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Architecture, implementation and parallelization of the software to search for periodic gravitational wave signals[☆]

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ABSTRACT

The parallelization, design and scalability of the `PolGrawAllSky` code to search for periodic gravitational waves from rotating neutron stars is discussed. The code is based on an efficient implementation of the $\mathcal{F}$-statistic using the Fast Fourier Transform algorithm. To perform an analysis of data from the advanced LIGO and Virgo gravitational wave detectors' network, which will start operating in 2015, hundreds of millions of CPU hours will be required—the code utilizing the potential of massively parallel supercomputers is therefore mandatory. We have parallelized the code using the Message Passing Interface standard, implemented a mechanism for combining the searches at different sky-positions and frequency bands into one extremely scalable program. The parallel I/O interface is used to escape bottlenecks, when writing the generated data into file system. This allowed to develop a highly scalable computation code, which would enable the data analysis at large scales on acceptable time scales. Benchmarking of the code on a Cray XE6 system was performed to show efficiency of our parallelization concept and to demonstrate scaling up to 50 thousand cores in parallel.

Program summary

Program title: parallel PolGrawAllSky

Catalogue identifier: AEUX_v1_0

Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AEUX_v1_0.html

Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland

Licensing provisions: Standard CPC licence, http://cpc.cs.qub.ac.uk/licence/licence.html

No. of lines in distributed program, including test data, etc.: 163747

No. of bytes in distributed program, including test data, etc.: 28989030

Distribution format: tar.gz

Programming language: C.

Computer: Any parallel computing platform supporting MPI standard.

Operating system: Linux as well any other supporting MPI standard.

Has the code been vectorized or parallelized?: Yes, using MPI. Tested with up to 50208 processors

RAM: 1 Gigabyte per parallel task

Classification: 1.5.

External routines: MPI v.2 or newer, FFTW v.3 or newer

[☆] This paper and its associated computer program are available via the Computer Physics Communication homepage on ScienceDirect (http://www.sciencedirect.com/science/journal/00104655).

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Nature of problem:
Search for periodic gravitational waves from rotating neutron stars.

Solution method:
The F-statistic method using the Fast Fourier Transform algorithm.

Running time:
The example provided takes approximately 30 mins with 256 processors.

1. Introduction

Gravitational waves (GWs) – variations of the curvature of spacetime, able to propagate through spacetime in a wave-like fashion – were first predicted by Albert Einstein [1], and they are a direct consequence of the general theory of relativity that he proposed. Several properties of GWs are similar to those of electromagnetic waves. GWs also propagate with speed of light and are polarized (two polarizations in the description of general relativity). The best empirical, yet *indirect* evidence for gravitational radiation comes form the observations of tight relativistic binary pulsar systems; first such a system was discovered by R. Hulse and J. Taylor with the radio observations from the Arecibo telescope [2]. Direct detection of GWs will constitute a very precise test of Einstein's theory of relativity and open a new field—GW astronomy. Currently, the most promising GW detector concept is of the Michelson–Morley interferometer type. The detection principle is as follows: while a GW passes through such a detector, it changes the length of its arms and affects the interference pattern of the laser light circulating in the interferometer [3].

State-of-the-art interferometric GW detectors, LIGO[1] in the USA and Europe (Italian–French, with the contribution of Hungary, the Netherlands and Poland) Virgo[2] have collected a large amount of data that are still being analyzed. Meanwhile, the advanced LIGO and Virgo detectors are under construction and they are forecasted to start collecting new, more sensitive data at the end of 2015. It is expected that these advanced detectors will be sufficiently sensitive so that the direct detection of GWs can finally be achieved. As the GW signals are extremely weak, their detection constitutes a major challenge in data analysis and computing. Several types of astrophysical GW sources are investigated: coalescence of compact binaries containing neutron stars and black holes, supernova explosions, quantum effects in the early Universe as well as rotating, non-axisymmetric neutron stars.

The departure from axisymmetry in the mass distribution of a rotating neutron star can be caused by strong magnetic fields and/or elastic stresses in its interior. The search for such long-lived, periodic GW signals generated by the spinning star is nevertheless particularly computationally intensive. This is because the GW signal is very weak and one needs to analyze long stretches of data in order to extract the signal "buried" in the noise of the detector. Due to this, the modulation of the signal due to the motion of the detector with respect to the solar system barycenter has to be taken into account; it depends on the location of the source and a modulation that is a function of the intrinsic change of rotation frequency of the deformed neutron star. Moreover, we do not know the polarization, amplitude, and phase of the GW signal. Consequently, the parameter space to search for the signal becomes very large.

The *Polgraw–Virgo* team, working within the LIGO scientific Collaboration (LSC) and the Virgo Collaboration has developed algorithms and a pipeline called `PolGrawAllSky` to search for GW signals from spinning neutron stars [4]. The pipeline was applied to the analysis of the data gathered by the Virgo detector during its first science run denoted as VSR1. The analysis involved 5 million CPU hours and took almost three years to complete [5]. The serial code's design allowed to use only one processor core and was run on a number of computer clusters with standard queuing systems. This performance turned out to be not entirely satisfactory for current and future requirements of the GW data analysis. To analyze all the data collected by the Virgo detector, 250 million CPU hours are required, whereas the analysis of all the data that will be collected from the advanced detectors expected to be available by the year 2018 will require four times more resources, i.e., 1000 million CPU hours. To perform this analysis one would need 1petaFLOPS computer working continuously for one year.

To estimate the computational requirements we have performed representative tests with the Gaussian noise data at different band frequencies illustrated in Figs. 1 and 2. For example, a serial search for GWs at frequencies 600, 1000, 1700 and 2000 will require a total of 20 thousand CPU hours of computation, which is more than two years on a single CPU and correspondingly the output generated by this simulation would be ca. 4 GB.

To alleviate the computations, this paper proposes a massively parallelized version of the `PolGrawAllSky` code that uses the Message Passing Interface (MPI) library [6]. MPI is a distributed memory parallelization scheme commonly used in high performance computing (HPC). This parallelized version is able to run on high performance computers with tens of thousands of cores. We are reporting a sufficient performance increase of the parallel `PolGrawAllSky` code enabling its usage on massively parallel HPC systems for production analysis of data already collected by GW detectors and also of data from the advanced GW detectors that will start to be available by the end of the year 2015 [7].

1.1. Mathematical methodology

The algorithms to search for gravitational wave signals from rotating neutron stars implement the $\mathcal{F}$-statistic [8], derived by one of us and commonly adopted in other pipelines (see e.g., [9]). By using the $\mathcal{F}$-statistic one does not need to search for the polarization, amplitude and phase of the signal. Instead, one is left with a 4-dimensional space parameterized by the GW frequency, frequency derivative (spindown, reflecting the fact that the pulsar is spinning down) and the two angles determining the location of the source in the sky. To implement a computationally efficient algorithm we are faced with two problems. Firstly, one would like to minimize the number of grid points on which the $\mathcal{F}$-statistic is evaluated, achieving at the same time a certain target sensitivity of the search. This is equivalent to a well-known geometrical problem called the *covering problem*. Secondly, we would like to

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[1] http://www.ligo.org.

[2] https://wwwcascina.virgo.infn.it.