A Programmable VLBI Correlator Using Parallel Computing

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Abstract. This paper describes one application of a new data processing system installed at the Centre National d’Etudes Spatiales (CNES) in Toulouse France. Based on high speed interface to disk and on parallel computing, a VLBI correlator has been designed and tested. The main characteristics of the system are presented, and the results obtained from it are compared with that from comparable systems for validation. The use of this device for the analysis of millisecond pulsars data is discussed.

1. Introduction

A new VLBI correlator has been developed at the CNES in Toulouse, France. The design is based on a high speed interface to a computer disk and on parallel computing. So far one interface has been developed, which allows to process VLBI data in the MarkII format. Section 2 describes the technical solutions chosen to implement the system. A more detailed description can be found in (Fayard et al., 1993).

The validation of this correlator was carried out by comparing its results with those obtained by using other VLBI correlators. This is presented in Section 3. We then discuss in Section 4 one application made possible by the design of this new correlator. In processing millisecond pulsar VLBI data, it is possible to remove the dispersion of the signal and to gate the data before correlation. This facilitates the detection of the pulsar signal and should help in determining VLBI positions of pulsars, which have important astrometric applications.

2. Overview of the CNES VLBI Correlator

The major constraints are the data transfer rate (500 Kbytes s for MarkII) and the need of computing power. The design should also be easily expandable to accommodate future needs and availability of new processors. The choice was to develop a system based on transputer technology. Transputer is a brick designed to build parallel computers. It contains a powerful processor (30 Mips presently), some memory, and four bidirectional links. The programming language OCCAM is specially designed for transputer applications, and has the capability to handle concurrent processes which exchange data.
Figure 1 shows the block diagram of a versatile data acquisition system. In the case of the MarkII data, the main problem is the non synchronization between the video track used for data and the audio track used for time tags. Our system tests the audio track and passes the video data from tape to hard disk via a serial to parallel interface. The task of assigning a date to the video data is performed in the next step (formater). The performance of the interface is about 1.7 Mbytes/s. Actual performance of the acquisition system depends on the amount of processing that has to be performed by the transputer. The present set-up allows 1.1 Mbytes/s which is quite sufficient for MarkII.

The formater assigns a date to the video data by finding the Begin Of Frame (BOF) bit sequences. The continuity of the data between two BOFs is ensured by finding the synchronization words of the MarkII format. Presently this task is accomplished in about twice real time with one transputer. The next generation of transputers should allow real time formatting, which would be done at the same time as the acquisition.

In order to allow parallelization and versatility of the correlator system, elementary tasks are identified and realized in modules. Primary modules are the ones that actually perform some processing on the data such as shift in time, digital filter, or correlate. Secondary modules manage the propagation of the information over the transputer network. The proper configuration of modules to perform a given correlation task is called an application. In the application where standard correlation is done on standard MarkII data on 10 transputers, the processing rate is presently about 2.5 times real time. Other applications allow to filter and gate data before correlation (Fig. 2). Such application is used for millisecond pulsar correlation (see Fig. 1. Data acquisition system.
Section 4).

In principle, one application can be developed for any data format (number of bits per sample, sample rate, etc.). In the application designed for standard MarkII correlation, the model phase is passed as linear over the (settable) integration interval and the fringe stopping is realized with three-level sine and cosine. The correlation sums are passed to the host PC for later processing.

An environment, running on the host PC, manages the whole system and allows the user to run a specified application on specified data. Its main functions are to manage the data on the SCSI hard disk, to set up the information files needed by the application through menu driven input, and to configure the network. The system can be run in batch mode.

3. Validation of the Correlator Output

The correlator computes, for each integration interval, the complex correlation function for a given number of lags. Each value is phase shifted to account for the average effect of the discrete delay tracking over the integration interval (fractional bitshift correction). After an optional coherent addition over a number of consecutive intervals, the complex correlation sums are passed to the fringe fitting program, which has been adapted from PHASOR, the CIT/JPL MarkII fringe fitting routine (CIT, 1988).

In the fringe fitting program, the complex correlation sums are Fourier transformed from the lag domain to the baseband frequency domain. In the standard set-up, data from nine lags provide four estimates of the cross-power spectrum. Such
Table 1. Comparison of CNES and BlockII/Block0 from MarkII data taken at 1.66 GHz: Difference between total phases (cycles) and total phase rates (ps/s).

Scan 1 (3 minutes on 3C454.3):

<table>
<thead>
<tr>
<th>Baseline code</th>
<th>Phase diff wrt BlockII/Block0 (cy.)</th>
<th>Sigma</th>
<th>Rate diff wrt BlockII/Block0 (ps/s)</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>-0.247/-0.247</td>
<td>0.003</td>
<td>-0.02/-0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>EK</td>
<td>-0.258</td>
<td>0.016</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>WK</td>
<td>-0.256</td>
<td>0.07</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>BK</td>
<td>-0.253</td>
<td>0.07</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>EB</td>
<td>-0.257</td>
<td>0.002</td>
<td>-0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>WB</td>
<td>-0.260</td>
<td>0.006</td>
<td>-0.09</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Scan 2 (3 minutes on 1923+210):

<table>
<thead>
<tr>
<th>Baseline code</th>
<th>Phase diff wrt BlockII/Block0 (cy.)</th>
<th>Sigma</th>
<th>Rate diff wrt BlockII/Block0 (ps/s)</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>-0.248</td>
<td>0.004</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>EM</td>
<td>-0.252</td>
<td>0.003</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>EL</td>
<td>-0.246</td>
<td>0.01</td>
<td>0.07</td>
<td>0.1</td>
</tr>
<tr>
<td>EB</td>
<td>-0.248</td>
<td>0.003</td>
<td>-0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>EM(*)</td>
<td>/-0.252</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*This scan is from a different experiment.

data for a number of integration intervals (forming a section) are used to estimate the set of parameters (amplitude, delay, phase rate, phase at mean time) that produce the best fit (in the least squares sense) of the data to the theoretical formula (Moran, 1976). The values of the estimated residual phase and phase rate are then added to the model to provide estimates of the total observables for the mean time of the section.

Similar processing can be done with data correlated on the CIT/JPL Block0 and BlockII systems. For Block0 data, the fringe fitting routine PHASOR is used, while for BlockII data the routine is BWSFIT (Fort, personal communication, 1993). Data from several MarkII experiments have been processed with the CNES correlator, and with Block0 and/or BlockII. All experiments are at L band (1662.99 MHz), with baselines between Effelsberg (Germany), DSS63 (Spain), Westerbork (The Netherlands), Medicina (Italy), Bear Lakes (Russia) and Kashima (Japan). Comparisons between the total phase and phase rate produced by the different correlators have been carried out, and are reported in Table 1. It emerges from the comparisons that the phase and phase rate observables generated by the CNES correlator agree with those produced by other MarkII correlators to within measurement noise. The constant phase difference of -0.25 cycle, which is visible in the results, is thought to originate from the different realization of the fringe stopping, and will eventually be included in the phase model.

4. Application to Millisecond Pulsar VLBI Data

Millisecond pulsars provide a direct way to link the extragalactic celestial
reference frame with the dynamical reference frame of the solar system, by comparing astrometric positions of pulsars obtained in the former frame with VLBI, and in the latter with timing observations. Millisecond pulsars are weak sources for VLBI but, noting that their signals are regularly spaced in time and dispersed by the interstellar medium, it is possible to gain significant Signal to Noise Ratio (SNR) by gating and dedispersing the VLBI data before correlation. This scheme has been tested on a limited amount of data (PETIT et al., 1990).

The CNES system allows such processing to be carried out on a significant amount of data in a reasonable time duration. The de-dispersion is realized by digital filtering a number of narrow bands in the recorded bandpass, aligning the filtered data and adding them to perform the correlation (Fig. 3). The gating window can be specified with one microsecond resolution, and its position and period are determined a priori from the timing observations of the pulsar. Preliminary tests indicate that such processing allows a net gain in SNR, by a factor of 3. It is thus possible to detect the pulsar in more scans than would be achievable otherwise.

A 5-station 12-hour experiment was carried out on June 16,1992 with the European VLBI Network in order to obtain the position of PSR1937+214 relative to nearby quasars. It will be processed using the proposed scheme with the CNES system.
5. Conclusion

A new VLBI correlator is now operational at CNES. It can process VLBI data in the MarkII format, and the phase and phase rate observables that can be formed from its cross correlation sums have been shown to agree with those obtained from independent processing on other systems.

The software implementation of the system is not designed to process massive amounts of data, but it allows special treatments to be performed on the data and is quite versatile in accommodating new data formats. One present application is to perform dedispersion and gating of millisecond pulsar VLBI data in order to improve the detection of the signal. Application of this technique to one full-scale VLBI experiment on PSR1937+214 is under way.

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REFERENCES

CIT, 1988, VLBHELP, on line VLBI library documentation.