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Next Generation Software Based Instruments for Pulsar Astronomy

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Abstract. High time resolution studies of pulsars require specialized instrumentation to counter the degradation in the quality and time resolution of their radio signals due to dispersion in the inter-stellar medium. The availability of cheap computer hardware in recent years has provided a new alternative to dedicated hardware based solutions used in the past for this purpose. In this paper, a comparison of old and modern instrumentation to obtain high time resolution data is presented and future trends in pulsar instrumentation are discussed. The salient features of Coherent On-line baseband receiver for astronomy (COBRA), a new digital receiver for pulsar observations at Jodrell Bank Observatory, are listed followed by a brief description of our benchmark code used for designing such systems.

Keywords : instrumentation : radio pulsars – instrumentation : polarimeter – Coherent dedispersion

1. Introduction

Pulsar signals are dispersed by the electrons in the interstellar medium (ISM) causing their pulsed radiation to arrive at progressively later times with progressively decreasing frequencies of observations. This smears their pulse and reduces its signal to noise ratio (SNR) for a given observational bandwidth. Most pulsars are weak (typical flux $\sim$ 10 mJy at 400 MHz) and require a high signal to noise ratio for studying their properties. Large observational bandwidths are desirable for this purpose and there exists a trade-off between the bandwidth and the time resolution of pulsar data. In this paper, the science that can be done with this data is briefly reviewed and the traditional and new approaches for obtaining such data are compared.

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2. Role of High Time Resolution Data in Pulsar Astronomy

Most of our knowledge of radio pulsars is derived from pulsar timing studies. Pulsars are timed by associating an arrival time (TOA) at the solar system barycenter to the average pulse or integrated profile. The phase of this pulse at the measured arrival time is then compared with a model incorporating the rotation of the star and other effects. The systematic deviations in phase residuals provide information about the magnetic field, right ascension, declination and the proper motion of the star. If the star has a companion, its binary parameters can likewise be obtained. For example, the measurements of parallax distance of PSR J0437−4715 with an unprecedented accuracy have recently been reported by van Straten et al. (2001) based on their high time resolution data. They also estimate the inclination angle of this binary system, which enabled them to detect the Shapiro delay in the system and to estimate the neutron star mass.

High time resolution data are necessary for a wide variety of pulsar studies. Apart from high precision astrometry, such data are useful in pulse emission mechanism studies (Kramer et al 1999, Sallmen et al 1999) and studies of pulsar polarization (Stairs, Thorsett and Camilo 1999). The astrophysical applications of these studies extend beyond an understanding of pulsar - neutron stars themselves. They include evolutionary models for binary systems (Taam and van den Heuvel 1986, Bhattacharya and van den Heuvel 1991, van den Heuvel and Bitzaraki 1995), tests for general theory of relativity (Taylor and Weisberg 1989, Ryba and Taylor 1991, van Straten et al 2001) and the detection of primordial gravitational wave background (Foster and Backer 1990). The involved signal processing in obtaining such data is becoming more varied and is difficult with the conventional equipment.

3. Comparison of Traditional and Modern Pulsar Instrumentation

The uncertainties in TOA measurements affect the goodness of fit for the model and the precision of the measurements, enumerated in the last section, depends on both the time resolution and SNR of the integrated profile. As explained earlier, the dispersion in the ISM leads to a trade-off between bandwidth and time resolution. Traditionally, this trade-off was minimized by subdividing the overall bandwidth into a large number of subbands using large filterbanks, either with fixed channel bandwidth analog filters (e.g. Jodrell bank 32 channel filterbank, Parkes 96 channel and 512 channel filterbanks) or with hardware autocorrelators or FFT engines (e.g. Arecibo Fourier transform machine, Giant Meterwave Radio Telescope Pulsar processor or Green Bank Telescope spectral processor). The former are bulky and inflexible as the individual channel bandwidth cannot be easily retuned, but they are also easy to build. The latter type of filterbanks are more flexible, but still take time (2 - 3 years) and specialist manpower to develop and design. Moreover, as new technology becomes available, they become obsolete. More importantly, all filterbanks introduce a finite dispersion smear due to finite channel bandwidth and this places a limit on the time resolution.

One way to achieve the desired time resolution is the method of coherent dedispersion. In this method, the ISM is treated as a unity gain phase delay filter. The dispersion smear caused by ISM is then eliminated by passing the pulsar signal through a filter which has an inverse behaviour to that of ISM. This method was proposed by Hankins and Rickett (1975), but practical implementations were carried out only in the last decade. In some of the newer instruments, the baseband data was recorded at high time resolution and the coherent dedispersion was carried out offline (e.g. Parkes S2 baseband recorder, Princeton Mark IV recorder and Caltech baseband recorders for Arecibo and Parkes telescopes). Another approach was to use dedicated filter chips as in Berkeley Pulsar processors at Effelsberg, Arecibo and GBT. An interesting combination of hardware and software was also employed as in the Westerbork Pulsar processor PUMA. Alternatively, the baseband data was recorded to disks and post-processed offline and this method has been used in the recently commissioned Swinburne software based instrument at Parkes. As against these approaches, the pulsar group at Jodrell Bank Observatory realized that falling computer prices coupled with an exponential increase in compute power provides a unique opportunity to develop a software based online instrument that is not only flexible and upgradeable, but has longevity as the software once developed does not require much maintenance while the underlying commercially available processor backbones can seamlessly be changed to more modern processors. The salient features of a new digital receiver, being developed at this observatory, are described in the next section.

4. Coherent Baseband Receiver for Astronomy (COBRA)

COBRA is implemented on a Linux Beowulf cluster consisting of 182 Intel Pentium III 1.13 GHz commercially available processors connected by a wide bandwidth interconnect called Scalable Coherent Interface (SCI) and is capable of processing 80 MHz bandwidth online - a throughput of 320 Mbytes/sec. The data from the telescope is digitized with 8 bit sampling providing sufficient dynamic range for Radio Frequency Interference mitigation. The system also acts as a polarimeter. The pulsar signal processing is carried out entirely in concurrent software, which was written using Message Passing Interface (MPI). The software code features logical separation between data acquisition, communication and signal processing. Different plug in software modules can implement software filterbanks with flexible channel resolution, coherent dedispersion, polarimeter, one-bit search data acquisition and giant pulse flagging. Note that each of the abovementioned functionality would have required a dedicated system previously. The system became operational in August, 2002 and is being used routinely to acquire data with JBO 13 m telescope.

Similar initiatives are afoot at other observatories. At Westerbork Synthesis Radio Telescope, an instrument based on SHARC DSP processor was commissioned about four years back (Voute et al 2002). This instrument can be configured to record the baseband signal for both the polarizations in addition to operating as a hardware filterbank with a flexible selection of number of channels. Similarly, a 128 MHz baseband recording system called CPSR2 was designed by Swinburne pulsar group and has been made operational at Parkes radio telescope recently. This system features high speed data recording to disks and simultaneous playback and processing of the recorded data by offline software on a dedicated computer cluster. Both these systems represent interesting alternatives to COBRA and predate COBRA. However, the *online* nature of

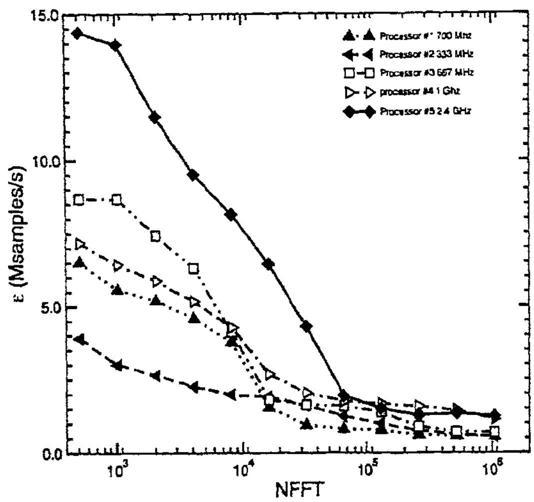

Figure 1. Figure shows the efficiency factor ϵ as a function of FFT length for different processor architectures. The number of processors required for specified observational bandwidth, observing frequency and DM can be estimated from this plot as explained in the text

COBRA gives it an edge over these systems. Since COBRA was announced at a pulsar meeting at Crete last year, similar instruments have been installed at the Arecibo Observatory and Nancay telescope.

5. Benchmark Code

A benchmark code was developed by the authors to design COBRA like systems. The code carries out two tests to calibrate the efficiency of coherent dedispersion algorithm. The efficiency factor for Fast Fourier Transform (FFT), obtained in the first test, is plotted in Figure 1 for different architectures tested by us. This can be used to estimate the required number of processors for given observational parameters and processor type in the following manner.

The length of one FFT computation in our algorithm is given by

$$N_{fft} = 1.66 \cdot 10^{10} \cdot DM\, \delta\nu^2/\nu^3 = 1.66 \cdot 10^{10} K \tag{1}$$

where DM is the dispersion measure of the pulsar in $pc\ cm^{-3}$, $\delta\nu$ and ν are the bandwidth and the observing frequency in MHz. K summarizes the observational specification. The required length for a given K is used to read the efficiency, ϵ, from Figure 1 for a processor type. In practice, small N_{fft} is desirable due to limited processor cache size as is evident from Figure 1. Hence,

Telescope	ν (MHz)	Overall Bandwidth (MHz)	n_b	$\delta\nu$ (MHz)	N_p
GMRT	610.0	16.0	8	2.0	10
ORT	325.0	10.0	10	1.0	12

Table 1. Estimates of the required number of processors for typical configurations of GMRT and ORT for a pulsar with a DM of 100 $pc\,cm^{-3}$

the overall bandwidth is processed in n_b separate parallel pipelines, each with $\delta\nu$ bandwidth. The required number of processors is then given by

$$N_p = n_b \cdot A \cdot \delta\nu/\epsilon \tag{2}$$

Here, A is a scaling factor between the theoretical and actual values and takes into account the overheads in the computer. It is usually between 3 to 5 (Kramer 2001).

As an example, the calculations for typical configurations of Giant Meterwave Radio Telescope (GMRT) and Ootacumund Radio Telescope (ORT) are summarized in Table 1 using the results for the latest commercially available processors.

6. Future trends

In this concluding section, the probable alternatives for new pulsar instrumentation are discussed. In principle, COBRA like flexibility can be achieved by using reconfigurable hardware built around comparatively inexpensive programmable chips called Field Programmable Gate Arrays (FPGA). These can be reprogrammed using hardware languages. Such hardware can handle large data rates and is ideal to reduce data rates by pre-processing to a level compatible with a conventional Peripheral Card Interconnect (PCI) bus in a personal computer. As of today, such systems indeed represent a low cost per MHz of bandwidth, but there is a hidden cost component in terms of developing this hardware which involves specialist manpower and long developmental lead times.

On the other hand, a full software approach like COBRA has the advantage of using commercially available off the shelf hardware as well as flexibility. This approach has two variants. While the Swinburne pulsar groups' CPSR2 relies on fast recording followed by playback and software processing on a cluster, the data acquisition and processing is fully online in COBRA. However, both these are relatively costlier solutions for large bandwidths as these are limited by the rate at which data can be transfered to computer's memory. Our tests have shown that the commercially available PCI cards have a sustained data transfer rate of 32 – 128 Mbytes/s which is much smaller than current processor - memory bandwidths (typically ~ 4 Gbytes/s). In the coming years, this limitation is likely to be surpassed and recently a new card handling sustained data transfer rates in excess of 150 Mbytes/s has been announced. Thus, this approach is likely to be in widespread use by the end of decade.

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