Prospects for gravitational wave astronomy with next generation large-scale pulsar timing arrays

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Abstract.

Next generation radio telescopes, namely the Five-hundred-meter Aperture Spherical Telescope (FAST) and the Square Kilometer Array (SKA), will revolutionize the pulsar timing arrays (PTAs) based gravitational wave (GW) searches. We review some of the characteristics of FAST and SKA, and the resulting PTAs, that are pertinent to the detection of gravitational wave signals from individual supermassive black hole binaries.

1. Introduction

The high-frequency \((10–10^4 \text{ Hz})\) gravitational wave (GW) window in observational astronomy and cosmology has been opened by LIGO with the first direct detection of GWs from the merger of a stellar-mass black hole binary [1]. Progress on opening up the GW window at lower frequencies continues [2; 3] with the \(10^{-9}–10^{-6} \text{ Hz}\) being probed by pulsar timing arrays (PTAs). This frequency regime is expected to host GW signals from supermassive black hole binaries residing in the innermost regions of merged galaxies. Other potential signals that could be detected are stochastic GW background from cosmic strings [4], inflation [5] and first-order QCD phase transition [6].

Three main regional collaborations are involved in advancing the search for GWs with PTAs: the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) [7] based on the Arecibo observatory and Green Bank telescope; the Parkes Pulsar Timing Array (PPTA) [8] based on the Parkes telescope; the European Pulsar Timing Array (EPTA) [9] based on five one-hundred meter class radio telescopes such as Effelsberg and Lovell. These collaborations share observational data and analysis tools within the framework of the International Pulsar Timing Array (IPTA) [10]. The IPTA has recently released timing data for 49 millisecond pulsars (MSPs) gathered over a period of 5 to 22 years [11].

The sensitivities of PTAs to stochastic GW background [12; 13], continuous waves from individual sources [14] and bursts with memory [15] have constantly improved over the past five years. The first PTA-based GW detection, possibly a stochastic background signal, is anticipated in the next a few years.

Next generation large-scale radio telescopes, such as the Five-hundred-meter Aperture Spherical Telescope (FAST) [16] and the Square Kilometer Array (SKA) [17], will bring profound...
changes and challenges in the enterprise of PTA by discovering hundreds of new stable MSPs and substantially improving timing precision.

Pulsar timing measures the arrival time of a fiducial phase point (usually the peak) on the integrated pulse profile which is obtained by folding the individual pulses across integration time and (after dedispersion) radio frequency channels. At 100 ns timing precision level, the main contributors in the error budget of the TOA measurement are the pulse phase jitter noise (due to the fluctuation in the shape and arrival time of individual pulses) and the additive radiometer noise (due to sky background and instrumental thermal electron noise) that can be estimated respectively by the following formulae [18; 19]

\[ \sigma_j \approx 0.28W \sqrt{\frac{P}{\Delta t}}, \]  
\[ \sigma_r \approx WS \frac{\sqrt{W}}{F \sqrt{2\Delta f \Delta t} \sqrt{P - W}}. \]  

Here \( \Delta t \) is the integration time to obtain an integrated pulse profile, \( P \) is the rotation period of the pulsar, \( W \) is the effective width of the integrated pulse profile, \( F \) is the flux density, \( \Delta f \) is the bandwidth. \( S = 2\eta k_B (A_{\text{eff}}/T_{\text{sys}})^{-1} \) is the system equivalent flux density (SEFD) [20], where \( \eta \sim 1.0 \) is the system efficiency factor, \( k_B \) is the Boltzmann’s constant, \( T_{\text{sys}} \) is the system temperature, \( A_{\text{eff}} \) is the effective collecting area, and \( A_{\text{eff}}/T_{\text{sys}} \) is called the telescope sensitivity. The signal-to-noise ratio (S/N) of integrated pulse profile is defined as the height of the pulse profile divided by \( \sigma_r \). The total noise of TOA \( \sigma_t \) satisfies \( \sigma_t^2 = \sigma_j^2 + \sigma_r^2 \).

2. Next generation facilities

2.1. FAST

FAST is located in the karst depression area in southwest China. It is the largest filled-aperture single dish radio telescope in the world, having a reflector that is 500 m in diameter with \( A_{\text{eff}} = 67,000 \text{ m}^2 \) (equivalently an aperture of about 300 m diameter). The active surface and feed cabin suspension systems enable a zenith angle coverage of up to 40° which gives a declination range of 66° to –14°. Potentially, the zenith angle can be extended up to 60° with \( A_{\text{eff}} = 31,000 \text{ m}^2 \) (equivalently an aperture of 200 m diameter). First light of FAST was achieved in September 2016 and it is currently under testing and commissioning.

Several sets of receivers have been proposed for FAST to cover the frequency range from 70 MHz to 3 GHz [21]. Among them, a 19-beam L-band receiver with \( T_{\text{sys}} = 20 \text{ K} \) and bandwidth of 400 MHz will be used ultimately to conduct the pulsar survey and timing. Simulations based on pulsar population models and the designed system parameters of FAST show that more than 5000 new pulsars would be discovered by the 19-beam receiver, among which about 10% would be millisecond pulsars. This survey can be carried out efficiently with eight hours survey time each day for 200 days [22]. During the early science run when the active control and 19-beam receiver are not available, FAST can discover new pulsars in the drift scan mode [23; 24]; this has already yielded eight new discoveries so far [25].

2.2. SKA

SKA is a global effort to build the world’s largest radio telescope with an effective collecting area of more than one square kilometer formed out of two major arrays: (i) SKA-Mid (350 MHz – 14 GHz) consisting of up to two thousand 15-m parabolic antennas (dishes) most of which will be located in South Africa, and (ii) SKA-low (50 MHz – 350 MHz) consisting of up to one million dipole antennas located in western Australia. SKA-Mid is the relevant instrument for the purpose of high-precision pulsar timing, while SKA-Low will help in pulsar detection as well.
as studying the interstellar medium through which radio pulses propagate. The SKA can access the entire sky that is visible from its geographic latitude to an angle off zenith of at least 85°.

The construction of SKA will be divided into two consecutive phases, SKA1 and SKA2. The construction of SKA1 is scheduled to last from 2018 to 2023, with early science operation starting as soon as 2021. Depending on progress in technology demonstration through SKA1 and funding, the construction of SKA2 is planned to start in 2023 and finish around 2030. Once completed, SKA is intended to be operational for more than fifty years, the typical lifetime of major radio telescopes.

In SKA1, 500 stations with each containing about 250 low frequency dipole antennas will be constructed for SKA1-Low, while SKA-Mid will have about 200 dishes incorporating 64 already existing ones from one of the SKA precursors, MeerKat [26]. The sensitivity $A_{\text{eff}}/T_{\text{sys}} > 2000 \, \text{m}^2 \, \text{k}^{-1}$ for SKA1-Low and $A_{\text{eff}}/T_{\text{sys}} > 1000 \, \text{m}^2 \, \text{k}^{-1}$ for SKA1-Mid. $A_{\text{eff}}/T_{\text{sys}} > 10^4 \, \text{m}^2 \, \text{k}^{-1}$ for SKA2-Mid which is mostly relevant for the SKA era PTA.

Study based on astrophysical models of the pulsar population in our Galaxy and SKA design parameters shows that SKA1 is expected to discover 9000 canonical pulsars and 1500 MSPs by a survey with 65 day on SKA1-Low and 130 days on SKA1-Mid. For SKA2, up to 14000 canonical and 6000 MSPs can be discovered [17]. Due to their high intrinsic rotational stability, combined with the improved sensitivity of SKA, a timing uncertainty of $<100 \, \text{ns}$ is likely for a substantial fraction of the MSPs [27; 28].

3. Large-scale PTAs

In the following, we estimate the properties that a PTA can be expected to have in the FAST and SKA era. We will focus here on SMBHB sources in the frequency band $10^{-9} – 10^{-6} \, \text{Hz}$. The Nyquist rate for the timing data, corresponding to twice the upper end of this frequency range, is one data point every two weeks.

3.1. Pulsar timing

For FAST, Smits et al. [22] found that it will take about 24 hours to time all of the 50 brightest MSPs once in order to obtain an integrated pulse profile for each pulsar at S/N of 500 that is required for high-precision timing. This estimate assumes a five minutes of integration time for pulse profile stabilization.

It is interesting to see what the make up of a future large-scale PTA may look like if the restriction on telescope time allocation for pulsar timing were removed. One can then work backwards and deduce how a given telescope time allocation will impact the science that can be done. In this spirit, we take Eq. 1 and Eq. 2 along with the design parameters of FAST and SKA to estimate the distribution of timing noise rms levels for the MSP population simulated by Smits et al. [17; 22]. Fig. 1 shows the number of MSPs having timing noise rms $\sigma_t \leq \alpha$, where $\alpha \in \{50, 100, 200, 500\}$ ns, one can expect to see with FAST or SKA given a certain maximum integration time per pulsar. (Note that this is a gross simplification of the actual situation where the integration time will depend on the pulsar brightness.) Specifically, we see that with FAST, 72 (99, 115) MSPs can be timed to be 100 ns or better with 10 (20, 30) mins integration time, which takes 0.7 (1.8, 3.3) day. For SKA, the pulse phase jitter noise will dominate the radiometer noise for most of bright MSPs due to the high telescope sensitivity. In this case, the limiting
factor governing timing precision is the integration time. Therefore, an optimized way to operate telescope, e.g., observing multiple MSPs simultaneously [29], can be implemented to reduce the aforementioned observation time.

3.2. Single continuous wave source

The non-detection of a stochastic signal from the SMBHB population in the most sensitive search carried out till date [12] indicates that SMBHBs are sparser than anticipated by population synthesis models [30]. This may increase the likelihood of isolated SMBHB sources to be the first to be detected by PTAs. Based on simulations of a cosmological population SMBHBs, Rosado et al. [31] found that the probability of detecting single sources within 10 years operation of SKA1 will be 40% considering this probability will increase to 80% for SKA2. In a different work, Rosado et al. [32] emphasize the role of redshift bias in the detection of massive black hole system and how neglecting it underestimates the distance reach of current and future PTAs. Wang and Mohanty [33] conducted a realistic investigation, in the context of individual SMBHB sources, of the performance of a SKA-era PTA comprised of $10^3$ MSPs selected from the simulated pulsar population in [17]. It was found that a SKA era PTA can significantly increase the distance reach to SMBHBs. For example, an all sky search can detect systems with redshifted chirp mass of $10^9 \, M_\odot$ to redshift $z \sim 1$ and redshifted chirp mass of $10^{10} \, M_\odot$ to redshift $z > 20$.

It is interesting to consider the possibility of merging detections of SMBHBs by a SKA-era PTA with ongoing and future searches for these systems, through luminosity variations in quasars, in the optical. Simultaneous observations in GW and optical can teach us much about the accretion physics in SMBHB systems by correlating the GW signal with optical variability. Typical error region for bright GW sources can be expected to be $\sim 100 \, \text{deg}^2$ [33], which can contain a large number of variable objects. However, the frequency of optical variability could be linked strongly to the (highly accurate) measured frequency of the GW signal and may help in narrowing down the optical counterpart. The depth of the search also implies that SMBHB candidates identified in the optical, such as PG 1302-102 [34], can be followed up in GWs. A detection of the GW signal from a candidate will provide the smoking gun evidence of its true
3.3. Resolving multiple sources

The focus in current PTA-based GW searches has traditionally been on detecting a Gaussian, isotropic stochastic signal. However, the true signal is likely to be more complex [35; 36], and the multiple source problem [37] is getting more recognition in the PTA community. So far, studies [37; 38] of multiple source detection have assumed a simplified model in which the signals are embedded in white noise, the so-called pulsar term is dropped from the waveform of each, and there is no stochastic GW signal. Under these simplifications, it was shown that the simultaneous fitting of multiple SMBHB signals can be accomplished using a Genetic Algorithm. For a realistic assessment of a large-scale PTA, further development of data analysis methods that can work without these simplifying assumptions is required.

The high redshift reach of an SKA era PTA based search for SMBHBs implies that multiple resolvable systems may be detectable in the PTA data. Hence, the data analysis methods for future large-scales PTAs should not only be capable of handling $O(10^3)$ pulsars but also multiple sources and signal types, ranging from isolated sources to the stochastic signal from an unresolved population.

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