Lab 7: Radio Astronomical Observing using the SRT

This laboratory project uses the radio telescope installed on the roof of VAN for undergraduate teaching and research. The learning goals of the project are to learn basic concepts of observational radio astronomy. In the first part of the lab, each team will determine some fundamental characteristics of a radio telescope (system temperature, sensitivity, beam angular size) using observations of the Sun. In the second part of the lab, teams will observe the 21 cm (1420 MHz) spectral line of neutral hydrogen in the galactic plane.

Useful web sites

- The official SRT (Small Radio Telescope) site at Haystack Observatory is at:

  http://web.haystack.mit.edu/SRT/

- An introductory tutorial on observational radio astronomy:

  http://web.haystack.mit.edu/urei/tutorial.html

- The National Radio Astronomy Observatory (NRAO) educational site :

  http://www.nrao.edu/education/

- An index of web sites describing major radio telescopes around the world

  http://www.astro.utoronto.ca/~yao/Radio/links.html

Background and Theory

In the summer of 2003 the Department of Physics and Astronomy purchased a SRT system (Small Radio Telescope) for use in undergraduate astronomical laboratory projects. The SRT was designed at MIT's Haystack Observatory (see SRT link above) using a commercial satellite dish and a custom digital receiver system designed at Haystack. There are currently more than 70 SRT installations around the world, mostly at Universities and Colleges.

The SRT telescope was delivered in August 2003 and was mounted on the roof of Van Allen Hall. A remote telescope control room (725 VAN) was renovated from an old storage room and outfitted with computers and electronic test equipment.

☐   The super-heterodyne receiver

We replaced the digital receiver originally supplied with the SRT with a conventional 'super-heterodyne' receiver of the type used in all research radio telescopes such as the Arecibo Observatory, the VLA, and the VLBA antennas. This allows students to understand how radio astronomical receivers work and to measure the signal properties. The basic principles of super-heterodyne receivers are described in:

http://www.fas.org/man/dod-101/navy/docs/es310/superhet.htm

The receiver consists of three parts: The RF unit ('front end box') the IF unit, and the video unit. Here's a diagram of the RF and IF units,. The 'front end box' is mounted in a box at the focus of the SRT telescope:
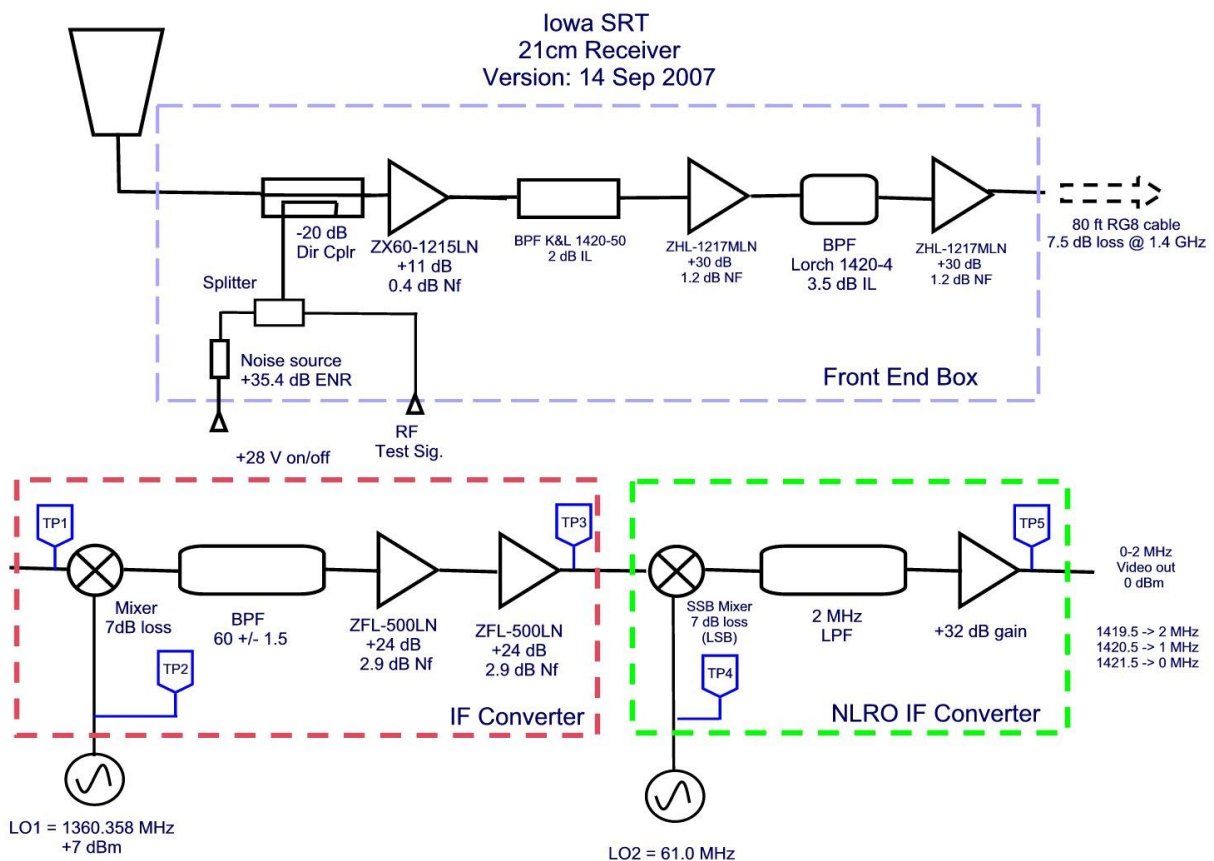
The noise diode (appx 2.6 dB ENR) can be switched on or off by a switch on the telescope control panel. The test points (shown in blue) are located on the front panel of the IF unit.

☐   Definition of flux density (Jansky)

The power from a celestial radio source by a radio telescope is conventionally described a the flux density unit called a **Jansky** [1 Jansky (Jy) = 10^{-26} W m^{-2} Hz^{-1}] , named after the pioneer Karl Jansky who discovered radio waves from the galaxy in 1933 while working at Bell Labs (http://www.gb.nrao.edu/~fghigo/fgdocs/jansky/jansky.html).

Celestial radio sources routinely studied by instruments such as the VLA and VLBA have flux densities of order 0.1 Jy – 10 Jy, although the most sensitive observations can detect source as weak as 0.01 mJy (1 mJy = 10^{-3} Jy). The SRT is a very small and hence insensitive telescope relative to the large research telescopes, so it can only detect sources with flux densities in the 1,000's of Jy, of which there are only a few:

Object	Description	Flux density 1.4 GHz
Sun	Nearest star!	30,000 Jy (Solar min) - 150,000 Jy (Solar max) The Current flux density can be found at http://www.sec.noaa.gov/ftpdir/lists/radio/7day_rad.txt
Cygnus –X	Star formation region	~ 5000 Jy (extended)
Cas-A	Supernova remnant 3 kpc	1570 Jy (2007, decreases by 1% per yr)
Cygnus-A	Active Galaxy, 200 Mpc	1564 Jy
Crab (M-1)	Supernova remnant 2kpc	940 Jy

☐   Definition of system temperature, system sensitivity

All objects at non-zero temperature emit 'thermal' radiation, also known as bremsstrahlung (German: 'braking radiation'). At long wavelengths ($h\nu \ll kT$) the Planck law for thermal radiation takes the approximate form (Rayleigh-Jeans approximation)

$$I = \frac{2kT}{\lambda^2} \tag{1}$$

where I is the specific intensity, k is Boltzmann's constant, and T is the physical temperature of the object. The flux density of an object is the integral of the specific intensity over solid angle

$$S = \int I d\Omega \sim I \theta_s^2 \tag{2}$$

where S is the flux density and θ_s is the angular size of the object as seen by the observer. Combining equations (1) and (2)

$$S = \frac{2kT}{\lambda^2} \theta^2 \tag{3}$$

for the SRT (1.42 GHz, $\lambda = $ 20cm), this equation can be written in convenient units

$$S = 10.4 T_K \cdot \theta_{\text{deg}}^2 \; Jy \tag{4}$$

For example, the Moon has a physical temperature T~200° K and an angular size $\theta = 0.5°$, so the expected flux density is S ~ 520 Jy.

The received power can be expressed in two ways

$$P = \frac{1}{2} S A_{eff} \Delta \nu \qquad (5)$$

where P is the received power (W), A_{eff} is the effective area of the telescope (typically ~50% of the physical area), and $\Delta \nu$ is the bandwidth (Hz), and the ½ arises because only one polarization is received. The power can also be written

$$P = k T_B \Delta \nu \qquad (6)$$

where T_B is the **brightness temperature.** This is the same as the physical temperature for an (optically thick) thermal body, but it can be defined by equation (6) no matter what mechanism is responsible for the radiation. Combining equations (5) and (6)

$$\frac{S}{T_B} \equiv \xi = \frac{2k}{A_{eff}} \qquad (7)$$

The variable ξ is the **system sensitivity**, and is measured in Jy/K. For the SRT (diameter 3m), the system sensitivity is $\xi \sim 975$ Jy/K (assuming 40% aperture efficiency, typical for parabolic dishes).

If the radio telescope is pointed to a 'cold' area of sky with no discrete sources of radiation, there will still be a significant power level. This power is most conveniently described in temperature units as per equation (6), and is known as the **system temperature** (T_{sys}). The system temperature is the sum of several contributions

$$T_{sys} = T_R + T_{sky} + T_{gnd} \qquad (8)$$

Where T_R is the receiver noise temperature, T_{sky} is the contribution from the cold sky (3° K cosmic background radiation), and T_{gnd} is the ground or 'spillover' temperature. The latter is variable, depending on the elevation of the telescope, but typically 40K near zenith to more than 100°K at low elevation. The receiver temperature is $T_{sys} \sim 200°$K for the SRT.

One way to measure the system temperature is insert extra power into the system using a noise diode with known power (measured in degrees Kelvin). The ratio of powers is:

$$R = \frac{T_{sys} + T_{cal}}{T_{sys}} = 10^{\frac{\Delta(dB)}{10}} \qquad (9)$$

Once R is measured, $Tsys$ is easily calculated.

☐ Calibration diode

Like most radio telescopes, the SRT is equipped with a calibration noise source which can be used as a secondary calibration of system temperature and a means to

determine the flux density of radio sources. Since the noise power is additive, the ratio of 'on' to 'off' power is

$$R = \frac{T_{sys} + T_{ND}}{T_{sys}} \qquad (10)$$

Since R is measured and T_{sys} is known from the 50 ohm load measurement, the noise diode temperature can be determined directly. Alternatively, once the noise diode temperature has been determined, the flux density of a source can be determined by measuring the ratio of "on source" power to the "on" noise power (in both cases first subtract the T_{sys} contribution)

$$R = \frac{\xi S}{T_{ND}} \qquad (11)$$

☐ Signal to Noise Ratio for Continuum Sources

The ability to detect a source with a given flux density depends on the expected signal to noise ratio (SNR). A highly reliable detection requires SNR> 5. The noise level of the telescope system is simply the standard deviation of the system temperature variations, which depends on the effective number of independent measurements

$$N \sim \Delta \nu \cdot \tau \qquad (12)$$

where $\Delta \nu$ is the bandwidth (Hz) and τ is the integration time (sec). Hence the standard deviation of the system temperature is

$$\sigma = \frac{T_{sys}}{\sqrt{N}} = \frac{T_{sys}}{\sqrt{\Delta \nu \cdot \tau}} \qquad (13)$$

The SNR of an object with flux density S is

$$SNR = \frac{T_B}{\sigma} = \frac{S \sqrt{\Delta \nu \cdot \tau}}{\xi T_{sys}} \qquad (14)$$

where the system sensitivity ξ is defined in equation (7). For the SRT observing continuum sources, the integration time per point is fixed at 0.5 sec, the bandwidth is ~2 MHz, and the system temperature is ~200K, so

$$SNR_{continuum} = 0.007 \cdot S_{Jy} \qquad (15)$$

This means that the minimum continuum flux density that can be reliably measured (SNR = 5) is ~700 Jy.

This is actually an underestimate since the calculation assumes a perfectly stable receiver gain for the entire observation. Even a 0.5% gain variation will result in a system temperature fluctuation $\Delta T_{sys} \sim 1°K$, which is equivalent to a 975 Jy source!

☐ Signal to Noise Ratio for Spectral Line (HI) Observations

For spectral line observations, the bandwidth is much smaller (bad), but the integration time can be increased (good). Also, gain variations tend to cancel since spectral line mode uses frequent beam or frequency switching. Furthermore, the HI line strength is typically measured in degrees K since it is not a point source. Therefore, the noise is best expressed in temperature units also. For example, for a typical HI observation with 64 channels spanning 500 KHz (7.8 KHz per channel) results in

$$\sigma_{line} = \frac{2.2°K}{\sqrt{\tau_{sec}}} \qquad (16)$$

where τ_{sec} is the (on-source) integration time. Hence the SNR is:

$$SNR_{HI\ line} = \frac{T_{line}}{2.2}\sqrt{\tau_{sec}} \qquad (17)$$

In the galactic plane, the HI line strength is often $T_{line} > 20° K$, so that SNR > 10 in a few seconds.

☐ Antenna Beam Pattern

The far-field beam pattern of an ideal uniformly illuminated circular aperture is

$$P(\theta) = \left[\frac{2J_1\left(\pi\frac{D}{\lambda}\sin\theta\right)}{\left(\pi\frac{D}{\lambda}\sin\theta\right)} \right]^2 \qquad (18)$$

Where J_1 is the first-order Bessel function, and D is the telescope diameter. The half-power beamwidth (HPBW, angular width between ½ power points of the beam power pattern) is

$$\theta_{HPBW} = 1.22\frac{\lambda}{D} \qquad (19)$$

A realistic telescope (e.g. SRT) has a tapered illumination, which modifies the form of equation (9) somewhat[1], leading to a somewhat larger beam (coefficient ~1.27 in equation 10).

---

[1] See Rohlfs 'Tools of Radio Astronomy,' chap 5.

Observing Protocol

Part 1: Properties of a Super-heterodyne Receiver

1. Set the test signal generator (HP synthesizer at the bottom of the receiver rack) to the rest frequency of the hydrogen line (1420.358 MHz).

   Note: This synthesizer cannot generate frequencies above 1 GHz directly, so we have added a frequency doubler at the output. Set the synthesizer to ½ the desired frequency.

2. Check that the first LO (local oscillator) frequency is set correctly (check block diagram above) Check this using the 'First LO) test point and the spectrum analyzer (use peak marker).
3. Check the signal after the first mixer. What frequency do you expect? Record again.
4. Check the second LO frequency (61.0 MHz) using the 'second LO' port. Record.
5. Check the signal after the second mixer. What frequency do you expect now? Record.
6. Finally, record the video (baseband) spectrum. At what frequency is the original test signal now?
7. If you have measured everything correctly, you should be able to show that the following relationship holds:

$$f_{baseband} = (f_{LO1} + f_{LO2}) - f_{RF}$$

8. Change the test signal frequency by ±100 KHz (0.1 MHz) and record the resulting baseband (video) signal. Confirm that the equation given in the last step is valid.

Part 2: Basic calibration: Determining the system temperature and spillover temperature vs. elevation

2a. System Temperature using calibration diode

1. Read the introductory material carefully.
2. Point the telescope at the zenith.
3. Connect a spectrum analyzer to the BNC connector labeled 'RF from front end'
4. Adjust the spectrum analyzer to measure power in dBm at 1420 MHz with averaging.(See instructor for setting spectrum analyzer controls to do this).
5. Record the average power.
6. Switch on the noise diode which we will assume has an insertion power (measured in temperature units) T_{cal} = 120 K. Record the power with the cal diode on.
7. Repeat the off-on several times and average the results.
8. Compute the system temperature at zenith by solving equation (9). Propagate the uncertainties (determined from the repeated –on-off measurements) to determine uncertainty in the result (Tsys).

2c. Spillover temperature vs. elevation

9. Move the telescope to 80,70,60,….10 degrees elevation. For each position, measure the system temperature by firing the noise diode and measuring the ratio.
10. Make a plot of spillover temperature (excess system temperature) vs. elevation (assume a nominal value of 40° spillover at zenith)

Part 3: Solar Flux Density and FWHM beam size

This section requires observations of the Sun, which means observations must be scheduled when the Sun is well above the horizon. During December this means you must observe between 10am and 2pm CST, otherwise the Sun will be too low in the sky.

1. Drive the telescope to the Sun by double-clicking on the 'Sun' in the sky map box.
2. Peak up manually using the az-el control button and the video display of the dish surface. Keep entering azimuth and elevations until the front-end box shadow is centered on the dish center.
3. Actually the peak of the response is a bit off-center. Look at the total power response to get a real maximum.
4. Record the maximum power.
5. Move the telescope off the sun by 10° and record the power again. Repeat this sequence at least 3 times to determine measurement uncertainty.
6. Using your previously measured value of Tsys, find the ratio of 'on' to 'off' to measure the sun's 'temperature. Convert to flux density by using the conversion discussed in the introduction. The Solar flux density, which varies with solar activity, can be found for the date and time of your observation at the following website: http://www.sec.noaa.gov/ftpdir/lists/radio/7day_rad.txt Be sure to use the 1415 MHz flux listing closest to the time of your observation.
7. To measure angular beam size of the telescope, scan the Sun in 1° increments. This can be done using the **grid scan tool** in the telescope control program..
8. Plot the scan in each direction (az/el) and fit equation 18 to your plots. From the fit, determine the full-width at half-maximum (FWHM) beamsize in degrees. Compare to the simple estimate 1.22 λ/D.