Full length article

The beamformer and correlator for the Large European Array for Pulsars

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ARTICLE INFO

ABSTRACT

The Large European Array for Pulsars combines Europe's largest radio telescopes to form a tied-array telescope that provides high signal-to-noise observations of millisecond pulsars (MSPs) with the objective to increase the sensitivity of detecting low-frequency gravitational waves. As part of this endeavor we have developed a software correlator and beamformer which enables the formation of a tied-array beam from the raw voltages from each of telescopes. We explain the concepts and techniques involved in the process of adding the raw voltages coherently. We further present the software processing pipeline that is specifically designed to deal with data from widely spaced, inhomogeneous radio telescopes and describe the steps involved in preparing, correlating and creating the tied-array beam. This includes polarization calibration, bandpass correction, frequency dependent phase correction, interference mitigation and pulsar gating. A link is provided where the software can be obtained.

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1. Introduction

One of the remarkable predictions from the theory of general relativity is the existence of ripples in space–time, called gravitational waves (GWs), which are created for example by the acceleration of masses. The first proof of their existence came from the observed decay of the orbital period in compact systems of two orbiting stars as the GWs carry energy away (e.g. Taylor and Weisberg, 1982). More recently, the LIGO Scientific Collaboration and the Virgo Collaboration observed the first direct detection of a transient GW signal originating from a binary black hole merger (Abbott et al., 2016). LIGO and similar detectors probe GWs at kHz-frequencies making them most sensitive to signals from merging binary neutron stars and black hole systems. Regular observations of radio pulsars have the potential to probe GW frequencies down to nanohertz. This could provide a direct detection of the stochastic GW background originating from the ensemble of coalescing supermassive black hole binaries throughout universe (e.g. Haehnelt, 1994; Jaffe and Backer, 2003; Sesana et al., 2008) and

possibly also a detection of single sources such as near coalescing binary systems and cosmic strings (e.g. Lee et al., 2011; Sanidas et al., 2012; Lommen, 2012). Radio pulsars are spinning neutron stars that emit narrow beams of radio emission along their magnetic axes. As the beam passes across the telescope, a pulse of radiation can be observed with the time between pulses corresponding to the highly regular rotation of the neutron star. This makes pulsars act like cosmic clocks. In a Pulsar Timing Array (PTA) experiment the emission from the most stable pulsars, millisecond pulsars (MSPs), act as the arms of a huge Galactic GW detector (Detweiler, 1979; Hellings and Downs, 1983). The timing of pulsars for PTAs now spans well over a decade and are typically performed on a monthly basis (e.g. Desvignes et al., 2016; Manchester et al., 2013; The NANOGrav Collaboration et al., 2015). This long time span is what makes a PTA sensitive to GW frequencies down to nanohertz and makes it complementary to the ground-based detectors.

The ongoing efforts for the detection of GWs via a PTA experiment are pushing the precision limits of what is possible when using the existing telescopes individually. They currently fall short in achieving the required timing precision for a large enough sample of pulsars to get a detection (Demorest et al., 2013; Shannon et al., 2015; Lentati et al., 2015). The precision can be improved by increasing the telescope sensitivity.

The Large European Array for Pulsars (LEAP) is an ERC-funded experiment to combine the raw voltages from individual telescopes to form a tied-array telescope to provide high signal-to-noise observations of MSPs with the objective to increase the sensitivity for a GW detection (Bassa et al., 2016). It combines the data from the telescopes participating in the European Pulsar Timing Array (EPTA). These telescopes are the Effelsberg telescope (EB), the Lovell telescope at Jodrell Bank (JB), the Nançay radio telescope (NRT), the Sardinia Radio Telescope (SRT) and the Westerbork Synthesis Radio Telescope (WSRT). Combined coherently, the effective area is equivalent to that of a 195 m dish.

The observations are performed at L-band from 1332–1460 MHz in monthly observing sessions of 25 h. Pulsars are typically observed for 45 min to 1 h. Each pulsar observation is either preceded or followed (or both) by an observation of a phase calibrator for a few minutes. The calibrators were selected from the VLBA Calibrator List[1] and are offset by no more than about 5° from the pulsar position. The Nyquist sampled timeseries from all observations are recorded to disk. These disks are shipped to Jodrell Bank Observatory (JBO) where the baseband data is correlated which yields the exact time-delays and phase-offsets between each pair of telescopes. These delays and offsets are then applied to the timeseries and the timeseries are added together resulting in the LEAP tied-array beam.

There are several software correlators already in existence. Most notably and versatile are Distributed FX (DiFX) (Deller et al., 2007) and SFXC (Keimpema et al., 2015). DiFX is a correlator for Very Long Baseline Interferometry (VLBI) that can utilize a multi-processor computing environment by parallelizing the computations. It is widely used by radio interferometers. It allows for pulsar binning, but does not do beamforming. SFXC is the EVN data processor and is used to perform global VLBI in real-time. It can perform pulsar binning and both coherent and incoherent dedispersion. In recent years, the ability to phase up the VLBI telescopes to create a tied-array beam has been added. The benefits of developing an independent LEAP correlator and beamformer are the natural integration of the data format used (i.e. the DADA format, van Straten et al., 2012), bandwidths and available computing hardware (see Section 3), the requirement of accurate polarization calibration (see Section 4.2), but also the lack of beamforming capabilities in the existing software correlators at the start of the LEAP project.

Kramer and Stappers (2010) first introduced LEAP. Bassa et al. (2016) provide a detailed description of its experimental design and initial science results. In this paper we describe in detail the techniques used in the correlation process and the pipeline that has been developed specifically for the purpose of processing the raw voltages from the LEAP telescopes and creating the tied-array beam. All software that has been produced as part of this pipeline is available for download from http://www.epta.eu.org/aom.html.

2. Technique

During an observing session, each of the LEAP telescopes observes the same sources simultaneously. The raw voltages are Nyquist-sampled and recorded as baseband data, thereby preserving both the amplitude and phase information of the observed radio waves. This allows the individual time series to be shifted in time and phase offline such that all time series are perfectly aligned as though they were observed with a (very large) single dish. Adding the time series after they have been aligned in time and phase is called beamforming. The resulting beam is called a tied-array beam.

The time and phase delays between the time series from individual telescopes consists of four components. First, the largest delays are due to differences in the path lengths that the signal has to travel to reach each telescope, called the geometric delay, which corresponds to a time delay. Second, there are differences between each observatory's local clocks which introduces a time delay. The third component consists of instrument-specific delays due to cables and electronic components which introduce both a time and a phase delay. Finally, the atmosphere (both ionosphere and troposphere) introduces a time delay as well as a phase shift of the radio-wavefront, which depend on the time-varying conditions of the local atmosphere as well as the wavelengths of the radio waves.

The geometric delays can be largely corrected for by using the known terrestrial positions of the telescopes, telescope pointing models and celestial position of the source (calibrator or pulsar). This is achieved using the software program CALC.[2] The time-varying geometric delays from CALC are stored as polynomials in CALC-files, which are read by the LEAP correlator (see Section 4). For LEAP we make use of a wrapper for CALC, which is part of the software correlator DiFX (Deller et al., 2007). Where known, the pulsar positions are corrected for proper motion to the epoch of the observation. EB is used as the geometric location of the LEAP tied-array beam, even when EB does not participate in the observation session. This fixed reference point is necessary to obtain a consistent LEAP dataset for pulsar timing. The clock delays between the observatories are determined from the local Global Positioning System (GPS) measurements at each observatory. These are performed multiple times per day. For each month the daily average of these measurements are placed on an ftp-server[3] in GPS-files. As part of the LEAP pipeline, these GPS-files are downloaded for each epoch and read by the LEAP correlator.

The delays from the signal-path and the atmosphere are measured by first cross-correlating the complex sampled voltages of each polarization and each pair of telescopes from either a calibrator or the pulsar signal itself. A cross-correlation is performed by multiplying the Fourier transformed voltage series and integrating over time. This procedure is visualized in Fig. 1. The resulting time-averaged visibilities contain the phase-relationship between the two time series. This can be visualized by plotting the phase of the visibilities as a function of frequency channel as shown in Fig. 2. If they are perfectly in phase, then the resulting visibilities all have a phase of zero. If the phase has a constant value, then the two time series have a phase offset, but no time offset. A time offset between the two time series corresponds to a slope. These can be measured by applying the fringe-find method from Schwab and Cotton (1983). This method makes use of phase closure and involves a fit of the averaged visibilities to find the fringe solution, which consists of the best values for the time offsets (fringe delay), the phase offsets (fringe phase) and the phase drift (fringe rate) (see Section 4.7).

Once the fringe solution is found, it is applied to the complex samples from all telescopes which aligns them in time and phase. This is done by rotating each complex sample by an amount $\phi[p, t]$, which consists of:

$$\phi[p, t] = \phi^p_{\text{samples}} + \phi^p_{\text{fringe\_delay}} + \phi^p_{\text{fringe\_offset}} + \phi^p_{\text{fringe\_rate}}(t), \quad (1)$$

where p is the telescope index and t is time in seconds. ϕ^p_{samples} corrects for the shift of the phases due to the skipped samples as follows:

$$\phi^p_{\text{samples}} = 2\pi N^p_{\text{samp}} \frac{f_{\text{sky}}}{B}, \quad (2)$$