ASTRO 4410 LAB 4

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Abstract

The first step in the path towards correct usage of a radio telescope in order to perform astronomical observations consists in familiarization with the equipment that is going to be used and determination of the radiometrical parameters related to the antenna upon which the analysis of the observations is going to depend on. This experiment implements certain procedures in order to find some of these parameters for the radio telescope on top of Cornell University's Space Sciences Building, and uses a subset of these calculated values in order to measure the temperature of the Sun at the 1.42 GHz frequency. It also provides some of the necessary background data and experience for performing more complicated observations in the future.

1 Introduction

Radio telescopes, as their name suggests, are telescopes sensitive to the radio frequency part of the electromagnetic spectrum, which ranges from 300 GHz to 3 kHz. They consist of an antenna, a receiver, and a signal processor. The antenna intercepts the radio waves and transforms them into electrical pulses, which pass through the receiver, which in turn produces a signal that is analyzed by the signal processor. The antenna and the receiver have some basic properties that need to be experimentally determined in order to be able to extract meaningful measurements from observations made by the telescope. Among the most important of these are the system temperature, the constant of proportionality that converts from the voltage produced by the antenna into temperature units (the gain), and the effective temperature of the antenna's calibration diode. Another important property of the telescope is its response to signal attenuation, which can be used to quantify the linearity of its behavior as a function of time. This gives us an idea on how reliably the signal is being produced on the basis of the waves being captured by the antenna. Finally, a reliable estimation of the antenna's beam width is necessary in order to be able to determine the effective temperature of the objects that are to be observed with the telescope. The procedure for calculating the beam width also provides an opportunity to test the accuracy of the measurements performed in order to estimate the aforementioned parameters, which in this case is done by using the beam width in conjunction with some of the parameters in order to calculate the effective temperature of the Sun at a specific frequency of observation.

2 Objectives

1. Estimate the radio telescope's system temperature, gain, and linearity response, as well as the effective temperature of the calibration diode.

2. Estimate the antenna's beam width.

3. Measure the effective temperature of the Sun at a frequency of 1.42 GHz, and compare with accepted value.

3 Setup

3.1 Date of observations and telescope characteristics

The data for this lab was acquired on Thursday, November 5th, from approximately 13:50 to 16:15, using the radio telescope mounted in the roof of Cornell University's Space Sciences Building. The antenna's reflector is a 3.8 m paraboloid with a helical feed at the prime focus that accepts circularly polarized radiation between 1 and 2 GHz. Behind the helix there is a circular ground plane where the antenna terminals connect to a receiver box that contains a low-noise amplifier and a noise diode that can be used for calibration purposes. This antenna is mounted on a king post that allows it to move in azimuth and elevation. The signal produced by the low-noise amplifier is sent to an analog receiver in a lab room in the floor directly below the roof. The signal goes through a bandpass filter that selects a 57 MHz band around 1420 MHz, and is then mixed into an intermediate frequency, and a second bandpass filter centered at 260 MHz is used to eliminate aliasing. The antenna's movement and orientation is controlled by a computer in the same lab room, which is also used for producing the data files generated by the observations.

3.2 Procedures for data acquisition

Two runs of data acquisition were performed, the first one with the purpose of fulfilling objective (1) above, namely estimating the system temperature, the gain, the linearity response and the effective temperature of the calibration diode, and the second one with the purpose of fulfilling objectives (2) and (3), namely measuring the antenna's beam width and measuring the effective temperature of the Sun at 1.42 GHz. The first run consisted in pointing the antenna at a fixed position in the sky containing no strong radio sources for a period of 900 seconds, throughout which a series of artificial alterations were made to the signal coming from the antenna. For instance, the noise diode was turned on for periods of about 30-40 seconds and the signal attenuation was increased by 3 dB for about 30 seconds and later decreased by 3 dB for about 50 seconds. Also, a rectangle of microwave absorber material was physically held between the helical feed antenna and the reflector dish two times for a period of 30-40 seconds.

The second run of data acquisition had a duration of approximately 2 hours and consisted in pointing the telescope at the position that the Sun would have an hour in the future in order to observe the effect of a full Sun crossing through the telescope's field of view. Both data runs used a sampling period of 1 second and the data was recorded on two .out scripts that later formed the basis of the data analysis.

4 Data reduction

4.1 System parameters and linearity

The data reduction was performed using Python. The data acquired during the first run was used to extract the values of 5 different voltages that were used to calculate the effective temperature of the system, its gain, the effective temperature of the calibration diode, and the linearity response of the system. Figure 1 shows a plot of the voltage amplitude as a function of time. As can be seen, there are 5 different levels of approximately constant voltage amplitude. 4 of of these amplitudes are the result of one of the different artificial alterations that were mentioned in 3.2. Since certain alterations were performed more than once, and in order to account for random variations in the readings, the procedure for measuring the voltage amplitudes consisted in averaging the values obtained for the amplitude over the periods of time in which the alteration was in place. These voltages were then used to calculate the system parameters via the following equations:

$$V_1 = gT_{sys} \tag{1}$$

$$V_2 = g(T_{sys} + T_{cal}) \tag{2}$$

$$V_3 = g(T_{sys} + T_{abs}) \tag{3}$$

Where V_1corresponds to the baseline voltage amplitude, that is, the readings obtained when no alterations where made, V_2corresponds to the voltage amplitude with the noise diode turned on, and V_3corresponds to the voltage amplitude obtained when the absorber was placed between the reflector and the antenna feed. The parameter g is the constant of proportionality used to convert from voltage amplitude to current, or gain, T_{sys}corresponds to the system temperature, $T_{\mathrm{cal}}$to the effective temperature of the calibration diode, and $T_{\mathrm{abs}}$to the temperature of the microwave absorber, which was assumed to be equal to 300 K. This equations can be manipulated to yield the parameter g in terms of known quantities:

$$\frac{V_3 - V_1}{T_{abs}} = g \tag{4}$$

Which can then be used in order to calculate T_{sys}using equation (1). Rearranging (3) and substituting from (1), we find that $T_{\mathrm{cal}}$is given by:

$$T_{cal} = \frac{V_2 - V_1}{g} \tag{5}$$

This expression allows us to find the value of T_{cal} by plugging in the value for g found previously.

The other two voltages, $V_4$and V_5, were obtained by changing the attenuation up and down by three decibels. If the system were perfectly linear, one of the voltages should be exactly half g times T_{sys}, and the other should be exactly two times g multiplied by T_{sys}. That is

$$V_4 = \frac{1}{2}gT_{sys} \tag{6}$$

$$V_5 = 2gT_{sys} \tag{7}$$

Comparing the theoretical values with the actual measurements gives us an idea of how constant g actually is and allows us to account for this as a possible error source.

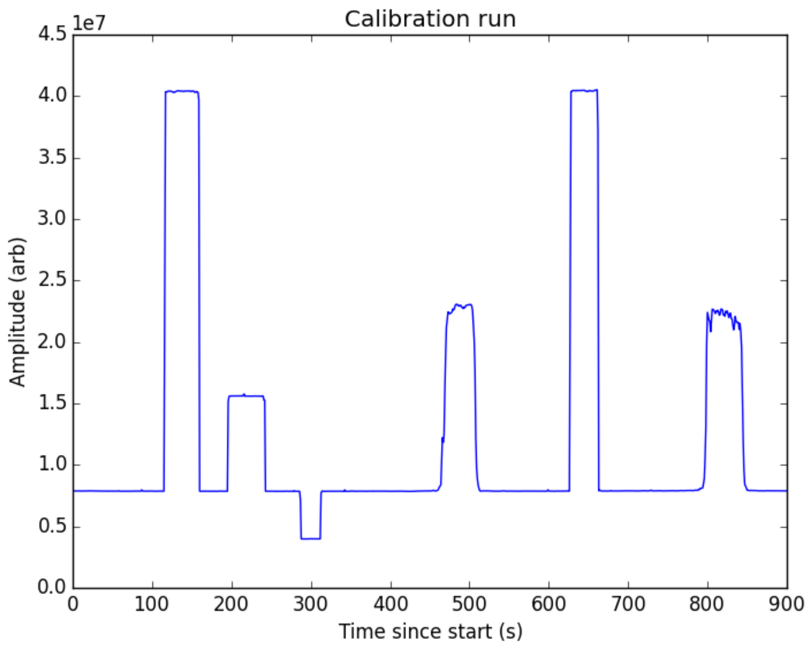

Figure 1: Voltage amplitude vs time for calibration run

4.2 Beam width and the Sun's temperature

Figure 2 shows the plot of voltage amplitude vs time for the second data acquisition run. Calculation of the beam width was done by first substracting the baseline voltage, as shown on Figure 3, and then finding the value of the peak amplitude, subsequently dividing it by two in order to find the value of the half-maximum. Then, the time that it took for the voltage to go from the first instance of the half maximum to the second instance of it can be used in order to calculate the beam width, in radians, via the following formula:

$$\theta_A = t \cdot \cos(\delta) \cdot \frac{2\pi}{3600} \tag{8}$$

Where t corresponds to the time between half maxima, δ to the antenna's declination, and the numerical factor corresponds to the number of radians per second that spanned by the antenna due to the Earth's rotation. This value can be used to calculate the solid angle of the antenna, via the equation

$$\Omega_A = \pi \left(\frac{\theta_A}{2}\right)^2 \tag{9}$$

Using this and the values of the parameters obtained earlier, the effective temperature of the Sun at the frequency of observation can be calculated from the expression

$$T_{sun} = \frac{A_{peak}}{g} \cdot \frac{\Omega_A}{\Omega_S} \tag{10}$$

Where $A_{peak}$is the maximum amplitude of the curve in Figure 3, and Ω_s is the solid angle of the Sun, equal to $6.87 \cdot 10^{-5}$ steradians.

5 Results and analysis

5.1 System parameters

The methods of data reduction described in 4.1 applied to the first data run yields the following voltages (approximated to the nearest whole number):

$$V_1 = 7,875,268\, units$$

$$V_2 = 39,960,843\, units$$

$$V_3 = 21,700,626\, units$$

Using equations (1), (4), and (5), the following values for each of the parameters are obtained (again approximated to the nearest whole number):

$$g = 46,084\, {}^{units}/_{K}$$

$$T_{sys} = 171\, K$$

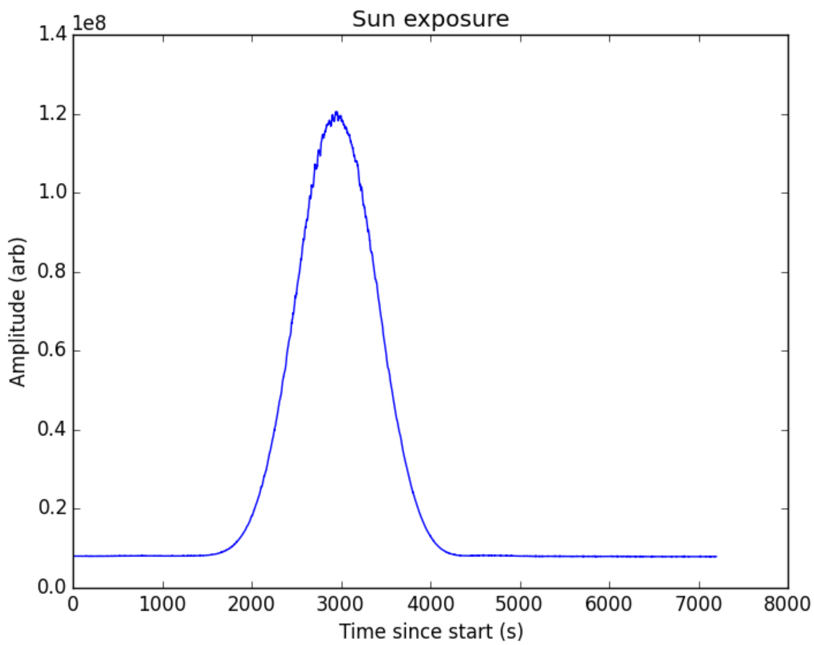

Figure 2: Voltage amplitude vs time for Sun drift scan

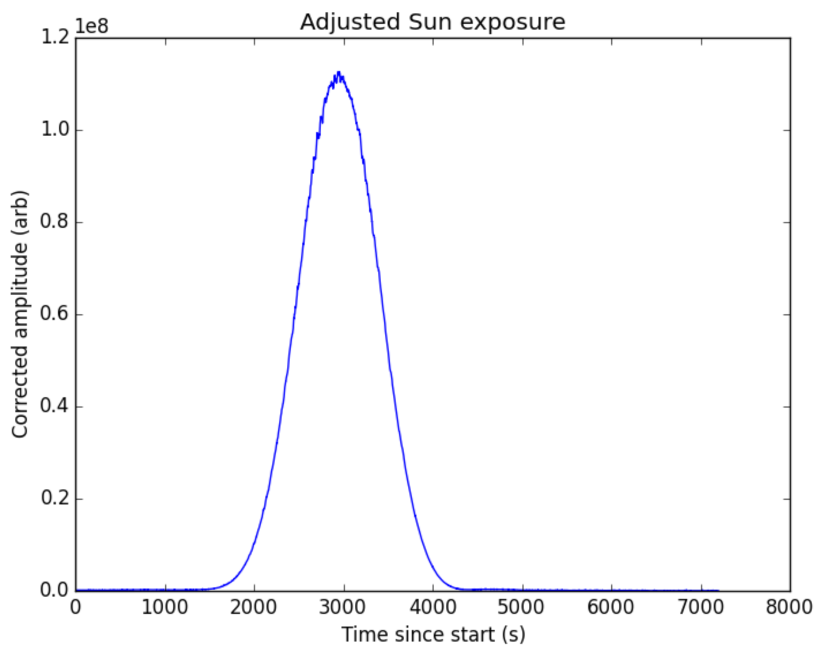

Figure 3: Adjusted voltage amplitude vs time for Sun drift scan

$$T_{cal} = 696\,K$$

There are several sources of error involved in this calculations. First of all, they assume that the system is perfectly linear, that is, that g is a constant, when in fact this is not necessarily true, as will be seen in 5.2. It was also assumed that the temperature of the sky was essentially 0 K, since strictly speaking, the measurements made give 3 equations in 4 unknowns, one of which is T_{sky}. This is a reasonable assumption given that the cosmic background radiation has a very low temperature at the observation frequency of 1.42 GHz that was used. However, it is possible that other radio sources from the sky could have altered the results in small levels that would be indistinguishable from noise. To be able to calculate T_{sky}it would be necessary to produce another voltage via some other artificial alteration to the system, like another absorber with a different known temperature. The temperature of the absorber used was not directly measured but assumed to be close to 300 K, which is another source of error that needs to be kept in mind. Finally, placing the absorber in front of the helical feed involved imperfect human manipulation of it, and as a result was not always at the same distance from the feed, meaning that the signal produced by the antenna varied more than it did during the period of time when the other alterations were made. This can be clearly appreciated in Figure 1: the periods of time during which the absorber was put in place correspond to the last and the third to last deviations from the baseline voltage.

5.2 Linearity

The values found for $V_4$and V_5were the following (to 3 significant figures):

$$V_4 = 0.506\,units$$

$$V_5 = 1.98\,units$$

Thus the percent deviation in linearity is calculated as 1.2% from $V_4$and as 1% from V_5. This implies that even if all other sources of error were to be ruled out, there would still be at least a 1.2% error in any of the measurements made with this radio telescope.

5.3 Beam Width

The value for θ_A, as defined in section 4.2, was found to be (to 3 significant figures):

$$\theta_A = 0.0706\,rad$$

Which corresponds to an antenna solid angle Ω_A of $3.92 \cdot 10^{-3}$ steradians. θ_A is commonly approximated to an ideal value of λ/D, where λ corresponds to the observation wavelength, and D to the diameter of the antenna. The theoretical value for θ_A in this case is then given by:

$$\theta_A \approx \frac{\lambda}{D} = \frac{c}{fD} = \frac{3 \cdot 10^8\,ms^{-1}}{1.42 \cdot 10^9\,Hz \cdot 3.8\,m} = 0.0552\,rad$$

Which gives a 27.9% discrepancy between both values. Given that the approximation is just that, an approximation, this discrepancy does not appear to be unreasonable. Apart from the universal sources of error mentioned before, in the particular case of this calculation, it must be noted that the fact that because the sampling and integration time for the measurements consisted of a little more than a second, the value of the full width at half maximum is not exact in the sense that the two points of half maximum used were not equal. In other words, the line corresponding to the width that was measured was not exactly parallel to the x-axis. However, this is not expected to have had an important effect on the resulting value, since it could only change the parameter t in equation (8) by a fraction of a second.

5.4 Temperature of the Sun

The peak value of the curve from Figure 3 was found to be (to the nearest whole number):

$$A_{peak} = 112,621,731\, units$$

Using this and the values for Ω_A, Ω_S, and g found previously, together with equation (10), the temperature of the Sun was measured (to 3 significant figures) as:

$$T_{sun} = 140 \cdot 10^3\, K$$

Using the unadjusted peak value from Figure 2 and using a modified version of equation (10), one can use this temperature to retroactively calculate T_{sys}, which was again found to be equal to 171 K, although this cannot be regarded as a completely independent calculation since the resulting value still depends on the parameter g and the voltage V_1.

This value for T_{sun} differs significantly from the value of $70.5 \cdot 10^3$K given in a paper by Zirin et al. (see [1]). However, the Sun's temperature is known to vary widely depending on what part of its cycle it is in. The observations for the Zirin et al. paper were made during a solar minimum, while the observations on this paper were made about three quarters of the way through the last cycle that started on January 2008 (cycles usually last between 10 to 12 years). A better point of comparison would be a 1960 paper written by N. R. Labrum (see [3]), who used observations near the solar maximum of 1958 to arrive at an upper limit temperature of $160 \cdot 10^3$K. With this in mind, the temperature derived from the observations made in this experiment still looks a little too high, since (without going into details about the relative magnitude of the last solar maximum and the solar maximum that occurred in 1958) we would expect that T_{sun} now were half-way between $70.5 \cdot 10^3$K and $160 \cdot 10^3$K, which is equivalent to about $115 \cdot 10^3$K. Given the numerous sources of error described previously, in particular the assumption that the absorber temperature was 300 K and the 1% deviation from linearity observed, and the fact that each of the errors were added to each other in the course of our calculations, the result obtained does not appear to be too far off from the accepted value as to be unreasonable.

6 Conclusion

The purpose of this lab was to calculate some of the system parameters of the radio telescope on top of Cornell's Space Sciences building, and use it to perform a Sun crossing in order to measure its temperature at an observational frequency of 1.42 GHz. These objectives were fulfilled, and a value for the Sun's temperature was obtained that does not perfectly agree with the expected value, but nonetheless appears to be reasonable given the sources of error involved. Further experiments along this line with stricter error controls should be able to find a value closer to the expected one.

References

[1] Zirin, H., Baumert, B. M. and Hurford, G. J. *The Microwave Brightness Temperature Spectrum of the Quiet Sun,* 1991, ApJ, 370, 779.
[2] Labrum, N. R. *The Radio Brightness of the Quiet Sun at 21 cm Wavelength near Sunspot Maximum,* 1960, Australian Journal of Physics, 13, 700.

[3] Hathaway, David H. *The Sunspot Cycle* NASA/Marshall Solar Physics. NASA, 17 Nov. 2015. Web. 18 Nov. 2015. <http://solarscience.msfc.nasa.gov/SunspotCycle.shtml>.