The Small Radio Telescope at Haverford College

Operations Guide, Year-End Report, and Plan for the Future

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10 May 2003

Fall 2002 – Spring 2003 Research

An Introduction to Radio Astronomy

Unlike physicists, chemists, and biologists, astronomers do not have the luxury of controlling most of the variables in their lab. They are subject to the whims of the cosmos: line-of-sight limits, obscuration due to dust, and low signal to noise ratios. But these obstacles have never been enough to stop astronomers from looking to the skies: for hundreds of years, astronomers have studied what they could see of the universe. The optical band, however, is subject to much obscuration and spans but a narrow part of the electromagnetic spectrum. Developments in the last century have made it possible to detect radiation outside the narrow band we can actually see with our eyes. Today, optical astronomy still enjoys the best media and the prettiest pictures: but gamma ray astronomy has taught us what happens to the biggest, brightest objects; microwave astronomy has offered clues to the beginning of the universe; and radio astronomy has allowed us to map out the universe.

Hydrogen, the most common element, comprises 74% of the cosmic mix by mass, and over 92% by number. Thus, naturally, hydrogen observations are typically very informative: few structures in the universe are not emitting something due to hydrogen. Optical hydrogen lines, however, are subject to obscuration by dust. Infrared wavelengths are long enough not to be diffracted by dust particles, but the amount of water in our atmosphere makes Earth-based infrared observations practically impossible, and so hydrogen's infrared emissions prove to be equally troublesome to study. Luckily, hydrogen also has a strong emission line in the radio band: neutral hydrogen can have the quantum spins of its proton and electron either parallel or anti-parallel, and the transition from one to the other results in a photon emission at 1420 MHz, corresponding to a wavelength of 21 cm. This frequency is a strong emission in the quiet L-band of the electromagnetic spectrum, evidence of the most abundant element in the universe (even if only in its cold, neutral state), and easily detectable with radio telescopes.

Radio astronomy, however, is not as perfect a gift as it may seem to be. Radio waves' long wavelengths may not suffer diffraction off dust but are very much subject to diffraction off larger objects like radio telescopes, causing much trouble. Also, radio waves are low energy, and the low incident signal strength becomes an immense problem when one considers the continuum emission from the Earth, how strong a noise it is, and, with the aforementioned ease of diffracting off of the telescope itself, how easily the earth may contaminate an observation.

Overcoming low signal-to-noise ratios has been the constant and primary struggle in radio astronomy.

The actual components of today's radio telescopes are quite straightforward. A dish reflects incident waves to a feed placed at the dish's focal point. Most receivers today are super-heterodyne: they mix into the incident signal a low-frequency wave in order to allow an amplifier to better amplify the signal. After amplification, the signal is filtered to remove all frequencies except the desired one and then squared to make the wave's amplitude proportional to the intensity coming from the source. Then a detection (i.e., conversion to a DC signal) takes place. The technology behind radio astronomy is simple: amateurs and students could conduct radio astronomy if only they had access to the proper equipment.

In January, 2001, MIT's Haystack Observatory implemented their Undergraduate Research Educational Initiative with the following goal: "To use radio astronomy, which is an interdisciplinary field, to study concepts in physics, chemistry, engineering and computer science." To this end they developed the Small Radio Telescope (SRT), an inexpensive, self-contained kit designed to introduce undergraduate students to the technology behind radio astronomy. The SRT is designed to perform continuum and spectral line observations around 1420 MHz, the neutral hydrogen spin-flip emission frequency: simple in design and operation, the SRT is capable of conducting significant experiments in radio astronomy at a level suitable for undergraduates. In the Spring of 2001, Haverford College purchased one of the original twenty SRT beta models. For a year and a half, it lay dormant in storage. Then, in the fall of 2002, I began the process of constructing, configuring, and setting up a system of operation for the SRT with the eventual goal of integrating the SRT into the astronomy curriculum.

Construction: The Components of the SRT

The complete SRT weighs approximately 130 pounds and cannot easily be moved. In places where a permanent mounting location is unavailable, a steel Non-Penetrating Roof Mount (NPRM) constructed by Kaul-Tronics[1] may be used. The SRT at Haverford is mounted on a NPRM on the high (4^{th} storey) roof of Stokes Hall. 2160 pounds of concrete (27 slabs weighing

[1] http://www.orbitroninc.com/

80 pounds each) currently secure the NPRM and the attached SRT to the roof. The vertical pole on which the SRT is fit is supported by three diagonal rods. At the end of each of these is a threaded screw: one can level the vertical pole by manipulating these three diagonal lengths. The NPRM was installed, leveled, and secured in November, 2002.

In order to be able to point the SRT at any point in the visible sky there are two separate drive motors, one for azimuth movement and one for elevation movement. The two motors are mounted 90° off axis from each other, allowing for total sky coverage in the following way: the azimuth motor has 180° of motion, and at each point along this span, the elevation motor can move from 0° (forward horizon) to 90° (zenith) to 180° (opposite horizon), tracing out a semicircle. Summing all the semicircles results in a hemisphere:

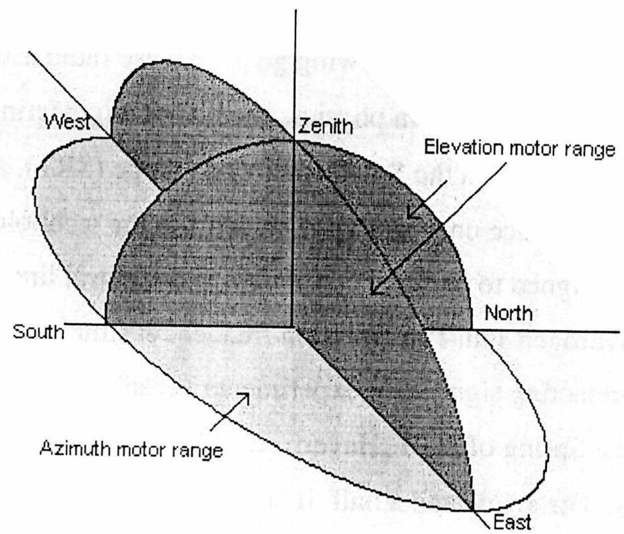

Figure 1: A map of SRT motion: The two motors allow for total sky coverage.

Two 24V motors drive rotational movement by spinning worm gears that in turn rotate sector gears. Attached to the azimuth motor's sector gear is the 90° adapter pipe upon which the elevation motor is fixed; attached to the elevation motor's sector gear is the antenna mounting ring upon which the dish is fixed.

The azimuth motor is secured to the NPRM with five bolts. These bolts do not penetrate the vertical pole of the roof mount, however: they act as stand-offs to the pole, allowing the azimuth motor to be leveled along one axis. A 13-inch threaded tie-rod allows for leveling along the other axis: to increase or decrease the angle of the motor to the shaft attached to the NPRM, move the securing bolts up or down the tie-rod. The elevation motor fits snuggly onto the adapter pipe, ensuring levelness along one axis. It, too, has a threaded tie-rod to allow for leveling along the other axis. It is imperative that the motors are level: the sector gears must have exact planar motion in order for the SRT to point and track accurately.

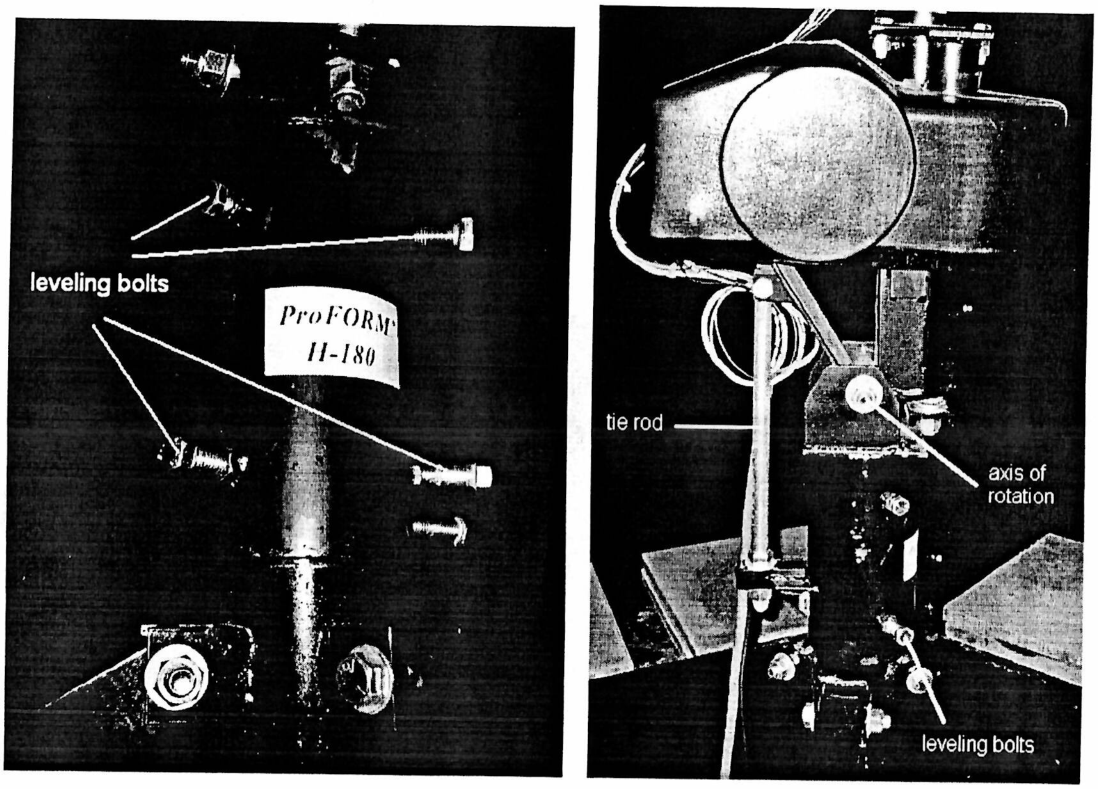

Figure 2: The leveling bolts and the tie rod, allowing for leveling the motor in both axes. The two images are perpendicular views of the azimuth motor.

The 7.5' parabolic dish is affixed to the antenna mounting ring. Since the wavelengths of interest to the SRT are long compared to the mesh size, the dish is reflective to the radiation while still allowing wind and shorter wavelengths (light, for example) to pass right through. At the focal point of the dish a feed horn is attached, but this is simply a generic C-band feed, serving no function to the SRT except as housing for the L-band receiver. Attached to the rear of the C-band feed is a blue-painted polarization rotator, also not used in SRT operation. To the outside of the C-band feed a thin metal circular ring was affixed, extending the shielding around the L-band receiver and serving as a mount for the vane calibration motor. The actual feed for the SRT is an inch-and-a-half long wire protruding from the center of the C-band feed. The wire should be at a 45° angle to the focal axis for optimum reception. Signals incident on the feed wire travel through a band-pass filter and a low-noise amplifier and then into the receiver, wherein the signal is mixed, squared, and digitized. The data then travels down to the computer control box via a coaxial cable attached to the rear of the receiver.

Figure 3: Detail of the feed horn, primary SRT components, and components of feed apparatus

For detailed schematics of each of the aforementioned electronic components and a more comprehensive description of the circuits involved, consult Haystack Observatory's SRT receiver information website.[2]

Wiring: The Electronics of the SRT

Two separate cables carry all commands, power, and data between the computer controlling the SRT and the SRT itself: a RG-59 (20 AWG) coaxial cable, and a nine-conductor (16 AWG) shielded control cable. The cables run from the lab in the basement of Stokes (room 006) up a cabling shaft to the lower (3rd storey) roof of Stokes; from there, they run outside of the building through an 1.5-inch diameter metal conduit along the 4th storey roof line to a junction box at the base of the SRT. The total run is approximately 180 feet.

To ease in troubleshooting, and to provide a way to operate the SRT while simultaneously witnessing its operation, terminators for the nine-conductor control cable and the coaxial cable are located both in the lab in the basement of Stokes and in the junction box at the foot of the SRT. A 120V power supply is also available in the junction box, allowing a laptop computer with the necessary SRT software installed—together with the control box—to operate the SRT locally. Also, VNC[3] remote-control software has been installed on the computer in the lab. To use VNC, ensure the computer and the control box are on, then login to the control computer's IP (165.82.15.161) with the password "haverfordsrt" (all lower-case) from any terminal on the Haverford College network.

The coaxial cable runs from the computer control box to the receiver. It carries the digitized data from the receiver down to the computer as well as +5V up to the receiver to power the amplifiers and other circuitry.

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[2] http://web.haystack.mit.edu/SRT/receiver_3.html

[3] Visit http://www.realvnc.com/ for details

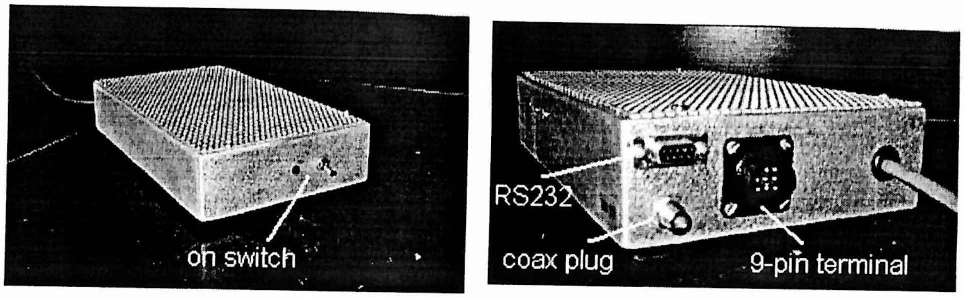
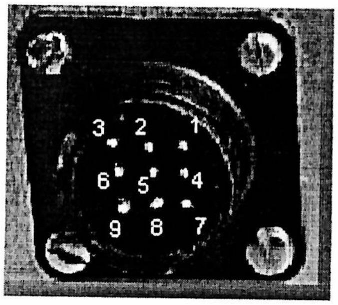


Figure 4: The Control Box, front and back

The nine-conductor wire carries the power to drive the azimuth, elevation, and vane motors. At the rear of the control box is a nine-pin male jack, and at this jack each conductor becomes associated with a certain motor function. At the SRT, the conductors are attached to the terminal block pins (or wires, for the vane) linked to the associated function. *Table 1* describes these connections.

Table 1: Wiring Details

Control Box Pin	*Function*	*Wire Color*	*Motor, Pin*
1	Azimuth +	Red	Az, 2
2	Azimuth -	Red+Black	Az, 1
3	Calibration +	Orange	Cal, Red
4	Elevation +	Green	El, 1
5	Elevation -	Green+Black	El, 2
6	Calibration -	Blue	Cal, Black
7	Elevation Pulse	White	El, 3
8	Ground	Black	Az and El, 5
9	Azimuth Pulse	White+Black	Az, 3



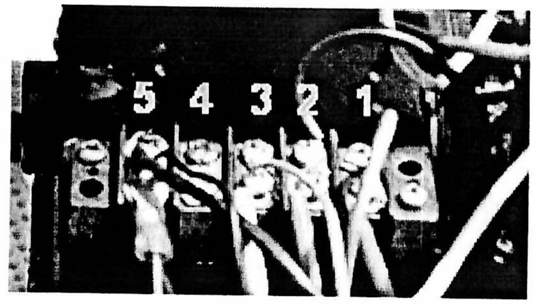


Figure 5: Control box pin orientation, azimuth/elevation terminal block pin numbering

The motors are operated thus: contact pins at the motor terminal block are connected to ground, +24V, -24V, and a "pulse-in" function, all via the Stamp[4] controller—the BASIC programming hardwired in the control box. The java software issues a "move" command to the Stamp controller, along with a particular axis to move and how many ticks to move it. The Stamp controller closes a contact between the ground pin and either the +24V or the -24V pin at the appropriate motor, moving the motor in the appropriate direction. A small magnet attached to the motor shaft sends pulses back down to the Stamp controller: by counting the pulses from the magnet, the Stamp controller can keep track of exactly how far the motor has turned, thereby calculating its exact position on the sky. Every 11.70 ticks of the motor correspond to 1° of movement.[5] Each motor also has two microswitches—one to trigger in each direction—acting as hardware stops: when the worm gear has turned the sector gear to its end, a protruding stem triggers the microswitch, which open the circuit driving the motor before the sector gear can dislodge from the worm gear. The resulting pulse sent back to the Stamp controller is interpreted as either a hardware stop or a motor stall.

[4] For more information about BASIC Stamp, visit http://www.parallax.com/

[5] For a derivation of this number, consult http://web.haystack.mit.edu/SRT/receiver_3.html

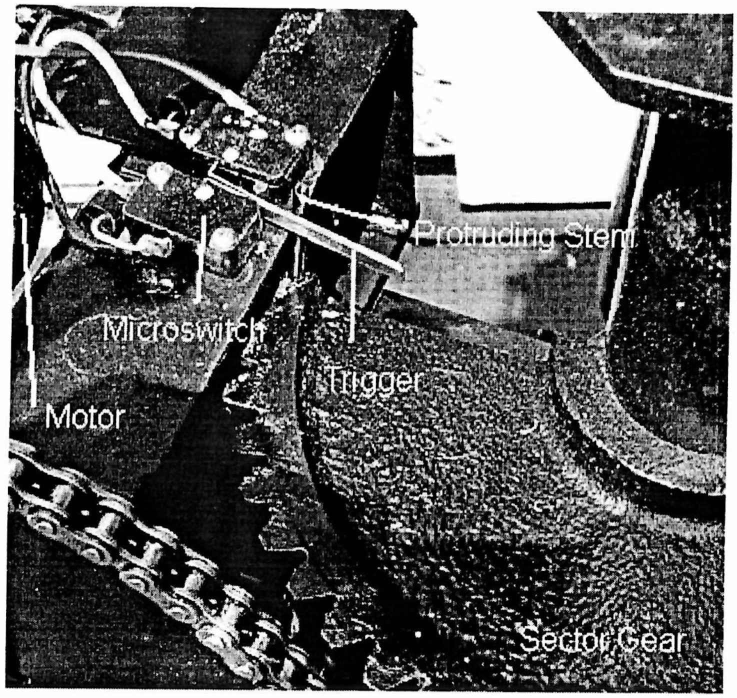


Figure 6: Detail of the motor gears at stow. Note that the microswitch has been triggered by the protruding stem to stop motor motion.

The operation of the vane calibration motor is much simpler. Upon initiating the automated calibration sequence, the Stamp outputs +12V DC to the calibration motor, swinging the attached vane over the feed. Halfway through the sequence, the Stamp outputs –12V to the motor, moving it the other way and, thus, swinging the vane away from the feed. Due to there being no way to know the exact location of the vane arm—it can be easily moved by hand—it would have been unwise to program the motor only to run for a certain length of time (the time necessary to completely swing the vane around). Therefore, the Stamp commands only turn the motor on: the motor comes to a halt itself when it encounters enough resistance, that is, at the C-band feed horn and then again at the weatherproof casing around the receiver components.

Software: Controlling the SRT

Communication between the operator and the SRT begins at a computer console running JavaScript. Before the program can be run, ensure that Sun's Java 2 Software Development Kit

(SDK)[6] is installed and running. Then, go to the Haystack software website[7] and download the 14 SRT java files. (Also available for download are two Stamp programs, though the proper one—with or without coding for the electronic noise calibration which Haverford does not have—is already uploaded onto the control box and having the program would serve only as a reference or a learning tool.) Follow the instructions on the software download page to ensure all software is installed, all programs are compiled, and all necessary environment variables are set before continuing. The computer currently in Stokes 006 is already configured for SRT operation.

To run the control program, open up an MS-DOS window, go to the directory in which the SRT files were downloaded (C:\SRT), and run the command "java srt 0" for normal operation. To simulate the receiver, run the command "java srt 1"; to simulate the antenna, run "java srt 0 1"; to simulate both, "java srt 1 1"; and for a list of other options, just run "java srt". The program will open its own window, and the MS-DOS window will become inactive until you close the java program. At startup, the java program reads in the list file *srt.cat*: in this file the user defines station latitude and longitude, source locations, motion limits, and certain variables indicating manual or automated calibration, digital or analog receiver, size of beamwidth, etc. Only at startup is this file read: after you have changed *srt.cat*, the java software must be restarted.

Actual operation of the SRT is simple: for a more comprehensive description of every command, consult the SRT User's manual, pages 3-13.[8] *Figure 7* is a screen capture of the SRT console, and *Table 2* is a quick summary of the pertinent windows and commands:

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[6] Available for download from http://java.sun.com

[7] http://web.haystack.mit.edu/SRT/srtsoftware.html

[8] Available for download from http://web.haystack.mit.edu/SRT/SRTManual.pdf

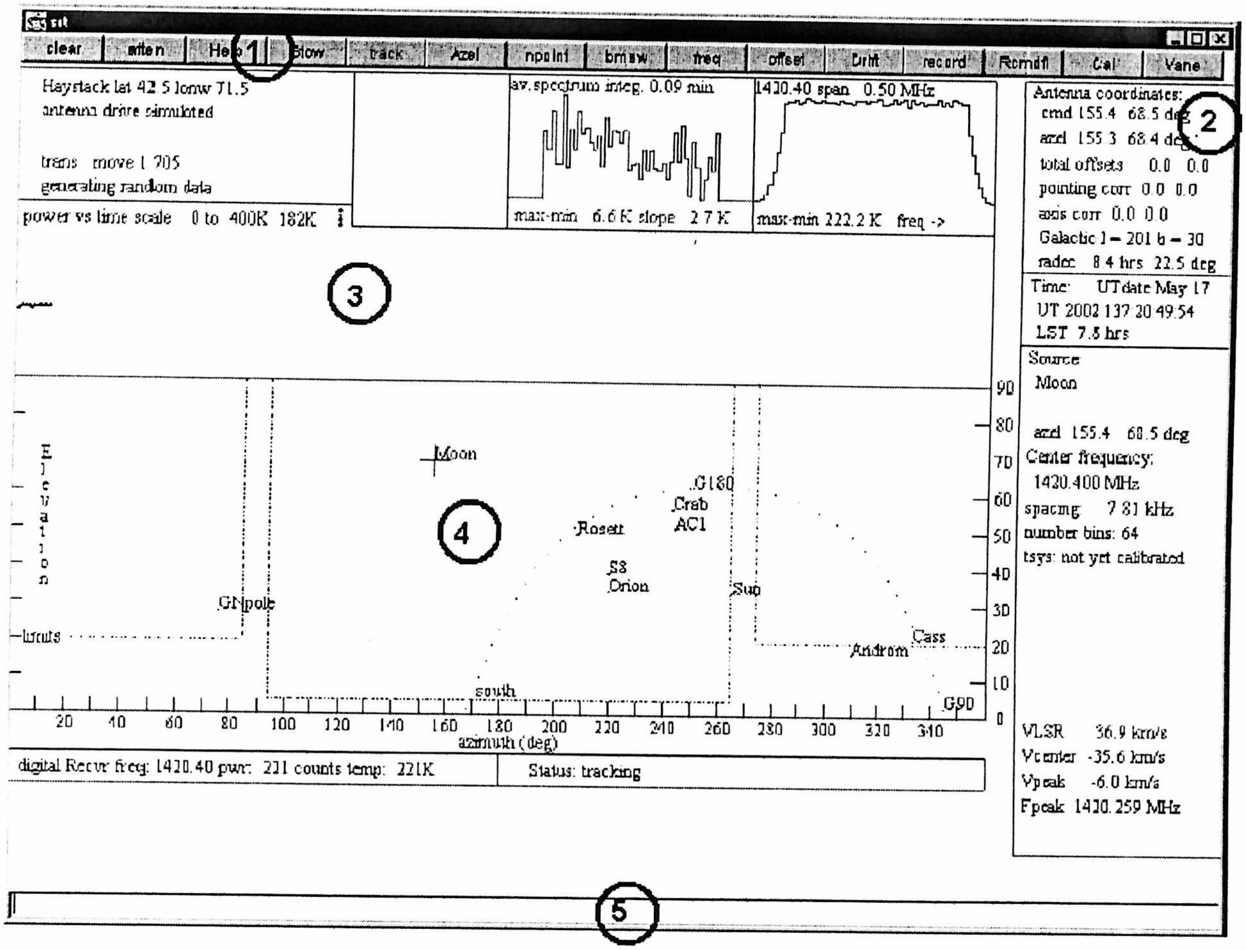

Figure 7: The SRT Console

Table 2: SRT Console Window Descriptions
1. Command Toolbar: shortcut buttons to common commands (see below) 2. Information Sidebar: pertinent location, temperature, time, source, etc. information 3. Power Chart Recorder: real-time scrolling antenna power 4. Sky Map: a plot of current position, boundaries of movement, of position of sources 5. Message Board / Text input: line for entering frequency, Az/El position, other requested information; message box for instructions and responces from the software
Stow: Return the SRT to the horizon at due east; restart motor tick counting Track: Enable/disable SRT source tracking (following source vs. drift scan) Azel: Manually enter azimuth and elevation to slew to Freq: Manually enter frequency to scan, number of bins, and size of each bin Offset: Move the SRT a select number of degrees from the source (while maintaining tracking) Record: Record receiver power to specified file Rcmdfl: Run a command file (scripted list of commands) Vane: Initiate the automated calibration sequence

Operation of the SRT can be conducted command by command by using the buttons at the top and the text input line at the bottom of the console. But the console is also able to read and execute script files, line-by-line lists of commands to run. This allows for repeating detailed procedures accurately and efficiently, taking exact durations, precise LST or UT timing, and countless other conveniences. For a detailed description of syntax, see the SRT User's Manual, pages 13-14; for some example scripts, see Appendix A.

However extensive the java program is, it cannot alone control the SRT: the program communicates with an external control box via a serial (DB-9 RS-232) connection. The control box has a separate 120V power supply, complete with the necessary transformers, to provide the 24V necessary to power the motors. A programmable single-board computer—called a BASIC Stamp—runs the program stored in its memory (the codes for which are the BASIC scripts available for download from the SRT file download site) in order to interpret the low-voltage RS-232 signal carrying the information from the java software. The Stamp is responsible for translating the java software's requests into the proper higher-voltage signals sent to the SRT motors, as well as counting pulses from the motors.

One can bypass the java software and communicate with the Stamp directly to aid in troubleshooting if it becomes necessary to do so. Window's HyperTerminal program *hypertrm* can send strings directly to the control box. For example, to test the motion of a motor, run *hypertrm*, make sure the program is communicating with the proper serial port, and then type " move 0 100 ", being sure to precede and conclude each string with a space. This command is translated by the Stamp controller to mean "initiate movement of the 0 motor (that is, the azimuth motor in the negative direction) for 100 ticks." If the control box is on but the motor not connected, the Stamp will return "T 0 0 100," meaning an error returned after 0 successful counts of moving the 0 motor 100 pulses. Since the Stamp and the java program run independently, it may at some point become necessary to test one without the other, and understanding the syntax and response of one will aid in understanding the syntax and response of the other.

The First Motion Test: Pointing the SRT

Before operating the SRT, make sure the sector gear shafts are greased: there is a grease fitting in the middle of the rotating-shaft columns on both the azimuth and the elevation motors. Be sure to use viscous motor grease, for aerosol lubricants like WD40 can evaporate. Also, ensure that the coaxial cable and the vane motor cables are strung in such a way that they will not catch or come under any stress over the full motion of the SRT.

The sun is an ideal first source because the shadow of the receiver on the dish offers a visual verification of proper pointing. Ensure that the station location—Haverford's latitude and longitude—is properly entered in the *srt.cat* file, and then run the control software to point the SRT at the sun. Then loosen the five bolts securing the azimuth motor to the NPRM, and rotate the entire SRT until the shadow of the receiver falls as close to the center of the dish as possible: the shadow should line up with the elevation motor's axis of motion. Re-secure the azimuth motor to the NPRM. The elevation motor cannot be physically adjusted in this manner: elevation pointing (and more precise azimuth pointing) is corrected by software.

Once the azimuth is as aligned as visually as possible, one must use the *AZLIMITS* and *ELLIMITS* lines in the *srt.cat* file to position the shadow directly over the center. Recall that the software program returns the SRT to stow upon startup, and that the software only knows where to point by counting ticks from the stow position. The azimuth and elevation values the software sets as starting points (the stow position) are the first entries in the *AZLIMITS* and *ELLIMITS* lines. Increasing the number after *ELLIMITS* by 3° will ~~have~~ cause the software to start counting elevation movement from 3° higher. So, if the sun's shadow was below the center of the dish, increasing the elevation lower limit will result in virtual "higher" starting position, thus there will be less elevation movement up, and the SRT will point slightly lower, which will in turn raise the shadow of the sun. Similarly, increasing the lower *AZLIMITS* will result in less westward movement and move the shadow eastward. Once the shadow is centered, the SRT is properly pointed, and since all of the telescope's movement is in relative tick counts, it will remain properly pointed for any source.

Next, a maximum software-driven-motion limit needs to be set in order to ensure the software always remains in control of the SRT. Recall that when the sector gear reaches its hardware stop, the microswitch stops the motor, sending a pulse back to the Stamp controller.

The Stamp interprets this back-pulse as either the motor stalling or the sector gear reaching the hardware stop. In either case, the java software's response is to attempts to return the SRT to the stow position in order to reset its pulse-counting scheme. With software stops set to trigger before the hardware stops, the software simply returns a "command out of bounds" error and does not reset. These maximum values are the second entries in the *AZLIMITS* and *ELLIMITS* lines in *srt.cat*. To set these values, move the SRT towards the end of its azimuth motion (260°), and then increase the azimuth by 1° until the hardware stop is reached; then, simply set the second *AZLIMITS* variable to a couple degrees before the hardware stop. Repeat this procedure for the elevation motor to ascertain the full range of SRT motion. The dotted lines on the sky map (in the center of the SRT program console) outline these limits.

In the event that a motor stalls or the software is convinced the SRT has reached a hardware stop when it has not, there are some possible adjustments. The motor drive shaft attached to the 8-tooth sprocket has some translational play in order to allow it to be perfectly aligned with the chain driving the 54-tooth worm gear sprocket. Also, there are two bolts securing the worm gear to the iron frame: loosening these bolts allow for a change in the separation between the sector gear and the worm gear. These two adjustments should be able to correct any motor problems that may arise.

The Current State of the SRT

Having ensured the SRT was properly constructed, wired, leveled, and pointed, the next step was to attempt a full operating run of the SRT. This goal, however, is yet to be achieved. The receiver functions inconsistently, sometimes working properly, sometimes partially working or working only for short time periods, and sometimes not working at all. The following behaviors have been witnessed both at the horizon (in stow position) and on source (pointing at the sun): no signal response (constant 0 K), "popcorn" response (proper read temperatures dispersed in flat line 0 K signal lack), constant random leaping (0 K to 900 K to 3600 K), falling power (starting upwards of 3000 K and quickly falling), and also rising power (300 K, increasing). I have spent countless hours verifying and re-verifying the continuity and cleanliness of all cables, terminal connections, and contact points—ensuring the feed wire was free of corrosion, resoldering coaxial terminators, etc.—and I will state with relative certainly that the SRT is properly wired and mechanically sound. Over this semester I have replaced the control box when it ceased to function and have restrung a newer, higher quality coaxial cable from the SRT to the basement lab in an attempt to limit variables and isolate the faulty component.

The nature of the inconsistency, combined with my relative certainty that environmental variables are controlled as possible, has lead me to suspect that the troubles are electronic in origin. Perhaps one of the components along the feed line is faulty or depends upon a variable (moisture, temperature, etc.) that I have am unaware is affecting operation. One who takes on the SRT project at Haverford is advised to try replacing the receiver, the preamp, the band-pass filter, or even the feed wire, as well as to continue to guarantee mechanical reliability.

Eventual Uses of the SRT[9]

In order to be able to accurately interpret data from the SRT, the telescope must be calibrated frequently: internal noise and environmental contamination (spillover) are highly and quickly variable. The first lab using the SRT should aid in understanding how to calibrate the noise inherent in the observation since every other experiment will depend on that procedure. For an explanation for why power is given as a temperature in radio astronomy, see Appendix B.

The SRT has an internal command (*vane*) that initiates an automated calibration sequence. Running the command swings a piece of absorber material—emitting as an ambient temperature blackbody—over the feed horn, blocking all radiation coming from the dish: the receiver then records a power proportional to the vane temperature and the system temperature—a measure of internal noise from the amplifiers, filters, etc. Twenty seconds later, the motor swings the absorber away, exposing the feed to the sky at the same position: this power is proportional to the system temperature, the sky temperature, and the spillover temperature—a measure of the all the radiation not reflected off the dish but still received by the feed from diffraction around the feed horn itself, off the edges of the dish, etc.

[9] Since the SRT is yet to be brought to full operating status, these experiments are projects suggested by Haystack, available at http://web.haystack.mit.edu/SRT/srtprojects.html . Actually conducting these experiments may result in modifications to the procedures and goals.

$$
\begin{aligned}
P_{vane} &= T_{sys} + T_{vane} \\
P_{sky} &= T_{sys} + T_{spillover} + T_{sky}
\end{aligned}
\tag{1}
$$

Knowing these relations, having values for P_{vane}, P_{sky}, and T_{vane}, and assuming $T_{spillover} \approx 20$ K, the software solves for T_{sys} and prints this value in the information sidebar. The ratio P_{vane}/P_{sky} (known power to unknown power) is the calibration constant used to correct all subsequent measurements.

It is important to note that calibrating the SRT does not account for off-source noise arising from the antenna's side and back lobes: these sources of contamination will need to be corrected for separately by using beam-switching or frequency-switching techniques. The calibration is simply to derive proper sky temperatures by relating them to a known (vane) temperature. Also, two particular different calibration options exist. One can calibrate on source but off frequency: the SRT is pointed at the eventual intended source but the frequency use for calibration is not the frequency of interest. This will keep all lobes and spillover constant, but then frequency dependent incident radiation will not be as accurately measured. Another option is calibrating off-source (at least two beamwidths) but at the frequency of interest. The goal of the lab would be to execute both calibration techniques, correctly calculate the system temperature T_{sys} and the calibration constant *calcons*, understand how the SRT does it internally, and argue which technique should be employed in future observations.

Once calibration techniques are understood, the SRT is ready for standard use. However, a detailed knowledge of conducting radio astronomy—the eventual goal of the SRT project—requires knowledge of antenna beamwidths. The sun is a particularly powerful source of radio emission: by using the sun as a strong signal source, one can measure the beamwidth of the SRT and map out the entire beam pattern. (For an explanation of beamwidth and beam pattern, see Appendix C.) To determine these, point the SRT at the sun and set the number of frequency bins to one (total power mode). Then take temperature readings at successive increments in azimuth and elevation away from the center of the sun, or let the sun drift through the beam and continuously record the temperature. By plotting the received temperature as a function of offset from the center of the sun—remembering to adjust azimuth motion by cos(El) to correct the scaling—one can easily determine the beamwidth. Since the SRT is circular, the azimuth and elevation plots should be identical: differences are indicative of either dish deformity or polarization effects. Also, at the completion of the lab the student should be able to discern the side lobes in addition to the main lobe and thus generate a map of the power pattern of this particular SRT's reflector.

The above experiments are both intended to increase understanding of the operation of a radio telescope. But the SRT is also capable of performing real astronomy: it can, for example, be used to map out the rotation curve of the Milky Way, an experiment which can aid in research about dark matter at the extremities or a massive black hole at the center of the galaxy. Configure the SRT to measure a wide spread of frequencies around the 21 cm Hydrogen spin-flip line, and then make these observations at a range of points extending out along the galactic equator. Plotting antenna temperature vs. frequency at each point will allow one to discern a maximum frequency of emission. Knowing this observed frequency and the true emitted frequency of 1420.4 MHz allows one to calculate a Doppler shift proportional to γ, and from that one can easily calculate a velocity, though this velocity will need to be carefully corrected for the Earth's peculiar velocity relative to that particular galactic point. The resulting corrected velocities plotted a function of galactic radial distance will map out the rotation curve of the Milky Way.

These three experiments are but a small sample of what the SRT can be used for in the future. Not only are there more experiments about telescopes—aperture efficiency, gain variation, etc.—there's more astronomy to do—full-sky radio maps, daily sun flux observations, etc.—and perhaps even interferometry in the future. The possibilities are many, and the SRT will undoubtedly prove to be a useful addition to the astronomy program here at Haverford College.

Appendix A: Sample Scripts[10]

Using command scripts will make using the SRT easier and more efficient. Scripts are just text files with line-by-line commands similar in form to the commands one might enter into the text input line in the SRT console message board. Note that a colon and a space precede each command unless the command is simply a wait command (to actually wait for a particular time or to allow data collection for x seconds).

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[10] All scripts adapted from http://web.haystack.mit.edu/srt/srtprojects.html

1.) Sample script for calibration sequence:

: record calib.rad	Record the data in a file called calib.rad
: azel 130 45	Move to certain azimuth/elevation position
: freq 1420 1 0	Calibration frequency (off-source)
: calibrate	Run the calibration sequence
: Sun	Move to the sun (or any source)

2.) Sample script for measuring beamwidth and beam pattern:

: record sun.rad	Record data in file sun.rad
: azel 130 45	
: 1415 5 0	Set frequency 1415MHz, 5 bins, 0 kHz spacing
: calibrate	(5 samples/measurement)
: Sun	
* Azimuth Scan	Comments in scripts must be signified with *'s
: offset -30 0	Move the SRT from -30 to 30 in azimuth around the sun,
: offset -29 0	recording temperature at each offset (tracking)
. . .	
: offset 29 0	
: offset 30 0	
* Elevation Scan	
: offset 0 30	Increment the SRT from –30 to 30 in elevation around sun
: offset 0 29	recording temperature at each offset (tracking)
. . .	
: offset 0 29	
: offset 0 –30	
: roff	End recording

3.) Sample script for measuring galactic rotation:

LST:18:00:00	Wait until 18:00:00 before continuing (position galaxy)
: 1420.4 50	Set frequency (exact 21cm line) and number of bins (50)
: azel 180 45	
: calibrate	
: galactic 0 0	Move SRT to Galactic center
: record g00.rad	Record to file g00.rad
:60	Take data for 60 seconds (no space after colon)
: roff	Stop recording
: galactic 10 0	Move SRT to Galactic longitude of 10 degrees
: record g10.rad	
:60	
: roff	
. . .	Etc.

For these more extended experiments, the SRT should be recalibrated a number of times over the course of the data collection in order to ensure the most accurate data. Remember to be off-source or off-frequency when calibrating.

Appendix B: Antenna Temperatures

Because the wave nature of radiation at radio (i.e., long) wavelengths is more prominent than the particle nature, it is difficult to digitize the signal by counting photons the way optical and higher-energy detectors do. Rather, in the radio regime it is more convenient to discuss strength of signals by using temperatures. Consider the Planck formula, describing the brightness (intensity) of a blackbody at a particular temperature:

$$B(\nu) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1} \quad . \qquad (2)$$

In the radio band of the electromagnetic spectrum, $h\nu/kT << 1$, and the Planck formula reduces to

$$B(\nu) = \frac{2\nu^2 kT}{c^2} \quad , \qquad (3)$$

which can then be rearranged and solved for temperature:

$$T \equiv \frac{\lambda^2 B}{2k} \quad . \qquad (4)$$

In this way, the power received by the telescope can be described as a temperature, calculated as a function of the emitted intensity and the wavelength of interest. The Earth, for example, when approximated as a room-temperature blackbody, is a 300K source.

Appendix C: Beam Patterns

Low signal-to-noise ratios have always been the primary difficulty in conducting radio astronomy. Because wavelengths in the radio regime are long, they diffract easily around objects and pass through many mediums. Interference and contamination from terrestrial sources cannot be avoided by careful pointing, as is the case for bright optical sources. Babinet's theorem states that plane waves incident on an opaque object will diffract around the object same as the waves would through an aperture of the same size and shape. A radio telescope's reflecting dish is such an opaque object: the electromagnetic waves from the cosmos reflect off the dish back to the feed with a diffraction pattern. But other waves, emanating from behind and to the sides of the dish also diffract around the edges of the dish, directly into the feed when coming from the proper angle. Also, radiation from other cosmic sources can reflect off the telescope off-focus but still have elements from their diffraction patterns incident on the feed.

The non-main-beam (i.e., off-axis) hotspots in the diffraction pattern are referred to as side lobes. The power detected by the feed is the sum of all incident radiation, whether in the main lobe or the side lobes: off-source contamination can flood a response by flooding a side lobe with a high temperature, even though the side lobes' response is low compared to that of the main lobe (10^{-5}).

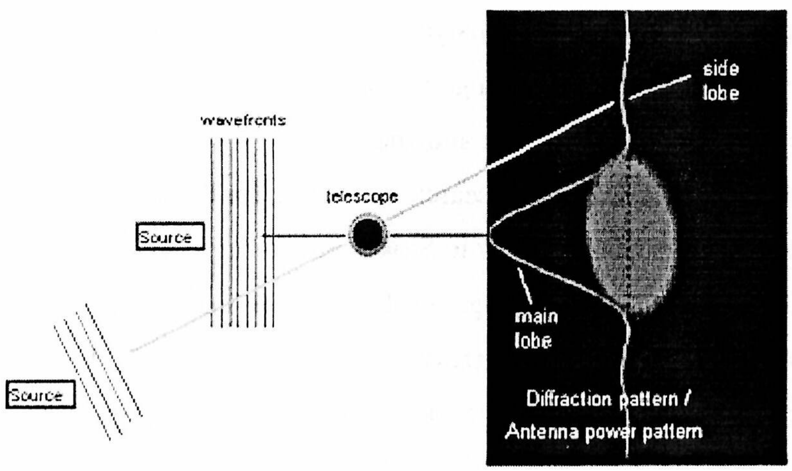

Figure A: Power received equals the sum of all power incident within the power pattern. The total power would equal the integral under the diffraction pattern curve.

The diffraction pattern of the dish, complete with hot and cold spots in reception, is called the beam pattern; all observations made by the telescope are adjusted to this form. Beamwidth is defined as the full width at half maximum of the main beam: it is a function of the telescope size and shape and dictates the resolution of the telescope.

Most radio sources are very weak with respect with to the earth, for example. The earth as a high-temperature source diffracting around the telescope dish into the any ~~hot-spot~~ side lobe in the diffraction pattern is simply summed with the cosmic source incident in the main beam. Radio telescopes have to be designed carefully to reduce this background as much as possible through techniques of construction (tapering) and operation (beam- and frequency- switching).

Acknowledgements

I would like to take a moment to quickly thank those who have helped me with this most frustrating of projects over the course of this year. First and foremost, thank you Phil Shute for your unfaltering enthusiasm and interest in getting the SRT up and working: pass on my thanks to everyone at Haystack who devoted time and energy into Haverford's SRT, too. Another big thank you to Bruce Boyes, Haverford's research machinist, for the countless times he gave me ideas and the countless times he came over to Stokes just to help me cut a pipe or to deliver extra bolts. And special thanks to Bruce Partridge for the hours he spent teaching me radio astronomy (again) and his patience with the slow progress this year. As I continue to work on the SRT this summer—it will be working before I leave!—it's likely I'll be going to each of them again and again for help, so here's one more big thank you for the all the help that's still to come.

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