Subject: System Temperature *Measurements set 4*
Memo: 4, rev 3
From: Glen Langston
Date: 2015 July 7

This note describes a Radio Astronomy horn antenna and system for use by citizen scientists. We report a fairly major improvement in the measured system temperature of a newly re-configured amplifier chain and AIRSPY Software Defined Radio (SDR) dongle. The amplifier chain is described, calibration method summarized and first astronomical observations presented. These results are encouraging and, with tweaks in the system, the performance of the system is sufficient for educational and research uses.

System Overview

The telescope consists of a waveguide horn, feed port integrated with waveguide (band-pass) filter, RF electronics box with power supply and a computer for configuring the data acquisition system and receiving spectral data. This configuration is shown schematically in Figure 1. Figure 2 shows profile of the system (left), configuration for an overnight of observations (center) and system inverted for calibration (right). The waveguide horn is constructed from 0.5in thick foam insulation board with aluminum coating. The feed horn described here is the second generation version. Initially a single pyramid horn was used, but this horn was too large and unwieldy for testing.

The size of the test system was set by the size of the door and porch access widths, as shown in Figure 2. The horn opening width is 32 inches wide and 36 inches tall. The aperture is 0.74 meters square. The horn is folded at a 45 degree angle for convenience of handling. The fold base is 24inches long by 20inches wide. The taper of the horn is set to match the size of an L-band waveguide, 8. inches by 4. inches. The waveguide probe position was optimized through a series of measurements, described in Light Works Memo 3.

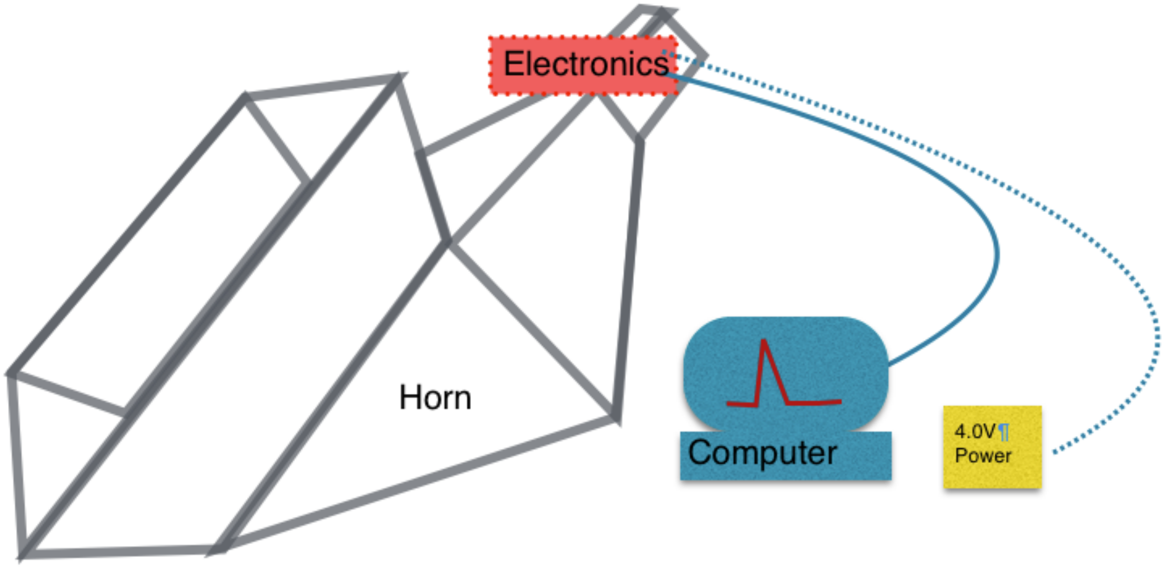


FIGURE 1: SYSTEM SCHEMATIC SHOWN MAJOR COMPONENTS OF THE TELESCOPE SYSTEM.

FIGURE 2: WAVEGUIDE FEED HORN AND ELECTRONICS BOX SHOWN IN PROFILE (LEFT), WAVEGUIDE IN POSITION FOR OVERNIGHT ASTRONOMICAL TESTS (CENTER) AND WAVEGUIDE HORN INVERTED FOR CALIBRATION MEASUREMENTS (RIGHT). IN THE LEFT AND RIGHT FIGURES A 48" RULER IS SHOWN TO PROVIDE SCALE.

The horn was assembled with aluminum coated tape (used for car muffler repair). The waveguide port and band pass filter were constructed from a single 24"x24" galvanized steel sheet, riveted. The waveguide port is described in LightWorks memo 5. It might be possible to construct the feed port out of foam board as well, but this has not been tested. The horn is used on top of a plywood sheet with angle markings at 10 degree intervals, roughly the horn beam width for observations at 1420 MHz. The horn usually observes at 45 degree elevation, and rotated over a range of azimuths.

The major improvements in this system, over the previously tested configurations, were 1) using a larger electronics box enabling a simpler signal path, 2) use of two Mini-circuits (ZX60-P162LN+) amplifiers, with much better performance, and 3) use of the AIRSPY Software Defined Radio system. Figure 3 shows the electronics box with components annotated.

The ZX60-P162LN+ amplifiers have ultra low Noise Figure, 0.6 dB at 1420 MHz, and high dynamic range in the frequency range 700 to 1600 MHz. The gain at 1420 MHz is roughly 20 dB. These amplifiers have lower performance, but operate over the frequency range of at least 100 to 2000 MHz. (For specifications see: http://www.minicircuits.com/pdfs/ZX60-P162LN+.pdf)

After the first amplifier, with 20dB of gain, a 3 dB attenuator was added to reduce resonate features in the IF chain. Also a 800 MHz high pass filter is inserted to reduce interference generated by much higher power, low frequency signals. Assuming a 1 dB insertion loss for the high pass filter, altogether the system has a total gain of +36 dB, before input to the AIRSPY.

Internal to the AIRSPY, each of the three amplifiers were set to +14 dB of gain, yielding a total system gain for these tests of +78 dB.

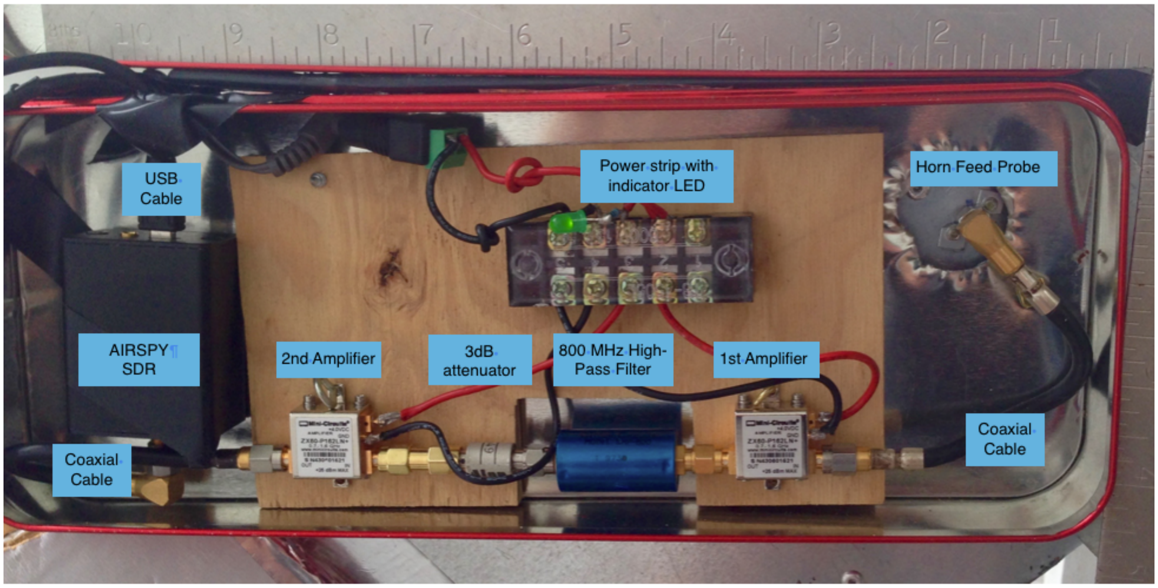


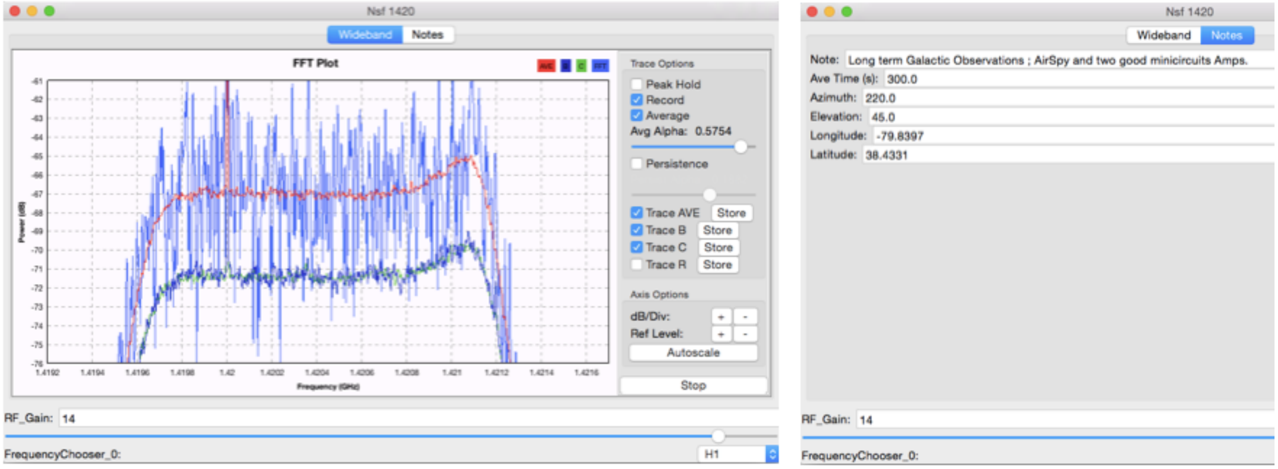
FIGURE 3: INTERIOR OF THE ELECTRONICS BOX WITH COMPONENTS ANNOTATED. SIGNALS ARE INPUT ON THE RIGHT SIDE OF THE BOX, AMPLIFIED, FILTERED AND AMPLIFIED IN THE CENTRAL COMPONENTS. THE AIRSPY SOFTWARE DEFINED RADIO (SDR) CONTAINS THREE ADDITIONAL AMPLIFIERS AND HIGH SPEED SAMPLERS. THE OUTPUT DIGITAL SIGNALS ARE TRANSFERRED TO THE COMPUTER VIA A USB CABLE. AN 11 INCH RULER, ON TOP, SHOWS THE SCALE.

Software system

A MacBook Air computer (1.6 GHz Intel Core i5, 11in display, release mid 2011) was used to configure the AIRSPY and capture the data. The software was custom created by the author, based on the very capable GNU Radio Companion (GRC) suite of software. Major additions were 1) addition of integration times for spectral recording, 2) an ascii file format for data writing and 3) a method for user input of observational parameters.

The previous measurements were made with a different SDR dongle, and the AIRSPY dongle was automatically detected and operated nearly flawlessly when plugged in. The author greatly appreciated the efforts by others to create such a user friendly software package. The core software was written in C/C++ and python.

Figure 4 shows the two panels of “NsfRecord”, the program used to record the spectral data. Users of GRC will note the similarities with the base system. The two panels are for 1) display of wideband data and the 2) observing notes. The spectral plot panel shows intensity (logarithmic in dB) versus frequency in MHz. The colored lines show 1) average of observations 300 seconds of the sky (green, lowest line), 2) average of 300 seconds of observations of the ground (red, higher smooth curve) and 3) blue single observation (0.0016 seconds) of the ground (blue noisy line).



☐ Peak Hold
☑ Record
☑ Average
Avg Alpha: 0.5754
☐ Persistence
☑ Trace AVE
☑ Trace B
☑ Trace C
☐ Trace R
RF_Gain: 14
FrequencyChooser_0: H1

Note: Long term Galactic Observations ; AirSpy and two good minicircuits Amps.
Ave Time (s): 300.0
Azimuth: 220.0
Elevation: 45.0
Longitude: -79.8397
Latitude: 38.4331
RF_Gain: 14
FrequencyChooser_0:

FIGURE 4: TWO PANELS OF THE NSFRECORD SOFTWARE INTERFACE TO THE AIPSPY HARDWARE. THE LEFT PANEL SHOWS THE WIDE-BAND SPECTRAL DATA AND RIGHT PANEL SHOWS THE OBSERVER NOTES, WHICH ARE ADDED TO ASCII RECORDED DATA.

The AIRSPY (http://airspy.com/index.php/specifications/) SDR system is, according to the vendor, currently the SDR with the "highest dynamic range in its price range". The system has a very precise clock, and numerous features making it useful for Astronomical applications, including 12 bit samplers and a very low noise figure, less than 3.5 dB between 42 and 1000 MHz.

The single adverse feature of the AIRSPY noted was the strong, narrow line, feature at exactly 1420 MHz, probably due to leakage from the clock into the down converter. The system was setup for a center IF frequency of 1420.45 MHz and a bandwidth of 2.5 MHz. (The AIRSPY could also operate with a 10 MHz bandwidth, but that bandwidth was not tested.) Figure 5 shows plots of raw intensity versus frequency from data recorded during the observations. The Intensity (vertical) axis is in units of linear counts. The horizontal axis is frequency (MHz).

Measurements

These measurements were carried out on July 4 and 5, 2015 under good weather conditions. The horn was located underneath the porch of my cottage and pointed out towards the sky at a 45+/-5 degree angle. The Azimuth of all observations was 220+/-5 degrees. The elevation was either 45 degrees or during calibrations at -90 degrees, when pointing at the ground.

The digital data have arbitrary units and are termed "counts". The goal of calibration is to turn the digital data into physically meaningful quantities. The measured values, Chot, are the hot load counts and Ccold, the cold load counts. Delta_C is the difference between Hot - Cold load counts. Figure 5 shows a roughly 4 dB difference between hot and cold load or a factor of 2.5

The estimated beam size of the horn is roughly the wavelength, 21cm, divided by the aperture size, 36 inches or 91cm. This corresponds to 0.22 radians, or 13 degrees. The exact direction of the horn beam was not determined before the astronomical tests, and is probably uncertain by +/- 10 degrees.

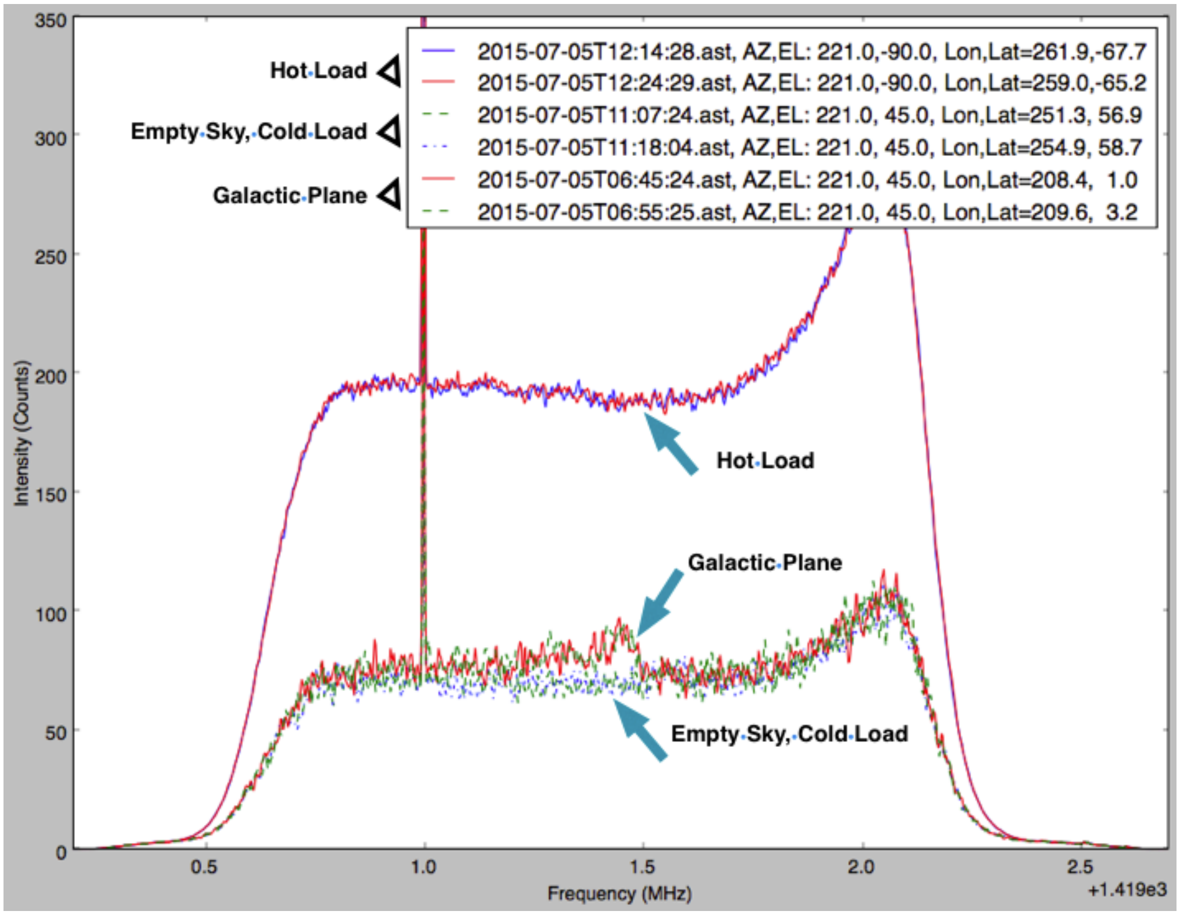


FIGURE 5: RAW (UNCALIBRATED) INTENSITY VERSUS FREQUENCY PLOT OF SELECTED DATA FROM THE OVERNIGHT OBSERVATIONS. INTENSITY UNITS ARE LINEAR HARDWARE COUNTS AND FREQUENCY AXIS IS MHZ. SIX 10 MINUTE AVERAGE OBSERVATIONS ARE PRESENTED. THE TOP MOST TWO LINES SHOW THE HOT LOAD DATA, WHEN THE HORN WAS POINTED AT THE GROUND (ELEVATION = -90). TWO OBSERVATIONS WERE MADE WHEN THE HORN WAS POINTED WELL AWAY FROM THE GALACTIC PLANE, AT LATITUDE 58 DEGREES. THE OTHER TWO OBSERVATIONS WERE TOWARD THE GALACTIC PLANE, LATITUDE 2 DEGREES. THE INTERFERENCE FEATURE AT 1420 MHZ IS ALSO SEEN.

The observed signal, C_measured, by the hardware, measured in Counts, is related to the observed sky brightness, T_sky, and the receiver system temperatures, T_sys, both measured in Kelvins. This is shown in equation (1).

$$C\_measured\ (counts) = S * (T\_sys + (G\ T\_sky) \qquad (1)$$

The factor S is the scale factor due to the accumulated gain of the amplifier chain. The S Factor converts physical temperature in Kelvins to voltages which are in turn converted into digital counts. The Gain factor, G, is the gain due to the connection between the horn and waive guide probe. The Gain factor is 1 for a perfect feed probe and G=0 if the feed probe is disconnected (i.e. G factor range is 0 to 1).

The gain factor S is determined by measurements of “Hot” and “Cold” loads. For radio astronomy the ground is a convenient hot load, with assumed temperature of 295 Kelvin.

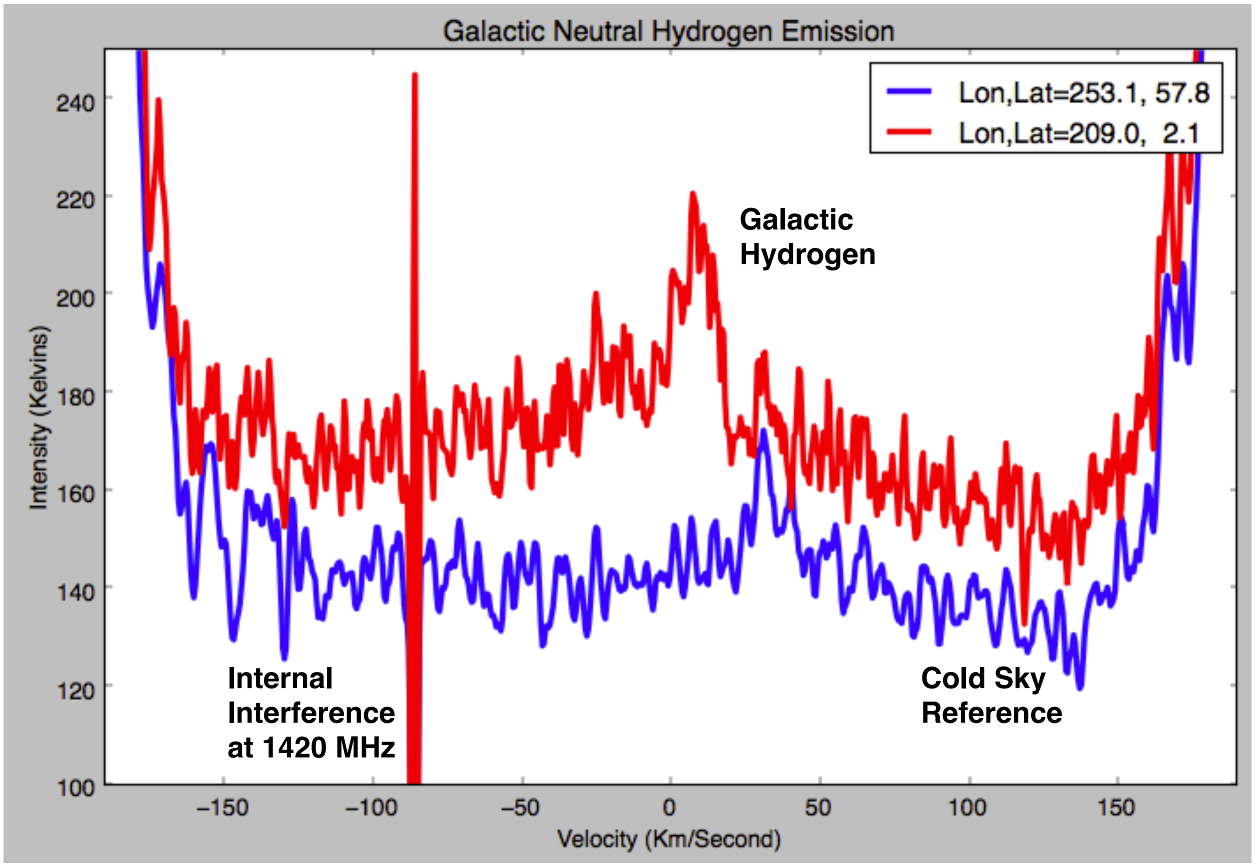


FIGURE 6: CALIBRATED ASTRONOMICAL OBSERVATIONS OF THE MILKY WAY GALAXY MADE WITH THE HORN SYSTEM. THE PLOTS SHOW CALIBRATED SYSTEM TEMPERATURE MEASUREMENTS, CALIBRATED, IN UNITS OF KELVIN, VERSUS EMISSION VELOCITY, IN KM/SEC. THE PLOTS ARE COMPUTED FROM THE OBSERVATIONS PRESENTED IN FIGURE 5. THE UPPER, RED,, CURVE SHOWS EMISSION IN THE GALACTIC PLANE, WHILE THE LOWER, BLUE, CURVE SHOWS THE EMISSION AT THE DIRECTION IDENTIFIED AS THE COLD LOAD REFERENCE. THE PEAK IN THE UPPER CURVE, NEAR 10 KM/SEC, IS GALACTIC HYDROGEN

When pointing away from the galactic plane and other bright sources the Sky is a very good cold load, with estimated temperature of 15 Kelvin with an antenna pointed at 45 degrees elevation.

Counts Hot Load = C_Hot = S (T_sys + G T_Hot) (2)
Counts Cold Load = C_Cold = S (T_sys + G T_Cold) (3)

Solving for Tsys/G yields:

Tsys/G = (Chot * (Thot - Tcold)/Delta C) - Thot (4)

A pair of 10 minute observations of the ground were made before the sky observations. The software was setup for recording the entire night, at 10 minute intervals. In the morning, following all observations, additional 10 minute observations of the ground were made. (The comparison of the hot load signals has not yet been completed in detail, but superficially the data appeared similar for all ground (hot load) observations.). Figure 5 shows the uncalibrated

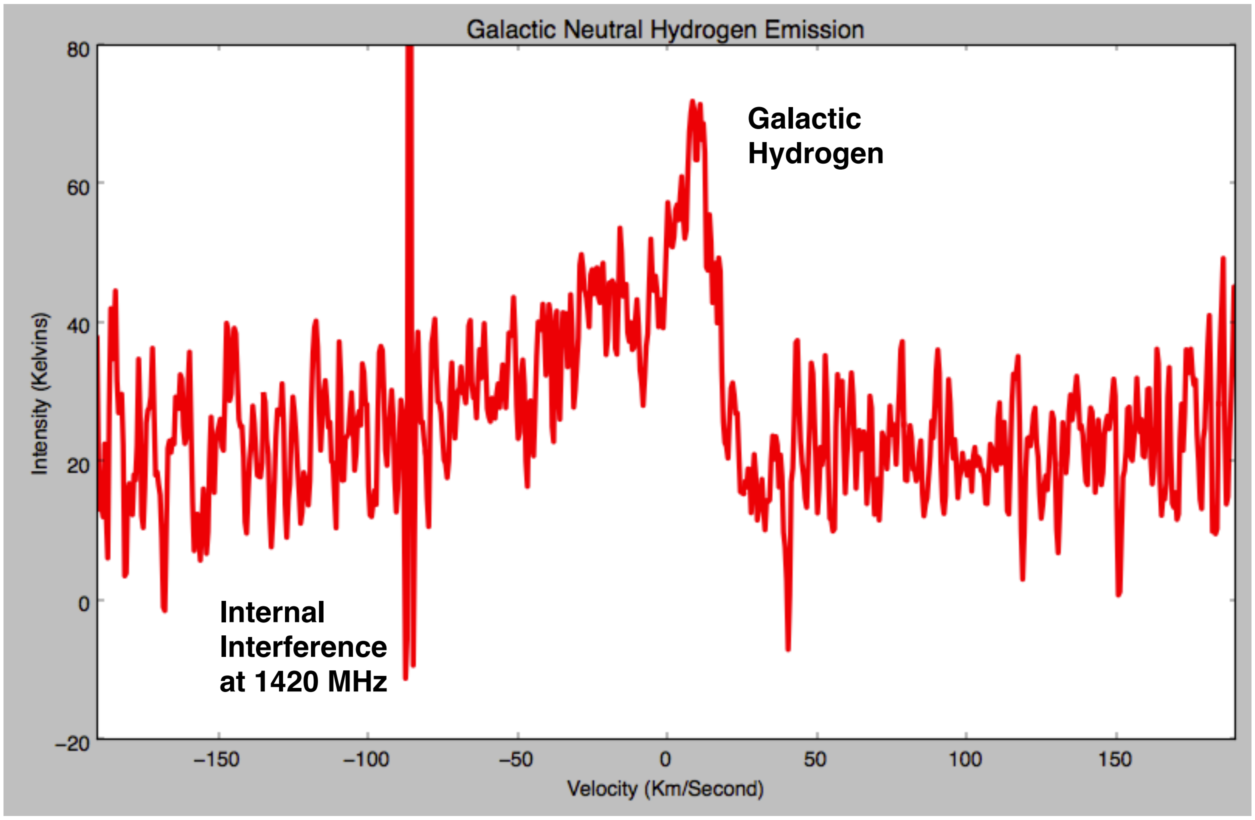


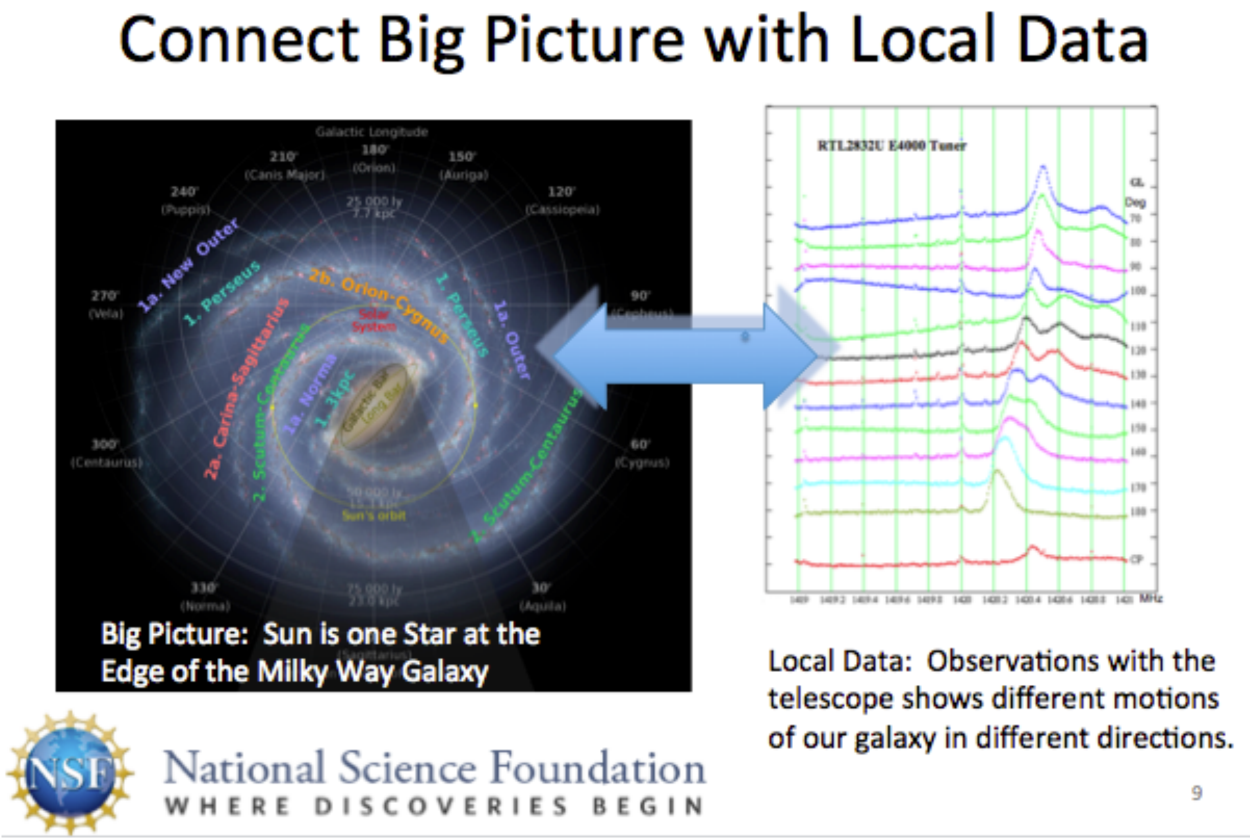
FIGURE 7: FULLY CALIBRATED OBSERVATIONS OF GALACTIC NEUTRAL HYDROGEN, FROM THE DIFFERENCE IN THE TWO CURVES IN THE PREVIOUS FIGURE. THE 20 KELVIN AVERAGE VALUE ACROSS THE BAND IS DUE TO THERMAL AND SYNCHROTRON EMISSION FROM STARS, GAS AND SUPERNOVAE REMNANTS IN OUR GALAXY. THE ATOMIC, EMISSION LINE, SIGNAL IN THE VELOCITY RANGE -50 TO 30 KM/SEC IS DUE TO HYDROGEN GAS AT DIFFERENT LOCATIONS IN OUR GALAXY. BECAUSE THE GALAXY IS ROTATING FASTEST AT THE CENTER, THE LOCATION OF THE GAS CLOUDS CAN BE ESTIMATED BY THE VELOCITY AND DIRECTION AT WHICH THE GAS IS DETECTED. THIS IS THE BASIS FOR OUR UNDERSTANDING OF THE STRUCTURE OF OUR MILKY WAY GALAXY.

hot, cold and sky measurements. Figure 6 shows the system temperature calculation deduced from the hot and cold load measurements.

Finally, the sky brightness at a particular location in the sky is determined by subtraction of the system contribution, defined as the observations at the position of low emission, in this case at Galactic longitude 253+/-5 degrees and latitude 58+/-5 degrees.

Tsky/G = (Csky * (Thot - Tcold)/Delta C) - Thot - Tsys (5)

Data reduction software was written in python to process the data after the observations. The observation reduction was done by reading in the ascii data files and implementing the equations above. Using the assumed values for Thot (295K) and TCold (15K) yield the plot of system temperature and sky brightness shown in Figures 6 and 7.



Connect Big Picture with Local Data

Big Picture: Sun is one Star at the Edge of the Milky Way Galaxy

Local Data: Observations with the telescope shows different motions of our galaxy in different directions.

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FIGURE 8: SCHEMATIC DIAGRAM OF OUR MILKY WAY GALAXY AND SUGGESTION OF A CONNECTION BETWEEN OBSERVATIONS WITH THE HORN, OR OTHER SYSTEMS, AND THE STRUCTURE OF OUR GALAXY. PLOTS AT RIGHT ARE CURTESY OF MARKUS LEECH, WHO DEVELOPED A VERY CAPABLE SYSTEM WITH A DIFFERENT ANTENNA DESIGN. (WWW.SBRAC.ORG/FILES/BUDGET_RADIO_TELESCOPE.PDF)

The 2.5 MHz bandwidth of the AIRSPY system corresponds to a velocity range of roughly +/- 190 km/sec. Due to the effect of the bandpass filters on the inputs, the apparent system temperature rises dramatically at the band edges. The system temperature shown in the plots is the sum of the amplifier system and the galactic emission. In the frequency ranges free of galactic emission the amplifier system temperature is deduced to be roughly 140 K.

The galactic emission is much stronger in the galactic plane (when the latitude is near zero). The galactic center is located near longitude = 0, while the outer galaxy is located at longitude = 180. The locations of the frequency of peak emission versus coordinate are consistent with expectations. The angular position of the horn should be better determined by measurements with a test source.

Different measurements of hot and cold load shows system temperatures as low as 110 K. There maybe some gain variation and the cause of the differences in system temperature measurements should be investigated. None the less, this 140 K system temperature value is much better performance than the first measurements of nearly 800 K, when the amplifiers were insufficient.

Conclusions

A compact horn, amplifier and data capture system was built and shown to have a competitive system temperature and sensitivity. The system was used to detect the neutral hydrogen emission from our Milky Way Galaxy. The emission was seen to be strong in a direction in the galactic plane and fairly weak when observations were made away from the galactic plane.

As is suggested in Figure 8, the system presented here enables citizens to build a system to find themselves in the Milky Way galaxy. Enabled by greatly advancing hardware capabilities, at very low cost, students have an excellent opportunity to both understand their scientific horizon and expand beyond the current limits.

Lessons Learned

This system has much greater sensitivity than previous versions of the device. The critical improvements were made by:

1. Optimizing the position of the feed probe in the waveguide.
2. Using a sufficiently large box to allow efficient layout of the components
3. Firmly attaching all components to a non-conducting board, so that no waveguide components were used for holding the position of the elements
4. Using very low noise amplifiers optimized for the target frequency range.
5. Using a very sensitive SDR dongle, enabling detection of weak signals.

To Be Done

The system presented here still could be improved in a number of ways. These include

1. Further tests of the feed port position for the current RF amplifier configuration
2. Reduction in the loss of the cable connecting feed probe to amplifier.
3. Test the 10 MHz sampling mode
4. Confirm that all data samples are being captured and averaged (it is possible that some spectral samples are being provided before the software is able to complete the previous round of data averaging).
5. Improve the spectral plotting, placing the data in the context of the galactic plane model.
6. Develop educational plans for use of the system in schools, clubs and museums.
7. Confirm the orientation of the horn beam and measure the beam profile.
8. Test different versions of horn with larger panels to enable more sensitive observations.

Thanks

Thanks to my wife, family and colleagues for their patience and encouragement.