

# **Development of a New Generation Small Radio Telescope**

## *REU Summer 2012 Report*

Dustin Johnson  
*Dalhousie University*  
Alan Rogers  
*Haystack Observatory*

10 August 2012

### **Abstract**

The original Small Radio Telescope (SRT) developed at Haystack Observatory is no longer in production and has become obsolete due to technological advances. We describe the design of the new SRT, its capabilities, and improvements made over the old. Several radio frequency interference (RFI) problems were encountered and addressed. Astronomical observations were taken to examine the performance of the new SRT. Some software was developed for the new SRT and thorough documentation and instructions on its assembly were prepared.

### **Introduction**

The Small Radio Telescope was developed by Haystack Observatory to serve as an educational tool for universities and colleges for teaching astronomy and radio technology. The original SRT was popular, with several hundred being built and is still in use at many colleges. It is no longer available new, however, and advances in electronics have rendered the original obsolete. Development of a new SRT was undertaken by Haystack in summer 2012. This report documents the new design and improvements over the old, interference problems encountered, testing based on several astronomical observations, software development, and prepared documentation.

### **Why is a new SRT needed?**

The original SRT was developed in 1998 at Haystack Observatory. Analog-to-digital conversion and signal processing were carried out in the receiver by a microchip. The receiver, rotor controller, and other components were built by CASSI, a company founded to produce the SRT. The individual electronic components were all soldered onto custom PC boards.

In the past fourteen years, electronics have advanced significantly, allowing higher data rates and more processing to be done on the desktop computer controlling the telescope. CASSI ceased providing the SRT in 2011 when the maker of the dish went out of business, but demand remains.

Consequently, it was decided to develop a new SRT, taking advantage of the advances in electronics and approaching the design from a build-it-yourself standpoint.

### **Design of the new SRT**

The primary philosophy of the design for the new SRT is that the users should build the telescope themselves from commercially available equipment, based on plans, instructions, and software provided by Haystack. It is designed to be assembled easily with minimal need for special tools or skills. This approach allows the SRT to be independent of a single company dedicated to its production and provides an educational opportunity to the users who build the telescope. Also, users of the SRT will be

more familiar with how it works if they assemble it themselves, allowing better in-house technical assistance.

The SRT is composed of several main components:

- A 2.3m satellite dish on a fully steerable, motorized azimuth-elevation mount
- A feed composed of a helical antenna backed by a cavity
- A low-noise amplifier
- A super-heterodyne receiver providing 10 MHz bandwidth centered on the 1420.4 MHz (21-cm) hydrogen line
- A/D conversion on a dedicated PCI card
- A rotor controller to run the motors which steer the telescope
- Software on a desktop computer to receive and process data from the telescope and control it

Figure 1 on the next page shows the block diagram of the entire system, with key elements and the theoretical gain and attenuation of the signal at each stage. Table 1 below summarizes key data for the new SRT.

Parameter	Value
Theoretical gain	71 dB
Measured gain	71.5 dB
HPBW	6.5°
Feed S11	-23.5 dB
System temperature	171 K

**Table 1: Key data for the new SRT**

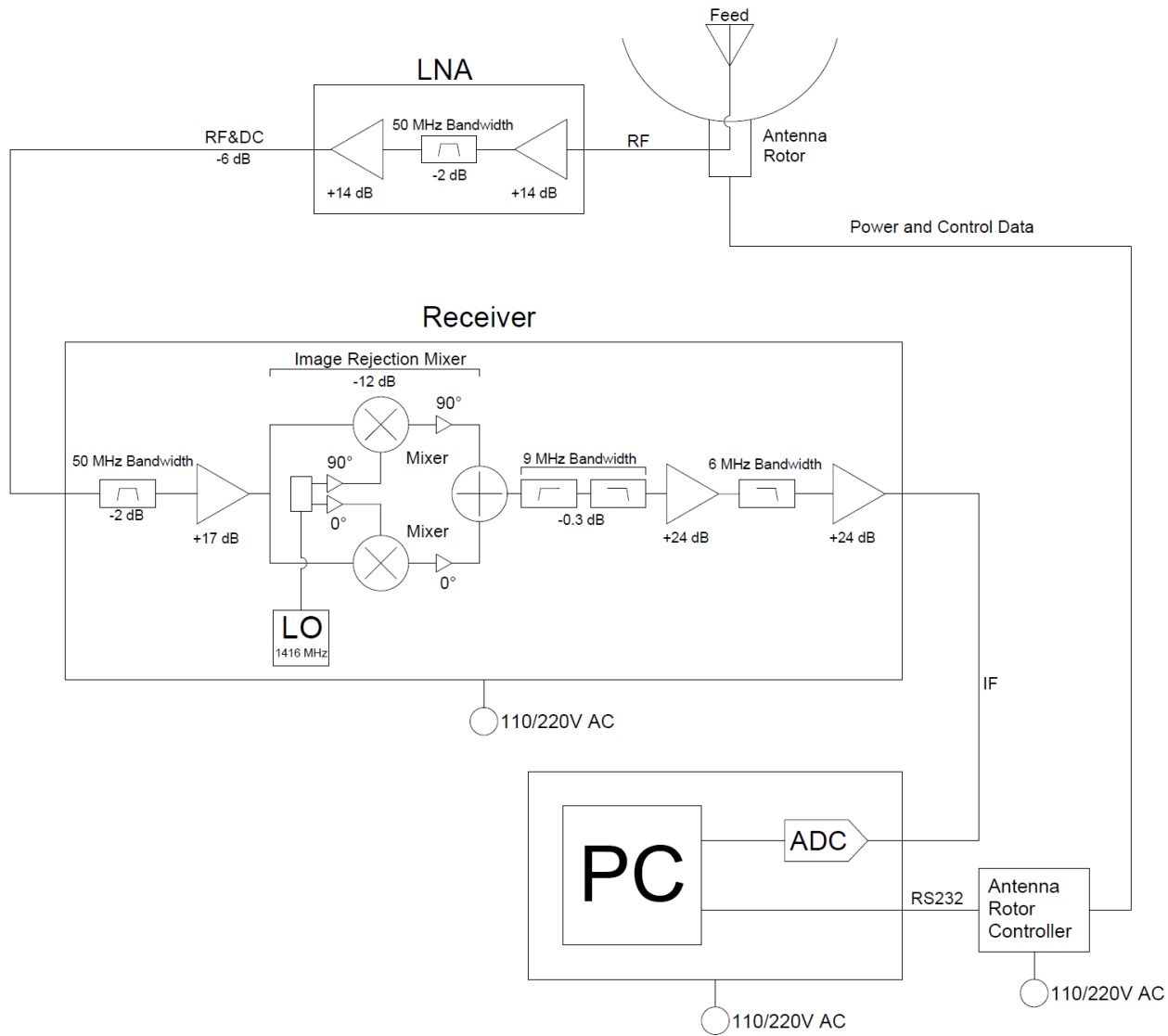


Figure 1: Block diagram of the new SRT

### *Feed*

The feed is based on the second feed model from the original SRT. It uses a helical antenna, made from copper foil tape wrapped around a core made from a polystyrene foam cylinder, designed for 1420 MHz, based on several designs from the literature<sup>1,2</sup>. The helix is  $0.3\lambda$  in diameter, with a turn spacing of  $0.14\lambda$  and a pitch angle of  $8.6^\circ$ . It is wound to be left-hand circularly polarized, to give right-hand polarization upon reflection by the dish.

The helix is backed by a cavity which is an aluminum cake pan. The cavity is  $0.85\lambda$  in diameter and  $0.36\lambda$  in depth. The antenna is attached to the center pin of a SMA connector which passes through the back of the cavity. A quarter wavelength stub constructed of semi-rigid coaxial cable provides a DC path to ground for lightning protection of the LNA and receiver.

Two main modifications were made to the feed from the original design. The LNA was moved from a small PC board underneath the foam core of the helix to an enclosure on the back of the cavity. The impedance matching method was changed from a tapered section at the end of the helix, which gave a reflection coefficient of  $-13.2$  dB, to a  $1/8\lambda$  by  $1/16\lambda$  copper foil plate<sup>3</sup> parallel with the helix, centered on the first quarter turn. This method reduced the reflection coefficient to  $-23.5$  dB.

### *Low-Noise Amplifier*

The new SRT's LNA is in a waterproof aluminum enclosure mounted on the back of the feed, causing minimal additional blockage of the aperture. All of the components of the LNA are modules from Mini-Circuits which can be easily connected with SMA cables. Two amplifiers running on 12V DC provide a nominal 28.4 dB of gain. A 1420-1470 MHz bandpass filter is located between the two amplifiers to cut

out interfering signals, and causes 2.2 dB of attenuation. A bias-tee allows the 12V DC for the amplifiers to be transmitted along the coaxial cable with the RF. The LNA is connected directly to the feed with a right-angle adapter, minimizing path length from the helix to the first amplifier.

The selected enclosure comes with a gasket to ensure the LNA remains dry in adverse weather conditions, and both SMA connectors penetrating the box are sealed with o-rings.

An approximately 3-m long section of LMR-240 coaxial cable runs from the LNA along one of the feed supports, along the back surface of the dish, and to a connection with a 15-m section of LMR-400 that runs inside to the receiver. The connection is protected from the weather by a shield made from a plastic drink bottle. The two sections of cable together cause 4 dB of attenuation.

### *Receiver*

The receiver is a super-heterodyne with a fixed local oscillator at 1416 MHz and an image rejection mixer. Most of the components are modules from Mini-Circuits and are connected with SMA cables and mounted on an aluminum plate within an enclosure.

The line from the LNA enters the receiver through a bias-tee to add the 12V DC required to power the LNA. The signal passes through a second 1420-1470 MHz bandpass filter and an amplifier with 17 dB of nominal gain.

In the image rejection mixer, the local oscillator signal is fed through a splitter with one output being shifted in phase by  $90^\circ$ . After mixing, this branch of the signal is once again shifted by  $90^\circ$  in the combiner to select the upper sideband and reject the lower sideband image frequency. The mixer causes a nominal 12.8 dB of attenuation and provides  $-34$  dB of image rejection.

The signal then goes through a 1 MHz high pass filter, a 10 MHz low pass filter, an amplifier, a 7 MHz low pass filter, and a second amplifier. Each amplifier provides a nominal gain of 24.4 dB, and the filters cause 0.3 dB of attenuation.

A wall connected switching power supply provides 15V, while two voltage regulators provide 12V and 5V DC to power the amplifiers and local oscillator. Capacitors on the two voltage regulators and a capacitor and inductor on the first IF amplifier remove low frequency noise from the power supply (see the appended circuit diagram for details).

The 90° combiner and high pass filter are not available as connectorized modules. The user must install these components in a box with BNC connectors. Soldering is required to power the amplifiers and LO. Mounting holes must also be drilled in the receiver component plate (see the appended mechanical drawings).

The new SRT shifts all of the data acquisition and processing out of the receiver and into the computer, leaving the receiver to only mix the signal down to the intermediate frequency. The local oscillator in the new receiver is fixed at 1416 MHz, while the old LO could be tuned between 1370 and 1800 MHz in 40 kHz steps.

#### *Analog-Digital Conversion and Data Acquisition*

The new SRT uses a commercial analog-to-digital converter on a PCI card. The converter has 12 bit resolution and a sample rate of 20 megasamples/second. The fast Fourier transformation (FFT) of the data and spectrum accumulation all takes place in the SRT software. This allows continuous, high-resolution collection of data.

The original SRT conducted the A/D conversion, FFT, and spectrum accumulation in the receiver itself on

dedicated microchips. Due to the speed at which the receiver could conduct the FFT, only a portion of the data could be used for the spectrum, reducing the effective integration time and therefore raising the noise level.

#### *Rotor Controller*

Both the old and new SRTs use the SPID RAS antenna rotor, made by the Polish company SPID Elektronik. The old SRT used a custom controller made by CASSI to interface between the computer and the rotor. The controller primarily acted as a power supply and transformed the position pulses from the rotor into a form the computer could read. Most of the control routine took place in the computer.

For the new SRT, there are two possible controllers, both made by SPID. These controllers use a simple communications protocol and take care of controlling the rotor, only needing the computer to tell the controller where to point the telescope. This system requires a different but simpler control routine in the software, which is still under development, and is discussed in more detail in the software section of this report. Due to financial constraints, as of this writing an actual control unit was not available for testing.

#### *Telescope Dish*

The old SRT and the prototype new SRT both use a 2.3m mesh satellite dish manufacturer by Kaul-Tronics. However, this dish is no longer commercially available. RF Ham Design carries a 2.4m mesh dish<sup>4</sup> which should be ideal for the SRT. A variety of solid dishes can be purchased, though many are expensive. One exception is a 1.8m dish from Sadoun<sup>5</sup>. Solid dishes are heavier than mesh ones, but the SPID rotor is capable of supporting very large loads, so weight will only be an issue for very large dishes.

### System Calibration

For the SRT to produce accurate measurements, it must be calibrated. The SRT software includes a calibration routine, which relies upon knowing the system noise temperature. This can be determined easily by finding the telescope's Y factor and calculating the system temperature from it<sup>6</sup>.

The Y factor is defined as:

$$y = \frac{P_H}{P_L}$$

Where  $P_H$  is the observed power on a load at high temperature and  $P_L$  is the observed power on a load at low temperature. For the SRT, the high temperature load was an absorber assumed to be a 300 K and the cold temperature load was cold sky, assumed to be at 3 K. The system temperature can then be calculated by:

$$T_{sys} = \frac{T_H - T_L y}{y - 1}$$

For the prototype SRT, the Y factor was found to be approximately 2.71, for a system temperature of 170.9 K.

The system temperature includes contributions from a number of different sources, three of which are of primary importance. The spillover is caused by the feed's non-ideal illumination of the dish and by its sidelobes, which pick up noise from the ground. The LNA and receiver also add a certain amount of noise, termed  $T_{amp}$  and  $T_{ss}$ .

Using Y factor measurements, the values of the components of  $T_{sys}$  can be approximated. When the measurements are taken for the Y factor, the power received with the feed and LNA disconnected is recorded. This is subtracted from the powers for the high and low temperature loads, and a new Y factor is calculated, which only takes into account the noise from the LNA and spillover:

$$y_c = \frac{P_H - P_{ss}}{P_L - P_{ss}}$$

The Y factor can also be calculated from the system temperatures present in the measurement of the hot and cold loads:

$$y = \frac{T_{amp} + T_{ss} + T_H}{T_{amp} + T_{spill} + T_{ss} + T_L}$$

Similarly, if  $T_{ss}$  is removed from the above equation, the equation for  $y_c$  is obtained. If  $T_{spill}$  is assumed to be 80 K, a reasonable value, then  $T_{spill} + T_{amp}$  can be calculated. Knowing this value,  $T_{ss}$  can then be calculated.

For the SRT, it was found that  $y_c$  was approximately 2.99, giving  $T_{ss}=65.1$  K and  $T_{amp}=25.8$  K.

### Interference Problems

Three main interference problems were encountered during development of the new SRT, though only two are issues for SRTs in general.

Due to the prototype's location at Haystack Observatory, it encountered interference from the nearby Millstone Hill Radar, which operates at high power at 1295 MHz. Consequently, a stub filter was constructed from semi-rigid coaxial cable and placed at the input to the receiver. It caused approximately 2.4 dB of attenuation at 1420 MHz but reduced the radar interference. Such interference could also be reduced by incorporating a cavity filter designed for 1420 MHz.

Due to the prototype SRT's location close to the buildings at Haystack, it experienced high levels of interference from computer systems in the observatory. Most of this interference was at very specific frequencies, and so an addition was made to the software to allow the user to remove certain frequencies from the spectrum

during processing. The level of interference experienced can be reduced by placing the SRT as far away as possible from any buildings or other systems containing computers or other noisy equipment.

The local oscillator in the receiver, built by Luff Research, operates at 1416 MHz, but uses a 4 MHz reference. Consequently, it produces a small spur at 1420 MHz. This signal is detectable in the SRT software. For the prototype, it can be removed using the method described above for computer interference. Contact has been made with Luff Research over this issue, and future oscillators are not expected to have this problem.

### Astronomy

Three astronomy projects were undertaken with the prototype new SRT to test its capabilities. These projects were:

- Comparing spectra of several standard regions against their spectra from the literature
- Measuring the galactic rotation curve
- Constructing a velocity-longitude plot of the galactic plane and comparing it to a plot from the literature

#### Standard Regions

Several regions of neutral hydrogen emission have been well characterized and studied in radio astronomy. Spectra of these regions were taken by the SRT and compared to spectra from the literature, provided by Williams<sup>7</sup>. These regions can be used to calibrate equipment and allow the comparison of different surveys.

For the purposes of the SRT, only the shape and location of various spectral features were compared. Since the SRT beam is wider than the hydrogen line structure in these regions, the SRT antenna temperatures

are lower than those of Williams, which were measured on a 25-m dish.

For all four regions data was averaged over approximately ten minutes before the spectra were produced. Observations were conducted manually for regions S7 and S8, and automatically for S6 and S9. All spectra were produced using the pswriter program described in the Software section of this report.

The following figures show the spectra of the standard regions with the locations of key features highlighted, both from Williams and from the SRT. Note that the listed location of features relative to VLSR is only approximate.

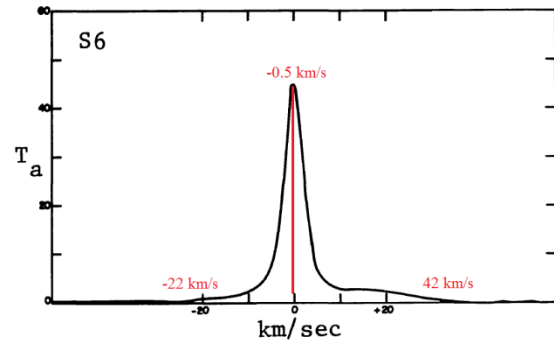


Figure 2: Spectrum of region S6 from Williams

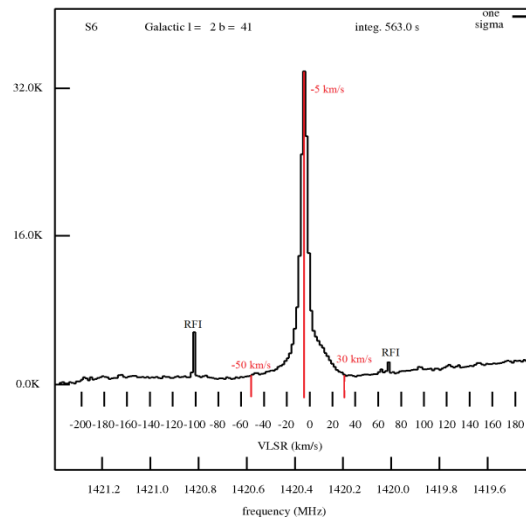


Figure 3: Spectrum of region S6 from the SRT

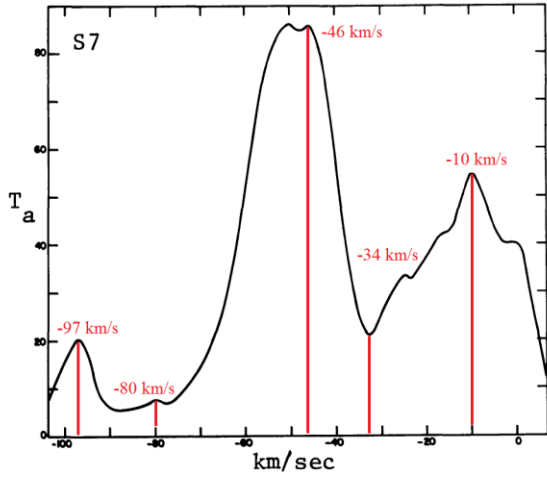


Figure 4: Spectrum of region S7 from Williams

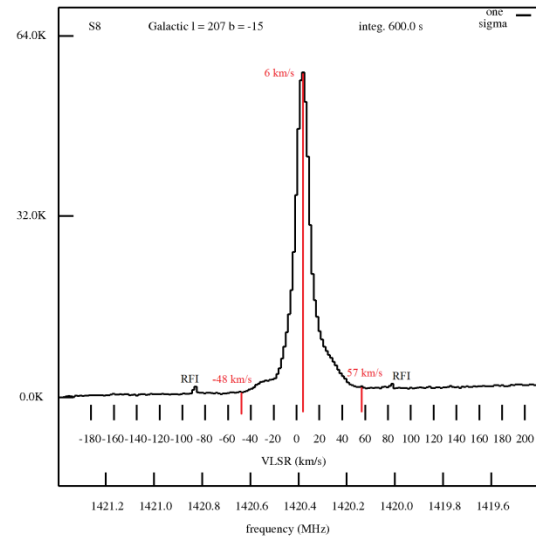


Figure 7: Spectrum of region S8 from the SRT

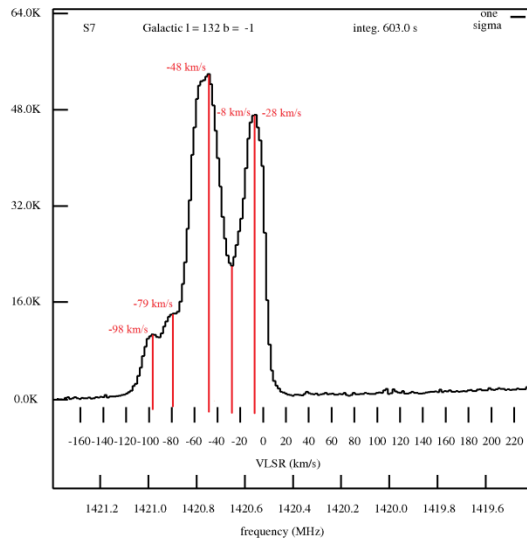


Figure 5: Spectrum of region S7 from the SRT

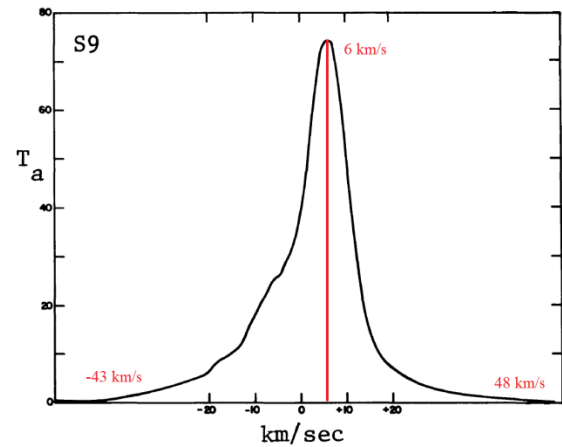


Figure 8: Spectrum of region S9 from Williams

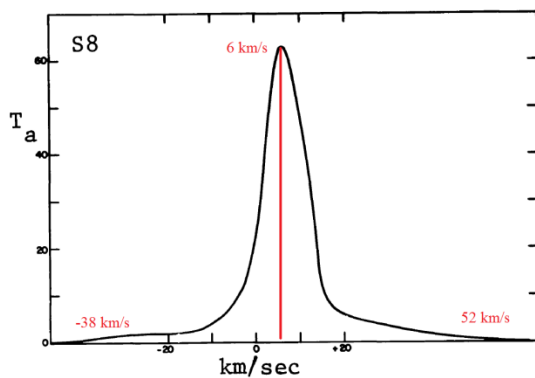


Figure 6: Spectrum of region S8 from Williams

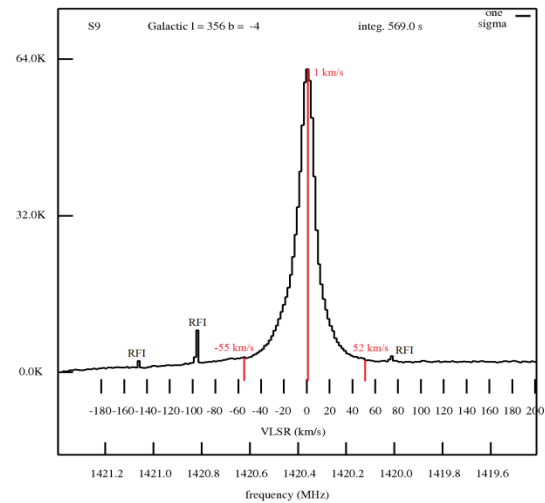


Figure 9: Spectrum of region S9 from the SRT



For all regions the locations of key features of the spectra match closely to exactly between the SRT and Williams, though the exact locations of where the spectral line merges with the noise can be difficult to determine. For regions S6, S8, and S9, the shape of the spectra also match closely, while for region S7 there are greater differences. These are likely due to the differences in beamwidth of the telescopes for the two surveys. Williams employed the Hat Creek 85-foot telescope with a half-power beamwidth (HPBW) of  $0.58^\circ$ , while the SRT has an HPBW of approximately  $6.5^\circ$ . Contour plots of these regions from Williams exhibit significant structure at the fraction of a degree scale which cannot be resolved by the SRT.

### *Galactic Rotation Curve*

A simple but educational experiment that can be conducted with the SRT is measuring the galactic rotation curve. The procedure

summarized below is fully described in the report by Ballard et al.<sup>8</sup> To do so, spectra are taken at several points along the galactic plane, usually between galactic longitudes of  $0^\circ$  and  $90^\circ$ . The maximum velocity edge of the neutral hydrogen spectral line is determined from each reading. This maximum velocity is due to the hydrogen whose movement in its galactic orbit is along the line of sight from Earth.

Knowing the orbital velocity of the solar system and its galactic radius, the orbital velocity and galactic radius along each line of sight can then be computed. When plotted against each other, this series of values displays how the orbital velocity of the galaxy varies with orbital radius.

The following two figures show the galactic rotation curve as measured by the new SRT, and by the old SRT from the report by Ballard et al.

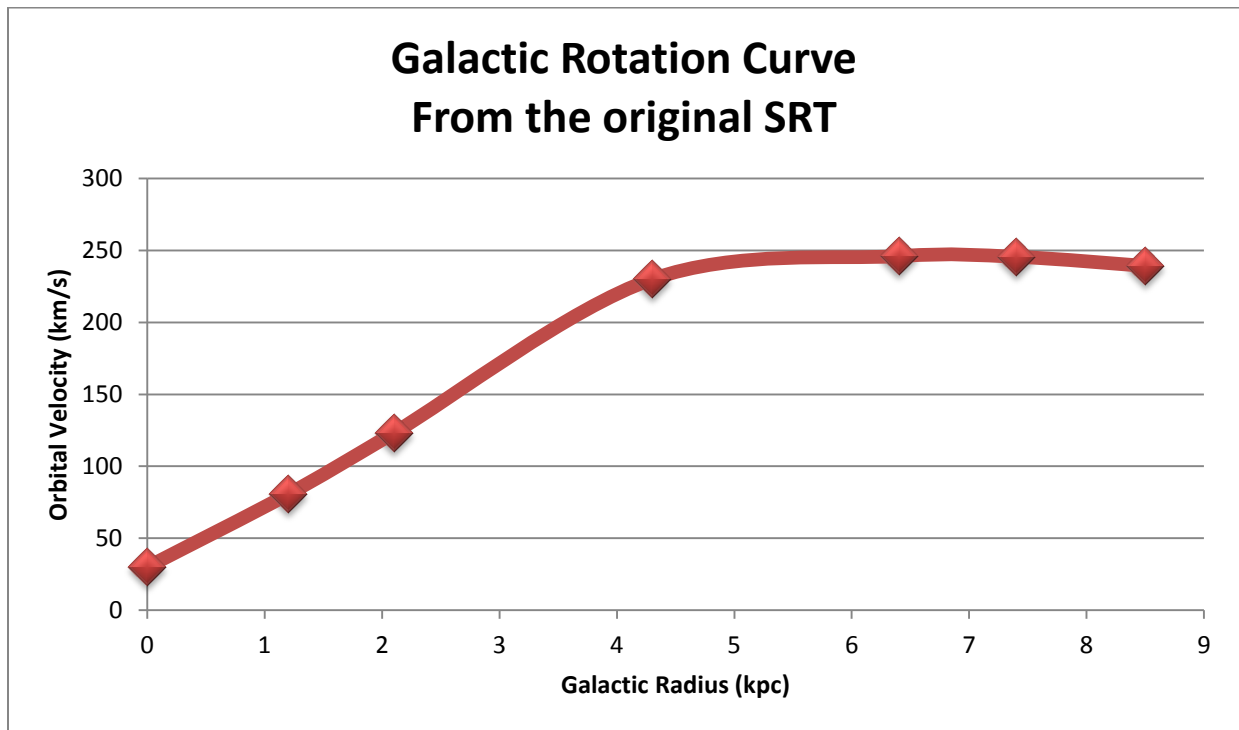


Figure 10: Galactic rotation curve, replotted with data from the report by Ballard et al.

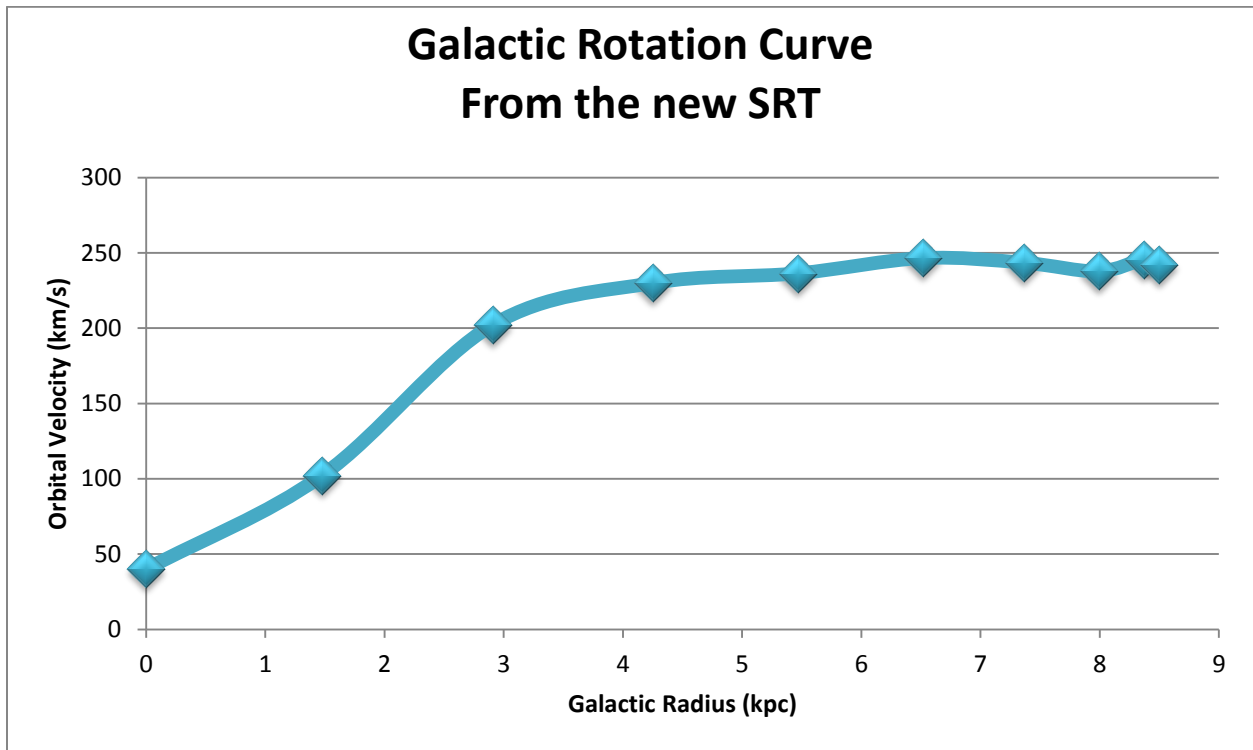


Figure 11: Galactic rotation curve taken by the new SRT

The curve from the new SRT conforms quite well to the original, as well as to two curves from Ballard et al. which were taken with the original SRT. They begin leveling off at almost the same point ( $r=4.3$  kpc,  $v=230$  km/s) and reach approximately the same maximum. The rise of the curves is also very close.

#### *Galactic Plane Velocity-Longitude Plot*

A more complicated and lengthy experiment that the SRT is capable of conducting is measuring neutral hydrogen spectra at many points along the galactic plane and plotting the VLSR and intensity of the spectra versus galactic longitude. Due to the use of a single telescope at Haystack, the profile produced by the SRT does not cover the entire galactic plane. The following figures show a high resolution HI velocity-longitude plot compiled from multiple surveys<sup>9</sup>, and the HI

velocity-longitude plot made by the new SRT.

The data was collected automatically by the SRT. Some regions were not observed, causing the low spatial resolution visible in several places, such as the galactic center. Due to the limited time available, data were only integrated for 15 seconds per  $2^\circ$  section of the galactic plane. The data was processed using C code with simple provision for error correction to remove anomalously intense spectra. The plot was produced in MATLAB. Data was collected from  $l=0^\circ$  to  $l=250^\circ$ .

Comparing the plot from the SRT to that from the literature, the general shape and location of main features are similar. There is good correspondence between regions of greater intensity, though there are some anomalies that may be caused by interference.

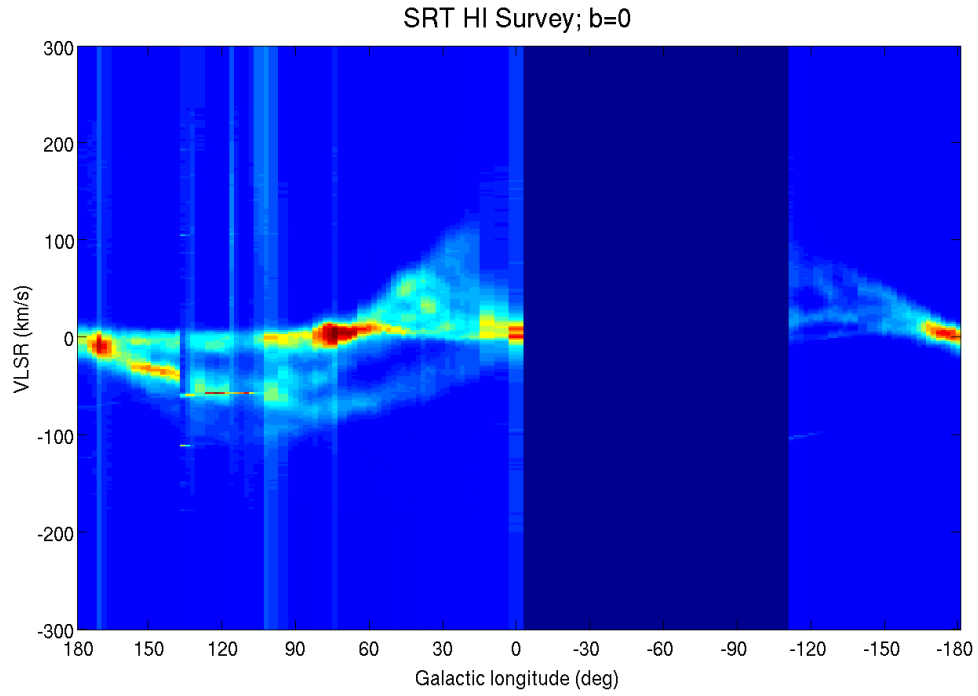


Figure 12: Neutral hydrogen along the galactic plane from the new SRT

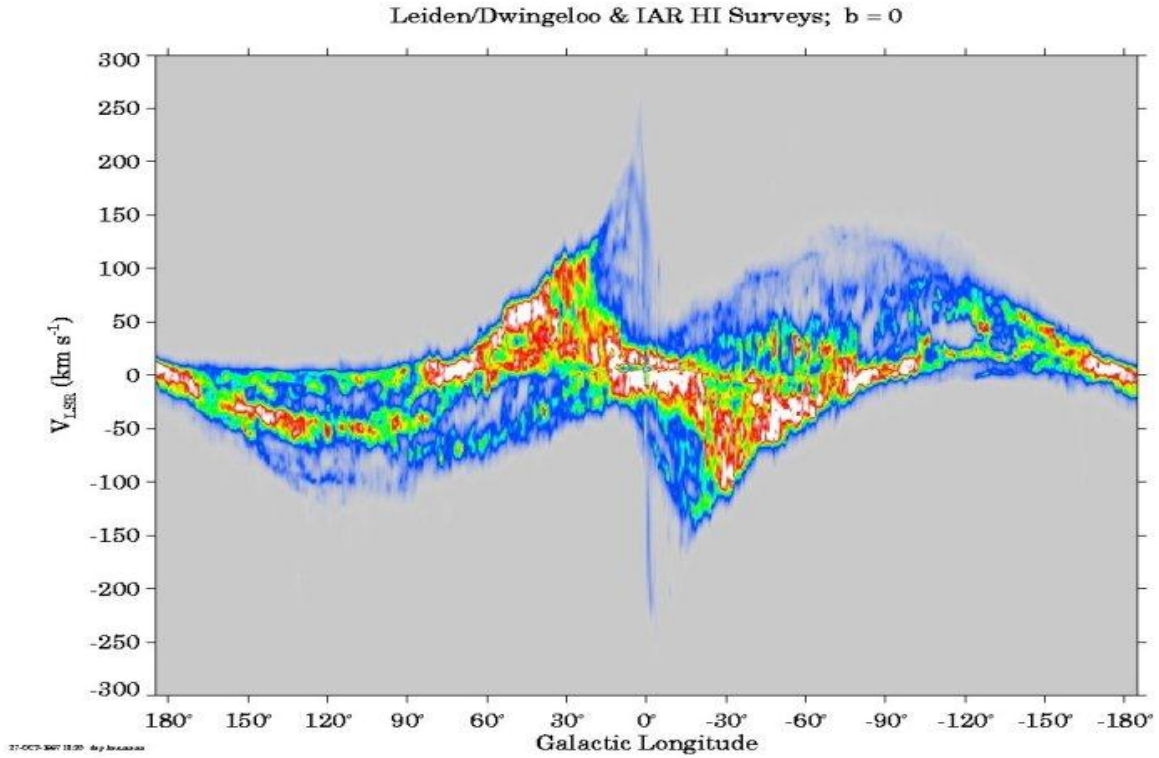


Figure 13: Neutral hydrogen along the galactic plane

These three experiments show that despite the SRT's small size, it is capable of collecting astronomical data usable for educational applications, which agree well with data from the literature collected with much more sensitive and sophisticated instruments.

### **Software**

The development of the new SRT included the design of two new pieces of software: a program to read data recorded by the SRT software and produce spectra plots from it; and code to communicate with the new rotor controllers from SPID.

Pswriter is a stand-alone command line program written in C. The SRT program records data every ten seconds to a text file, including the average spectrum at that point and information about the telescope's settings and where it was pointed. Also recorded is a unique observation number. The user supplies pswriter with the name of a data file and the desired observation number. The program reads the corresponding set of spectrum data in from the data file and draws the spectrum in a postscript file.

The code is largely a modification of code from the SRT program which allows the user to generate postscript files of spectra from within the SRT program. However, there was no ability to generate such files after the fact from data files, such as might be recorded during automatic observations. Pswriter supplies this ability.

The two rotor controllers available from SPID function very differently from the original controller from CASSI. The CASSI controller served primarily to power the rotor and pass on location information from the rotor to the computer. The SPID

controllers only require the computer to provide target coordinates and they carry out the movement of the antenna autonomously.

This difference required the development of new code to send target information to the controller and receive position feedback. Due to time constraints, this code could not be fully developed, integrated into the existing program, and tested. The currently developed code takes the azimuth and elevation command from the program and creates the command string that would be sent to the SPID controller. Also developed was a function to simulate the SPID controller so that the program could be tested before an actual controller was available. Further work is needed to develop the new control routine.

### **Documentation**

An important part of this project was the development of thorough documentation of the new SRT's systems so that users can easily assemble the SRT. There are three main components of this documentation: a manual describing the construction and installation of the required hardware; a list of required parts; and mechanical/electrical drawings of the SRT's components to provide mechanical dimensions and information on the electronics.

#### *Manual*

The manual is a single document covering the assembly and set-up of the physical components of the SRT. It contains information on selection of a dish, installation of the pier that the rotor and dish sit on, detailed assembly instructions for the mechanical and electrical components of the LNA and receiver, and instructions on the set-up and alignment of the rotor. Photographs at multiple points show the

physical layout of components and clarify complicated portions of the assembly.

### *Parts List*

A full list of all the parts required to build the SRT was also prepared. It includes their price, manufacturer, where they were purchased from, and part numbers. Several options for the telescope pier and dish are included. The parts list is appended to this report.

### *Drawings*

A series of five drawings were produced with CAD software to fully document the electronic and mechanical design of the new SRT.

Three drawings cover the mechanical aspects of the SRT. One describes the feed, showing the design of the helical antenna and the placement and size of all the required holes in the cavity and LNA mounting plate. Another shows the receiver mounting plate with the size and locations of all of the required holes. The third shows the location and size of the holes in the receiver case. The receiver mounting plate and feed drawings reference the locations of the holes to a single point, allowing these components to be easily manufactured on a milling machine with digital read-out.

Two drawings cover the electronic components of the SRT. One is a block diagram of the entire system, displaying key components, how they are connected to each other, and the gains and losses throughout the system. The other is a schematic of the electronics of the LNA and receiver, displaying all components with their part numbers or values and how they are connected including the labels on the ports of the modular components.

All of the drawings except the block diagram are included in the hardware manual for easy reference, as well as in

separate pdf format files. They are appended to this report, except for the block diagram which was included earlier.

## **Conclusion**

The original Small Radio Telescope was developed at Haystack in 1998 as an educational tool, providing universities with an inexpensive radio telescope for teaching astronomy and radio technology. Since then, it has remained popular with several hundred being built and deployed, but it is no longer available and electronics have advanced significantly. The new SRT has been designed to allow universities to build it themselves from commercially available components based on plans and software provided by Haystack. Tests of the prototype have shown that the new SRT is as capable as the old, with better spectra resolution and signal-to-noise ratio, and can be used for a variety of educational purposes.

## **Acknowledgements**

I would like to thank my mentor Alan Rogers for all his help, advice, and patience; Phil Erickson and Vincent Fish for running the REU program; Jim Traffie, Ken Wilson, Mark Derome, and Peter Bolis for their technical expertise; K.T. Paul for getting us here and back again; all of the lecturers for sharing their knowledge and experience; the other REUs; the entire Haystack community; and the National Science Foundation for making it all possible.

---

## References

- <sup>1</sup> Keen, K.M. "Low profile cavity antenna with small pitch angle helix feed." *Electronics Letters*, 4 March 1993, Vol. 29, No. 5, pp. 501-502.
- <sup>2</sup> Nakano, H., Takeda, H., Honma, T., Mikami, H., & Yamauchi, J. "Extremely low-profile helix radiating a circularly polarized wave." *IEEE Transactions on Antennas and Propagation*, Vol. 39, No. 6, June 1991.
- <sup>3</sup> "Circularly polarized helical antenna 7.5 -13 dBi – new: wave trap match." Retrieved from: <http://www.rcgroups.com/forums/showthread.php?t=1377791>
- <sup>4</sup> "2.4m Mesh Dish Kit." RF Ham Design. Retrieved from: <http://www.rfhamdesign.com/products/parabolicdishkit/24meterdishkit/index.html>
- <sup>5</sup> "Sadoun SD180 w/Polar Mount." Sadoun. Retrieved from: <http://sadoun.com/Sat/Products/S/Dishes/SD180PM-180CM-Prime-focus-Satellite-Dish-Polar-Mount.htm>
- <sup>6</sup> Rohlfs, K., and Wilson, T.L. "Tools of Radio Astronomy." Berlin: Springer, 1996.
- <sup>7</sup> Williams, D.R.W. "Studies of four regions for use as standards in 21-cm observations." *Astronomy and Astrophysics Supplement*, Vol. 8 pp. 505-516.
- <sup>8</sup> Ballard, S., Harris, R., Lanz, L., Maruca, B., & Muñoz, D. "Astronomy 218 Haystack Observatory project report." Harvard University (2007). Retrieved from: [http://www.haystack.mit.edu/edu/undergrad/pdf/haystack\\_FINAL\\_2\\_8.pdf](http://www.haystack.mit.edu/edu/undergrad/pdf/haystack_FINAL_2_8.pdf)
- <sup>9</sup> "HI 21-cm Intensity." University of Alberta. Retrieved from: [http://www.ualberta.ca/~pogosyan/teaching/ASTRO\\_322/images/fig2\\_20\\_color.jpg](http://www.ualberta.ca/~pogosyan/teaching/ASTRO_322/images/fig2_20_color.jpg)