Subject: Observations with the NSF Horn during December 17, 2016 to January 16, 2017
Memo: 14, Revision 9
From: Glen Langston
Date: 2017 February 17

This note describes measurements with a Neutral Hydrogen (HI) Radio Telescope based on a metal surface horn and Low Noise Amplifier (LNA). These observations were made with the AIRSPY Software Defined Radio (SDR) hardware in wide bandwidth (10MHz) mode to map the entire northern sky for neutral hydrogen emission. The data look promising and initial maps are presented. The images clearly show the Milky Way galaxy.

Our aim was to make a first map of the radio sky with a radio telescope that can be constructed by a *Science Aficionado*, the name we've given for anyone with a strong interest in radio astronomy. *Aficionados* wanting to build their own telescope will need some basic mechanical, electronic and software skills, but construction can be accomplished by high school students and hobbyists. The details of the horn and electronics design are were described in a previous memos, *Light Work Memo 4*. The step-by-step guide to building the telescope is coming in a future memo.

The observations with the hardware and updated software were successful! Our Milky Galaxy is clearly seen in individual observations of the sky and also combined to map the location of our Galaxy in the sky. This memo summarizes the hardware built, and the horn used as a radio telescope. We've recently made many improvements in software, now easily showing our Milky Way galaxy in radio images of our sky.

Observation Overview

These observations are another in a sequence of tests of mapping the sky with a personal telescope, constructed from simple aluminum faced foam board. The radio horn has the shape of a square pyramid (See Figure 1). The funnel shape collects the radio waves into a location where they are amplified by a Low Noise Amplifier. Compared with previous tests, the hardware was configured to avoid a few problems discovered with the electronics-software combination.

The observations were conducted using a python program, based on software provided by the GNU Radio Consortium (http://gnuradio.org). The GNU Radio group is great! They have made the programs very user friendly and are easy to install on Linux and Apple Macintosh computers. I've tested the software on both types of operating systems, and believe that the software could also be run on Windows computers as well. Compared with data taken earlier, and described in previous Light Work memos, the basic software infrastructure is unchanged. This note adds an overview of a few programs were created to put the data on the maps and convert from antenna positions measured in the back yard do coordinates on the sky. These programs are described in the software section.

The observations were made in Green Bank, WV in my backyard, near a small barn. The observations were made over the period of December 18, 2016 to January 16, 2017. The observations were made pointing the horn (described below) either due north or due south, with the horn pointing at a variety of elevations. I was working and at meetings during this time, so would only change the horn elevation once a day or once a week. The weather was cold but

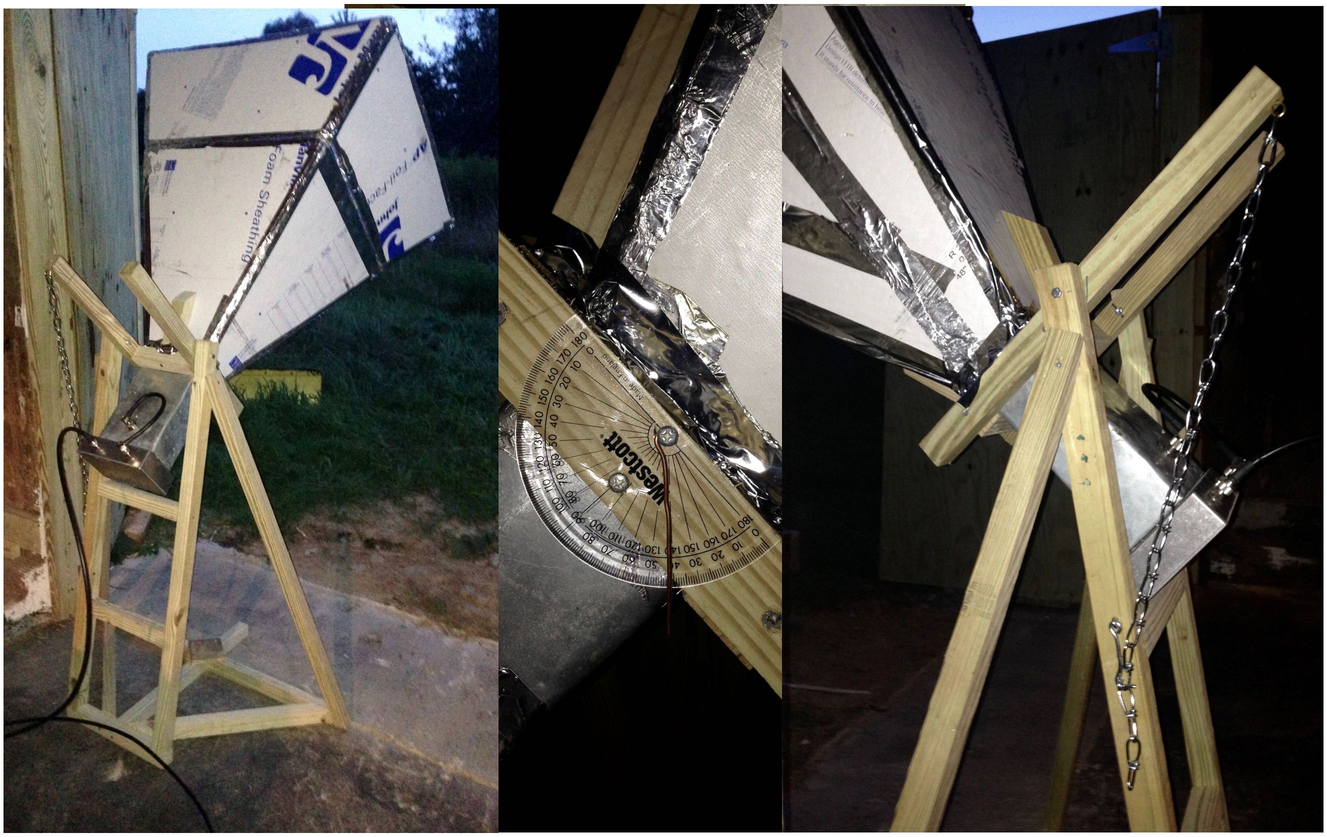

Figure 1: Images of the Horn you can Build and use to map the Milky Way. *The image at left shows the exterior of the horn, which is a 4 sided pyramid, with large, open end pointed at the sky. The opening is a 36x32 inch rectangle. The horn is constructed of aluminized foam insulation, held together with aluminum tape. The lower end feeds a 4x8 inch wave guide. The waveguide is constructed from a riveted aluminum sheet. The image at center shows the gauge used to read the horn elevation. The image at right shows the hook and eye mechanism for locking the horn at a specific elevation. The chain links had a spacing that corresponds to between 5 and 10 degree steps in elevation. Since the horn has a 13 degree full width at half maximum resolution, the chain links provided sufficiently small steps to cover the entire sky.*

occasionally snowy, and accumulating snow made some observations unusable. The software was very reliable allowing uninterrupted observations of more than a week.

During the observations I kept a notebook of the elevations of the horn. After completing this series of observations, I found that some of the data were not usable, which results in missing sections in my maps of the sky. This will be visible to you in later sections of this memo.

Hardware Tested

The horn is shown in Figure 1. The left shows the horn pointed outside my barn. The middle shows the protractor used to measure the elevation, the right shows the chain used to fix the elevation for an observation. The features the system are described in *Light Work Memo 13* and are summarized below:

***Figure 2: At left, Nathaniel and Regina are setting the horn elevation for an observation.** Next they start the computer collecting spectra. After a 24 hour period of observations, the data are calibrated by a half hour observation of the ground. At right, Regina and Nathaniel have just started a calibration observation. The weather was cold but clear for their observations. Note in the left image, a sheet of green foam insulation covers the horn to allow observations in bad weather. This foam is very transparent to radio waves. However data taken during the snow storm were not usable, due to snow piling up on the top of the horn.*

- Practical-sized rectangular horn with 36”x32” opening, constructed from aluminized foam and reflective tape.
- The horn feeds a custom waveguide with integrated band pass filter.
- Feed probe is a 4mm diameter copper tube soldered onto a female N connector.
- The signals from the horn are connected to a low noise amplifier by a low loss LMR-400 cable, 1-ft long.
- A critical component is the first Low Noise Amplifier (LNA), a TAMP-1521GLN+ from Mini-circuits (http://www.minicircuits.com/pages/npa/TAMP-1521GLN+_NPA.pdf). The amplifier is mounted in the Mini-circuits test board. The board has SMA connectors.
- The output of the amplifier is connected to a band-pass filter to remove interfering signals. The filter is critical to the function, as otherwise man-made signals corrupt our observations of the galaxy. The output of the filter is connected to a Bias Tee.
- A Bias T is used to put electrical power and radio signals on the same coaxial cable.
- A 20ft coaxial cable provides power to the LNA and amplified signals to digital sampler.
- For this experiment we used the AIRSPY (airspy.com) Software Defined Radio (SDR). This device has a number of important features.
    - Wide bandwidth, 10 MHz
    - Built in Bias Tee, easily allowing us to power of the first LNA.
    - Additional high gain amplifiers, needed for detection of the weak astronomical signals.

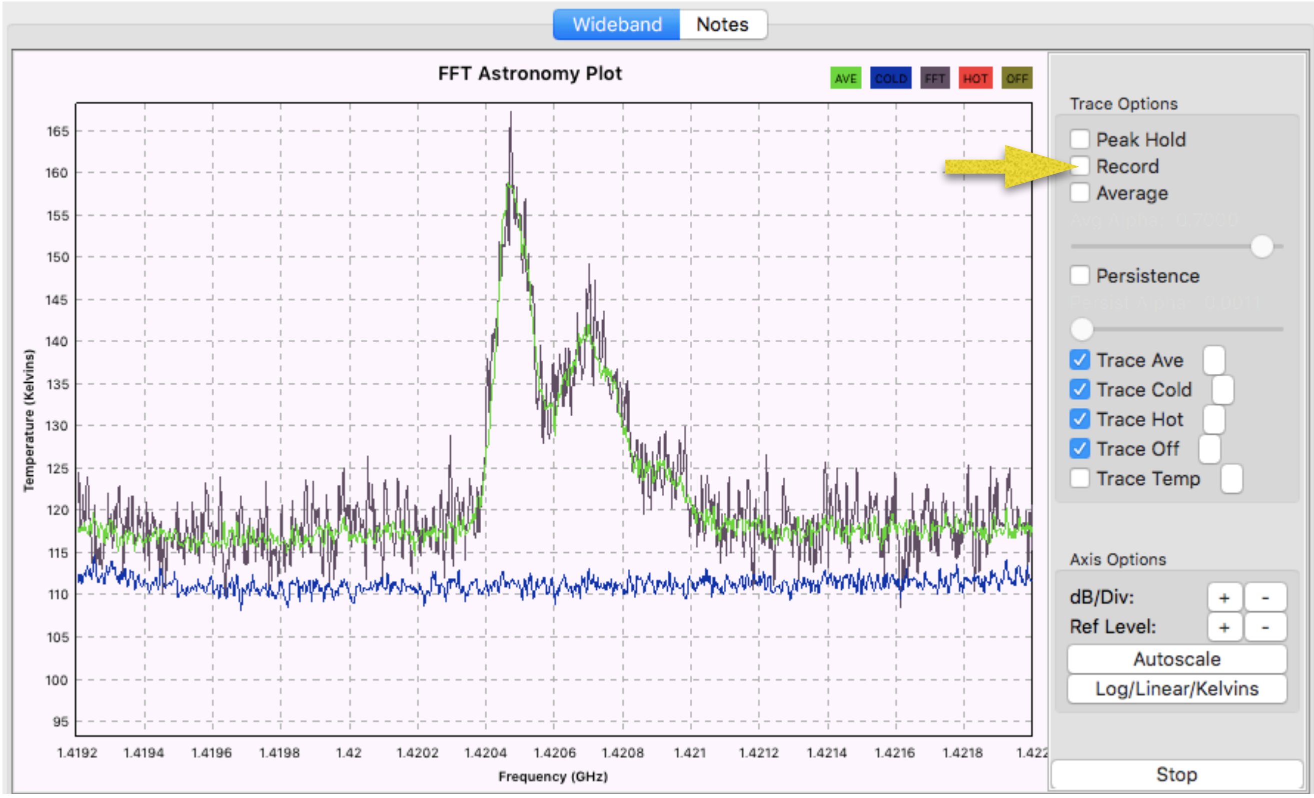

Figure 3: Interface to the GNU Radio software *for recording observations of the sky. The plot shows the Calibrated Hydrogen Sky Brightness (in Kelvin units). The X axis is frequency and the Y axis is intensity. In the right column of the window different control commands are shown. The most important is the* ***Record*** *button, which starts and stops data taking. The display shows the calibrated observations. The blue curve is an reference observation at a frequency without hydrogen. The noisy, black, curve shows the latest observation of the sky, a few seconds in duration, and the green curve shows a minute long average of the observations.*

    - The AIRSPY is powered by USB connector to the computer
- Dual core Linux laptop (Must have a clock speed greater than 2 GHz). Quad core laptop would be preferred.
- The computer we used boots with the Microsoft Windows Operating system and is configured to allow booting with a USB thumb drive to run Linux. The Linux operating system can be downloaded for free or purchased from GNU Radio (recommended).
- Note it is important that the laptop have a good battery and an ethernet connection, so that the time and coordinates of the system can be accurately recorded, so that the astronomical coordinates can be recorded precisely.

Figures 1 and 2 show the horn tilted outside of a building and also outside to allow observations at different angles. Figure 1 shows the cabling to connect the horn to the first amplifier, the protractor used to measure the horn elevation. At the right in Figure 1, a hook and chain are shown holding the elevation elevation constant at a desired angle. By moving the chain by one link, the elevation changes by about 5 degrees.

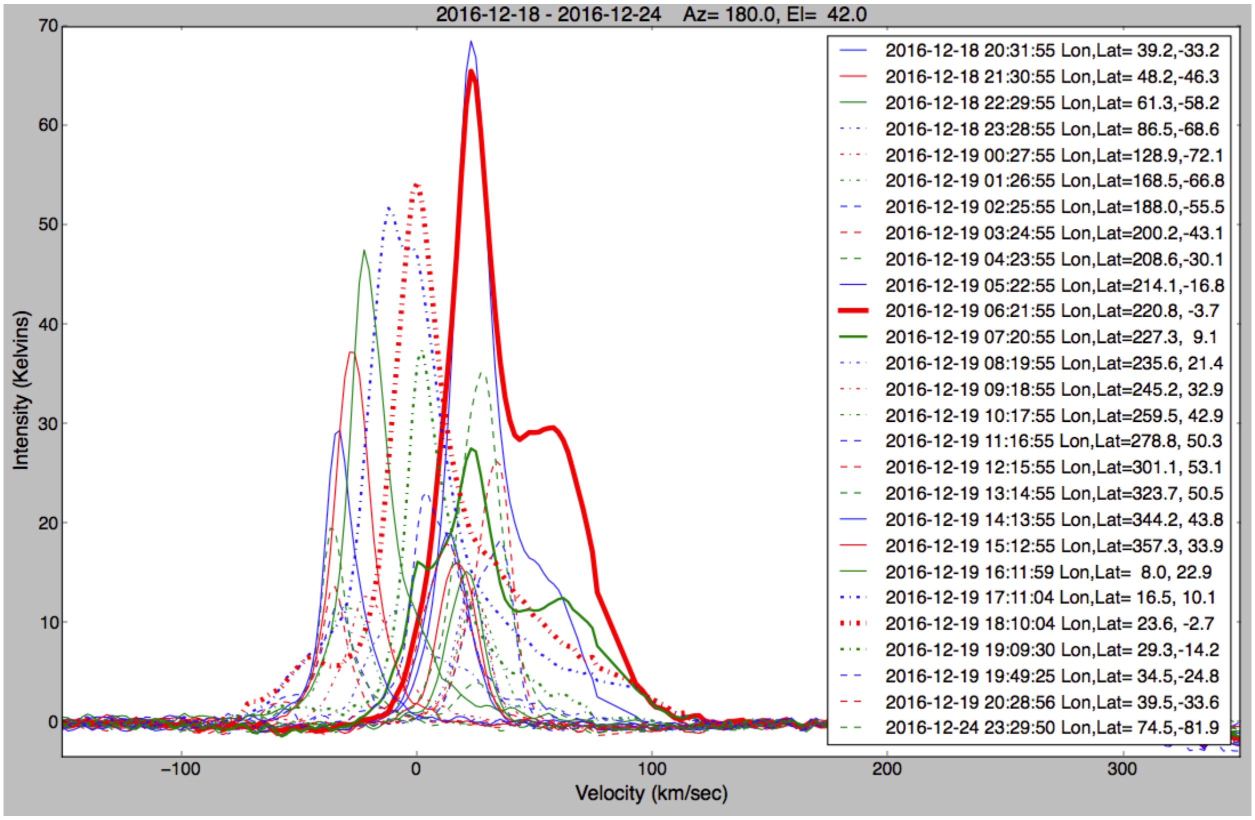

Figure 4: One hour averages of one day of measurements. *The plot shows calibrated measurements of intensity versus the velocity of the gas relative to the Earth. These observations were made on 2016 December 18 and 19. The telescope was pointed due south with elevation of 42 degrees. The spectra were recorded once a minute. These plots show one hour averages. Thick lines are plotted when the average galactic longitude is less that 5 degrees from the galactic plane. The strongest emission, thick red line, is seen looking away from the galactic center, towards 225 degrees longitude, through the galactic disk. The emission is still strong, but weaker, close to the galactic center, at 24 degrees galactic longitude (thick dashed red line).*

Observing Steps

The observations are carried out in several steps. The first step is to point the horn, either due north or due south, then pick an elevation, the angle above the ground. Next the direction is entered into the “Notes” screen.

Figure 2 shows Nathaniel, my son, and Regina, his friend, setting up for an observation outside. At left they are pointing the telescope a little north of straight up. At right they are preparing for a “hot-load” observation”, by recording the intensity from measurements pointed down at the Earth. The Earth is much hotter than the cold sky. Only a relatively short calibration observations are needed.

The observations are started by clicking the “Record” button on the side of the plot of the spectrum. These observations are averaged by the computer and written to the internal disk. The interface is shown in Figure 3.

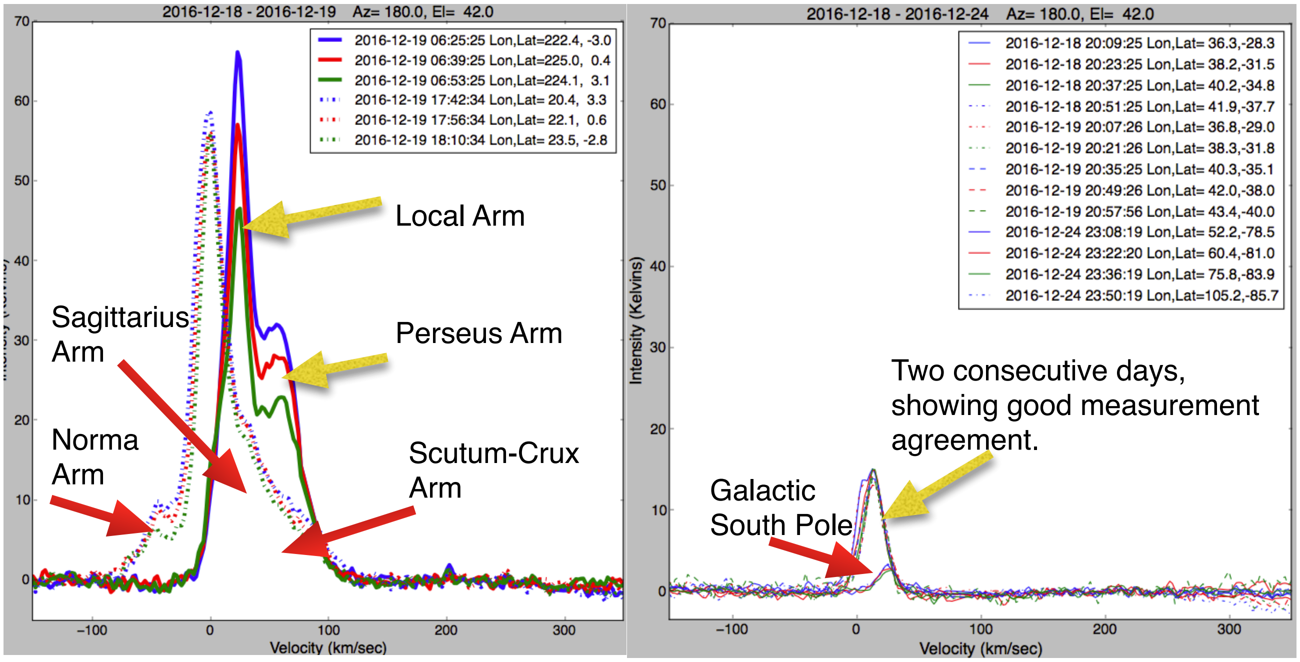

Figure 5: Comparison of HI emission in different directions in the sky. *Both plots show intensity in Kelvins versus velocity of the gas. These data are from the same observations as shown in the previous figure. These plots show 15 minutes averages to show measurement uncertainty and changes with small changes of position. At left, the plot shows observations along the galactic plane (latitude=0), at 22 and 225 degrees longitude. The observations at close to the direction of our galactic center, at 22 degrees longitude (dashed lines) show parts of 4 named arms of the Milky Way. The solid lines show observations out of our galaxy, towards 225 degrees longitude, toward the Perseus and Local arms. The plot at right shows the good agreement in intensity measurements between the beginning and end of a day of observations and also compare the weak emission near the South Galactic Pole (right) with the strong emission in the galactic plane (left).*

The telescope geographic latitude and longitude are recorded, along with the time of the observations. With this information, the sky coordinates of the observation are calculated. The geographic coordinates can be obtained from a GPS receiver, but they also can be obtained from the estimated location of the nearest ethernet router. Software is provided to get these coordinates. We set the averaging time to record data once a minute.

The astronomical observations also require the time zone to be set correctly on the computer, so that the times can be converted from local time to "Universal Coordinate Time", abbreviated UTC. Next the azimuth and elevation of the horn must be set. It is important to accurately read and record the elevations before the observations start.

The observations ran between December 18, 2016 to January 16, 2017.

These observations were taken a variety of weather conditions and elevations so the system temperature ranged between 120 and 250 K for different sets of observations

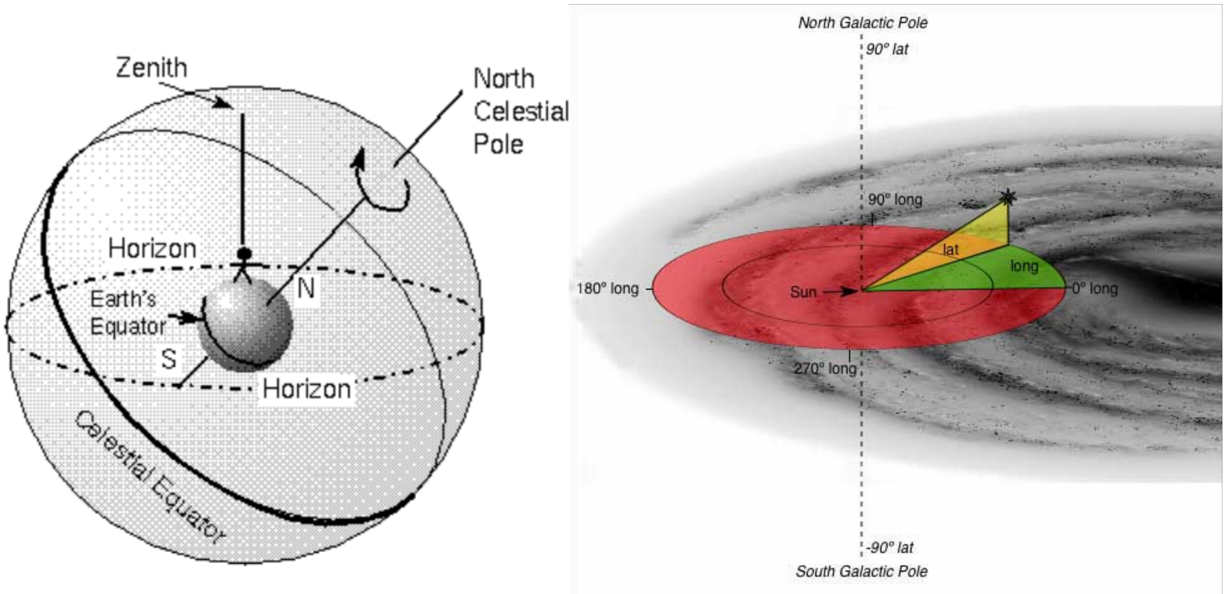

Figure 6: Coordinates in the Sky. *At left is a chart of Right Ascension and Declination with a symbol of you, the observer, standing on the Earth while it rotates. The sky rotates over our head once each day. At right is a sketch of the Sun's place in the galaxy, showing the directions of galactic coordinates. First consider the figure at left. We need to keep track of the direction in the sky when the making observations. Consider when you are outside, looking straight up. Since the Earth rotates once a day, the direction sky is constantly changing with time. However we'd like a map of the unchanging sky, so astronomers picked the North Pole as one fixed direction and defined by a star's position on the equator at 0 hours Right Ascension. The Earth's equator is 0 degrees Declination and the North Pole is at 90 degrees Declination. Note that we are represented by the little person on the Earth, at an odd angle relative to the coordinates. For us, it is most convenient to measure the Azimuth, angle relative to North, and Elevation, angle above the horizon, in your back yard. After your measurements, we will use a formula, and the time, to calculate Right Ascension and Declination.*

At right, shows the Sun and Earth's position in our galaxy. The Sun and Earth are about half way out from the center of our galaxy. The Galactic coordinates have 0 degrees longitude in the direction of the center of our galaxy and 180 degrees in the opposite direction. The Galaxy is rotating on its axis as well, and the strongest signals come from the Galactic Plane, latitude = 0 degrees.

Understanding Spectra

The radio spectra make sense because all hydrogen atoms floating freely in space, both on Earth and at the Center of our Galaxy, transmit a weak signal at exactly the same frequency, 1420.4058 MHz. To emit this frequency the atoms must not be in molecules, and must not be ionized, that is, still having their electrons. These types of hydrogen atoms are called HI (pronounced H-one). On Earth and in space, hydrogen is more commonly found in molecules. Two hydrogen naturally bond to form hydrogen gas. These hydrogen molecules also do not radiate at the neutral hydrogen frequency.

Fortunately our galaxy is full of HI atoms. Figures 4 shows spectra obtained on December 18 and 19, 2016. We had pointed the telescope at 42 degrees elevation and left the computer taking data for a littler longer than one day.

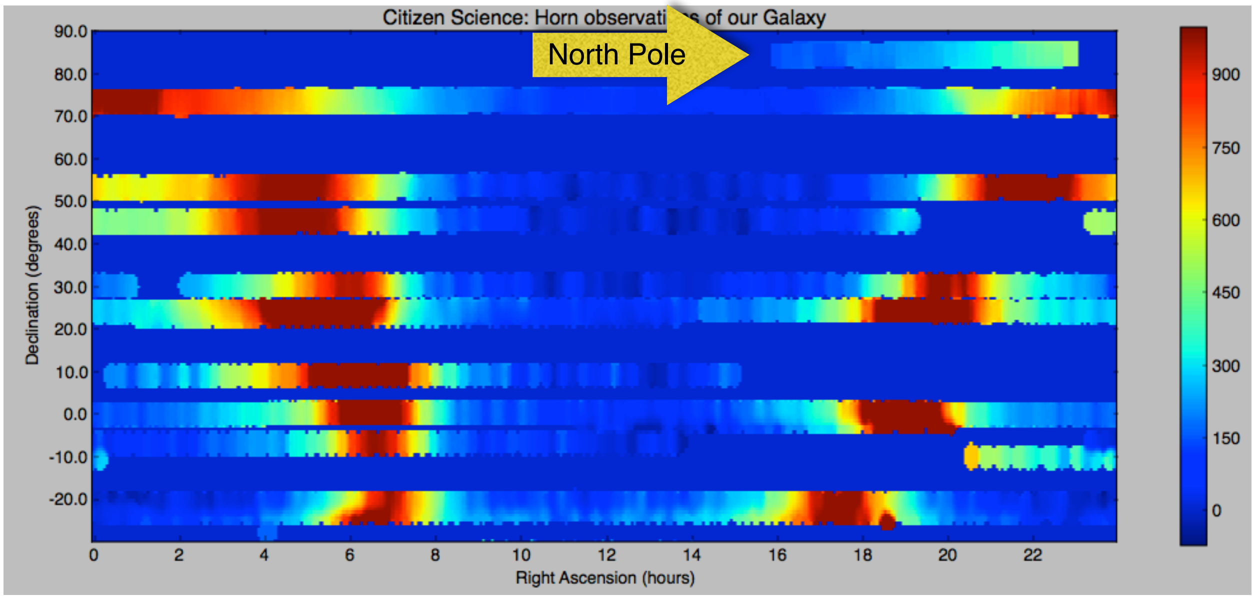

***Figure 7: Right Ascension, Declination Map of the neutral hydrogen** emission in the whole sky visible from my back yard. The horizontal axis is hours of Right Ascension, over the entire 24 hours of a day. The vertical axis is Declination, with the North pole at 90 degrees and the equator at zero degrees. Since the data are taken with the horn at a fixed elevation, a day of observations corresponds to a horizontal strip in the sky. The top line is from data taken with the horn pointed near the North pole. Notice colors show the hydrogen emission is connected, because you've discovered the Sun and Earth sit in the disk of our Milky Way galaxy.*

Since the data are recorded once a minute, we have 1440 spectra at the end of each 24 hours. This is too much to plot, so we average the data in one hour chunks. The 24 spectra (+1) are shown in Figure 4. The plot shows HI intensity versus velocity for one entire day of observations. The sky slowly rotates around and the observations continue over the same part of the sky one day later. The plot shows a number of interesting features, which correspond to different arms of the Milky Way galaxy. Figure 5 shows selected 15 minute averages of the observations. These plots show three averages of observations in the galactic plane, near 23 degrees galactic longitude (dashed lines) and three averages near 225 degrees latitude. The arms of the Milky way are moving at different speeds relative to the Earth, so can be distinguished by their speed and direction.

Mapping the Observations

Our Radio Telescope observations measure the sky at only one location at a time, but the way through the galaxy. As shown in Figures 4 and 5, measuring the velocity of a region lets us separate the parts of the galaxy in that direction. As the direction of the telescope is changed, either by pointing the telescope, or waiting while the Earth rotates once a day, different parts of the sky are measured.

In order to get a complete picture of the intensity of the sky the data must be combined into a single image. This combination is called "Gridding", which really just means defining the map shape wanted, then calculating which pixels should get the measurements. We've provided

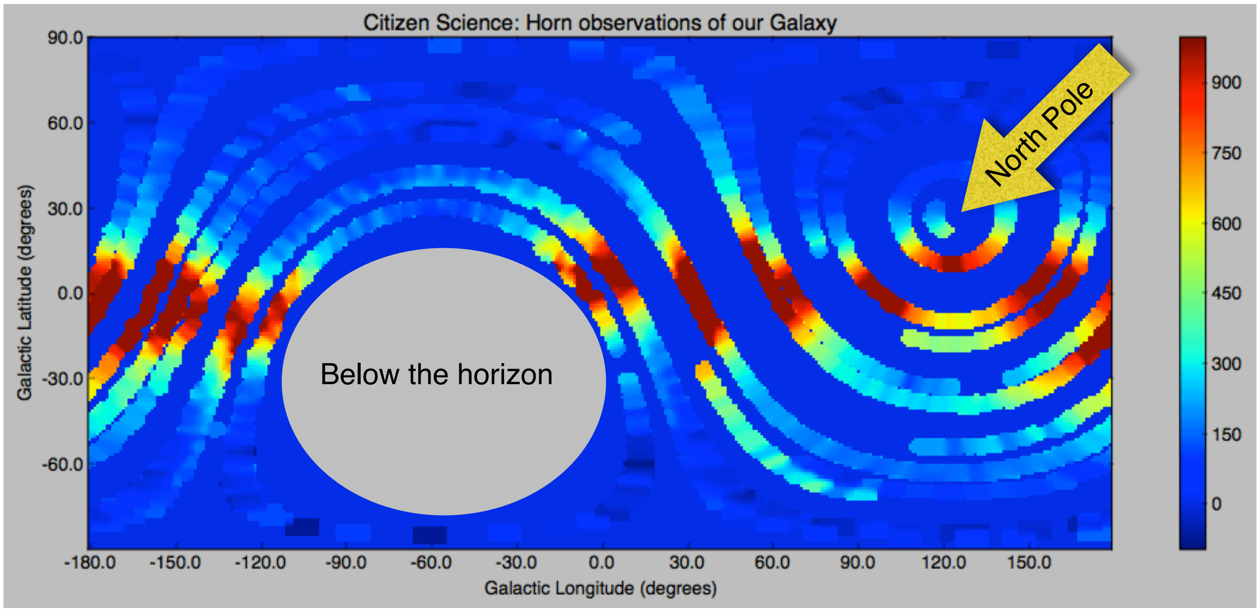

***Figure 8: Galactic Coordinate Map of the neutral hydrogen** emission in the sky from the same data as shown in figure 6.. However the coordinates are now Galactic Longitude along the bottom and Galactic Latitude on the vertical axis. The coordinates are defined by the galactic center at 0,0 and the galactic north pole at the top. The galactic plane is the location where all of the strong hydrogen emission is seen. The circle of data near longitude 120 degrees and latitude 40 degrees is data taken near the Earth's north pole, the top line in Figure 7.*

python programs to do these calculations for you, but you could do them yourself if you wanted. Finally the intensities need to be turned into colors so that we can look at the images.

This process is described more completely in Light Work Memo 15, and summarized here. Figure 7 shows the data obtained during these observations in a map of Right Ascension (time of day) on the X-axis and Declination on the sky in the Y-axis. For all these observations, we set the telescope elevation, fixed for day, then let the computer record the spectra. After day's the observations were complete, we'd check the data by making plots like those shown in Figures 4 and 5. If the spectra looked good, without too much noise due to bad weather or spikes of interference, we would further average the data and store the averages in a file.

Finally after we'd taken enough data at different Elevations, we'd gather them up a create a map. The maps can either be in coordinates based on the North Pole of the Earth and the time of day, like Figure 7, or based on the rotation of the Milky Way Galaxy around the pole of rotation, like Figure 8.

Note in both maps, only part of the sky is seen from our back yard. Figure 7 shows only the region above Declination -30, since the rest is below the horizon to the South. We could observe the rest of the sky by making friends with someone in the South who has built a radio telescope and asking them to share their observations. We could share our northern sky observations with them.

Because the direction of the Earth's North pole has little to do with the rotation of our Galaxy, the lines of constant elevation trace curves in Galactic Coordinates. The color of the strong emission in Figure 8 lies in a roughly straight line in Galactic Coordinates along the angle of 0 degrees Galactic Latitude. This is how Galactic Coordinate are defined. Also note that we can not see all of the Milky Way galaxy from the Northern Hemisphere.

In future, we will plot the distribution of hydrogen gas at different velocities, so that the motions of the Milky Way are more clearly shown.

Conclusions

We tweaked the observing software and saw different parts of our Galaxy each time we observed with our telescope. The individual spectra show the motions of our Milky Way, and observations along the Galactic plane show the different arms of our Galaxy.

We've created new mapping software for *Science Aficionados* to use with a simple-to-build Horn Radio Telescope. The telescope works very well and we produced the first *Science Aficionados* maps of the Milky Way Galaxy.

We hope that *Science Aficionados* will use our designs as the basis for their own Telescopes. It is clear that the Galaxy is within reach of anyone with time and inclination.

This project was undertaken to enable groups of A*ficionados* to contribute to existing large scale research projects and to invent and carry out their own experiments.

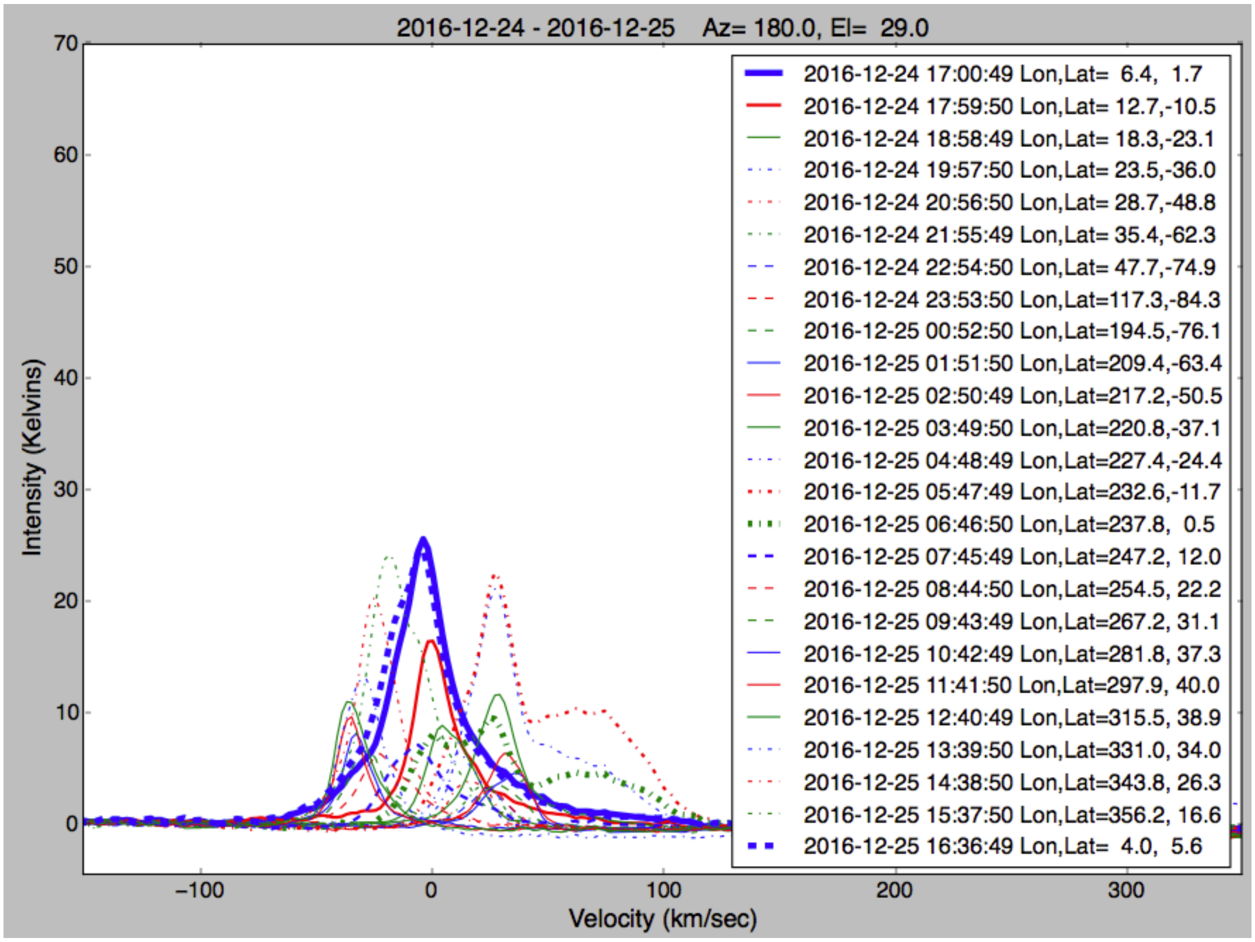

Figure 9: HI in the direction of the Galactic Center. *This plot of intensity versus HI gas velocity was taken over a 24 hour period containing Christmas Eve 2016. The emission strength is considerably weaker than is seen at higher elevations.*

Appendix: More Galactic Spectra

This appendix is an examination of the hydrogen spectra obtained by observations in different directions. Of particular interest are the differences in intensities and velocities of clouds of hydrogen in our galaxy.

Figures 9 shows spectra obtained during Christmas Eve, 2016. We were busy with preparing for Christmas and the Christmas Eve service, so the horn was in our barn, pointing south, at low elevation (29 degrees), out the barn door. At this elevation the Galactic Center is visible to the horn once a day. We had left the computer taking data. The data are plotted in Figure 9. Note the first observations, thick blue solid line, is towards the Galactic center and 24 hours later the Earth rotates around so that the Galactic center is again in view, as is shown by the thick blue dashed line. There is very good agreement between these two observations.