RAA 2021 Vol. **21** No. **8**, 185(4pp) doi: 10.1088/1674-4527/21/8/185
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Research in Astronomy and Astrophysics

Spatial modulation search applied to the search and confirmation of highly scintillated pulsars at FAST with a pulsar discovered in M3

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Received 2021 May 6; accepted 2021 June 29

Abstract We present a pulsar candidate identification and confirmation procedure based on a position-switch mode during the pulsar search observations. This method enables the simultaneous search and confirmation of a pulsar in a single observation, by utilizing the different spatial features of a pulsar signal and radio frequency interference (RFI). Based on this method, we performed test pulsar search observations in globular clusters M3, M15 and M92. We discovered and confirmed a new pulsar, M3F, and detected the known pulsars M3B, M15A to G (except C) and M92A.

Key words: (stars:) pulsars: general — methods: observational — methods: data analysis

1 INTRODUCTION

In the pulsar search, one key step is to pick pulsar signals out of an ocean of radio frequency interferences (RFIs). Besides the dispersion phenomenon, there are at least two main differences between a pulsar signal and an RFI. The first difference is temporal. Usually, a pulsar without very severe scintillation is more persistent than an RFI, in the sense that this pulsar will appear in different observations but a particular RFI usually appears in only one observation. The second difference is spatial. A pulsar is a point source, whose signal goes into the main beam while an RFI is usually picked up by the side-lobes, so the RFI does not vary much when the telescope moves away from a pulsar.

Currently, the confirmation of pulsar candidates is normally done by re-observing in the same direction, i.e., utilizing the temporal differences between a pulsar signal and an RFI. However, it would be difficult for this strategy to be applied to highly scintillated candidates or candidates with possibly significant acceleration since it would require several observations to re-detect such pulsars, i.e. it takes a longer time to verify or falsify such candidates. As an example, the Globular Cluster (GC) pulsars M3C and NGC 6749B were detected only once in the former tens of observations (Ransom et al. 2005), and still not confirmed. An extreme example is the GC pulsar 47 Tuc aa, detected with a statistically-based search method (Pan et al. 2016). It has a very low detection probability (4.2% or a detection rate of 1.38 detections per year, Freire & Ridolfi 2018). The searching and confirmation of these pulsar candidates need much observation time.

The identification of pulsar candidates is normally based on the pulse profile, time-domain features, frequency domain features and the dispersion measure (DM) features. Although artificial intelligence helps a lot in the identification of pulsar candidates (Zhu et al. 2014), all the candidates still need to be re-observed for confirmation or falsification. In this paper, inspired by the position-switch observing mode, we introduced the spatial modulation search, making use of the spatial differences between a pulsar signal and an RFI. This method was tested with the Five-hundred-meter Aperture Spherical radio Telescope (FAST, Nan 2006; Nan et al. 2011; Jiang et al. 2019; Qian et al. 2020). As a result, a GC pulsar, M3F, was discovered and confirmed. The data and search method are described in Section 2. In Section 3 we present the results and some discussion. The conclusions are provided in Section 4.

2 DATA AND METHODS

Usually, a pulsar is considered confirmed if it is re-detected at least once. Inspired by the observing mode widely utilized in spectral observations, we suggest that the searching and confirmation of pulsars (distinguishing them from RFIs) can be combined into one observation by considering their spatial characteristics. To be specific, the position-switch mode can be used. A signal from a celestial point source, e.g., a pulsar, should disappear when we observe the OFF positions (point the telescope away from the source) and may appear again when we move the telescope back to the source (the ON position). We keep recording data during the whole observing process. Thus, the pattern of appearing and disappearing of a candidate's signal can be examined to distinguish a pulsar from an RFI, i.e., to confirm or exclude a pulsar candidate.

The test observations with this strategy were performed with FAST in January and February 2021, by targeting the GCs M3, M15 and M92. Among these three GCs, M3 and M15 were chosen because of the scintillating pulsars in them, while M92 was selected because the pulsar M92A is eclipsing for about one-third of its orbital period (Pan et al. 2020), making it a good example to test if eclipsing affects this pulsar search strategy. The GCs M15 and M92 were observed once each. Since the pulsars in M3 have detection probabilities lower than 50% (Hessels et al. 2007), we observed M3 twice in order to have more pulsar detections. All the observations lasted for two hours, except a 5-hour observation of M3. To optimize these test observations, we observed the OFF position ($5'$ east to the cluster) six times during each 2-hour observation. The details of the observation are listed in Table 1.

The 19-beam receiver was employed in these observations. It covers a frequency range of 1.05 to 1.45 GHz. The data were channelized into 4096 channels (with a channel width of 0.122 MHz). The system temperature is $\sim$24 K (Jiang et al. 2020), and the beam size is $\sim 3'$ at 1.4 GHz. The data were sampled in two polarizations with 8-bit precision every 49.152 μs.

The data were processed with PRESTO (Ransom 2001). The routines `rfifind`, `prepsubband`, `realfft` and `accelsearch` were applied for RFI masking, dedispersion, fast Fourier transform (FFT) and acceleration search (Ransom et al. 2002), respectively. To identify the binary signals, we used a zmax value of 1200 for `accelsearch` in all the 2-hour observations. For the 5-hour M3 observation, a zmax of 600 was used, due to the limitation of memory and computing power. We checked all the search results to catch any possible known pulsar signals. The details of the observations and the results are listed in Table 1.

3 RESULTS AND DISCUSSION

We detected nine pulsars among the 13 previously known pulsars in these three GCs. In the four undetected pulsars, M3A (detected only once previously, Hessels et al. 2007) was detected and confirmed by FAST recently (Pan et al. 2021), but not detected in this work; M3C was not detected in this work; M15C was not detected due to either its orbital period being too short compared with the observation time, or it is too faint; M15H was not detected because it is too faint. Both M15C and M15H were discovered by Arecibo at 430 MHz with a 10 MHz bandwidth (Anderson 1993). According to the results of FAST M15 observations, M15C, G and H are the three pulsars most difficult to detect, due to the lowest detection rate. This can be explained as follows. In an eccentric and highly accelerated compact orbit, M15C is not easy to detect in the pulsar search although it is relatively bright. M15G and H are faint for most of the time and can only be detected in a relatively bright state due to scintillations. In the M15 observation of this work, M15G was luckily detected. For M15H, even with FAST, it is only possible to detect it in observations lasting 3 hours or longer. Among the detected pulsars, M3E was a binary pulsar previously discovered (Pan et al. 2021). It was confirmed in our test observations. Moreover, a new pulsar, M3F was discovered and confirmed in our test observations in this work.

Examples of known pulsar detections and RFIs are displayed in Figure 1. All the known bright pulsars have similar discontinuous vertical line patterns due to the position-switch observation, but the RFI signal exhibits continuous vertical line patterns throughout the whole observation. It is clear from these comparisons that the signals with such discontinuous vertical patterns can be confirmed as pulsars. We detected the pulsar M15G with luck. It is a very faint pulsar never detected by FAST before. This is an example demonstrating that the spatial modulation search may not work well for extremely faint candidates when checking candidates by eye. A possible statistical method of signal checking may be applied to find those faint signals in future works.

Figure 2 shows the details of the pulsars detected in the GC M3. In the search, we cannot remove all the period variations of M3B caused by the orbital movements. This caused the signal to noise ratio to decrease slightly, while the time domain signal appearances were clear and similar to that of a celestial source. The M3D signal is affected by scintillation but it is still easy to see that the signal appeared and disappeared according to the ON/OFF switches in the observation. The pulsar M3F was detected and confirmed in the observation done on 2021 January 4 for the first time, while M3E was detected previously also by FAST and confirmed in the observation on 2021 January 12. Due to scintillation, the gap between the detections of either M3E or F can be as long as several months by checking the archival data. Thus, we only obtain their orbital parameters by timing them with JUMPs. M3E is a binary pulsar in a circular orbit with an orbital period of

Table 1 Observation Details and the Pulsar Detected

GC Name (1)	Obs. Date (YYYYMMDD) (2)	Obs. Length (h) (3)	ON-OFF Time (s) (4)	Pulsar Detections (5)
M3	20210104	2	**2200**-300-**1980**-300-**1200**-300-**720**-300-**240**-300-**420**-300	B, F
M3	20210112	5	300-**17700**	B, D, E
M15	20210202	2	**2200**-300-**1980**-300-**1200**-300-**720**-300-**240**-300-**420**-300	A, B, D, E, F, G
M92	20210113	2	**2200**-300-**1980**-300-**1200**-300-**720**-300-**240**-300-**420**-300	A

Notes: Col. 1: Name of the GC; Col. 2: Observing date; Col. 3: Observing time length; Col. 4: The observing cycle, with the ON observation times marked with bold font; Col. 5: The pulsar detections.

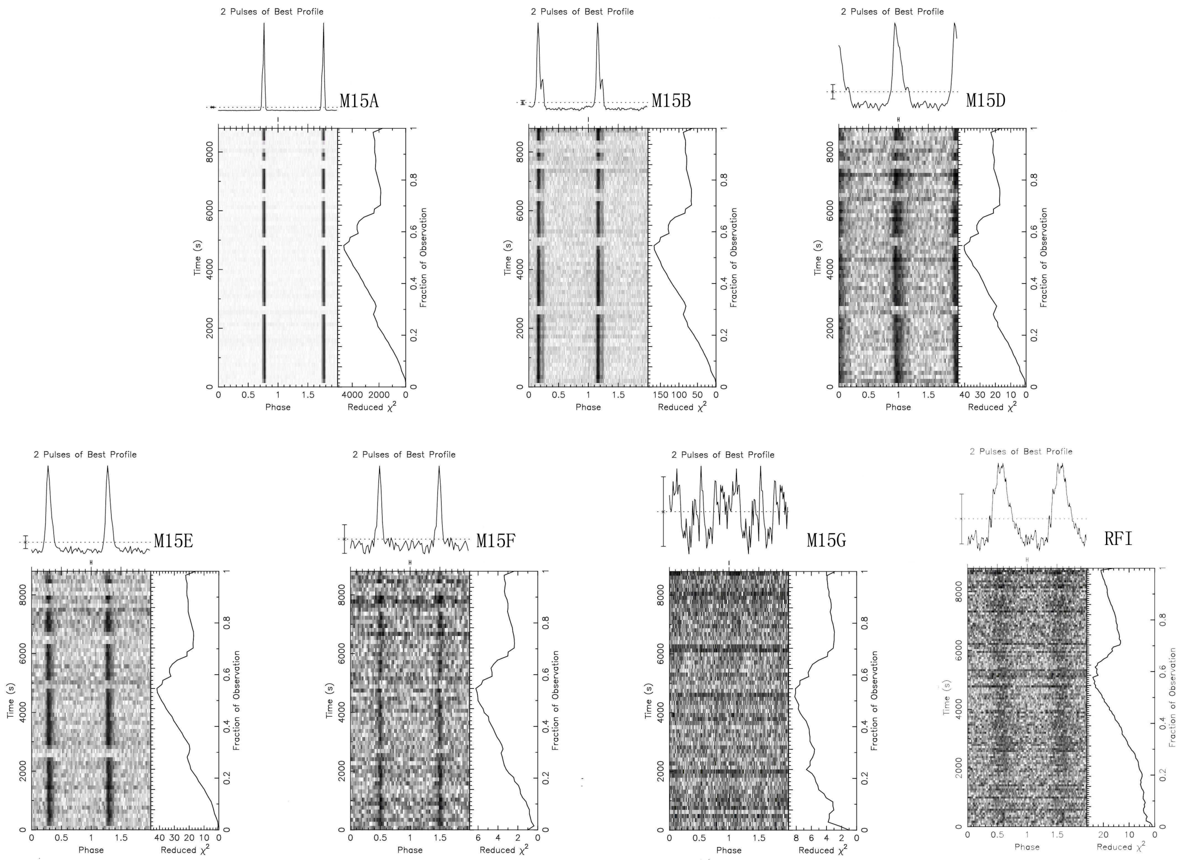

Fig. 1 The examples of known pulsar detections and RFIs. The upper three plots are M15A, B and D from left to right respectively. The lower four plots are M15E, F, G and an RFI from left to right respectively.

7.1 d and a minimum companion mass of $0.2\,M_\odot$. M3F is a binary pulsar in a 3.0 d circular orbit with a minimum companion mass of $0.15\,M_\odot$.

This strategy requires extra observation time for the OFF positions. In our test, about 10% of the time is dedicated for the OFF position observation. We estimated the searching and confirmation efficiency as follows

$$\begin{aligned}\mathrm{PSR_{eff}} &= \frac{T_{\rm tot}}{N_{\rm psr}} = \frac{T_{\rm search} + T_{\rm confirm}}{N_{\rm psr}} \\ &= \frac{T_{\rm search} + T_{\rm obs} \times N_{\rm cand}}{N_{\rm psr}}\,. \end{aligned} \quad (1)$$

Here $\mathrm{PSR_{eff}}$ is the searching and confirmation efficiency, in the unit of hours per pulsar, $T_{\rm tot}$ is the total observation time, $T_{\rm search}$ is the time used for detecting a pulsar candidate, $T_{\rm confirm}$ is the time used for candidate confirmation, $T_{\rm obs}$ is the time used to confirm or falsify a candidate, and $N_{\rm cand}$ and $N_{\rm psr}$ are numbers of candidates and pulsars, respectively. If the spatial modulation search requests for extra time are a fraction of x, the searching and confirmation efficiency is

$$\mathrm{PSR_{eff}} = \frac{T_{\rm search} \times (1 + x)}{N_{\rm psr}}\,. \quad (2)$$

Comparing Equations (1) and (2), it is obvious that if the confirmation time is longer than the extra time expended for the OFF position observation, the pulsar searching and confirmation efficiency is lower when relying on the spatial

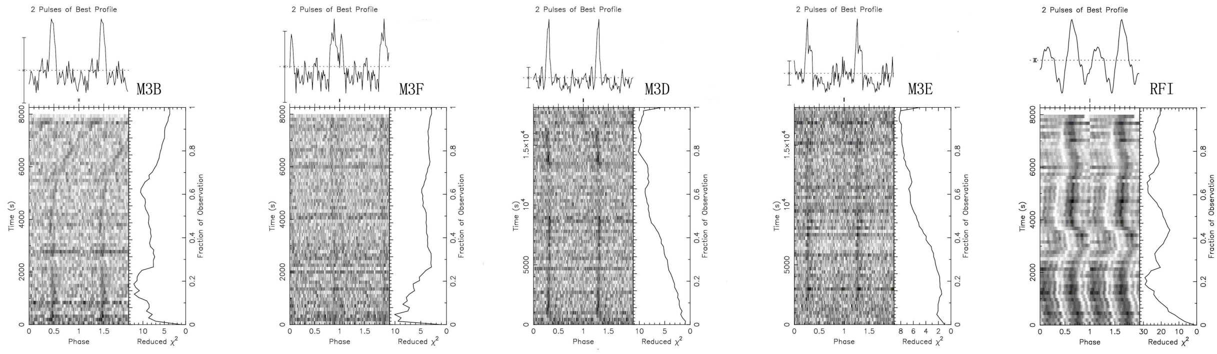

Fig. 2 Pulsars in M3 and an RFI. From left to right: detection plots of M3B, F, D, E and an RFI. Though affected by the orbital movement (M3B in 20210104, the first panel) and scintillation (M3D in 20210112, the third panel), pulsars have discontinuous vertical line patterns corresponding to position switching. They are easy to be identified by eye.

modulation search. In typical pulsar surveys, one pulsar discovery may need tens of hours. On the other hand, for targeted search and confirmation of faint candidates, normally two or more observations are needed. Thus, in general, the search efficiency could be improved by following the spatial modulation search method.

When utilizing the position-switch observing mode, the coherence of pulsar signals in FFT analysis will be affected. One possible way to avoid this effect is to set the OFF position observation at the beginning or the end of the observation. Current tests on faint M3 pulsars indicate that adding several short OFF-position observation segments has little effect on the pulsar searches.

4 CONCLUSIONS

We have performed test observations with the spatial modulation search method, with pulsars discovered and/or confirmed. With these observations, we came to the following conclusions.

1. Observing with a mode similar to the ON-OFF mode forms an artificial pattern in the phase-time diagram of a real pulsar, which is absent for an RFI.

2. We tested the spatial modulation search method with FAST, with a binary millisecond pulsar, M3E, confirmed, and the other one, M3F, discovered and confirmed.

3. M3E and F (J1342+2822E and J1342+2822F) are pulsars in binary systems having circular orbits, with spin periods of 3.47 and 4.40 ms, and orbital periods of 7.1 and 3.0 d, respectively.

4. Previously known pulsars M15A, B, D, E, F and G, and M92A were also detected, but no new pulsars were discovered in the GCs M15 and M92.

Acknowledgements This work is supported by the National SKA Program of China No. 2020SKA0120100. Lei Qian is supported by the Youth Innovation Promotion Association of CAS (id. 2018075). This work is supported by the Basic Science Center Project of the National Natural Science Foundation of China (Grant No. 11703047). ZP is supported by the CAS "Light of West China" Program. FAST is a Chinese national mega-science facility, built and operated by the National Astronomical Observatories, Chinese Academy of Sciences. We appreciate all the people from the FAST group for their support and assistance during the observations.

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