New Approaches for the Real-Time Detection of Binary Pulsars with the Square Kilometre Array (SKA)

E. van Heerden1, A. Karastergiou2, S.J. Roberts3, and O. Smirnov*1

1Rhodes Centre for Radio Astronomy Techniques & Technologies (RATT), Department of Physics and Electronics, Rhodes University, Grahamstown, 6140, South Africa; email: g14v8634@campus.ru.ac.za; o.smirnov@ru.ac.za

2Astrophysics, University of Oxford, UK; email: aris@astro.ox.ac.uk

3Department of Engineering Science, University of Oxford, U.K.; email: sjrob@robots.ox.ac.uk

Abstract

Data rates from the Square Kilometre Array will be huge, rivalling the sum total of current global internet traffic. This deluge of data prompts a demand for significant progress in techniques for signal processing, data analysis and time-series modelling of vast data sets. Developing novel, real-time, machine learning algorithms is paramount if the SKA project is to meet its science objectives [1]. As a case study in SKA data analysis, this paper outlines some intrinsic difficulties in the search for binary pulsars, briefly describes known techniques for binary pulsar detection and proposes new detection approaches. Our current focus is to model more accurately sources of non-Gaussian, non-stationary noise in a typical pulsar search. Any solution must be scalable, to satisfy the real-time requirement of the SKA pulsar surveys.

1. Introduction

The Square Kilometre Array (SKA) is a next generation ultra-sensitive radio telescope that will be built in southern Africa and Australia. It will consist of three components, made up either of numerous coherently connected radio dishes or aperture arrays [2]. The vast collecting area and large instantaneous fields of view will result in a deluge of data. It is expected that, once operational, the SKA will collect in excess of an Exabyte of data per day [3]. Consequently, most signal processing needs to happen in real-time as it is near impossible for the raw data acquired by the SKA to be stored for off-line processing.

A paradigm shift from off-line to real-time data processing is of grave importance if the pulsar science objectives of the SKA project are to be met, such as providing strong field tests of gravitational physics by discovering pulsars orbiting black holes. The discovery and high-precision timing of binary pulsars will contribute to Pulsar Timing Arrays, which will be used for the detection and study of very low frequency gravitational waves. Newly discovered pulsars in binary systems are also excellent probes of the equation of state of nuclear matter [4].

A binary pulsar is a pulsar with a binary companion, often a white dwarf or neutron star. Radio pulses from pulsars originate from a radio beam along the magnetic axis, which is generally misaligned with the axis of rotation. For detectable pulsars, one radio pulse is seen per rotation. Rotation periods are very stable, owing to the fast rotation and large moment of inertia of pulsars. Figure 1 illustrates schematically how periodic radio pulses emitted by binary pulsars are affected as they propagate towards Earth. Radio pulses from binary pulsars typically exhibit Doppler shifts in their rotational period (Figure 1.1), caused by the acceleration of the pulsar around its companion. These need to be accounted for in any efficient search, a so-called acceleration search. In the time domain, such a search involves stretching and squeezing the data to compensate for particular Doppler shifts. Given that the orbital parameters of systems that are being searched for are by definition unknown, there is significant computation involved in this process.

Furthermore, radio pulses from pulsars, at frequencies relevant to SKA (~100 MHz to ~3 GHz), interact with the free electrons in the interstellar medium (Figure 1.2 and Figure 1.3), resulting in frequency dispersion, i.e., the arrival time of the high frequency components of a broadband radio pulse precedes the arrival time of its lower frequency counterparts. When these dispersed radio pulses reach Earth, they are recorded together with signals from satellites, aeroplanes, other terrestrial sources as well as instrumentation noise. Such signals will show up as spurious signals in the recorded intensity time-series (Figure 1.3) which is searched for periodic pulses from new pulsars, and may result in slow or abrupt baseline drifts of the noise (Figure 1.4).
Having corrected for interstellar dispersion, detecting periodic radio pulses produced by binary pulsars is an intrinsically difficult task due to the computational cost of acceleration searches, the low duty cycles of pulsars, low signal strengths and the presence of non-Gaussian noise. Radio pulses emitted by binary pulsars have a range of duty cycles. As a consequence, when looking for periodic or quasi-periodic signals through Fourier transforms, the pulse power may be distributed between the fundamental frequency and a significant number of harmonics in the power spectrum. In order to recover the power distributed over these harmonics, a technique known as “harmonic summing” is almost always used to increase the sensitivity of the survey [5].

Existing binary pulsar search techniques are described in more detail in Section 2. Novel approaches to binary pulsar detection are introduced in Section 3 with concluding remarks given in Section 4.

**2. Current Approaches to Binary Pulsar Detection**

Two successful and widely used methods for finding binary pulsars, in addition to the aforementioned time-domain technique, were developed by Ransom [6]. These methods examine small regions of the Fourier transform of a time-series data set in order to identify the distinctive but weak periodic patterns produced by binary pulsars.

The first method is a Fourier-domain version of traditional “acceleration” searches which can coherently detect a binary pulsar if the orbital period is longer than the observation time. This approach is based on Fourier-domain matched filtering. The second method is an incoherent search technique for binary pulsars with an orbital period much shorter than two thirds of the observation time. This search technique detects periodic sidebands created by orbital phase modulation of a binary pulsar’s signal using a two-stage Fourier analysis [6].

These approaches to binary pulsar detection are limiting in three ways. Firstly, they model the noise affecting the radio pulses as additive white Gaussian noise; a strong assumption that constraints the solution space and discards possible higher order spectral information [7]. Secondly, the discrete Fourier transform implicitly assumes that the signal in the time-series is periodic and that an integer number of periods are used in each frame. Without the application of taper functions, this implicit assumption leads to leakage and errors in the spectral estimate of the time-series [8]. Lastly, these approaches, although highly successful, are computationally demanding. Thus, to gain sensitivity in the survey one has to pay with longer integration and folding times. Consequently, these approaches are not able to detect binary pulsars in real-time. The need for a real-time approach to detect binary pulsars is therefore an imperative.

**3. Novel Approaches to Binary Pulsar Detection**

The novel approaches presented here aim to update the existing binary pulsar detection methods by relaxing the assumption of the noise being Gaussian and using more sophisticated techniques to adequately describe non-stationary low signal-to-noise ratio (SNR) periodic signals embedded in noise. Additionally, these approaches aim to account for any uncertainty inherent to the data acquired during pulsar surveys.
Generalised autoregressive (GAR) models have proven successful at modelling non-Gaussian periodic signals [9], and autoregressive integrated moving average (ARIMA) models have proven successful at modelling non-stationary time-series [10]. Additionally, GAR and ARIMA models are alternative models (i.e., non-Fourier models) for spectrum analysis. These models allow information extraction beyond second order spectral analysis [11]. Therefore, we aim to combine these methods to model the non-stationary non-Gaussian periodic time-series acquired during binary pulsar surveys and extract possible higher order spectral (HOS) features. Whether there is additional information embedded in these HOS features remains to be seen.

To estimate the model parameters we will use a Variational Bayesian (VB) learning framework. The VB framework prevents overfitting and provides model order selection criteria both for the model and the noise [9].

These approaches offer advantages over existing binary pulsar detection methods in that they make no assumptions on either the type of noise present or the periodicity of the time-series. They allow for the extraction of HOS features, which we believe contain supplementary information that will help with the detection of binary pulsars. Lastly, the estimation of the model parameters with the VB learning framework results in a linear system of equations. This linear system of equations is amenable to massive parallelisation, allowing for optimism that it can be numerically solved in real-time.

4. Conclusion

There is considerable development required with regard to hardware, software, data analysis and time-series modelling to ensure that the SKA is the premier instrument for pulsar surveys. Achieving one of the main SKA science objective of providing strong field tests of gravitational physics requires many more binary pulsars to be detected and timed. Binary pulsar detection is intrinsically difficult due to the variable period of these weak signals and the presence of non-Gaussian noise in the data. Existing techniques achieve high SNR detections at a cost of time-consuming off-line processing. This paper proposes that the non-stationary, non-Gaussian time-series acquired during a binary pulsar survey should be described by a model that combines the properties of GAR and ARIMA models. This model is to be estimated in a VB framework, whereafter HOS are to be extracted. These HOS are believed to be informative for the detection of periodic binary pulsars.

5. References
