GPU-accelerated Signal Processing for Search of Pulsars

Stanislav Klimenko(1), Kira Konich(2), Igor Nikitin(3), Lialia Nikitina(3), Sergey Tyul'bashev(4)

(1) Institute of Computing for Physics and Technology,
Moscow Institute for Physics and Technology (State University), Protvino, Russia

(2) Bauhaus University, Weimar, Germany

(3) Fraunhofer Institute for Algorithms and Scientific Computing, Sankt Augustin, Germany

(4) Pushchino Radio Astronomy Observatory, Lebedev Physical Institute, Pushchino, Russia

email: stanislav.klimenko@gmail.com, kira.konycheva@uni-weimar.de,
igor.nikitin@scai.fraunhofer.de, lialia.nikitina@scai.fraunhofer.de, serg@prao.ru

***Abstract*—This short paper describes the accelerated signal processing for the search of radio pulsars recorded by Big Scanning Antenna telescope at Pushchino Radio Astronomy Observatory. Acceleration is achieved by parallelization of computations on multiprocessor systems and, especially, on Graphics Processing Units. Parallelization provides computational speeds sufficient for signal processing and pulsar detection in the observations in real-time.**

***Keywords*–Statistical signal processing; Big data analysis; Monitoring and control systems; Radio astronomy applications.**

I. INTRODUCTION

Big Scanning Antenna (BSA) is a unique instrument used at Pushchino Radio Astronomy Observatory of Lebedev Physical Institute. This radio telescope has the structure of a phased array of size 187 m x 384 m (10 football fields, see Figure 1). It has no moving parts, consists of 16,384 half-wave dipoles located in a grid of 64 dipoles in 256 lines. The telescope performs simultaneous measurements along the meridian plane and uses the rotation of the Earth to scan the celestial sphere. The telescope has a working frequency band of 109-113 MHz. It is one of the most sensitive telescopes in the world in this frequency range. The telescope is used in a number of projects: in studying pulsars, dynamic processes in near solar and interplanetary plasma, analyzing the structure of compact radio sources, studying active galactic nuclei [1]–[3].

The signal of the radio telescope consists of 1536 channels, representing simultaneous measurements in 48 spatial directions (beams) and 32 frequency bands. Each measurement represents a stream of 32-bit numbers taken at a frequency of about 80 Hz, so the total density of the data stream from the telescope is about 4 Mbps.

A typical one-hour observation is shown in Figure 2. The image is similar to a snapshot of a night sky from an ordinary optical telescope, the difference is that here the signal is recorded in the radio range and only the sources of periodic signals are reconstructed. The typical signal level is so small that it is usually not visible directly in the observation data and is extracted from noise only by special processing algorithms.

The telescope simultaneously detects the signal in 32 frequency bands, in which the signal manifests a phase shift. The reason for this shift is the dispersion in the interstellar medium, i.e., the propagation velocity of radio waves deviates from the speed of light in a vacuum and begins to depend on the frequency. As a result, the signals in different frequency bands arrive at different time. The shift is proportional to the total propagation time of the signal, i.e., the distance to the source. Thus, the phase shift of the signal in frequency bands allows to measure the distance to the source.

Similar effects appear in Search for Extraterrestrial Intelligence (SETI), [4]–[6]. When looking for narrow band radio signals from deep space, one needs to account for Doppler drift due to the relative motion of the telescope and the signal source. Doppler drift is time dependent, since the Earth is rotating together with the telescope fixed on its surface. Also, the source of the signal is presumably located on the surface of a planet or orbits around a planet. The both effects, frequency dependent time shift in the search of pulsars and time dependent frequency shift for SETI, lead to the signal smearing over the exposition time, like shaking the camera smears the snapshot. To increase the sensitivity of detection, the both type of effects should be compensated on processing stage.

In [7] [8], we described a method of statistical accumulation, specially developed for the search for pulsar signals. The method consists in computing the integral of the form

$$corr(T, a, b) = \int df\, dt\, s(t, f)\, \Delta((t - (a + bf))/T), \quad (1)$$

where $s(t, f)$ is the signal depending on time and frequency, $\Delta()$ is the periodic delta function, T is the period, $a+bf$ is the phase shift, linearly depending on frequency. The integral over the frequency-time plane defines the functional scalar product of the measured signal with the expected waveform, i.e., periodically repeating pulses with the phase shift proportional to frequency variation. When the signal is normalized to unity, the integral represents a correlator of the signal with the expected shape. The method consists in finding the signal parameters (T, a, b) maximizing this correlator.

The reconstructed signal parameters: the period T, the common phase a and the frequency shift b represent individual characteristics of the pulsar. The period is determined by the rotation speed of the pulsar, the phase describes the profile of the pulse, the shift can be used to determine the distance to the source.

This paper is devoted to the acceleration of the processing of signals of this kind. The processing is computationally expensive and requires massive parallelization. For acceleration we use multiple Central Processing Units (CPUs), Graphics Processing Units (GPUs) and compare their performance in application to the search of pulsars.

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Figure 1. BSA telescope at Pushchino Radio Astronomy Observatory. On the left: satellite view. On the right: phased array structure.

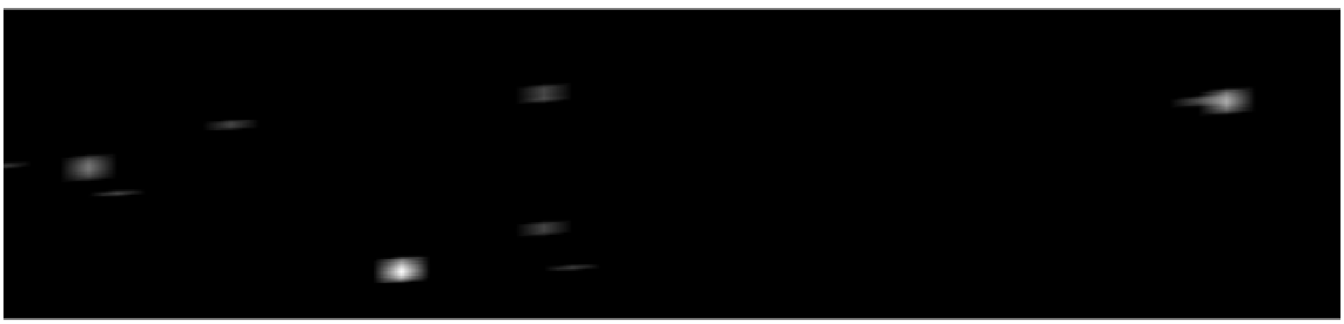

Figure 2. A typical one-hour observation. The window $21^\circ \times 15^\circ$ of the celestial sphere is shown, grayscale represents the intensity of the signal in the interval 0...15 dB. Intensity spots correspond to the sources of periodic signals, pulsars.

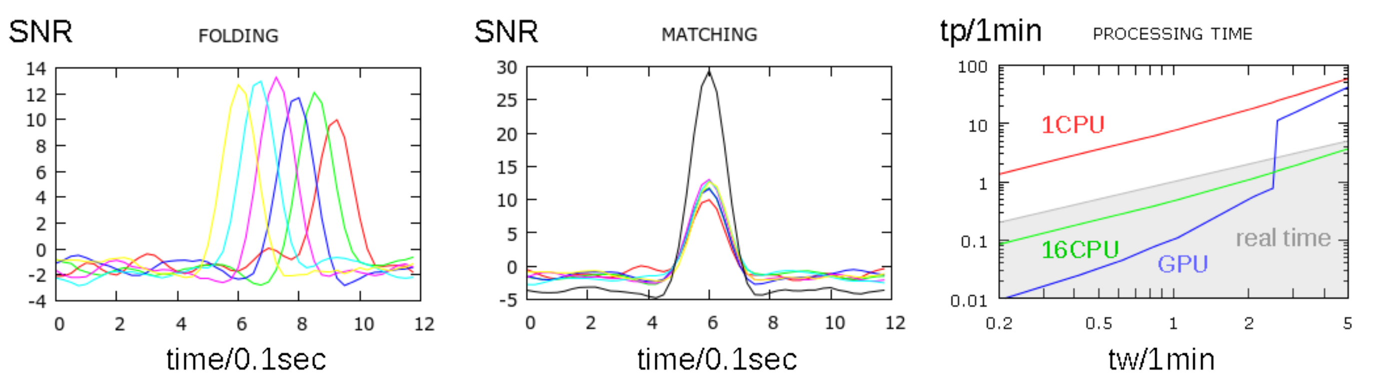

Figure 3. Signal processing algorithms. On the left: the result of folding algorithm, peaks in six frequency bands arrive at different times due to dispersion on the interstellar medium. In the center: matching algorithm collects peaks together and increases the resulting intensity. The horizontal axis represents the elapsed time, measured in data points. The vertical axis represents signal-to-noise ratio. On the right: processing time tp as a function of processing window size tw. Real time zone is marked by gray color.

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Algorithm folding(T,x,y):

```
// T - probe period, x - input signal,
// y - output
// consts: np - num.datapoints,
// nf - num.freq.bands

{ int nT=(int)(np/T), nphase=(int)T;
  // loop over phase
  for(int j=0;j<nphase;j++){
    // loop over periods
    for(int i=0,n=0;i<nT;i++){
      float t=T*(i+(float)j/nphase);
      if(t<np-1){ int i0=(int)t; n++;
        // loop over freq.bands
        for(int f=0;f<nf;f++)
              y[f+nf*j]+=x[f+nf*i0];
      }
    }
// normalization
    if(n>0)for(int f=0;f<nf;f++)
              y[f+nf*j]/=sqrt(n);
  }
}
```

Algorithm matching(dp,yt,s):

```
// dp - probe dispersion parameter
// yt - input (transposed array from the prev.alg.)
// s - output signal
// max_sum, phase_max - output signal metric

{ int nphase=(int)T;
  // loop over freq.bands
  for(int f=0;f<nf;f++){
    int d0=dp*(nf-1-f),d1=nphase*f;
    int i0=d0%nphase+d1,i1=(nf*nphase-d0)%nphase;
    // loop over phase, with a jump at j=i1
    for(int j=0,k=i0;j<i1;j++,k++)s[j]+=yt[k];
    for(int j=i1,k=d1;j<nphase;j++,k++)s[j]+=yt[k];
  }
  // normalization
  for(int j=0;j<nphase;j++){ s[j]/=sqrt(nf);
    // metric evaluation
    if(s[j]>max_sum){ max_sum=s[j]; phase_max=j; }
  }
}
```

Figure 4. Signal processing algorithms.

Recently, multiprocessor architectures and GPUs have been used to accelerate the processing of astrophysical signals, also, for the search of pulsars. In particular, [9] [10] describe the implementation of Fourier Domain Acceleration Search Method, using GPU acceleration for the search of pulsars with Square Kilometre Array telescope. In [11] GPU acceleration is applied for pulsar signal processing on Goldstone Apple Valley radio telescope. In the present paper, we concentrate on the usage of multiple CPUs and GPUs for acceleration of signal processing from BSA radio telescope.

In Section II, we describe general computational aspects of signal processing algorithms used for the search of pulsars. In Section III, we present the acceleration of computation using multiprocessor systems. The obtained results are summarized in Section IV.

II. Signal processing algorithms

Calculating in (1) the integral over the time dt, it can be converted to the sum of the signal over the periods T, i.e., the signal folding over the trial period in each frequency band. The integral over the frequency df then corresponds to the matching of the signals in different frequency bands, taking into account the shift between the bands. The principle of the reconstruction methods is shown in Figure 3, the prototype algorithms are shown in Figure 4.

The processing is a multiple summation of data segments in different combinations, requiring extremely intensive computations. The estimates of [7], [8] show the computational complexity of the order $O(N_f N_b N_p^2 \log(T_1/T_0))$, where N_f is the number of frequency bands, N_b is the number of observation beams, N_p is the number of data points taken in the analysis, $T_{0,1}$ is the search limits for the period. Previously, to process one-hour observation in less than one hour, the coarser, shortened data consisting of 6 frequency bands with a time resolution of 0.1 sec have been considered. In this paper, we investigate the possibility of processing complete data in real time, which requires additional acceleration of processing methods. For this purpose, we use a massive parallelization of computations.

III. Acceleration of signal processing

At first, the full one-hour data occupying 1.8 GB are cut into segments, containing observations in every beam in a given time window tw, which we consider as a parameter in our study. In order not to loose the signals spreaded across the cut borders, we use an additional collocated segmentation, shifted by $tw/2$. This doubles the total processing time, but guarantees the reconstruction of all signals. The optimal value for tw is related with the size of the beam and constitutes 3-5min. Reducing the window size is possible, but leads to sensitivity loss, i.e., reducing tw by factor k reduces the sensitivity by factor $k^{1/2}$. An important aspect is a capability of the algorithms to perform in real-time, i.e., to have processing time not more than the time of data capture.

After the data splitting, each segment is processed in parallel, using the maximum number of available processors. We have experimented with Intel 3GHz CPUs vs 0.812TFLOPS Nvidia Quadro K620 GPU. The processing time tp as a function of window size tw is shown on Figure 3 right. Real time zone corresponds to $tp \leq tw$ and is displayed on this figure in gray. One CPU cannot reach the real time zone for all values of tw. When using 16 CPUs, the required real-time reconstruction speed is achieved for all tw. For the variant with collocated segmentation, 32 CPUs should be used.

At large tw, processing on GPU brings only insignificant advantage over 1CPU variant and is also located outside the real time zone. At about $tw = 2.5$ min, the data in processing window start to match shared memory of the device, bringing performance boost by a factor 15. Then, GPU outperforms 16CPU variant and is located completely in real time zone.

IV. Conclusion and Future Work

The accelerated signal processing for the search of radio pulsars recorded by Big Scanning Antenna telescope at Pushchino Radio Astronomy Observatory has been presented. For this purpose the parallelization of computations on multiprocessor systems has been implemented. Typically, 16 CPU systems are sufficient for real-time processing of raw data from the radio telescope. The best results are achieved with GPU processing, which ensures the maximum degree of parallelization of computations. Here, below the threshold $tw < 2.5$ min, the data in processing window match shared memory of the device, providing a significant 15x performance boost. This allows to reach the computational speed, sufficient with a margin to process the signal from the radio telescope and to reconstruct pulsars from the observations in real-time.

Our further plans include the development of efficient algorithms, separating near Earth Radio Frequency Interference (RFI) from deep space signals. Interference from terrestrial and near-Earth radio sources poses a serious problem for detection of weak radio signals. In practice, the telescope receives high gain signal from the main beam and low gain signals from all possible directions. Low gain signals are not correlated with the position of the main beam and penetrate the telescope through the side lobes. On the other hand, the near-Earth RFI has a significantly higher intensity than the deep space signals. Therefore, at the output of the telescope, near-Earth RFI can overexpose the intensity of the sought-for signals. The main idea for filtering algorithms is to use correlation between different beams to select those signals highly localized on celestial sphere, i.e., deep space signals.

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