Basic Properties of the Josephine L. Hopkins Teaching Radio Telescope

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(Data collected with: Edward Li)
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Abstract

This paper details some of the very basic characteristics of the 3.8 meter parabolic radio telescope atop the Space Sciences Building located on Cornell's Ithaca campus. Through the use of an absorber material, which is held directly in front of the helical receiver, a noise diode, which is capable of injecting noise into the analog signal path prior to any processing, and manipulation of the attenuation, I calculate the system temperature and the effective temperature of the calibration diode. In order to determine the beam width of the antenna, a drift scan is performed on the sun, which has a well-known angular size. I use the previously determined system temperature and the same drift-scan data to estimate the effective temperature of the sun. The system temperature is found to be about 160K and the calibration temperature is around 860K. The experimentally determined beam width is about 4 degrees (14 deg^2).

Introduction

The 3.8 meter (f/D = 0.413) parabolic radio telescope features a helical feed antenna that receives circularly polarized radiation in a band from 1 to 2 GHz. The antenna terminals are routed to a receiver box that contains a low noise amplifier and a noise diode. The analog signal is then directed to an analog receiver where it passes a bandpass filter of 57 MHz centered on 1420 MHz. The signal is then passed to a mixer that converts the signal to an intermediate frequency. The signal is then passed through another BPF to eliminate aliasing. Finally, a variable attenuator is used to adjust the level appropriately before digitization.

The analog signal is digitized using the "Roof Spectrometer" (RSPEC), which is just a FFT spectrometer built from a Field Programmable Gate Array. RSPEC utilizes an 8 bit ADC. For spectral data, the digital signal is then processed using a discrete fourier transform.

In this lab, I aim to determine the telescope's system temperature, the calibration temperature, the gain, the antenna beam width, and the radiation temperature of the sun. I will also study the accuracy and precision of these results.

Radiometer noise includes contributions from the sky (the CMB, synchrotron radiation, etc.) and contributions from the actual instrumentation. Determining the calibration temperature can be useful in later experiments as a quick and simple, although probably less reliable, way of calibrating the digital data. A proper determination of the beam diameter is critical for later study of point sources.

Procedures

Data was collected on the afternoon of November 10, 2014 on the previously described radio telescope. For all parts of the lab, we obtained a series of one second "total-power" measurements. First, we directed the telescope to a low elevation towards a non-distinct part of the sky, where holding the absorber might be somewhat easier. We recorded data for 15 minutes (900 data points). We also determined the temperature of the absorber to be approximately 290 K. We measured sky for about 40 seconds, turned the noise diode on for about 40 seconds, and then turned it off. We then went to the roof and held the absorber directly in front of the helical receiver for an impressive 100 seconds. This concluded the first part of the lab.

For the second part of the lab, which involved observing the sun, we determined the position of the sun one hour in the future (using the "sun_pos_future" utility provided) and moved the telescope to that position (Azimuth = 255.313° and Elevation = 17.126°). We turned the noise diode on for four minutes. Three minutes later, we reduced the attenuation by 3 dB for three minutes. The rest of the two hour data set measured only the sky as the sun passed into and out of the beam. (These changes are easily seen in the calibrated plots in results.)

Data Analysis

The data were all analyzed in Octave. I used the first file, the one in which we used the absorber, to determine the means and standard deviations in digital numbers (DNs) associated with the sky temperature, the temperature with the noise diode turned on, the temperature with the absorber in place, and the temperature with adjusted attenuation. I used these mean and standard deviation values, in conjunction with the known temperature of the absorber (290° K), to determine the gain within a certain degree of error. Having determined the gain, one can easily calculate the system temperature and calibration temperature (or indeed any temperature) in Kelvin. I then calibrated the data obtained from the drift-scan of the sun. The linearity of the radiometer is also examined using the 3 dB decrease in attenuation. The following equations were used in the previous analysis in conjunction with separate equations for error propagation calculations:

$g^*(T_{sys} + 290)$ = Measured Power with absorber (DNs)
$g^*(T_{sys})$ = measured power with noise diode off / sky (DNs)
$g^*(T_{cal})$ = measured power with noise diode on (DNs)

These three equations give one a value for the gain in units of DNs / °K. The 3 dB increase in attenuation provides a good check of linearity. The relevant equation is:

$10^{-3/10}$ = (measured power without attenuation) / (measured power with attenuation)

The full width at half maximum (FWHM) of the solar data was determined by finding the mean and standard deviation near the peak and the mean and standard deviation of the noise floor. From these, a value of half maximum can be determined with associated error. There is also an error associated with measuring the width to within about 4 seconds. All these errors were used to determine a lower limit for error since there is some difficulty in quantifying systematic error.

Using a known value for the sun's angular size and the previously determined beam width, one can determine the effective temperature of the Sun at 1.42 GHz.

Results

Calibration

The above equations were used to determine the gain with random error given by the standard deviation of the measured power in DNs.

$g = 5{,}400 \pm 2300$ DNs / °K.
$T_{sys} = 165 \pm 7.1$ °K
$T_{cal} = 860 \pm 37$ °K

$10^{-3/10} = 0.50119$
(measured power with attenuation) / (measured power without attenuation) = $(9.0001*10^6)/(1.7763*10^7) = \underline{0.507 \pm 0.006}$

This is quite close to the actual value given above, which suggests a good degree of linearity.

Since the data have now been calibrated it is possible to plot the measured temperature in Kelvin with respect to time.

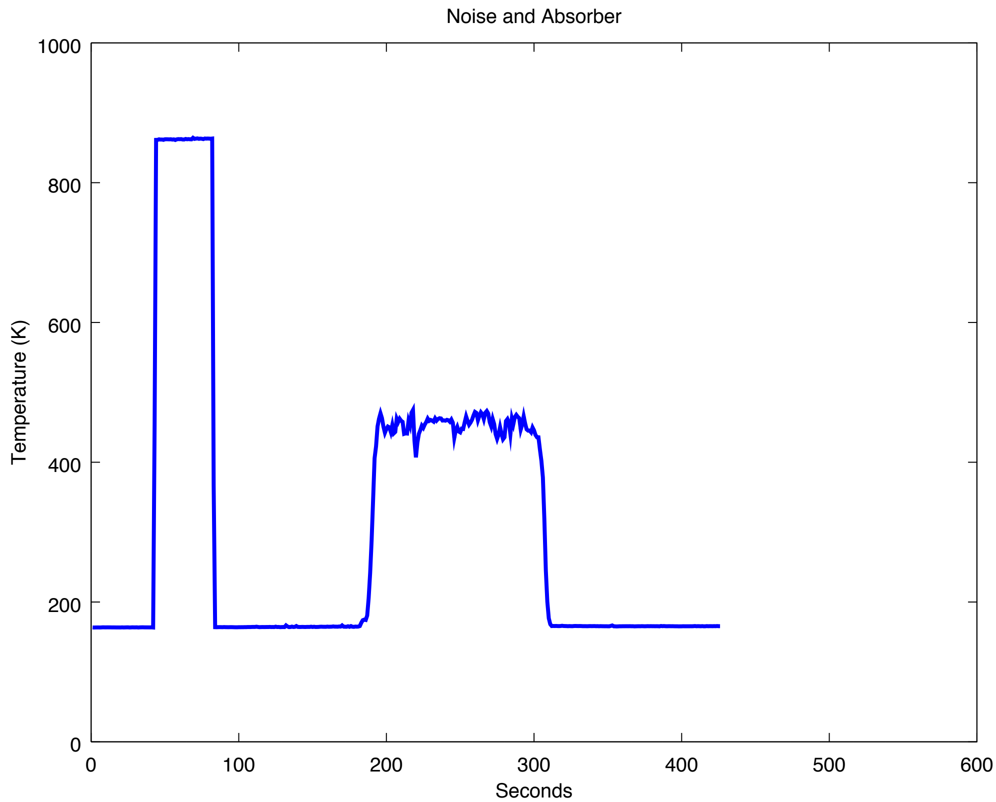

Figure 1

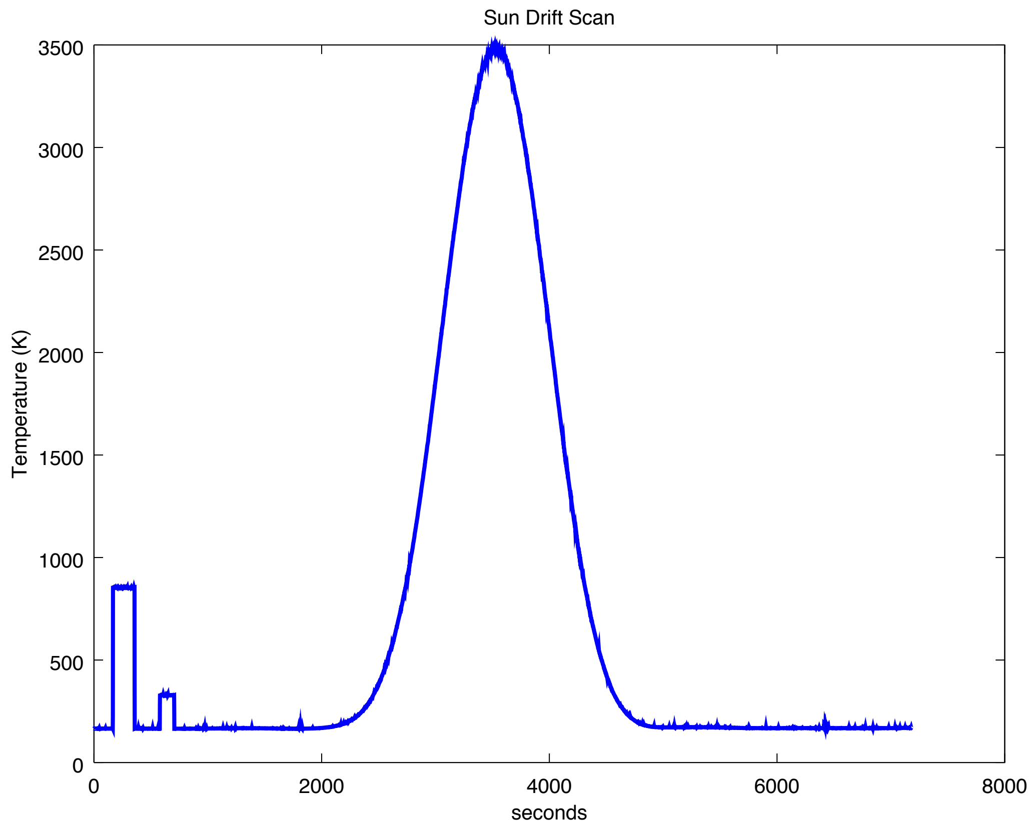

Figure 2

Beam Width

360°/(24*3600) * cos(17.126°) = 0.00398 °/sec.

This value is used to convert the FWHM in seconds into degrees.

A mean value of peak temperature is found by averaging 30 values centered at the maximum. There is also a standard deviation associated with this temperature.

$T_{peak,sun}$ = 3490 ± 10 ° K.

This suggests a maximum increase in temperature of: (3490 ± 10) – (165 ± 7.1) = 3325 ± 17 ° K.

The beam width is determined to be 1070 ± 4 seconds = 4.26 ± 0.02 deg = 0.0743 ± 0.0004 rad.
Solid angle (π*(∠/2)): Ω_A = <u>14.3 ± 0.1 deg^2 = 0.00434 ± 0.00005 steradians.</u>
Approximation: λ/D = 0.21/3.8 = 0.055263 rad. <u>Solid angle: 0.0023986 steradians.</u>

The error takes into account both the random error associated with the uncertainty in the value of half maximum and the uncertainty in width, but it does not take into account any form of systematic error, so it should be treated as a lower limit on the possible error. The fact that the approximation is half the measured value suggests either the approximation is very far off, the measurement is inaccurate, or some combination of the two.

Radiation Temperature of the Sun

$T_{peak,sun}$ = 3325 ± 17 ° K.
Ω_{Sun} = 6.87*10^{-5} steradians
Ω_{Sun} / Ω_A = 0.0158 ± 0.0001 (The experimentally determined value of Ω_A is used.)

$T_{eff,sun}$ = $T_{peak,sun}$ / (Ω_{Sun} / Ω_A) = 210,000 ± 1800 ° K (using the experimental beam width)
$T_{eff,sun}$ = 116,160 ± 20 ° K (using approximate beam width)

The value for the quiet sun quoted in Zirin et al. at 1.4 GHz is 70,500° K. The sun must have been loud on November 10, 2014.

Summary and Conclusions

The purpose of this lab was to determine some of the basic properties of the telescope. I determined the system temperature, which is highly variable day-to-day, and the calibration temperature, which may prove useful in lab five. My experimentally determined value for beam width was quite high. It’s unclear where this source of error originates. The high effective temperature of the sun isn’t too worrying since an active corona, for example, could contribute to a higher temperature than might be expected.

Reference

Zirin, H., Baumert, B. M. and Hurford, G. J., 1991, ApJ, 370, 779.