Single Dish Radio Astronomy: Reaching First Light

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Bachelor of Science

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ABSTRACT

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We present the status and future plans of the radio astronomy observatory at Brigham Young University. The Physics and Astronomy department and the West Mountain Observatory already have optical facilities that offer students the opportunity to observe in the optical and NIR, but not in any other wavelengths. An array is being built for students to obtain data in the radio spectrum. The array is being built around the operational 4 meter dish on top of the Eyring Science Center and will eventually contain baselines up to 20 km and a 10 m dish. We currently have four sites for additional baselines. The array initially will be ready to observe HI at 1420 MHz and the OH MASER lines at 1665 MHz and 1667 MHz. We present preliminary spectra in L-band (21cm-18cm) with the 4 meter dish. The system will be using LNA's for signal amplification and will have digital correlation and spectral analysis through CASPER. The system is locked to a rubidium clock with a GPS master. In the future, we hope to extend the frequency coverage to C-band (5 GHz).

Keywords: senior thesis, undergraduate research, radio astronomy, radio interferometry, astronomy education, radio array, radio observatory

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Chapter 1

Radio Astronomy at BYU

1.1 Astronomy at BYU

BYU currently offers a bachelor's of science in physics-astronomy, and a minor in astronomy. Both of these paths require that the student gain experience in observational astronomy. Currently, the program has the students learn how to run the 16" David Derrick Telescope in the Orson Pratt Observatory (OPO) and analyze the data they gather. The student also has the possibility to try to work at the West Mountain Observatory (WMO). These are optical observatories, and optical is just a small portion of the observable frequencies. The observing process and the data reduction process for each frequency are very different. Having a radio observatory means expanding the capabilities of the department.

1.2 Educational Benefits of a Radio Observatory

Many educational benefits come from building a radio observatory at BYU. There have been and will be multiple presentations on the matter in the local, regional, and national setting. The observatory provides the opportunity for the user to gain an in-depth understanding of the observations, pointing calibration, antenna characterization, principles of interferometry, and the data reduction process. There are future opportunities to learn the mechanics and engineering of a radio interferometer through system maintenance and upgrades. Our work will be a resource for other universities looking to expand their astronomy program with a cost effective, research grade radio observatory.

Opportunities to present research have facilitated the learning process. I have given both oral and poster presentations to the local scientific community at BYU, including the annual Spring Research Conference. The project was presented at the Four Corners physics conference in 2010 [1] and 2011 [2] by D. Blakley. I presented a poster at the 223rd semi-annual conference for the American Astronomical Society (AAS) [3]. Also, there are two theses that will be submitted on the development of the primary radio antenna. One is this thesis and the other is a master's thesis for D. Blakley.

This array provides more training opportunities for students. As a former member of the workforce, the more training one has the higher likelihood he/she has of being employed. A trained person saves the employer time, money, and resources. Graduate study in astronomy is no different. Trained individuals save advisors time, money, and resources. This is favorable and he/she has a higher likelihood of being successful in graduate studies. Prospective students with experience in observations, data acquisitions and data reductions are more likely to be accepted to a graduate program. A radio observatory run by the students is an excellent way to provide hands-on training. The training comes from repeated usage of the system, and troubleshooting the system when problems arise. Let us not forget, there is invaluable information transferable to industry in this project as well. Satellite communications, wireless networking and cellular telephones (as noted in Parthasarathy, et al. [4]), signal processing, computation, and programming are just a few examples of the possible applications of radio astronomy engineering.

In using the equipment, there are processes that the observer will run through on a given night to obtain data from astronomical sources. These processes include but are not limited to: pointing calibration, amplitude calibration, source tracking, array correlation, and data reduction. All of these processes deal with a different aspect of the observing process and a different aspect of the engineering. When the student learns these processes he/she will inevitably learn some of the engineering behind the process. For example, when one understands how seeing effects the data, one is better able to decide whether to observe for standard star work or not. As the student becomes familiar with the radio antenna, he/she will be able to understand both the observational errors and the errors in the signal due to the instruments.

1.3 The First Student Operated Radio Observatory at the University Level

There are large radio arrays and large diameter single dish radio telescopes around the world [5] [6], and see Appendix A. These telescopes are usually affiliated with a conglomerate of universities or national laboratories and the federal governing body of the country of origin because of the incredible construction and operation costs. Typically, a committee is appointed to select how to best allocate observation time for the telescope. Professional astronomers will submit proposals and the committee will review the project and decide to whom the time is given, based on the quality of the science. This requires more time and resources for both the facility and the astronomer. Having more, smaller telescopes allows initial data to be taken to strengthen astronomical theories and proposals. The optical astronomy community has been building small robotic observatories for monitoring projects for the past few years, e.g., ROVOR [7], La Luz, WWT [8], etc., and the radio astronomy community can do the same.

The BYU radio observatory will truly be the first of its kind. At U. C. Berkeley, Parthasarathy, et al. [4] [9] [10] has built a radio antenna for instructional purposes. Their antenna is setup for detection of the HI emission line; however, with the focus of their system being lab instruction, it would appear they have simpler equipment than we require. Currently, there are no small scale radio interferometers with equipment sophisticated enough to be used on a research level monitoring project or all sky survey. There are radio arrays that have been built by universities, such as: the Long Wavelength Array (LWA) [11] and the Very Small Radio Telescope (VSRT) [12]. These arrays are either non directional or they are not sophisticated enough to be operated automatically. The Stephen F. Austin Very Small Array (SFAVSA) has a small interferometer, with two 3 meter antennas and a baseline of 10 meters [13]. At Stony Brook, there is a two element array [14] that is used for education, but more for demonstration than research. Haystack Observatory has an REU program that has proposed [15] and built [16] a Very Long Baseline Interferometer (VLBI) array, but the longest baseline is 1.4 km. The Very Small Radio Telescope (VSRT) is a small prepackaged radio antenna that can be built for under $500 [12]. This is the first four element, directional, research grade radio array to be completely built and run by students. Our radio array builds upon these other student projects in the radio instrumentation/engineering community, and my hope is that it will be a useful resource for other universities to build upon in the future.

1.4 Is a Low Cost Radio Interferometer Feasible?

Developing a research grade radio interferometer is feasible. In Section 3.1 I lay out the cost of our first antenna. This cost is low, which makes this type of telescope within the reach of many universities and facilities. For under $20 000 we are able to observe sources at 1.42 GHz and 1.66 GHz.

1.5 The Physics of Telescopes and Interferometry

There are two main physics principles to keep in mind when building a telescope. They are angular resolution and light collection. Angular resolution is how far apart two light sources have to be for the telescope can resolve them independently. Light collection is how many photons can the primary mirror collect. These are both fairly simple principles to understand and they are extremely important to astronomy.

Angular resolution is important when trying to observe objects close together and objects very far away. Upon inspection of the equation, $\sin(\theta) \approx 1.22\lambda/d$, it is easy to see the resolution is dependent on both the wavelength of incident light and the diameter of the primary reflector. In radio astronomy, observing is often limited by resolution. When observing at such long wavelengths, the diameter of the primary reflector needs to be very large. For example, a 1 meter optical telescope has $\theta \approx 0.126$ arcsec for $\lambda = 5000$ Å. For a radio telescope to have the same angular resolution for $\lambda = 21$ cm, the dish needs a reflector of 420 km in diameter! It is easy to see that radio observatories have a very difficult time resolving objects.

The other main factor in observing is the light gathering power of the telescope. The light gathering power is $P \propto D^2$. Think of the telescope as a photon bucket. The larger the radius of the bucket is, the more photons that will be able to fit inside it. In radio astronomy, we build really large buckets. This allows us to detect photons from objects that are very faint. However, we still have the problem of resolving the object. This is why we build multiple antenna arrays.

Interferometry is a combination of single dish physics and signal combination from multiple detectors. The incident light is typically modeled as a wave front, see Fig. 1.1. As the wave front approaches the array, the antenna separation creates a time-lag between when each antenna will receive the signal. This difference in time can easily be calculated. With a precision timing device, the signal from all the antennas is easily convolved to map the source.

Combining signals from multiple antennas is what makes radio interferometry so powerful.

However, there are both advantages and disadvantages to building a radio interferometer. The advantages are:

- Greater angular resolution
- More light gathering
- Observe fainter objects

The disadvantage to building an interferometer is the cost. To build an array that has the necessary angular resolution and light gathering power can cost a lot of money. This is why we are building an array for minimal cost.

1.5.1 Signal Combination

Radio antenna signals can be combined either in real time or at a later time. What are the advantages or reasons for choosing one over the other?

Radio signals can be combined in real time. This requires direct, high speed communication between all the antennas and a computer. This means there is less memory allocation required.

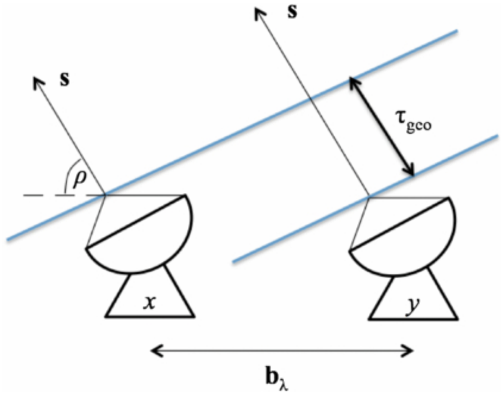


Figure 1.1 This diagram shows the wavefronts as they reach the antennas. The second antenna detects the signal at a time difference τ later than the first antenna. This requires the signal to be correlated in either real-time or after the observation has finished [17].

Only the combined signal information will be stored in a memory location. However, this communication can be very costly and is only effective for short range communication. If there is a communication failure, the data will be lost. For short distances, gigabyte communication speeds are feasible. For long distances, direct, high speed communication is not a very good choice.

Radio signals can be recorded and combined at a later time via data correlation. The recording process is fairly simple. First, the dish detects a signal generated from an astronomical source. Then, this signal is recorded as a voltage or current, depending on the engineers choice. Finally, this information is stored on some type of external storage device, i.e., an external HDD or a CD and then sent to the Array Operations Center (AOC). Many arrays, such as the VLBA, ship the data to the AOC.

Data correlation is the preferred method of signal combination for very long baselines in radio astronomy today. This method works by placing a time stamp on the data as it being recorded. It doesn't require high speed communication as real-time correlation does. This means one doesn't have to worry about communication failures. The data can be transferred over very long distances by fiber optics, coaxial cables, and postal service. This means arrays such as the VLA can be used for observations. The major setback with this method is the vast amounts of storage space required for the data. All of the data from each antenna needs stored in a location, and then the combined data needs stored as well. This is a reason why one sees entire rooms dedicated to correlation and memory storage at the VLBI and the ALMA.

There is even an array that is a hybrid of the two correlation systems. MERLIN, in the UK, uses microwave antennas to transmit the data to the AOC. This can cause similar problems as an interconnected array, due to electrical storms or some other form of interference between the site and the AOC.

In trying to keep costs as low as possible, we have decided the BYU radio array will combine the antenna signals later through data correlation. This means we need a precision timing device and a precision location device for each antenna. This will be discussed further in Chapter 2.

1.6 The New Radio Observatory

1.6.1 BYU Single Dish

We have been developing a four meter radio telescope on top of the Eyring Science Center (ESC). This telescope will be used for long term monitoring projects and all-sky surveys at 1.42 GHz and 1.66 GHz. The main observing mode of this system will be spectral line. This means when we point at an object we do so using a very narrow bandwidth centered at the doppler shifted rest frequency of a particular emission by an object. Using our sophisticated equipment, we will record this spectral profile. These spectral profiles contain information about the underlying physical processes of each object. For example, spectral profiles can have lines that are doppler shifted. Shifted lines tell us about the dynamics of the object. The HI spin flip at 1.42 GHz is used to determine galaxy dynamics. The OH MASER line at 1.66 GHz is used to detect star forming regions and stellar evolution. We will be observing both types of sources in hopes of better understanding the physics behind them.

This telescope has six different systems built into it. We are observing at two frequencies, 1.42 GHz and 1.66 GHz, and each frequency has three configurations. These configurations are: spectral analysis, single dish observing and low-precision interferometry through spectra cyber, and high-precision interferometry with the HW*CASPER Roach. These three systems are specific to three different phases in the development process. The three phases are: calibration, single dish observations, and interferometry.

The control room and Array Operations Center (AOC) are on top of the ESC. This antenna has been installed and the mechanical calibration is finished.

Figure 1.2 The 4 meter antenna on top of the ESC. This is at our AOC.

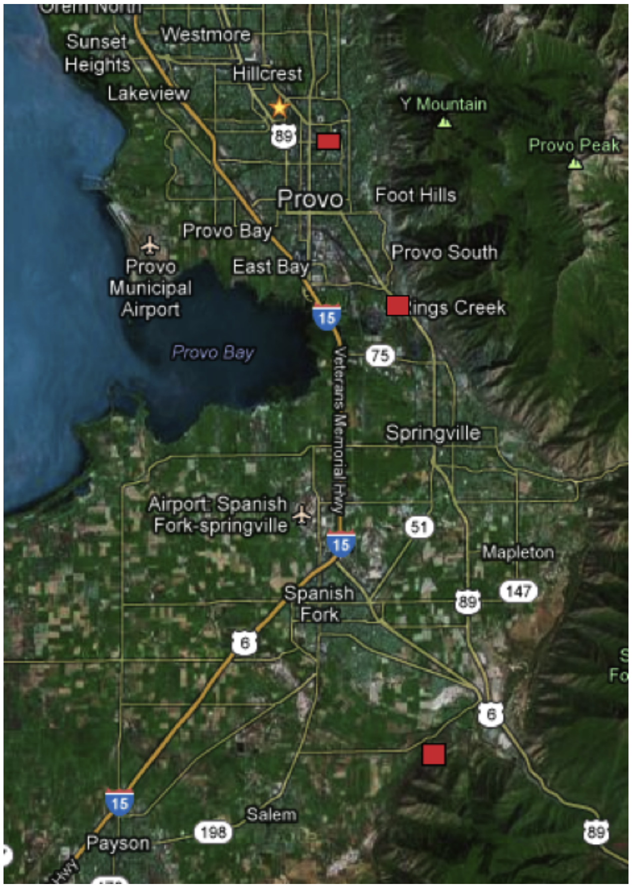
1.6.2 BYU Radio Interferometer

We currently have four antennas which will be located throughout Utah county with their location information shown in Fig. 1.3 and Table 1.1. The equipment needed for the radio array has been purchased or donated. Two of the four antennas have been donated to us from other departments. One of the antennas is currently operational as a radio telescope while the other three are either being worked on or plans are being made to work on them.

The primary antenna, the one at the AOC, is located on the ESC at BYU. This antenna has been a priority due to its location and ease of access. The radio dish is 4 m in diameter, and it is made of an alloy that has been shaped into a parabolic reflector. The mast has a four legged support pod that is secured to the roof with weights. The control room is also on the roof of the ESC in the Radio Astronomy Laboratory, again for ease of access.

The closest antenna to the primary is on top of the Clyde Engineering Building, roughly 180 m

Figure 1.3 Locations of the radio antennas. The northern most location is the 4 meter antenna on the Eyring Science Center and the 2.7 meter antenna on the Clyde Engineering building at BYU. The next location further south is another 4 meter antenna on the old *classical 89* broadcasting building approximately 10 km away. The farthest south location is in Spanish Fork, UT. This is our 10 meter antenna and it was donated by the communications department.



away. This antenna belongs to Dr. Jeffs and Dr. Warnick in the electrical engineering department. They are currently studying signal processing methods and are working with many of the larger telescopes in the world. This antenna is 2.7 m in diameter and has a parabolic, mesh design similar to the 4 meter on the ESC. This antenna is operational and will eventually join the array.

The third antenna will be located in south Provo, UT. The control room will be in the old *Classical 89* broadcasting building and the antenna will be installed on the roof. This antenna

Figure 1.4 The 2.7 meter and the 4 meter antennas, respectively. The 2.7 meter antenna on the Clyde building is part of an array Dr. Warnick and Dr. Jeffs use for research in signal processing. The 4 meter antenna in Springville, UT will be stationed at the old BYU *Classical 89* building.

(a) The 2.7 meter antenna on the Clyde building.

(b) The 4 meter antenna in Springville, UT.

is also a 4 meter parabolic antenna. Since the diameter of the dish is the same as our primary telescope, the motor controls will be the same. This dish is currently awaiting setup, calibration and testing before being installed.

Lastly, the fourth antenna is roughly 20 km to the south on a farm. This radio dish was donated to us by the communications department. The site houses the 10 meter antenna, a small control building and a communication antenna. The dish is non-directional because it was pointed directly

Antenna Locations

Location	Latitude (deg)	Longitude (deg)	Diameter (m)
ESC	40.247	-111.650	4
Clyde	40.247	-111.648	2.7
South Provo	40.201	-111.623	4
BYU Farm	40.071	-111.619	10

Table 1.1 This is a table of planned antenna locations.

at a geosynchronous communications satellite. The site has a control room, designation ’shack’ due to its small rickety properties, that used to house the broadcasting equipment. There is also a line-of-sight communications antenna for data communication with the original broadcasting station.

Figure 1.5 The 10 meter antenna in Spanish Fork, UT. This is currently unidirectional, so we will be undertaking the project to make it pointable.

The antennas will be equipped for frequency coverage in the L-band. We hope to extend the frequency coverage to the C-band. Also, The communications department has graciously offered us a site on Mount Vision on the west side of Salt Lake City, UT. This would give us quite a baseline extension, but this is far in the future.

1.6.3 My Contribution

My contribution to this project has been in different areas. I have done manual labor, developed software, performed systems testing and done system construction. The coordinate transformation software I wrote is currently being used for pointing calibration. I have been building a GUI for automated control. This is still in development mode and I hope to have this completed by the end of the academic year. I helped install the feed line and conduit running to the antenna. I set the physical and electrical limits for the system, and helped setup those limits. I helped install the

LNAs and also helped setup the spectral analyzers to observe in the proper frequencies.

1.7 A Roadmap for the Journey

In chapter two, I will discuss the radio telescopes in use today, the fundamentals of building a radio telescope, the specifics of the primary BYU radio antenna, and the challenges that kept us from first light. In chapter three, I will discuss reaching first light, spectral analysis, pointing and tracking, software design, the observatory's projects, removing the kinks in the process, the next steps in reaching first light for interferometry, and how building the array is beneficial to students, the department, and the university.

Chapter 2

Methods

2.1 Current Radio Telescopes

Most of the large radio telescopes are affiliated with national facilities and run by the country with primary funding responsibility. For instance, the NRAO funds the Very Large Array (VLA) in Socorro, NM and The Netherlands funds and operates ASTRON. A few of these telescopes are affiliated with universities, e.g., the Multi-Element Radio Linked Interferometer Network (MERLIN) is affiliated with the University of Manchester.

I have included a list of some of the most important single dish telescopes, radio interferometers, and upcoming observatories, see Appendix A.

2.2 Fundamentals of Building a Radio Telescope

The following is a short 'how to' manual for building a research grade radio telescope. This includes a bit of information about the type of equipment and where one might find it. There are several excellent sources for more information on build radio telescopes and possible observing projects. The list of sources is:

- *Radio Astronomy Teacher's Notebook, 3rd Ed.* [18]
- *Radio Astronomy Projects, 3rd Ed.* [19]
- *Radio Astronomy, 2nd Ed.* [20]
- *Interferometry and Synthesis in Radio Astronomy, 1st Ed. or 2nd Ed.* [21]
- *The NRAO website* [22] and [23]

2.2.1 Do It Yourself: Radio telescopes

A few fundamental ideas go into building a radio telescope. The antenna needs to be able to slew to objects, detect the signal, track the object through the sky, and have a good signal to noise ratio. All good science works to improve itself, and observational astronomy is no different. Increasing the ratio of signal to noise in the system is a lifelong endeavor, and I will discuss some ways to get started.

2.2.2 Directional Antenna

The antenna must be directional.[1] Telescopes that can't move can have a lot of limitations.[2] This requires the telescope to have some kind of manual control. (I have seen this in a joystick system, an electronic break system, and a control box system.) Moving the antenna will require stepper motors of some kind. Depending on the antenna setup, a counter balance system may be needed to reduce strain on the gear system.

There is one exception to the "immobile dish" rule. Arecibo Observatory in Puerto Rico is directional, but the dish does not move. Arecibo has a 300 m spherical radio dish, and it is built

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[1] Arecibo is an exception because it is pointable even though it is not steerable.

[2] You might as well use it for communications if you can't point it. All joking aside, I don't mean to ruffle any feathers with communications people. Their contribution to this project has been invaluable.

into the mountains. This means the dish is always facing normal to the surface of the earth. The ingenuity is in the receiver. Once the observer has the target in mind, the receiver is moved to a precise location to image the source object. Because the dish is spherical, the light rays will always converge to a focal point no matter where the receiver is located.

For a small diameter antenna, seeking out a communications company or a company that deals in RADAR systems is sufficient for a control setup. One can even buy the encoders and build the control hardware and software oneself. We opted to go the pre-built package route to minimize costs.

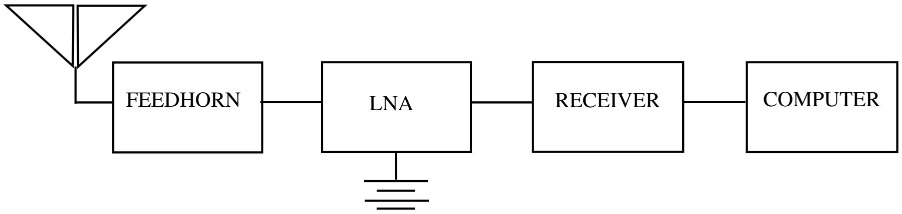

Figure 2.1 A general schematic for a radio telescope. This requires a reflecting dish, a dipole, a feed horn, an LNA, a receiver, and a computer.

2.2.3 Signal Detection

Radio waves can be detected with different types of radio antennas. In radio astronomy, signal detection is done with a dipole antenna. A radio telescope requires a collimator or collector, a feed horn, a dipole, an LNA, a receiver, and a computer. The general schematic is in Fig 2.1. The feed horn, the LNAs, the filters and the receiver are specific to each frequency. If you want to observe in three different frequencies, then you need three different sets of electronics. All of the system electronics are independent of one another. The only shared equipment is the dish.

The Photon Collector

Electromagnetic radiation at radio frequencies interact with specific metals and alloys, e.g., copper, aluminum, etc. These metals are usually very common and easy to find. Radio antennas can be made from these materials, and Ham radio operators will often make their own.[3] Some antenna types are better suited for specific applications than others. One can use a dipole antenna, a yagi antenna, a circularly polarized antenna, or others[4] (see Fig 2.2). The LWA uses an array of dipole antennas [11]. The low frequency portion of the Square Kilometer Array (SKA) uses simple dipole antennas without a collimating dish [24]. We have chosen to use a dipole antenna for our system due to the simple and compact nature of the antenna.

A typical antenna setup for radio astronomy has a reflector and a dipole. The reflector is necessary because astronomical sources are typically very faint at the surface of the earth. This is mostly due to atmospheric losses and the inverse square law for light. In order to detect the most signal at a ground based observatory, the radio waves are focused to a single point using a concave reflector. The dipole antenna is placed at the focal point of the reflector. To detect all of the incoming photons, the dish has to focus the light perfectly. This is impossible due to physical limitations in the engineering of the optics. Radio wavelengths are long, so the optics are a lot more forgiving than in optical astronomy. However, a dish with imperfections will still have losses. Some of the larger antennas minimize these losses by constructing the dish in a honeycomb like structure and moving the individual pieces to have the least amount of dispersion. We don't have such a sophisticated system, and we will have to accept the losses due to imperfections in our dish.

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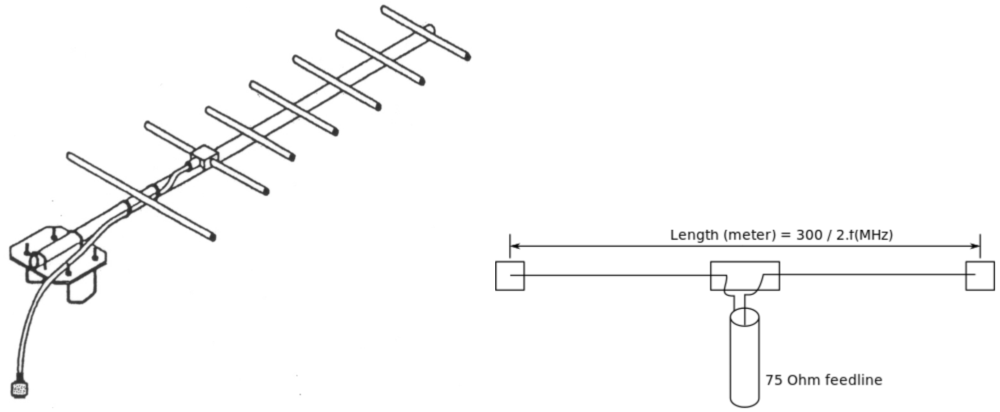
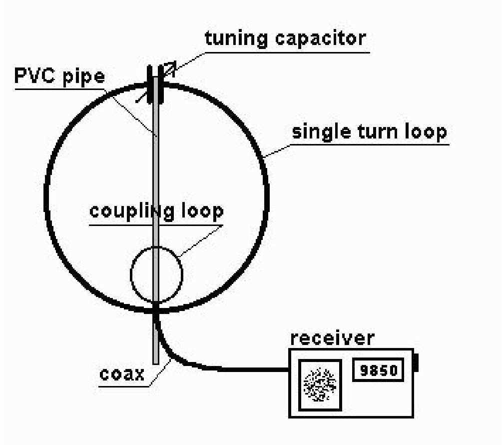
[3] The fundamental principles of signal transmission and reception are the same in any application of radio waves.

[4] Some antennas can be fabricated, such as a dipole or half dipole antenna. I'm sure it would be simple enough to find a yagi considering they were installed on virtually every home in the mid 1900s for radio and television broadcasts.

Figure 2.2 Different types of radio antennas.



(a) Yagi Antenna **(b)** Dipole Antenna



(c) Loop Antenna

The Feed Horn

The resonator cavity is placed at the focal point of the radio dish. It has a simple design, but provides a very important function. The radio waves enter the feed horn and reflect off the inner surfaces. This will create a standing wave inside the cavity. There is a dipole antenna inside the feed horn, and it is placed at a specific position to coincide with a fractional distance of the resonant wavelength. When the waves come in, they will interact with the dipole and generate a signal. This signal runs a short distance through the feed line to the LNA.

The Low Noise Amplifier (LNA)

The signal gets to the LNA and it is very faint. This signal needs to be amplified to gather information from it. As it passes through the circuitry in the LNA, the signal becomes amplified. The LNAs are typically broadband filters, so it is most likely necessary to filter the line at some point.

The Receiver

The amplified and filtered signal comes into the control room, and runs to the receiver. The receiver takes the signal from the coaxial cable and turns it into other useable sources of information. Because we are working in two different wavelengths, our receiver has two different selections to choose from.

2.2.4 Data Recording

An important part of measuring astronomical sources is recording the data. For most systems, it is simple enough to buy a computer. At BYU, there is a surplus sale roughly once a month. One can buy a computer at the surplus sale that is almost sufficient to store the data. One can even buy components and build the computer from a barebones setup. The only part missing is the required volume of storage for the data. Digital storage has increased in capacity and decreased in cost rapidly over the past 5 years. It is cheap to buy an external hard drive disk with terabytes of capacity. Purchasing an internal HDD is also a feasible option.

2.2.5 Tracking Objects

Tracking an object in the sky is a necessity for astronomy. The sidereal rotation of the earth causes an apparent rotation of the celestial sphere. In order to image an object for more than a fraction of a second, it is necessary to correct for this rotation. The telescope must track at the exact rate of the rotation of the earth to compensate, $v_r \approx 465.1 \text{ m s}^{-1}$. Tracking control software is inexpensive, i.e., NOVA for Windows is approx. $60.

The tracking control software must be able to communicate with the telescope control hardware/software. This requires automated control. The control computer might need to convert between coordinate systems, depending on the mounting type for the telescope. The majority of radio telescopes are azimuthal/elevation (Az/El) systems, so the coordinate conversion is from equatorial (RA/Dec) to horizontal (Az/El). I was unable to find any kind of software in the open source world, so I have spent a large portion of my time writing such software. This will be released under an open source license once it is in working order (see Appendix B).

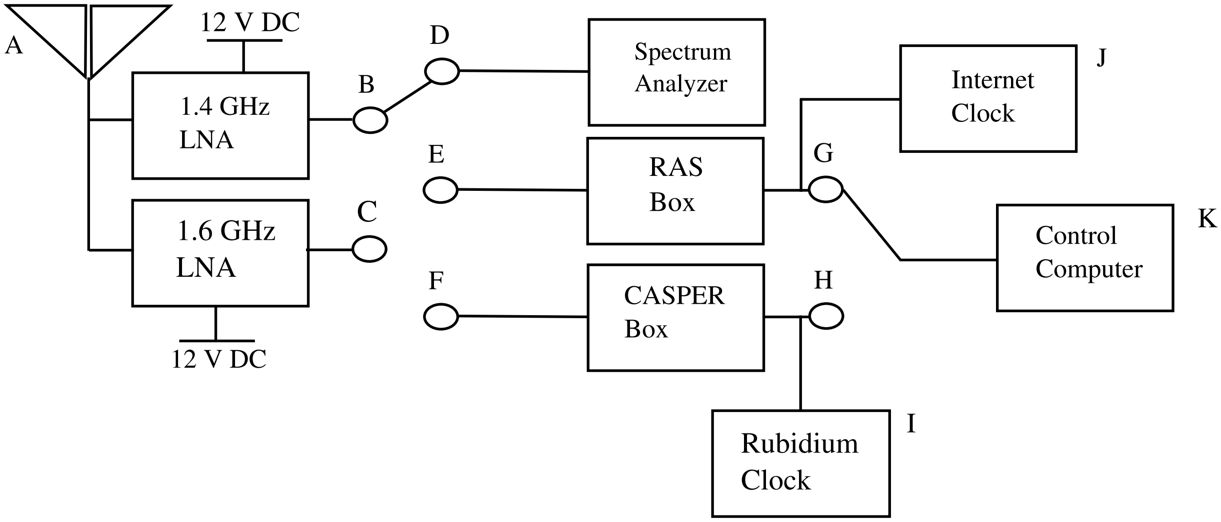
2.2.6 Reducing Noise

In every radio telescope, there is noise inherent in the system. This noise is typically from the electronics. One should reduce or eliminate, if possible, this noise to improve the data. There are a few ways to accomplish this. Some larger systems have a liquid cooling system, usually liquid nitrogen. Most smaller systems use thermoelectric cooling, and this is sufficient for our system. Remember, the colder the system needs to be, the more expensive the cooling equipment is. The most important idea when cooling is to have a regulated temperature. We are using peltier coolers, which are simple thermoelectric coolers with a fan and a heat sink.

There are some mechanical ideas for noise reduction as well. We ran galvanized aluminum conduit to house the signal lines and the electrical lines separately. This reduces noise from the electrical lines and provides housing from the elements. We are installing a battery charging system to power the LNAs during observations. There are also inline filters in our feed lines for each frequency.

2.3 Specifics of the BYU Radio Antenna

Figure 2.3 The schematic for our radio antenna. The parabolic dish focuses the incoming photons to the dipole antenna A. There is a coaxial output from each receiver, B and C, that runs into the control room. The LNA output can be connected to either D, E, or F. In the preliminary stages, switch D is used for pointing and system calibration. This setup is limited because only one receiver can be connected to one spectrum analyzer at a time. The RAS box E is used for selecting between 1.4 GHz and 1.6 GHz. Switch F connects to the CASPER box, the sophisticated signal processing device. The output of the RAS box G is connected to the control computer, and it uses the internet time stamp J on the incoming data. The output of the CASPER box H connects to the control computer, and it uses the rubidium time standard I for the time stamp. Switches G and H are mutually exclusive and will be used with switches E and F, respectively.



The first antenna to come online is the 4 meter on top of the ESC. We will be observing at 1.42 GHz and 1.66 GHz. This antenna has two LNAs at the feedhorn. The LNA's have a gain of $G \approx 28$ dB. The feed lines run about 80 ft from the antenna to the control room. I installed 1.5" conduit to shield the signal lines from the electrical lines. The feed lines are hooked into a frequency selection device. This allows us to choose whether to observer the HI line or the OH MASER lines. We also have equipment readily available for system testing and calibration.

2.4 Challenges That Kept Us from First Light

The positional calibration has been the biggest setback. We had to work very closely with M^2, the pointing system manufacturer, to calibrate the electrical and physical limits. These are necessary to prevent cable wrapping. We quickly learned the cables will wrap around the mast and rip out of the servo motor. After we finished the physical calibration, we also had to test our tracking control software. This software was rendered incompatible with the antenna controller we have. The company upgraded the hardware, but this independent software had not been updated. We were in contact with the author of the software, and he wrote a patch for us. We had to test this patch and make sure it worked properly with the system we have. The last major hangup we had was pointing the telescope from the computer. I started writing a GUI for this task. It has taken a lot of man hours to code this control program. I have included the finished pieces of code in Appendix B.

We have also had forces of nature working against us. There have been two times when the dish has detached from the mast. The first occurrence was the less severe of the two. First, the dish is attached to a piece of metal and the metal is bolted to the mast. During a wind storm, two of the nuts came off of the bolts and the connecting piece of metal was bent. The dish was pointed about 30 deg off of zenith, the park position. We had the metal repaired and we had spare bolts to repair the antenna. The second time was much more severe. We had a storm with extremely high winds, and the antenna was severely affected. The dish was ripped of the top of the mast in this storm. Connecting bolts actually ripped through the metal, and we found the dish lying on top of the roof. Fortunately, the roof is flat and the dish didn't injure anyone. We did have to machine a new connecting piece for the top of the mast.

Chapter 3

Results

3.1 Reaching First Light Is Possible

The 4 meter antenna is operational. We will present preliminary spectra in the next two months to show that we have done the work properly. We are observing several radio loud sources for our initial pointing calibration, amplitude calibration, and system determination. I have included a list of our calibration sources in Table 3.1. This list contains both OH MASER sources and HI spin-flip sources.

Calibration Source List

OH Source	Coordinates (B1950, RA/DEC)	VLSR (km/s)	FluxDen (Jy)	Tran/Pol
W3(OH)	02:23:16.5 / 61:38:55.9	-45.0	40	1665 RCP-LCP
W51-e1	19:21:26.3 / 14:24:36.0	62.0	120	1665 LCP
W49N	19:07:50.2 / 09:01:16.2	20.0	70	1665 LCP
NGC6334	17:17:32.3 / -35:44:02.5	-10	140	1665 LCP
SGRB2S	17:44:10.6 / -28:22:43.4	66.0	200	1665 LCP
Orion-KL	05:32:46.8 / -05:24:35.0	8.0	30	1665 LCP
HI Source	Coordinates (J2000, RA/DEC)	VLSR (km/s)	FluxDen (Jy)	Tran/Pol
CAS-A	23:23:24.0 / 58:48:54.0	NA	NA	NA
Sgr-A*	19:59:28.3 / 40:44:02.1	NA	NA	NA
CYG-A	17:45:40.0 / -29:00:28.2	48	NA	NA

Table 3.1 This is a table of system calibration sources. The information was resolved by SIMBAD. VLSR is the source velocity. FluxDen is the flux density of the object. This is related to the amplitude of the emission line we observe. Tran/Pol is the Polarization of the incoming signal. This is important in MASER emission. We are observing with a 400 KHz bandwidth for both OH and HI.

The equipment costs have been laid out in Tables 3.2 and 3.3. These purchase prices do not include labor. Our system is set up for three different stages, namely the calibration stage, the introductory stage, and the advanced stage.

For an introductory system, only the *SpectraCyber* by *RAS* is needed. The box will time stamp the data through an internet connection. The Spectral Analyzer, the DC Power Supply, and the control computer were all found within our department at no cost to us. The total equipment cost for the introductory four meter antenna is $\approx$ \$19 132. This system includes the dish/mast setup, the feed horn and the LNAs, the DC power supply, the servos and the controller, spectral analyzers, a signal generator, and a frequency selector (RAS box).

Introductory System Equipment Costs

Equipment Piece	Price (USD)	Equipment Piece	Price (USD)
Dish	1500	Mast	500
Servo Motors	8000	Control Box	5237
RAS SpectraCyber	2650	spectral Analyzer	2200(NA)
DC Power Supply	400(NA)	Computer	500(NA)
LNA and Cooler (2)	780	Can	125
Software	60	Inline Filter (2)	280

Table 3.2 This is a table of equipment costs for the *introductory* system. The total cost for parts is $19 132. This does not include labor. The DC power supply, the spectral analyzer, and the computer all came from within the department, at no cost to us.

For an advanced system, only the *CASPER Roach* by *HW*CASPER* is needed. This correlator will time stamp the data through the rubidium time standard and the GPS receiver. The Spectral Analyzer, the DC Power Supply, the Lock-In Amplifier, and the control computer were all found within our department at no cost to us. The total equipment cost for the advanced four meter antenna is $\approx$ $23 692. This system includes the dish/mast setup, the feed horn and the LNAs, the DC power supply, the servos and the controller, spectral analyzers, a signal generator, a frequency selector/correlator (HW*CASPER Roach box), a rubidium time standard, and a GPS receiver.

Advanced System Equipment Costs

Equipment Piece	Price (USD)	Equipment Piece	Price (USD)
Dish	1500	Mast	500
Servo Motors	8000	Control Box	5237
Spectral Analyzer	2200(NA)	DC Power Supply	400(NA)
Lock-In Amp	4000(NA)	GPS Receiver/Rubidium Clock	3245
CASPER	3965	Inline Filter (2)	280
LNA and Cooler (2)	780	Can	125
Software	60	Computer	NA(500)

Table 3.3 This is a table of equipment costs for the *advanced* system. The total cost for parts is \$23 692. This does not include labor. The DC power supply, the spectral analyzer, the Lock-In amplifier, and the computer all came from within the department, at no cost to us.

3.2 Observational Control

There have been two pieces of software written specifically for this project. The first piece of code is a patch between NOVA for Windows and the M^2 servo control box; and the software was written by Michael Owens. The second piece of code is software for controlling the telescope while on an observing run, and I wrote it. I will discuss the operation and implementation of both pieces of software.

3.2.1 Nova to M^2 Patch

For the telescope to be able to retrieve information for any amount of time the antenna must be in retrograde motion with the earth. This requires special software called tracking software. This software sends small coordinate adjustments to the encoders. This counteracts the rotation of the earth. We decided to use NOVA for Windows. This software has been proven to work well in the Ham radio community. However, there have been a few setbacks for us. The current software version (2006) is only compatible with Windows XP which requires us to use a legacy operating system (OS) on the control computer. And, with there not being a current software version, the manual telescope control box is not compatible with the software. We unsuccessfully tried modifying the control box to be backwards compatible with the software. We have had to contact the original software author, Michael Owens, to find a solution. He has graciously provided a patch for us, which we are currently testing.

3.2.2 Telescope Control GUI

In this day and age, all research level astronomical instruments have a control computer. This allows for long observing runs, proper coordinate transformations, accurate pointing, sidereal tracking, non-sidereal tracking, automated observing, dome controls, on-site weather conditions, etc. The defense company M^2, Inc. uses their antennas for RADAR, ICBM's, and other defense applications. This system did not come with any astronomical control software, nor did we expect it to. The task was left to us, and I volunteered for the project. I started writing a control GUI that interfaces with the control box and slews the telescope to different locations. The GUI also provides the observer with information such as airmass, LST, UTC, Hour Angle, and other useful observing parameters. *Python* was chosen for its robustness. The code is modular keeping it as simple and maintenance free as possible. This also allows the different pieces of code to be distributed throughout the astronomical community with an open source license.

The finished piece of the code is the coordinate transformation and precession routine. This lets us take Equatorial coordinates from a catalog and transform them into Horizontal coordinates for our telescope. The Horizontal coordinates are dependent upon the observer's location and the time of day. This is a fairly straight-forward calculation, but was somewhat difficult to implement. However, this piece is working and we use it constantly to find our sources.

3.3 Small Array Projects

This array will be used for long term object monitoring and sky surveys. The angular resolution is low, but the larger telescopes can not afford to do observing runs such as this. Time is too costly for them to scan the sky. This is why the optical community started moving to smaller, remote observatories.

3.4 Down the Road

We will be installing the second four meter antenna on the former *Classical 89* broadcasting building at the south end of Provo, UT. This antenna will be identical to the one on the ESC. We don't foresee any major obstacles in getting this antenna up and running. Dr. Warnick and Dr. Jeffs, in the electrical engineering department, are allowing us access to one of their 2.7 meter antennas. This antenna is fully operational. The only work we will have to do is learn their system and figure out how to interface with it. We have acquired a 10 meter antenna on the BYU farm in Spanish Fork, UT. This is the antenna that will take a considerable amount of time to get up and running. There is no antenna pointing system in place and the control room has a lot of old communication equipment that we probably won't be able to use. A fairly simple improvement we will make to the system is extending the frequency coverage to the C-band. This will be as simple as installing compatible feedhorns, LNAs, and receivers.

3.5 The Benefits of Building an Observatory

There are many benefits to building a radio observatory. This array is a very clear avenue for future student theses. Upgrades to the system will give students the opportunity to learn the electronics side of radio astronomy. There will be many opportunities for observational theses also. More research will be performed in-house due to potential immediate access to telescope time. Students will be able to take data for their own projects. Expanding the research possibilities in the astronomy program attracts more students. Students that learn how to work with the array will be better graduate school candidates.

There are currently two theses coming out of this project. This thesis and Daniel Blakley's master's thesis will both be written from this project. During the writing process, I had the opportunity to reflect back on my work. I have had an incredible learning experience. I have gained a lot of knowledge about observational radio astronomy from working with the nuts and bolts of an antenna. There is something unique about building a system that allows one to know the intimate details of it. For future students that work with this array, they will have the opportunity to expand the system and perform maintenance on it.

3.6 Working out the Kinks

When developing a radio antenna, there is a very steep learning curve. I have had to do a lot of research on the system we are using. This meant reading user manuals multiple times until I had a thorough understanding of equipment operation. This also means that once the first antenna is built, it will be much easier to build the others, assuming the systems are similar. The second antenna will be much easier considering we understand the calibration process, have working tracking software, and working control software. We have most of the pieces for the other antennas, it just requires putting the puzzle together.

There is one large obstacle we still will have to overcome. The telescope control hardware company, M^2, Inc., only makes equipment for antennas up to six meters. This means we have to design and build our own control system for the 10 meter dish. This will take a lot of planning and design, which has been started by the department machinist.

Appendix A

Large Radio Telescopes

There are several large radio dishes and radio interferometers throughout the world [25]. A few of the large single dishes are[1]:

- Parkes, Australia, 75 MHz to 43 GHz, $d = 64$ m
- Effelsberg Telescope, Germany, 395 MHz to 95 GHz, $d = 100$ m
- Medicina, Italy, 1.4 GHz to 43 GHz, $d = 32$ m
- Noto, Italy, 0.3 GHz to 86 GHz, $d = 32$ m
- Large Millimeter Telescope (LMT) in Volcán, Mexico, 75 GHz to 350 GHz, $d = 50$ m
- Arecibo Observatory in Puerto Rico, USA, 300 MHz to 10 GHz, $d = 300$ m
- Green Bank Telescope (GBT), USA, 290 MHz to 100 GHz, $d = 100$ m
- Deep Space Network (DSN), Goldstone, USA, Madrid, Spain, and Tidbinbilla, Australia, with $d = 70$ m, $d = 70$ m, $d = 70$ m

---

[1] Location, Frequency Coverage, Diameter

A few of the interferometers are[2]:

- Australia Telescope Compact Array (ATCA), Australia, 700 MHz to 1800 MHz, $d = 36$x12 m
- Very Large Array (VLA), USA, 73 MHz to 50 GHz, $d = 27$x25 m
- Very Large Baseline Array (VLBA), USA, 0.3 GHz to 96 GHz, $d = 14$x25 m
- Atacama Large Millimeter/Sub-Millimeter Array (ALMA), USA in Chile, $d_1 = 54$x12 m and $d_2 = 12$x7 m
- European VLBI Network (EVN), Europe, Asia, South Africa, USA, 1.6 GHz to 22 GHz, 18 antennas with varying diameters
- VLBI Exploration of Radio Astrometry (VERA), Japan, 2 GHz to 43 GHz, $d = 20$x4 m
- Westerbork Synthesis Radio Telescope (WSRT), The Netherlands, 123 MHz to 8.3 GHz, $d = 14$x25 m

Some of the exciting new arrays are[3]:

- Square Kilometer Array (SKA), South Africa, 200 MHz to 2 GHz, multiple dipoles
- Square Kilometer Array (SKA), Australia, 200 MHz to 2 GHz, multiple dipoles

---

[2] Location, Frequency Coverage, Array Dimensions: Number of Antennas by Diameter of Antennas

[3] Location, Frequency Coverage, Array Dimensions: Number of Antennas by Diameter of Antennas

Appendix B

Code

B.1 Telescope Control Software

```
# -*- coding: utf-8 -*-
'''

This piece translates between Equatorial and Horizontal coordinates.

This is a part of the software for controlling the 4 meter dish on the ESC.
This will eventually be used for the BYU radio Interferometer.

The Greenwich Apperent Sidereal Time is calculated using the instructions fr
the USNO, http://aa.usno.navy.mil/faq/docs/GAST.php

Chuck Honick
23 July 2013
```

```
honickchar@gmail.com

A special thanks to John Lucey and Durham University for making his Java
source code available at
http://community.dur.ac.uk/john.lucey/users/lst.html
'''

####################################################################
#
####################################################################

### Import necessary packages
from astropy.time import Time   # Astropy's Time module
import scipy as sp    # scientific evaluation package

####################################################################
#
####################################################################

### These are the astronomy routines ###
## The attributes need set inside a root.after() to update ##
## Set the observer location
# 4 meter on top of ESC

''' Equatorial to Horizontal Coordinate Transformations
```

```
A=azimuth, a=altitude, alpha=RA, delta=Dec, h=Hour Angle,
lambda0=observer's longitude, phi0=observer's latitude, thetaL=LST,
thetaG=GST

HA=LST-RA or HA=thetaG-lambda0-RA

tan(A)=sin(h)/(cos(h)sin(theta0)-tan(delta)cos(phi0))

sin(a)=sin(phi0)sin(delta)+cos(phi0)cos(delta)cos(h)

'''

"""
A=azimuth
a=altitude
alpha=RA
delta=Dec
H=Hour Angle
lambda0=observer's longitude
phi0=observer's latitude
thetaL=LAST or LMST ???
thetaG=GAST or GMST ???
"""
####### Run Test ########
def LSTClock(*args):
```

```
"""This computes the LST and other information
"""
# Input target information from the user
RA=raw_input('Enter target RA as HH:MM:SS.SS :\n')
Dec=raw_input('Enter target Dec as +DD:MM:SS.SS :\n')

# Convert RA and Dec to decimal degrees
# RA Conversion from sexigesimal hours to decimal degrees
var1 = RA.split(':')
a = int(var1[0])  # hours
b = int(var1[1])  # minutes
c = float(var1[2])  # seconds
d = c / 60.0
e = b + d
f = e / 60.0
g = a + f
h = g * 360 / 24
alpha = h # decimal degrees
# Dec Conversion from decimal hours to decimal degrees
var2 = Dec.split(':')
a = int(var2[0])  # hours
b = int(var2[1])  # minutes
c = float(var2[2])  # seconds
d = c/60.0
e = b+d
```

```
f = e/60.0
g = a+f
delta = g # decimal degrees

#print alpha, delta
# Set Lat and Long from Google maps
lat=40.246915   # deg
lon=-111.650108 # deg; E is +, W is -
phi0=lat
lambda0=lon

# Set the times
currentUTC=Time.now()  # UTC
print '\nThe current Universal Coordinated Time is {:s}'.format(\
    currentUTC.now())

# Find GAST using the USNO algorithm
JD = currentUTC.jd
JD0 = int(JD) + 0.5
ut = (JD - JD0) * 24.0
#print JD, JD0

#MJD = JD - 2400000.5
#MJD0 = int(MJD)
#ut1 = (MJD - MJD0) * 24.0
```

```
#print ut1, ut
#T1 = (MJD0 - 51544.5) / 36525.0

# Compute the number of fracitonal days from 2000 January 1, 12h UT (J20
J2000 = 2451545.0
D = JD-J2000
D0 = JD0-J2000
#print D, D0

# Find the GMST in hours
#H = JD-JD0 # H is the number of hours of UT elapsed since (0h) UT
#H=0 # This is GMST
T = D0 / 36525   # Number of Centuries since 2000
GMST = 6.697374558 + 1.0027379093 * ut + (8640184.812866 + \
    (0.093104 - 0.0000062 * T) *  T) * T / 3600.0
# Reduce the GMST to the range of 0h to 24h
if GMST < 0 or GMST > 24:
    rem = GMST / 24
    GMST = GMST - int(rem) * 24
    #GMST = GMST / 24 # Reduce to range of 0h to 24h
    #print GMST
else:
    GMST
print 'GMST is {:f} hours'.format(GMST)
```

```
# Calculating the Local Apparent Sidereal Time
"""GAST = GMST + eqeq, with eqeq = deltaPhi * cos(epsilon).
deltaPhi is the nuation in longitude:
    deltaPhi = -0.000 319 * sin(omega) - 0.000 024 * sin(2L)
omega is the longitude of the ascending node of the Moon:
    omega = 125.04 - 0.052 954 * D
L is the mean longitude of the sun:
    L = 280.47 + 0.985 65 * D
epsilon is the obliquity:
    epsilon = 23.4393 - 0.000 000 4 * D
Note: omega, L and epsilon are units of degrees
"""
omega = 125.04 - 0.052954 * D
L = 280.47 + 0.98565 * D
epsilon = 23.4393 - 0.0000004 * D
deltaPhi = -0.000319 * sp.sin(omega) - 0.000024 * sp.sin(2 * L)
eqeq = deltaPhi * sp.cos(epsilon)
GAST = GMST + eqeq  # hours
# convert to decimal degrees for thetaG
thetaG = GAST * 360 / 24
#print GAST, thetaG
print "GAST is {:f} hours".format(GAST)
# Convert Longitude from degrees to hours
lon1 = lon * 24 / 360
LAST = GAST + lon1
```

```
if LAST < 0:
    LAST = 24 + LAST
elif LAST > 24:
    LAST = 24 - LAST
print "LAST is {:f} hours".format(LAST)

# Convert GMST to hh:mm:ss
time5 = GMST
hours1 = int(time5)
minA1 = (time5-hours1) * 60
minutes1 = int(minA1)
seconds1 = (minA1-minutes1) * 60
s2 = "The GMST is {:d}:{:d}:{:d}".format(hours1, minutes1, int(seconds1
print s2

# Convert LAST to hh:mm:ss
time4 = LAST
hours = int(time4)
minA = (time4-hours) * 60
minutes = int(minA)
seconds = (minA-minutes) * 60
s1 = "The LAST is {:d}:{:d}:{:d}".format(hours, minutes, int(seconds))
print s1

############# Using Spherical Trig, compute the transformation ########
```

```
# Define the required variables
thetaL = thetaG + lambda0  # LST in decimal degrees
if thetaL < 0 and thetaL > -360:
    thetaL = 360 + thetaL
elif thetaL >= 360:
    rem = thetaL / 360
    thetaL = thetaL - int(rem) * 360
    #thetaL = abs(thetaL)
elif thetaL <= -360:
    rem = thetaL / 180
    thetaL = thetaL - int(rem) * 180
    thetaL = 180 + thetaL
else:
    thetaL

#print thetaL
h = thetaL - alpha          # Hour angle in decimal degrees
#print thetaL, thetaG

# Transform the coordinates to altitude and azimuth
# Convert frome degrees to radians
h = h * sp.pi / 180 # rad
phi0 = phi0 * sp.pi / 180 # rad
delta = delta * sp.pi / 180 # rad
```

```
#print h, phi0, delta

# Altitude Transformation, A
var1 = sp.sin(h)
var2 = (sp.cos(h) * sp.sin(phi0) - sp.tan(delta) * sp.cos(phi0))
A = sp.arctan2(var1, var2)    # quadrant specific arctan
A = A * 360 / (2 * sp.pi)
if A < 0 and A > -180:
    A = 180 + A
elif A >= 180:
    rem = A / 180
    A = A - int(rem) * 180
    #A = abs(A)
elif A <= -180:
    rem = A / 180
    A = A - int(rem) * 180
    A = 180 + A
else:
    A

# Azimuth Transformation, a

var3 = sp.sin(phi0) * sp.sin(delta) + sp.cos(phi0) * sp.cos(delta)\
    * sp.cos(h) # radians
a = sp.arcsin(var3)
```

```
a = a * 360 / (2 * sp.pi)


#print alt, az
#print tanA, sina
s3="The horizontal coordinates are\nel = {0:0.2f}\naz = {1:0.02f}"
print s3.format(A, a)
```

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