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Identifying pulsar candidates in interferometric radio images using scintillation

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Abstract

Pulsars have been primarily detected by their narrow pulses or periodicity in time domain data. The detection sensitivity of time-domain searches for pulsars is affected by dispersion smearing, scattering, and rapid orbital motion of pulsars in binaries. Pulsars also show diffractive interstellar scintillation and can be detected in radio images. Identifying pulsar candidates allows sensitive, focused time-domain searches, saving computational effort. Pulsar scintillation is independent of its timing properties and hence offers a different selection of pulsars compared to time-domain searches. Candidates identified from this method could allow us to find hard-to-detect pulsars, such as sub-millisecond pulsars and pulsars in very compact, highly-accelerated binary orbits. We have developed a new technique to select pulsar candidates in interferometric radio images by identifying scintillating sources via the cross-correlation of dynamic spectra and measuring their scintillation bandwidth and timescale. We use uGMRT observations in PSR B1508+55, PSR J0437-4715, and PSR B0031-07 as test cases for our technique. We demonstrate that the technique correctly differentiates between the pulsar and other non-scintillating point sources and show that the extracted dynamic spectrum of the pulsar is equivalent to that extracted from the uGMRT phased array beam. We also developed a pipeline based on the technique and applied it to the GMRT archival data. We found 80 known pulsars and 1 pulsar candidate. We have done simulations by combining the pulsar population synthesis model (PsrPopPy) and galactic electron density distribution (YMW16), showing we can detect around 50 new normal pulsars and 70 MSPs that can't be detected by time-domain searches at 610 MHz.

1. Introduction

In radio images, pulsars can be identified as a steep spectrum, compact, and circularly polarized sources. The first-ever millisecond pulsar, J1939+2134, was discovered in radio continuum images as an unusual compact source with a steep spectrum [1]. More recently, the Australian Square Kilometer Array Pathfinder telescope (ASKAP) has successfully detected another pulsar in radio images by leveraging its high polarization characteristics [2]. Furthermore, the identification of a circularly polarized variable radio source in the Large Magellanic Cloud (LMC) suggests the potential for detecting new pulsars in this region [3].

In 1996 a paper came that suggested a new technique to detect pulsars. The title of the paper is 'Variance Imaging in Radio Astronomy' [4]. They suggested that we can utilize the scintillation property of pulsars to detect them in variance images. In 2016, Dai et al. [5] applied variance imaging on a known pulsar. Through simulation, they found that the sensitivity of detection is maximum when the scintillation bandwidth and time scales are comparable to the frequency and time resolution. However, in practice, they found that the sensitivity of this method is limited due to background noise.

We built on the Dai et al. [5] paper but instead of using variance imaging, we are using correlation to identify scintillation sources in radio images. Using correlation, we are incorporating the detailed scintillation information, including its frequency and time characteristics, we aim to enhance the sensitivity and accuracy of the pulsar identification process.

2. Technique

Scintillation studies are most often performed using dedicated phased array beams from interferometric telescopes or single beams from single-dish telescopes. To demonstrate our technique, we took a bright scintillating pulsar PSR B1508+55 and formed an interferometric radio image. From the calibrated image, we first identify all the point sources. Then we constructed their dynamic spectrum.

The dynamic spectrum is constructed using the visibility addition (VA) method. In this, we first subtract all the point sources from the uv-plane. Then shift the point source at the phase center. At the phase center, the phase of the source visibility is zero, which means that only the real part of the visibility contributes to the intensity. We then construct the dynamic spectrum for that source by averaging the real part of these visibilities over polarizations and baselines. To verify our method we compare the resulting dynamic spectrum measured with the standard phased array beam.

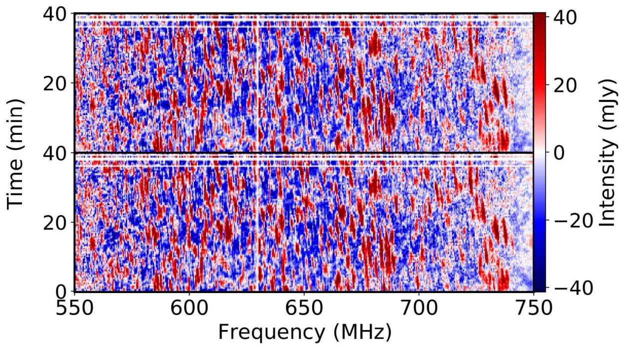

Figure 1. Dynamic spectra of PSR B1508+55 created from different sets of baselines, selecting antennae and baselines that are less susceptible to RFI.

After constructing the dynamic spectra, we perform auto- or cross-correlation to analyze the scintillation characteristics, including the scintillation bandwidth, timescale, and modulation. Here we apply the auto- and cross-correlation on a background that is located near the PSR B1508+55. In an ideal case, the background shouldn't scintillate because the background represents the noise, not a source. We found the auto-correlation of the background which is located near the PSR B1508+55 shows scintillation whereas when we perform cross-correlation the background does not show scintillation. This is because cross-correlation uses two dynamic spectra which reduces the effect of local RFI by creating two realizations of noise. Henceforth, we will apply the cross-correlation analysis technique to determine the scintillation parameters.

We cross-correlate the dynamic spectra and then fit the 2-D Gaussian to measure the scintillation parameters. For PSR B1508+55, the scintillation bandwidth and timescale are 562 kHz and 200 s respectively with a modulation index of 0.93.

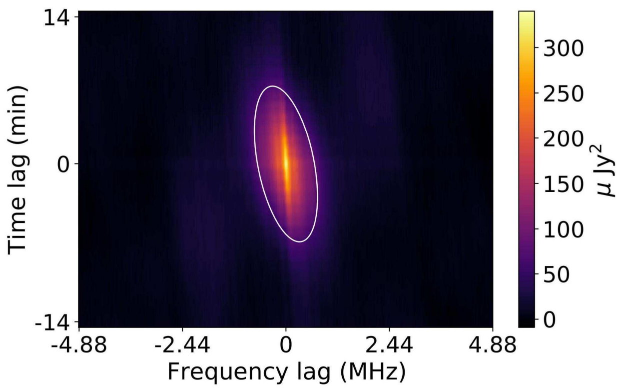

Figure 2. Cross-correlation of dynamic spectra with two-dimensional Gaussian fit.

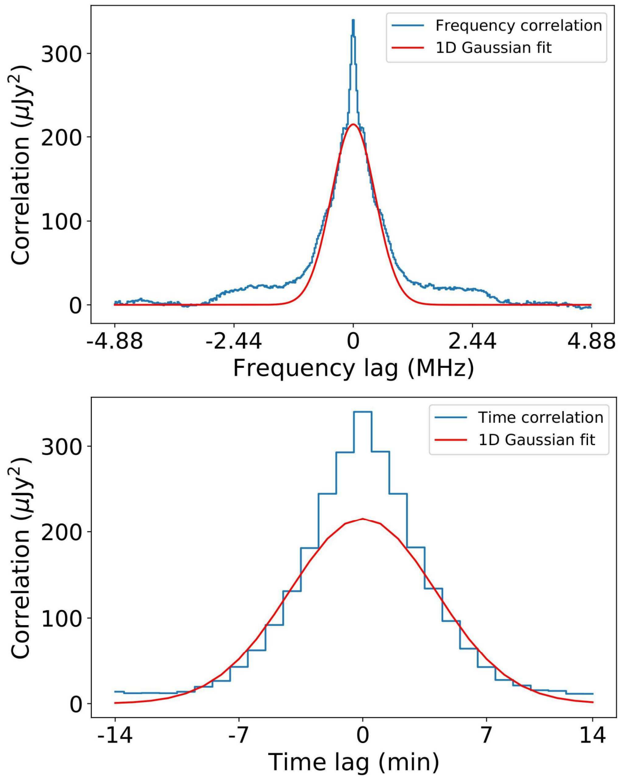

Figure 1. Cross-correlation of frequency (time) at zero time (frequency) lag with the projected one-dimensional fit, along with time and frequency correlation, respectively.

3. Theoretical Sensitivity

To get confidence in the scintillation detection in cross-correlation, we defined the correlation SNR as the ratio of the correlation amplitude to the amplitude uncertainty. To formulate the correlation sensitivity, we consider a dynamic spectrum with mean S and standard deviation $\boldsymbol{\sigma}_{DS}$. We also assume that the scintillation bandwidth is f_s and scintillation timescale is τ_s. Then the amplitude and noise in the correlation is S^2m^2 and $\frac{\sigma_{DS}^2}{\sqrt{N}}$ respectively. The amplitude uncertainty is calculated using the Fisher matrix.

$$SNR_{cor} = \frac{A}{\sigma_A} = \sqrt{N}\frac{S^2m^2}{\sigma_{DS}^2}\sqrt{\frac{\pi f_s \tau_s}{2}} \qquad (1) \ .$$

To verify the theoretical sensitivity and set the minimum limit on the correlation SNR for the detection of scintillation in correlation. We have done noise injection verification, we started by taking PSR B1508+55 visibility data and added Gaussian random noise to the visibility data. With the increment of added noise, the correlation SNR decreases much faster than the image SNR because the correlation SNR is inverse square of the noise, although the scintillation parameters remain almost constant their error increases at about correlation SNR of 5 the scintillation is barely detectable and the scintillation parameters are measured at the limiting confidence level of 5 sigma. This gives the minimum correlation SNR of 5 at which the scintillation is detectable in correlation.

4. Simulation

To simulate a pulsar population, we utilize the PsrPopPy software package [6]. We've extended this package to include correlation analysis and millisecond pulsar population synthesis. We trained the PsrPopPy with a fiducial population of 1038 normal pulsars in Parkes Multibeam surveys to generate a population of 120 000 normal pulsars [7] and 48 millisecond pulsars in High Time Resolution Universe (HTRU) survey [8] to generate a population of 41 000 millisecond pulsars.

Our initial simulation focused on various GMRT settings. By analyzing the results, we identified the specific configuration that maximizes the detection of new pulsars. Notably, large bandwidth, high frequency, low channel width, and extended observation time were key factors in achieving this outcome. We have also simulated surveys like TGSS and ASKAP including future radio continuum surveys like SKA and DSA-2000. The PsrPoPy simulation predicts that we can detect 50 new normal pulsars and 70 new millisecond pulsars using this technique at 610 MHz of GMRT.

Simulation also shows that we can detect pulsars up to a range of 500 pc/cm^3 via this technique. The large number of pulsar populations it detects resides at low DM. This is because sensitivity is driven by scintillation timescale and bandwidth which decreases with DM. Although decreasing the channel width increases the modulation index, the net effect on the detection of pulsars remains insignificant. This suggests that it is difficult to detect the pulsars at higher DM using this technique.

PsrPopPy simulation reveals the following results for pulsar detection:

Normal Pulsars: In timing surveys and correlation analysis, we can detect 56% and 17% of the normal pulsars previously identified in radio images. About 95% of the normal pulsars detected in correlation analysis are also detected in timing surveys. We identified 5% new millisecond pulsars in correlation analysis.

Millisecond Pulsars: We can detect 35% and 25% of the millisecond pulsars previously detected in radio images using timing surveys and correlation analysis. About 88% of the millisecond pulsars detected in correlation analysis are also detected in timing surveys. we identified 12% new millisecond pulsars in correlation analysis.

Binary Pulsars: The number of new detections for binary pulsars is even higher because of the sensitivity loss due to orbital motion.

4. Scintillaition Pipeline

We also developed a comprehensive pipeline based on our technique, which automates the process of data cleaning, calibration, imaging, analysis, and classification of scintillating sources. Briefly, the pipeline ingests raw visibility data (CASA measurement set; `MS' or the uGMRT long-term accumulation `LTA') and applies flags for bad baselines, bad antennas, and extreme channels. Initial flagging is performed, identifying and removing bad calibrator scans and science scans. The pipeline performs three cycles of calibration and cleaning. The pipeline runs two rounds of self-phase calibration on the science data, and using PyBDSF [9], it creates a catalog of all the point sources in the field. The pipeline then creates dynamic spectra, and correlation fits for each point source to calculate the scintillation parameters and classify the scintillating sources. A file containing metadata of the observation and various parameters associated with each source is generated. These parameters include scan number, source number sorted according to the SNR_{Im}, right ascension, declination, flux density, scintillation timescale and bandwidth with amplitude and associated errors, modulation index, SNR_{cor}, dynamic spectrum noise, the goodness of correlation, and the number of pixels in the dynamic spectrum.

We applied the scintillation pipeline to about 100 GMRT archival radio data and identified 80 scintillating sources as known pulsars. We constructed the dynamic spectrum of these 80 sources from the radio continuum data. We have done the statistics of the scintillation parameters of these scintillating sources and compared them with those from the simulation.

In one dataset we found a scintillating source with scintillation characteristics as of known pulsars and does not associated with a known pulsar. Further investigation shows that it is a steep spectrum source with a spectral index of -1.2. We wrote a proposal to follow up on the pulsar candidate using GMRT. It is accepted and we took the observation with an observation bandwidth of 200 MHz at 400 MHz and 1360 MHz in both interferometric and phase array mode. We found a candidate in periodic searches that looks like a pulsar. It is in binary and has a DM of around 20.2 pc/cm^3 and a period of 1.42 ms. We are still analyzing the data to confirm it.

5. References

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