Digital Systems for the MITRA

(GPU Computing)

Submitted by

Ruben Anderson Louis

Project submitted in the partial fulfillment for the degree of

BSc (Hons) Physics with Computing

UNIVERSITY OF MAURITIUS

FACULTY OF SCIENCE

DEPARTMENT OF PHYSICS

March, 2015

Declaration of Authorship

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- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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“Write a funny quote here.”

If the quote is taken from someone, their name goes here

UNIVERSITY OF MAURITIUS

Abstract

Faculty of Science
Department of Physics

BSc (Hons) Physics with computing

Digital Systems for the MITRA

by Ruben Anderson Louis

In this report we give a brief account about imaging in the field of Radio Astronomy specifically on the technique coined Aperture Synthesis.

Acknowledgements

I am grateful to the Dr. G. K. Beeharry for his useful suggestions, guidance and remarks, and for the opportunity he gave me to work on the topic. Also I express my thanks to the following for their help: Assoc. Prof. R. Somanah, Dr S. Oree and the technical staff of the department of physics.

Contents

List of Figures

List of Tables

Abbreviations

EM	**E**lectro**m**agnetic
FFT	**F**ast **F**ourier **T**ransform
MEM	**M**aximum **E**ntropy **M**ethod
MITRA	**M**ultifrequency **I**nterferometry **T**elescope for **R**adio **A**stronomy
MRT	**M**auritius **R**adio **T**elescope
NNLS	**n**on-**n**egative **l**east **s**quare **a**lgorithm
R.A.	**R**adio **A**stronomy
VLA	**V**ery **L**arge **A**rray (Radiotelescope)

Physical Constants

Speed of Light $c = 2.997\,924\,58 \times 10^{8}\ \mathrm{ms}^{-\mathrm{S}}$ (exact)

Symbols

a	distance	m
P	power	W (Js^{-1})
ω	angular frequency	rads^{-1}

For/Dedicated to/To my…

Chapter 1

Introduction

1.1 About the report

The aim of this report is to introduce the topic of Imaging in Radio Astronomy to students with an introductory university background in signal & image processing and having a secondary school knowledge of physics. This was done so that the reader would acquire the basic knowledge about what is done actually, the practical issues, and thus those interested to learn or try out things on their own on the topic would be encouraged to read the literature referred to.

The report is composed of 4 main chapters where the literature from the book, **Interferometry and Synthesis in Radio Astronomy** by Thompson, Moran, and Swenson Jr [3] has been put and reformulated in a concise way along with literature from other sources, so original work is not expected here. The report is structured as follows *chapter 1* is an introduction to the field, the main goals people aim for in the area and it also stands as a basis for the other chapters. Then *chapter* **??** continues more thoroughly on the topic of cross-correlation, and we pass on to *chapter 3* which deals more with theorems, sampling considerations, data calibration, and image reconstruction/retrieval, generally things related to linear processes. Then finally *chapter 4* expounds about the actual processing of the raw image with enhancing techniques which usually deal with non-linear processes. So we hope that the reader will find this small piece of work that we put together very fluent and comprehensive on the topic. Feel free to mail us on our project group mail the-radio-imagists@googlegroups.com if you have questions on the topic discussed in the report and/or suggestions on the report itself.

1.2 The pioneers

As Assoc. Prof. R. Somanah usually says, one cannot talk about Radio Imaging without mentioning a main pioneer in the field, Sir Martin Ryle. He was a British radio astronomer who did develop revolutionary radio telescopes systems and used them for the accurate location and imaging of weak radio sources. Earlier he worked on the study of radio waves from the Sun and sunspots, and later discovered the first quasi-stellar object known as the Quasar[2]. Martin Ryle and his colleague Anthony Hewish were the first **astronomers** to ever receive the Nobel prize in Physics in 1974 for their overall contribution to **radio astronomy** (Encyclopedia Britannica [1]).

FIGURE 1.1: Sir Martin Ryle[1]

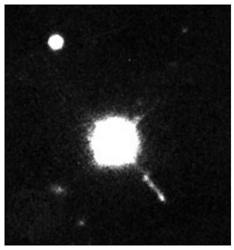

FIGURE 1.2: Quasar 3C273 [2]

1.3 Introductory basic concepts

1.3.1 Imaging by Interferometry in R.A.

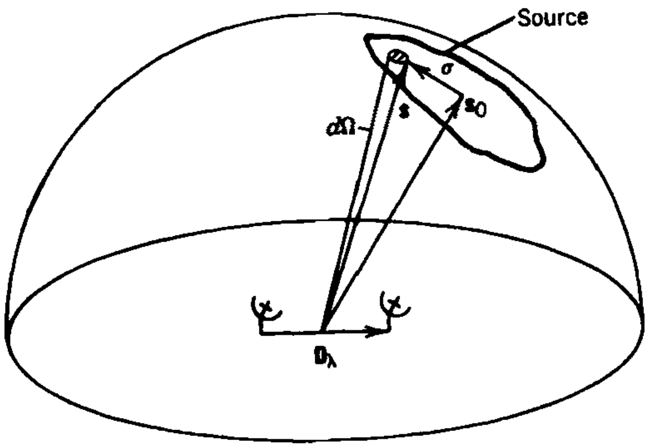

FIGURE 1.3: A Radio interferometer setup diagrammatic representation [3, Pg. 69, Fig. 3.1]

Interferometry is a technique where electromagnetic waves are superimposed in order to extract information about the waves. As concern Radio Astronomy when at least 2 radio telescopes are working in tandem, the setup is given the name of radio interferometer. Radio Telescopes are actually antennas which basically are devices that respond to incoming electromagnetic radiation and output electrical currents related to this response. For application in Radio Astronomy passive radio telescopes i.e. receiving antennas are used.

[1]Stamp, Sir Martin Ryle - Radio Surveyor of the Universe. http://colnect.com/en/stamps/stamp/184650-Sir_Martin_Ryle_-_Radio_Surveyor_of_the_Universe-Eminent_Britons-United_Kingdom_of_Great_Britain_Northern_Ireland

[2]Quasar, an astronomical object of very high luminosity found in the centres of some galaxies and powered by gas spiraling at high velocity into an extremely large black hole. Quasar 3C 273, the brightest and closest of the quasi-stellar radio sources (Encyclopedia Britannica [2]).

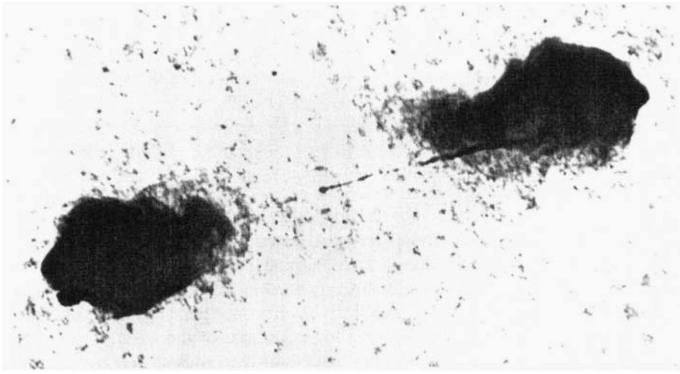

FIGURE 1.4:
Radio image of Cygnus A made with the VLA at 4.9 GHz by Perley, Dreher, and Cowan (1984) [3, Pg. 33, Fig. 1.18]

1.3.2 Why are radio interferometers used?

(a) (b)

FIGURE 1.5:
Diffraction Effect [4, Appendix B.1, Fig. B.1]

(From Woods et al. [4, Appendix B.1]) To answer this question one must introduce the concept of angular resolution, the latter describes the angular distance between two point sources that can be differentiated by an aperture. Because of the diffraction effect, an antenna pattern (Fig. 1.6) has side lobes, which are sensitive to sources outside the main antenna beam, limiting resolution. When a planar electromagnetic wave enters an aperture, the electromagnetic wave is distorted in what is called a diffraction pattern (Fig. 1.5). Therefore a finite sized aperture cannot correctly record the radio brightness without some distortion of the original signal. The diffraction distortion is due to the interaction of the original EM wave with the edges of a finite sized aperture, which creates the fringe pattern of destructive and constructive interference. Diffraction affects all types of EM waves when entering an aperture, but is more severe for longer wavelengths. The distance to the first zero of the diffraction pattern of a circular aperture is given by

$$R \simeq 1.22\frac{\lambda}{D} \tag{1.1}$$

If two objects are closer than the first minima (1.7(a)), for a particular aperture, they cannot be distinguished. Therefore the first minima, determines the resolving capabilities of an aperture and

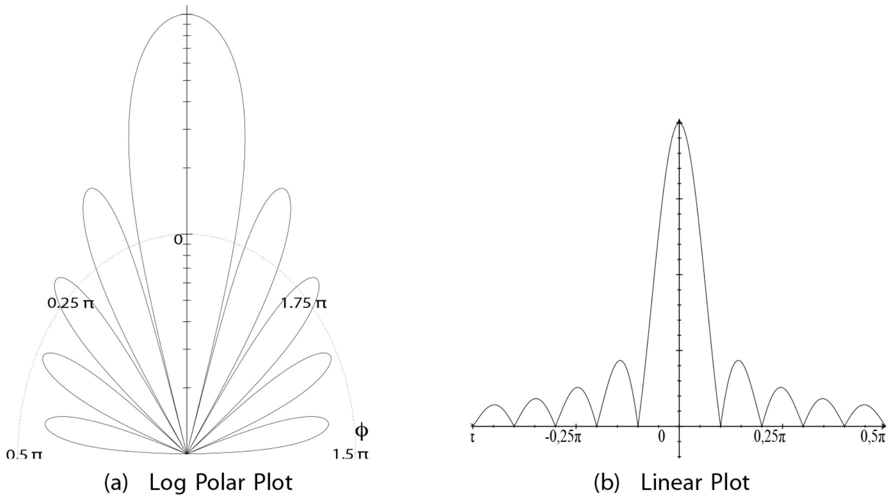

FIGURE 1.6:
Antenna Pattern [4, Appendix B.1, Fig. B.2]

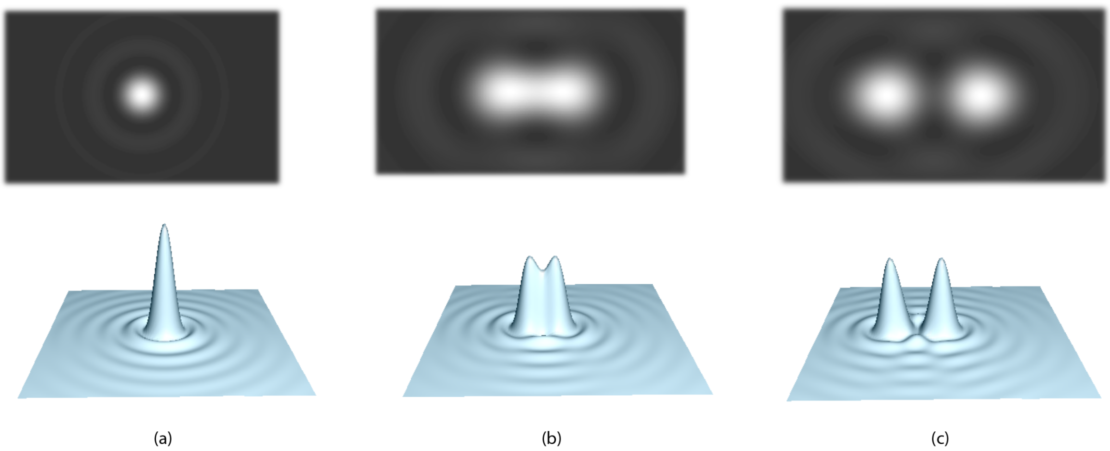

FIGURE 1.7:
Angular Resolution [4, Appendix B.1, Fig. B.3]

is called the angular resolution R. The angular resolution, represented in the right-hand side of the equation 1.1, depends on both the wavelength and the aperture diameter. As a consequence of dealing with radio waves, which have a long wavelength, radio astronomy requires large telescopes in order to improve the resolution and produce detailed images (radio brightness readings). The dimensions of a single radio aperture needed to meet the angular resolution requirements are extremely impractical in terms of strict design requirements and physical constraints. For example, to achieve the same angular resolution as the naked human eye, a radio antenna's aperture observing a source at 4GHz must be 750m in diameter. Therefore the way this issue is coped for is by using a radio interferometer setup, in the latter case its effective aperture diameter now corresponds to the largest separation of the 2 telescopes and actually a much better resolution can be obtained more easily, as one can have telescopes with a desired distance between them (in that small calculation $\sim$ 750m) which is more practical than having to build a single radio telescope with a large aperture diameter. This is from that fact that the technique is coined *Aperture Synthesis* as with that setup the aperture diameter and in consequence the resolution of a much larger telescope can be emulated by the aforementioned mean. Knowing the impulse response of an aperture, a closer reconstruction of the original source can be made by performing a deconvolution, this will be discussed in *chapter 4*

1.3.3 The principle of a radio Interferometer

[From 3, Sec. 2.1] Consider the figure 1.8 below which shows the direction of incoming electromagnetic planar wavefronts received at the antenna from the sky. Depending on the direction of

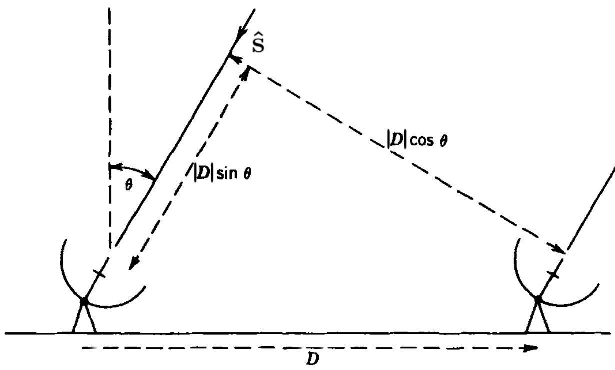

FIGURE 1.8:
Geometry of an elementary interferometer [3, Pg. 51, Fig. 2.1]

the wavefront relative to the direction the antennas point to, here characterised by the angle θ, the same wavefront from the sky will reach a particular antenna first, here the right one, or both would get the same wavefront at the same time, in the first case it is only after a certain lapse of time that the wavefront reaches the other antenna, the left one. The extra distance the wavefront has to travel to reach the left antenna is the projection of the baseline direction on the unit vector in the source direction which is equal to $\mathbf{D} \cdot \hat{\mathrm{s}}$.

$$\mathbf{D} \cdot \hat{\mathrm{s}} = |\mathbf{D}| \cdot \cos(90^\circ - \theta) = |\mathbf{D}| \sin(\theta) \tag{1.2}$$

This is also the extra time that the wavefront takes at speed of light to reach the left antenna known as the geometric delay or time delay. The geometric delay, τ_g is thus the following,

$$\tau_g = \frac{\mathbf{D} \cdot \hat{\mathrm{s}}}{\mathrm{c}} \tag{1.3}$$

where, c, is the speed of light in vacuum.

As mentioned in section 1.3.1 antennas output electrical signals in response to the incoming wavefront, thus it is quite obvious that the signal output at the left antenna would be similar to that from the the right antenna but delayed by the geometric delay. Therefore, what we do in radio interferometry is that we have a measure to characterise this antenna pair - signal relationship in response to the EM radiation from a direction in the sky and it is called the **visibility**. The relationship between the visibility and what is observed is direct. So one can make a map of the visibility and be able to have information about the sky observed and this is discussed further in the section 1.3.5

1.3.4 A free coordinate system

[From 3, Sec. 3.1, Pgs. 68-71] Before we continue further let us first use an adequate coordinate system that will be the basis of our subsequent discussion. Consider the figure 1.9. Suppose that

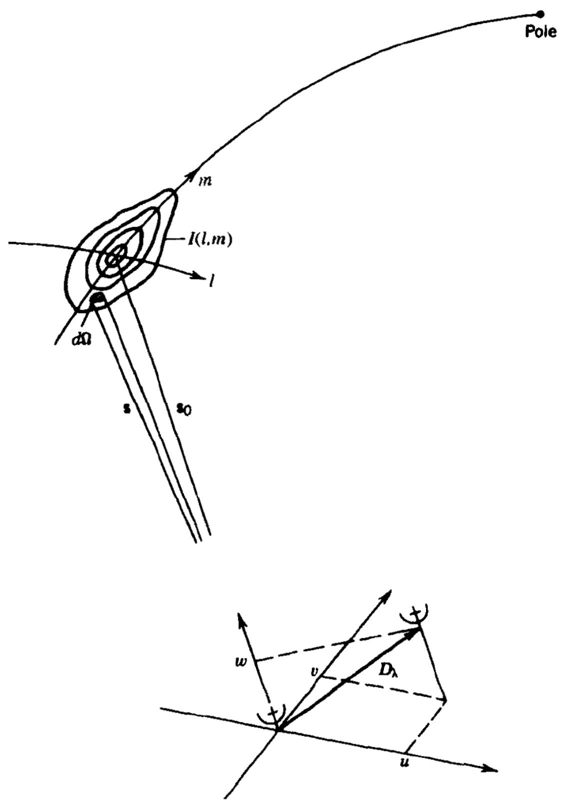

FIGURE 1.9:
Free coordinate system [3, Pg. 70, Fig. 3.2]

the antennas track the source under observation, which is the most common situation, and let the unit vector $\hat{\mathbf{s}}_0$ indicate the phase reference position. This position, known as the phase-tracking centre, becomes the centre of the field to be mapped. The magnitude of the baseline vector, $|\mathbf{D}_\lambda| = \frac{|\mathbf{D}|}{\lambda}$, is measured in wavelengths at the centre frequency of the observing band, and the baseline direction, $\mathbf{D}_\lambda$, has components (u, v, w) in a right-handed coordinate system, where u and v are measured in a plane normal to the direction of the phase reference position. The spacing component u is measured toward the north as defined by the plane through the origin, the source, and the pole, and v toward the east. The component w is measured in the direction $\hat{\mathbf{s}}_0$ and so is defined as follows,

$$\mathbf{D}_\lambda \cdot \hat{\mathbf{s}}_0 = w \tag{1.4}$$

Source direction or position on the celestial sphere have the components (l, m, n) which are simply, respectively the direction cosines of the components of the particular direction/position $\hat{\mathbf{s}}$ in terms of the (u, v, w) components i.e.

$$\hat{\mathbf{s}} = (l, m, n) = (\hat{\mathbf{s}} \cdot \hat{\mathbf{u}}, \hat{\mathbf{s}} \cdot \hat{\mathbf{v}}, \hat{\mathbf{s}} \cdot \hat{\mathbf{w}}) \tag{1.5}$$

Then, since $l^2 + m^2 + n^2 = 1$ we can re-express n in terms of l and m as follows,

$$n = \sqrt{1 - l^2 - m^2} \tag{1.6}$$

leading us to re-express source directions with the following components i.e.

$$\hat{\mathbf{s}} = (l, m, \sqrt{1 - l^2 - m^2}) \tag{1.7}$$

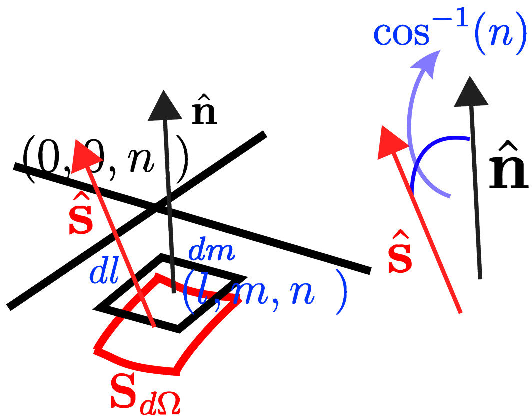

FIGURE 1.10:
Element of Solid Angle

One can also easily show that for an elementary patch of the sky $dl \cdot dm$, the solid angle, $d\Omega$, subtended from our reference is,

$$d\Omega = \frac{dldm}{n} \tag{1.8}$$

Refer to figure 1.10, note that the solid angle, $d\Omega$ is just the projection of the patch $dl \cdot dm$ on the unit sphere centred on the origin. Referring to the figure we denote the elementary surface at coordinate $(u = l, v = m, n = n)$ as $\mathbf{S}_{dldm} = S_{dldm} \cdot \hat{\mathbf{n}}$ and its projection on the unit sphere as, $\mathbf{S}_{d\Omega} = S_{d\Omega} \cdot \hat{\mathbf{s}}$. So we have the following relationship,

$$\mathbf{S}_{d\Omega} \cdot \hat{\mathbf{n}} = S_{dldm} \tag{1.9}$$

$$S_{d\Omega} \cdot \hat{\mathbf{s}} \cdot \hat{\mathbf{n}} = S_{dldm} \tag{1.10}$$

As the angle between $\hat{\mathbf{s}}$ and $\hat{\mathbf{n}}$ is $\cos^{-1}(n)$

$$S_{d\Omega} \cdot \cos(cos^{-1}(n)) = S_{dldm} \tag{1.11}$$

$$S_{d\Omega} \cdot n = S_{dldm}$$
$$S_{d\Omega} = \frac{S_{dldm}}{n} \tag{1.12}$$

$$d\Omega = \frac{dldm}{n}$$

$$d\Omega = \frac{dldm}{\sqrt{1 - l^2 - m^2}} \tag{1.13}$$

1.3.5 Visibility – Sky intensity distribution relationship

[From 3, Sec. 3.1, Pg. 71-73] As introduced very roughly in section 1.3.3 there is a direct relationship between the electrical signal received at the pair of antennas and the electromagnetic waves from the sky, we also mentioned the visibility which relates the antenna-pair electrical signal to the electromagnetic waves received. Most importantly the visibility is a function of the baseline vector and relates to the sky intensity distribution in the following way,

$$V'(u, v, w) = \iint\limits_{\text{sky patch}} A_N I(l, m) e^{-j2\pi(\mathbf{D}_\lambda \cdot \hat{\mathbf{s}})} d\Omega \tag{1.14}$$

$$V'(u, v, w) = \iint\limits_{\text{sky patch}} \frac{A_N I(l, m) e^{-j2\pi(ul + vm + w(\sqrt{1 - l^2 - m^2} - 1))}}{\sqrt{1 - l^2 - m^2}} dldm \tag{1.15}$$

where, $V'(u, v, w)$ is the measured visibility, A_N, the normalised product of the antenna beams, and $I(l, m)$, is the intensity distribution.

Based on an approximation that is valid so long as the synthesised field is not too large. If l and m are small enough that the term

$$\left(\sqrt{(1 - l^2 - m^2)} - 1\right) w \simeq -\frac{1}{2}(l^2 + m^2) w \tag{1.16}$$

can be neglected then what is left is the following:

$$V'(u,v) = \iint_{\text{sky patch}} \frac{A_N I(l,m) e^{-j2\pi(ul+vm)}}{\sqrt{1-l^2-m^2}} dldm \tag{1.17}$$

which is a direct Fourier transform relationship between visibility map and sky intensity distribution multiplied by the normalised antenna pattern. The actual calculation done to obtain a visibility is discussed in the chapter **??** and we shall focus on the use of a correlator.

Chapter 2

Literature Review

Prelimary gather up of abstract or similar

2008

Jheengut - Software Correlation

Software correlation is seen to replace digital correlation as a step forward in removing the excessive cost for dedicated hardware in the near future. A software correlator for radio astronomy has been designed in the FORTRAN *programming language with design considerations as an off the shelf project. The flexibility of a software correlation is being taken as an aid to solve problems found in dedicated hardware to be upgraded and maintained properly.*

S. Ord, L. Greenhill, R. Wayth, D. Mitchell, K. Dale, H, Pfister, R. G. Edgar - GPUs for data processing in the MWA

The MWA is a next-generation radio interferometer under construction in remote Western Australia. The data rate from the correlator makes storing the raw data infeasible, so the data must be processed in real-time. The processing task is of order 10 TFLOPs^{-1}*. The remote location of the MWA limits the power that can be allocated to computing. We describe the design and implementation of elements of the MWA real-time data processing system which leverage the computing abilities of modern graphics processing units (GPUs). The matrix algebra and texture mapping capabilities of GPUs are well suited to the majority of tasks involved in real-time calibration and imaging. Considerable performance advantages over a conventional CPU-based reference implementation are obtained.*

Chris Harris Karen Haines Lister Staveley-Smith -
GPU Accelerated Radio Astronomy Signal Convolution

The increasing array size of radio astronomy interferometers is causing the associated computation to scale quadratically with the number of array signals. Consequently, efficient usage of alternate processing architectures should be explored in order to meet this computational challenge. Affordable parallel processors have been made available to the general scientific community in the form of the commodity graphics card. This work investigates the use of the Graphics Processing Unit (GPU) in the parallelisation of the combined conjugate multiply and accumulation stage of a correlator for a radio astronomy array. Using NVIDIA's Compute Unified Device Architecture, our testing shows processing speeds from one to two orders of magnitude faster than a Central Processing Unit (CPU) approach.

Andrew Woods, Michael Inggs and Alan Langman -
Accelerating a Software Radio Astronomy Correlator using FPGA co-processors

This article presents and characterises our work on accelerating a software radio astronomy correlator using reconfigurable computing (RC) hardware. Radio astronomy correlation is an embarrassingly parallel signal processing application, which is used heavily in radio astronomy for imaging and other astronomical measurements. Radio astronomy correlators typically operate on huge data sets and often require real-time processing, as storage of raw data is impractical - resulting in substantial computational requirement. Currently FPGAs are the preferred processing architecture used in modern large radio astronomy correlators [1] and perform well on the types of DSP functions that correlators perform. In this paper we set out to accelerate the DiFX (Distributed FX) correlator, a software correlator, using FPGA reconfigurable computing hardware. —– hoping to inherit some of the advantages that larger production FPGA correlators have over software.

2009
NVIDIA -
NVIDIA's Next Generation CUDA™ Compute Architecture: Fermi™

Rob V. van Nieuwpoort, John W. Romein -
Using Many-Core Hardware to Correlate Radio Astronomy Signals

A recent development in radio astronomy is to replace traditional dishes with many small antennas. The signals are combined to form one large, virtual telescope. The enormous data streams are crosscorrelated to filter out noise. This is especially challenging, since the computational demands grow quadratically with the number of data streams. Moreover, the correlator is not only computationally intensive, but also very I/O intensive. The LOFAR telescope, for instance, will produce over 100 terabytes per day. The future SKA telescope will even require in the order of exaflops, and *petabits/s of I/O. A recent trend is to correlate in software instead of dedicated hardware. This is done to increase flexibility and to reduce development efforts. Examples include e-VLBI and LOFAR. In this paper, we evaluate the correlator algorithm on multi-core CPUs and many-core architectures, such as NVIDIAand ATIGPUs, and the Cell/B.E. The correlator is a streaming, real-time application, and is much more I/O intensive than applications that are typically implemented on many-core hardware today. We compare with the LOFAR production correlator on an IBM Blue Gene/P supercomputer. We investigate performance, power efficiency, and programmability. We identify several important architectural problems which cause architectures to perform suboptimally. Our findings are applicable to data-intensive applications in general. The results show that the processing power and memory bandwidth of current GPUs are highly imbalanced for correlation purposes. While the production correlator on the Blue Gene/P achieves a superb 96% of the theoretical peak performance, this is only 14% on ATI GPUs, and 26% on NVIDIA GPUs. The Cell/B.E. processor, in contrast, achieves an excellent 92%. We found that the Cell/B.E. is also the most energy-efficient solution, it runs the correlator 5-7 times more energy efficiently than the Blue Gene/P. The research presented is an important pathfinder for next-generation telescopes.*

2010

Andrew Woods, Michael Inggs and Alan Langman -

Accelerating a Software Radio Astronomy Correlator using FPGA co-processors

This thesis attempts to accelerate compute intensive sections of a frequency domain radio astronomy correlator using dedicated co-processors. Two co-processor implementations were made independently with one using reconfigurable hardware (Xilinx Virtex 4LX100) and the other uses a graphics processor (Nvidia 9800GT). The objective of a radio astronomy correlator is to compute the complex valued correlation products for each baseline which can be used to reconstruct the sky's radio brightness distribution. Radio astronomy correlators have huge computation demands and this dissertation focuses on the computational aspects of correlation, concentrating on the X-engine stage of the correlator. Although correlation is an extremely compute intensive process, it does not necessarily require custom hardware. This is especially true for older correlators or VLBI experiments, where the processing and I/O requirements can be satisfied by commodity processors in software. Discrete software co-processors like GPUs and FPGAs are an attractive option to accelerate software correlation, potentially offering better FLOPS/watt and FLOPS/$ performance. In this dissertation we describe the acceleration of the X-engine stage of a correlator on a CUDA GPU and an FPGA. We compare the co-processors' performance with a CPU software correlator implementation in a range of different benchmarks. Speedups of 7x and 12.5x were achieved on the FPGA and GPU correlator implementations respectively. Although both implementations achieved speedups and better power utilisation than the CPU implementation, the GPU implementation produced better performance in a shorter development time than the FPGA. The FPGA implementation was hampered by the development tools and the slow PCI-X bus, which is used to communicate with the host. Additionally, the Virtex 4 LX100 FPGA was *released two years before the Nvidia G80 GPU and so is more behind the current technologies. However, the FPGA does have an advantage in terms of power efficiency, but power consumption is only a concern for large compute clusters. We found that using GPUs was the better option to accelerate small-scale software X-engine correlation than the Virtex 4 FPGA.*

Nicolas PLATEL - Implémentation d'un corrélateur sur une carte GPU.
Le but de ce projet est d'implémenter un corrélateur de type FX en Software sur une carte GPU de la marque NVIDIA. Ce corrélateur permettra aux étudiants de finir la construction du télescope étudié et obtenir des images du ciel. Il a pour but également de donner quelques notions sur Cuda aux étudiants le désirants. Dans le but d'étudier des phénomènes physiques connus et de valider mon projet, des résultats expérimentaux ont été effectués grâce aux antennes et au récepteur numérique créé précédemment. Enfin, une interface graphique a été créée pour faciliter l'utilisation du corrélateur à l'utilisateur.

Hobiger T., Kimura M., Takefuji K, Oyama T., Koyama Y., Kondo T., Gotoh T., Amagai J.
GPU based software correlators-perspectives for VLBI2010
Caused by historical separation and driven by the requirements of the PC gaming industry, Graphics Processing Units (GPUs) have evolved to massive parallel processing systems which entered the area of non-graphic related applications. Although a single processing core on the GPU is much slower and provides less functionality than its counterpart on the CPU, the huge number of these small processing entities outperforms the classical processors when the application can be parallelized. Thus, in recent years various radio astronomical projects have started to make use of this technology either to realize the correlator on this platform or to establish the post-processing pipeline with GPUs. Therefore, the feasibility of GPUs as a choice for a VLBI correlator is being investigated, including pros and cons of this technology. Additionally, a GPU based software correlator will be reviewed with respect to energy consumption/GFlop/sec and cost/GFlop/sec.

Patrick Brandt, Ron Duplain, Paul Demorest, Randy McCullough, Scott Ransom, Jason Ray
Heterogeneous real-time computing in radio astronomy
Modern computer architectures suited for general purpose computing are often not the best choice for either I/O-bound or compute-bound problems. Sometimes the best choice is not to choose a single architecture, but to take advantage of the best characteristics of different computer architectures to solve your problems. This paper examines the tradeoffs between using computer systems based on the ubiquitous X86 Central Processing Units (CPU's), Field Programmable Gate Array (FPGA) based signal processors, and Graphical Processing Units (GPU's). We will show how a heterogeneous system can be produced that blends the best of each of these technologies into a

real-time signal processing system. FPGA's tightly coupled to analog-to-digital converters connect the instrument to the telescope and supply the first level of computing to the system. These FPGA's are coupled to other FPGA's to continue to provide highly efficient processing power. Data is then packaged up and shipped over fast networks to a cluster of general purpose computers equipped with GPU's, which are used for floating-point intensive computation. Finally, the data is handled by the CPU and written to disk, or further processed. Each of the elements in the system has been chosen for its specific characteristics and the role it can play in creating a system that does the most for the least, in terms of power, space, and money.

GINOURIE Sabera Bibi

A prototype front-end and back-end receiver system for radioastronomy

The first part of the project consisted of designing and building a front-end and back-end system for radioastronomy. Eight Log-periodic dipole antennas (available at the MRT) were used for the front-end. In the second part, a new data acquisition card was used. This card was studied and programmed before used. The card was tested several times in order to check whether the analog data were digitised. Next, the whole system was tested and observations were carried out. Celestial objects like Virgo A and Centaurus A were successfully observed.

2011

V. K. Veligatla, P. Labropoulos, L. V. E. Koopmans -

Adaptive Beam-forming for Radio Astronomy On GPU

The LOFAR radio telescope consists of tens of thousands of dipole antennas that combine their signals to operate as a single large radio telescope. The truly innovative aspect of this new telescope is that its pointing system is not mechanical. It is steered by combining the electric signals from different elements using advanced beam-forming software. Imaging software is one of the important aspects of processing the high-volume data streams produced by LOFAR, and is one of the best places to use GPUs to achieve processing speed. We were able to achieve up to 30 times performance gain compared to the CPU implementation in novel, computationally intensive techniques such as the Minimum Variance Distortionless Response (MVDR). We have gained 5-6 times speed-up compared to the CPU implementation for standard imaging algorithms.

M. A. Clark, P. C. La Plante, L. J. Greenhill -

Accelerating Radio Astronomy Cross-Correlation with Graphics Processing Units

We present a highly parallel implementation of the cross-correlation of time-series data using graphics processing units (GPUs), which is scalable to hundreds of independent inputs and suitable for the processing of signals from "Large-N" arrays of many radio antennas. The computational part of the algorithm, the X-engine, is implementated efficiently on Nvidia's Fermi architecture, sustaining up to 79% of the peak single precision floating-point throughput. We compare *performance obtained for hardware- and software-managed caches, observing significantly better performance for the latter. The high performance reported involves use of a multi-level data tiling strategy in memory and use of a pipelined algorithm with simultaneous computation and transfer of data from host to device memory. The speed of code development, flexibility, and low cost of the GPU implementations compared to ASIC and FPGA implementations have the potential to greatly shorten the cycle of correlator development and deployment, for cases where some power consumption penalty can be tolerated.*

2012

NVIDIA -
NVIDIA's Next Generation CUDA™ Compute Architecture: Kepler™ GK110

V. K. Veligatla, P. Labropoulos, L. V. E. Koopmans -
Adaptive Beam-forming for Radio Astronomy On GPU
The LOFAR radio telescope consists of tens of thousands of dipole antennas that combine their signals to operate as a single large radio telescope. The truly innovative aspect of this new telescope is that its pointing system is not mechanical. It is steered by combining the electric signals from different elements using advanced beam-forming software. Imaging software is one of the important aspects of processing the high-volume data streams produced by LOFAR, and is one of the best places to use GPUs to achieve processing speed. We were able to achieve up to 30 times performance gain compared to the CPU implementation in novel, computationally intensive techniques such as the Minimum Variance Distortionless Response (MVDR). We have gained 5-6 times speed-up compared to the CPU implementation for standard imaging algorithms.

John W. Romein -
An Efficient Work-Distribution Strategy for Gridding Radio-Telescope Data on GPUs
This paper presents a novel work-distribution strategy for GPUs, that effciently convolves radio-telescope data onto a grid, one of the most time-consuming processing steps to create a sky image. Unlike existing work-distribution strategies, this strategy keeps the number of device-memory accesses low, without incurring the overhead from sorting or searching within telescope data. Performance measurements show that the strategy is an order of magnitude faster than existing accelerator-based gridders. We compare CUDA and OpenCL performance for multiple platforms. Also, we report very good multi-GPU scaling properties on a system with eight GPUs, and show that our prototype implementation is highly energy effcient. Finally, we describe how a unique property of GPUs, fast texture interpolation, can be used as a potential way to improve image

quality.

Alessio Sclocco, Ana Lucia Varbanescu, Jan David Mol, Rob V. van Nieuwpoort -
Radio Astronomy Beam Forming on Many-Core Architectures
Traditional radio telescopes use large steel dishes to observe radio sources. The largest radio telescope in the world, LOFAR, uses tens of thousands of fixed, omnidirectional antennas instead, a novel design that promises ground-breaking research in astronomy. Where traditional telescopes use custom-built hardware, LOFAR uses software to do signal processing in real time. This leads to an instrument that is inherently more flexible. However, the enormous data rates and processing requirements (tens to hundreds of teraflops) make this extremely challenging. The next-generation telescope, the SKA, will require exaflops. Unlike traditional instruments, LOFAR and SKA can observe in hundreds of directions simultaneously, using beam forming. This is useful, for example, to search the sky for pulsars (i.e. rapidly rotating highly magnetized neutron stars). Beam forming is an important technique in signal processing: it is also used in WIFI and 4G cellular networks, radar systems, and health-care microwave imaging instruments. We propose the use of many-core architectures, such as 48- core CPU systems and Graphics Processing Units (GPUs), to accelerate beam forming. We use two different frameworks for GPUs, CUDA and OpenCL, and present results for hardware from different vendors (i.e. AMD and NVIDIA). Additionally, we implement the LOFAR beam former on multi-core CPUs, using OpenMP with SSE vector instructions. We use autotuning to support different architectures and implementation frameworks, achieving both platform and performance portability. Finally, we compare our results with the production implementation, written in assembly and running on an IBM Blue Gene/P supercomputer. We compare both computational and power efficiency, since power usage is one of the fundamental challenges modern radio telescopes face. Compared to the production implementation, our auto-tuned beam former is 45–50 times faster on GPUs, and 2–8 times more power efficient. Our experimental results lead to the conclusion that GPUs are an attractive solution to accelerate beam forming.

V.Vamsi Krishna, Dr. Panos Labropoulos, Prof. Leon V.E. Koopmans -
GPU's for Radio Imaging
- Signals from Sources (e.g. galaxies)
- Next Gen Antennas (e.g. LOFAR, SKA, ...)
- Image acquired after Processing (RFI elimination, Calibration).

Mike Clark with Lincoln Greenhill and Paul LaPlante -
Accelerating Radio Astronomy Cross-Correlation Beyond 1 Tflops Using Fermi

2013

Harshavardhan Reddy Suda, Pradeep Kumar Gupta -

Powering Real-time Radio Astronomy Signal Processing with GPUs. Design of a GPU based real-time backend for the upgraded GMRT

Nitisha Pirthee -

Digital back end for MITRA prototype

In the first part of the project, USRP1 was used on GNU radio. A log periodic antenna was connected to one channel of the USRP and the expected peaks were observed. The second channel was not operational when tested. An array of sixteen channels was used as front end. A PCI-ADC card already available at MRT was used to do data acquisition. The program for data acquisition was improved. The card was tested several times and observations were carried out. Celestial objects like CAS A and Pictor A were successfully observed.

Harshavardhan Reddy Suda, Pradeep Kumar Gupta -

Powering Real-time Radio Astronomy Signal Processing with GPUs. Design of a GPU based real-time backend for the upgraded GMRT

Ben Barsdell, Mike Clark, Lincoln Greenhill, Jonathon Kocz -

ACCELERATING RADIO ASTRONOMY CROSS-CORRELATION USING THE KEPLER ARCHITECTURE

Kepler GK110 optimisation

2014

Ben Barsdell, Mike Clark, Lincoln Greenhill, Jonathon Kocz -

PETASCALE CROSS-CORRELATION

Amr H. Hassan, Christopher Fluke, David Barnes, Virginia Kilborn -

Astronomical “Big Data” Analysis and Visualization

Alex Bogert, John Holdener, and Nicholas Smith -

Interactive Visualization of Astrophysical Data

yt [1] is an analysis and visualization system for astrophysical volumetric data that is openly developed and freely available. At its core, yt provides a method of describing physical rather than computational objects inside an astrophysical simulation. yt provides methods for selecting regions, applying analysis to regions, visualizing (including volume rendering, projections, slices, *phase plots) and exporting data to external analysis packages.*

S. Bhatnagar,P. K. Gupta, M. Clark -
GPU based imager for radio astronomy

Mario Guillaume CECILE -
Enhancement of some computational physics algorithms using Parallel Computing and the Graphical Processing Unit
Scientific computing has become an important method for testing and improving current scientific models and theories. Recent developments in computer architecture have helped to study more complex systems using High Performance Computing (HPC). In this project,Grain Growth simulation and the soft-sphere Discrete Element Method (DEM) are enhanced to be able to consider larger matrix sites in the Grain Growth simulation and a large number of particles in the DEM model. Parallel computing using Message Passing Interface (MPI) is used as well as CUDA for programming on the GPU. For the Grain Growth simulation, effects of foreign particles are investigated while for the DEM model, free-falling of particles in a packed bed is studied. The results presented in this work help to give further understanding about the physics involved behind both the Grain Growth and DEM. This work furthermore demonstrates how the use of parallel processing can helps scientists to enhance their code.

NVIDIA -
NVIDIA GeForce GTX 750 Ti Featuring First-Generation Maxwell GPU Technology, Designed for Extreme Performance per Watt

Chapter 3

Distributed FX Correlation

Chapter 4

Tiled Memory Tasking Algorithm

Chapter 5

Conclusions, and future developments

To conclude this report we might say that the field of Imaging in Radio Astronomy is a non-exhaustive one, it is interesting to appreciate that there are an innumerable set of factors which come into the play and sum up as a whole to produce an end-result. We have approached the subject from the viewpoint of the Signal & Image Processing module where we have focused on physical and extensively mathematical descriptions which would enable one to have a clue on how the data is to be processed, however even in this scope we have certainly not taken the most effective route, there is still much improvement to be done in this report to make something more comprehensive and self-supporting on the subject to avoid unexplained areas, or to reduce the focus to more effective areas in the scope of the module. An improvement could be the inclusion of actual practical examples for the reader to practice with simple generated or raw data by using the acquired techniques and knowledge during the course, so that in this way the unexplained areas mostly concerning the use of particular mathematical functions can be easily grasped. To wrap up we thus encourage the target readers to consult the literature, where everything is extensively explained and the scope of this field does not end at image processing, the broader field of physics behind is something that we encourage the reader to look for.

Appendix A

Appendix Title Here

Write your Appendix content here.

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