Pulsar Search Techniques and Prospects for Pulsar Search with the FAST Telescope: Postprint

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Abstract

We analyze the feasibility and necessity of existing pulsar search methods for the upcoming early pulsar search with the FAST telescope, and attempt software and hardware acceleration for pulsar search data processing. We review and summarize existing pulsar search methods and their corresponding discoveries, and analyze the characteristics of these methods. A parallel data processing program based on PRESTO was developed. The feasibility and efficiency of using GPU computing acceleration to perform single-pulse search were estimated. The developed parallel data processing program based on PRESTO reduced the processing time for a typical file (100 MB) from the Parkes multi-beam survey from approximately 95 min to less than 10 min. The GPU-accelerated single-pulse search achieved approximately a 20-fold speedup, with data processing time shorter than the time required to acquire the observational data. For pulsar search using early observational data from the telescope, the phase modulation search algorithm for short-orbital-period pulsars is unnecessary, the acceleration search algorithm for longer orbital periods is also not essential, and the fast folding algorithm for long-rotation-period pulsars is only required when searching for weak pulsars with long rotation periods. During the data processing, software and hardware aspects can accelerate the processing speed, enabling the data processing time to be shorter than the data acquisition time.

Full Text

Pulsar Search Techniques and Prospects for FAST Pulsar Searches

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Abstract

This study analyzes the feasibility and necessity of applying current pulsar search methods to the early pulsar search phase of the Five-hundred-meter Aperture Spherical radio Telescope (FAST), and explores software and hardware acceleration techniques for pulsar search data processing. We review and summarize existing pulsar search methods, their corresponding discoveries, and characteristics. Parallel data processing scripts based on PRESTO were developed, and the feasibility and efficiency of using Graphics Processing Unit (GPU) acceleration for single-pulse search were evaluated. The parallel processing program achieved approximately a 10-fold speedup for a typical Parkes Multi-beam Pulsar Survey (PMPS) data file (100 MB), reducing processing time to less than 10 minutes—shorter than the data acquisition time. For FAST' s early observation data, phase modulation search algorithms for short orbital period binaries are unnecessary, acceleration search algorithms for longer orbital periods are not critically important, and the fast folding algorithm for long-spin-period pulsars is only required when searching for faint, long-period pulsars. Both software and hardware acceleration can reduce processing time below data acquisition time.

Keywords: pulsar; radio telescope; FAST

1. Introduction

To date, over 2,000 pulsars have been discovered. Some special pulsars have provided new insights: the discoveries of binary pulsars [?] and double pulsars [?] offered opportunities to test general relativity with higher precision and further constrain the equation of state for compact stars. The discovery of numerous millisecond pulsars in globular clusters [?], particularly 34 millisecond pulsars in Terzan 5, and pulsars near the Galactic center indicate extremely high electron density along the line of sight. For example, the discovery of the X-ray pulsar near the Galactic center [?] suggests that extragalactic pulsar science is imminent. The discovery of PSR J1745-2900 constrains the evolution of globular clusters. More efficient discovery of new pulsars requires breakthroughs in hardware or software. While larger telescope collecting area and lower receiver noise improve sensitivity in hardware, more powerful computers enhance data processing efficiency. To process observational data faster and more effectively remove interference while searching for potential signals, various methods have been attempted to detect periodic signals in the data.

This paper reviews low-frequency radio pulsar data processing methods commonly used over the past decade, assessing their necessity and feasibility for early pulsar searches with FAST—the world' s largest single-dish telescope currently under construction. We attempt to implement parallel acceleration for the pulsar search pipeline using simple programs and explore GPU acceleration for the search process.

2. Pulsar Search Methods

The first pulsar was arguably discovered by Jocelyn Bell Burnell through visual inspection [?], but today’ s pulsar discoveries rely entirely on computers. From initial time-domain signal searches to obtaining frequency-domain information through dedispersion and Fourier transforms, pulsar search methods have become relatively mature. When testing new techniques, the common practice is to use historical survey datasets to find as many known pulsars as possible and search for previously undiscovered pulsars in the data. Researchers tend to use the Parkes Multi-beam Pulsar Survey (PMPS) data as a benchmark.

The PMPS, conducted with the Parkes telescope and a 13-beam receiver, covered a sky region of ±5° around the Galactic plane. Since data processing began concurrently with observations, some important results were published earlier [?]. The survey’ s first review paper [?] documented pulsars discovered from PMPS data. Notable discoveries include PSR J1740-3052 with a companion mass up to 11 solar masses [?], PSR J1811-1736 and PSR J1814-1744 with extremely strong magnetic fields [?], and PSR J1141-6545 in a highly eccentric binary system with a 4.74-hour orbital period [?]. The survey found very few millisecond pulsars with orbital periods shorter than one day, prompting questions about whether this was a selection effect. Some papers using PMPS data to discover new pulsars addressed this question, reporting new binary pulsars, millisecond pulsars, and pulsars with spin periods as long as 7.7 seconds [?]. The search methods included the acceleration search technique later widely used for binary pulsar searches.

Since 2006, 11 papers have been published reporting new pulsars found in PMPS data using various methods, summarized in Table . These include discoveries of a new object type (Rotating Radio Transients, RRATs), new candidate ranking methods, radio frequency interference (RFI) removal techniques, neural network-based candidate selection, coherent acceleration searches, and the Einstein@Home project that systematically reprocessed data with volunteer participation.

3. Necessity and Feasibility of Different Search Methods for FAST Early Pulsar Searches

The pulsar search process can be divided into three main stages: (1) RFI inspection and removal, (2) data processing and periodic signal search (including dedispersion, Fourier transform, etc.), and (3) candidate signal screening.

FAST will initially conduct pulsar searches at low frequencies around 300–500 MHz. This range includes strong RFI from television signals (433 MHz), public communication frequencies, mobile phone communications (900 MHz), and GPS signals (1,227 MHz, 1,575 MHz) [?]. These strong interfering signals significantly impact subsequent data analysis during dedispersion.

Figure [Figure 1: see original paper] shows PRESTO processing results for a

PMPS data file containing a known pulsar. The diagonal stripes in the lower-left grayscale image represent residual RFI after removal of the most influential interference. Although the pulsar signal is strong enough that the results are not fundamentally affected, RFI remains a critical issue even for the Parkes telescope in a quiet radio environment. Although FAST' s design attempts to avoid many potential interference sources, RFI identification and removal remain essential in data processing.

The main methods for searching periodic pulsar signals are acceleration search [?, ?], phase modulation search [?, ?], and the Fast Folding Algorithm (FFA) [?]. We analyze the necessity and feasibility of each method for FAST' s early observations.

FAST' s early observations will use drift-scan mode, where the telescope points at a target and records data as the source drifts through the beam. The single-observation duration depends on beam size, which is frequency-dependent. At 1.4 GHz, the beam width is approximately 12 arcminutes, corresponding to a drift time of 56 seconds. At 300 MHz, the beam width increases to about 4 arcminutes, reducing the observation time to 12 seconds. This short integration time fundamentally changes the requirements for search algorithms.

Phase Modulation Search: This method targets binary pulsars with extremely short orbital periods and works best when observation times approach or exceed the orbital period. Compared with known binary pulsars, FAST' s early observation times are extremely short—far shorter than typical orbital periods. Therefore, phase modulation search is unnecessary for FAST early pulsar search data processing.

Acceleration Search: This method uses a constant acceleration approximation to eliminate pulse arrival time variations caused by binary orbital motion. It is suitable for systems where the orbital period is much longer than the observation time. We can estimate its effectiveness for circular binary systems using the parameter z_{max}, which controls the maximum acceleration searched in PRESTO:

$$z_{\text{max}} = \frac{a_{\text{survey}} T^2}{P}$$

where a_{survey} is the acceleration parameter, T is observation time, and P is the pulsar spin period. The maximum acceleration is:

$$a_{\text{max}} = \frac{2\pi x c}{P_{\text{orb}}^2}$$

where x is the projected semi-major axis in light-seconds and P_{orb} is the orbital period in seconds. If $P_{\text{orb}} > A_{\text{max\_survey}}$, orbital motion significantly affects the search.

Table estimates acceleration search effectiveness for known pulsars in the globular cluster 47 Tucanae (though FAST cannot observe this cluster, we use these parameters for estimation). With $z_{\max} = 100$ and $T = 1$ minute, all these millisecond pulsars show minimal orbital effects. For slower pulsars (e.g., $P = 0.1$ s), $A_{\max\_survey}$ increases further, allowing even smaller $z_{\max}$ values or no acceleration search at all. While this means potentially missing some binary signals, pulsars in short-period binaries might still be detectable. For FAST early searches, low-acceleration searches are sufficient; acceleration search can be omitted unless specifically targeting very short-period binaries.

Fast Folding Algorithm: This method searches for pulsars with extremely long spin periods. For example, PSR J1001-5939 with a 7.7-second period achieved a signal-to-noise ratio of 69.3 in PMPS data, while its second harmonic reached 51.8. Strong long-period pulsars can be detected through harmonics even when the fundamental is missed. However, weak long-period pulsars may require FFA. PRESTO does not include FFA, but Sigproc’ s segmented search method, which accumulates data from 9-hour observations of 47 Tucanae, successfully discovered new pulsars [**?**]. This approach could be adapted for FAST’ s short drift-scan observations by stacking data from different epochs, though it would increase computational load by hundreds of times due to searching many dispersion measures.

For candidate screening, computer programs are essential. While complex methods like artificial intelligence can be used, they may miss rare genuine signals. Given that FAST may generate hundreds of millions of candidates annually, combining computer filtering with human inspection (as in Einstein@Home) may be optimal.

4. Acceleration Attempts for PRESTO Pulsar Search and Heimdall Single-Pulse Search

PRESTO’s pulsar search proceeds sequentially: RFI analysis and flagging, dedispersion and file output, Fourier transforms, periodic signal searches across dispersion measures, candidate ranking, and final quality assessment plots. Since Fourier transforms, searches, and plot generation are independent for different dispersion measures, we parallelized these processes. The acceleration effect is significant: on a dual X5690 node with 96 GB RAM, processing time for a single PMPS file decreased from >1,070 seconds to approximately 600 seconds with 96 threads, saving over 90 minutes. On higher-configuration nodes, processing time can be reduced to <200 seconds. FAST data will be processed on multi-core clusters, making simple parallelization highly beneficial initially.

We also attempted single-pulse search acceleration. Single pulses are dispersed, individual bright pulses from known pulsars, RRATs, or fast radio bursts. The steps mirror periodicity searches but use specialized algorithms. We tested Heimdall [**?**], a GPU-accelerated program, on an NVIDIA M2090 GPU server. For PMPS data, Heimdall completed single-pulse searches in 32–34 seconds compared to 600 seconds with PRESTO—a ~20× speedup—while successfully detecting RRAT pulses.

Figure [Figure 2: see original paper] shows processing time versus thread count for parallel PRESTO processing. For this node, increasing threads below ~100 significantly reduces processing time.

PMPS files have 250 s resolution and ~2.1-hour duration (~100 MB). FAST early drift-scan observations last ~1 minute. With 1-bit sampling, FAST' s data volume per source is about one-third of a PMPS file. PRESTO processing on a single node takes ~200 seconds, while Heimdall single-pulse search completes in ~10 seconds—already shorter than the observation time. A small cluster can thus achieve real-time processing.

5. Summary and Outlook

Based on analysis of previous search methods, we conclude that for FAST early pulsar searches: - Phase modulation search is unnecessary - Acceleration search is only needed for binaries with very short spin and orbital periods - Fast folding algorithm is only necessary when searching for faint, long-period pulsars

Both software and hardware acceleration should be employed. GPU-accelerated single-pulse search achieves ~20× speedup, while parallelization reduces processing time to ~1/10th of the original. These efforts will help process FAST's pulsar data more efficiently, enabling processing speeds faster than data acquisition for drift-scan data.

Given FAST' s exceptional sensitivity and search capabilities, we expect to discover numerous new pulsars in early drift-scan data. We recommend: 1. Rapid single-pulse search using GPU acceleration (completes in seconds) 2. Periodicity search with no or minimal acceleration range 3. For long-period weak signals, consider reprocessing with Sigproc' s fast folding algorithm or segmented search

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