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ASSSEMBLY AND DEPLOYMENT OF THE UAEU 256-ELEMENT RADIO ARRAY FOR SPACE SCIENCE

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College of Science

Department of Physics

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Space Science

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Cover: The radio telescope array which has been built in UAEU.

(Photo: By Ibrahim J.M. Alghoul)

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Declaration of Original Work

I, Ibrahim J.M. Alghoul, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Assembly and Deployment of the UAEU 256-Element Radio Array for Space Science*", hereby, solemnly declare that this is the original research work done by me under the supervision of Dr. Aquib Moin, in the College of Science at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

The scope of this project, a 256-element Radio Interferometer Array was assembled and deployed as part of the "UAEU Radio Astronomy Pathway Project", which is jointly supported by the College of Science and the National Space Science & Technology Centre (NSSTC) at the UAE University. This antenna array was deployed at the NSSTC site, and it will serve as the central part of the ground-based radio observations facility to be utilized for multi-disciplinary space science research at the UAEU. The facility is capable of making low frequency radio observations of astronomical sources and events, measurements for spacecraft tracking, atmospheric studies, planetary studies, and more. The project work begins with the design, preparation, and placement of a steel mesh ground plane for the array, followed by the extensive assembly and integration of 256 bowtie dipole, dual polarization antennas. The next step is to design the spatial configuration of the array and deploy the array in that configuration. The elements of the array are then interfaced with 16 beamformers on site. After that, the site infrastructure is connected with the backend hardware in the NSSTC ground facilities control room. In the end various connectivity and deployment tests are carried out to validate the readiness of the array for scientific observations.

Keywords: Radio Array, Radio Interferometer, Radio Astronomy.

Title and Abstract (in Arabic)

تجميع ونشر 256 عنصراً من مجمعات موجات الراديو لعلم الفضاء

الملخص

نطاق المشروع تم تجميع 256 عنصراً من مقياس التداخل الراديو ونشره كجزء من مشروع مسار علم الفلك الراديوي في جامعة الامارات العربية المتحدة والذي يدعمه بشكل مشترك كلية العلوم والمركز الوطني لعلوم وتكنولوجيا الفضاء في جامعة الامارات وتم نشر المجموعة في موقع المركز الوطني وسيكون بمثابة الجزء المركزي من منشأة مراقبة الراديوية الأرضية لاستخدامها في أبحاث علوم الفضاء متعددة التخصصات في جامعة الامارات العربية المتحدة. المرفق قادر على اجراء ملاحظات لاسلكية منخفضة التردد للمصادر والاحداث الفلكية وقياسات لتتبع المركبات الفضائية ودراسات الغلاف الجوي ودراسات الكواكب والمزيد. يبدأ عمل المشروع بتصميم واعداد ووضع مستوى ارضي شبكي فولاذي للصفيف يليه تجميع شامل ودمج 256 هوائي ثنائي القطب. الخطوة التالية هي تصميم التكوين المكاني للصفيف ونشر المصفوفة في هذا التكوين. يتم بعد ذلك ربط عناصر المصفوفة بـ 16 مشكلاً للحزم في الموقع ومن ثم يتم توصيل البنية التحتية للموقع بأجهزة الواجهة الخلفية في غرفة التحكم في المرافق الأرضية للمركز الوطني وبالنهاية سيتم اجراء العديد من اختبارات التوصيل والنشر للتحقق من جاهزية المصفوفة للمراقبات العلمية.

مفاهيم البحث الرئيسية: مصفوفة راديو، مقياس تداخل راديوي، علم فلك راديوي.

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Special thanks go to Curtin University for providing all the needed help throughout this project. Not everyone gets to be able to build a whole radio telescope from scratch, but I was able thanks to your assistance. I would like to thank Ms. Nusrin for all her help through this project, it wouldn't be possible to finish without your help and support. Thank you for all the laughter while making sure I understood every single detail of the process. I would also like to thank my colleagues in the space science for their help and encouragement to pursue higher positions. I am extremely thankful for UAEU's Physics department faculty, staff, and especially Dr. Nacir Tit. Thank you all for your help, and assistance throughout my master's journey.

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Dedication

To my beloved parents and family

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List of Abbreviations

ALMA	Atacama Large Millimeter Array
ASKAP	Australian Square Kilometer Array Pathfinder1
CHSS	College of Humanities & Social Science
CIT	College of Information Technology
EDA	Engineering Development Array
ICRAR	International Center for Radio Astronomy Research
IORA	Indian Ocean Rim Association
LNA	Low Noise Amplifiers
LOFAR	Low Frequency Array
LWA	Long Wavelength Array
MWA	Murchison Widefield Array
NSSTC	National Space Science & Technology Centre
RFI	Radio Frequency Interference
SKA	Square Kilometer Array
UAEU	United Arab Emirates University
URAPP	UAEU Radio Astronomy Pathway Project
VLA	Very Large Array

Chapter 1

Chapter 1: Introduction to Radio Astronomy & Interferometry

1.1 Background

Radio astronomy is a new dimension in the vast field of astronomy. It is the branch of the astronomy where all observations of celestial objects are done by detecting radio waves emitted by these objects. Radio astronomy has made some of the major breakthroughs in the field of astronomy as it can even observe the farthest parts of the universe by detecting radio waves coming from them. All parts of the electromagnetic spectrum are not visible to the human eye and even they cannot enter the earth’s atmosphere, radio astronomy becomes vital as it can enter the earth’s atmosphere and can be detected by specialized instruments as it's not visible to the human eye.

Radio astronomy has opened new chapters in the discovery of the universe starting from the observation of star births till the evolution of galaxies. It has uncovered the hidden universe as each object in space emits specific characteristic radio waves which can be detected and studied to get detailed information about these celestial objects.

1.1.1 History

The emergence of radio astronomy can be dated back to 1933 when Karl Jansky at Bell laboratories detected the first radio waves from celestial objects (Hicks et al., 2012). He was working as a radio engineer in Bell Laboratories on a project where he must study radio interference from thunderstorms (Figure 1). This project aimed to build an antenna that will reduce the static when beaming radio-telephone signals across the ocean. While working on this project he recorded some static that was interfering with the voice communication. After some observation, he deduced that the source from where this static was originated was some extraterrestrial source and as it completed a cycle of 24 hours so it must be the Sun. After observing the source for several months Jansky concluded that the source was something even farther from the sun. Tracking the source, he came to know that it was something outside our solar system and even our solar system was moving towards it. He discovered something in the heart of our galaxy Milky Way and finally published his first work in the field of radio astronomy with the title "Radio Waves from Outside the Solar System".

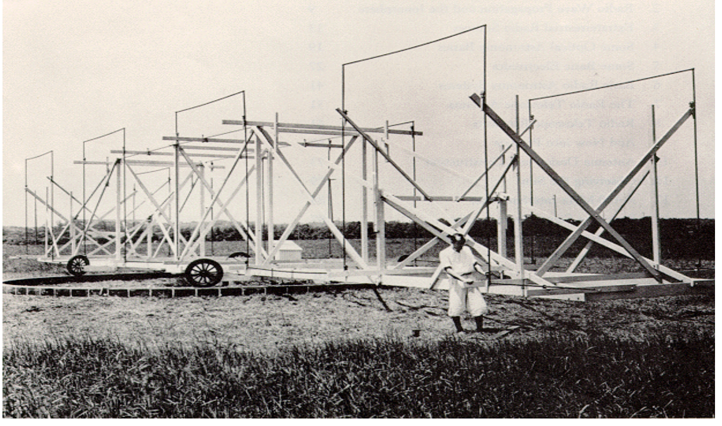

Figure 1: Karl Jansky's Antenna that detected radio waves from the Milky Way

Another major breakthrough in the field of radio astronomy happened when Jocelyn Bell, who was a young student at Cambridge and was assisting in building a radio telescope, on a cold night got a print from her radio telescope having a strange significant signal. The signal was similar to the ticking of the clock. After analyzing the printed signal Jocelyn and her teammates concluded that the source of these signals was producing high-intensity radio pulses at a steady and regular rate of almost

30 times per second. Jocelyn and her teammates named this source “little Green Men” which was later called Pulsars. Pulsars are massive objects that are almost the size of a city and weigh more than the sun. When massive stars collapse pulsars are formed and then they explode as a supernova. Pulsars are highly magnetized dead neutron stars that emit magnetized radiations that appear as blinking stars.

1.1.2 Radio Instrumentation

Optical telescopes have been widely used for a long time to observe celestial objects but they don’t give a complete picture of these objects as the optical telescopes can only detect visible parts of the electromagnetic spectrum while these objects are emitting radiations at all wavelengths. To study them thoroughly and in detail, we need to look at them at other wavelengths as well. Radio astronomy opened a new door for studying these objects as we can study radio waves emitted by these objects using radio telescopes. Radio telescopes can be used to study stars, galaxies, planets, quasars, pulsars, black holes, clouds of dust, molecular gases, and other astronomical objects (Figure 2). Radio telescopes are also used to study cold and dark parts of the universe which cannot be studied using optical telescopes as they don't emit any visible light.

Figure 2: A quasar and pulsar observed with radio telescopes

Radio waves from astronomical objects are detected by radio telescopes which at the backend amplify these signals and convert them into images using different software so this data can be used by astronomers to study these celestial objects. Radio telescopes consist of radio antennas that may work singly, or they may be connected to other antennas and all these antennas work together making use of the technique of interferometry. The basic structure of a radio telescope consists of a parabolic dish antenna that collects radio waves emitted by astronomical objects in space. These collected radio waves are then reflected by the parabolic dish to the receiver in the same way as visible light is reflected by the mirror in optical telescopes. The receiver then sends the signals to the amplifier which amplifies the weak radio signals received from the extraterrestrial source so that they can be analyzed and measured. The amplified signal is then sent to the recorder where this data is stored on a computer and then processed by using different software to be converted into a useful form that can be used by astronomers for their studies. The data can be converted into colorful images representing different temperatures and the strength of radio waves coming from different celestial objects.

1.1.3 Interferometry

Interferometers are a tool used to investigate different phenomena in science and technology. They have been given this name due to the fact that they make use of the principle of interference. In interferometers, two waves combine together to form an interference pattern. This interference pattern can be studied to get information about the phenomena being studied. Very small measurements can be precisely done by interferometers which would have been difficult to achieve with other instruments. Albert A. Michelson in 1880 for the first time worked with an interferometer. Michelson’s interferometer was based on the interference of light waves. In Michelson’s interferometer, a laser beam was used. Light from the laser beam was split into two parts and these two light waves were combined after passing through an interferometer giving an interference pattern on the detector screen. Till now Michelson interferometer forms the basis of modern interferometers in optical and radio astronomy. Optical and radio interferometers are based on the same principle where light from the same celestial source is collected by different antennas and then these signals are combined to get an interference pattern that contains information about the celestial object.

1.1.4 Astronomical Interferometers

When a set of mirror-based telescopes (optical telescopes) or radio antennas come together to work on a single celestial object they form an astronomical interferometer which gives better resolution images of the observed object that can be a star, planet, galaxy, nebula, etc. The main pro of this technique is that you can get images of the same angular resolution as you would have got from a giant telescope with an aperture of the same size as the distance between different component telescopes of the interferometric array. Interferometric arrays can achieve a resolution of a few microarc seconds using a radio telescope while in infrared and visible light milliarcsecond resolution can be achieved. The main con of this technique is that it does not collect the same amount of light as a single large aperture telescope so it can observe more luminous objects like close binary stars better (Thompson et al., 2017).

In interferometry, multiple antennas look at the same source of signals. The signal from each source reaches the antennas at different timings due to the difference in distance covered by each signal to reach the antenna. A correlator is used to fix the time difference between different signals from each antenna. When these signals from different antennas are combined, they interfere with each other to give the resultant signal. The image created from this resultant signal is much sharper and bright compared to the image created from a signal obtained from a single antenna. This interference also gives us information about the source related to its distance from the observer, its spectral properties. Optical interferometry was first used by Michelson stellar interferometer in the Mount Wilson Observatory. This interferometer used a reflector telescope, and it measured the diameter of stars using interferometry. In 1920, the diameter of Betelgeuse was measured for the first time using this technique. In the 1940s radio interferometry was introduced and the research in this field continued for the coming decades resulting in efficient observatories such as Very Large Array (VLA) and Atacama Large Millimeter Array (ALMA). To date, this field is dominating optical interferometry, and projects like Square Kilometer Array (SKA) are in line to discover the far ends of the universe using interferometry.

1.2 Radio Astronomy Principles

1.2.1 Astronomy at Radio Wavelengths

The field of astronomy has drastically been changed after the emergence of radio astronomy as it has reached points in the universe that were unapproachable for human beings. For example, in the 1960s radio astronomers discovered the Cosmic Microwave Background Radiation which is known as the afterglow of the Big Bang. Hydrogen which is the most abundant element in the universe is widely being used by radio astronomer to trace out the structure of galaxies as hydrogen is a vital part of galaxies and emit characteristic radio waves that astronomers use to study galaxies. Newly discovered objects like pulsars, quasars, supernova explosions, etc. have all been discovered and studied by radio astronomers.

Two types of radio emissions that are used in radio astronomy are thermal and nonthermal radio emissions.

Charged particles such as molecules and atoms emit thermal radio emissions. When atoms vibrate they emit electromagnetic radiations due to the heat energy stored in them, the greater the vibrations, the greater is the heat energy stored which in turn result in greater emission of thermal radio waves (Matthews, 2019).

Another type of thermal radio waves are emitted due to the spin of electrons while revolving around the nucleus (Matthews, 2019). As electrons gain energy, they move to higher energy states where they are in an unstable state. To gain back their stability sometimes electrons lose their energy by flipping their spin. Characteristic discrete wavelength radio waves are produced in this case. For example, in the case of a neutral hydrogen atom 21 cm wavelength radio waves are generated which were the first-ever detected radio emission due to the abundance of hydrogen in the universe.

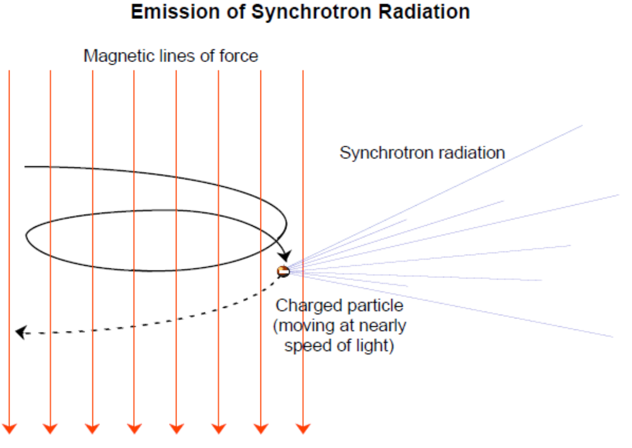

Figure 3: Emission of Synchrotron radiation

Radiations produced by objects that are not related to temperature are non-thermal radiations. Most of the radiations coming from our galaxy and other galaxies are non-thermal in nature including the first radio waves that were detected by Jansky. These radiations are generated when charged particles interact with strong magnetic fields. Synchrotron radiation is the main source of non-thermal radio waves. When electrons in a strong magnetic field are moving at the speed of light, they generate synchrotron radiations. When electrons interact with the magnetic field, they are forced to move in a spiral path due to which they are accelerated and emit radiations. Quasars, active galactic nuclei, and supernovas are some of the very powerful sources that can generate synchrotron radiations (Figure 3).

Another difference between thermal and non-thermal radiation is that thermal radiation's intensity increases with frequency while for non-thermal radiations intensity decreases with increasing frequency.

Radio astronomers make use of the complete radio window while working with radio interferometers. The radio window is divided into bands with a wavelength around 20-, 13-, 6-, 3.5-, 2-. 1.3- and 0.7 cm which are named as L, S, C, X, U, K, and Q bands respectively. Radio bands with wavelength 20-, 13-, 6-, 3.5-, and 2cm are used for continuum observations for example they are used while observing HII regions and synchrotron continuum while the wavelengths of 1.3 and 0.7cm are used for spectroscopy, for example, they are used for observing molecular lines in cool, thermal dust in star-forming regions. In some cases, the 20-, 13-, 6-, 3.5-, and 2 cm wavelength radio waves are also used in spectroscopy for example for studying 21 cm HI spin-flip and different radio recombination lines.

Celestial objects emit radiation in all wavelengths of the electromagnetic spectrum but only a few of them can reach the earth's surface and the instruments on earth. This is due to the reason that most of the radiations are blocked by the atmospheric layers except visible light, some infrared radiations, and short-wavelength radio waves. The main frequency range of radio waves that cross the atmosphere reaches the earth's surface is between 5 MHz and 300 GHz which is known as radio window. This radio window is the part of the radio waves spectrum that is the major source of information about extraterrestrial objects. The visible light reaching the earth's surface is badly affected by the clouds and dust particles while these being opaque increases the importance of radio astronomy. Hence radio astronomy is being widely used to study star formation areas as they are filled with dust and cannot be studied with optical instruments.

1.2.2 Radio Interferometry

Modern radio astronomy is extensively using the technique of radio interferometry. Radio interferometry is based on Michelson interferometer with some changes according to radio telescopes. In radio interferometry, multiple radio antennas are used together to observe a single radio source. This improves the signal quality generating high-resolution images that are not possible with a single radio antenna. This technique is not only providing radio astronomers better resolution but it's also very convenient to handle and affordable compared to a single very large radio telescope.

Radio interferometric array means a collection of radio telescope that works together and combines the signal from a different radio telescope to provide us with a better signal. This whole setup of radio telescopes works as a single very large telescope whose diameter is in kilometers. The size of the aperture depends upon the distance also known as baseline distance between different radio telescopes that are part of the array. It can be considered as a single telescope with a very big aperture that is not filled like ordinary telescopes. Using the technique of interferometry, we can get images that have a resolution even better than Hubble telescope images. Radio interferometric array enables us to get a resolution of as low as 25 microarc seconds or even lower which is fair enough to get clear radio maps of faraway galaxies and black holes.

There are two ways in which radio observations can be done. The first method is like optical observations where a large dish antenna is used to collect all the data. In this method, radio telescopes behave the same way as optical telescopes where a detector can be placed at the focal point of the radio telescope to collect all the signals in radio range from space.

The second method is radio interferometric arrays where we use a group of radio telescopes connected electronically to each other to get high-resolution results (Anderson & Weighman, 1997) All the radio telescopes of the array are pointed in the same direction to get information from the same source. Interferometry allows us to combine all the information gathered by different telescopes to get better resolution for celestial objects. The resolution depends upon the distance between different component telescopes of the array. The greater the distance the better the resolution. This is the main advantage of interferometry that we can have an interferometer of the size of the earth or even we can include radio telescopes from space to our array.

To choose a perfect location for a radio interferometric array we need to consider certain things. It should be a built-in radio quiet place where there is minimum radio interference as the rays coming from celestial objects are very faint compared to man-made sources of radio waves so these faint waves can be easily collected (Tingay, Goeke et al., 2013).

Humidity is another distortion as water molecules interrupt the radio waves crossing them. Another problem is that they give off their radio waves which cause interference. So, radio telescopes should be placed in deserts away from the city in a radio-quiet area.

Advantages:

- The biggest advantage of this technique is that it allows us to get better resolution images as the size of the aperture can be made as large as required by adjusting the distance between different components of the array.
- Radio observations are advantageous over optical observations because they can pass through dust particles which makes it possible for us to observe gases and dust clouds.
- Radio observations can be done throughout the day and night and in all kinds of weather conditions.
- Most of the celestial objects are made of hydrogen which does not emit visible light, so radio observations are used to observe such objects.

Disadvantages:

- The main disadvantage of this technique is that it needs many components radio telescopes and very sensitive antennas need to be built very carefully and precisely as radio waves from celestial objects are very faint.
- Another disadvantage is the interference of man-made sources of radio waves because of which we must build it away from the city.

1.3 Radio Antennas

1.3.1 Single Antenna

Single element radio antennas and radio interferometric arrays both play a vital role in radio astronomy while in some cases one can be preferred over another. For example, while studying the structure and taking measurements of huge structures in the sky single element radio antennas are best suited while for example obtaining high-resolution images radio interferometric arrays are preferred.

Single element radio antennas are parabolic dishes that look at a fixed radio source in the sky. The dish is parabolic in shape so that all the waves coming from celestial objects are focused at a single point known as the focus while covering the same paths or having the same time delay (Figure 4). In such a situation all the waves meet at the focus in phase with each other. At the focus or focal point, there is a receiver that receives all the waves reflected by the parabolic dish. This receiver or detector is connected to an amplifier which amplifies the signal to a point that is strong enough to be measured.

If we want to observe a different point in the sky, the parabolic dishes are so easy to handle in this scenario as all we have to do is just tilt the antenna a little to be pointing at the source, this is possible in slight changes of direction if the source is in some other direction, then sometimes, we have to move the parabolic dish completely.

Figure 4: Single element radio telescope at Parkes observatory

Another advantage of a single element radio antenna is that it's up gradation is very simple and convenient compared to an array of radio antennas. Single element radio antennas can also be easily reconfigured during an observation according to the need of the astronomers.

Single element radio antennas sometimes use bolometers which are incoherent detectors that are highly sensitive to the continuum as they accept high bandwidth in mm and sub-mm range. Bolometers are preferred to be used in single dish antennas as in arrays the limit the technological advantages of the array.

Single dish antennas are also preferred in the case where a large collecting area is required such as while studying pulsars and transient phenomena.

1.3.2 Multi-element (Array)

The major difference between a single element and multi-element radio antenna is that in single element radio antenna signal is brought in phase to the focal point due to the parabolic reflector dish while in multi-element radio antennas signals received by individual antennas are made in phase at the focus by using cables of the same length. These cables carry the signal to a common point where these signals are added together and then amplified by the amplifier before sending them to the detector.

If we want to observe a different point in the sky using a radio array it is comparatively difficult to tilt the whole array in that specific direction instead of these astronomers use another technique in which they adjust the length of the cables from the dipole antenna to the receiver in such a way that all the waves reach the receiver in phase. In this case, the cables of the dipole antennas closer to the radio source are made comparatively long than the dipoles farther from the source. This makes the signal from the sources reach the receiver in phase. In this wave, the beam is tilted without moving the diploe antennas of the array. The multi-element radio antenna is comparatively easy to handle mechanically but it is electronically more complicated than a single element radio antenna.

Multi-element radio antennas have complicated instrumentations compared to the single dish where there is only one dish with a single receiver at the focus while in arrays there are multiple antennas with multiple receivers and correlators to correlate the individual baselines. In a single element radio antenna, both the front and back-end systems are quite simple to develop and handle.

These single-dish antennas can be used to create a multi-element radio array as in VLA. But the future of radio astronomy says that we have to use a combination of both single element and multi-element radio antennas to reach the parts of the universe that are still not discovered.

1.4 Radio Astronomy Backend

At the backend of a radio observatory, the signal received by the antennas is transferred through the optic fiber cable to the control room. The received signal is amplified by an amplifier. Modern amplifiers are very sensitive and are maintained at low temperatures to reduce noise generated by the atoms in the metal. This signal is received as a DC voltage signal. This signal is then converted into a digital signal using an analog to digital converter device. This device is a simple chip that converts the analog DC voltage signal into a digital DC voltage signal. This conversion device requires a specific voltage, so it is continuously connected to a power supply to perform its functions properly with an adequate supply of power. It is necessary to convert this analog signal into digital as the rest of the processing will be done by software in the computer which only accepts digital signals. This digital signal is then stored on a PC card. This PC card is a bridge between the computer and the converter. It builds a communication system between the computer and converter giving the computer enough time to process the input signal and generate useful outputs that can be used by radio astronomers for their research and studies (Figure 5).

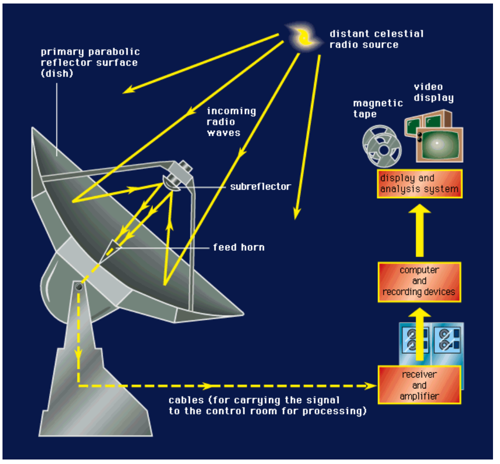

Figure 5: Backend of a Radio Telescope

The main problem with a radio telescope is the amount of data it is collecting (Tingay, Goeke et al., 2013) Since the telescope is all the time observing the radio waves coming from the celestial source until and unless the power supply to the telescope is stopped, it is collecting an enormous amount of data. For all this time when the telescope is on it is gathering signals and sending them to the analog to digital converter following the same path as explained above. The huge amount of data is controlled by the computer mainly because the data is only stored on the computer when it communicates with the converted and receives its digital signal for the rest of the time the signals gathered are not stored on the computer. So, we can say that the telescope is truly observing the celestial source only for the time when the computer is functional and storing the data sent by the telescope. For the rest of the time, all the signals collected by the telescope are grounded and no record is maintained for them. The assistant in the control room has the authority to manage when the telescope and converted are going to interact with the computer and data will be stored on it.

1.5 Radio Observation

With the emergence of radio astronomy and advancements made in radio observation instrumentations, astronomers have touched the far ends of the universe. Starting from the studies of the cosmic microwave background, star formation, supernova explosions, galactic nuclei, quasars, pulsars till the evolution of galaxies, astronomers have opened a new era in the field of radio astronomy.

Starting with 1933 when Karl Jansky in bell laboratories for the first time detected extra-terrestrial radio waves that were later identified to be coming from our galaxy Milky Way (Burke et al., 2019).

In 1937, Grote Reber developed the first-ever radio telescope that was used to map the emissions from our galaxy Milky Way (Burke et al., 2019).

In 1942, James Hey during World War II for the first-time detected radio emissions from the sun while he was working with his radar systems. These emissions were later found to be coming from sunspots and solar flares (Burke et al., 2019).

In 1948, in Australia, John Bolton discovered the two most powerful sources of radio waves Taurus A which is also known as the Crab Nebula, and Cassiopeia A (Burke et al., 2019).

In 1951, radio spectroscopy was initiated simultaneously in USA, Netherlands, and Australia and 21 cm Hydrogen lines were discovered. Spectroscopy changed our perspective of our own galaxy and other far-away galaxies (Burke et al., 2019).

In 1954, Cygnus A was accurately identified and located using the technique of interferometry for the first time in Australia and UK (Burke et al., 2019).

In 1962, the aperture synthesis technique was developed by Martin Ryle at Cambridge, and radio links for long baselines were developed by Henry Palmer which have formed the basis of the modern radio telescope and interferometric arrays. Even the largest Square Kilometer Array (SKA) is also inspired and based on them (Burke et al., 2019).

All these discoveries prove that radio astronomy has expanded human knowledge about the universe. It not only made the previously discovered objects even more clear but also discovered new celestial objects such as pulsars, quasars, and radio galaxies which were not approachable with optical instrumentations. Radio astronomy opened a new chapter about the dark matter in the universe which is a vital part of our universe and was unknown before the emergence of radio astronomy. But this is just the beginning we still have so much to discover with the help of radio astronomy. New techniques and better instrumentations are expected to come which will further improve our understanding of this universe.

Chapter 2

Chapter 2: Radio Arrays of the World

2.1 Overview

A field of radio astronomy is emerging as new technologies and development are being made in constructing innovative and high-performance radio telescopes. Studying radio waves below 100 MHz enables us to study non-thermal phenomena such as pulsars and Jovian radio emissions. These developments help us to study in detail those parts of our universe, the space around our planet, and the solar system that were unapproachable.

A big boom was seen in radio astronomy when large centimeter wavelength aperture synthesis radio telescopes were first constructed. Projects such as the Very Large Array (VLA) were some of the very first projects that laid the foundation of interferometric arrays opening doors for radio astronomers to search the farthest parts of the universe. Several developments were made that contributed to the revival of low-frequency radio astronomy. Self-calibration was used for the first time in the early 1990s to avoid the problem of ionospheric limit to short baseline which allowed us to view the universe at sub arcminute resolution at very low frequency. This technology was used in VLA to get high-resolution images of the universe. In the same period, new cost-effective technologies were developed for receivers and digital signal processing which were considered appropriate to be used for large bandwidth beamforming arrays. New developments were being made in computing which helped in improving the computational part of radio astronomy. All these developments led the radio astronomers to think of new areas of research that were unapproachable before. By constructing highly sensitive instruments with high resolution that was not achievable before, radio astronomers discovered parts of the universe that had never been seen before.

All these advancements in technologies are encouraging radio astronomers and engineers to build new radio observation facilities with high sensitivity and resolution. Interferometric arrays and the technique of aperture synthesis are enabling us to construct radio telescopes that can work at longer and shorter wavelengths. Astronomers are now planning to build radio telescopes of the size of the earth to picture our universe using these techniques and new areas of research are being opened using these highly sensitive instruments.

2.2 The Very Large Array

The very Large Array (VLA) is one of the largest ground-based radio telescopes that was built in New Mexico is operating since 1980. Funds for this project were provided by National Science Foundation while its operations are controlled by National Radio Astronomy Observatory. VLA consists of 27 radio antennas each of which is 25 meters in diameter that are arranged in three arms of a Y-shaped configuration. This distribution is extended up to a 35-kilometer area. (Hjellming & Bignell, 1982) An interesting fact about VLA is that it has a rail track over which these antennas can be moved and different configurations for the array can be achieved (Figure 6). The array can be arranged in four different configurations spreading in areas 1,3.5,10 and 35 km. arranging the array in these configurations makes it possible to attain high resolutions for four wavelengths that are 1.3,2,6 and 21 cm. The array can also be split into two or more smaller arrays just by moving the antennas (Heeschen, 1967)

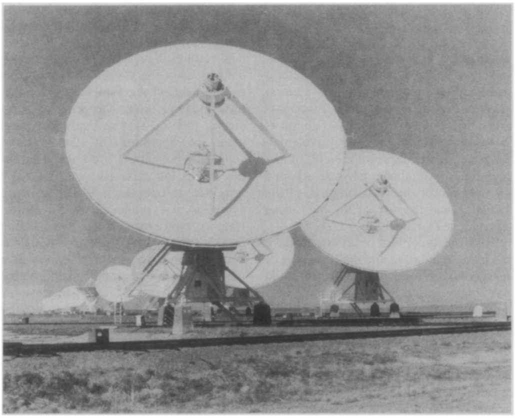

Figure 6: Close up of VLA antennas and the railway track for transportation of antennas

Due to the moveable parts of VLA, it is very convenient for VLA to switch between different wavelengths and observe different spectral lines. Some modes of operation at different frequencies are given in the table below (Hjellming & Bignell, 1982).

Table 1: VLA observing frequencies and associated spectral lines

Possible frequencies (GHz)	Protected* frequencies (GHz)	Atomic and molecular lines
1.34 to 1.73	1.40 to 1.427	Neutral H: 1420.4 MHz H, He, and so on: recombination lines $HCONH_2$ (formamide): 1538 to 1542 MHz OH: 1612, 1665, 1667, and 1721 MHz HCOOH (formic acid): 1639 MHz
4.5 to 5.0	4.99 to 5.0	$HCONH_2$: 4617 to 4620 MHz OH: 4660, 4751, and 4766 MHz H_2CO (formaldehyde): 4830 MHz H, He, and so on: recombination lines
14.4 to 15.4	15.35 to 15.40	H_2CO: 14.489 GHz H, He, and so on: recombination lines
22.0 to 24.0	23.6 to 24.0	H_2O: 22.235 GHz NH_3: 22.834 to 23.870 GHz

*Frequencies specifically allocated for radio astronomy by international treaties.

As shown in Table 1 each antenna of VLA comprises of parabolic collecting dish with a hyperbolic surface sub-reflector. The parabolic dish focuses the radiation on the sub-reflector that is supported by four support structures. The rotation of the sub-reflector is controlled by computers which focuses the reflected radiation on the feeds. With each antenna, there is a room built that carries the electronic part of the antenna. Signals received by the feed are transmitted to the electronics room where these signals are amplified, and the frequency selection process is carried out. Signals received from all 27 antennas are converted to the same frequency range and compensation for time delay is done as the signals arrive at different times from different antennas. The signals are then cross-correlated and averaged over 10 seconds to generate measurements of complex visibility functions. Once all the data from a particular radio source is stored on a computer then astronomers perform their corrections, calibrations, and compute the images using specific programs (Hjellming & Bignell, 1982).

With time new technologies are being introduced and the advancements made in radio astronomy call for upgrading the system of VLA. More sophisticated computers and electronics are added to the system of VLA that will dramatically increase its sensitivity, resolution, and overall performance. The core of the array that is the correlator is upgraded to a supercomputer that will process, compare, and combine the signals received from the antennas. The upgraded correlator can manage bandwidth 80 times greater than the previous VLA correlator. all previous waveguides are replaced by new optic fiber cables to carry signals from antennas to the correlator. Receivers in the dish antennas are also replaced with the new ones that can handle band coverage of 50 Giga Hertz. This upgrade was completed in 2016 which improved the performance of VLA so well that it can detect a faint signal of the phone call from Jupiter even (Heeschen, 1967).

The major science goal behind the construction of VLA was the mapping of distant galaxies using radio emissions associated with these distant galaxies. Since VLA provides a wide range of resolutions so it's a perfect facility to detect weak radio sources. It was also expected that VLA will help create a map of extragalactic radio sources. VLA is also being used to observe different atomic and molecular spectral lines.

VLA being capable of producing high resolution makes it a perfect facility for searching and mapping quasars. It also makes astronomers capable of mapping radio structures that are generated by stars and stellar systems. A map of SS433 that was generated at a 6-cm wavelength by VLA is shown in Figure 7 below. The high sensitivity of VLA also enables astronomers to dig deeper into our solar system. Radiation belts surrounding Jupiter have also been observed by VLA. Radio events happening on the sun are also one of the key observations made by VLA (Hjellming & Bignell, 1982).

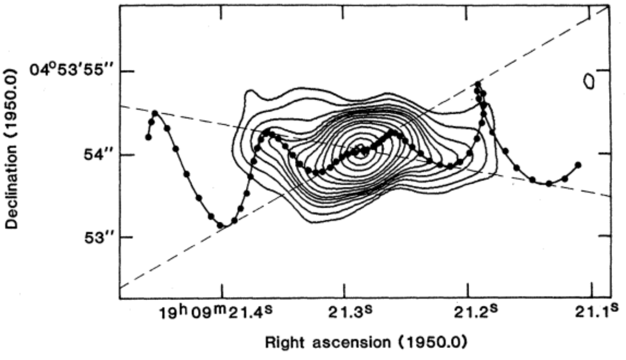

Figure 7: Map of SS433 made at 6-cm wavelength using VLA

2.3 The Long Wavelength Array

The Long Wavelength Array (LWA) is a versatile radio telescope operating since 2015 in New Mexico. LWA consists of 256 dipole antennas that operate at the frequency range of 10-88 MHz. Initially, only 256 antennas are deployed however future plans include deployment of 53 such stations making the total number of antennas in LWA 13000 diploe antennas (Figure 8). These 256 antennas have a maximum baseline of 400 km. this facility is based on aperture synthesis techniques where signals collected by antennas are transferred to the main station by beamformers attached to the antennas. In the main central location, the signals are correlated, and images are formed.

LWA is quite similar to LOFAR (Low-Frequency Array) as both of them operate at a low-frequency range but still, the frequency range observed by LWA (10MHz) is smaller than LOFAR. The major difference between them is their location and their sky view. LOFAR is located in the Netherlands at latitude 55N which makes sit a perfect spot to observe extragalactic sources while LWA is located in New Mexico at latitude 34N favoring inner galaxy regions. The high density of LWA stations makes it an excellent site for galactic observations (Ellingson et al., 2009).

Figure 8: LWA antenna

Being a versatile instrument operating at low-frequency LWA has some unique specifications that are mentioned in Table 2 below.

Table 2: LWA specification

Frequency range, bandwidth		20–80 MHz, 0.05–3.0 MHz
Total collecting area	@ 20 MHz	10^6 m^2
	@ 60 MHz	10^5 m^2
Angular resolution	@ 20 MHz	8″
	@ 80 MHz	2″
Pointing/frequency conversion time		< 1 ms
Sky coverage		$< 60°$ zenith distance
Sensitivity ($\Delta\nu = 3$ MHz, $t = 8$ hr)	@ 20 MHz	~ 3 mJy
	@ 80 MHz	~ 1 mJy
Polarization		Full
Field of view	@ 20 MHz	$\sim 12°$
	@ 80 MHz	$\sim 3°$
Number of instantaneous baselines		1300
Time resolution		10 ms

Having these specifications signal from each antenna at the LWA site is received by a sampling receiver which consists of two components an analog receiver and an analog-digital converter that samples 196 million samples per second. Beams are generated by time-domain delay-and-sum equipment, which allows the complete 10-88 MHz passband associated with each antenna to be processed as a single wide-band data stream. This is then sent to the correlator. At the LWA site, the correlators are connected to the stations by gigabit ethernet cables. The main function of the correlator is to calculate the correlations between stations to form the raw image which is then calibrated to get the required image. Since a large number of signals are sent for correlation, this process is highly complicated and needs extremely sophisticated instruments for it.

LWA is constructed to work for long-wavelength astrophysics and ionospheric science. LWA is being used to observe cosmic evolution, the science of interstellar and intergalactic media. It is also studying our solar system and space weather. It is also aiming to work on extrasolar planets by using Jupiter-type decametric radio emissions. LWA is also capable of studying high redshift radio galaxies (Ellingson et al., 2009).

2.4 The Murchison Widefield Array

Murchison Widefield Array (MWA) is in the Murchison radio astronomy observatory in Western Australia. It is one of the Square Kilometer Array precursor telescopes. It operates at a low-frequency range of 80-300 MHz. MWA consists of 128 aperture arrays which cover an area of 3 km diameter. They are arranged in 8 groups each containing 16 diploe antennas arranged in 4x4 square (Figure 9). This is phase 1 of MWA which in Phase will deploy more diploe antennas. The site of MRO was chosen for MWA as it is a radio-quiet zone having minimum radio frequency interference (Tingay, Goeke et al., 2013).

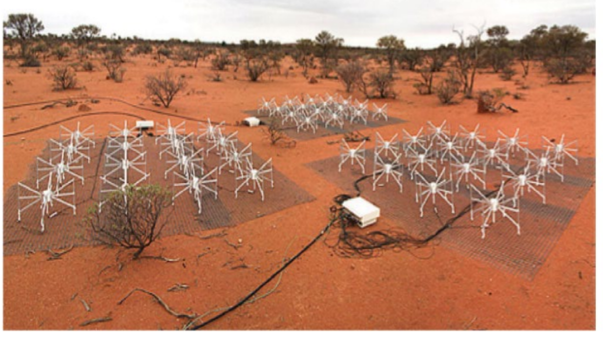

Figure 9: MWA antennas arrange in 4x4 square

Tiles are arranged in such a way that the core area holds 50 tiles which are evenly distributed over a 100 m diameter. This core region is surrounded by 62 tiles which cover an area of 1.5 km diameter. The rest of the 16 tiles are deployed a little farther in a 3 km diameter area. These dipole antennas are arranged in this way to get maximum angular resolution.

A ground screen is used for MWA tiles that are resting directly on the ground. This ground screen is a mesh reflecting screen which is made from galvanized steel wire with 50 mm x 50 mm wire spacing and 3.15 mm wire thickness. All 16 antennas form a 4x4 grid on the ground screen. The antenna has two pairs of orthogonally mounted broadband dipole bat wings. These wings are made of aluminum. Antennas are mounted on the mesh in such a way that one dipole is aligned in a north-south direction while the other one is aligned in the east-west direction. Few of the system parameters for MWA are given in Table 3 (Tingay, Goeke et al., 2013).

Table 3: MWA specification

Parameter	Symbol	150 MHz	200 MHz
Number of tiles	N	128	128
Area of one tile at zenith (m^2)	A_{eff}	21.5	19.8
Total collecting area (m^2)		2 752	2 534
Receiver temperature (K)	T_{rcv}	50	25
Typical sky temperature[a] (K)	T_{sky}	350	170
Field of view[b] (deg^2)	Ω_p	610	375
Instantaneous bandwidth (MHz)	B	30.72	30.72
Spectral resolution (MHz)		0.04	0.04
Temporal resolution		0.5 s uncalibrated 8 s calibrated	0.5 s uncalibrated 8 s calibrated
Polarisation		Full Stokes	Full Stokes
Minimum baseline (m)		7.7	7.7
Maximum baseline (m)		2 864	2 864
Angular resolution (1.5-km array)		~3 arcmin	~2 arcmin
Angular resolution (3-km array)		~2 arcmin	~1 arcmin

[a] Nijboer, Pandey-Pommier, & de Bruyn (2009).
[b] Based on the FWHM of the primary beam. Imageable area is significantly larger.

The dipole antenna of MWA has a collecting area of 1 square meter at 150 MHz. these dipoles are connected to beamformers where signals from these antennas are combined. Each of the beamformers generates two wideband analog outputs representing orthogonal linear polarizations.16 receivers are dispersed over the whole area; each receiver collects signals from 8 dipole antennas. The receivers are arranged in such a way that none of the antennas are more than 500 m away from their respective receiver. The receivers get power from the main 240 V circuit and send their signals through optic fiber links. The data from all 16 receivers are transmitted to data processing hardware. This signal is then sent to the correlator which sends its product to the real-time system for processing, which will generate real-time calibrated images every 8 seconds.

At the MWA site, there is a monitoring and control system that will maintain the schedule of observations and keep a record of system health. Images generated by the real-time system are then transmitted to the Pawsey High performance Computing center for SKA in Perth, where MWA has reserved data storage of 15 PB for 5 year time period (Tingay, Kaplan et al., 2013).

MWA has four key science goals which are as follows:

1. Detection of fluctuations in the brightness temperature of the diffuse redshifted 21-cm line of neutral hydrogen from the Epoch of reionization.
2. Studying galactic and extragalactic radio emissions to survey the full sky visible to the array.
3. Time-domain astrophysics through exploration of the variable radio sky (transients).

4. solar heliosphere and ionosphere imaging and characterization via propagation effects on background radio sources (Tingay, Kaplan et al., 2013).

To achieve all these scientific goals MWA needs to be maintained and upgraded on regular basis. In 2017 MWA was upgraded and phase II of MWA was deployed in which the number of antennas was doubled installing 128 more antennas making the total number of antennas 256. Among the newly installed antennas, 72 were deployed in the core area while the remaining 56 antennas are deployed in long baselines which will double the baseline of the array. these new tiles have improved the surface brightness and sensitivity of the array. Radio telescopes operating at a low frequency such as MWA are very convenient to upgrade as the frontend infrastructure is quite simple and easy to upgrade and install and the backend system can be upgraded as electronic technology is very rapidly improving bringing more sophisticated and efficient types of equipment (Wayth et al., 2018).

2.5 The Square Kilometer Array

In 1997, a Memorandum was signed by 8 institutions from 6 countries including Australia, Canada, China, India, Netherlands, and the U.S.A to cooperate in the program of building a very large radio telescope known as the square kilometer Array (SKA). The site chosen for SKA lies in the southern hemisphere that is South Africa and Australia. The advantage of these sites is that they give the best view of the Milky Way galaxy and have the least radio frequency interference (Barbosa et al., 2012).

SKA was built in two phases, and it consists of a variety of arrays including aperture synthesis arrays and dishes which will operate from a few tens to megahertz and gigahertz frequency range. The total collecting area of the SKA will be 1 square kilometer or 1,000,000 square meters hence making it the world’s largest radio telescope. To do so SKA will utilize hundreds and tens of dishes and low-frequency aperture arrays. instead of gathering all the telescopes in the core region, they will be arranged in spiral arm configuration in which the distance between dishes will be several meters building a long-baseline interferometric array. the reason for choosing spiral arm configuration is that it enables us to have different baselines and angles between antennas which will improve the resolution of the array. the random arrangement provides more baselines and angles between antennas, but the spiral arrangement is more practical and cost-effective, so it's preferred over the random arrangement.

Australia and South Africa being the primary sites for the SKA will have the phase 1 ok SKA. Australian Square Kilometer Array Pathfinder1 (ASKAP) is included in phase 1 which consists of 12m diameter dishes that are fitted out with phased array feeds hence giving a large field of view.   Meer Karoo Array Telescope is also part of phase 1 which consists of 13.5 m diameter dishes that are fitted with low noise single-pixel receivers, hence giving high sensitivity. In phase 1 only intermediate baselines will be utilized while expanding them to continental-sized baselines in phase 2. Some component arrays of the SKA will have an extremely large field of view which will enable us to picture very large areas in the sky simultaneously. Utilizing focal plane arrays using phased array technology will provide multiple fields of views which will help us to monitor multiple pulsars. Combining these two characteristics of a large field of view and high sensitivity will make SKA more efficient than any other telescope enabling us to survey large parts of the sky very rapidly.

For SKA all the dishes will be spread over thousands of kilometers while the aperture array antennas will stay in about 200km diameter from the core region in Africa and Australia. All the component telescopes will be connected to the central core which will gather data from all of them through correlators. These data packets will then be transported worldwide via high-speed links. Table 4 shows the number and type of different elements of SKA.

Table 4: Number and type of different elements of SKA

	phase 1	phase 2
dishes (0.45–3 GHz)	190 (South Africa) + 64 MeerKAT dishes	
	60 (Australia) + 32 ASKAP dishes	
dishes (0.45–10 GHz)		3000 (southern Africa)
low-frequency aperture array stations (0.07–0.45 GHz)	50 (Australia)	250 (Australia)
mid-frequency aperture array stations (0.4–1.4 GHz)		250 (southern Africa)

Some of the main scientific goals of the SKA area:

1. SKA is aiming to generate an image of 3-D volume via mapping of hydrogen with redshifted HI at 100-300 MHz.
2. SKA will generate a deeply detailed image of the lives of the galaxy and the dark energy.
3. Due to the frequencies at which SKA will operate and the high sensitivity it has it is possible to dig deep into star formation regions (Koenig, 2006).

Chapter 3

Chapter 3: The UAEU Ground-based Radio Array Facility

3.1 Introduction & Background

Astronomy is not just about observing celestial objects using light waves. Other parts of electromagnetic spectrum are of equal significance if we use proper equipment. Radio astronomy is the branch of science where we make use of radio waves from electromagnetic spectrum and study celestial objects. The main advantage of this type of study is that it can be done both on ground and in space, as this is one of those few electromagnetic waves that cross earth's atmosphere and reach to the ground. Radio astronomy deals between 10 MHz to approximately 100 GHz frequency range.

Radio astronomy facilities generally consists of instruments that are used to detect radio waves coming from celestial objects. This is done in the same way as we use a radio while tunning to a specific radio channel. The radio astronomers tune their instruments with the signals coming from a specific radio source in the universe. Signals collected by these detectors are enhanced and then converted into useful data with the help of special digital signal processing devices built for this purpose. All these equipment have a regular power supply. The whole setup for Radio observatory is usually built-in radio quite area to minimize the interference from man-made radio sources.

Previously radio telescopes were just considered to be large dishes collecting radio signals from universe. With the advancements in technology and induction of interferometry the field of radio astronomy has taken a new turn where along with large radio dishes small radio antennas are also coming in action proving astronomers with better resolution as they have a larger collecting area while using small radio antennas. Interferometric arrays are much cheaper, easy to maintain, and handle compared to large dishes which are difficult to move, maintain and construct as they involve complicated infrastructure.

With all these advancements made in the field of radio astronomy over the last decade several research organizations and universities have started developing their own radio observatories. Some of the famous research organizations working in radio astronomy and coming up with new research papers are Murchison-Widefield Array (MWA), Very Large Array (VLA), Long-Wavelength-Array (LWA), Low-Frequency Array (LOFAR) etc. are publishing their work in high impact journals worldwide. With each passing year these observatories are improving their facilities and coming up with more advanced equipment, open new doors of discoveries in the universe.

A major development in the field of astronomy started in 1997 when a memorandum was signed by eight leading universities from six countries including Australia, Canada, China, India, Netherlands, and the United States of America. Main theme of this memorandum was to build the largest radio telescope of the world using the phenomenon of interferometry known as square kilometer Array (SKA). Australia and South Africa being in the southern hemisphere were chosen as the sites for Phase 1 of SKA as these sites give a perfect view of Milky Way Galaxy and are considered as radio quite areas.

UAEU Radio Astronomy Pathway Project (URAPP) is a high-impact and marvelous space science research facility that is a joint project of the College of Science and National Space Science & Technology Centre (NSSTC) at UAE University (UAEU).

3.2 Astronomy & Space Science at UAEU

UAEU have all been trying to create opportunities for students in every field. Space sector being an emerging field in UAE was the main focus of UAEU. The thought behind building the Radio Astronomy Facility in UAEU was to promote space science education in UAE and provide students with some hands-on experience. UAEU Radio Astronomy Pathway Project (URAPP) is a fabulous radio astronomy research facility being built at UAEU which is a joint project of College of Science and National Space Science & Technology Centre. UAEU is now offering M.Sc. Space science course in collaboration with College of Science, College of Engineering, College of Humanities & Social Science (CHSS) and College of IT (CIT) at UAEU, with the support of National Space Science and Technology Center (NSSTC) providing an opportunity for those students who want to pursue their career in space sector.

This is a versatile program that is being offered for students and professionals belonging to different science and technology field. This program is a blend of classroom lectures, laboratory work, and hands-on experience related to space science in the form of internship program upon the completion of the degree. This program is designed in such a way that it covers almost every area related to space science to give the students a taste of different space related fields which will help them to decide about their inclination towards a specific area in space sector.

The UAEU Radio Astronomy Pathway Project (URAPP) being built at UAEU is of great significance as it will open new opportunities for students and researchers. It will give students and faculty members of UAEU the chance to be a part of a prestigious international level project and have on ground hands-on experience of radio observations. This facility will also provide a chance for researchers to track and monitor space objects which can help in spreading space situational awareness which is of key importance in space sector. This facility will also let researchers study about short time span phenomenon like pulsars, exploding stars etc. as this facility will lets us dig deep in the sky. The sun being the closest star will be another focus of this radio astronomy facility. Solar flares and sunspots can be studied using these equipment's. Planets in our solar system also emit radio emissions which help us to study about them in detail doing radio observations of different planets which are good radio sources. Near earth objects such as meteors, asteroids and space debris can also be tracked and monitor by using this facility and predictions can be made to avoid any damage from them. Space physics is another dimension that can be studied using UAEU radio facility including study of ionosphere. URAPP being such a versatile instrument will enable its students, faculty, and researchers all around the world to study each aspect of space science.

The main objective of UAEU is to fulfil lifelong learning needs of UAE and produce space graduates that can actively participate in coming space projects being initiated in UAE and provide necessary technical and research related support for all these projects. This facility will also be great source for collaboration between UAEU and international universities. While studying at UAEU students will develop necessary professional and educational skills that will help them excel in their respective fields.

3.3 The UAEU-Curtin University, Australia Collaboration for Radio Astronomy

The UAEU Radio Astronomy Pathway Project is a collaboration between UAEU and Curtin University Australia. Curtin University has been providing all the necessary support for the construction of radio facility at UAEU. This radio facility will be a part of international network of radio observatories called the Murchison Wide Field Array Consortium which consists of six member countries. This collaboration between UAEU and Curtin University will initiate high standard space research at UAEU. Later on, this facility will help UAE to become a part of SKA as well.

3.4 The MWA Connection

The Murchison Wide Field Array (MWA) is situated in western Australia in Murchison Radio Astronomy Observatory which is known best for its radio quite nature. MWA is one of the SKA precursors telescopes which was developed in two phases. This radio facility is already providing and publishing high impact papers about space science and is improving its facility day by day up advancements in technology. MWA has a special connection with URAPP as it has been constantly providing all the technical and scientific support for the construction of URAPP. The radio facility at UAEU is built on the same concept of MWA using same type of small dipole antennas that operate at low frequency and reach those parts of the universe that were not touched before.

3.5 The Emergence of the UAEU Ground-based Radio Array (GRAF) Project

UAEU is the first university in the middle east developing such a radio observatory on campus. This project is initiated with the development of a small-scale radio observatory which in future will enhance its capacity and will become a part of SKA. The main objectives of URAPP are building, commissioning and operating radio observatory in UAEU. This observatory will operate at low frequency same as MWA and its aim is to reach such a level of performance that it can be a part of international projects like MWA and SKA. URAPP will help students and researchers at UAEU to take full advantage of this radio facility for the purpose of research and education. Since this facility is present on campus it will provide students a better chance to be educated and trained for future radio astronomy projects.

3.6 The Initial Development of the UAEU Radio Array

The development of UAEU Radio Astronomy Pathway Project will be completed in different phases. Curtin University Astronomy department and MWA will be constantly proving necessary support during each phase of development and UAEU together with Curtin University will try its best to make this radio facility a part of international network of radio observatories and make it available for international researchers to take advantage of this radio facility.

During phase 1 a small-scale radio array will be built in the campus of UAEU. This phase is all completed in collaboration with the International Center for radio astronomy research (ICRAR) at Curtin University in Perth, Western Australia. This will be a low frequency array which like MWA will operate at a frequency range of 50-300 MHz. This array will make use of all the experience gained by MWA starting from its design, development, deployment, commissioning, and operations. During phase 1 only 128 MWA type dipole antennas will be deployed on the site of URAPP and made functional using the same design and technology as MWA.

During Phase 2 the main aim will be to make URAPP at part of Indian Ocean Rim Association (IORA) so that the array can make significant astronomy research in collaboration with Curtin University Australia and its way to the development of an operational radio array. This array later will be utilized for space situational awareness projects in

Indian Ocean. This project will also be carried out in collaboration with Australia being the main collaborator in URAPP while Mauritius will also be included in collaborators. Funds for this project will be obtained from IORA.

During Phase 3 with all the advancements made till that point URAPP will be ready to become a part of Murchison Widefield Array consortium. 21 institutions from six countries are already part of MWA consortium and then UAEU will be becoming a part of it paving way for other universities in UAE to develop such facilities and become part of this prestigious international collaboration. After this collaboration students and faculty members will start working with MWA and such programs will be started where students and faculty members will visit western Australia Radio Array site to gain advanced knowledge and expertise in the field of radio astronomy. Bring their knowledge and experience back to the country these students and faculty members will lead the research being carried out at URAPP and will generate valuable research work and data that will be available internationally.

After completion of all these phases the next aim will be to extend the radio facility to such an extent that it can generate revenue by offering special services to those who are interested in projects related to science and technology specifically space sector. The capacity of this radio array can be specifically utilized in space situational awareness projects. In addition to this the completion of this project will create a team of world class space scientist who can carry out sustainable and beneficial development in the field of science specially space science and become an asset for the nation.

Once completed this array will open new field of research for researchers in UAE paving way further development of such type of facilities in the country. It will be a flagship radio astronomy project in the whole region. Using this facility researchers will improve their understanding of our universe including stars, pulsars, blackholes, quasars, galaxies, planetary systems, earth atmospheres and near-earth objects and attain a significant position for UAE on international forum. After the completion of first three phases the next phase will focus on making URAPP a part of world's largest radio telescope SKA. This telescope has not yet been completed and is still under construction but once completed it will form one of the largest collaborations in the world. If we can do so this will open new doors for our students and researchers and will let them sit with prestigious international researchers in the field of astronomy. UAEU will lead the radio astronomy community in UAE and will create a consortium within UAE which can be presented on international level.

Chapter 4

Chapter 4: Preparatory Work for the UAEU Ground-based Radio Array Facility

4.1 Site Surveys and Selection

The UAEU Radio Astronomy Pathway Project (URAPP) was initiated in November 2019. It is a joint venture of UAEU and Curtin University, Australia. After the completion of the initial documentation, design, and configuration process the next and most important step was site selection. This step is not as easy as it seems, it's quite a difficult step as we must take into consideration different criteria. It requires a lot of work and time as the future performance of the array depends a lot on the location where it is located. A key factor that was considered in this phase of site selection was to choose a radio-quiet site where there is minimum radio frequency interference due to man-made radio sources especially the inference from FM as the array was designed to operate at a low-frequency range (Tingay, Kaplan et al., 2013). Another important thing was the view of the sky should be clear from the site and should comply with the scientific goals of the array. The site chosen should have the necessary infrastructure and power supply and receivers and other pieces of equipment should be close to the antennas. Ideally, short cables are used to minimize signal attenuation. The climate of the site is another important factor that should be kept in mind. For radio array sites dry climate is preferred and lower altitudes are preferred for low-frequency radio arrays. Considering all these factors four sites for the Radio Array were suggested which are as follows:

a. Sweihan (70 km Northwest of Al Ain).
b. Al Foah (30 km Northeast of Al Ain).
c. Site at UAEU Falaj Hazza campus.
d. NSSTC site at UAEU Al Maqam campus.

After conducting several site visits, surveys, and studies for all the four considered sites the NSSTC site was finalized as the site for Radio Array deployment. Every site had its own pros and cons, and numerous factors were considered while finalizing the site such as ease of accessibility, observational conditions, infrastructure, logistics, administrative matters including permissions from site managers and municipality, and most importantly radio interference. After taking into consideration all these factors NSSTC site was considered the best option since it had convenient access for all the staff and students and the previous infrastructure and other facilities of NSSTC were available to be used for array which helped in cost-cutting.

Once the site was finalized the next step was conducting radio observations and measurements for site characterization. Radio observations were conducted on the NSSTC site using a single element radio array coupled with a purpose-built testing system and Radio Frequency Interference testing equipment (Figure 10). Rohde & Schwarz FSH4 Spectrum Analyzer; Rohde & Schwarz HE300 Antennas, a single-element testing system was used for characterization of the array site. This observation was conducted with the cooperation of the College of Engineering. Dr. Aquib along with his team including Dr. Mahmoud F. Al Ahmad; Engr. Abdulrahman Daher; Engr. Abdulla Aldhaheri and several students conducted this observation for characterization of the site (Figure 10). This testing was done to predict the optimal performance of the Radio Array on the NSSTC site and to predict the array's behavior in the given physical environment while operating at a frequency range of 20-500 MHz. This observational test was also carried to out in the same frequency range to predict how would the Radio-array capture and monitor celestial radio emissions.

Figure 10: Characterization of Radio-Array site

After conducting radio observations on the NSSTC site and taking measurements by using testing equipment it was concluded that within the operating radio frequency range of the radio-array several clean sub-bands can be found which can be used to conduct a variety of astronomical observations (Figure 11). Along with this some very strong RFI sources (Figure 12) such as FM band were also pointed out which were obvious in this range at this location, but the good news is that they can be very conveniently filtered out. Since the chosen location is not situated in a remote area so background noise is also found as excepted. This background noise can affect the sensitivity of the instruments, but we can overcome this problem by increasing the time of integration.

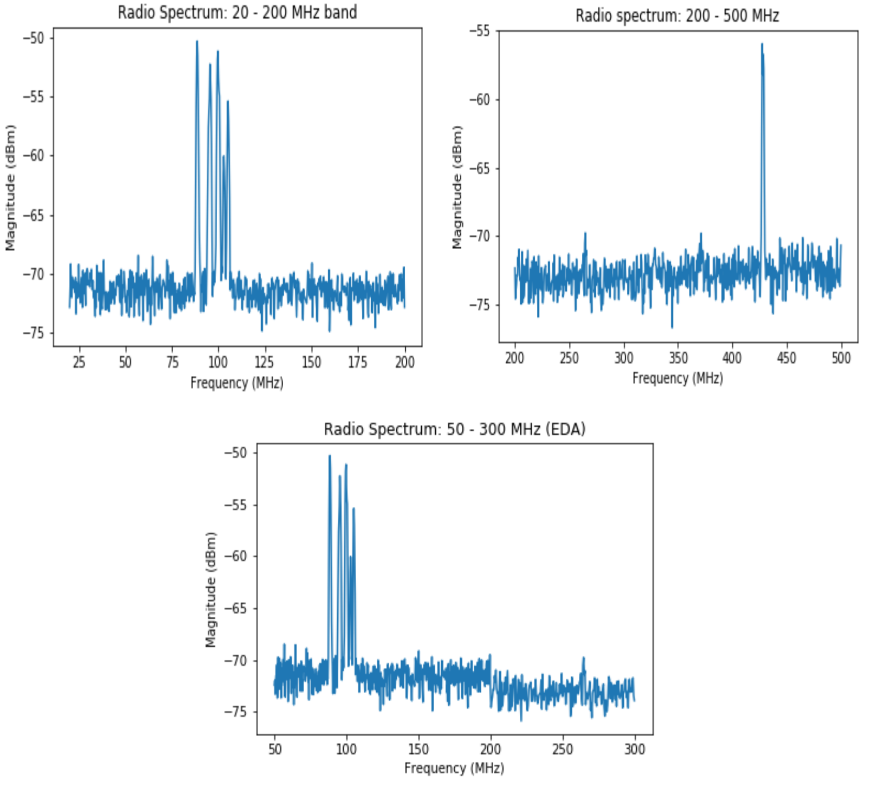

Figure 11: Clean bands identified during characterization of site

After conducting thorough testing for characterization of the Radio-array site it was concluded that this site had certain drawbacks in terms of conducting observations as it wasn't located in a remote area, there was a lot of radio frequency interference and the background noise but all these issues can be resolved one way or the other and once one starts counting the benefits of this site, it was far more advantageous compared to other sites as it was very easily accessible, most of the basic infrastructure required for the array was already present, and all the facilities previously existing on the site of NSSTC were already available for Radio array

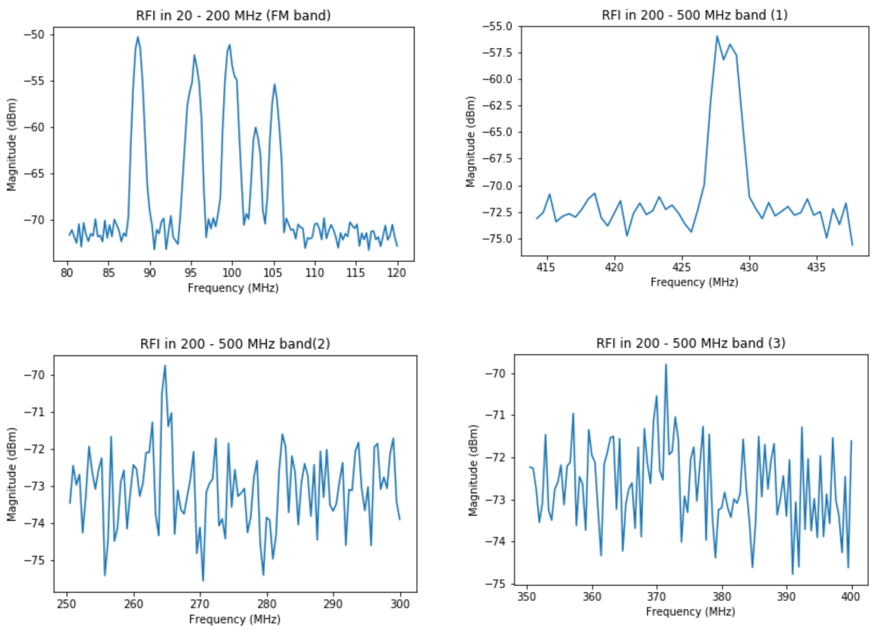

Figure 12: Sources of RFI in the Radio-Array band

4.2 Site Preparation

Once NSSTC was chosen as the site for Radio-array the next step was the preparation of the allotted area. For the array, a dry and flat surface was required so leveling of the site was initiated. All the civil works facilities were provided by NSSTC according to the agreement. Initially, the site was cleaned, and then compacting and leveling off the ground was done. A circular area was prepared for the radio array which was 40 meters in diameter. During this phase, NSSTC at UAEU supported the radio-array team to complete the work. Along with the preparation of the field, they had to dig trenches and lay ducts for cables from the radio-array site to the control room.

4.2.1 Civil Works

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4.2.2 Steel Mesh Grid

Initial work of site preparation was done and then in the next step, we had to obtain and place Steel mesh Grid. Two types of mesh were available to us, one was stainless steel hot dipped galvanized mesh wire and the second one was sprayed galvanized mesh wire. Hot dipped galvanized mesh wire was chosen as its resistant to corrosion and is long-lasting compared to sprayed galvanized. Special sheets of size 3 x 2.3 m were prepared for placement on the radio array field. The wires used in mesh flooring were 5 mm thick and a spacing of 5 cm was maintained between wires. For the preparation of the whole radio-array site, 196 steel mesh sheets were used out of which 148 sheets were completely used in the center area while 48 sheets were cut out to cover the circular sides of the Radio-array field (Figure 13).

Figure 13: Preparation of steel mesh floor at UAEU Radio-array site

4.3 Procurement of Array Equipment

The site preparation work was going in parallel when the next step was to procure equipment from Australia, the main collaborator of this project was initiated. Before we could start with the procurement process, we had to do some obligatory paperwork, approvals, and some other requirements that must be accomplished. Once all the formalities were done the procurement process was started. In this process, a container filled with radio-array equipment was shipped from Australia which finally arrived at the radio-array site in February 2021. This shipment included the following pieces of equipment:

- 256 bow-tie type dual-pol antenna and all their components.
- 16 Beamformers.
- 2 Beamformer controllers.

- 1 Kaelus second stage Beamformer.
- Cables and accessories.

Once the shipment reached UAEU it was thoroughly inspected and evaluated, and all the hardware was stored in a warehouse till the site was prepared for the deployment of this equipment.

Chapter 5

Chapter 5: The Deployment of the Radio Array at UAEU

5.1 The Radio Antenna Assembling

Once the site preparation and procurement process were completed the next phase was the deployment of the radio array. Deployment of the radio array consisted of multiple tasks starting from the assembly of the antennas, their positioning, and placement, connections of the antennas to beamformers and backend control system till the last step of the configuration of the array. The process of antenna assembly was started as soon as the shipment from Australia reached UAEU.

To involve students in assembly it was necessary to engage them at each step of radio array deployment and made sure that students participated actively and productively at every step. To assemble the 256 antennas a team of 25 students from B.Sc. physics, Space Science, and some other departments was created. This team was trained for the tasks they were given. Other students kept entering the team in coming semesters. Before students can initiate the process of the antenna assembly, they were given comprehensive training. Trainings were arranged virtually due to covid-19 restrictions by our Australian collaborators. These trainings continued for a period of one month before the students can start the assembly work.

To proceed with the assembly of antennas students used to gather at the radio array site at the UAEU campus where they were given the task of assembling a few antennas in the beginning as a practice. Later, once they became proficient in the assembling process, assembly of antennas at a bulk scale was initiated.

Figure 14: Assembly Training

By the end of July 2021 first Phase of radio-array deployment was done which included training the students for antenna assembly and giving them practice for it (Figure 14). After that in August 2021, the second phase was initiated in which 256 antennas were assembled at the bulk scale to be ready for placement on the radio-array site. Students used to gather twice a week for 3-4 hours to complete their given tasks:

1. Antenna assembling.
2. Attachment of parts.
3. Grid measurements.
4. Field placement of antennas.

All these tasks were being carried out by different groups in parallel to complete all tasks on time.

Figure 15: Bulk Assembling all the antennas

To accomplish the antenna assembly phase students were provided a space to work in UAEU Sports Complex on the male side of the UAEU Campus. Antenna assembly had two phases (Figure 15). Assembly of the central cup and then attachment of four legs to the central part. The central cup consisted of a column, a bottom lid, and the LNA which was fixed at the top of the cup. Each cup was supported on four legs with plastic caps at the bottom to protect the antenna from heat conduction through the legs from the metallic mesh floor.

5.2 The Radio Antenna Positioning

Along with antenna assembly, another task that was being done was antenna positioning. A group of students was assigned the task to mark accurately the positions of the antennae. They used specific positioning and measuring tools to mark the positions of all the 256 antennae. The positions of the antennas were provided by our collaborators at Curtin University, Australia. Figure 16 shows the positioning of the antennae. The antennae are arranged in such a way to get the required sensitivity and resolution for the array. They are more closely packed in the central part compared to the outer area.

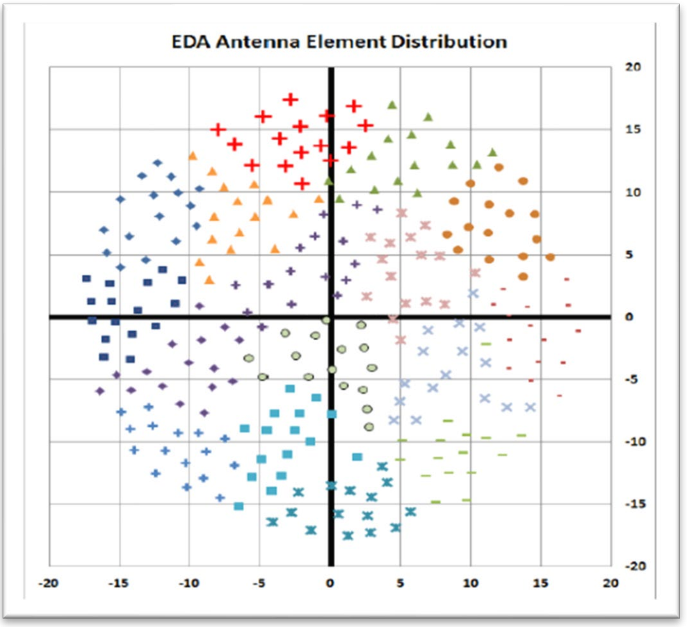

Figure 16: Positioning diagram of the antennae in the array

After completing the assembling of the antennas and marking the position on the mesh grid, the next step was the placement of the antennas on the mesh floor. During this phase, students worked together to place the antennas according to the positioning diagram on the mesh floor. The antennas need to be fixed on the mesh floor with the help of screws. A total of 256 antennae were assembled and deployed on the site by students of UAEU. This whole phase of assembling, positioning, and placement of the antennae was completed by October 2021 and the radio-array antennae were deployed at their respective site (Figure 17).

Figure 17: Placement of radio antenna

During the placement phase, another task that was being carried out in parallel was the connection of the antennae to the beamformers. All the 256 antennae were connected to 16 beamformers through cables. A group of 16 antennae was connected to a single beamformer. These 16 beamformers were then connected to the beamformer controller in the control room. This whole connectivity phase took almost one month and by the end of November 2021, all the antennae were connected to their respective beamformers (Figure 18).

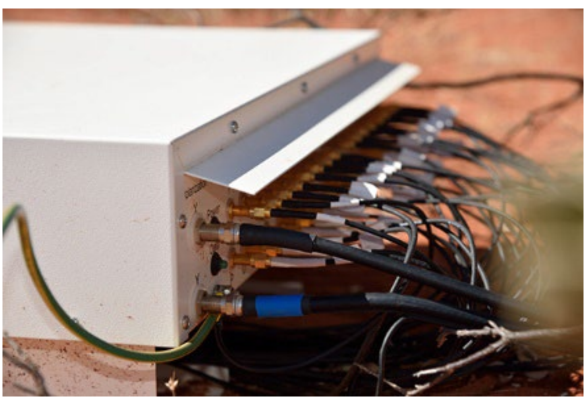

Figure 18: Beamformer connected to 16 antennas

5.3 The Radio Array Configuration

The next thing to be done was configuration and software installation on the radio-array server control system. This process was started while students were still working on making connections between antennae and beamformer and connecting the beamformer to the control system. Both these tasks were carried out in parallel with the help of DoIT and our collaborators in Australia. We required software to operate and maintain the radio array and for that purpose Linux, Ubuntu OS was installed. After completion of the necessary setup and configuration, the server was connected to the UAEU IT network, and the server administration scheme was completed where user accounts, access, utilities, and resources were provided.

Alongside this setup, connectivity of various other components of the backend of the radio array was also being carried out. Beamformer controllers, digital beamformers, signal digitizer, and digital beamformer controlled, all these pieces of equipment were shipped from Australia from our collaborators and were installed in the control room. After installation, these equipment was configured for the data flow. The purpose of this backend setup is to control the setup in the radio-array site by obtaining, arranging, and processing the raw data that the array will collect as a result of its observations. This whole setup will provide the data in a user-friendly format that will be understandable and will be used for analysis, modeling, interpretations, and research

5.4 The UAEU Radio Array on the Ground

Once the backend setup was complete, we can now say that the deployment phase of radio-array has been accomplished. This next phase that is currently underway is testing observations and measurements to commission the radio array and initiate its regular and official operations.

Currently, the cable and connectivity system are being tested and we are waiting for the new cables to be shipped from our collaborators in Australia. The commissioning phase will include the following events:

1. Antenna performance tests.
2. The signal path to field beamformers.
3. Connectivity tests and troubleshooting.
4. Signal acquisition and processing at the backend.
5. Hardware/software interface.
6. Radio-array control and operations through the Server system.
7. Data management, acquisition, and verification.

With all the efforts of our students and support from our Australian collaborators at Curtin university, it was possible for us to deploy the radio array and we will need their support in the future as well to complete the commissioning process and make the radio array operational.

Chapter 6

Chapter 6: The Radio Array Connectivity & Commissioning

6.1 The Radio Array Backend

A backend computing system is one of the major components of the radio array and it was necessary to maintain, operate and control the functions of radio array. The antennas and rest of the parts were procured from our collaborators in Australia but for backend computing system it was considered convenient to procure it from UAE's local market. It was an important step as it involved the procurement of a very technical, highly sophisticated, and high-performance backend system. The system was installed in a small room on radio array site that was built specifically for the installation of radio array backend system. This room was kept close to the antenna site to reduce the length of the cables from antennas to the backend computing system. After installation the process of setup and software installation was initiated along with the process of configuration. During this whole process DoIT played a very important role and helped us in connecting the server to UAE network to make the system ready for operations. After this the server was then connected with the array through various network switches and beamformer controllers.

Once the server was configured and software installation was done the team moved on to the connectivity of different components of the radio array backend hardware. This process involved the connection of beamformer controllers, digital beamformer, signal digitizer and digital beamformer controller. The main function of this backend computing system is to control the function of radio array. It will also acquire the data, then arrange it and process the raw data resulting from observations done with the radio array. The function of this system is to convert the data into useful form that can be used for analysis, interpretations, and research purposes.

Along with all these processes the backend system was also being connected to high performance computing system which includes computing server and the network switch. All these connections are made through ethernet to form a data flow between the computing system and the backend hardware. This setup was configured for data management and storage. This whole setup will help us to access the data anytime even from distant connection between the server and the user. This will help to interpret and analyze the data by using special software to produce useful results related to radio astronomy, astrophysics, space sciences, atmospherics science and different filed of astronomy and space sector.

6.2 The Radio Array Support Equipment

To install the support equipment of radio array NSSTC provide a space on the site of radio array where a control room was built to store and install all the support equipment of the radio array. It is advisable to have the support equipment close to the radio array site to reduce the length of cable from the array site to the control room. This will reduce signal attenuation due to long cables. The support equipment of the radio array includes the beamformers. They are present on the site of the radio array very close to the antennas. Each beamformer is connected to 16 antennas. These beamformers are then connected to the beamformer controllers which are installed in the control room. The beam formers are in turn connect to the second stage beamformers. In second stage beamformers signals from all the 16 beamformers are collected with necessary delays. This is done to obtain a phased-array signal from the whole array. The second stage beamformers provide two signal outputs one for each polarization.

6.3 Cable Connections

After the completion of the deployment of the radio array on the filed the next step to be initiated was the connection of the array elements. This activity involved the connections of 256 antennas to their respective beamformers. Each beamformer was connected to 16 antennas and there were 16 beam formers in total. The beamformers were in turn connected with beamformer controllers in the control room on the radio array site. The beamformers were connected to the beamformer controllers by using an RG 6 coax cables. The main purpose of beamformer controller is to provide power and communication to the beamformers on the field. These beamformer controllers are then connected to the second stage beamformers. This task of making connections between different element of the array was completed by the team of students working on radio array

Chapter 7

Chapter 7: Conclusion & Future Outlook

UAEU Radio Astronomy Pathway Project is one of its kind in the whole middle eastern region. The project that is built in collaboration with Curtin University Australia will open new doors of research in the space science sector in UAE. This project will escalate research in the fields of Radio astronomy, space science, space weather, atmospheric physics, astrophysics, etc. covering the themes ranging from research on galaxies, black holes, pulsars, quasars, solar system, planetary atmosphere, earth atmosphere, meteor, and near-earth objects, to radar applications and satellite tracking and positioning. This project is in line with UAE's national vision of being a significant part of the space sector internationally and enabling its population with education and training related to the space sector.

After completion of deployment of the array and making it operational the next step will be to make this array a part of the Murchison Widefield Array Consortium which will pave the path for UAE to become a part of the world's largest radio telescope Square Kilometer Array (SKA). This will be a breakthrough in the UAE space sector which will put the UAE on the global platform in the field of radio astronomy making it possible for the youth to excel in space science-related fields. This project will put UAEU as a pioneer in the field of radio astronomy in UAE and it will lead other institutions in the country to initiate projects related to radio astronomy. This will be a very significant step towards the formation of the UAE Radio Space Science Consortium formation in the UAE where different institutions from the country will work together on a different project of radio astronomy taking it to the next level in science and technology.

This project will let UAE appear on the international platform of advanced research in an area related to astronomy and space science and will attract researchers to UAEU from across the globe which will let it produce high-impact work on a global scale and improve the quality and quantity of publications. This project will initiate training, education, and research opportunities for students and will prepare Future generations equipped with skills related to the space sector by initiating academic and research programs related to this project. This project will not only accelerate research work in UAEU, but it will also initiate collaboration with industry and commercial organizations to provide them services related to the space sector the scope of which will include monitoring of space-borne targets, studies of stars, sun, and other celestial phenomena and all-sky surveys programs and campaigns. This facility will also improve space situational awareness and will make UAE capable of monitoring tracking its own space presence and also provide tracking and monitoring data to others.

The significance of this instrument is that it can act as both as a stand-alone instrument and as part of a global network of telescopes which will enable the UAEU to do international collaborations with existing radio observatories in the world. This instrument will also increase the importance of the UAE space sector in the middle eastern region as it's the only radio observatory being launched on this scale in the region which will be a part of the international consortium.

This project is very significant academically as it will let UAEU initiate multidisciplinary academic programs at the university which will help in providing educated and professionally skilled space scientists. Since this project is being built on the NSSTC site on the UAEU campus this will provide an opportunity for students and faculty members to gain hands-on experience while being part of the deployment and commissioning phase. It will also improve their technical knowledge about radio observatories around the world. It will also let the students to work with international collaborators and take advantage of their expertise and experience and gain significant knowledge and skills from them which will help them to grow the space sector.

This project will also be proved significant in improving communication systems. It will help us track and monitor near-earth objects such as meteors, asteroids, and space debris in the earth's atmosphere. It will also enable us to clearly study physical phenomena related to the interaction of some bear-earth particles. It will also let us study the ionosphere deeply at low frequencies where we will be able to study ionosphere reflections which play a vital role in space and terrestrial communication.

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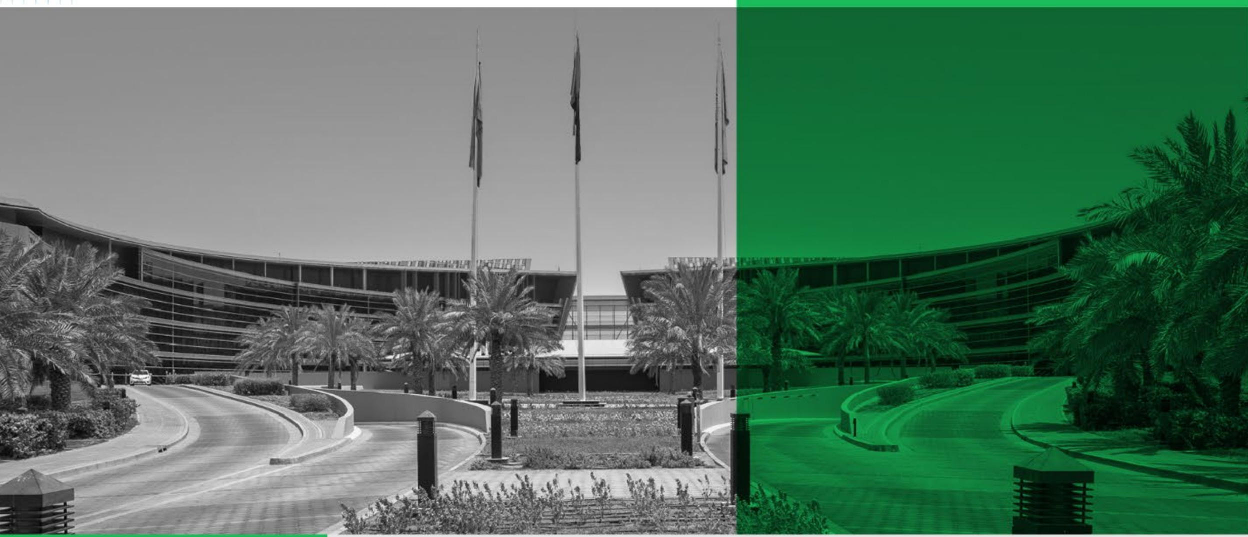

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