EVLA Memo 57

A Time Standard for Radio Astronomy

The New Mexico Array

Final Report

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Senior Design Group 5

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Abstract

The National Radio Astronomy Observatory is a facility funded by the National Science Foundation, to design, build, and operate large radio telescopes for research in astronomy. One of the tools that the NRAO has built and maintained for over 20 years is the Very Large Array. The technology used to control and obtain data from this very useful tool is becoming outdated, so a new project has been launched, the Expanded Very Large Array. There are 2 phases of this project. Phase I is a revamping of the electronic systems to more up to date computers and fiber optic cable instead of waveguides. This will allow scientists to use the array more fully. Phase II of this project is the addition of the New Mexico Array to the VLA. The NMA consists of 8 new antenna installed up to 250km away from the VLA which will increase the "accuracy" of the array by 10 fold.

In order to integrate these 8 antennas into the system, they must be synchronized with the rest of the array. This means that their internal clocks can not be more than 1.4 picoseconds different than any of the other antennas. In order to do this, the clocks from each antenna must be synchronized by a central clock.

The system designed by this group uses a single fiber to transmit a signal from a base location to the antenna location and set the clock there. This same signal will be sent back to the correlator at the base location with the data being received at the antenna. The phase difference between the sent and received timing signal will be measured and used by the correlator to correctly time stamp the data. This time stamp will then be used to correctly match all of the data obtained so pictures can be formed of astronomical phenomena.

It was shown through testing that 6-8 picoseconds of stability could be obtained over a fiber-optic system using a single fiber. While this is good, it does not meet the original specifications. We believe that this is caused by 2 things. First, the instruments used to measure the stability are not accurate enough to be measuring in the pico- and femtosecond range. Second, it is highly unlikely that in our first attempt to build and test this complicated circuitry that we could get it perfect. We believe that it is necessary for further testing to be done to come to a more accurate conclusion.

Table of Contents

Table of Figures

1. Project Description

Senior Design group 5 was assigned a project by the National Radio Astronomy Observatory (NRAO). The purpose of this project is to design a time synchronization system. This system has the express purpose of keeping eight antennas synchronized with a base station. This time synchronization system is required for the proper operation of the New Mexico Array (NMA), an expansion of the NRAO's Very Large Array.

Previous designs for time synchronization systems have relied on the use of a hydrogen maser, a clock that uses the physical properties of hydrogen as the standard for counting time, to be located at each antenna in an array. A single hydrogen maser has a cost of over $200,000. The primary goal of this project is to reduce the cost of a time synchronization system to $10,000 per antenna, while providing the same level of precision as a hydrogen maser system.

Through the course of this project, Group 5 performed research into radio astronomy in general as well as research into the available options for fulfilling the time synchronization task. The team selected a time synchronization method, provided a basic design, and provided preliminary proof-of-concept testing of the proposed system

2. Project Specifications

The phase difference between the base station oscillator and the antenna oscillators is of key importance in the synthesis of multiple data streams from the antennas. Phase stability refers to how much and in what way this phase difference fluctuates. The phase stability requirements of the time standard system fall into three categories.

2.1. Short Term Stability

Short term stability refers to the phase deviations over a 1 second interval. This system must achieve a short term stability of .5 picoseconds in a given second.

2.2. Long Term Slope

Long term slope is a description of the rate of change of the phase difference over a 30 minute period. The slope of the phase difference must not be greater than 200 femtoseconds per minute over a period of 30 minutes.

2.3. Peak-to-Peak Phase Deviation

Peak-to-peak phase deviation is a measure of how much the phase difference deviates from the long term slope. This value cannot exceed 1.4 picoseconds over a 30 minute interval. Following discussions with the customer regarding project specifications, it was determined that the primary focus of the group should be to meet this peak-to-peak phase deviation requirement above requirements 2.1 and 2.2.

2.4. Cost

A maximum of $10,000 per antenna can be spent on the implementation of the time synchronization system.

3. Background

For hundreds of years, astronomers observed the sky using their eyes or telescopes as their only tools. These tools use the visible spectrum, with wavelengths of micrometers. In 1932, it was discovered that many astronomical objects also emit radio waves, and tools were invented in order to observe such phenomena. These tools allow the astronomers to make pictures of the objects using the radio waves. This is made easier by the fact that radio waves can penetrate most of the gas and dust in space, so we can obtain much clearer pictures than is possible with optical observations.

3.1. What is Radio Astronomy?

The basic theory of radio astronomy is as follows. Astronomical objects broadcast electromagnetic waves. These waves travel through the universe, and oftentimes arrive on the earth. The waves of energy can be picked up by very precise tools and used to map the sky. A single antenna has limited directivity, or ability to focus on a single point. In order to improve directivity beyond what a single antenna can achieve, multiple antennas can be used in an array. . The theory is that the rotation of the earth completes the dish of the antenna, making the radius of the virtual antenna as long as one leg of the array.

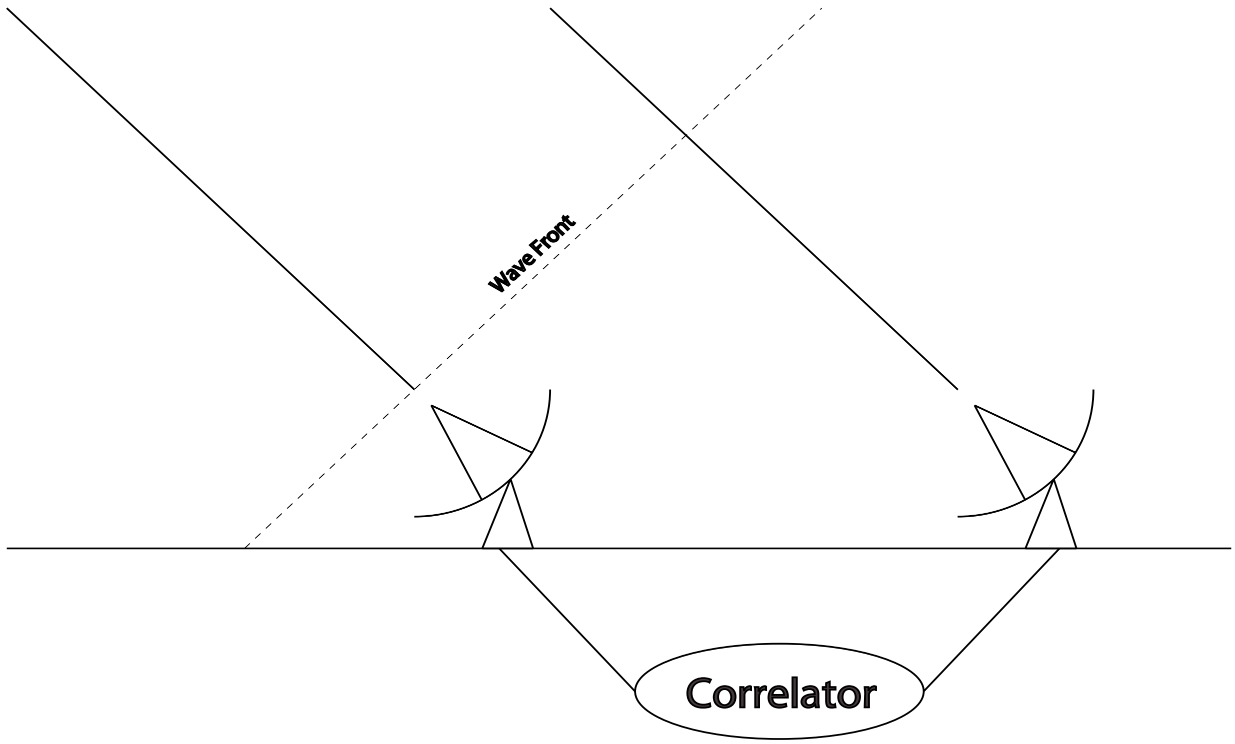

Figure 1: Overview of Interferometry

Figure 1 shows how a front of electromagnetic waves approaches 2 different antennas. The antennas transmit this signal to a correlator where the 2 different pictures are put together to make a larger, more accurate picture of the sky. This can be done with multiple antennas. When all the pictures for one image are taken at the same instant, that image is much clearer than if the pictures are taken at varying instants in time. The goal is to get the pictures making up an image taken at precisely the same instant. Since that is not feasible, the next goal is to get the pictures taken at nearly the same instant in time. These pictures are put into a correlator which produces the images that we can observe. By using antennas in this manner, the array can achieve the same directivity as an antenna large enough to encompass the area spanned by all the antennas in the array.

In order to process the signal received by each antenna, the signal is sampled and quantized at evenly spaced time intervals. The exact time the signal is sampled must be known. It is therefore necessary to provide some mechanism to ensure the samples are taken at known times. These samples are later correlated utilizing the time stamp information to generate a single image. If the antennas are physically close to one another, it is feasible to transmit a timing signal from a central location that can be used to time the samples taken at each antenna. Otherwise, the signals received by each antenna can be transmitted to a central location to be sampled.

If the antennas in the array are not located close enough together such that a physical medium can be used to transmit signals from the antennas, numerous problems arise. Some mechanism must exist to ensure that the samples are taken at known times. In addition, the data collected must be transferred to a central location for correlation. The use of radio communications provides its own distinct problems. The most substantial problem is the unpredictable dispersive nature of the atmosphere. A signal transmitted through the atmosphere will travel at a slightly unpredictable velocity. It is therefore impossible to know exactly when a received signal was transmitted. In addition, it is much more difficult to transmit data wirelessly, let alone achieve similar bandwidths to that achieved over a physical media.

There are a few alternatives to real time communication between antennas in an array. One option is for a very accurate clock to be placed at each antenna in the array. This clock will determine when the samples should be taken. The value of the samples can then be recorded on a physical medium like tapes. This medium would then be shipped to a central location for correlation. However, this requires that a physical disk or tape be present at each location, and a physical site must exist to correlate the tape data.

3.2. The National Radio Astronomy Observatory

The National Radio Astronomy Observatory is a facility of the National Science Foundation and is operated by the Associated Universities, Inc., a non-profit research organization. The NRAO provides state-of-the-art radio telescope facilities for use by the scientific community. They also design, build, operate and maintain radio telescopes for that same purpose.

The NRAO has long been working on observing the stars and improving methods which allow for increasingly accurate analysis of astronomical phenomena. In order to do this, the NRAO has established the Very Large Array (VLA) and the Very Long Baseline Array (VLBA). The VLA consists of 27 antennas in a "Y" formation. The VLBA consists of 10 antennas, located throughout the northern hemisphere. These impressive tools use the combined power of all 37 antennas to create a single antenna with a radius of nearly 5000 miles. This allows a resolution of milli-arcseconds to be obtained in astronomical observations.

The VLA functions in the manner of the system shown in Figure 1. The wave front reaches each antenna where it is received. This signal is then sent to the correlator, along with a time stamp. The time stamp tells the correlator when this picture was taken so the correlator can put the correct pictures together in order to form each image. The time stamping can only be done if a very precise oscillator is used to measure time. Unfortunately, when dealing with the minutiae of astronomical observation, time stamping to the level of minutes and seconds isn't nearly good enough. For the purpose of the VLA, nanoseconds and picoseconds are the correct time scale. In order to do this, the antennas measure time using a hydrogen maser. Since all of the antennas of the VLA are in close proximity to each other (22km), they are all connected to the same central oscillator. This allows the NRAO to save money by not purchasing a maser for each antenna.

The VLBA, on the other hand, works in a slightly different manner. The wave fronts reach the antennas just like they do at the VLA, but each antenna is too far from the VLA central station to be able to have one central clock. Therefore, each antenna has its own hydrogen maser. These masers are synchronized approximately every 30 minutes so that when the tapes containing the data and the time stamps are sent back to the correlators, the pictures can be made into very clear images.

In order to increase the resolution of this important tool, the NRAO has a new project: the EVLA. There are two phases of this project. Phase 1 includes renovations to the VLA. This requires removing all of the waveguide and replacing it with fiber, as well as modernizing the electronics infrastructure. Phase 2 of the project, dubbed the New Mexico Array (NMA), includes the addition of 8 radio telescopes to the existing VLA. This will increase the radius of the VLA from 27 miles to almost 250 miles. The NMA expansion will increase the resolution of the VLA from .04 arcseconds to .004 arcseconds at 50 GHz.

3.3. Time Synchronization for the NMA

Part of the phase 2 expansion includes the design and installation of a time synchronization system. The time synchronization system that will be used in the phase one expansion of the VLA can not be used over distances longer than 50 kilometers. The dispersion and attenuation of the signal over such distances would result in the loss of too many data. Such a system would require 2 fiber lines as well as amplifiers in order to make the plan work.

There has been a massive amount of research done for this project and projects of the same caliber in the past. The options investigated by group 5 are described below.

3.3.1. Hydrogen Maser at each site

The VLBA uses a hydrogen maser placed at each site to time stamp the signals received. The masers are synchronized using astronomical source referencing. In this method the antennas of the VLBA focus on a known astronomical source and synchronize their oscillators based on the emitted signal of the source. This synchronization is done multiple times a day, and requires the high stability of the hydrogen masers to be effective

The stability of a hydrogen maser is 1fs/day for frequency drift and the frequency stability is 0.2 ps. This is a very good system for keeping time since the masers are so stable, but the expense of multiple hydrogen masers mandates that other options be explored.

3.3.2. Alternative Oscillators

With hydrogen maser oscillators currently in place in high performance time-synchronization systems such as that of the VLBA, the question arises as to whether a different kind of oscillator could do the job equally well at a lower cost.

The National Institute of Standards and Technology (NIST) develops and operates standards of time and frequency and maintains the primary frequency standard for the United States. The NIST is at the cutting edge of research in support of improved standards and services. This includes improvements on current oscillator technology as well as the development of new oscillator technologies. The current time standard operated by the NIST is a cesium fountain oscillator, which is more accurate and stable than a hydrogen maser but it is also more expensive. The latest research involves variations on the cesium or rubidium fountain oscillators and optical clocks based on laser-cooled atoms and ions. These new technologies show great promise for accuracy and stability improvements. Unfortunately, they are still in the experimental stage and therefore cannot be considered as available hydrogen maser alternatives.

3.3.3. Quantum Entanglement

As interest grows and research progresses in the field of quantum mechanics, the phenomenon of quantum entanglement may become well suited for time synchronization purposes. Quantum entanglement is a term used to describe the potential for a correlation between two parts of a whole. For instance, two subatomic particles can interact with one another thereby becoming a system such that they remain under each other's influence, even when separated by great distances. If one object is observed, the other object behaves as if it were observed. This applies over any distance and occurs instantaneously. There are no known signals involved in transmitting the information regarding the state of the particles. After the observation of one of the particles takes place their mutual influence on one another breaks down.

Jonathan P. Dowling, a scientist at Jet Propulsion Laboratories in California, has proposed a method of synchronizing clocks using entangled particles. Basically, the plan would involve entangling two particles and sending them to remote clocks requiring synchronization. When one of the particles was observed at one clock, the particle at the other clock would instantaneously behave as if it were observed and the clocks could be synchronized at that moment. This method could possibly be used to circumvent the use of costly, high-performance oscillators by synchronizing less stable oscillators repeatedly in a short time period.

Unfortunately, the current state of research into quantum entanglement does not currently allow for a practical time synchronization system. However, the advances that must be made in order to realize a quantum entanglement time synchronization system could also prove useful for the further development of more conventional methods.

3.3.4. Two Way Satellite Time Transfer

One accepted method of time synchronization involves the use of round trip satellite transmission. This methodology utilizes orbiting satellites to distribute time signals to remote locations from a base station. There has been a large amount of research in this area, and the techniques are used in practice in numerous systems. S. H. Knowles, et. al., discuss the use of round trip radio signals to synchronize VLBI systems in their paper, entitled “A Phase-coherent Link via Synchronous Satellite Developed for Very Long Baseline Radio Interferometry.” In this paper Knowles discusses the use of a round trip radio signal to measure and compensate for phase differences in local and remote oscillators. Similarly, Paul Koppand and Paul Wheeler, in their paper “Working Application of TWSTT for High Precision Remote Synchronization,” discuss the use of Two Way Satellite Time Transfer (TWSTT) to synchronize the standard clocks of the United States Naval Observatory (USNO). The systems have proven very successful in the synchronization of clocks needing high accuracy. However, these systems, despite their accuracy, do not at the present time provide the needed level of accuracy that is required for the EVLA expansion. The system described by Knowles provides for time synchronization on the order of 300ps. Similarly, the USNO system provides for synchronization on the order of 1ns. However these numbers, while impressive, do not reach the required stability of 1.4ps needed for time synchronization in the EVLA.

Though Senior Design 5 chose not to pursue the satellite time transfer technique, research in this area is continuing. Of particular interest is the work of Joesph Bardin, graduate student at the University of California-Santa Barbara. Bardin proposes a TWSTT system using a two-tone transmission, with phase differences between the two tones used to correct the local oscillator references. Bardin believes that phase synchronization on the order of 2 ps could be achieved utilizing this system.

Joe Bardin's work makes a strong stand for using orbiting satellites in order to synchronize the antennas. But it does bring up many problems. First, the signal must be transmitted from an earth station to the satellite and back again. Since it is not practical to house an accurate time keeping device in the satellite due to the power and size considerations, the timing signal must be sent from earth and retransmitted by the satellite back to earth. In order to make the system work, Bardin suggests sending two signals of different frequencies on top of each other to ensure proper observation of any anomalies during the propagation of the signal. This technique requires a continuous microwave link to maintain a high degree of coherence between the signals generated on the satellite, and the signals generated at the ground station.

The specific advantages to the satellite synchronization system is that it scales well over varying distances, a large advantage in the case of the NMA, and that research has been done on this project.

3.3.5. Astronomical Source Referencing

Astronomical Source Referencing is a method of synchronizing clocks by focusing a small auxiliary antenna on a reference astronomical object. The signals being emitted from the reference objects have been well characterized, and can be used to calibrate a local oscillator at each antenna site. Currently, astronomical source referencing is used to periodically synchronize hydrogen masers for the VLBA. Continuous astronomical source referencing could allow us to forgo the hydrogen maser, and instead make use of a cheaper oscillator.

The disadvantages of this system are that each site would require a separate antenna exclusively for oscillator synchronization. This may cost more than a maser, as well as taking more time to construct and implement. Since there are more moving parts, this system may be prone to more mechanical maintenance issues.

3.3.6. Global Positioning System

A system based on GPS was explored. GPS systems utilize an accurate time synchronization system to allow receivers to determine their geographical location. The military uses this system to aim their weapons and communicate with outlying military posts. The military bands are protected by Selective Availability which causes the frequency to vary slowly. Military bands have an accuracy of 10 ns, but with Selective Availability turned on, accuracy decreases to 100ns. Our research has shown that GPS stability is limited to approximately 100ps, far higher than the needed 1.4ps stability. For this reason the option was disregarded.

3.3.7. Fiber Optic Time Synchronization

The final methods examined herein are those utilizing fiber optics to transmit time synchronization data from the base location to the remote antennas. For the purposes of this project the team has selected a fiber optic system to distribute a local oscillator signal to the remote antennas in the NMA setup. This choice was made after a very extensive literature search. Many of our references have come from past work completed at the NRAO. One primary source for information is memo 44 of the EVLA project, "Operational Performance of the EVLA LO [Local Oscillator] Round-Trip Phase System." In this memo Steve Durand and Terry Cotter of the NRAO discuss the creation of a round trip fiber optic LO distribution system for phase one of the EVLA project. Their research discusses the requirements for radio astronomy, and provides for a round trip system using unidirectional transmission of light down a fiber loop. This memo provides us with a basic system for LO synchronization. However, the system as proposed will only work for short range synchronization. Nevertheless, the basic concepts laid out in this memo have been of invaluable use in creating a long range LO synchronization system.

Fiber optic systems are an effective means of communication. However, there are challenges to creating a quality fiber optic system. Over longer distances, attenuation causes the strength of the signal to fall off. In order to continue propagating the signal, an amplifier must be used. Normal electrical amplifiers will introduce large amounts of noise to the signal. The project requirements will not allow for such large noise problems. In order to combat this problem, an optical amplifier must be found that meets the requirements.

There are two basic design choices when considering a fiber optic time synchronization system:

3.3.8. Double Fiber

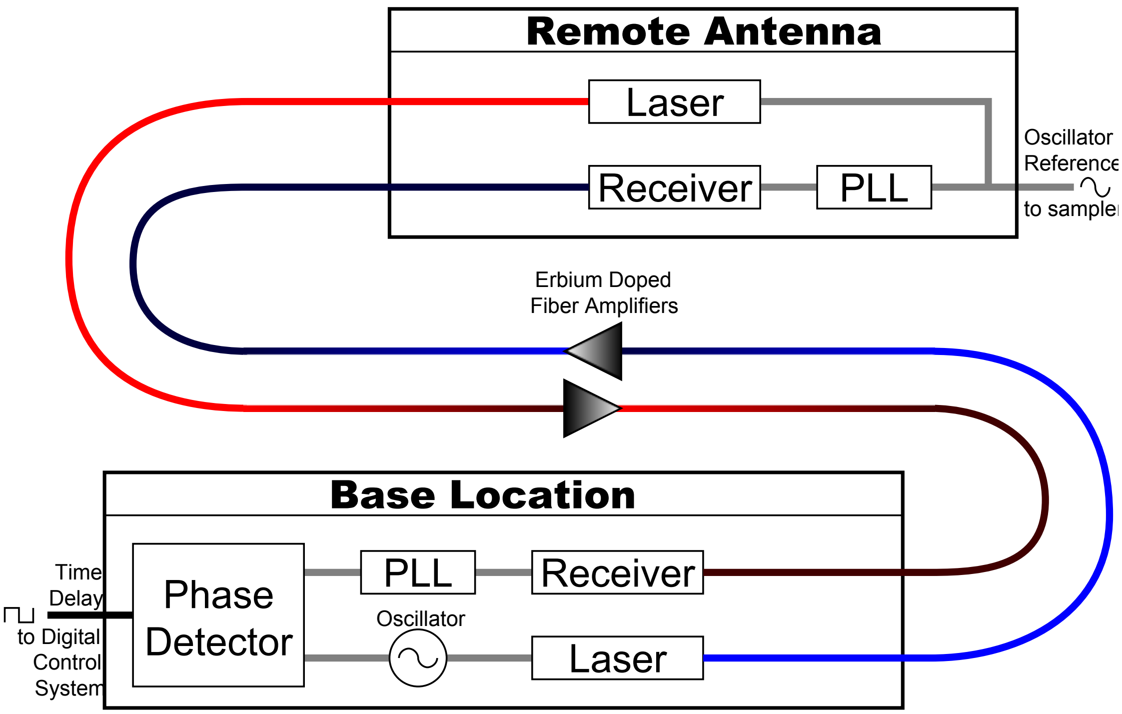

Figure 2: Double Fiber Synchronization System

This system works much like the TWSTT linkage described previously. Two fiber lines are laid from the base location to each antenna. The first line is used to send the local oscillator signal to the antenna. This signal is received and relayed back to the base location on the second line, where the phase of the original signal is compared to the phase of the received signal. The phase difference is used to determine the time it took for the signal to reach the antenna. This can be used to determine when a signal was received.

This system is very similar to that used by the NRAO to synchronize the VLA. However, in the case of the NMA expansion, the cost of leasing two fiber lines to connect each site to the VLA control center is cost prohibitive.

3.3.9. Single Fiber

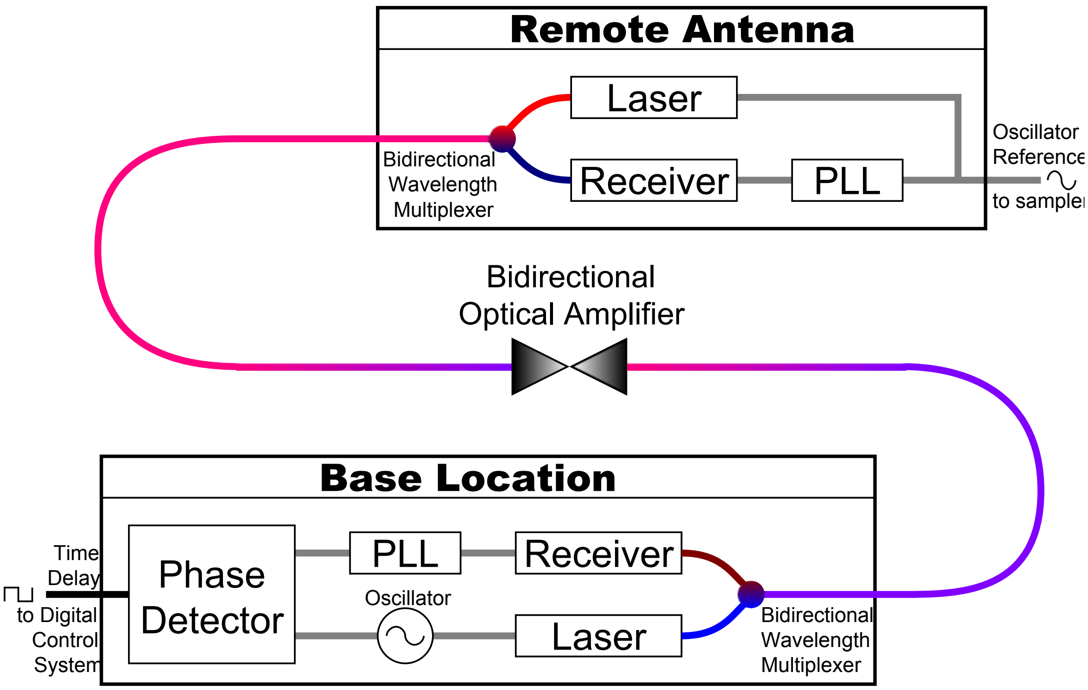

Figure 3: Single Fiber Synchronization System

This method works similarly to the double fiber method but at roughly half the cost. In the single fiber system, a single fiber is used to transmit the oscillator signal from the base location to the remote antenna, as well as to transmit the return signal from the remote antenna to the base location. Since only one fiber is laid and both signals are sent on the same line, the cost of an additional fiber is removed.

The advantages of the direct fiber links are that fiber is available and will be used for data transfer. In the case of the NMA, the fiber will be used to transmit data from the remote antennas to the VLA control center. Since the fiber is already available, this is a very cost effective method. All of the necessary components for this type of system such as amplifiers are necessary for aspects of the project other than ours, which means that these parts would be available for testing.

4. Fiber Optics: A Technical Background

Fiber optic communication system is similar to other types of communications systems. It contains a source, transmitter, transmission medium, receiver, and destination. Typically an electrical signal is modulated onto an optical carrier, which may be a laser or a light emitting diode. The signal is then put onto an optical fiber medium for transmission. The receiver then converts the optical signal back into an electrical signal using a photodiode and sometimes a phototransistor.

Optical signals can either be analog or digitally modulated Analog modulation is easier to implement but is less efficient and requires higher signal to noise ratio at the receiver. For these reasons analog signal links are generally limited to shorter distances and lower bandwidths.

4.1. Advantages

Optical fiber communication systems have several advantages. Fiber optic systems have the potential for wide bandwidths allowing for greater information capacity. Losses in wideband cable systems at bandwidths over one hundred megahertz restrict the transmission distances to a few kilometers. Fiber optic systems typically operate in the 10^{13} to 10^{16} Hz range and allow wideband transmission distances beyond 20 kilometers without additional amplifiers or repeaters.

The diameter of optical fibers are often no bigger than a strand of hair which is considerable smaller and lighter than corresponding electric cables.

Since the optical fibers are fabricated from glass or plastic polymers and thus they are good electric insulators and perform well in electrically hazardous environments. Also fibers provide a dielectric waveguide, which gives freedom from electromagnetic interference (EMI), radiofrequency interference (RFI), or switching transients. Optical fibers are also not susceptible to optical interference from other fibers and so crosstalk from multiple fibers is negligible.

Progressive work on optical fibers has resulted in fibers that have very low attenuation or transmission loss as compared to the best electric transmission cables. With losses as low as 0.2dB km^{-1} long transmission distances without intermediate repeaters or amplifiers is possible. Optical fibers are manufactured with very high tensile strengths that allow twisting and bending to small radii without damage.

4.2. Optical Waveguide

Fiber consists of a core with a constant refractive index surrounded by cladding with a slightly lower refractive index. This is known as step index fiber. Multimode step index fibers allow the propagation of a finite set of modes to be passed thru the fiber. The number of modes is dependent on the physical characteristics of the fiber. A disadvantage of multimode fiber is that different modes propagate at different velocities causing delays at the reception of the signal(s).

Single mode step index fiber allows only one mode to pass thru the fiber. Since single mode fiber allows only one mode, propagation delays are not an issue. The biggest difference between multimode and single mode fiber is the diameter of the core and cladding. Multimode fiber has a significantly larger core than single mode fiber. The diameter of the core is in relation allowing multiple or single modes to travel on the fiber.

4.3. Transmission Characteristics

Attenuation largely determines the distance over which optical signals can be sent without intermediate amplifiers or repeaters. Loss from attenuation can be influenced by material composition, material preparation, purification techniques, waveguide structure, connectors and splices.

5. System Design

5.1. Rationale

The primary purpose of this project is to provide a less expensive solution to a hydrogen maser for time synchronization. The fiber link has the potential to cost substantially less than any of the possible solutions capable of matching the specifications.

All of the antennas in the New Mexico Array will be connected to a central location via a dedicated fiber optic link. The link will be used to transmit in real time the digital data sampled at each antenna to a correlator. This project will strive to place the time synchronization signals and the digital data on the same fiber. If this can be achieved, it is expected that transmitting the time synchronization signals will add a nominal cost to fiber transmission system as a majority of this cost is leasing the fiber cable.

5.2. Proposed NMA Fiber Design

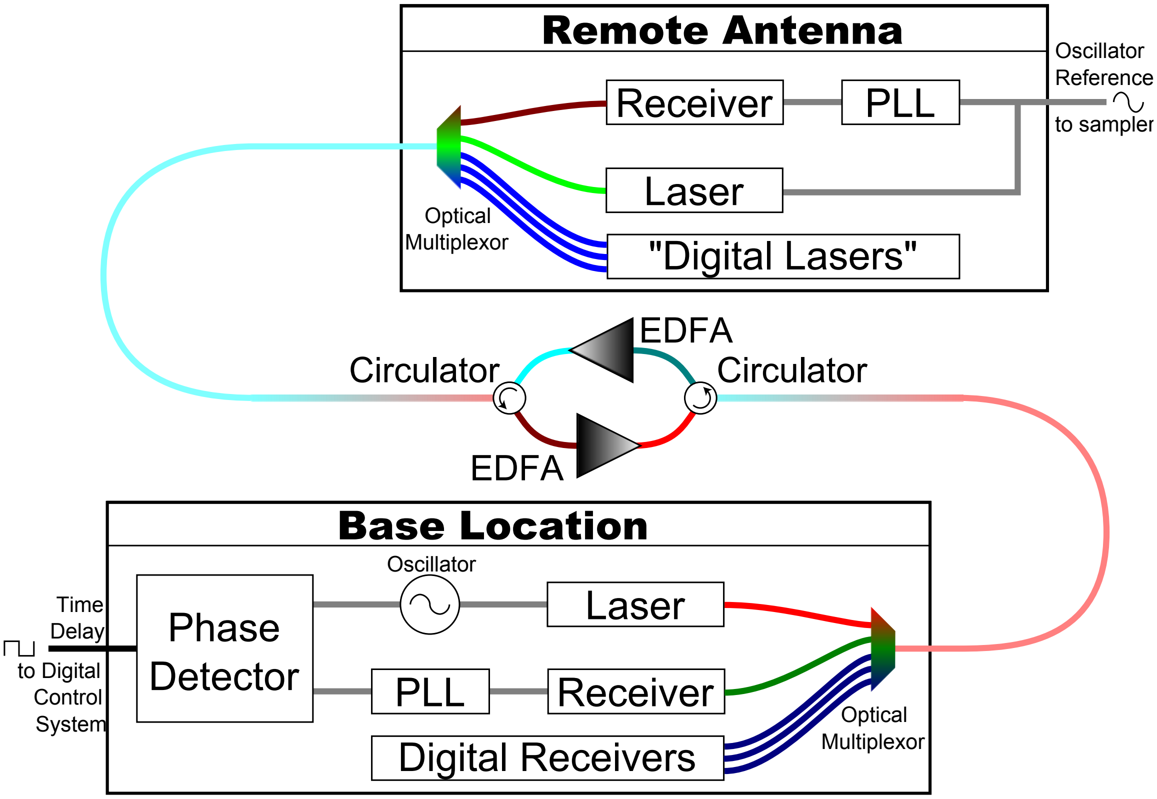

Figure 4: Overall System Design

The system begins with a stable 512 MHz local oscillator at the base location. The signal generated by the oscillator is fed to an analog-modulated laser, which transmits a modulated signal. This signal passes through a multiplexor onto the fiber line and is transmitted to the remote station. While on the fiber the signal must pass through an erbium doped optical amplifier to increase the signal power, which has attenuated over the distance of fiber. The signal arrives at a multiplexor at the remote antenna, and is split off to the receiver. The 512MHz optically modulated signal is converted to an electric signal by the receiver, and used to train a phase locked loop that will serve as the local oscillator for the antenna. This signal is also used to modulate a laser located at the antenna. This signal is then transmitted to the multiplexor at the remote antenna, where it, along with the digital data generated by the antenna, is placed on the fiber for the trip to the base location. On the return trip the signal will be amplified. It will then arrive at the base location, and will be split by the multiplexor at the base location and sent to the receiver. The signal received by the receiver will train a phase locked loop (PLL) at the base location. The phase detector will then compare the phase of the local oscillator with that of the PLL. This will allow for corrections due to changes in propagation time.

This design will multiplex all of the time synchronization and digital signals on a single fiber. In order to achieve this and ensure the signals do not interfere with each other, the signals must be transmitted at different optical frequencies, including those propagating in opposite directions. Therefore it is necessary that the signal received at the antenna is demodulated, passed through a phase lock loop (PLL) to clean up noise, and then retransmitted at a different optical frequency back to the base location. In addition the transmitted and received signals must be combined onto a single fiber. The distance the signal must travel for the NMA is much greater than the VLA. It will therefore be necessary to place optical amplifiers capable of amplifying signals traveling in both directions along the fiber.

5.3. Amplification

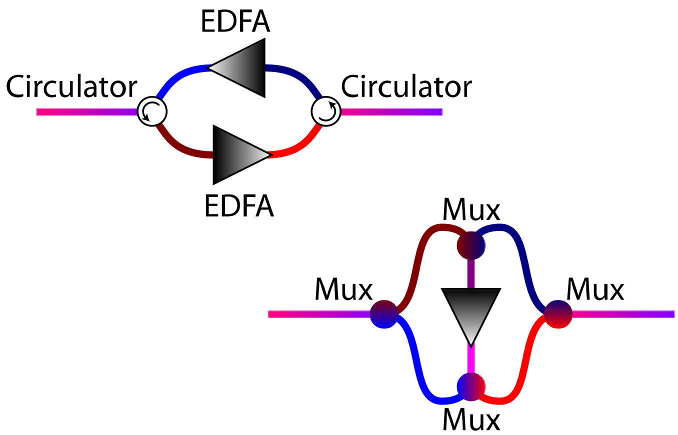

Figure 5: Two different amplification schemes

A few viable methods exist for amplifying a bidirectional optical signal. The most flexible in terms of bandwidth transmitted each direction utilizes two erbium doped fiber amplifiers (EDFA) and two optical circulators. The circulator divides the bidirectional signal on one fiber into two fibers, one for each direction. Once split by the circulators, a different EDFA can be used to amplify the signal in each direction. A less expensive alternative utilizes multiplexors in a configuration that places all the signals to be amplified on one fiber. The output of the EDFA is then split sending part of the signal in each direction.

5.4. Optical Isolation

In order for the round trip phase system to work properly, the signals multiplexed on the fiber optic cable must not interfere with each other significantly. Signal crosstalk could make it difficult or impossible to measure the phase difference between the transmitted and received signals at the base station. Crosstalk could also interfere with the PLL's ability to lock on to the received signal at the antenna. Because of these possible problems, the time signals need to be isolated by 60-70dB.

Careful selection of system components will assure sufficient isolation of the sent and return signals from each other as well as from the digital data.

5.5. Design Details

One of the major components of the proposed fiber optic solution is the actual fiber optic link itself. To save cost, attempts will be made to utilize the same fiber that will be used by the NRAO in their digital communication system that is planned for the NMA. Therefore, the system is designed to function on 9/125 single mode fiber. The term "9/125" describes the physical dimensions of the fiber. In this case, it means that the core of the fiber is 9 micrometers in diameter, and the cladding is 125 micrometers in diameter. This is a common fiber used for long distance communication. The fact that it is single mode means that modal dispersion is not an issue.

Signal transmission will be done in the fiber optic "C-Band," which is centered at 1550 nm. This band was selected by the NRAO due to the low attenuation at this frequency. The fiber used at the NRAO has attenuation rates of approximately 0.3 dB/km.

As discussed earlier, the location of the furthest antenna in the NMA will be 250 km from the base location. However, since the fiber is being leased from local phone companies, the route to the antennas is not direct. Therefore, the longest actual fiber path may be between 500 and 600 km.

5.6. Design Challenges

The use of fiber as the transmission media presents some challenges to the system design. The first major issue is that of attenuation. Although attenuation is minimized at 1550nm, it is still an issue. To ensure that the signal strength is enough for proper detection of the transmitted signal, a signal amplification system will be required. The amplifiers will increase the power of the signal, allowing it to go longer distances. However, the amplifiers may introduce noise and reflections into the system, which will have to be either removed or accounted for.

Second, temperature changes in the fiber must be accounted for. Changes in temperature can vary the length of the lines, causing contraction and expansion of the fiber. It can also change the propagation velocities of the light, so compensation will need to be done to ensure that the time synchronization system is not affected.

Finally, physical variations in the transmission system must be considered. Primarily, compensation for the motion of the antennas as they search the sky is needed. The motion of the dish introduces noise, and can change the length of the fiber. These issues must be accounted for.

6. System Testing

Due to limitations in time and equipment availability, it became unfeasible to conduct full scale tests of the proposed design. Nevertheless, testing did proceed to validate the basic concept of the time synchronization system.

Our initial tests focused on confirming the functionality and optical isolation of the various components needed to create the time synchronization system. We began by testing the laser, modulator, and analog receiver. We utilized a 640MHz signal for our laser modulation due to the availability of a stable 640MHz oscillator. We confirmed that we were able to accurately modulate the laser and transmit the signal over a fiber.

Our second test was to confirm the optical isolation of the multiplexors. In our initial design specifications, it was suggested that 70dB of optical isolation was needed between our transmitted and received signals to accurately read the data. The lasers available to us necessitated the use of C-band channels 21 and 31 for our laser transmissions. By testing data transmissions through both of these channels simultaneously and analyzing the signals on the spectrum analyzer, we were able to confirm acceptable isolation between the two channels.

Finally, we tested the amplification system. This section of the system was our most problematic, as we had very little information on the amount of phase noise which could be generated by the EDFAs. Our tests suggested that there was little phase noise introduced by the EDFAs. We saw no appreciable phase noise differences between tests using the EDFAs, and tests without the EDFAs. We also confirmed that the circulators used in the amplification system had sufficient isolation between bidirectional signals.

After the individual components were tested, we proceeded to test the system as a whole.

We completed two major tests of the system. The first test consisted of the modulated analog signal and the digital signal being transmitted in the same direction. The analog signal was received by an analog receiver and translated into an electrical signal. This signal was compared with the original oscillator signal using a network analyzer. Analyzing these traces, we were able to view the phase difference between the signals. We were able to show phase fluctuations of ±1 degree at 640MHz. This corresponds roughly to 8-10 picoseconds of phase variance between the transmitted and received signals. Though the scope display indicated the ability to measure resolutions as close as 0.00001 degree, the team feels that this reading is unreliable.

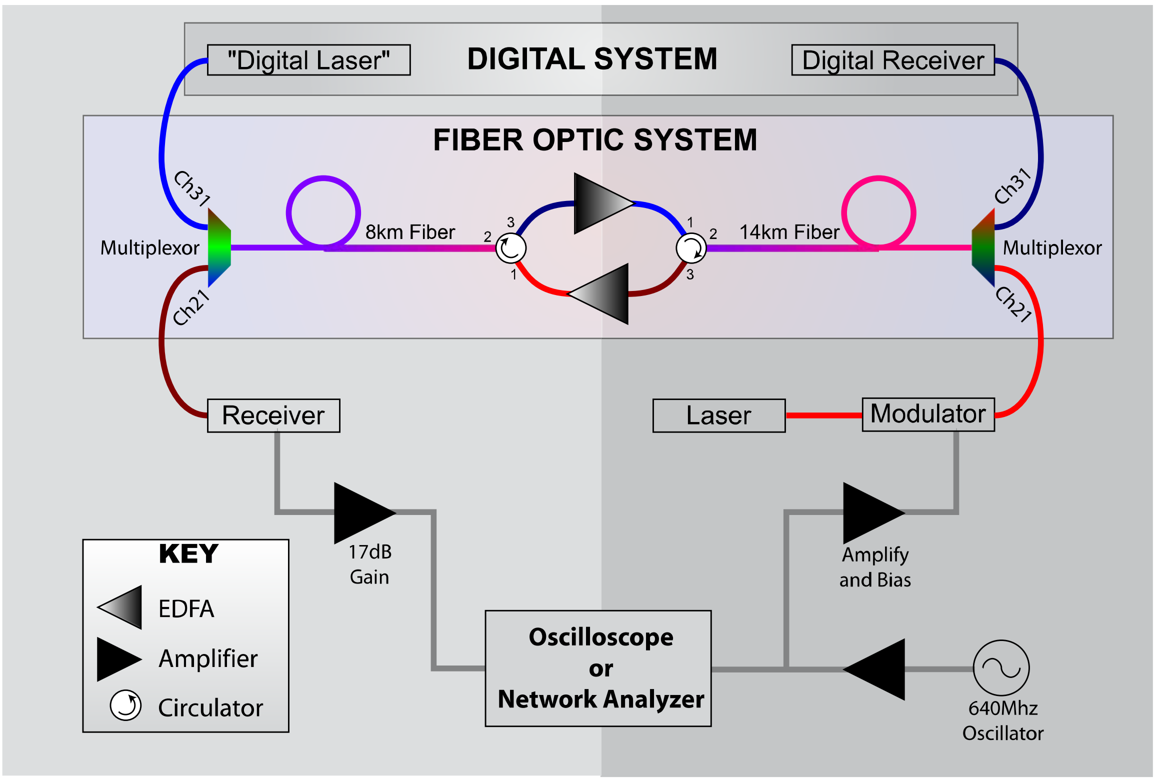

Figure 6: Experimental Setup

In the second test the direction of the digital data stream was reversed, placing it in opposition to the analog signal. The same phase comparison test was run, and no noticeable interference from the digital signal was detected. Again, we measured phase variance of ±1 degree, indicating stability on the order of 8-10 picoseconds.

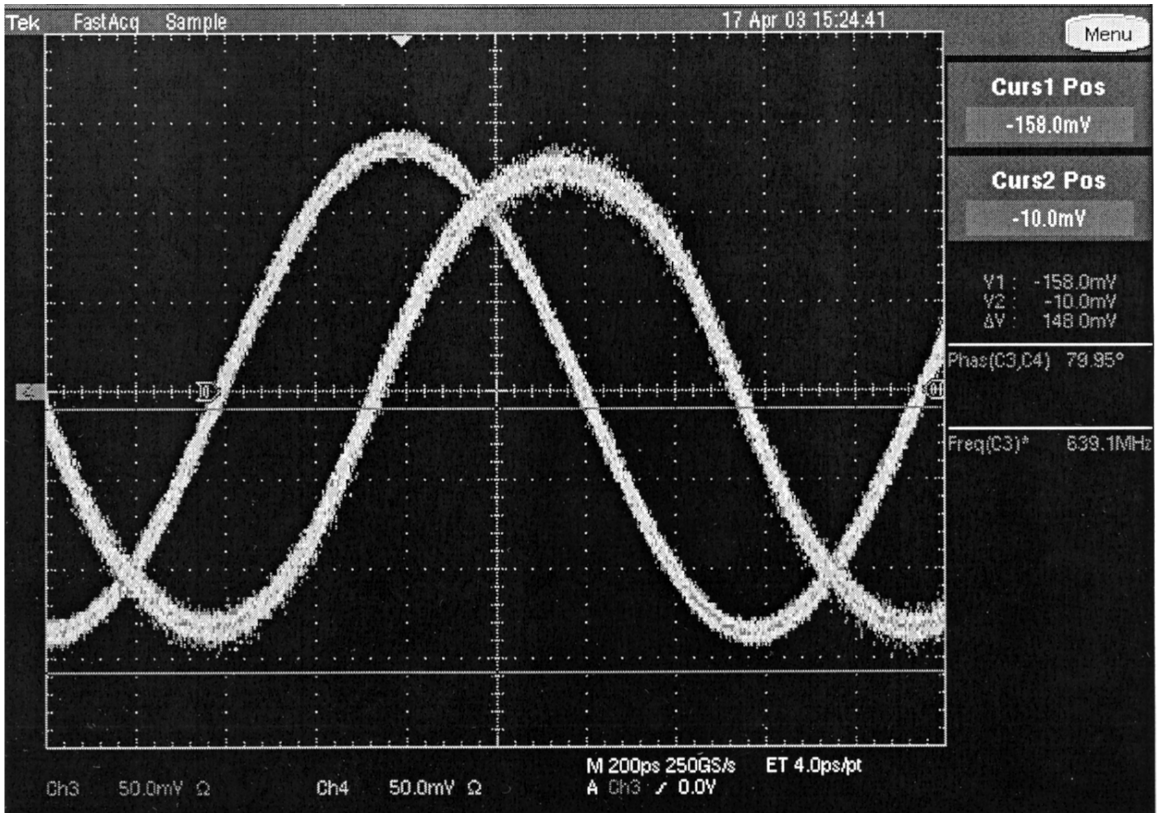

Figure 7: Waveform from oscilloscope

Figure 7 is a waveform from the oscilloscope showing the signal from the oscillator and the signal following transmission. The phase difference between the two signals can be seen on the right side of the image. Constant monitoring of this phase measurement showed rapid fluctuations of ±1 degree. However, we believe much of these fluctuations are the result of noise generated by the oscilloscope. We tested the scope by running the oscillator signal to both inputs simultaneously, and the same level of phase fluctuations were observed.

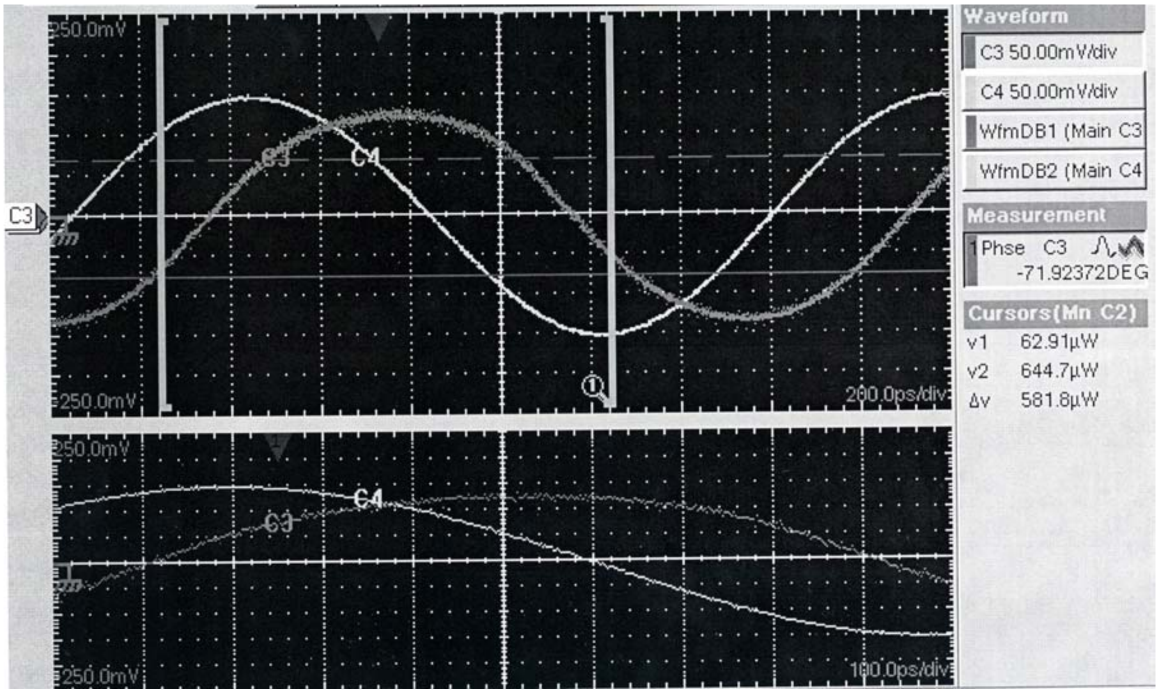

Figure 8: Waveform from network analyzer

Figure 8 is a representative waveform gathered during the system tests. The number seen under the "measurement" tab on the right side indicates the phase difference between the C3 (signal following transmission) and C4 (signal from oscillator) waveforms. Monitoring the changes of the phase angle allowed us to see the phase fluctuations in the system. In the case of figure 8, the data was obtained using a network analyzer, which has a degree of internal averaging and smoothing. This may introduce error to our measurements, as we are seeing an averaged signal, rather than the actual signal. However, it was suggested that the results as viewed through the network analyzer may be closer to the output of the original signal had it been "cleaned" using a phase lock loop. The phase measurement seen on the network analyzer also had the tendency to drift in one direction over time. We believe that this drift was caused by temperature changes affecting the fiber length.

These tests provide interesting results. Though the tests do not demonstrate the stability required by the NRAO (1.4ps), they do indicate levels of stability of 8-10 picoseconds. This indicates that there is a strong possibility of further developing this design into a full-fledged time synchronization system.

The complete analysis of the system was limited by multiple elements. First, our measurements were limited by the equipment used in the tests. The instruments we used introduced their own degree of noise to the system. For example, the oscilloscope introduced a large amount of noise on the time scale that we were examining. The noise, while insignificant in the analysis of digital systems, greatly affected our analog analysis. The laser receiver may also have been a source of noise. Fiber length may also have varied due to temperature. This condition, while addressed automatically in the full two way analog system due to the round trip timing, was an issue in examining the signal sent in one direction. Finally, the team encountered problems predicting the response of the systems to our analog transmissions. Fiber optic equipment is predominantly used for digital transmission, and is ideal for these purposes. Digital signals can tolerate much higher levels of noise than an analog system at our level of precision. In our case, noise that would not even be noticeable in a digital system could affect our analog system greatly.

The isolation between the two channels in our test we believe was not the limiting factor in the performance of the system. But, when placing 12 digital channels in conjunction with the 2 analog channels on a single fiber, isolation is likely to become a substantial concern. To alleviate this problem, two channel bidirectional wide band multiplexors could be used to replace the circulators in the bi-directional amplifier circuit. For even greater isolation, the returning analog signal can be placed in the L-band, requiring an L-band EDFA for one direction. The use of C and L band EDFAs in both directions could provide even greater isolation.

An EDFA will provide a roughly constant total output power across all the channels. This means that adding an additional carrier channel on the fiber will reduce the output power of the other channels given the same output power setting on the EDFA. It is possible that this effect will slightly distort the analog channel amplified by the same EDFA amplifying the other digital channels. This problem is minimized considering the digital signal has been formed to ensure the mean signal value remains half way between 0 and 1.

Our tests didn't reveal any substantial effect other than a reduction in gain caused by the presence of the digital signal passing through the same EDFA as the analog signal. But, it is possible that this effect will become evident after analyzing the signal in more detail in addition to passing it through many EDFAs. A proper configuration of multiplexors could be used to amplify the two analog channels with one EDFA while amplifying the digital channels with another EDFA. Even in this configuration, it is possible that the two analog channels will interfere with each other when amplified by the same EDFA.

7. Personal Contributions

7.1. Jennifer Coleman

7.1.1. NRAO History Research

One of my primary responsibilities was examining the history of time synchronization research performed by the NRAO. The knowledge of this history was a necessity because of integration that will happen between our system and theirs. In order for our system to integrate smoothly, knowledge of NRAO techniques was essential.

7.1.2. Satellite

A second focus of my work was research into satellite systems, in order to consider the feasibility of TWSTT methods. Much of my work involved locating and contacting satellite companies regarding leasing bandwidth on orbiting geosynchronous satellites. However, I was unable to successfully acquire cost and availability information. This became a major factor in the selection of the fiber optic methodology. Despite a lack of concrete data, discussions with other scientists led us to believe that bandwidth was quite expensive, so testing would be expensive and difficult to schedule.

7.1.3. EDFA

It was my responsibility to research different amplifier suppliers and come up with an option that would amplify our signal without adding extra noise. We were able to find quite a few different brands, but the NRAO had a preferred supplier, so we used the ones they ordered for other functions before they were put to use elsewhere.

7.1.4. Population of boards

Once the PCB was designed, it was sent off to be fabricated. When boards are fabricated, they aren't populated. When they came back, it was my responsibility to populate them.

Since our design required a number of surface mount chips, these had to be put on the board first. The NRAO has a machine to glue them on, and once they are glued on, a person can actually solder the leads. Following the chip mounting, I mounted and installed the remaining board components. I also conducted basic tests of PCB functionality.

7.2. Quinn Harris

7.2.1. PCB Design

I designed the laser controller printed circuit board with Protel 99SE. This included creating the circuit diagram for one laser controller. The netlist from this diagram was used to ensure the PCB design was correct.

7.2.2. Diagram Art

I created all the diagrams using Adobe Illustrator 10

7.2.3. Documentation

I assembled the documentation for the PDR and CDR using DocBook. I did not do this for the thesis because it was required in the proprietary Microsoft Word format.

7.2.4. Testing

I helped during the testing.

7.2.5. Design

I contributed to the design of the bidirectional fiber system.

7.2.6. Group Pessimist

I was a continuous source of pessimism for the group.

7.3. George Henckel

7.3.1. GPS

I examined current ideas and methods of using the Global Positioning System as a distributed local oscillator system.

7.3.2. TWSTT

I examined two-way satellite transfer system for use as a distributed local oscillator system. As a part of this I also examined Joseph Bardin's plan.

7.3.3. Testing

I participated in testing the isolation specifications of the multiplexers provided by the NRAO.

7.4. Adam Moritz

My contributions to this project include research into alternative oscillator technology as well as time synchronization through quantum entanglement. In addition, I was the official point of contact for the design group, fulfilling the duties of scheduling meetings, establishing communication with outside parties and distributing information within the group

7.5. Aaron Prager

7.5.1. Fiber Optics

I was responsible for much of the research into the feasibility of the fiber optic system. I researched EDFAs, modulators, and lasers for use in the optical system.

7.5.2. Testing

I participated in the testing of the isolation specifications of the multiplexors, the functionality of the lasers and modulators, and the EDFA noise testing. I also assisted with the test design and construction of our final unidirectional and bidirectional tests.

7.5.3. Design

I contributed to the design of the overall system.

8. Conclusion

Senior Design group 5 was assigned the task of investigating alternatives to a hydrogen maser system for time synchronization. Numerous alternatives were reviewed but one solution utilizing fiber optics stood out as the most viable. Accordingly, the group investigated this solution further, leading to a basic design for such a system. Critical aspects of this design were experimentally tested with promising results. From the research and testing, Senior Design Group 5 has shown that a fiber optic solution similar to the one proposed is a viable candidate to replace a hydrogen maser system.

Further testing and analysis will be needed to ensure a fiber optic solution can meet the requirements for the NMA. This testing would include the addition of a phase lock loop to the system, the output of which would be returned back along the fiber. In addition, the system should be tested with longer fiber runs and the use of multiple bi-directional amplifiers. If successful, these tests would help confirm the practicality of using a fiber optic time synchronization system for the New Mexico Array.

9. Glossary

AOC - **A**rray **O**perations **C**enter; the building that houses scientific, engineering, technical, computer and support staff for both the Very Large Array and the Very Long Baseline Array

Arcsecond - a unit of angular measurement equal to 1/3600 of a degree

Attenuation - a decrease in the amplitude of a signal as a result of propagation through a lossy medium

Circulator - a passive fiber optic three-terminal device including one bidirectional port and two unidirectional ports; used to separate or combine incoming and outgoing fiber optic signals

Cladding - in a fiber optic cable, the protective material surrounding the glass fiber; used as optical isolation and thermal insulation

Core - in a fiber optic cable, the glass fiber used to transmit the optical signal

Correlation - the integration of data from multiple radio telescopes

Correlator - a device used to integrate data from multiple radio telescopes

Demultiplexor (DEMUX) - a passive fiber optic device with a single input port and an arbitrary number of output ports; used to separate combined signals according to wavelength

Dispersion - the process by which an electromagnetic signal is distorted due to the different propagation characteristics of each of the wavelength components of the signal

EDFA - **E**rbium-**D**oped **F**iber **A**mplifier; a device that amplifies a signal entirely in the optical domain, without conversion to electrical signals.

EVLA - **E**xpanded **V**ery **L**arge **A**rray; a project to improve the capabilities of the VLA; consists of two phases:

Phase I - dubbed "The Ultrasensitive Array"; involves infrastructure upgrades to the existing VLA

Phase II - dubbed "The New Mexico Array"; involves the addition of 8 new radio telescopes to the VLA (see NMA)

Hydrogen MASER - a device that utilizes the natural oscillations of hydrogen atoms for amplifying or generating electromagnetic waves in the microwave region of the spectrum; used as a highly precise oscillator reference (**MASER** is an acronym for **M**icrowave Amplification by **S**timulated **E**mission of **R**adiation)

Interferometry - the use of interference phenomena for measurement purposes

Multiplexor (MUX) - a passive fiber-optic device with an arbitrary number of input port and a single output port; used to combine multiple signals, each modulated at a specified wavelength, onto a single line

NMA - **N**ew **M**exico **A**rray; the goal of phase II of the EVLA; 8 new radio telescopes within the state of New Mexico at distances up to 300km from the VLA

NRAO - **N**ational **R**adio **A**stronomy **O**bservatory; a government-funded organization that designs and operates the world's most sophisticated and advanced radio telescopes

PLL - **P**hase-**L**ocked **L**oop; an electronic system consisting of a phase detector, a filter, a voltage-controlled oscillator and sometimes a frequency divider and phase shifter; used for signal cleanup, radio and wireless communications

Radio Astronomy - the study of astronomy using electromagnetic waves with wavelengths ranging from about 1 millimeter to 10 meters

Rayleigh Scattering - the scattering of light by particles smaller than the wavelength of the light; occurs when light travels in transparent solids and liquids, but is most prominently seen in gases; The sky is blue because of Rayleigh scattering of sunlight from the particles in the atmosphere.

Time Standard - a timekeeping system that provides a reference for a radio telescope array

Time Synchronization - a method of maintaining a certain degree of phase-alignment between the local oscillators of multiple radio telescopes

TWSTT – **T**wo **W**ay **S**atellite **T**ime **T**ransfer; a time synchronization method using geosynchronous satellites

VLA - **V**ery **L**arge **A**rray; an array of 27 radio telescopes in a Y-shaped configuration on the plains of San Augustin, fifty miles west of Socorro, New Mexico

VLBA - **V**ery **L**ong **B**aseline **A**rray; an array of ten radio telescopes spread across the United States and its territories from St. Croix, Virgin Islands to Mauna Kea, Hawaii

VLBI - astronomical interferometry using an array of terrestrial radio telescopes separated by great distances

10. References

10.1. Publications

David W. Allan and Marc A. Weiss, "Accurate Time And Frequency Transfer During Common-View of a GPS Satellite," Proc. 34th Annual Frequency Control Symposium, Ft. Monmouth, NY, May 1980.

Joseph Bardin, "Precision Time Transfer Using a Commercial Satellite," University of California-Santa Barbara, 2002.

Barry Clark, "A Satellite LO System," March 2002.

M. Oskar van Deventer, Fundamentals of Bidirectional Transmission over a Single Optical Fibre, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996.

Steve Durand and Terry Cotter. "Operational Performance of the EVLA LO Round-trip Phase System," EVLA Memo Series, NRAO, August 30, 2002.

D.W. Hanson, "Fundamentals of Two-Way Time Transfers By Satellite," 43rd Annual Symposium on Frequency Control, 1989.

James Jackson and Steve Durand, "Operational Performance of the EVLA Digital Transmission System," EVLA Memo Series, NRAO, August 30, 2002.

S.H. Knowles, W.B. Waltman, J.L. Yen, J. Galt, D.N. Fort, W.H. Cannon, D. Davidson, W. Petrachenko, and J. Popelar. "A phase-coherent link via synchronous satellite developed for very long baseline radio interferometry," *Radio Science*, Volume 17, Number 6, pages 1661-1670, November-December 1982.

Paul Koppang and Paul Wheeler, "Working Application of TWSTT for High Precision Remote Synchronization," Proceedings of the 52nd Frequency Control Symposium, 1998.

John M. Senior, Optical Fiber Communications Principles and Practice, Prentice Hall, 1985.

Wavelength Electronics, Specification Sheet "WLD3343 Ultrastable Driver for Laser Diodes," April 2, 2002.

Wavelength Electronics, Specification Sheet "WTC3243 Ultrastable Thermoelectric Controller," January 11, 2002.

10.2. Web Sites

Fred Alan Wolf, Ph.D., http://pw1.netcom.com/~wolfmirror/.

National Institute of Standards and Technology Physics Laboratory Time and Frequency Division, http://www.boulder.nist.gov/timefreq/.

www.galaxyfareast.com.tw/english/service/content/gps_ec.htm

Time Service Department, U.S. Naval Observatory, tycho.usno.navy.mil/maser.html.

Very Long Baseline Array, National Radio Astronomy Observatory, www.aoc.nrao.edu/vlba/

Expanded Very Large Array, National Radio Astronomy Observatory, www.aoc.nrao.edu/evla/

11. Appendix A: PCB

The laser controller board ensures that the lasers receive the appropriate driving current and remain at a specific temperature. A board consists of 3 identical circuits to control 3 lasers. Each circuit contains an thermoelectric controller IC and a driver for laser diodes IC with supporting components.

The schematics design for the laser controller circuit was provided by the NRAO. This design was modeled after the suggested implementations from the specification sheets for the two IC's used. The group developed a printed circuit board design for the laser controller from the schematic design given to us.

11.1. Description

The thermoelectric controller has been implemented with a WTC3243 IC from Wavelength Electronics. This analog device measures the voltage across a current biased thermistor embedded in the laser. A controllable reference voltage established with a potentiometer and a bandgap voltage reference device is compared against the voltage across the thermistor. This difference after integrated is used to control an H-bridge that drives the thermal electric device in the laser. This results in a control loop that ensures the temperature of the laser remains constant.

The driver for laser diodes has been implemented with a WLD3343 IC from Wavelength Electronics. The current to the laser passes through a current sensing resistor. The potential across this resistor in conjunction with an adjustable voltage reference is used to ensure a consistent current is delivered to the laser.

11.2. Calibrating the board

In the time available, limited tests were run in order to find out if the board worked properly as set, and then adjust the potentiometers so that the proper current flows through each component. First the PCB was populated with all of the components except the thermoelectric controllers and drivers for the lasers. Power was applied and all test points were tested for the desired voltages. These were found to be acceptable, so the chips were added to the system and the same voltage tests were run. All voltages were as expected. Since there was a problem with the laser power up sequence, we didn't add the lasers for fear of destroying them. This particular part of the testing will be done after the production of a daughter card (with the purpose of controlling the power up sequence), and will show the functionality of the board.

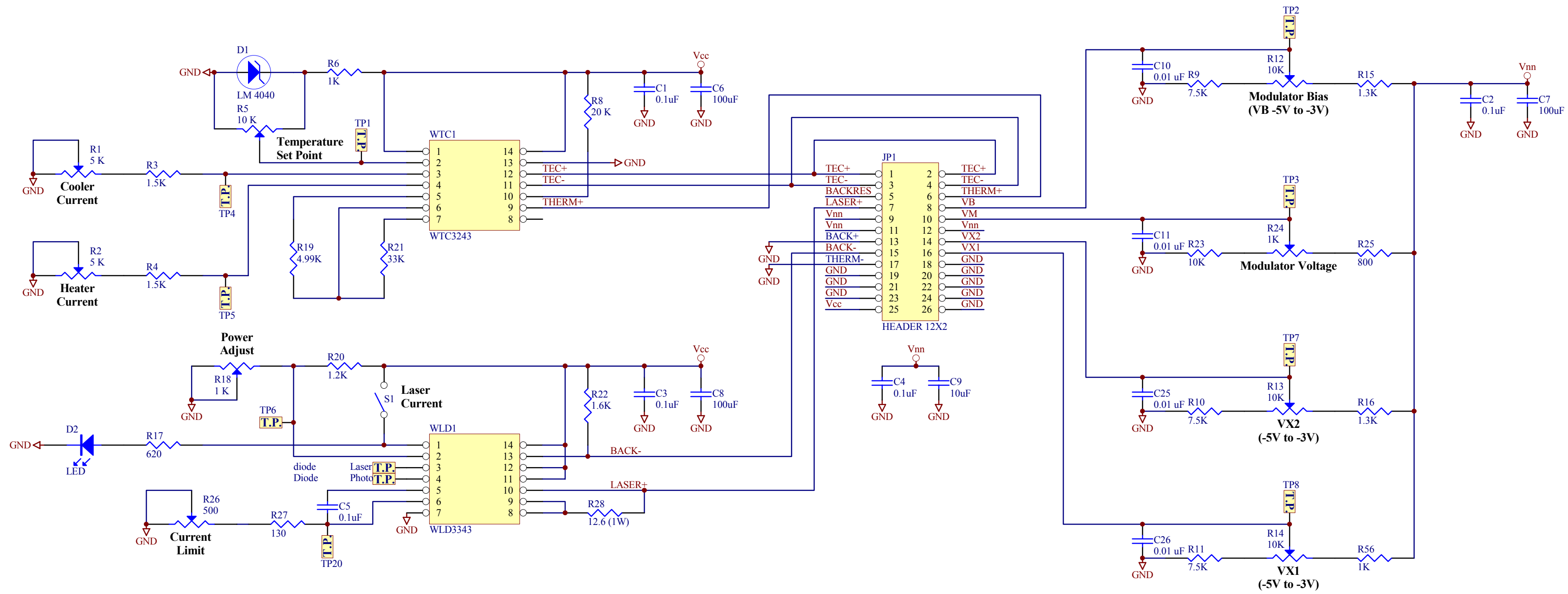

Figure 9: Laser controller schematic

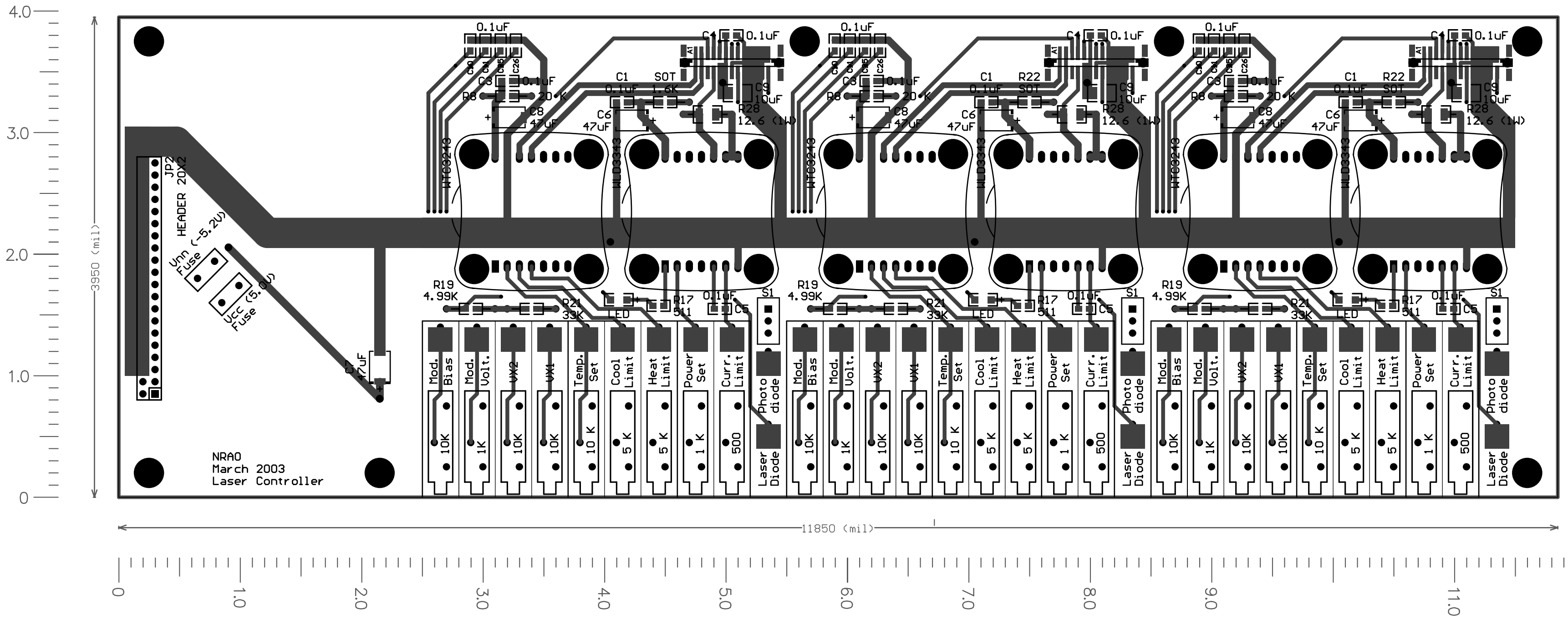

Figure 10: PCB layout, top side

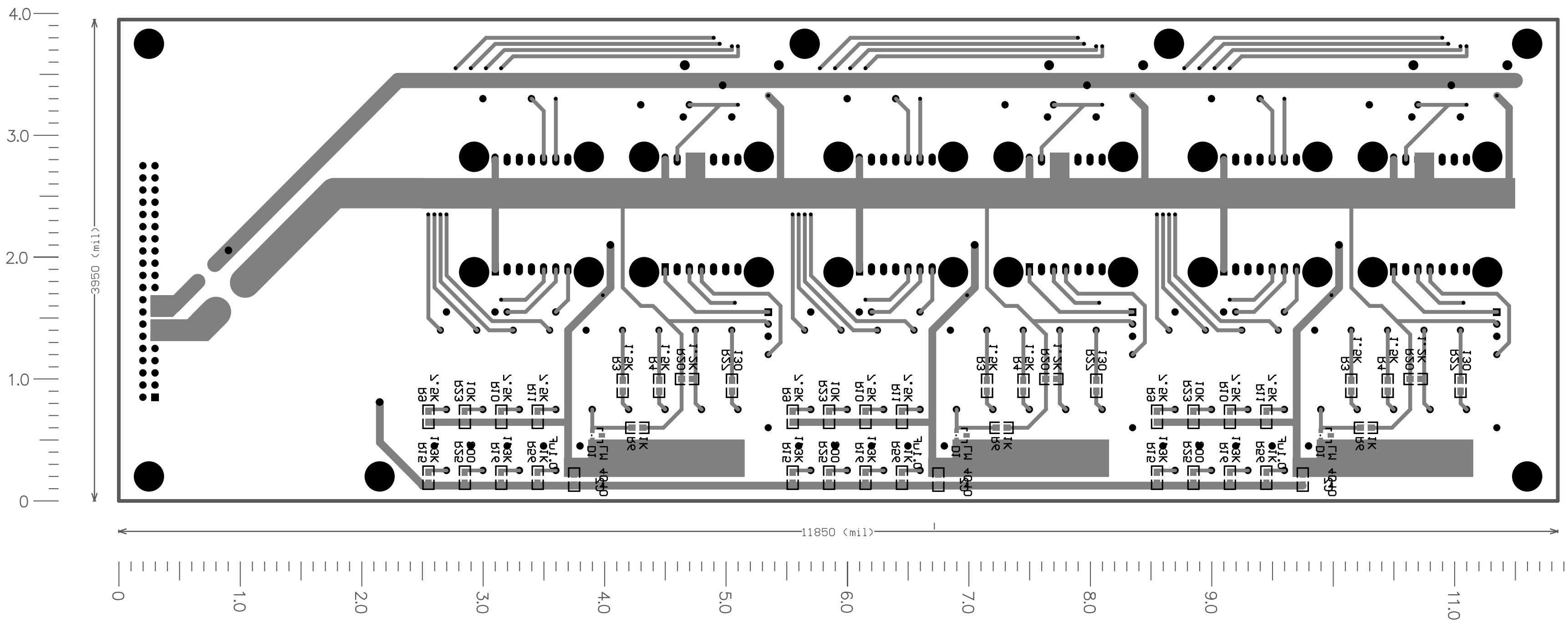

Figure 11: PCB layout, bottom side