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BURST MODE VLBI AND PULSAR APPLICATIONS

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ABSTRACT The technique of Burst Mode (BM) VLBI is described and its particular application to the observations of pulsars is explored. The wideband pulsed radiation from these objects is exploited to acquire data at two ends of an interferometer baseline in high-speed bursts and only during the pulsar on-times. The result at the VLBI correlator is an improvement in sensitivity by as much as the inverse pulsar duty cycle, and is a consequence of the bandwidth expansion offered by BM and the intrinsic use of gating. As a result, precision astrometrical studies of pulsars will benefit through the greatly increased instantaneous bandwidths achieved by pulsar BM. The problems, implications, and limitations of acquiring and processing pulsar BM data are discussed.

INTRODUCTION: THE BURST MODE CONCEPT

Burst Mode (BM) is a technique to increase the effective bandwidth of a VLBI recorder. It differs from conventional VLBI techniques in that instead of sampling continuously in time at a number of discrete frequencies, it samples a large continuous frequency band discontinuously in time. Although BM has been discussed for years (e.g. Yen 1982, Wietfeldt 1987), only recently have the critical components of a BM system at large bandwidths become commonly available, *viz.* high-speed digitizers, and large memories at reasonable cost.

The basic BM observing scenario is to observe at frequency ν_0 at burst bandwidth $\Delta\nu_{\rm burst}$, sampling at the Nyquist rate of $R=2\times\Delta\nu_{\rm burst}$ at each acquisition period P seconds for precisely the burst length w seconds, and write the burst rate data to a fast memory. The burst data is subsequently read out of memory and written to the data recorder at nominal recorder rate r during readout time $T_{\rm readout}$ (typically P or P−w) seconds. The next acquisition burst repeats the process.

The BM acquisition system schematic and timing is shown in Fig.1. Note that although the number of samples obtained via BM over nominal-rate (continuous) recording during time w is increased by the factor $\rho = R/r$, where

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ρ is referred to as the bandwidth expansion factor, the total number of samples between bursts $M = R \times w = r \times T_{readout}$ is constant.

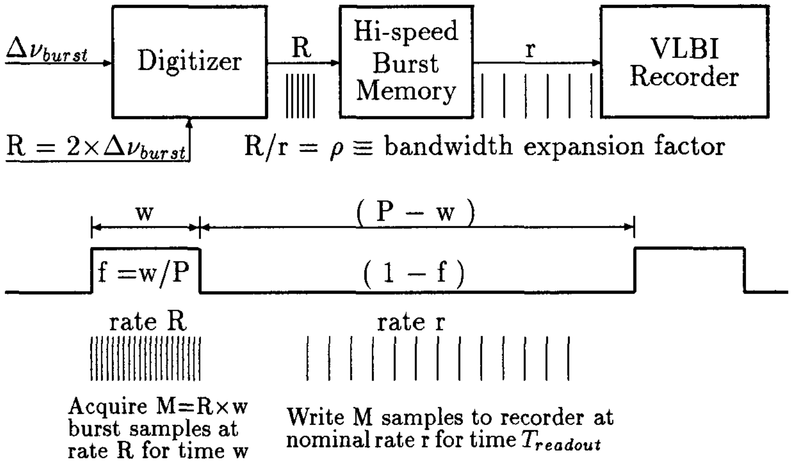

Fig. 1. BM acquisition system schematic and timing.

APPLICATION TO PULSAR OBSERVING

The application of BM to mm-VLBI has been described elsewhere in this volume by Kawaguchi. Here, the application of BM VLBI to pulsar observations will be described. In particular, we focus our attention on pulsar astrometry, which includes proper motion and parallax of nearby pulsars, and accurate positions of millisecond pulsars for reference frame tie-ins.

The principal difficulties in current astrometric VLBI observations are limited sensitivity, ionospheric effects, and the unavailability of suitable reference sources. Pulsars are steep spectrum sources which are best observed at low frequencies; however, the competing consideration of larger ionospheric effects at these low frequencies dictates that the near optimum frequencies for pulsar VLBI are at L-band (1.4-1.6 GHz).

The key idea of BM as applied to pulsars is to exploit the pulsed nature of the signal: typically the pulsed radiation is "ON" for only a small interval w of the pulsar period P. By BM sampling during this ON-time only, it can be shown that there is a (maximum) total increase in sensitivity of $1/f$ where f is the pulsar duty cycle ($\equiv w/P$). This improvement is a result of two factors:

- An inherent use of "gating" in which data is acquired only during the ON-time of the pulsar. The increase in sensitivity of $\sqrt{1/f}$ may be considered as a direct result of eliminating uncorrelated noise during the pulsar's OFF-time.
- The increase of effective bandwidth due to sampling the data during the pulsar ON-time at a rate ρ times greater than the nominal sampling

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rate, where ρ ($\approx$1/f) is the bandwidth expansion factor. The maximum sensitivity gain due to bandwidth expansion is $\sqrt{1/f}$.

Various gating strategies for pulsars have been implemented in VLBI systems, using both hardware (e.g. Bartel *et al.* 1985) and software schemes (Erickson 1972). A notable success is Gwinn *et al.* (1986) who used gating in a MkII VLBI experiment to measure parallax for PSR 0823+26 and PSR 0950+08. As described above, BM provides this gating function *naturally* as part of the data acquisition digitization process, but in addition simultaneously achieves bandwidth expansion for further sensitivity gain. The additional sensitivity gain of BM over systems employing gating alone is $\sqrt{1/f}$.

For an average pulsar with a duty cycle f of 3%, BM may boost the sensitivity by as much as a factor of 33, i.e. nearly a 6-fold improvement over and above gating-only schemes. An estimate of 10 mJy for the detection threshold in a typical L-band VLBI pulsar experiment reveals that BM *doubles* the number of pulsars to which current VLBI systems are sensitive; in particular, for annual parallax measurements, we find that BM increases the sample size over gated-only observations from 10 to 40 pulsars. In general, the increased sample size should facilitate the search for pulsars with nearby reference sources with which to do differential astrometry, and the increased sensitivity will improve the accuracy of individual measurements, as well as lessen the ionospheric problem for some pulsars by permitting observations at higher frequencies.

BM ACQUISITION AND PROCESSING CONSIDERATIONS

As shown in Fig.1., the BM acquisition system differs from a conventional VLBI acquisition system in its use of a high-speed digitizer and burst memory preceding the data recorder (a more subtle requirement is the necessity for wider band RF and IF signal paths to the digitizer input). The output of the digitizer following buffering of the high-speed samples is a *continuous* stream of data samples at the nominal rate of the recorder. The acquisition (and playback) recorders are oblivious to the *pulsed* nature of the incoming astronomical signal; however, this pulsed nature requires specific changes in the record and playback data handling.

On record the special requirements of a BM VLBI acquisition system are to derive the high-speed digitizer trigger pulse each acquisition period, and to provide a mechanism for transferring these "gate" boundaries and their UT times to the correlator. The complications in a *pulsar* BM system are the requirements to update the phase of the gate signal to track the doppler-shifted pulsar period, and to support arbitrary duty cycles. Setting and tracking of the gate phase may be accomplished by providing an ephemeris for each station in advance of observations, or preferably by a "rate generator" hardware unit that runs a geometrical "wavefront" model in real-time (Wietfeldt 1987).

On playback the initial task is to identify the epochs, times, and lengths of the gate boundaries. One simple scheme to transfer these parameters to the correlator is to insert on record an embedded sync and time code of each gate in the burst data stream, to be extracted by special playback hardware that reconstructs the pulsar gate phase and time code. We have also considered somewhat more elaborate schemes involving no loss of actual burst data. Of course, implementations in existing and/or future systems depend very much on the details of specific system architectures.

Although BM data is acquired in bursts on record, the playback data is a continuous stream at the nominal record rate. When this data is processed, e.g. for pulsars on a pulse by pulse basis (which corresponds to the ON-time only), the standard VLBI delay and phase modeling must be applied *much slower than usual* (approximately ρ or 1/f times slower); in addition, at each subsequent burst, the model needs to be "jerked" forward to the precise time of the next burst.

It should be noted that the wide bandwidths offered by BM may present some problems or limitations to the technique. Although dispersive pulse broadening for nearby pulsars at modest burst bandwidths ($<$ 100 MHz) is negligible at L-band, this is not the case for distant and/or fast pulsars, and unless special care is taken to provide de-dispersion, or divide the large burst bandwidth into narrower bands (multi-channel BM), or perform observations at higher frequencies, BM observations will not be feasible. Interstellar scintillation is known to induce small-scale frequency structure in the received pulsar power-spectrum, which BM would average over the burst bandwidth; in this case, perhaps a narrow-band multi-channel system would be optimum. Finally, RF interference over large bandwidths may be troublesome, but could be monitored and flagged either at the acquisition site or correlator.

CONCLUSIONS

BM has the potential for significant sensitivity gains in pulsar VLBI at modest cost and system development. Through its sensitivity gains BM will increase the number of pulsars to which VLBI observations can be made, and may open the door for higher frequency pulsar observations where ionospheric and dispersive effects are greatly reduced. Although BM may not be directly applicable to millisecond pulsars at L-band, powerful de-dispersion devices of the future, or higher frequency observations may yet prove BM useful for these objects. It should be emphasized that BM is most effective for smaller, inexpensive, narrow-band VLBI systems where recorder bandwidth is very restricted. Although BM may always be utilized to increase the sensitivity in pulsar VLBI observations, certainly if an equivalent continuous capacity *exists* in a given (larger) recorder, and *is available*, then the attractiveness of pulsar BM diminishes.

REFERENCES

Bartel, N., Ratner, M.I., Shapiro, I.I., Cappallo, R.J., Rogers, A.E.E., Whitney, A.R. 1986, *Astron. J.*, **90**, 318.

Erickson, W. 1972, *Ap. J.*, **177**, 101.

Gwinn, C.R., Taylor, J.H., Weisberg, J.M., and Rawley, L.A. 1986, *Astron. J.*, **91**, 338.

Wietfeldt, R.D. 1987, *Data Processing with a Wavefront Clock VLBI System*, M.A.Sc. Thesis, University of Toronto.

Yen, J.L., 1982, personal communication.

Peter Wilkinson: Can you really use 400 MHz instantaneous bandwidth at L-band in the face of powerful interference - especially from satellites such as GPS and Glonass?
Rick Wietfeldt: 400 MHz was used because for many instruments, it is the maximum bandwidth available from the L-band receiver; depending on the observing configuration, not all the bandwidth will be used. Interference may be a concern at some level however, but likely will be uncorrelated at two stations and in addition will be averaged over the entire burst bandwidth.

Ron Ekers: Burst mode would also be an advantage for correlators which allow a tradeoff between bandwidth and the number of baselines. Since playback will be at much lower bandwidth more simultaneous correlations will be possible.
Rick Wietfeldt: Yes, I agree. Furthermore, in speaking about system efficiency for large systems, pulsar burst mode data acquisition is more efficient with respect to tape consumption as only on-time samples are actually recorded to tape, unlike current systems that record the whole period.