COBRA – a digital receiver at Jodrell Bank

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1. Introduction

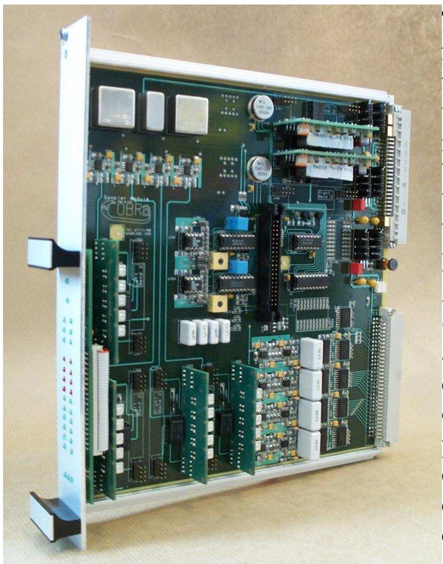
Pulsars are unique radio sources. They emit short radio pulses at very regular intervals. Observed periods range from 1.5 ms to about 8.5 s. Measuring the arrival times of these pulses very accurately, one can use them as tools for a large variety of (astro–) physical problems. Among the applications are tests of general relativity, cosmology, and studies of neutron star interiors, binary systems and their evolution, as well as the structure of the Milky Way. Revealing the Galactic structure, for instance, is possible since the pulsar signals interact with the magnetic field of the Galaxy and the free electron component of the interstellar medium. The ionized interstellar medium causes a dispersion of the pulses, such that pulses emitted at low radio frequencies arrive later than those emitted at higher frequencies. The dependence of arrival time onto sky frequency leads to a smearing of the pulses measured on Earth when observing with a finite bandwidth. The easiest approach to, at least, reduce this dispersion smearing, is to divide the bandwidth in a number of smaller channels and to delay the high frequency pulses accordingly until the low frequency pulses arrive. This method is, however, limited by the response time of the filters and the smearing across the filter bandwidth itself. Fortunately, for a known dispersion measure, the dispersive effects on the original signals can be accurately described by a relatively simple phase rotation ("chirp" function). If during data processing all phase information is kept, e.g. by converting the signal to base–band prior to complex mixing and sampling, one can apply a filter function which is the inverse of that of the interstellar medium. The implementation of this "coherent de–dispersion" which completely removes the effect of dispersion and restores the original pulse, basically consists of complex base–band mixing, a Fast–Fourier–Transform (FFT) to bring the signal into the frequency domain, and the correction of the phases by subsequent application of a "chirp" function, before finally transforming the signal back into the time domain with another FFT. The necessary FFTs are usually long and therefore computationally expensive, so that despite the development of this technique by Hankins & Rickett (1975) more than 25 years ago, a routine implementation has only been possible in recent years. The current systems can be divided into on–line processors using special purpose hardware and off–line processors using software and high–performance computers. Both systems have their advantages and disadvantages.

Hardware solutions, particularly recent models like the Berkeley–Pulsar–Processors (installed at Green Bank, Effelsberg and Arecibo; Backer et al. 1997) or PUMA (installed at Westerbork, Kouwenhoven et al. 2000), can obtain wide bandwidths and usually provide on–line access to the data. From many observational aspects, these are huge advantages. The disadvantage is, however, that data cannot be re–processed (e.g. with a different dispersion measure) and response to external circumstances like Radio Frequency Interference (RFI) is difficult to implement on–line.

Software systems like the MkIV which originated from Princeton (installed at Arecibo and Jodrell Bank, Stairs 1998, Ord 2001) or the Caltech base–band recorder (installed at Arecibo and Parkes, Jenet et al.1997) sample the pre–detection voltage data and write them to a high–speed tape facility which limits the available bandwidth to 10 or 20 MHz, usually. The data are later played back onto a high performance computer and processed off–line. The huge advantage of these systems is the flexibility during data processing. Data can be re–analysed using different variables like dispersion measure and, increasingly more importantly, can be subject to sophisticated RFI mitigation schemes. Moreover, in order to obtain polarization information no special polarimeter is needed. This is similar to the hardware systems, but here the calculation of the cross–products of the incoming signals can be done with trivial computations in software.

At Jodrell Bank we are currently developing a system which will combine the virtues of both hardware and software approaches. The constructed processor will be the first pulsar data acquisition system that will perform the data processing on–line in software. Besides producing pulse profiles perfectly corrected for dispersion smearing, it will also offer the chance to react instantaneously to threatening RFI signals.

2. COBRA



The word COBRA stands for "**CO**herent **B**aseband **R**eceiver for **A**stronomy". It will use hardware similar to that used in the MkIV system to create complex−mixed base−band data which are Nyquist− sampled. One such mixing and sampling module ("Sampler card", shown left) will acquire a bandwidth of 5 to 10 MHz, whereas the total bandwidth will be above 100 MHz. The data of 10 to 20 sampler cards will be fed via high speed DMA PCI−interface cards into a Beowulf cluster consisting of about 150 PC−type processors. All processors will be connected with a high−speed network ("switch") over which the data, pouring into the cluster with a minimum data rate of 400 MB/sec (= 24 GB/min!), are distributed. Each processor will only process a small fraction of the total 100 MHz bandwidth, making it possible to perform the computation in real time. The data will be de−dispersed and folded on−line, before all individual results are combined. For that purpose, each dual−processor node of the cluster will have at least 512 MB RAM and 10 GB disk space. The combined disk capacity will be about 2 TB with a total RAM of about 75 GB. All processors and sampler cards will be rack−mounted and screened, as COBRA may otherwise become a significant source of RFI itself. At the moment, we are constructing a small 4−node prototype which will serve as a backend to the 42−ft telescope at Jodrell Bank. This telescope continuously monitors the Crab pulsar in the search for rotational glitches. First light was obtained with this prototype some weeks ago, when observing the strong pulsar B0329+54 with 1.25 MHz bandwidth at 610 MHz . The full COBRA system will serve as the standard pulsar backend for the 76−m Lovell telescope and should be in operation by the end of 2001.

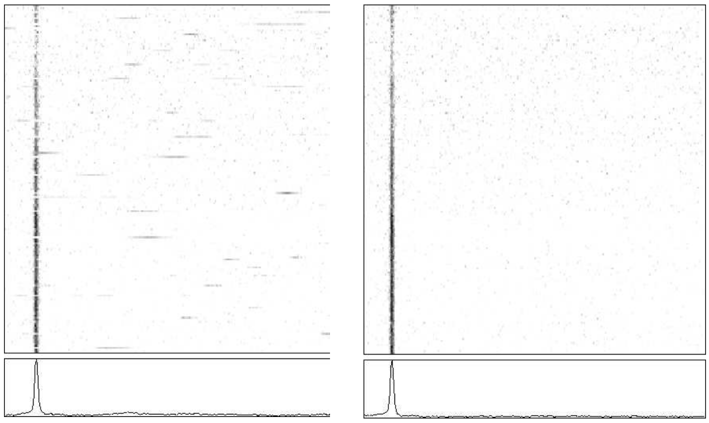
3. RFI – Mitigation

COBRA will combine the virtues of the on−line systems in allowing immediate data quality assessment, while permitting the application of software RFI filters computed on−the−fly from incoming data.

At the heart of any successful RFI mitigation scheme lies the requirement for sufficient dynamic range. COBRA will sample the data with 8 bits, which is an important improvement over the 2 bits often used in the past. In addition, the separation of the total bandwidth into several modules ensures that a saturation in one part of the band will not affect adjacent parts. It will also be possible to set the mixing Local Oscillators (LO) such that known interference signals at given frequencies can be avoided. It seems therefore desirable to develop strategies to identify such RFI signals on−the fly and to eventually modify the LO frequency during the observations.

Stairs et al. (2000) developed further RFI mitigation schemes for the off−line MkIV system. These techniques can be applied if the RFI signals change with time. In a broad−band mitigation scheme, the incoming levels are monitored. Any sample exceeding a median power level is zeroed before further processing, effectively suppressing short time−scale, wide band signals. In order to excise narrow−band signals, short 256−pts FFTs are calculated and a running average of these short FFTs is computed. As pulsar emission is broad−band, significant artificial signals can be flagged and corresponding filter masks can be produced. These filter masks are then applied to the incoming data in the frequency domain in addition to the correction of the phases with the chirp function. These techniques have been successfully applied off−line (see Fig. 2), but are also be applicable in the on−line case. Over time a database can be built up, which logs all identified narrow−band RFI signals, so that permanent filters can be developed for spectroscopy applications (see below). The total data flow can hence be summarized in Figure 3.

Figure 2: Demonstrating the success of the RFI–mitigation scheme to data of the pulsar B1534+12. The left hand side shows the data without any RFI rejection, while the right hand side shows the clean Data after an off–line RFI mitigation technique.



4. Prospects

The COBRA system will not only be used as an on–line pulsar processor, but will also serve as the backend for a new 6–GHz Methanol receiving system to be installed on the upgraded Lovell telescope. The pulsar processing scheme already includes the computation of a spectrum across the whole available bandwidth. Hence, a slightly modified code running on the cluster will therefore be able to produce high resolution spectroscopy. This demonstrates the advantage of a software solution based on off–the–shelf type PC–processors: as the PC cluster of COBRA essentially represents a general–purpose super–computer, several different applications are possible. For off–line use, for instance, COBRA will analyze pulsar search data, another computationally expensive task. In the future, an upgrade of the cluster (or parts of it) with faster processors will enable us hopefully to keep up the pace in the fight with RFI.

Figure 3: Flow of data and processing stages in the full COBRA system.

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References

Backer, D.C., Dexter, M.R., Zepka, A.., Ng., D., Wertheimer, D.J., Ray, P.S., & Foster, R.S. 1997, PASP, 109, 61

Hankins, T.H., & Rickett, B.J. 1975, in Methods of Computational Physics, Vol. 14 – Radio Astronomy, (New York: Academic Press), 55

Jenet, F.A., Cook, W.R., Prince, T.A., Unwin, S.C. 1997, PASP, 109, 707

Kouwenhoven, M.L.A., van Haren, P.C., Driesens, D., Langerak, J.J., Beijaard, T.D., Voute, J.L.L., Stappers, B.W., & Ramachandran, R. 2000, in Pulsar Astronomy – 2000 and Beyond, eds. M. Kramer, N. Wex, R. Wielebinski, PASP, 202, 279

Ord, S. 2001, PhD thesis, University of Manchester

Stairs, I.H. 1998, PhD thesis, Princeton University

Stairs, I.H., Splaver, E.M., Thorsett, S.E., Nice, D.J., & Taylor, J.H. 2000, MNRAS, 314, 459