

Lab 2

Astronomy with the 21 cm Line
Some Microwave Electronics

Ramsey Karim
with R. Bentley and S. Wishnek

University of California, Berkeley
HAIL SAGAN Research Group

August 31, 2016

ABSTRACT

This that and the other

1. Introduction

Radio astronomy requires more than the basic signal processing intuition covered in the last lab. Pointing a telescope at the sky requires some notion of time and location. This doesn't sound very difficult, in the scope of most other fields. Usually, time can be found on clocks, watches, and various other common time-keeping devices, and location is found on maps. Yet in astronomy, the concern is not (entirely) with local time or geographical location. The scope of astronomy lies far from this planet, so some non-geocentric conventions must be adopted. This lab will discuss several astronomical time and location coordinate conventions and how transform between them.

Next, some basic data will be taken from the Horn on top of Campbell Hall. Data processing will be discussed and the most successful method of data acquisition and processing will be determined. Once some guidelines for taking data have been laid down, the lab will use location coordinate transformations to point the telescope at a specific location in our galaxy and take some data. The 21cm line will be received specifically using a system of amplifiers, filters, and mixers that collectively take the ~1420.4 MHz signal down to ~0.4 MHz.

Lastly, some properties of waveguides and coaxial cables will be examined, with specific focus on reflections, standing waves, and wave velocity in media.

1.1. Date and Time

Locally, time is easy enough to discern: just check your watch. Yet around the planet, time varies by geographical longitude since it is linked to the sun's position in the sky; this is called local time. Astronomy requires more general time standards that are invariant around the planet so that astronomers everywhere will be on the same page when it comes to some object's position. Just like time coordinates, location coordinates must be generalized as well; one's zenith, for example, depends entirely upon their location on the planet (both latitude and longitude) and time, since the Earth is spinning on its own axis *and* orbiting the sun.

Luckily, astronomers have constructed several time and location coordinate systems. First of all, Civil Time is the current local time in the time zone corresponding to the observer's geographic longitude. Local times are based on their difference to Coordinated Universal Time (UTC), which is the Civil Time in Greenwich, England. Pacific Standard Time, for example, is the current time zone encompassing Berkeley, CA, and is 8 hours behind UTC, since it is approximately 1/3 of the way around the world from Greenwich,in the western direction. UTC time is synchronized with Earth's spin and can also be thought of as the Sun's hour angle plus 12 hours[1] (more on hour angle soon).

Local Sidereal Time is *almost* synchronized with Earth's spin, but actually keeps track of the Earth's spin with respect to the direction of the Vernal Equinox. That sounds like a bit of a mouthful; essentially, LST is 0 when the observer's meridian[2] is aligned with the point at which the Sun crosses the celestial equator during the vernal equinox. LST is on a 24 hour cycle, but these aren't the same hours as Civil Time. Sidereal hours are slightly shorter, such that 24 LST hours is only ~23:56 in Civil Time. This time system is useful for keeping track of when various objects will be in the sky, and is more general less heliocentric than Civil Time.

Lastly, there is the Julian Day. This is a very general time-keeping system since it is universal around the Earth and is a single non-cyclical number. It increases in integer steps at noon UTC every day, and it has decimal precision carrying the time information. Julian Day 0 was noon, January 1, -4713. This date was chosen in 1583 by Joseph Scaliger because it falls before any recorded history; any event in recorded human history can be earmarked with a *positive* Julian date. There is also a Modified Julian Day, which is shorter than the Julian Day (which is currently on the order of 10^6) and hits whole number values at 0 (midnight) UTC instead of 12 noon. MJD 0 was at 00:00 UTC on November 17, 1858.

1.2. Spatial Coordinates

There are four main astronomical coordinate systems that will become useful in this lab. Each is a spherical system of coordinates, so transformations are generally made with matrices that

[1] Ideally, the Sun is directly overhead at noon
[2] Great circle encompassing the celestial poles and the zenith

transform between each basis. Later in this report, there is an outline of a program that transforms between each of the four systems.

Galactic coordinates are the largest-scale coordinates we will deal with in this lab. They are right-handed and centered at our sun and consist of a latitude (b) and a longitude (l), in the form (l, b). Latitude ranges from 90° to −90° and gives the angle above or below the plane of the galaxy[3]. Longitude ranges from 0° to 360°, with 0° pointing from the Sun to the galactic center. Galactic coordinates are defined such that the galaxy rotates in the *negative* longitudinal direction.

One step down in generality are equatorial coordinates; the next two of our main coordinate systems are types of equatorial coordinates. Right ascension and declination (α, δ) are geocentric coordinates; the main plane lies along Earth's equatorial plane, so that objects move across the sky along great circles. Right ascension is right handed and measures how far east of the vernal equinox an object lies. It is generally measured in sidereal hours, ranging from 0 to 24, but can also be measured in degrees. Declination ranges from 90° to −90° out of the equatorial plane. An object's right ascension and decliation are constant; they don't change when the Earth rotates or orbits. They only change when the object moves[4].

Hour angle and declination (ha, δ) are also equatorial coordinates, but are left handed and follow the Earth's rotation. Declination is the exact same as in the last system. Hour angle is LST minus the object's right ascension and is measured in sidereal hours. This means that an object has an hour angle of zero if it lies along the observer's meridian, and a nonzero hour angle give the time (again, in sidereal hours) until it will cross the meridian again[5]. Hour angle, clearly, is extremely dependent on Earth's rotation, so it is *not* constant for the object.

Lastly, horizontal coordinates (az, alt) are entirely based on the observer and take into account where on Earth (latitude and longitude) the observer is. Azimuth ranges from 0° to 360° and lies in the horizontal plane, with 0° pointing north and increasing towards the east. Altitude ranges from 90° to −90° and comes out of the horizontal plane. Visible objects may have any azimuthal angle but necessarily must have a positive altitude (so that they are above the horizon). 90° altitude is the zenith. This coordinate system is ideal for pointing a telescope, but must take into account the observer's latitude when being transformed to or from another system.

1.3. Basic Data Collection and Processing

After coordinates have been identified, a telescope can be pointed at the sky, where it can pick up signals. Anything the telescope picks up is sent through a chain of amplifiers, filters, and mixers until the desired frequency range is delivered to the sampling device at a reasonable amplitude and frequency. The exact sequence of telescope-to-computer signal processing will be discussed in the next section. For now, this brief overview will have to suffice. Once the signal reaches the computer, the real[6] analysis begins. The signal coming from the telescope comprises several different sources of intensity[7]. T_{sys} is the total intensity, and it has two main components: $T_{continuum}$ and T_{line}. The continuum power is frequency-independent and is essentially noise; it is generated by the telescope and the subsequent electronics through various means. The line power is frequency dependent and generally contains the desired information from the sky. One must computationally distinguish between $T_{continuum}$ and T_{shape} in order to effectively remove $T_{continuum}$. This report will discuss a method of doing just that in the next section.

1.4. Waveguides

The last section of this lab will briefly cover some of the basics of coaxial cables and waveguides.

Coaxial cables consist of a central pin and a conducting shell around it, separated by a dielectric. This design allows signals to travel down the cable using the pin as one lead and the shell as the opposite. Coaxial cables[8] generally have an impedance of 50Ω; as long as it is consistent down the length of the cable[9], the signal will be fine. During a signal's travel down a coaxial cable or sequence of electronics, it may encounter this sort of change in impedance. This is similar to a light ray encountering a medium with a different index of refraction; some of the wave will be transmitted and some will be reflected. In most electronics, a reflection like this is undesirable for two main reasons: first of all, a reflected wave is a loss of power, and second, it may disrupt or damage some part of the device or system. Reflections can also cause standing waves in parts of the system (which will be covered in just a moment). To avoid this, electrical engineers[10] practice *impedance matching*, in which they attempt to keep impedance as constant as possible throughout the system so that these reflections do not happen. This is why 50Ω terminators are commonly teed at the end of coaxial cables.

Coaxial cables are just one way to move signals; waveguides are also made for this purpose. Simply put, waveguides are structures intended to act as a medium for waves that minimizes energy loss. They are often compared to talking through a long tube; the tube acts as a waveguide for sound waves, limiting the space in which the wave spreads. Normally, waves spread in all available dimensions, so a wave left to its own devices in 3D space will spread and lose energy over space. If the wave isn't given 3 dimensions in which to spread, if it is confined to 1 or 2, then it will retain more energy; that is the purpose a waveguide achieves.

If one end of a waveguide is shorted or opened, as opposed to being connected to some component, a standing wave can be created within the waveguide. Standing waves have fixed nodes[11], so it is possible to measure the wavelength of a standing wave using something like a voltmeter and a ruler. The last part of this lab will estimate the width of the waveguide and the wavelengths of several microwave frequencies in the waveguide.

2. Observations

Most of this lab's observations are detections of the 21cm line using the Horn and waveguide measurements. The rest of the topics either factor into these observations or are more theoretical[12].

[3] The galaxy is approximatley a disk, so this works out just fine

[4] They will technically change as the *Sun* moves, but we won't get into that, since it's negligible for our purposes

[5] assuming it is approximately stationary

[6] Technically, complex...

[7] Units of temperature (K) will be used for intensity

[8] Those that we have in lab

[9] It is.

[10] And astronomers

[11] Zeros

[12] Read as: We need to know it for the class but it didn't require direct observation

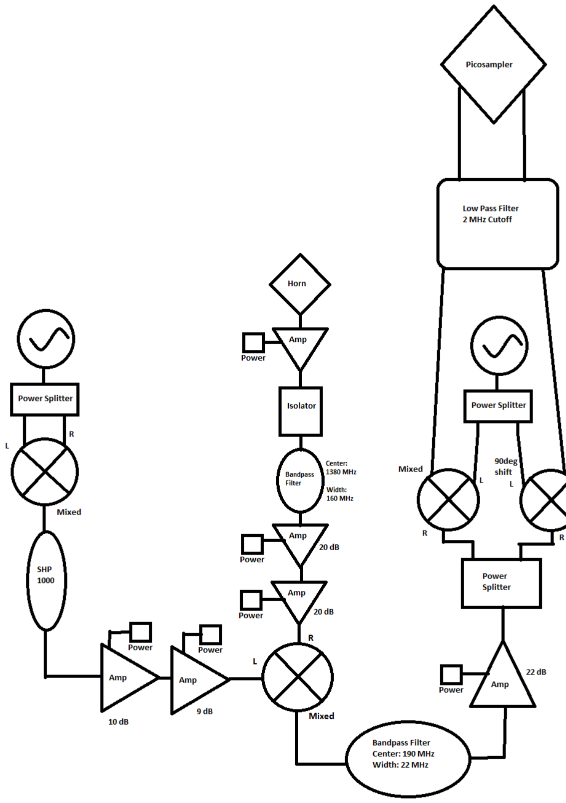

Fig. 1. The post-horn electronic system

2.1. Observing with the Horn

The Horn generally collects very weak signals. Because of this, it must be followed by a series of amplifiers that drive the signal up to a measurable level and account for attenuation within the system itself. Additionally, the 21cm line frequency of 1420.4 MHz is much to high for the picosampler used in the lab, so two stages of mixers must be used to cut the signal down. After some filtering and amplification, the first stage of mixing is met. It is approximately a 615 MHz signal that is first mixed with itself to double its frequency to 1230 MHz. Mixed with the 1420.4 MHz hydrogen line, the line is cut down to the difference frequency of 190.4 MHz and a large sum frequency. That signal is put through a bandpass filter centered at 190 MHz, which trims off the sum. After another amplifier, it meets the second mixer, this time an SSB stage; a local oscillator at 190 MHz is split with a 90° phase shift on one side. Each side is mixed with a split half of the 190.4 MHz signal remnant from the Horn, cutting the frequency to the 0.4 MHz that has been mentioned in this lab. The SSB mixer allows for complex input into the Fourier transforms, but that is the computer stage. After one final filtering stage (a 2 MHz cutoff low pass filter), the two signals are fed into the picosampler. The entire scheme is shown in Figure 1.

The very first measurements taken on the Horn were small data sets taken at 6.25 MHz with the Horn pointing at the zenith. These takes were not at all concerned with the content of the signal; they were much more for the purpose of understanding how taking data from the Horn worked. They have no apparent spectral content besides a strong fundamental at 0 Hz. A histogram of the data was created and two different methods of averaging the multiple data sets were attempted: mean and median. Their

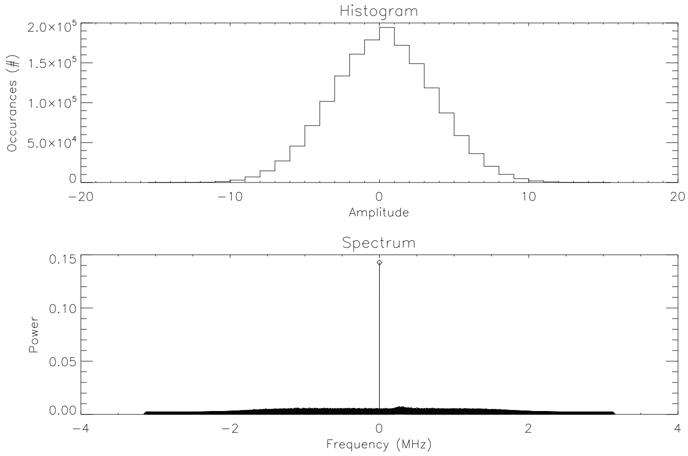

Fig. 2. Histogram of signal data

comparative success will be discussed in further sections. The header for this code is included in the Lab 2 Code attachment, Section 1-2.

Next, data was taken again from the zenith but this time at 7.8125 Hz[13]. Online and offline spectra were both taken. Data processing for this set included combining dual inputs to a complex signal, Fast Fourier Transforming, and averaging across the sample sets. Various sample and sample set numbers were used; generally both were on the order of 1000, with sample number always a power of 2.

The next data processing step was slightly more involved: the $T_{continuum}$ had to be effectively removed from the T_{sys} in order for T_{line} to be the only significant remaining artifact of the original signal. On top of that, $T_{sys,coldsky}$ had to be determined in order to give T_{line} proper units. These calibration steps required two additional takes of data: a 'cold sky' take and a 'noise diode' take. The cold sky take was simple; the Horn was pointed at the sky (no particular location) and set offline (so that the 21cm line wouldn't show up in calibration data). A sizeable data sample was taken. The noise diode take required some known source of thermal noise, so the Horn was pointed horizontally and two lab associates stood in front of the reciever, effectively broadcasting ~300K blackbody radiation. Those two takes became the calibration takes and were processed in the `GET_TSYS` procedure, for which documentation is provided below. The online and offline spectra taken previously were combined to make the shape of the signal (an unitless replica of T_{line}) using the `GET_SHAPE` procedure. Lastly, the value for $T_{sys,coldsky}$ from `GET_TSYS` and the shape of the line $|T_{line}|$ were multiplied together in the `GET_CALSPEC` to get the T_{line} spectrum in units of Kelvin. The precise mechanism for each program is outlined in its documentation. The essentially theory of the entire calibration boils down to

$$calibrated\ spectrum = \left[\frac{s_{online}}{s_{offline}} - 1\right] \times \frac{\sum s_{coldsky}}{\sum s_{300K} - \sum s_{coldsky}} T_{cal} \tag{1}$$

where the term in brackets is the dimensionless shape $|T_{line}|$ and the rest of the expression is the constant $T_{sys,coldsky}$. Operating through this with a large number of both samples and sample sets yields a very pleasant and readable spectrum with obvious emission lines[14].

[13] This sample rate is used for all subsequent samplings in this lab
[14] Or lack thereof, I suppose

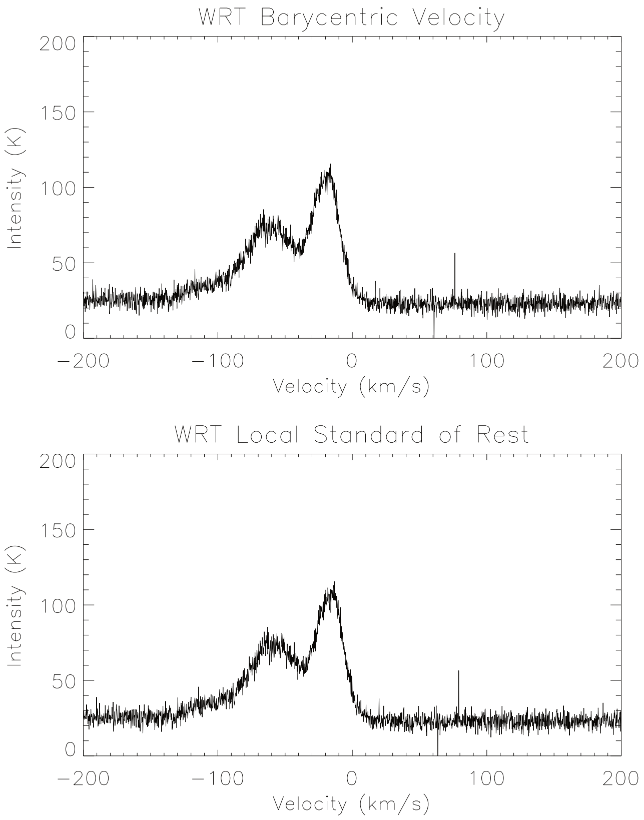

Fig. 3. Data from (120, 0) plotted against redshift velocity

Lastly, the UGDOPPLER procedure was called with Campbell Hall's coordinates in order to get the velocities of the observatory relative to the center of mass of the Milky Way (barycentric) and relative to the Local Standard of Rest. This information was used to plot 21cm line spectra against a redshift axis corresponding to 1420.4 MHz, so that it becomes easy to see if the peak is spread out much or shifted over. The axis, in units of velocity, shows how fast the various sources of 21cm lines are going relative to the selected coordinate system (barycentric or LSR).

The headers for these programs are included in the Code attachment, Sections 3-5.

2.2. Pointing the Horn

This next observation was a little more than an aimless scan of wherever the Horn happened to be pointed. The team was instructed to observe the galactic coordinates (120°, 0°), and in order to do that, the previously mentioned matrix transformations became important. A comprehensive coordinate transformation program was written, creating a user-friendly and intuitive way to make any of the 12 possible transformations between the 4 total systems. The documentation is provided in the Code attachment, Section 6; it thoroughly explains how to use the software. After the galactic coordinates were converted to horizontal coordinates correspoinding to the time at which data was taken[15], an offline and an online spectrum were taken and analyzed just as the last data set was. Slightly different programs were used since the data was saved in a slightly different format, but they follow the same exact procedures and will be included in the public code folder[16]. The results of the measurement will be discussed later.

2.3. Microwaves in Media and Waveguides

The first measurement was made on the modified coaxial cable using the attached probe and a ruler. A 3 GHz sine wave was sent from the signal generator into the modified coaxial cable (with the end left open) and several entire wavelengths were measured fairly accurately, by the team's estimation. Then the end of the coaxial was shorted with a short length of wire and measurements were taken again by the same method. The data was transcribed to a computer and a linear regression was calculated using the POLYFIT procedure. The fit will be discussed in the next section.

The second experiment involved the waveguide and slightly higher frequencies, ranging from 7 to 12 GHz. For every integer GHz frequency between 7 and 12, inclusive, open and short[17] data was taken in the same fashion as in the last experiment with the coaxial cable. Linear fits to the wavelenths worked better for higher frequencies with more nodes, but the real challenge here was to find the width of the waveguide based on the data. Given a free-space wavelength λ_{fs}, a wave's waveguide wavelength can be written as a function of the waveguide's width a:

$$\lambda_g = \frac{\lambda_{fs}}{[1 - (\lambda_{fs}/2a)]^{1/2}} \tag{2}$$

Using measured data of λ_m and theoretical[18] values of the free-space wavelengths of the frequencies, it should be possible to figure the width of the waveguide. The process isn't a simple calculation; it is iterative. It necessarily begins with a guess; call a good guess of the waveguide width a_G. The function $\lambda_g(a_G)$ will yield a 'guessed' version of the wave's waveguide wavelength, λ_G. This can be compared to the measured value[19], and a difference variable can be introduced: $\lambda_m - \lambda_G = \Delta\lambda$. Now this equation can be manipulated to incorporate a change in a_G, which will allow for modification of the guess.

$$\lambda_m - \lambda_G = \Delta\lambda_G \tag{3}$$

$$\lambda_m - \lambda_G = \Delta\lambda_G \times \frac{\Delta a_G}{\Delta a_G} \tag{4}$$

$$\lambda_m - \lambda_G = \frac{\Delta\lambda_G}{\Delta a_G} \cdot \Delta a_G \tag{5}$$

$$\frac{(\lambda_m - \lambda_G)}{\frac{\Delta\lambda_G}{\Delta a_G}} = \Delta a_G \tag{6}$$

The change in a_G now has an expression entirely dependent on known or accessible information. The measured wavelength λ_m is known, the guess wavelength λ_G is calculated from the current width guess by $\lambda_G = \lambda g(a_G)$, and the derivative of the λ_g function with respect to a can be calculated and evaluated at a_G. Crunching the numbers should yield a change in a_G that can be used to modify the current a_G. *Then*, the process starts over with a *new* a_G, one more accurate than the last. After several iterations of this, a fairly accurate value for a should be available.

[15] Data taken on JD=2457444.5 pointed at $(az, alt) \approx (338, 62)$

[16] Header for this software is in Code, Section 7

[17] Once again shorting with some wire

[18] But with very good confidence

[19] One concise measured waveguide wavelength can be calculated with a linear regression, just as with the coaxial cable experiment

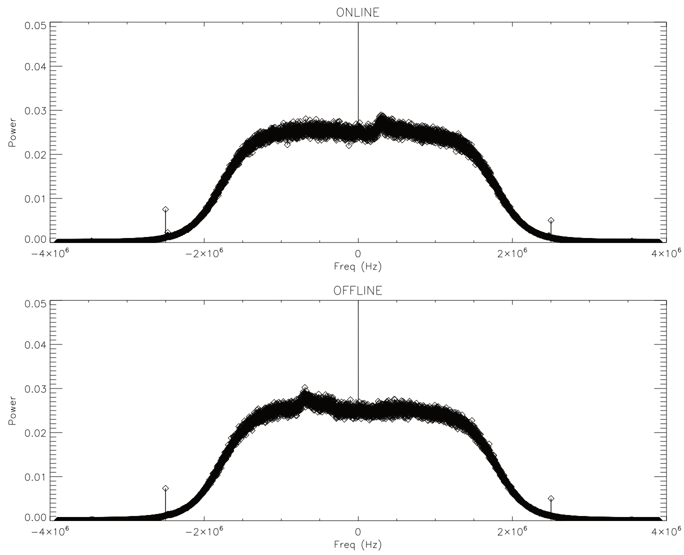

Fig. 4. Online and offline spectra

This program was primarily mathematical, as one could surmise. Much to the team's despair and confusion, a persistent and sublte bug kept the value of a_G from converging to the right[20] value of a, which had been measured by hand on the waveguide to be about 2.3 cm. The header for the code is included in the Code attachment, Section 8.

3. Analysis and Interpretation

Most of the experiments performed during this lab were successful and helped widen the team's knowledge of radio astronomy and signal processing. Only one experiment failed, and only due to an unknown programming error. This section will discuss in detail the results and significance of each experiment.

3.1. Radio Astronomy with the Horn

The initial measurements with the Horn were informative but not that spectacular. A sample rate of 6 or 7 MHz turned out to be excellent for measuring the 0.4 MHz line with plenty of leeway. An averaged power spectrum of just one online signal shows a sort of 'hill' with a small peak at 0.4 MHz: the 21cm line, as seen in Figure 4[21]. The offline spectrum shows the same peak on the other size of the y axis. When the shape is calculated by dividing the averaged online spectrum with the averaged offline spectrum, the entire spectrum gets flattened out and vertically centered around 1. The +0.4 MHz peak is still visible; the offline spectrum used places the now-inverted offline peak at about -0.4 MHz, but it's of no concern. Calibrating the signal using the cold sky and 300K data brings the line intensity to about 100-150K, which matches similar plots of the 21cm line found online[22].

The observation of $(l, b) = (120°, 0°)$ brought no surprises in the way of processing; the exact same treatment could be used for this signal as on the last. The surprise was the shape and placement of the calibrated signal, especially when plotted against a redshift axis. First of all, the observatory velocity calculated with `UGDOPPLER` was about 20 km/s for both barycentric and LSR; the two had a difference of about 5 km/s. The main peak of the 21cm line observed at those coordinates was blueshifted, moving at about 20 or 30 km/s towards us. Furthermore, it wasn't just one single peak; it was a smear. This suggests that there is certainly more than one source of the hydrogen line[23] and the different sources are moving at different speeds relative to each other. It is impossible to tell from the data whether the sources are close to each other. One may be across the galaxy from the other. The data only gives the speed and concentration[24]. The barycentric and LSR shifts were, as previously mentioned, only about 5 km/s different.

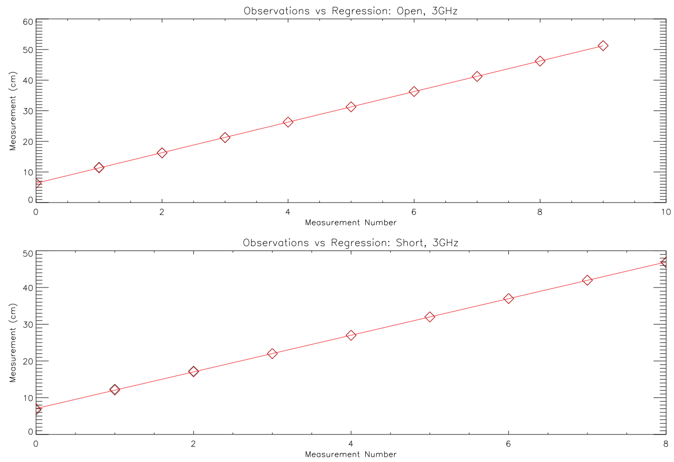

Fig. 5. Regression plot for 3 GHz wave in coaxial cable

3.2. Coaxial Cables and Waveguides

The coaxial cable experiment proved that a standing wave could exist both in the case of an open ended cable and a shorted cable. It was also a pleasant exercise in using the `POLYFIT` procedure and linear regression in general. The regression line was spot on; the team was shocked at how well the line fit the points, as seen in Figure 5.

The waveguide exercise was, as prevously mentioned, not nearly as succesful. The wavelength data taken by hand seemed fine and matched predictions, as the wavelength in the waveguide was shorter than the theoretical free-space wavelength[25]. The only problem was the bug in the iteration code. The results often would error out at infinity or an imaginary number, and sometimes would settle on a number like 1.25 cm, which while close, isn't close enough; it's an error bar of 50%. Whatever the case, the team knew that the waveguide was about 2.3 cm wide and that the velocity would necessarily be very high but not too close to or greater than the speed of light.

4. Conclusion

The team gained valuable experience in radio observation[26] and learned some particulars about using coaxial cables and waveguides as well. The data taken from the Horn was quite interest-

[20] Or any convergence at all; it would occasionally blow up or become imaginary, depening on the guess value
[21] Data is from the sky in general, no location in particular
[22] On the Internet, not the online spectrum
[23] Meaning that there is more than one clump of hydrogen in our galaxy - shocking
[24] The intensity of the line is likely proportional to the quantity of hydrogen moving at that speed
[25] If it weren't, then since the wave is travelling at the same *frequency*, it would end up travelling faster in the guide
[26] Our first experience, in fact

ing; the 21 cm line showed up more prevalently than any team member expected, and the hydrogen line source(s) at (120, 0) are quite curious due to the significant smearing and shifting of the peak. It is important to note that *every* measurement of the 21 cm line showed some smearing. The source at those coordinates had an exaggerated smear, but no data taken during this lab showed a perfect or even near-perfect peak. This lab has made the team eager to continue observing at microwave and radio wavelengths. The mystery of the (120, 0) 21cm line has not been solved, but we hope to uncover it soon.