UNIVERSITI PUTRA MALAYSIA

INTERFEROMETRIC ARRAY PLANNING USING DIVISION ALGORITHM FOR RADIO ASTRONOMY APPLICATIONS

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

January 2017

DEDICATION

All those individuals who behind the scene make me possible to complete my study successfully.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

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In order to measure the fine angular detail in the radio frequency range from the sky, two-element interferometers which form radio interferometers and synthesis array are utilized. The angular resolution of a single telescope does not provide sufficient information for astronomy applications, therefore a synthesis array or radio interferometers is used to fulfil the aim of the end users.

The light waves from very distant stars or galaxies take a long time to travel through space to our telescopes; therefore it makes limitation to astronomers to visually observe light waves in time. They are seen as they were a very long time ago.

This issue leads astronomers to build more powerful telescopes to visually recognize the first stars and galaxies formed. In terms of existing correlator array antenna like the Giant Metrewave Radio Telescope (GMRT), expansion of the array is required to obtain higher resolution. A project of the Square Kilometre Array (SKA), which involves more than ten countries worldwide, is the most powerful radio telescopes array to date. It will observe the blue sky and produce images from radio waves with very high resolution. However, the position of the telescope limits the image quality and has a direct effect on the sidelobe levels (SLLs).

In this thesis, we focus on the design procedure of algorithms and new methods of a correlator antenna array in radio frequency. It includes the process of designing the proposed algorithm and methods assisted interferometric, and how it can be implemented in a correlator antenna array and SKA scenario. The ability of the proposed receiver to suppress the severe effect of the SLL, increasing the u-v plane coverage, and smoothening out the linear ridges in u-v plane coverage at snapshot or low duration of observation is demonstrated through simulation. The algorithms and methods were

developed using Matrix Laboratory (Matlab) software, and the proposed position of the array was evaluated using Astronomical Image Processing System (AIPS) software.

This proposed method can be used as an application for astronomy projects such as SKA. This application lets the scientists to observe the sky according to the suggested configurations with the optimum enhanced image. New Zealand, Australia and 8 other African countries are involved with this project. It would be useful for Malaysia to be involved in this project in the context of astronomical observation.

In this thesis we also propose a new theory of localization an array of antennas for astronomy applications to suppress the side lobe levels and/or increase the samples in u-v plane coverage. The proposed methods optimize the data samples and minimize the side lobe levels in the angular domain to enhance the image quality as much as possible in addition to smoothen the linear ridges.

The first method uses the optimization of the array configuration problem with various changes of coordinates in a specific area with GMRT's arms as an illustrative example. The results show that spiral configurations give very good results in both aspects of u-v plane and side lobes. It is found that a spiral configuration result in less overlapped samples in both snapshot and hour-tracking observations than the antennas placed along three arms of the GMRT with 21.98% and 34.84% of overlapped samples at the snapshot and the hour-tracking observations, respectively. Using the arms of current GMRT configuration the spiral configuration reduces the first side lobe from -13.01 dB to -15.64 dB and the 5-arm spiral configuration has the minimum value of the first three side lobes and the peak side lobe of -17.68 dB and -11.64 dB, respectively.

In the second scheme, a genetic algorithm is developed, in order to optimize a correlator array of antennas by using Genetic Algorithm (GA). The algorithm is able to distribute the u-v plane more efficiently than GMRT with 49.77% overlapped samples. The calculated parameter of the overlapped samples for hour-tracking varies from 74.12% for GMRT, to 58.46 % for 25th generation configuration, and 53.36% 150th generation configurations. Finally, the algorithm is able to reduce SLL to -25.23 dB.

The third method develops a new algorithm named Division Algorithm (DA) to solve the optimization problems. The parameter of overlapped samples is valued at 50.11% compared to the GA (53.36%) for 6-hour tracking observation. The values of the first SLL, mean values of the first three SLLs, and peak SLL are -25.23 dB, -23.07 dB, and -21.74 in 150th generation using GA and -31.55 dB, -25.42 dB, and -22.14 dB in DA array, respectively. It shows that the DA outperforms SLL in decreasing the SLL.

The above methods are expanded to extend the interferometric array to investigate the feasibility of extending the interferometric array and 10 numbers of antennas that would be deployed in Malaysia.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PERANCANGAN PELBAGAI INTERFEROMETRI MENGGUNAKAN ALGORITMA BAHAGIAN UNTUK APLIKASI ASTRONOMI RADIO

Oleh

SHAHIDEH KIEHBADROUDINEZHAD

Januari 2017

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Untuk memperolehi pengimejan astronomi terperinci dalam frekuensi radio, penggunaan interferometer radio dan sintesis boleh diaplikasikan, Teknik ini menyedikan resolusi yang lebih tinggi berbanding pengunaan teleskop tunggal.

Gelombang cahaya dari bintang dan galaksi yang sangat jauh mengambil masa yang lama untuk tiba di teleskop. Ini menghadkan penyelidikan objek-objek tersebut kerana radiasi yang diterima berasal dari masa yang amat lampau.

Isu ini memberi inspirasi kepada ahi-ahli astronomi untuk membina teleskop yang lebih hebat untuk memerhati dan menyelidik antara bintang dan galaksi yang terawal. Untuk susunan antenna secara 'array' seperti Giant Metrewave Radio Telescope (GMRT), ia perlu dinaikantaraf untuk mendapatkan resolusi yang lebih tinggi. Projek seperti 'Square Kilometer Array' (SKA), yang melibatkan lebih dari sepuluh buah negara di seluruh dunia, adalah teleskop radio array yang paling berkuasa setakat ini. Ia mampu memerhati angkasa lepas dan menghasilkan imej radio dengan resolusi yang sangat tinggi. Namun, susunan dan lokasi teleskopnya di dalam array yang disusun menghadkan kualiti imej dan mempunyai kesan langsung terhadap tahap sidelobe (SLLs).

Dalam tesis ini, tumpuan diberikan kepada prosedur reka bentuk algoritma dan kaedah baru bagi 'correlator' antena array pelbagai frekuensi. Ini termasuk proses merekabentuk algoritma yang dicadangkan dan kaedah interferometer terbantu, dan bagaimana ia boleh dilaksanakan di dalam antena array tatasusunan dan SKA. Keupayaan penerima yang dicadangkan bagi tujuan untuk menindas kesan SLL, meningkatkan keluasan uv, meratakan rabung linear dalam kawasan uv bagi kaedah 'snapshot' dan bagi memperolehi tempoh cerapan singkat akan didemonstrasikan melalui simulasi.

Algoritma dan metodologi asas dibina dengan menggunakan perisian Matrix Makmal (Matlab), dan cadangan posisi bagi 'array' dinilai menggunakan Astronomi Sistem Pemprosesan Imej perisian (AIPS).

Kaedah yang akan dicadangkan ini boleh digunakan untuk projek-projek astronomi seperti SKA. Aplikasi ini membolehkan para saintis mendapatakan imej yang lebih jelas. Bidang kajian astronomi di Malaysia boleh mendapatkan manfaat seperti yang dirasai oleh New Zealand, Australia dan 8 negara Afrika lain jika ia terlibat dengan projek ini.

Dalam tesis ini, adalah dicadangkan suatu teori baru bagi penyetempatan antena array untuk aplikasi astronomi untuk menindas tahap lobus sampingan dan / atau meningkatkan sampel dalam liputan pesawat uv. Kaedah yang dicadangkan mengoptimumkan sampel data dan mengurangkan tahap lobus di sebelah domain sudut bagi meningkatkan kualiti imej yang sebanyak mungkin di samping perataan rabung linear.

Kaedah pertama menggunakan pengoptimuman konfigurasi pelbagai dengan cadangan pada perubahan koordinat di kawasan tertentu pada lengan GMRT sebagai contoh bagi ilustrasi. Keputusan menunjukkan bahawa konfigurasi lingkaran memberikan keputusan yang cemerlang dalam kedua-dua aspek pesawat uv dan sidelobes. Didapati bahawa terdapat pengurangan dari aspek penindanan sampel bagi kedua-dua kaedah snapshot dan pencerapan berterusan apabila dibandingkan dengan keadah di mana antena diletakkan di sepanjang tiga lengan GMRT. Pengeurangan adalah masing-masing, kurang daripada 21.98% dan 34.84%. Menggunakan lengan konfigurasi GMRT terkini, konfigurasi lingkaran mengurangkan sidelobe pertama dari -13.01 dB ke -15.64 dB dan konfigurasi lingkaran 5-lengan mempunyai nilai minima tiga sidelobes pertama dan sidelobe puncak sebagai -17.68 dB dan -11.64 dB, masing-masing.

Untuk kaedah kedua, algoritma genetik (GA) dibina untuk mengoptimumkan correlator antena array. Algoritma ini mampu menyediakan kawasan cerapan uv yang lebih efisien berbanding GMRT dengan kurang dari 49.77% sampel bertindih. Parameter pertindihan bagi pencerapan berterusan adalah 74.12% untuk GMRT, 58.64% untuk konfigurasi generasi ke-25, dan 53.36% untuk konfigurasi generasi ke-150. Akhir sekali, algoritma ini mampu mengurangkan SLL kepada -25.23 dB.

Kaedah ketiga membangunkan algoritma baru yang bernama Algoritma Division (DA) untuk menyelesaikan masalah pengoptimuman. Sampel bertindih dinilai pada 50.11% berbanding dengan GA (53.36%) untuk pencerapan selama 6 jam. Nilai SLL pertama, nilai-nilai min bagi tiga SLL pertama, dan puncak SLL adalah -25.23dB, -23.07 dB, dan -21.74 dB masing-masing dengan generasi ke-150 menggunakan GA dan -31.55 dB, -25.42 dB, dan -22.14 dB masing-masing dalam DA array. Ia menunjukkan bahawa DA menunjukkan prestasi yang lebih baik dari SLL dalam mengurangkan SLL.

Kaedah-kaedah di atas juga digunakan untuk mengembangkan interferometer array untuk mengkaji kemungkinan untuk membina 10 antena yang boleh digunakan sebagai array pertama bagi kajian astronomi radio di Malaysia.

ACKNOWLEDGEMENTS

First and foremost, I praise and acknowledge Allah, the most beneficent and the most merciful.

Secondly, I would like to express my special appreciation and thanks to my advisor, Professor Dr. Nor Kamariah, you have been a tremendous mentor for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your advice on both research as well as on my career has been priceless. I would also like to thank my committee members, Assoc. Prof. Ir. Dr. Aduwati Sali, Dr. Zamri for serving as my committee members even in hardship.

Finally, a special thanks to my family. Words cannot express how grateful I am to my mother and father for all of the sacrifices that you've made on my behalf. Your prayer for me was what sustained me thus far. I would also like to thank all of my friends who supported me in writing, and incited me to strive towards my goal. At the end, I would like express my love to my dear and loving husband, Adib.

I certify that a Thesis Examination Committee has met on 19 January 2017 to conduct the final examination of Shahideh Kiehbadroudinezhad on her thesis entitled "Interferometric Array Planning using Division Algorithm for Radio Astronomy Applications" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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2-circle	2-concentric circles
3-arm	spiral 3 arm
3-circle	3-concentric circles
5-arm	spiral 5 arm
ACO	ASKAP Configuration Option Recommendations
ADS	Almost Difference Sets
AIPS	Astronomical Image Processing System
ALMA	Atacama Large Millimeter/submillimeter Array
ASKAP	Australian SKA Pathfinder
BDCT	Block Discrete Cosine Transform
CS	Compressed Sensing
DA	Division Algorithm
DSs	Difference Sets
GA	Genetic Algorithm
GMRT	Giant Metrewave Radio Telescope
ILPSO	Inheritance Learning Particle Swarm Optimization
Matlab	Matrix Laboratory
MPSO	Multi-population Particle Swarm Optimization
MWA	Murchison Wide field Array
NRAO	National Radio Astronomy Observatory
OMP	Orthogonal Matching Pursuit
PSF	Point Spread Function
psfrms	Root Mean Square value of the Point Spread Function

RGA	Real coded Genetic Algorithm
rms	Root Mean Square
SKA	Square Kilometre Array
SLL	Sidelobe Level
SLLs	Sidelobe Levels
VLA	Very Large Array

CHAPTER 1

INTRODUCTION

A communication system that employs several antennas has been recognized as an appropriate mechanism to enhance the system directivity of new wireless communication technologies.

High-resolution telescopes are necessary for long-distance communication. The size or number of telescopes must be increased to obtain a high resolution for observation. The former approach is difficult or nearly impossible, whereas the latter is feasible.

Therefore, array antennas that consist of *n* number of antennas are utilized (Balanis 2010; Stutzman and Thiele 1981; Collin and Zucker 1969; Elliott 1981; Johnson and Jasik 1984). Two types of antenna arrays are currently available: phased and correlator arrays. Phased-array antennas have an important role in wireless communication systems as tracking beam antennas that can primarily be adopted in a proper beam steering system. These antennas have been utilized mainly for wideband and narrowband applications, such as satellite and radar communication systems, respectively. In particular, the amplitude weights in the phase array remain constant, and only the phases are changed as the beam is steered (Kyun et al. 2002). A correlator array of antennas has been studied in radio astronomy because of its high data-gathering efficiency (Jin and Rahmat-Samii 2008).

1.1 Background

Studying celestial objects is the scientific domain of astronomy, and observing them at radio frequency is called radio astronomy. The radio frequency is the preferred range due to the simplified observation of the planet Earth. This frequency ranges from approximately 3 kHz to 300 GHz. Several frequency ranges, such as X-ray and gamma rays, are blocked by the atmosphere before reaching the Earth, whereas others (e.g., infrared) are absorbed by the atmosphere.

One of the most important aspects that must be considered in designing an antenna array is the array configuration. The most popular example of this array type is the Giant Meterwave Radio Telescope (GMRT), which is located 80 km north of Pune, India (19° 5'47.46" N 74° 2'59.07" E). The GMRT has an open-ended configuration, resembles a Y shape, and has 30 parabolic dish antennas at 45 m in diameter each.

Antennas must be located in the GMRT based on several factors. The two main factors are obtaining the maximum coverage in the spatial frequency domain and the size of the sources to be studied. Long baselines are adopted for small sources, whereas short baselines are used for extended sources. Given that the antenna locations in the GMRT are fixed, both compact and extended arrays are employed to meet the desired requirements (Swarup et al. 1991).

A total of 14 antennas are located randomly in an area of approximately one square kilometer in this array. The remaining 16 dishes are extended along the three arms with the largest baseline of approximately 25 km. The operating frequency ranges of the GMRT are approximately 50, 153, 233, 325, 610, and 1,420 MHz, which are metered wavelengths and within the radio frequency ranges.

With the increasing demand for observing events and sources in space with high resolution, large-scale radio telescopes, such as the Square Kilometer Array (SKA), intend to utilize and optimize correlator antenna arrays. These issues have prompted researchers to develop telescope configurations that can observe the first stars and galaxies that have been formed. Many researchers have focused on the antenna array location in the literature. However, optimizing an interferometric array of next-generation antenna arrays, such as SKA, is still a crucial and challenging research issue to be solved.

Correlator antenna arrays for radio astronomy applications have been studied in depth and are well-documented over the past 60 years. Designating such an array consists principally of selecting the antenna localization in the array. An ideal arrangement must ensure optimal configurations to capture a clear image of a radio point source by either decreasing the side lobe level (SLL) in the *l*-*m* domain or increasing the sampled data in the spatial frequency domain, which is referred to as *u*-*v* plane coverage (Jin and Rahmat-Samii 2008).

Although various techniques have been developed for the synthesis of correlator arrays (Cohanim et al. 2004; Gauci et al. 2013; Jin and Rahmat-Samii 2008; Karastergiou et al. 2006; Oliveri et al. 2010; Sodin and Kopilovich 2002; Su et al. 2004), few studies have been conducted on optimizing the configuration of an interferometric array, which considers all desired requirements of smoothening linear ridges at snapshot observation, increasing the *u*-*v* data samples in the spatial frequency domain, and suppressing SLLs in the angular domain. An optimized configuration can attain a maximum *u*-*v* plane coverage in both observations and minimum SLL.

Karastergiou et al. (2006) presented the most appropriate *u*-*v* plane sampling for astronomical imaging based on the ideas of Keto (1997) and Boone (2001, 2002) for low-density interferometers without considering SLL suppression. Particle swarm optimization was applied to an interferometric array for radio astronomy applications by Jin and Rahmat-Samii (2008). The said researchers applied the algorithm on closed-arm and open-arm configurations, which shows that deploying antennas on three arms unequally can provide better *u*-*v* plane coverage with lower SLLs than placing antennas on three arms equally. The algorithm was run separately for each observation to attain maximum *u*-*v* plane coverage. Beardsley et al. (2012) proposed a Bessel decomposition-based algorithm that is sensitive to large-scale over and under densities in the *u*-*v* plane without considering minimizing SLLs. Gauci et al. (2012) utilized a genetic algorithm (GA) to determine the optimal configuration of the planned 250 and 3,000 dishes to be located in Phases 1 and 2 of the SKA, respectively. A new theory of compressed sensing was introduced by Fannjiang (2013) by utilizing orthogonal matching pursuit to solve the incomplete sampling of the Fourier plane by radio interferometry. Genetic optimization was applied to the radio interferometer configuration that considers the cable length constraints by Gauci et al. (2013). The algorithm was utilized to obtain the optimum solutions for *u*-*v* density distribution and point-spread function for the SKA. The said method was designed to work on several specific constraints and for a special array.

The more complicated problem of optimizing a correlator array that bears on all possible observation conditions, such as the lowest SLL in the angular domain (*l*-*m* domain) and maximum coverage in the spatial frequency domain (*u*-*v* domain), has been considered only recently. Therefore, the current thesis focuses on optimizing an interferometric array of antennas, especially in the two main aspects of maximizing the *u*-*v* sample distribution in the spatial frequency domain in both observations and minimizing SLLs in the angular domain.

The rest of this chapter is organized as follows. The problem statement of the thesis is covered in the next section, which is followed by the list of objectives. The third section covers the brief methodology and scope described in this thesis. Finally, the thesis organization is presented.

1.2 Problem statement

The following problems are considered in this thesis:

1. The sensitivity to a celestial source is proportional to the effective collecting area of an antenna multiplied by the number of antennas. Utilizing a greater number of antennas provides higher sensitivity, but only a certain number can be used because of the high cost of building up each antenna in practice. The data samples when observing an object can overlap based on the location of each antenna. Therefore, a crucial technique is to design an optimized configuration with less overlapped data to obtain extensive object information.
2. The high signal-to-noise ratio (SNR) and maximum resolution value can be obtained when the Fourier domain within the boundary is sampled uniformly. Incomplete sampling or linear ridges indicate non-uniform sampling. This lack of information can cause the image to have errors that are completely different from those caused by noise. Linear ridges of the *u*-*v* plane coverage provide less object information at snapshot observation or low-duration

observations. Therefore, this drawback must be considered when designing such an array.

3. The imaging qualities of an interferometric telescope are dictated by the characteristics of the synthesized beam. These characteristics depend mostly on the localization of the antennas that comprise the telescope and coordinates of the astronomical source during an observation. However, suppressing the SLL in the angular domain plays an important role in designing correlator array antennas.
4. The position of each added antenna to the current configuration attempts to improve the system resolution in existing correlator array antennas, such as the GMRT. If the existing array must be expanded to obtain a higher resolution, where would the additional locations be set to increase the *u*-*v* plane coverage and decrease the SLLs simultaneously?
5. An interferometric array with a curved shape of constant width provides better sensitivity than that with a Y shape. The GMRT has an open-ended arm with a Y shape, where the linear ridges in the *u*-*v* plane coverage are not smooth at snapshot observation. Therefore, obtaining the highest SNR and resolution must be considered during the extension of an interferometric array such as the GMRT.
6. An optimized configuration must provide high sensitivity to a point source, angular resolution, SNR ratio, and sampling accuracy, which can be utilized in either the snapshot observation or hour tracking. This scenario implies that the configuration can provide an optimum solution in both observations with one running algorithm or by utilizing a specific configuration.

These are the main problems that have recently prompted researchers to investigate an optimized array that considers all of the aforementioned aspects.

1.3 Objectives

This thesis attempts to investigate an optimized configuration of an antenna array for astronomy applications. The design of such an array involves main technical requirements that include linear ridges, overlapped samples, sample distribution, and SLLs. This thesis focuses on the issue of designing a correlator array of antennas with the following specific objectives:

1. To increase the sensitivity of an antenna array to a point source (e.g., SKA) with less overlapped data.
2. To design and develop high reliability, sensitivity, SNR, and distributed data ratio on the *u*-*v* plane to observe the radio frequency range.
3. To design an interferometer with a curved shape of constant width to provide better sensitivity to obtain a better range of *u*-*v* samples.

4. To develop new formulas in GA and a new algorithm to enhance the image by decreasing the SLL and increasing the sampling accuracy on the *u*-*v* plane to meet the desired requirements. These requirements include maximizing the resolution, SNR, and sampling accuracy in the snapshot and hour tracking observations.

1.4 Brief methodology

The number of antennas and effective collecting area of each antenna must be increased to ensure high sensitivity to a celestial source. The required information on the celestial object is provided by each ellipse that connects every two antennas in a correlator array. However, the larger ellipse number provides improved coverage of the u-v plane. A larger ellipse number involves utilizing more antennas, but only a certain number of antennas can be used in practice because of the high cost of building each antenna. The data samples when observing an object can be overlapped because of the location of each antenna. Therefore, designing an optimized configuration with the most accurate data sampling, as well as the highest SNR and resolution to obtain more information about the object, is a crucial technique.

Designing an interferometer with a curved shape of constant width provides improved sensitivity to obtain a better range of *u* and *v* samples than that with a Y shape. The most common properties of the imaging system must be considered, such as resolution, SNR, and sampling accuracy, in designing the configuration of the antenna spacing. The antenna configuration must have equal resolution in all directions to obtain a high-resolution image. However, the samples on the *u*-*v* plane must be circularly symmetrical to attain this goal (Keto 1997).

The other two properties show that the Fourier plane within this boundary must be sampled uniformly. The high SNR and maximum value of the resolution can be obtained when the Fourier domain within the boundary is sampled uniformly (Thompson et al. 2008; Keto 1997).

However, the highest SNR and resolution can be provided simultaneously if the Fourier plane is sampled uniformly. By contrast, an interferometric array obtains samples from the Fourier components discretely; incomplete sampling indicates a non-uniform sampling. This scenario results in samples being located at several areas on the *u*-*v* plane with higher densities (i.e., overlapped sampled data) and creating wider gaps in other areas. This lack of information leads to errors in the image, which are totally different from the errors caused by noise (Keaton 1997). An interferometric array with a curved shape of constant width provides better sensitivity than that attained with a Y shape.

The optimization of the array configuration problem with different changes in the coordinates is proposed for a specific area with the GMRT's arms to attain an optimized configuration and is shown as an illustrative example in Chapter 3. The Earth rotation effect is included to simulate the hour-tracking observations of the radio source with the same time duration and source declination, which results from the 16 antennas spread out along the three GRMT arms. The current chapter aims to provide an easy and flexible way to optimize an interferometric array and meet the desired requirements with one solution. Results show that spiral configurations provide suitable results in both aspects of the *u*-*v* plane and SLLs. A spiral configuration results in less overlapped samples in both snapshot and hour-tracking observations, as well as low SLLs than the antennas placed along the three GMRT arms.

The GA aims to identify a parameter set that optimizes the function output. Given several GA characteristics (e.g., functioning with a population of candidate solutions instead of a single solution, using the random transition technique and not deterministic search, and providing reasonable results), this algorithm has been selected as the primary focus of this chapter (Cohanim et al. 2004; Haupt 1994; Jones 2003; Jain & Mani 2011). Further information on the GA and its operators are provided by several books and papers (e.g., Jones 2003; Pan 2002). Therefore, a GA is developed in Chapter 4 to determine the optimum solutions for an interferometric array for radio astronomy applications. This study concentrates on the configuration problem to optimize an interferometric array (e.g., GMRT) by using GA. This algorithm can distribute *u*-*v* samples in the spatial frequency domain to improve the image quality. In particular, the algorithm determines the optimum solutions of the antennas in a specific area similar to the GMRT's. Moreover, the algorithm attempts to distribute the *u*-*v* coverage and suppress the SLLs from its first generation. The algorithm can distribute the *u*-*v* plane more efficiently than the GMRT. The calculated parameter of the overlapped samples for hour tracking shows that the algorithm can improve the distribution samples because it works with more generations. Finally, the algorithm can lower SLLs.

A new algorithm called division algorithm (DA) is developed in Chapter 5 to solve the optimization problems. Unlike the GA, the proposed algorithm can improve the overlapped samples and unsampled cells at snapshot observation. Results show that the DA configuration can also improve these two parameters for a 6-hour tracking observation. The results from the calculated SLLs show that the DA can decrease the SLLs better than the GA.

Suitable solutions to extend an interferometric array are investigated in Chapter 6 by utilizing the aforementioned methods and then applying them to 10 antennas to determine the antenna coordinates in Malaysia. All of the aforementioned methods to change the configuration by following the spiral formula, GA, and DA are applied to the interferometric array in the said chapter. The mathematical results suggest that the spiral configuration is an optimum arrangement that provides the desired requirements of suitable *u*-*v* coverage with low SLLs. The calculated SLLs show that the spiral has lower SLLs than the extended GMRT, and the linear ridges at snapshot are smoother than those of the extended GMRT. This approach can smoothen the linear ridges. The GA is then applied to the interferometric array. The results (different results of the *u*-*v* plane coverage) shown in the related chapter indicate that the GA extended configuration performed better than the extended Y shape, which increased the coverage of the *u*-*v* plane and suppressed the SLLs. This scenario means that the algorithm can improve the overlapped samples because it works with more generations. As the generation number increases, the unsampled cells are also enhanced. Finally, the DA is applied to such an array. Calculated results in a related chapter show that the DA can obtain sampled data with less overlapped data at snapshot observation unlike all the discussed configurations in the current chapter. This condition means that the algorithm can improve the overlapped samples more efficiently than the GA. The calculated SLLs show that the DA can be more efficient than the GA.

Moreover, we expect that the proposed methods in Chapter 6 can optimize the data samples and minimize the SLLs in the angular domain to enhance the image quality as much as possible. The methods discussed in this thesis are applied to 10 antennas to determine the antenna coordinates in Malaysia. The results indicate that the DA can improve the overlapped samples more efficiently than the GA for a 6-hour tracking observation.

As mentioned, the unsampled cells are enhanced as the generation number increases. However, this percentage is the same at the snapshot and 6-hour tracking observations in both algorithms, which show the same efficiency as that of the GA. The SLL values indicate that although the GA can decrease the SLL better than the DA, the latter algorithm can obtain reasonable SLLs and optimum parameters in the spatial frequency domain with the same population. Thus, the DA can obtain a configuration that provides almost all desired requirements in both the spatial frequency and angular domains.

1.5 Scope of thesis

Designing an interferometric array is the main objective of this thesis, which considers all possible performance metrics, such as the lowest SLL in the angular domain (i.e., the l-m domain), increase in the sensitivity of an antenna array to a point source, and increase in the SNR ratio and distributed data ratio on the u-v plane to observe the radio frequency range and maximum coverage in the spatial frequency domain (i.e., the u-v domain). To the best of our knowledge, a study on the integration of the aforementioned factors into one solution has yet to be published. Therefore, this thesis attempts to investigate various solutions to optimize such an array by considering almost all possible performance metrics.

This thesis develops a scheme to optimize the desired requirements for astronomy applications, such as decreasing the SLLs, and increasing the *u*-*v* plane coverage, sensitivity, SNR, and distributed data ratio on the *u*-*v* plane to observe the radio frequency range, as well as smoothing out the linear ridges on the *u*-*v* plane coverage at snapshot or low-duration observations. The said scheme also proposes a new method to minimize the SLL and maximize coverage in the spatial frequency region. Several approaches are proposed to achieve these objectives. One method is to optimize the array by considering that all possible observation conditions change the antenna positions in certain mathematical models. Various configurations are presented to render the effectiveness of the method in designing a correlator wearable with typical open-terminated and closed configurations. The said output can be attained by changing the optimum arrays that outperform habiliment arrays and represent existing designs. An interferometer with a curved shape of constant width is proposed to provide improved sensitivity by obtaining a better range of *u* and *v* samples. High reliability, sensitivity, SNR, and distributed data ratio on the *u*-*v* plane to observe the radio frequency range are obtained because of the low overlapped samples and suitable distributed samples. We then focus on optimizing the array configuration problem by utilizing GA, which can solve this problem and maximize the resolution, SNR, and sampling accuracy in the snapshot and hour tracking observations. The proposed algorithm and guidelines on how the algorithm works for a full array design are also explained. This algorithm attempts to distribute *u*-*v* samples in the spatial frequency domain to improve the quality of the simulated point source. In particular, the algorithm can determine the optimum localizations of the antennas at a specific area similar to those of the GMRT. Thus, this algorithm was designed to suppress the SLL in the angular domain and obtain a high resolution with the same telescope number and area. Finally, an algorithm is proposed to solve the aforementioned problems.

The last algorithm (DA) is designed to meet almost all of the desired requirements simultaneously. DA distributes the *u*-*v* data plane at the snapshot and hour tracking, as well as suppresses the SLLs and smoothens the linear ridges.

We expect that the proposed methods in the final chapter can optimize the data samples and minimize the SLLs in the angular domain to enhance the image quality as much as possible. The aforementioned methods are extended to check the optimized localizations of the telescope to expand the current arrays (e.g., GMRT) and are applied on 10 antennas to determine the antenna coordinates in Malaysia.

1.6 Structure of thesis

This thesis highlights the optimization problems associated with correlator array antennas for both snapshot and hour-tracking observations. This thesis is organized as follows.

Chapter 1 provides a general introduction to the research, background of the study, and objectives of the research topic.

Chapter 2 briefly reviews the background and technologies of a correlator array of antennas. Different proposed techniques that can increase the *u*-*v* plane samples and suppress SLL are also discussed. This chapter ends with an overview of the research that considers almost all of the desired requirements and demonstrates our research motivations.

Chapter 3 proposes an easy and flexible technique for optimization that considers almost all of the desired requirements. A simulation of the proposed method is also presented in this chapter.

Chapter 4 provides a general introduction to GA and utilizes it to optimize a correlator array of antennas. A simulation of the proposed method is also presented in this chapter.

Chapter 5 introduces a new algorithm to address the optimization problems. A general introduction to this algorithm is provided and then applied to a correlator array of antennas with small changes. A simulation of the proposed method is also presented in this chapter.

Chapter 6 applies the methods used in Chapters 3, 4, and 5 to optimize an extended correlator array. All proposed methods and techniques in this thesis are then applied to 10 antennas located in Malaysia. Simulations of the different configurations are also presented in this chapter.

Chapter 7 discusses several directions for investigation in future research.

REFERENCES

Allard, R.J., Werner, D.H., Werner, P.L., "Radiation pattern synthesis for arrays of conformal antennas mounted on arbitrarily-shaped three-dimensional platforms using genetic algorithms," IEEE Trans. Antennas and Propagation, vol. 51, Issue. 5, pp. 1054-1062, July 2003.

Assas, O., and Bouamar, M., " A Comparison of Evolutionary Algorithms: PSO, DE and GA for Fuzzy C-Partition, " International Journal of Computer Applications, vol. 91, pp. 0975 – 8887, No.10, April 2014.

Balanis, C. A., "Antenna Theory, Analysis and Design," New York: Wiley, 2010.

Ball, L., Braun, R., Edwards, P., Feain, I., Hobbs, G., Johnston, S., McClure-Griffiths, N., "ATNF Science Priorities Science in 2010 – 2015," ATNF Science, Version 2, November 2008.

Beardsley, A. et al., "A New Layout Optimization Technique for Interferometric Arrays Applied to the Murchison Widefield Array,", Monthly Notices of the Royal Astronomical Society, MNRAS, vol. 425, no. 3, pp. 1781-1788, Octobor 2012.

Bevelacqua, P.J., and Balanis, C.A. "Geometry and Weight Optimization for Minimizing Sidelobes in Wideband Planar Arrays," IEEE Transactions on Antennas and Propagation, vol. 57, no. 4, pp. 1285-1289, 2009.

Boone, F., " Interferometric array design optimizing the locations of the antenna pads,", Édition Diffusion Presse Sciences,EDP Sciences,Astronomy & Astrophisics, A&A, vol. 377, no. 1, pp. 368-376, 2001.

Boone, F., " Interferometric array design: Distributions of Fourier samples for imaging,", Astronomy & Astrophisics, A&A, vol. 386, no. 3 , pp. 1160-1171, February 2002.

Boone, F., "Weighting interferometric data for direct imaging," Springer, vol. 36, Issue 1-2, pp. 77-104, August 2013.

Bunton, J., talk in SKA workshop on array configuration design, http://www.jb.man.ac.uk/ska/workshop/Bunton5.pdf, 2000.

Cohanim, B. E., Hewitt, J. N., & de Weck, O," The Design of Radio Telescope Array Configurations using Multiobjective Optimization: Imaging Performance versus Cable Length,", The Astrophysical Journal Supplement Series, ApJS, vol. 154, no. 2, pp. 705-719 , May 2004.

Collin, R. E., & Zucker, F. J., "Antenna Theory," New York: McGraw-Hill, 1969.

Conway, J, "First Simulations of Imaging Performance of a Spiral Zoom Array; Comparisons with a Single Ring Array," ALMA memo, 291, February 2000b.

Conway, J, "Observing Efficiency of a Strawperson Zoom Array", ALMA memo, 283, January 2000a.

Cornwell, T. J., "Quality Indicators for the MM Array," MMA Memo 18, July 1984.

Das, S., Bhattacherjee, S., Mandal, D., Bhattacharjee, A.K. "Optimal sidelobe reduction of symmetric linear antenna array using Genetic Algorithm, ", IEEE Trans. India Conference (INDICON), 2010.

Davis, G. M., Mallat, S., & Avellaneda, M., "Adaptive greedy approximations,", Constr. Approx, vol. 13, Issue. 1, pp. 57-98, March 1997.

Dollet, C., Bijaoui, A., & Mignard, F., " All-sky imaging at high angular resolution: An overview using lossy compression," Astronomy and Astrophysics, A&A, vol. 426, pp. 729-736, November 2004.

Donoho, D. L., "Compressed sensing," IEEE Trans. Inform. Theory, vol. 52, Issue. 4, pp. 1289-1306, April 2006.

Dun-wei, G., and Yong, Z., "Multi-population Genetic Algorithms with Space Partition for Multi-objective Optimization Problems, "IJCSNS International Journal of Computer Science and Network Security, vol.6, No.2A, February 2006.

Elliott, R. S., "Antenna Theory and Design," Englewood Cliffs, NJ: Prentice-Hall, 1981.

Elsayed, S. M., Sarker, R. A., Essam, D. L., " A genetic algorithm for solving the CEC 2013 competition problems on real-parameter optimization,", IEEE Trans. Evolutionary Computation (CEC), pp. 356-360, June 2013.

Fannjiang, C., " Better images, fewer samples: Optimizing array configuration for compressed sensing in radio interferometry," The Leading Edge, vol. 30, Issue. 9, pp. 996-1003, September 2011.

Fannjiang, C., "Optimal arrays for compressed sensing in snapshot-mode radio interferometry," Astronomy & Astrophysics, A&A, vol. 559, no. A73, 11 pp, November 2013.

Feain, I., Johnston, S., & Gupta, N., " ASKAP Array Configurations: Options and Recommendations," ATNF SKA Memo Series, 017, August 2008.

Fomalont. E., “Earth-rotation aperture synthesis,” Proc. IEEE, vol. 61, no. 9, pp. 1211–1218, September 1973.

Gauci, A., Adami, K. Z., Abela, J., & Cohanim, B. E., "Genetic optimization for radio interferometer configurations," Monthly Notices of the Royal Astronomical Society, vol. 431, Issue. 1, pp. 322-326, May 2013.

Gharahdaghi, A., " Geometric Configuration Optimization for Baseline Interferometry,", Research Journal of Recent Sciences, Res.J.Recent Sci., vol. 2, no. 5, pp. 78-82, May 2013.

Ghosh, P., Banerjee, J., Das, S., & Chowdhury S.S., "Design of Non-Uniform Circular Antenna Arrays - An Evolutionary Algorithm Based Approach," Progress In Electromagnetics Research (PIER) B, vol. 43, pp. 333-354, 2012.

Gupta, N., Johnston, S., Feain, I., & Cornwell, T., "The Initial Array Configuration for ASKAP," ATNF SKA Memo Series, 016, Australia Telescope National Facility, CSIRO, October 2008.

Haupt, R. L., "Thinned arrays using genetic algorithms," IEEE Trans. Antennas and Propagation, vol. 42, Issue. 7, pp. 993-999, July 1994.

Ho. K., "Coherence theory of radio-astronomical measurements," IEEE Trans. Antennas Propag., vol. AP-15, no. 1, pp. 10–20, January 1967.

Jain, R., & Mani, G. S., "Dynamic thinning of antenna array using genetic algorithm," Progress In Electromagnetics Research B, vol. 32, pp.1-20, 2011.

Jin, N., & Rahmat-Samii, “Advances in particle swarm optimization for antenna designs: Real-number, binary, single-objective and multiobjective implementations,” IEEE Trans. Antennas Propag., vol. 55, no. 3, pp. 556–567, March 2007.

Jin, N., & Rahmat-Samii, Y "Analysis and Particle Swarm Optimization of Correlator Antenna Arrays for Radio Astronomy Applications," IEEE Transactions on Antennas and Propagation, vol. 56, no. 5, pp. 1269-1279, 2008.

Johnson, R. C., & Jasik, H., "Antenna Engineering Handbook," 2nd ed. New York: McGraw-Hill, 1984.

Johnston S., ;Bailes, M.; Bartel, N.; Baugh, C.; Bietenholz, M.; Blake, C.; Braun, R.; Brown, J.; Chatterjee, S.; Darling, J.; Deller, A.; Dodson, R.; Edwards, P. G.; Ekers, R.; Ellingsen, S.; Feain, I.; Gaensler, B. M.; Haverkorn, M.; Hobbs, G.; Hopkins, A.; Jackson, C.; James, C.; Joncas, G.; Kaspi, V.; Kilborn, V.; Koribalski, B.; Kothes, R.; Landecker, T. L.; Lenc, E.; Lovell, J.; Macquart, J.-P.; Manchester, R.; Matthews, D.; McClure-Griffiths, N. M.; Norris, R.; Pen, U.-L.; Phillips, C.; Power, C.; Protheroe, R.; Sadler, E.; Schmidt, B.; Stairs, I.; Staveley-Smith, L.; Stil, J.; Taylor, R.; Tingay, S.; Tzioumis, A.; Walker, M.; Wall, J.; & Wolleben, M. "Science with the Australian Square Kilometre Array Pathfinder, " Astronomical Society of Australia, vol. 24, pp 174-188, December 2007.

Jones, M. Tim., Al Application Programming (Hingham: Charles River Media), 2003.

Karastergiou, A., Neri, R., Gurwell, M. A. "Adapting and expanding interferometric arrays," The Astrophysical Journal Supplement Series, vol. 164, pp. 552–558, June 2006.

Keto, E., "The Shapes of Cross-Correlation Interferometers," The Astrophysical Journal, ApJ, vol. 475, no. 2, pp. 843-852, February 1997.

Kogan, L., "Optimization of an Array Configuration with a Donut Constraint," ALMA memo, 212, May 1998.

Kogan, L., "Optimizing a Large Array Configuration to Minimize the Sidelobes," IEEE Transactions on Antennas and Propagation, vol. 48, no. 7, July 2000.

Manian, D., James, M. K., & Emily, M. Z., "Using Genetic Algorithms to Optimize Bathymetric Sampling for Predictive Model Input", American Meteorological Society (AMS), vol. 29, Issue 3, March 2012.

Moffet, A., "Minimum redundancy linear arrays," IEEE Trans. Antennas Propag., vol. AP-16, no. 2, pp. 172–175, March 1968.

Montana, D., & Hussain, T., "Adaptive reconfiguration of data networks using genetic algorithms," ELSEVIER, Applied soft Computing, vol. 4, Issue. 4, pp. 433-444, September 2004.

Napier, P., Thompson, A., & Ekers, R., "The very large array: Design and performance of a modern synthesize radio telescope," Proc. IEEE, vol. 71, no. 11, pp. 1295–1320, November 1983.

Ng, C.K., Ashraf, G., Elsid, A., Nor, K.N., Sabira, K., Borhanuddin, M.A., and Ratna, K.Z.S., "Modeling and simulation of phased array antenna for LEO satellite tracking," Springer, Information Networking: Wireless Communications Technologies and Network Applications Lecture Notes in Computer Science, vol. 2344, pp. 359-371, 2002.

Oliveri, G., Caramanica, F., & Massa, A., "Hybrid ADS based techniques for radio astronomy array design," IEEE Trans. Antennas and Propagation Society, vol. 59, Issue. 6, pp. 1817-182, March 2011.

Oliveri, G., Caramanica, F., Rocca, P., & Massa, A., "ADS-based Y-shaped arrays for interferometry and radio astronomy applications" in Proc. IEEE International Symposium on Phased Array Systems & Technology, pp. 335-337 October 2010b.

Oliveri, G., Rocca, P., & Massa, A.,"Interleaved linear arrays with difference sets", Electron. Lett. vol. 45, no. 5, pp. 323 -324, March 2010a.

Pan, Z, 2002, A technical report submitted to the Department of Electrical and Computer Engineering, University of California, Davis.

Pati, Y. C., Renzaiifar, R., & Krishnaprasad, P. S., " Orthogonal Matching Pursuit: Recursive Function Approximation with Applications to Wavelet Decomposition,", Proc. 27th Asilomar Conf. on Signals, Systems, and Computers, vol. pp. 40-44, November 1993.

Polygiannakis, J., Preka-Papadema, P., & Moussas, X., " On signal–noise decomposition of time-series using the continuous wavelet transform: application to sunspot index," MNRAS, vol. 343, no. 3, pp. 725-734, August 2003.

Rao, N. N., "Uniform Plane Waves and Power Flow in An Electromagnetic Field," Elements of Engineering Electromagnetics, pp. 246-310, Prentice Hall, Inc., 2000.

Rega, R., and Dilip, K.P., " Particle Swarm Optimization Algorithm vs Genetic Algorithm to Develop Integrated Scheme for Obtaining Optimal Mechanical Structure and Adaptive Controller of a Robot" Intelligent Control and Automation, vol. 2, pp. 430-449, November 2011.

Sengupta, A., Chakraborti, T., Konar, A., & Nagar, A.K. "A Multi-Objective Memetic Optimization Approach to The Circular Antenna Array Design Problem," Progress In Electromagnetics Research (PIER) B, vol. 42, pp. 363-380, 2012.

Sodin, L. G., Kopilovich, L. E. "Hexagonal arrays for radio interferometers," Édition Diffusion Press Sciences, EDP Sciences, Astronomy & Astrophysics, A&A, vol. 392, no. 3, pp. 1149-1152, September 2002.

Stutzman, W. L., & Thiele, G. A., "Antennas Theory and Design," New York: Wiley, 1981.

Su, Y., Nan, R. D., Peng, B., Roddis, N., & Zhou, J., F " Optimization of interferometric array configurations by sieving u – v points, " Édition Diffusion Presse Sciences,EDP Sciences,Astronomy & Astrophisics, A&A, vol. 414, no. 1, pp. 389 - 397, January 2004.

Swarup, G., Ananthakrishnan, S., Kapahi, V. K., Rao, A. P., Subrahmanya, C. R., & Kulkarni, V. K., " The Giant Metre-wave Radio Telescope,", Current Science, vol. 60, no. 2, pp.95-105, January 1991.

Thompson, A.R., Moran , J.M., and Swenson, G.W., in Interferometry and synthesis in Radio Astronomy, Second Edition, John Wiley & Sons, 20 Nov. 2008.

Tropp, J. A., & Gilbert, A. C., "Signal Recovery From Random Measurements Via Orthogonal Matching Pursuit," IEEE Trans. Inform. Theory, vol. 53, no. 12, pp. 4655-4666, December 2007.

Türk, S., Liu, Y., Radeke, R., Lehnert, R., " Network Migration Optimization Using Genetic Algorithms,", Information and Communication Technologies Lecture Notes in Computer Science, vol. 7479, pp. 112-123, 2012.

Wang, Chung-Ho., Tsai, Kapadia, R. K., Patel, N. K., "Reactive power optimization using Genetic Algorithm," pp. 1-6, November 2013.

Weiying, S., Ji, W., " Optimization of antenna array for interferometric synthetic aperture radiometer,", IEEE Trans. Antennas and Propagation, Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, MAPE, vol. 1, pp. 293-296, Augest 2005.

Woody, D., "Radio Interferometer Array Point Spread Functions I. Theory and Statistics," ALMA Memo No. 389, August 2001a.

Woody, D., "Radio Interferometer Array Point Spread Functions II. Evaluation and Optimization," ALMA Memo No. 390, August 2001b.

Yun, M. S., & Kogan, L., "Straw person Donut/Double-Ring configuration," ALMA memo, 320, August 2000.

Zeenat, R., Debasree, D., Sarbani, and R., Nandini, M., “A Comparative Study of Partitioning Algorithms for Wireless Sensor Networks," Advances in Computer Science and Information Technology. Networks and Communications, vol. 84 of the series Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, pp. 445-454, 2012.