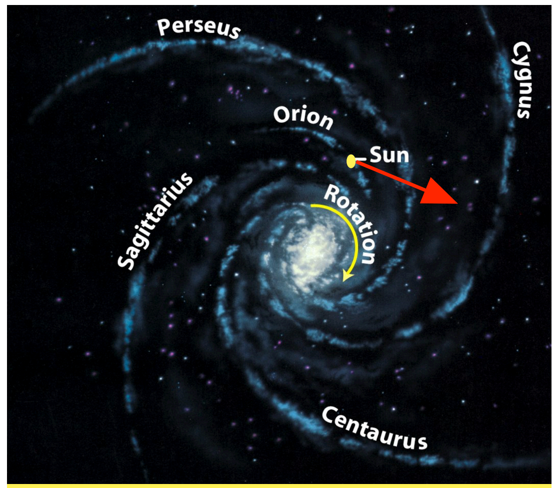

Figure 1: Sketch of the Milky Way, from top down, based on observations and a model of the Milky Way. (Philip Kaaret, U. of Iowa)

The Milky Way Galaxy is remarkably bright at certain radio frequencies. The brightest radio signal from the Milky Way comes from hydrogen atoms (H). Hydrogen is the simplest atom, consisting of a single positive proton (+) and negative electron (-). In the vast space between the stars, many, many,.many of these simple atoms are heated up by collisions with other atoms. The hydrogen radiates at exactly the radio frequency of 1420.406 MHz. This is very convenient for us astronomers, as it is easy to build a telescope for this frequency. For comparison, FM radio stations are transmitting at around 100 MHz, or about 14 times lower frequency than the hydrogen atoms you will discover. **Figure 2** shows a simplified picture of electrons flipping their spin in space. With your telescope you'll be watching quantum mechanics in action!

The neutral hydrogen frequency corresponds to wavelength of 21.12 cm, equal to 8.31 inches, about the width of a piece of paper. The shorter the wavelength, the easier it is to build a telescope, up to a point. This gives every student the opportunity to build a radio telescope.

We've been building and operating these telescopes for years, working to make radio astronomy easy and fun for everyone. Our history and construction guides are all on the web as LightWork memos. Enjoy these memos and document your own discoveries. All are welcome to write up your efforts and share your knowledge.

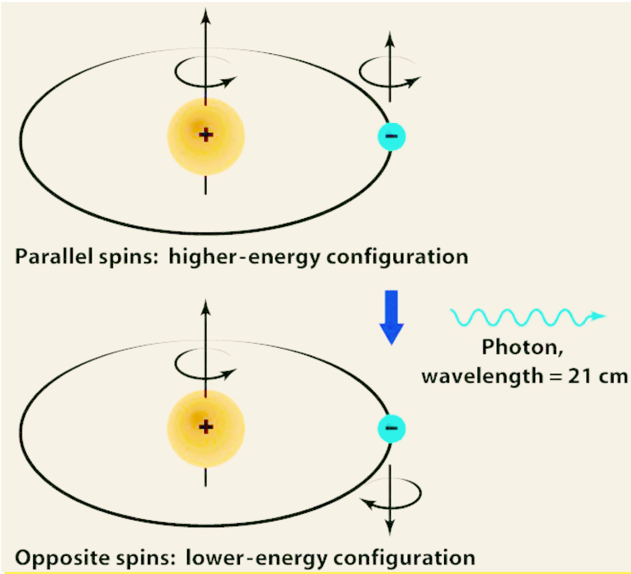

Figure 2: Hydrogen atom with electron (-) flipping from aligned with the proton (+) to opposite. When the spin arrangement flips a very weak signal (a photon) is released, but there are trillions and trillions of hydrogen atoms in our galaxy.

Steps to Discover the Milky Way

A radio telescope observatory has several major parts. The most important part is you, the ***Aficionado,*** the astronomer putting the telescope together. Congratulate yourself on becoming an ***Aficionado,*** advancing to rank of ***Explorer of the Milky Way!*** The goal of this project is to understand how You, Our Community, the Earth and Solar System fit into the Community of the Milky Way. Almost certainly there are other citizens out there in the Milky Way, although we've not met any others yet. We need to explore!

The key to success is ***dividing and conquering!*** Let's divide your radio observatory into major parts:

1. *Aficionados: You, Explorer of the Milky Way, leading others*
2. *Metal Horn and feed probe*
3. *Very Low Noise Amplifier (LNA) and weatherproof container*
4. *Cable connecting the amplifier to the Software Defined Radio (SDR)*
5. *A SDR with bias-tee for powering the LNA*
6. *Weatherproof box holding computer, SDR and cables connectors for radio signals, ethernet connections and power*
7. *Computer operating system*
8. *Gnuradio software to capture astronomical signals*
9. *Software to help understand your observations of the Milky Way*
10. *Your memos, videos, presentations and papers on your experiences and discoveries.*

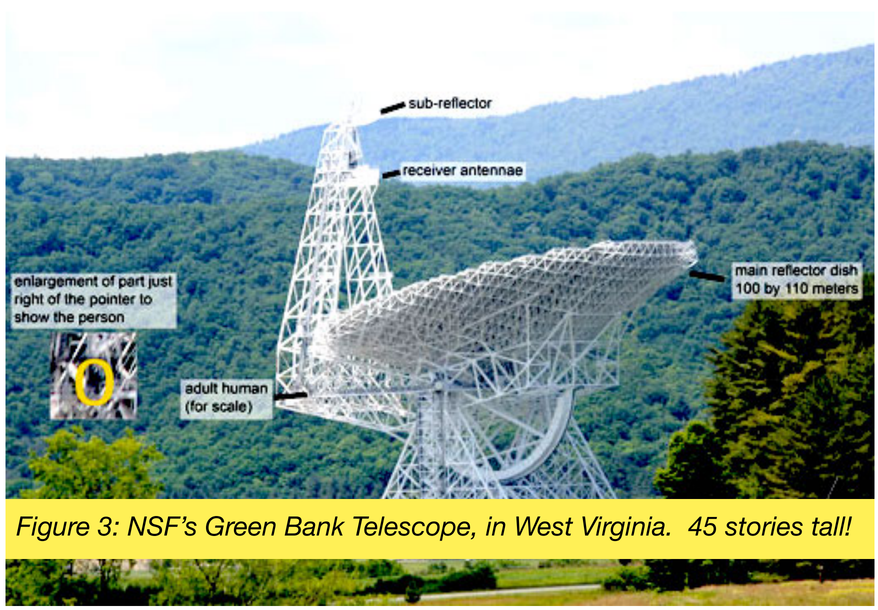

Figure 3: NSF's Green Bank Telescope, in West Virginia. 45 stories tall!

We summarize the uses/functions of each of these parts. Again, remember dividing and conquering is critical for success in any big project. We've already divided and conquered some of these components (See the Lightwork memos). Also remember complete success comes when you've progressed all the way to the final step: ***Sharing your experiences with others!*** You are very welcome to add to the Lightwork memos!

Figure 4: The NSF's Glen Langston with the Pail of Milky Way Feed horn. We'll collect some Milky Way with it!

Background

Radio Telescopes are created with a remarkable range of shapes and sizes, depending on the research focus of the astronomers. Near my backyard is a 45 story tall, 2.3 acre telescope, the National Science Foundation's (NSF) Robert C. Byrd Green Bank Telescope (GBT). Its 100 meters across. See **Figure 3**.

Here we're describing how to build a very small, but very sensitive telescope, only 10 inches wide, or 1/4 of a meter in diameter. It is 400 times smaller than the GBT. For scale, see **Figure 4**, showing Glen Langston with the Pail of Milky Way horn. The orange ruler is 8cm long (3.15 inches).

Horn radio telescopes have been built and operated by many other Aficionados. Of particular note are the instructions put together by high school teachers working with Prof. Kevin Bandura, of West Virginia University. He leads an NSF Education project and worked in collaboration with educators at the NSF's Green Bank Observatory (GBO). He's worked with teachers to describe, in detail, how to build amplifiers and an entire high school observatory. Bandura's focus is on engineering progress and has done a remarkable job working with a generation of teachers to share the engineering tricks needed to ***really see-for-your-self*** where we are in the Milky Way. His dedicated student, Pranav Singhavi, now a post doctoral fellow at Yale University, has been another spiritual leader of these efforts. Sue Ann Heatherly, at the GBO, has inspired and guided our education training.

We've been working with slightly bigger telescopes, and some teachers have asked how to build and use the smallest possible telescope. Here we'll show great success, giving your students a Milky Way Perspective.

Glen Langston put a video series together showing the steps for building your pail telescope: See the Pail of Milky Way Construction Guide videos. Remember to ***like*** the videos too; that makes it easier for other Aficionados to find them!

1: Aficionados: You, Exploring the Milky Way

This introduction is an example what really happens to advance any topic in science. Some people just love a particular topic. Those are the people who make progress happen and move the limits of our knowledge forward. Based on Kevin Bandura,'s leadership, and a little help from Glen Langston, a few dozen high school and college teachers in the world who have found discovering the Milky Way exciting.

These ***Aficionados*** have made remarkable discoveries, really measuring where they are in the Milky Way Galaxy and sharing that with their students. What does ***Aficionados*** mean? To us, ***Aficionados*** are amateurs becoming experts in radio astronomy. The ***Aficionados*** can explain to others how to r***eally-see-for-yourself*** where we are in the Milky Way and are also willing to help others make the same discoveries.

Remember, we strongly encourage and welcome others to write up a summary of your experiences. Particularly note Lightwork Memos 29, Welcome to ... The Astronomy Zone and 14, Galactic Mapping 2017.

Web pages are good for temporarily showing people what you've accomplished, but tend to disappear after a short while, due to computer changes. Memos are a little more reliable, especially with version numbers so we can compare changes.

Figure 5: Pail used for our simplest radio telescope. Almost any galvanized pail will do, The bottom should be between 13.5 and 17. cm in diameter. The pail should open up gradually to gather more signal. The pail must be at least 30 cm tall. Bigger is better.

2: Metal Horn and feed probe

A radio telescope gathers weak electrical waves and feeds them to amplifiers The shape of the telescope depends on the wavelength of the radio signal. We've tested a number of different shapes and found that circular funnels work well, like the Pail shown in **Figure 5.** Since we want everyone to become a radio astronomer all components should be easily available.[1] It is fairly remarkable that radio telescopes are made in amazing number of shapes and sizes. Here we're building about the smallest, but based on what you learn you can easily increase the size of your telescope and improve the sensitivity.

To build any telescope, the construction accuracy must be good to about 1/20 of at the wavelength. For this wavelength, 21 cm, you only need a cutting accuracy of about 1 cm, or 3/8 of an inch. This is easy to accomplish with common tools. You will need an electric drill, a cm ruler, drill bits and a 5/16 wrench for the SMA connectors. You'll also need metal tape and a empty plastic peanut butter jar (3.5 inch diameter lid). We will put the full lists of parts and tools in an appendix.

[1] https://www.amazon.com/Walford-Galvanized-Decorative-Bathroom-Farmhouse/dp/B089NW1KFW/ref=pd_rhf_ee_s_rp_c_1/

We greatly appreciate the guidance of Steve White, lead electrical engineer the NSF's Green Bank Observatory.   He helped us start this project by modeling the optimum location of a feed probe for a 6 inch diameter galvanized stove pipe, which are easily available and fairly low cost.   He found:

- Probe thickness = 0.07 cm = 21 gauge silver wire
- Probe to Rear   = 7.38 cm = 2.9 inches
- Probe Length   = 4.72 cm = 1.9 inches

The feed probe is the only unique piece of hardware in the radio telescope. It is created by soldering a 4.7cm (1.9 inch) piece of 21 gauge silver wire to an SMA female connector. Because the part is cheap, yet a little bit of a challenge, Langston will send one to each of the first 40 ***Aficionados*** who email and ask for one. You must ***like*** a few videos first, to confirm your commitment!

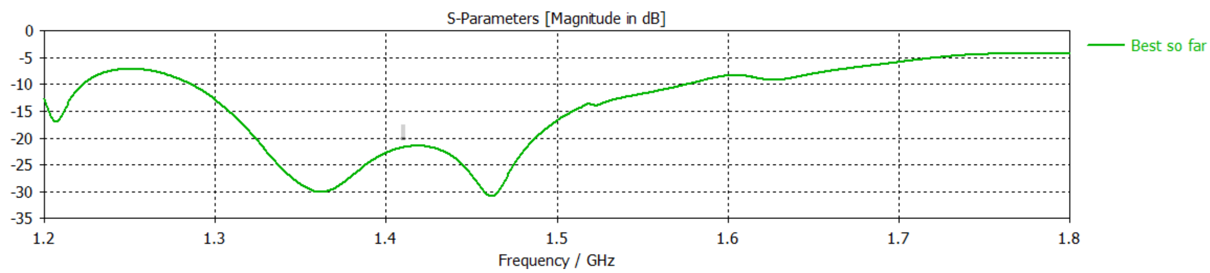

Figure 6: Steve White's model for return loss model for placement of the feed probe in a 6 inch (15.25 cm) galvanized pipe.   Frequency (GHz) on X axis, Y axis is return loss in (dB). Lower is better.

The feed probe is shown in **Figure 7**, along with the 8 cm orange ruler for scale, a GPIO Labs HI amplifier and a 50 Ohm load (more on these later).

To install the feed probe, drill a 1/4 inch diameter hole in the pail, 7.4 cm from the bottom. Place the probe SMA connector through the hole, from the inside. Later, we'll add the weather proof container.. The assembled feed probe and container are shown in **Figure 8**.

Figure 7: At the bottom of the image is the feed probe that will collect the Milky Way signal and feed it to the first very sensitive, Low Noise Amplifier (LNA). At the top is the 8 cm ruler, that show the scale in other feed horn images.

3: Very Low Noise Amplifier (LNA) and weatherproof container

The first amplifier in the telescope must be located very close to the feed to avoid the system noise degrading the telescope sensitivity. This is true for all radio telescope types, both professional and Aficionado. Fortunately LNA technology has greatly improved and several very good quality Low

Noise Amplifiers (LNA) are available. Tests of amplifiers and SDRs are described in Lightwork memo 28.

The low noise amplifier (LNA) boards contain an electronic circuit that connects to the antenna probe through a standard SMA connector. These amplifier boards are small, just a few cm (less than 2 inches) in each dimension, and actually are a combination of several amplifiers with filters to reject interference. The combination of amplifiers yield very high gain, > +32dB corresponding to a factor of 1585, times the input signal strength[2].

Figure 8: Completed assembly of the horn feed horn for the radio telescope. The orange ruler at the bottom of the Pail is 8 cm long. The narrow silver wire (4.7cm long) points straight into the center of the pail and is above the bottom of the pail by 7.4 cm.

Figure 9: A side view of the Pail with NooElec HI amplifier attached. The weather shielded container is a large empty plastic peanut butter jar. These are great because they are free, unbreakable and metal tape sticks to them well. The lid is taped to the horn, and the jar is covered with metal tape to shield the amplifier from interference from computers and phones.

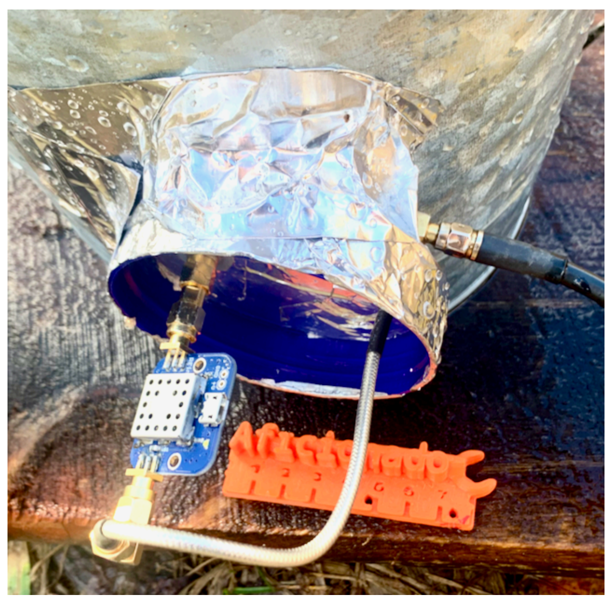

Figure 10: Inside view of the peanut butter jar lid with amplifier and connecting SMA cables. This example shows the GPIO Labs amplifier, which fits in the same place as the NooElec amplifier.

The gain is important, but additionally these amplifiers must be powered via a “Bias-Tee” which uses the +5V on the signal cable to power the amplifier. Some options for obtaining a low noise amplifier include the

[2] gain(dB) = 10^(dB/10). gain(32) = 10^(3.2) = 1585.

following. All of these will work with horn telescopes and software.

1. Best option: DSPIRA LNA – This amplifier board was designed for a 1420 MHz radio telescope by Professor Kevin Bandura at WVU. This option requires ordering the circuit board and components, and then assembling the components by soldering. Details on ordering the parts and instructions on how to solder the circuit are provided at this link.. The total cost for the parts of this circuit is approximately $30. This is a challenging soldering project, but these amplifiers have been successfully built by high school teachers and students.
2. Next best option: Nooelec SAWbird+ H1 - Premium SAW Filter & Cascaded Ultra-Low Noise Amplifier (LNA) Module for Hydrogen Line (21cm) Applications;
3. Next best option: Low Noise Amplifier Filtered Hydrogen Line 1420 MHz LNA 32 dB Gain LNA with Bias Tee;.

For ease and price, this example uses the NooElec HI amplifier.

Figure 9 show the NooElec HI amplifier attached to the horn. **Figure 10** shows another view, this time using the GPIO Labs HI amplifier. Some of Glen Langston's measurements show the GPIO Labs amplifier having better sensitivity, but at the cost of lower gain. Again, since the goal of this project is maximum discoveries at minimum cost and effort, use the NooElec Amplifier.

4: Coaxial Cable

The coaxial cable connecting the amplifier to the computer box is important, and is a relatively simple part. However this part has caused some Aficionado's trouble because they used relatively poor quality cable, instead of the higher frequency cable needed.

Figure 11: A low loss LMR240 coaxial cable, 10 ft (3 m), for connecting the horn to the weatherproof computer box.

Figure 11 shows a good coaxial cable is available from Amazon. The one I've used is 10ft (3 m) long and works well at 1420 MHz. The key parameter is the "loss" of signal as a function of length of the cable. These cables usually come with links to measurements of "loss" in dB. as a function of frequency for 100 ft lengths (30.5 m). This link reports a 1 dB loss in 10ft. This corresponds to loosing 20% of you signal in 10ft, on the positive side, 80% of your signal makes to the SDR. (see footnote)[3]. 80% is good enough, some lower quality cable loose 10dB, or only allowing 10% of the signal to make it to the SDR. Note that using a shorter cable might be better, but then you may have trouble with testing different configurations, because a shorter cable may not give you enough length to look directly at the ground, or point in some other direction.

[3] See LMR-240 Coaxial Cable Specification. This memo indicates for LMR-240 cable the signal loss is 1 dB, which corresponds to a gain factor factor of about 0.8. The gain equation is: g(db) = 10^(-db/10.). In our case, g(1 db) = 10^(-1/10) = 0.794). It is handy to know that a 3db loss means a loss of half your signal. g(3 db) = 10^(-3/10) = 0.501.

5: Software Defined Radio (SDR)

The SDR's are the remarkable advancement allowing everyone to become a radio astronomer. We've already done a detailed comparison of different SDRs and wrote this up in. Lightwork Memo 28.

To summarize, the AIRSPY Mini (6 MHz) bandwidth, the RTLSDR (2.4 MHz) bandwidth and the SDRPLay RSP1A clone (8 MHz) all give very good results. Wider bandwidth is better for transient event detection but not absolutely critical for observing the Milky Way.

For this minimum cost Radio Telescope Observatory, we'll use the RTLSDR, shown in **Figure 12.**

Figure 12: A low cost Software Defined Radio, which has a strong bias-tee and high gain. The down sides to this SDR is that it only has an 8-bit sampler and works well only below 2.4 MHz bandwidth.

6: Weatherproof box holding Computer, SDR and Connectors for Radio Signals, Ethernet and Power

Most of the experiments will require leaving your telescope and computer outside for days and days. This means you need to put the computer in a weather proof box. Langston initially used a small box for the Raspberry PI 4 B computer, the SDR and also a power-over-ethernet splitter. The entire computer system is shown in **Figure 13**. The box has a screw on lid with rubber gasket.

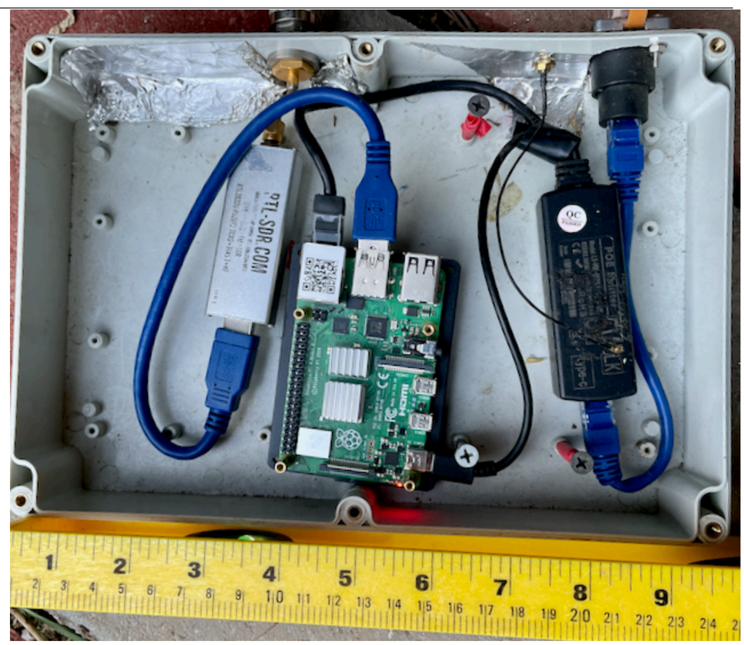

Figure 13: Raspberry PI 4B computer (middle) in weather proof box with RTLSDR (left) and POE splitter (right). A few cable connectors are also needed. The box is just about one 21cm wavelength wide!

For a *Key Science Project,* Langston hopes each high school will have a few radio telescopes. To simplify the wiring, the telescope horns are directly connected the internet via a Power-Over-Ethernet (PoE) system. This system is very common for remote cameras. Fortunately the Raspberry Pi computers don't need much power, so whole system can run this way.

A example of the telescope array is shown in **Figure 14.**

Figure 14: Langston and 4 horn telescopes observing different parts of the sky. These telescopes are on tilting bases. The computers are inside the bases.

There are some challenges to PoE systems, in that the parts are not super liable and telescopes occasionally stop working. It takes some time to figure out which part has failed. Sometimes the PoE router, sometimes the splitter.

During COVID-19 the Pi 4B became expensive, so we switched to the Pi 400. The Pi 400 is more powerful and more convenient to use, but was too big for the little box. Also the Pi 400 requires more power. We did have some trouble with the PoE Splitters and the Pi400s because these computers need more power to run at their higher capability. Try to get good high power, quality PoE splitters.

For some experiments your telescope will need a base and a bigger horn. See Lightwork Memos 21 and 22.

7: Computer operating system

There is a lot of work needed to set up the telescope computer software. Fortunately almost all that has been done for you by 100s of Linux computer volunteers. Kevin Bandar's web site lists the installation steps.

Langston has also created a complete downloadable software image for the Raspberry PI Radio Telescope System. See the PI GnuRadio Installation Guide in the linked directory. Select the most recent operating system image. They are big file downloads, around 3 Gigabytes.

8: Gnuradio software to capture astronomical signals

The radio astronomy data taking software was enabled by another fantastic group of software hackers. Gnuradio is a huge project with many contributors. To start, look at a few Tutorials.

Then look at the very short video by Sophie St. Georges, Evan White and Glen Langston at the Green Bank Observatory to get a feeling for the types of projects you can create for yourself.

9: Software to Understand Your Observations of the Milky Way

When running an observation, you will use the Virtual Network Connection on the Raspberry PI computer to setup your observations. **Figure 15** shows the interface you'll see when making an observation More description is in the Light Work Memo Series.

The code for making observations is downloaded with "git" to Linux computers. The process is documented at web site: https://github.com/WVURAIL/gr-radio_astro:

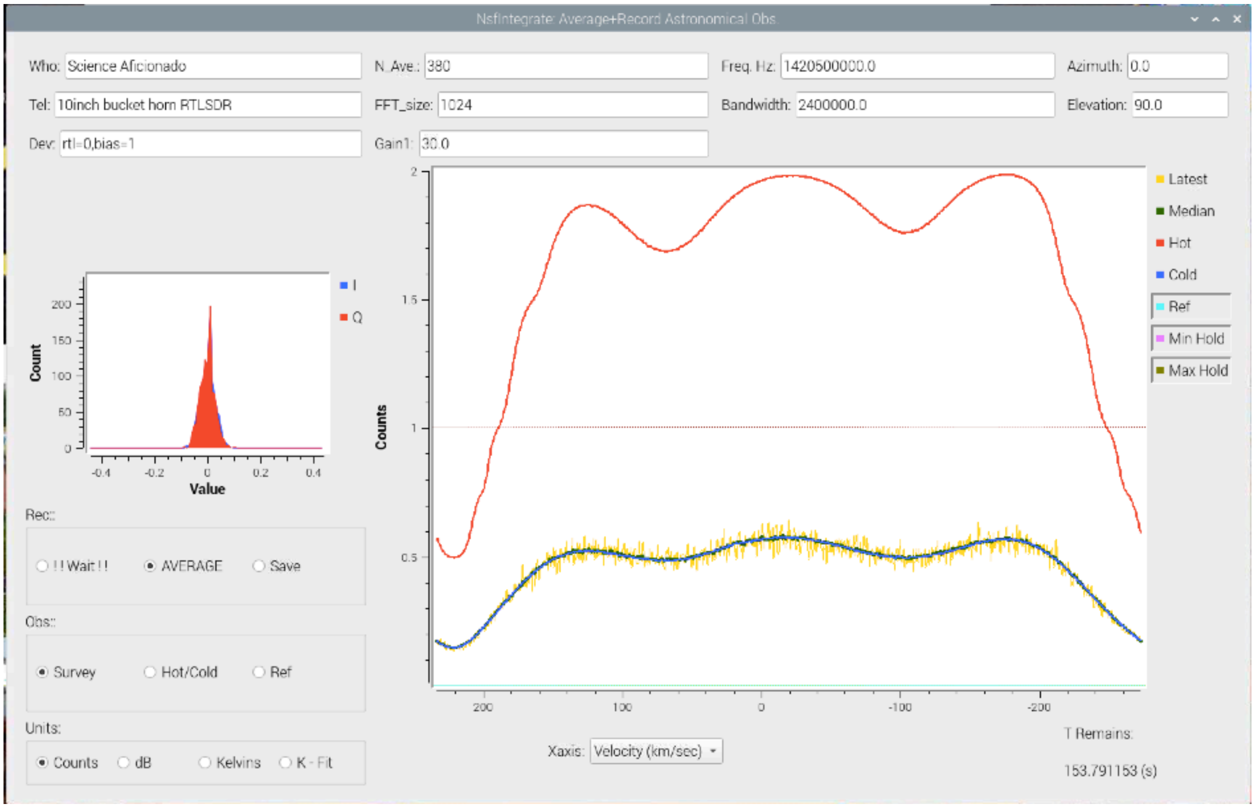

Figure 15: GnuRadio Running the design NsfIntegrate24.grc, which takes data from the RTLSDR dongle, Fourier Transforms it, averages and writes the observations to the computer.

Data reduction is also important for understanding your observations. The programs to understand your observations are all written in Python, with some hints on the web.

Langston has created a set of programs to calibration, plot, map, summarize and analyze your observations. See web site: https://github.com/glangsto/analyze. All the software is free to download and use. We Aficionados will all try to help you if you run into challenges. Of course discovering your place in the Milky Way is a great and worthy challenge!

10: Your Memos, Experiences and Discoveries!

Remember to complete your Exploration, by reporting your discoveries. **Figure 16** shows one day's observation of the sky, with the Pail of Milky Way looking straight up. There are 24 one hour averages plotted, with the Galactic Longitude and Latitude for each average.The plot shows Calibrated Intensity (Kelvins) versus Doppler shift Frequency velocity (km/sec) for one hour averages.

The peaks in this plot show concentrations of hydrogen moving a different relative velocities in the Milky Way. Each of the peaks is a spiral arm of our galaxy. The labels on the plot at right, show the average time of the observations (UTC Hours Minutes Seconds) and the Galactic Longitude and Latitude of the average. Latitude=0 corresponds to the Galactic plane. Latitude=90 corresponds to the Milky Way's "North" Pole.

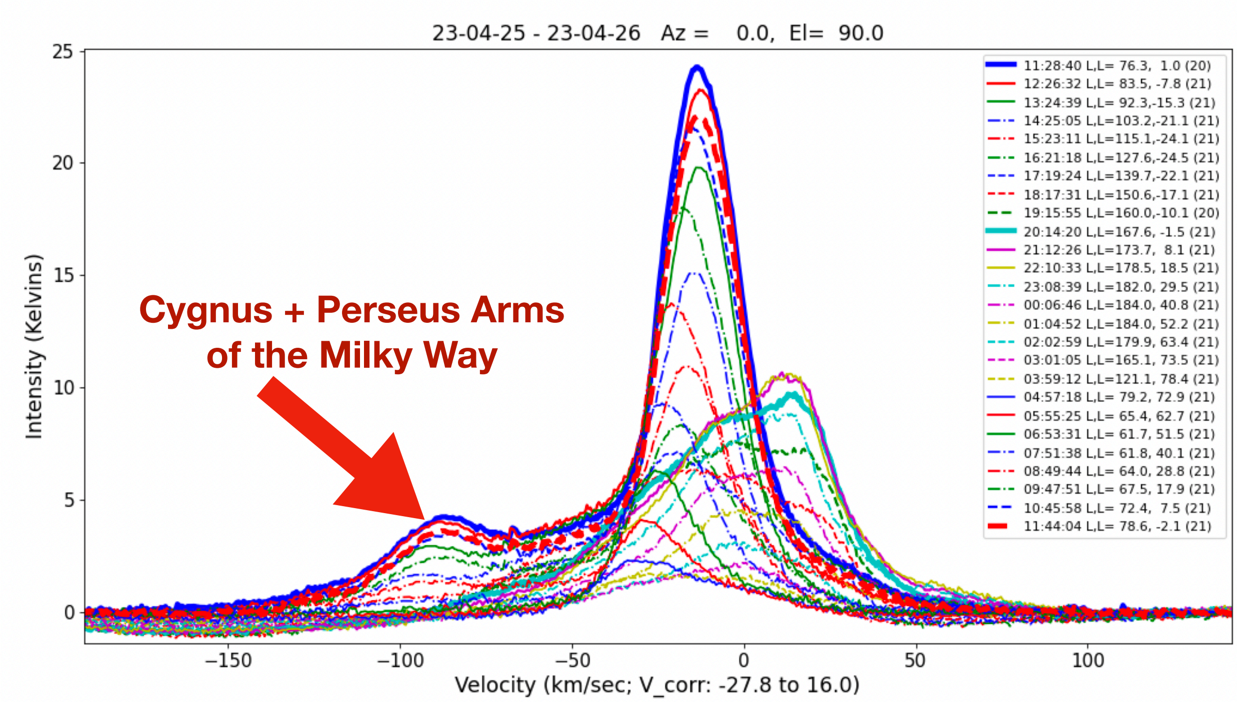

Figure 16: Discover the Spiral Arms of the Milky Way with your Pail of Milky Way Observatory. The Universe is yours to discover! The plot X-axis shows the Doppler shift velocity of different parts of the Milky Way relative to you. The Y axis shows calibrated intensity of the Milky Way in units of Kelvins (temperature). The amazing thing you find is that some of the Milky Way is moving towards us at the huge speed of 100 km/sec corresponding to 360,000 km/hour or 225,000 miles per hour, a hundred times faster than the speed of a bullet.

More descriptions of these observations will come in future memos (we hope)!

A high school teacher, Physics Man Dave (Dave Schultz) has done a great job of describing what you and your students will learn. *Visit his webpages!* He explains that the peak at -100 km/second is your discovery of the Cygnus and Perseus arms of the Milky Way.

The plot shows parts of the Milky Way are moving towards us at one hundred times the speed of a bullet. ***That's amazing!*** See what you can learn from one day's observations. (Doppler shift is defined such that positive is moving away from us and negative is moving towards us.)

Conclusions

The Milky Way is within your reach. We hope you will discover your place in the Milky Way. We also hope that later versions of this memo will expand and improve this description. Suggestions are welcomed from all ***Aficionados***!

Thanks to family, friends, the Green Bank Observatory and the National Science Foundation!