RADIO ASTRONOMY AT BRIGHAM YOUNG UNIVERSITY

by

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This thesis has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

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ABSTRACT

RADIO ASTRONOMY AT BRIGHAM YOUNG UNIVERSITY

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Senior Thesis

This thesis is offered as a resource to astronomy students wishing to become more familiar with radio astronomy at Brigham Young University (BYU). A radio telescope array entitled the Very Small Array (VSA) located on the Clyde Building at BYU is the focus of this thesis. Historical uses and descriptions of the VSA and its accompanying equipment, computer programs, and functions are given. Limitations due to the VSA's size and positioning are discussed with an example using the bright radio source Cygnus A. An image of several bright radio sources produced with Matlab programming is given to demonstrate the ability of the VSA. Possible future research uses of the VSA are discussed.

ACKNOWLEDGMENTS

This thesis is dedicated to my husband, Nick, and my son, Joseph. Without their encouragement I couldn't have completed this project. Thank you both.

I would also like to acknowledge the many professors and students who have helped me achieve the completion of this research thesis: namely Dr. Eric Hintz, Dr. Karl Warnick, Dr. Brian Jeffs, Jacob Campbell, Jonathan Landon, and James Nagel. A special thanks goes out to my cousin, Micah Lillrose, who first got me interested in the project and who has helped and encouraged me every step of the way.

Finally, I want to thank all of my family members and friends who have supported me in this last step to completing my degree. I love you all.

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Chapter 1

Introduction and Background

1.1 History of the Very Small Array

A small array of radio telescopes was first used by the Electrical Engineering Department at Brigham Young University (BYU) to simulate mitigation interferometry and solve the problem of radio frequency interference (RFI). There are two separately operated arrays used by the research group in the department, both of which are located on top of the Clyde Building on BYU campus. The first array features three antennas and sits above the fifth floor on the upper-most roof. This array is currently functional but unused by either the Electrical Engineering or Astronomy Departments. Another array, known as the Very Small Array (VSA), has four antennas and is located a floor below on the fourth floor roof. It is this second array that is the primary focus of this thesis.

Jacob L. Campbell, a past Masters student working on the array, is responsible for the construction of the VSA under the direction of Dr. Brian Jeffs and Dr. Karl Warnick. His Masters Thesis entitled *The Development of a Small Scale Radio Astronomy Image Synthesis Array for Research in Radio Frequency Interference Mitigation* is recommended as a source of information regarding details of the layout, design, function and history of the VSA (Campbell (1)). The appendices in his thesis detail the computer functions used to run the VSA at that time, though much of the programming has changed. Still, it remains a good source for understanding the initial use and development of the array.

1.2 Contents of Thesis

With respect to the given status of the VSA, the majority of this thesis is devoted to describing the equipment, its functions, and how to run the array. All of

the equipment associated with the VSA is described in Chapter 2. Chapter 3 lists the most recent step-by-step processes for running the VSA and data acquisition. Limitations of the VSA are discussed in Chapter 4 with an example image of Cygnus A. Chapter 5 details the calibration of the array and describes a project depicting the possible imaging power of the VSA using Matlab programming. This project involves a computer-based image of four bright radio sources and how a calibrated system would image them. Finally, possible research projects using the VSA are briefly discussed in Chapter 6 and the thesis is concluded.

1.3   Research with the Very Small Array

Astronomy research benefits much from the study of electromagnetic sources outside the short visible range including radio wavelengths. Using the VSA for supplementary or conclusive astronomy research is recommended as a possible research venue. This thesis can be used as a handbook for those wishing to familiarize themselves with the radio telescope array as it stands at this point in time. Although much more programming and development is needed for imaging with the VSA, there are other research possibilities available to astronomy students interested in the field of radio astronomy. These are discussed in Chapter 5.

Chapter 2

Equipment

2.1 Overall Layout of the Array

Four radio antennas or dishes comprise the VSA. These four antennas are located on top of the fourth floor of the Clyde Building on BYU campus. A description of the logistics for placing the antennas can be found in Chapter 3 of Campbell's thesis (Campbell (1)).

2.1.1 Equipment from Antenna to Computer

Each antenna is connected in series to several instruments located in the radio research room on the fifth floor of the Clyde Building. From the VSA, the signal acquired from each antenna is passed through a radio frequency receiver (RF receiver) (Figure 2.2), which is also connected to two local oscillators (LO1 and LO2) (Figure 2.3). Before entering the RF receivers the signals from each antenna have frequencies of 1.4 GHz, which are then modified by the LO's to transmit through the rest of the system between 2-3 MHz. From there, the signals are sent through intermediate frequency filters (IF filters) (Figure 2.4). Three IF filters can be used in this setup with bandwidths of 1.25 MHz, 2.5 MHz, and 5.0 MHz. For data acquisition the 1.25 MHz filters should be used because they work the most efficiently. Then the signals are sent through two amplifiers (Figure 2.4) and sent to an analog to digital (A to D) converter (Figure 2.5). This is the final stage before the signals enter the computer for analysis. Figure 2.1 shows the basic setup of the four antennas and each of the components of the array. Besides the LO's and the antennas themselves, the component parts are centrally located in a large black box in the research room as shown in Figure 2.6.
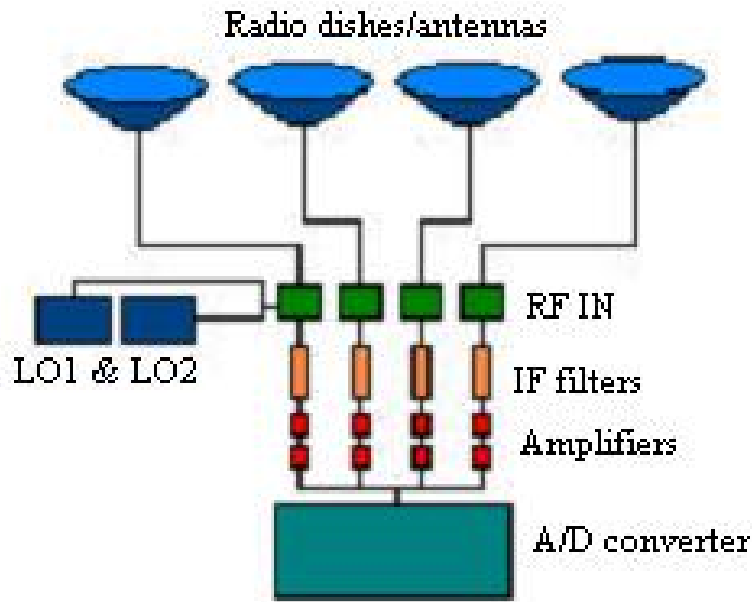
Figure 2.1: The array layout is similar to this, where the signal is gathered by the antennas and is transmitted through each component ending in Computer B.
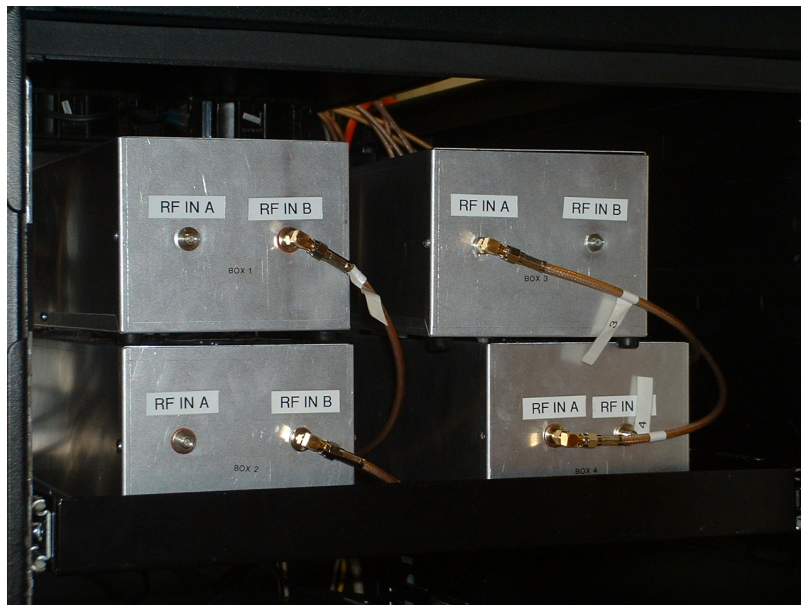
Figure 2.2: The RF receivers are each connected to LO1 and LO2 as well as to the signal feeds from each radio antenna. They are labeled RF IN for boxes 1 through 4, respective to each antenna.

Figure 2.3: LO1 and LO2 are standard signal generators that connect to each of the RF receivers for each antenna.
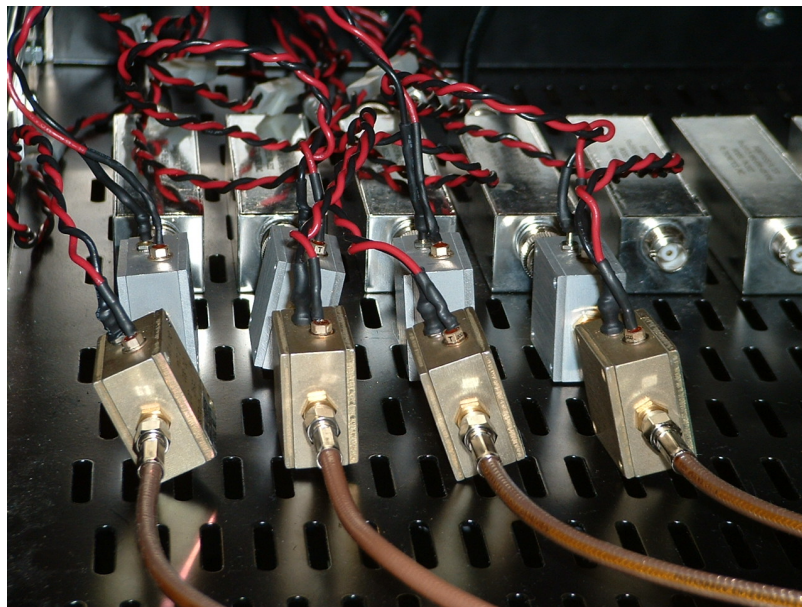
Figure 2.4: Shown here are the intermediate frequency filters (IF filters) and a set of two amplifiers. These are connected in between the RF receivers and the A to D converter.

Figure 2.5: The A to D converter sits below the IF filters and amplifiers. It is the last step before the signals acquired by the radio antennas reach the computer for processesing.

Figure 2.6: Many of the components of the array are located in a large black box located at the back of the research room. This is also the site for Computer B. This figure shows the layout from inside the front panel of the box.

2.2 Computers

Two different computers run the array. One controls the movement and tracking devices of the four dishes (Computer A). The second computer is found at the end of the signals' journeys from antenna to computer, both acquir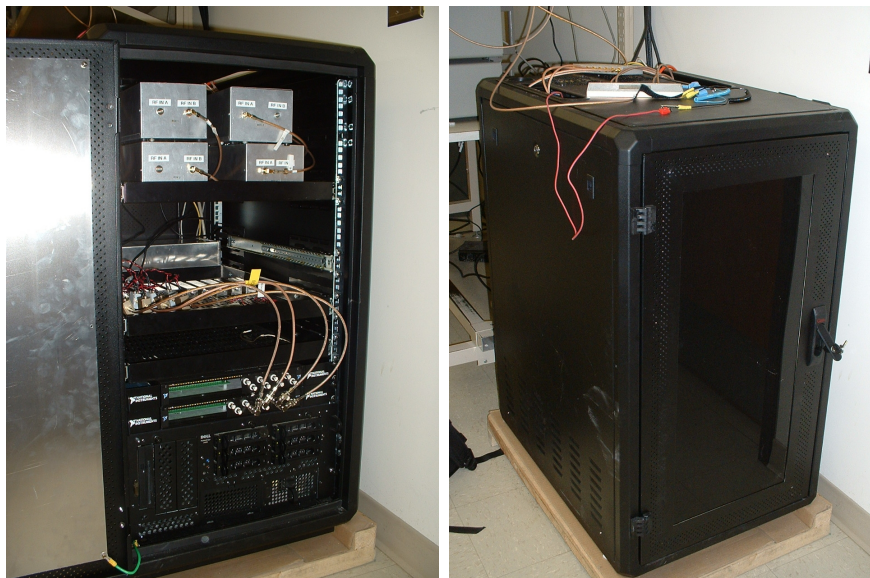ing and analyzing the signal input (Computer B). Programs on each of these computers in Matlab and Labview allow the array to function. Computer B is found within the large black box that contains the RF receivers, IF filters, amplifiers and the A to D converter.

2.2.1 Azimuth and Elevation Control Boxes

Computer A (Figure 2.7) works with twelve other boxes that supply power to the dishes and help the array to point and track. The dishes are named Eve, Sarah, Rebekah, and Rachel, respectively, and their names and/or numbers are labeled on each box. Figure 2.8 and Figure 2.9 show the twelve boxes that run in connection to Computer A. Figure 2.8 shows the power supply boxes for each antenna and Figure 2.9 shows the azimuth (Az) and elevation (El) control boxes.

Figure 2.7: This is Computer A labeled "Astronomy".

Figure 2.8: The four power supply boxes sit above Computer A. Each is labeled 1 through 4 respective to its antenna.

Figure 2.9: Four sets of azimuth and elevation control boxes sit beneath the power supplies and above Computer A. They are labeled with numbers and the names of each antenna: 1.) Eve, 2.) Sarah, 3.) Rebekah, and 4.) Rachel.

Chapter 3

Running the Array

3.1 Checking the Dishes

Before running the array the dishes need to be checked first. Poor weather poses a problem when running the VSA, so given snow, more than 7-10 mph wind, or rain, the VSA should not be used. Moisture on the dishes is not a problem as long as they are cleared of snow, which would interfere with the signal acquisition. The feeds from each antenna need to be loose and unencumbered to avoid the cords getting caught as the dishes rotate.

3.2 Starting the Array and Tracking

Given decent weather and that everything is set up properly, the following step-by-step process will set the VSA to track a desired area of the sky. This process will all be done on Computer A.

1. Four power supply boxes (Figure 2.8) located near Computer A are labeled 1 through 4, each one being connected to its respective radio dish. Turn each power supply on by flipping the "Line On" switch.

2. Also near Computer A are located the azimuth and elevation (Az/El) control boxes, eight in total (Figure 2.9). These need to be turned on in pairs, simultaneously. For example, the first dish, also knows as Eve, has one azimuth box and one elevation box stacked on top of the other. Flip each pair of boxes on at the exact same time until all Az/El boxes are engaged.

3. On Computer A open Matlab 7.0.1 and navigate into the "Observe" folder located in D:/MATLAB701/Work. Open and run the "controlcenter.m" program.

Figure 3.1: Antenna 1 (Eve) sits on the north-west corner of the Clyde Building.

It will take a little while for each antenna to connect. If each successfully is connected a graphical user interface (GUI) will open.

4. In the control center GUI make sure the antennas are communicating with the computer. Change the requested Az and El speeds ("AZ SPD REQ" and "EL SPD REQ") to any number between 1 and 9. This is the speed at which the antennas move if changing Az and/or El. The speed change should be visible on each control box and in the GUI. If this is unsuccessful, close the GUI, turn off the unresponsive Az/El boxes, wait five seconds and try again. Remember to turn the Az/El control boxes on simultaneously in pairs.

5. To track a sky object enter the correct right ascension (RA) and declination (Dec) in the GUI. "Copy 1 to All" transfers the RA/Dec information from the first antenna to the other three. Each antenna must be set to track by clicking the "Enable Track" button for each antenna and the "TRACK" button within the GUI.

6. If tracking is unnecessary, the antennas can be set and locked at a specific azimuth and elevation. This is done most easily by entering the desired Az/El in the control center GUI (labeled "AZ REQST" and "EL REQST"). Note: tracking can only be enabled if RA and Dec are entered.

7. Remember that the dishes can only track to about 10 degrees elevation before the mountains and campus buildings interfere with the received signal. It is best not to track below 15 degrees elevation for this aforementioned reason and because the dishes come close to touching the ground (**?**)).

3.3 Initializing Data Acquisition

After the array is set to track, data can be acquired on Computer B. This monitor is located near Computer A, but its computer systems are located in the large black box at the back of the room. The following is a step-by-step process for initializing data acquisition.

1. Turn the off the power supply boxes for the array.

2. Open the "Data Acquisition" folder located on the desktop of Computer B. In this folder there are several Labview VI's entitled "Multi Channel PSD*.vi". Open "Multi Channel PSD 1.25 MS.vi". This corresponds to the 1.25 MHz filter that is best used to acquire data.

3. In this program there are several plots, each corresponding to a given card and channel. In the large black box located on the floor near the computers, the A to D converter has each card and channel labeled. Make sure the same channels are hooked up to the A to D converter as those that appear in the Labview program window.

4. Also located in the large black box are the IF filters. Make sure if you are running the "Multi Channel PSD 1.25 MS.vi" program that the 1.25 MHz filters are installed. (They are labeled with a center frequency of $f_0 = 2.8125$ MHz

and a bandwidth of 435 kHz) They are installed if coaxial cables from the RF receivers enter in and exit out through the amplifiers to the A to D converter.

5. Turn on the power supply switches located inside the back panel of the large black box. They are illuminated in orange for easier location.

6. Two signal generators are used as LO1 and LO2. These are located above Computer B. Turn them on and make sure they have the following specifications. Each LO must say "RF off" while making any changes. LO1 should read something to the order of 1818 MHz; LO2 should read 396 MHz; and each LO must be set to 16 dBm. When these specifications are set change the LO's to read "RF on."

7. In order to determine the frequency of LO1 use this equation: $LO1 - (source frequency) - 396 MHz = (filter's central frequency)$. The source frequency is the frequency the sky object being observed emits at, and the central frequency of the filter can be found on the filter's label. Set LO1 to the frequency found from this equation.

8. Turn back on the array's power supply boxes.

3.3.1 Data Acquisition

After this process is complete, data can be acquired using simple VI's also located on Computer B. There are two programs, one that should be used for single, short to long acquisitions and the other for short acquisitions over intervals. Note that data cannot be fed through the system if the acquisition time is longer than about 2000 seconds. Therefore, if data must be gathered over a longer period of time, it is best to acquire data in a series of intervals leaving enough time in between gathering periods for the data to be unpacked.

The two programs are entitled "Acquire Data.vi" and "Acquire Data (over intervals).vi" and are located in the "Data Acquisition" folder found on the desktop.

The programs are similar to each other in set up with only minor differences. Depending on how data is acquired, open the correct program and make sure of the following:

1. The physical channels must be the same as those set up in the "Multi Channel PSD*.vi" program.

2. The "Sample rate (Hz)" is the frequency of the IF filter being used.

3. Change the "Acquisition time (sec)" to the desired time. If using the interval program "Acquisition time per interval (sec)," "Number of intervals to acquire," and "Time delay between intervals (sec)" must be set.

4. Choose a "File path" on the F:/ drive where the acquired data should be sent. Make sure to save the file name ending in ".bin".

   The programs can then be run to acquire data.

3.4 Shutting Down the Array

When research is completed and the array is ready to be shut down, do the following:

1. In the control center GUI on Computer A disenable the tracking system by re-clicking each button used to begin tracking.

2. Set the elevation to 90 degrees for each antenna. This process stows the dishes in an upright position.

3. When the array has reached a stowed position, close the control center GUI and other windows used on Computer A and Computer B.

4. Turn off the Az/El boxes and antenna power supplies.

5. Turn off the LO's.

6. Turn off the power switches at the back of the large black box.

Chapter 4

Limitations of the Very Small Array

4.1 Location of the Array

Although the array is currently useable for astronomical research, it maintains some limitations based on its size and orientation. Due to the surrounding mountains and the latitude of the observatory, celestial objects below -5 degrees declination cannot be observed. Such limitations are typical of any observatory depending on its situation on the earth's surface.

4.2 Resolving Power

Another limitation that is applicable to all astronomical observatories is the resolution obtainable with this array. Compared to optical wavelengths, radio waves are longer by a factor of one million or greater. To resolve two objects in the sky we would look at the following equation: $ResolvingPower = lambda/D$, where lambda is the observational wavelength (in meters) and D is the diameter of the telescope (in meters). It is evident that longer wavelengths significantly decrease the resolving power of a telescope. To make up for this deficiency, radio telescopes would need to have diameters phenomenally larger than optical telescopes to maintain similar resolving powers. Instead, interferometry is used and radio dishes are positioned at large distances from one another. With this technique two dishes spaced a mile apart would be able to make the same resolving measurements as one dish a mile in diameter.

4.3 Example of Resolving Power Limitations

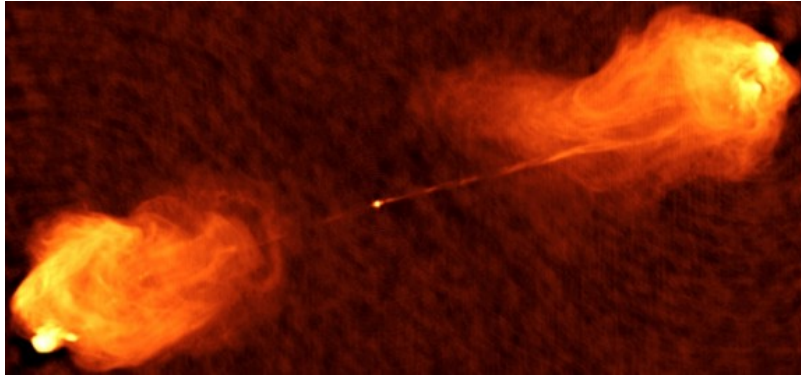An example of resolving power limitations of this array follows:

Figure 4.1: This is a radio image of Cygnus A. Image courtesy of NRAO/AUI.

4.3.1 Imaging Cygnus A

Cygnus A (3C 405) is a radio galaxy that consists of a bright radio source at its center and two large jets or "radio lobes". Figure 4.1 shows Cygnus A at radio frequencies. In order to test the resolving power of the four-dish array, a digital image of Cygnus A (Figure 4.1) was convoluted with an image of the dirty beam of the array. Matlab was used to first create an image of the dirty beam with the array pointed at the location of Cygnus A. This produced an image of the cell averaged dirty beam. Next, the image of Cygnus A was manipulated in Adobe Photoshop to measure the same angular dimensions as the dirty beam image, including having the same number of pixels. Images measuring 2 degrees by 2 degrees and 255 pixels were used in a simple Matlab program to then convolute the images. Hopes of resolving the two separate lobes with the array were high. However, after running the Matlab program it was evident that the angular separation between the two jets was not large enough to be seen by the array. Therefore, the dirty beam convoluted with the Cygnus A image resulted in an image similar to one of a single point source of the same flux as Cygnus A.

Chapter 5

Calibrating the Array

5.1 The VSA's Current Status

The array is currently able to track and gather data from radio sources in the sky, as described above. Images of Cassiopeia A (3C 461), a Super Nova Remnant and very bright radio source, have previously been produced (see Campbell (1) for methods and images). However, beyond Cassiopeia A, the array must be calibrated before other sources can be accurately imaged.

5.2 Calibration

Signals acquired by the array's four antennas are transferred through the RF receivers, IF filters, signal amplifiers, A to D converter, and finally into Computer B. At this point, the signals are stored and can be recovered to produce images. Yet the signals are not synchronized automatically, each having traveled through a different length of wire before being retrieved by the computer's data acquisition program. More importantly, the four antennas are located in four different positions on the earth's surface. This means each acquired signal differs from the signals gathered at the other antenna sites. These are the issues the project engineers face when attempting to ready the array for imaging. Calibrating the array means programming the data acquisition system to take into account the variations in position of the antennas and the phase difference of the incoming signals.

5.3 Imaging Bright Radio Sources

Given the difficulties of calibrating the received signals from the four antennas, another project was undertaken to analyze the imaging power of the array. Using the
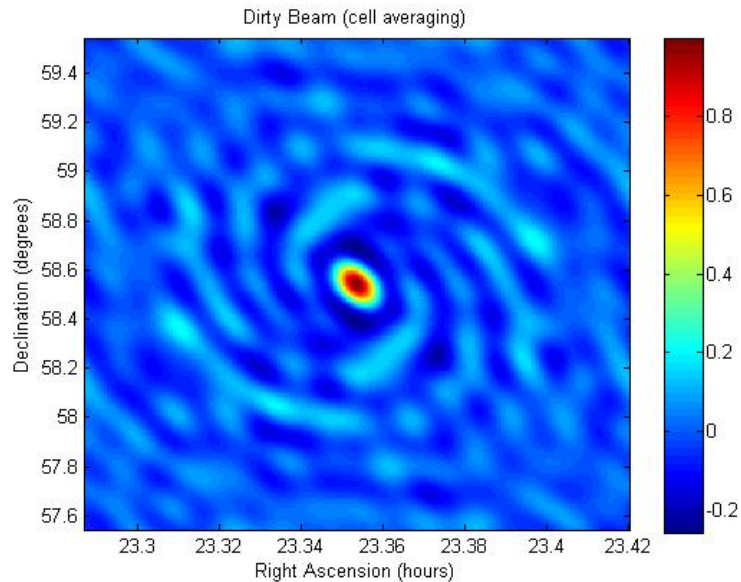
Figure 5.1:   This is the dirty beam image centered on the field for our four bright radio sources.

programming abilities of Matlab and a list of bright radio sources, an image was created that would be similar to that which a calibrated array would produce.

First, the list of bright radio sources was searched to find several high-flux radio objects within a 2 degree by 2 degree window, the size of the dirty beam image. Four sources were found: 4C+04.03, 4C+05.06, 4C+06.03, 4C+06.04. Then a program, the same used to image Cygnus A, was used to produce a dirty beam image based on the central RA and Dec of these bright sources (Figure 5.1). A matrix of the radio objects also had to be created, and was made of zeros and delta functions representing the sources at their given RA and Dec. The dirty beam image and source matrix were then convoluted, and an image similar to what the array would actually see was produced (Figure 5.2).
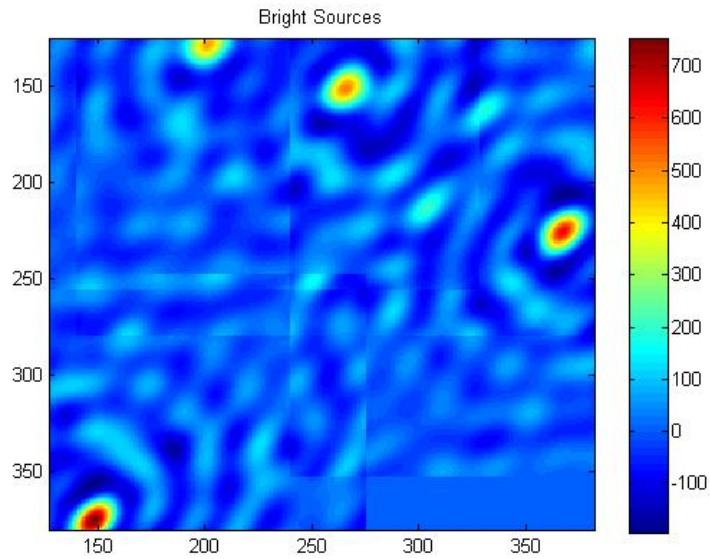
20

Figure 5.2: This is a convoluted image of the cell averaged dirty beam image and a matrix representing our four bright sources.

5.4   Usefulness of the Project

Many assumptions were made that makes this image slightly different than the array would actually produce. The actual radio sources, in the above example represented by delta functions, would not be single point objects. Also, these bright objects are not the only radio signal sources in the sky within that 2 degree by 2 degree window. Therefore, the actual image created by the array would have the basic form of this image, but it would still have many variations. It is a useful project, however, because this program-created image acts as a reliable template for calibrating the array. This image is useful to the array project engineers because it gives them a theoretical image of what a calibrated array could produce.

Chapter 6

Research Possibilities

Currently the Electrical Engineering Department is working on developing imaging techniques with the VSA. Future research involving radio sources other than Cygnus A and Cassiopeia A will soon be possible.

Of course, such radio sources would need to be large in angular diameter due to the small size of the array. The Sun would be a good point of research. Solar flares and sun spots produce a constantly changing radio flux from the different layers of the Sun. The VSA is capable of detecting such changes. This seems an interesting source of research to pursue. Another large source of radio frequency electromagnetic radiation located in our solar system is Jupiter.

Likewise, a study of the Cosmic Microwave Background (CMB) could be obtained through use of the VSA. In fact, the original *Very Small Array*, located on the Canary Islands off the coast of Spain, currently focuses its research on CMB radiation. Although this VSA is larger (it is made of fourteen radio dishes), BYU's VSA would also be able to produce interesting results in such a study (Cambridge (3)).

Joining the current research team is recommended for interested students to remain up to date with the VSA's developments. They currently are continuing with simulated mitigation interferometry (SMI), which is another option for astronomy research. SMI deals with extracting unwanted radio frequency interference (RFI) sources from usable data. Such sources are numerous, from satellites to earth-bound sources. In order to subtract them from the desired data, engineers create mathematical algorithms to place those sources in unused nodes of data. Campbell's thesis describes these techniques in detail (Campbell (1)).

Chapter 7

Discussion and Conclusion

This thesis was written with the expectation that it would be useful to students wanting to do research in the field of radio astronomy. It covers the basic equipment and functions of the VSA built on top of the BYU Clyde Building. Specifically, the step-by-step procedures section on how to run the array should be useful to anyone needing to become familiar with the VSA.

Limitations of the VSA have been discussed as have possible research projects. Despite the small size of the array there are many areas of research that can be explored making the VSA a valuable tool for both the Electrical Engineering and Astronomy Departments.

Working with the VSA and the many engineering students and instructors who run the array has been a long and enjoyable venture. I hope that many more astronomy students will take advantage of the equipment currently only used by the Electrical Engineering Department. Such research would broaden the fields of astronomical study typically explored by BYU astronomy students for their senior theses.

References

[1] Campbell, J. 2005, "The Development of a Small Scale Radio Astronomy Image Synthesis Array for Research in Radio Frequency Interference Mitigation" (Master's Thesis, Brigham Young University)

[2] Campbell, J. 2005, private communications

[3] University of Cambridge webpage on the Very Small Array, (http://www.mrao.cam.ac.uk/telescopes/vsa/description.html)