

Getting the Best out of the PRESTO *prepfold* Pulsar Analysis Tool

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Abstract

PRESTO, the professional pulsar search and analysis software, is now the package of choice for amateurs detecting and studying pulsars. This article investigates validation issues for the weaker pulsar intercepts with an integrated/folded signal-to-noise ratios (SNR) below 10:1. These are not clearly highlighted by the efficient statistical processes in PRESTO that are essentially designed to detect new pulsars in a low radio interference (RFI) environment. Here, it is shown that for keen amateurs prepared to examine the signal-to-noise ratio of PRESTO processed data over a range of search parameters, improved recognition of pulsars with integrated SNRs much less than 10:1 is possible.

Introduction

Amateur detection of pulsars has gone well past the stage of achieving the impossible and now there is a tendency to professionalism by using the academically developed software packages such as PRESTO, TEMPO, SIGPROC etc: in preference to producing homebrew software solutions. This is good as it brings some commonality, but there remain some constraints for amateurs with smaller antennas or even those with large antennas planning on detecting more pulsars just within the sensitivity limits of their more capable systems. The main difference between amateurs and professionals is that amateurs are unlikely to detect new pulsars and must content themselves with intercepting known pulsars with catalogued parameters. Indeed, the professional software packages have been developed specifically to search for new pulsar intercepts with unknown periods and parameters. Although this software is useful for amateurs, the results are not so well matched to the recognition of known pulsars at the lower amateur detected SNR levels as considered here, ranging below 10:1.

This article examines the most used software package, PRESTO and investigates the advantage for amateurs of adding maximum signal-to-noise ratio (SNR) profiling to aid in validation of the weaker pulsar targets using a real example B0329 pulsar intercept SNR of 5.5:1.

PRESTO⁽¹⁾

From the PRESTO Home site, the introduction states:- "PRESTO is a large suite of pulsar search and analysis software developed by Scott Ransom mostly from scratch. It was primarily designed to efficiently search for binary millisecond pulsars from long observations of globular clusters (although it has since been used in several surveys with short integrations and to process a lot of X-ray data as well). It is written primarily in ANSI C, with many of the recent routines in Python. According to Steve Eikenberry, PRESTO stands for: **P**ulsa**R** Exploration and **S**earch **T**oolkit!"

The PRESTO tutorial⁽²⁾ describes the optimum search procedure with the outline reproduced in Appendix 1. Inspecting this list, it is clear that the important items for amateurs seeking to intercept known pulsars are just entries 2 and 12, RFI mitigation and folding. Pulsar identification or 'Profile significance tests' discussed by Lorimer and Kramer,⁽³⁾ describe two possible measures, profile SNR and the Chi-square statistic. The success of the PRESTO software in discovering new pulsars with unknown rotation periods has been due to the fast core recognition process using a modification of the Chi-square (χ^2) statistic that measures how well observed data conforms to a specific model. In this case, the model is the Gaussian or Normal noise distribution, typical of system and sky noise. The statistic provides an indication of the deviation from Gaussian when a significant pulsar pulse train is present as the processing searches a range of possible pulsar periods. An added problem is of course noise distribution deviation due to local radio frequency interference (RFI) - hence the importance of RFI mitigation. PRESTO has an excellent tool for finding and zapping RFI, *rfifind*; the use of this program tool is described in the tutorial⁽²⁾. This tool and the folding algorithm tool, *prepfold*, are of most interest to amateurs. The spectrum harmonic search tools are also of interest to amateurs with larger dish systems as these processes need stronger pulsar signals to overcome losses due to the second order detection process involved in

spectrum monitoring. The χ^2 algorithm itself does not approach the discrimination of the pulsar folded signal-to-noise ratio (SNR) value as discussed below; but since the pulsar pulse phase/position is unknown in a folding search until it has been located and impulsive interference is suppressed, calculating SNR on-the-fly is not nearly as fast or robust against interference.

The plan here is to use the PRESTO tools, first to recognize and nullify RFI so potentially optimizing the data for folding analysis. Then to use the *prepfold* tools with a range of parameters to collect folded data to reproduce the Dispersion Measure (DM), period (P) and period rate (P-dot) PRESTO search sub-plots, but now to apply SNR profiling.

First, follows a definition the of Chi-square and SNR functions and then a comparison of their discrimination properties.

Reduced Chi-Square (χ^2) and SNR Algorithms

The reduced χ^2 algorithm is used in PRESTO as a goodness-of-fit measure on folded data assuming the data is pure Gaussian/Normal distributed noise. With just noise, the measure gives a value close to unity but when a large pulsar pulse is present the numerical measure can be very large. It is not dependant upon the pulse phase so can be useful in period, P-dot and DM searches to track the pulsar amplitude profile offset.

The reduced χ^2 statistic is given by,

$$\chi_{red}^2 = \frac{1}{N-1} \sum_{p=0}^{p=N-1} \frac{(x_p - \bar{x})^2}{\sigma_p^2} \quad (1)$$

where, N is equal to the number of fold bins (is a measure of the 'degrees of freedom' = $N-1$).

\bar{x} , and σ_p are the mean and standard deviation estimates of the folded noise.

If x_p were solely folded samples of Gaussian noise, the right-hand part of Equation 1 is equates to one, but if a significant pulsar pulse (or skewed RFI) is present then the result will exceed unity. A good approximation for Equation 1, assuming a Gaussian-shaped pulse and a pulsar duty cycle = W/P (W = half height pulse width; P = pulsar period) is, $1 + SNR^2 \frac{W}{\sqrt{2}P}$, which illustrates the duty cycle dependency. i.e. improved discrimination with increased pulsar duty cycle.

The corresponding definition of signal-to-noise ratio (SNR) is,

$$SNR = \frac{x_{pm} - \bar{x}}{\sigma_p} \quad (2)$$

where, x_{pm} is the folded data maximum response.

Note: SNR in Equation 2 is a linear ratio (sometimes referred to as multiples of sigma). Conventionally SNR is defined as a power ratio. The output from square-law detection is a voltage, so to state SNR in decibels, its value should strictly be calculated from $20\log(SNR)$. To minimize confusion here, the linear ratio form is preferred.

The efficacy of either algorithm depends on obtaining good estimates of the folded data mean and standard deviation (sd or root mean square, $rms = \sigma_p$) values. Lorimer and Kramer³ suggest obtaining these values from a quiet section of the raw data and dividing the standard deviation estimate by the folding downsampling ratio (= the square root of the number of samples/number of folding bins). For less stable amateur systems there are other options. A two-stage method of obtaining a good accuracy SNR (SNR1 in Figure 1) involves first calculating the folded data mean and rms, setting thresholds at say, $\pm 3 \times rms$ level, inserting random noise within the $3 \times rms$ range of the thresholded regions, and finally recalculating mean and rms values for incorporating in equation 2. A faster simpler version, losing accuracy and discrimination at higher SNRs is to just use the first stage mean and rms estimates in Equation 2 (SNR2 in Figure 1). There are other options based on peak location and blanking with performances between the methods described.

Chi-square/SNR Discrimination Comparison.

Figure 1 models the χ^2 algorithm with two approximate SNR responses for the approximately 1% duty-cycle B0329 pulsar over a modest range. The χ^2 curve (red) shows good pulse amplitude tracking at high SNR levels, but for weak signals with SNRs below 20, the curve slope is much reduced offering much less amplitude discrimination. The curve is dependant upon pulsar pulse duty cycle so the χ^2 plot's curvature sharpens for pulsars with increased on/off ratio. A limiting value in the SNR2 approximation occurs as eventually it becomes a measure of the SNR of a noiseless, fixed duty cycle pulse model. However, SNR2 may still be a quick and simple discriminant for low SNR pulsar intercepts.

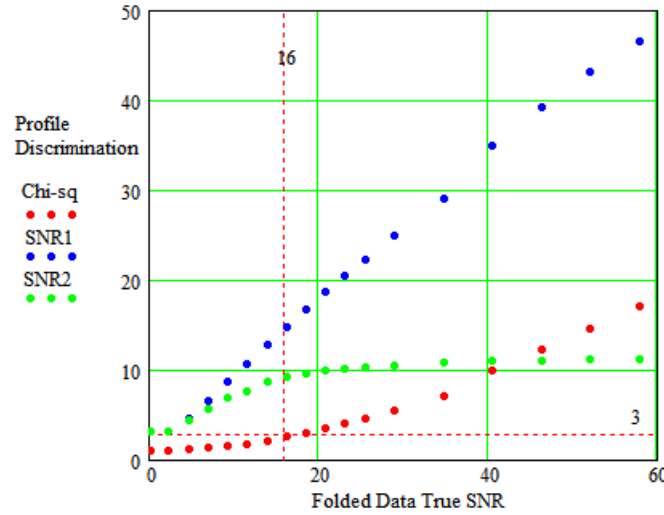


Figure 1. Comparison of Chi-square and SNR1 and SNR2 measures on a Folded Pulse Train
(Note: Reduced tracking of SNR1 due to the pulsar peak not lying centrally in a bin)

The plots are as defined, red: Chi-square, blue: best accuracy output SNR, green: approximate output SNR. The main conclusion drawn from Figure 1 is that due to the 'flatness', hence poor amplitude discrimination, of the χ^2 statistic at low SNR levels, it can only be expected to indicate good parameter search peaks for intrinsic SNRs greater than about 15:1 (certainly for 1% duty-cycle pulsars such as B0329). Below this level it seems that SNR is a better discriminant.

An interesting conclusion can be drawn from this graph. If there is sufficient amplitude discrimination using the χ^2 measure to validate Dispersion Measure search (DM), Period search and P-dot search graphs in the *prepfold* output plot for pulses with an SNR of **16:1**, then by manually applying the SNR1 algorithm, apart from possible confusion with noise peaks, the corresponding validation level could now drop closer to 3:1 - the expected residual noise peak line. In practice, there are other validating characteristics (Appendix 2) which can be used to further support recognition success.

The process to obtain SNRs of the relevant search parameter data for this experiment (results described later) involved manually running the *prepfold* program on the RFI-mitigated data over the search parameter space. For each of the parameter best-profile data folds, a maximum SNR is recorded and these values used to produce the duplicate search plots for comparison with the Figure 3 sub-plots. Both measures have similarities and can be seriously affected by RFI, hence the reason for attempts to first, mitigate it. Rolling SNR measurements are seriously affected by impulsive RFI and this is probably another reason why it is not the preferred measure in PRESTO.

The PRESTO *prepfold* Plot

A typical command line for the PRESTO RFI mitigating tool, *rfifind* is,

```
rfifind -o maskp2 -time 1 -chanfrac 1 -intfrac 1 -freqsig 18 -timesig 18 -zapchan 0:0,21:24  
-zapints 0:0,10000:10000 datafile.fil
```

This generates an RFI masking file: *maskp2_rfifind.mask* which detects and blanks or in-fills adjustable time and frequency sections as well as in this case, blanking frequency channels 0 and 21 to 24 from the data file, *datafile.fil*. The data file is assumed in a standard *.fil* format. The RFI masking file is then called up by the folding program *prepfold* with the full command line,

```
prepfold -mask maskp2_rfifind.mask -nsub 25 -n 714 -p 0.71447786 -topo -phs 0.5 -dm 27 -
pd 0.0000000000 -nosearch -fine datafile.fil
```

In this example, the RF band is divided into 25 sub-bands, the data folded into 714 bins (~1ms/bin for convenience). The topocentric pulsar period (available from TEMPO) is inserted, as is the expected DM. The command specifies no period searching. Period search, DM search and P-dot search test values replace the corresponding -p, -DM, -pd values as required.

On completion, the program displays the following main plot and produces a number of associated data files.

A typical PRESTO output plot after applying the *prepfold* tool on RFI cleaned data for a pulsar SNR of 15:1 is shown in Figure 2 (Double bi-quad antenna @ 422 MHz + Airsty R2 + 3 hours; A Dell'Immagine, July 2018). Top left is repeated the folded result of the best profile. Below this a time-waterfall plot on which faint trails indicate that the pulsar is present largely throughout the observation. To its right is the running reduced χ^2 integrated value. The final result is just under 5, indicating that the distribution is slightly more skewed than predicted for Normal noise but shows steady increase over the observation time.

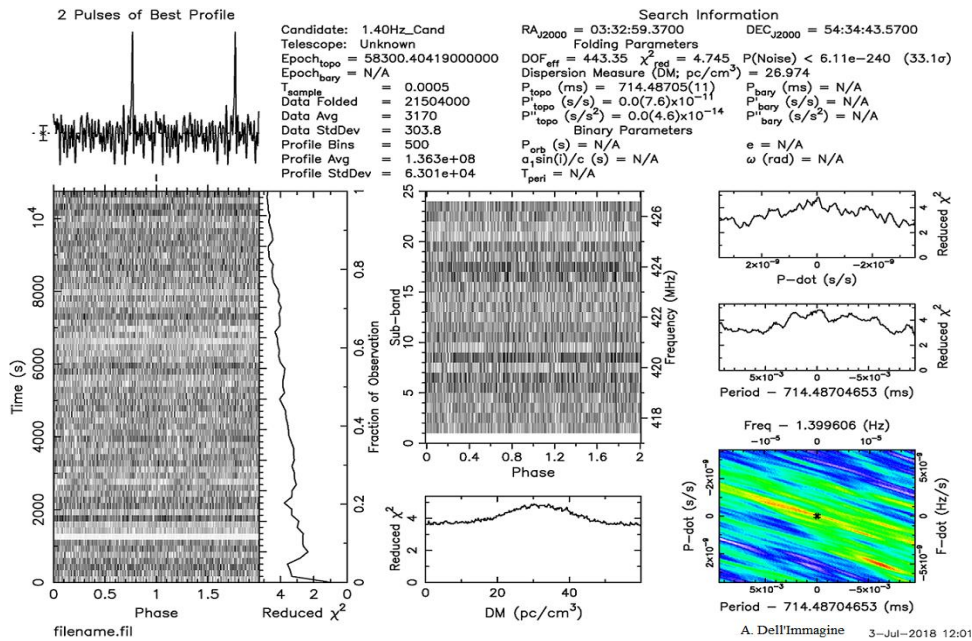


Figure 2. Typical PRESTO *prepfold* Data Plot with a folded signal SNR of 15:1

The waterfall shows that some RFI is still present. The center RF frequency graph again shows vestigial pulsar trails indicating the signal is indeed broad band.

The center-right graphs show the results of searching around the expected period and P-dot values. Both indicate a slight but 'noisy' (probably due to residual RFI) hump at zero error showing that the χ^2 discrimination response is just about adequate for B0329 at this site and 15:1 SNR.

The bottom-right color plot combines the period and P-dot measures and largely indicates a central peak (red). Probably the most important plot is at bottom-center. This is a DM search and correctly shows a peak around DM = 27 as expected for the B0329+54 pulsar, but with relatively poor amplitude discrimination. The period and P-dot searches, apart from the small central peak, show no real off-zero structure.

As a one-off data set, there is just about sufficient validation information here to confirm B0329 intercept but cleaner period and P-dot central peak plots expected from a continuous highly stable pulse train would certainly aid confidence.

Figure 3 shows a similar plot, but now with a pulsar SNR of 5.5:1 (Twin 2.5m, 17-element Yagi antenna @611MHz + Airsty R2 + 3 hours; PW East, August 2018). It is clearly evident that the reduced χ^2 statistic, value at around 3, cannot adequately confirm and validate that a pulsar is truly present from the DM, period and P-dot search plots although the 2-pulse best profile folded plot (top-left) looks promising and you might just fool yourself into seeing some very faint waterfall and frequency trails.

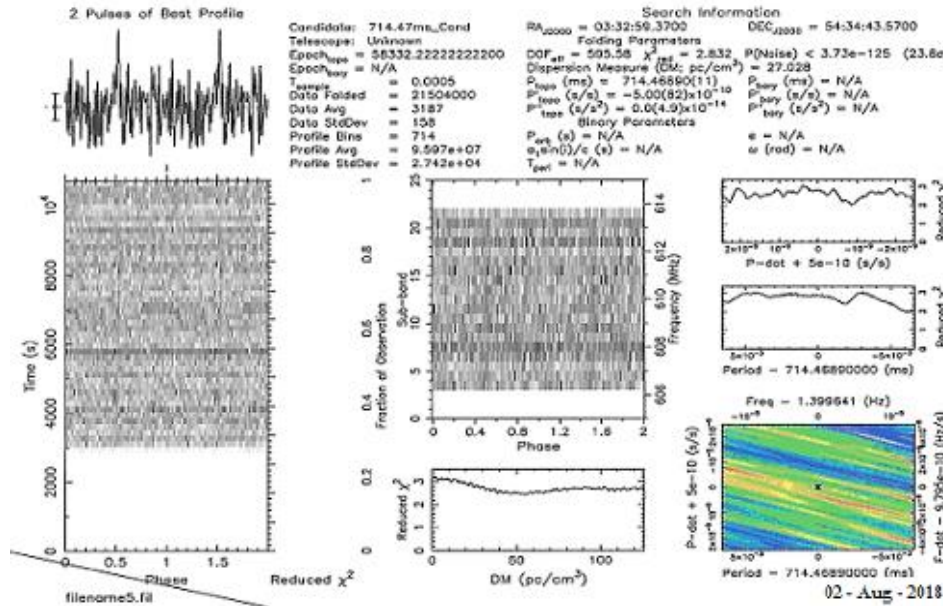


Figure 3. PRESTO *prepfold* Low SNR Data Plot with a folded signal SNR of 5.5:1

Fortunately, one of the files produced by *prepfold* contains the folded data bin values and is available for plotting separately, namely, *datafile_714.48ms_Cand.pfd.bestprof*. Giorgio and Andrea Dell'Immagine have produced a Python program that accesses this file to produce an SNR plot. With slight modifications it has been adapted to output the maximum SNR and its associated bin number. The next section describes a manual exercise to duplicate the SNR-based DM, period and P-dot *prepfold* sub-plots to assess pulsar recognition using SNR profiling to compare with the chi-square profiling.

Manual Search Results of 5.5:1 SNR Data

In each of the search plots reproduced in Figures 4, 5 and 6, the red points are the indicated maximum SNR values obtained from the *prepfold* best profile results using the SNR1 implementation on the Figure 3, *rfifind*-masked data.

The blue curves are those calculated assuming a continuous pulse train with frequency and pulse characteristics identical to the pulsar considered and folded using the standard algorithm. The three theoretical curves appear identical shapes, but in fact are slightly different, responding to the particular search parameter. The background theory is similar to the scoring methods of Reference 4 but is explained in Reference 5; this is applied here and takes into account the blanked RFI space over the first third of this recording.

Figure 4 shows the SNR DM search results which now indicate a clear peak around the expected B0329 pulsar DM of 27, not evident in the χ^2 version reproduced to the right of Figure 4. It is interesting to note that the form and accuracy of Figure 4 SNR result more closely matches the χ^2 version of the 15:1 SNR plot in Figure 2 supporting the improved discrimination claim for SNR profiling.

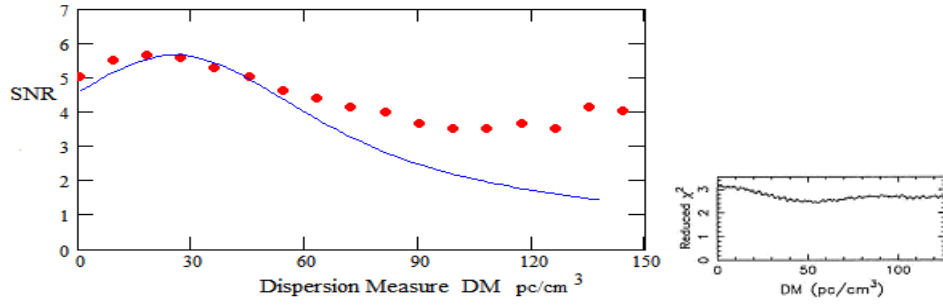


Figure 4. Dispersion Measure Search

This is sufficient to confirm that the source is broad band and dispersed as expected and the peak DM matches that of the expected source allowing for some distortion due to the underlying noise. The deviation from theory with increasing DM is anticipated as the source signal gets spread out in time, reducing its amplitude below that of the folded noise peaks.

Figure 5 shows the results for SNR period search with the period change ranging from -5 ppm to +5 ppm; the corresponding χ^2 version is on the right. There is a clear peak evident now in the SNR plot matching very closely to the expected value (TEMPO predicted) and the roll-off theory⁽⁵⁾ over the range -2 ppm to +2 ppm.

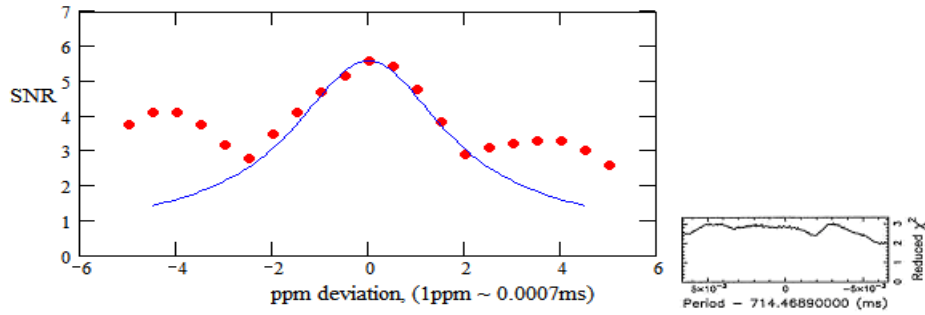


Figure 5. Period Search

Outside this range, random noise peaks appear to take over. The theory assumes a perfect pulse train matching the pulsar parameters implying that the pulsar pulse train is largely present throughout the data file. When the fold period is changed away from the correct value, for example, a true pulsar pulse position in the final period relative to the first period will have shifted. This has three effects after folding and they are, 1. the final summed pulse is broadened, 2. it is reduced in amplitude and 3. the pulse center will shift in relative time/bin. For a given data set these three effects are predictable for any substantially complete pulse train as described in Reference 5. Similar effects are predicted for DM and P-dot searches. Appendix 2 summarizes the part that matching these predicted responses has on validating the weaker SNRs.

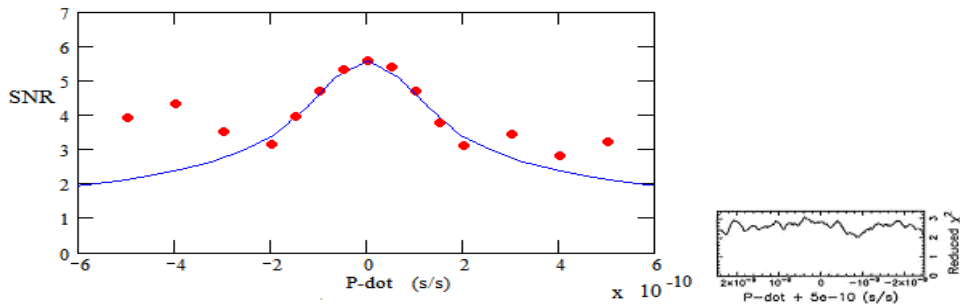


Figure 6. P-dot Search

The period-rate search, P-dot plot in Figure 6, again shows good conformity with theory over the range -2×10^{-10} s/s to 2×10^{-10} s/s, a peak at zero P-dot and the symmetry proving a high degree of frequency stability of the target ($\ll 1$ μ s over the observation period) as well as again demonstrating the presence of a continuous pulse train. Again for comparison, the χ^2 version on the same data is shown to the right.

Note that these searches report the maximum SNR value in the data fold. An alternative policy is to calculate⁽⁵⁾ the pulsar peak bin shift and report the data amplitude of this bin, adding confidence and possibly reducing the outlier values.

Spectrum Searches

A complementary method of pulsar searching is to Fourier transform (FT) the downsampled, RFI mitigated data file. With strong pulsar sources, these are visible as sets of predictable decaying harmonically related spectral lines. Figure 7 illustrates typical SNR results of the various methods with a model based on B0329 assuming an 8000 second data acquisition fully transformed in an 8 MB FT. The blue line represents the performance of maximum SNR with standard period folding. Spectrum folding performance⁽⁶⁾ (red curves) does not equal this: the solid red curve is the result of folding all the significant pulsar harmonics using harmonic spacing rather than period spacing on the basic folding technique. Harmonic visibility cannot be expected in and below the 3:1 SNR region. The lowest red-dash curve corresponds to the SNR of the fundamental spectral line, requiring an integrated standard fold SNR of greater than 20:1 to ensure visibility.

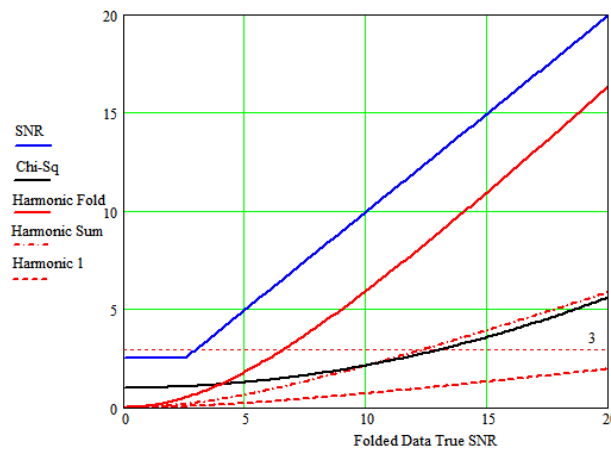


Figure 7. SNR Comparison with Chi-square and Spectrum Harmonic Folds

An improved harmonic visibility technique for narrow pulse pulsars is incoherent harmonic summing (centre red dash-dot curve). This involves stretching the frequency scale by factors 2, 3 etc: and summing the spectra so enhancing duplicating/overlapping harmonic lines. Sensitivity improvement up to a factor of 3 is possible for a 1% duty-cycle pulsar⁽³⁾.

The curves are as labelled, spectrum harmonic folding offering the best sensitivity advantage, but falling significantly short of the standard folding SNR (blue). The harmonic sum technique appears in this example to give a similar detection performance to the Chi-square statistic (black) method.

Conclusions

As a one-off acquisition, with the added SNR profiling, there is now sufficient validation information recovered from this 5.5:1 SNR data to confidently confirm it as a B0329 intercept. Accurate tracking of the DM, period and P-dot search plots with those calculated for a stable pulse train of the same parameters as the pulsar provides the extra confidence.

What can be concluded from these results is that whilst PRESTO software tools are fast and great for finding new strong pulsars and mitigating RFI, they are not intended or so well matched to the needs of amateurs wanting to validate weaker known acquisitions with SNRs much below 10:1.

However, comparing Figures 4 to 6 SNR plots to the corresponding PRESTO Chi-square sub-plots shows that with the addition of SNR profile analysis, considerably more detail and search discrimination is available. The close matching with the pulsar pulse train search theory is a measure over and above that of previous analysis software, but some automation of the manual process used here is to be desired.

A very large, correctly dispersed, broadband pulse of the right duration with a very stable period is a convincing pulsar. At lower SNRs however, it is important to increase validation confidence by closely tracking the defining pulsar parameters as listed in Appendix 2, coupled with a good understanding the differentiating characteristics of random noise and the various forms of RFI.

It is great bonus that professional radio astronomer's software is freely available to amateurs, but it is important for users to make themselves aware of its inner workings and what it was designed for, so that the results of the software tools can be properly interpreted.

With a little extra effort, as shown here, detection and recognition of pulsars in the SNR region well below 10:1, is definitely not out of bounds to amateurs with quite modest equipment.

Finally, from a detection sensitivity point of view no process or algorithm has been found that is as efficient as the standard period-folding algorithm when optimally band-limited.

Acknowledgements

The author acknowledges the ideas and support of Andrea and Giorgio Dell'Immagine for their guidance and use of the software⁽⁹⁾ they developed to acquire and process pulsar data.

References

1. PRESTO Home, <https://www.cv.nrao.edu/~sransom/presto/>
2. SM Ransom. Searching for Pulsars with PRESTO
https://www.cv.nrao.edu/~sransom/PRESTO_search_tutorial.pdf
3. D Lorimer, M Kramer., Handbook of Pulsar Astronomy. Cambridge University Press. 2005.
4. MJ Keith et al, 'Discovery of 28 pulsars using new techniques for sorting pulsar candidates' Mon.Not. R. Astron.Soc. 395, pp837-846(2009)
5. PW East. An Analytical Method of Recognizing Pulsars at Moderate SNR. Journal of the Society of Amateur Radio Astronomers. November-December 2018. p17.
6. PW East. Spectrum Techniques for Improving Low SNR Pulsar Detection. Journal of the Society of Amateur Radio Astronomers. March-April 2019.
7. PW East. A Correlation Method for Low SNR Pulsar Search and Recognition. Journal of the Society of Amateur Radio Astronomers. July-August 2019.
8. PW East. Getting the Best from the Pulsar Folding Algorithm. Journal of the Society of Amateur Radio Astronomers. November-December 2020.
9. G Dell'Immagine, A Dell'Immagine. Linux pulsar software for recording and analysis.
<https://github.com/gio54321/pulsar-distro-guide>

Appendix 1. Outline of a PRESTO Search - SM Ransom Tutorial²

- 1) Examine data format (readfile)
- 2) Search for RFI (rfifind)
- 3) Make a topocentric, DM=0 time series (prepdata and exploredat)
- 4) FFT the time series (realfft)
- 5) Identify "birdies" to zap in searches (explorefft and accelsearch)
- 6) Make zaplist (makezaplist.py)
- 7) Make De-dispersion plan (DDplan.py)
- 8) De-disperse (prepsubband)
- 9) Search the data for periodic signals (accelsearch)
- 10) Search the data for single pulses (single_pulse_search.py)
- 11) Sift through the candidates (ACCEL_sift.py)
- 12) Fold the best candidates (prepfold)
- 13) Start timing the new pulsar (prepfold and get_TOAs.py)

Appendix 2. Full Low SNR Validation Sequence

Validating Test Sequence	Evaluation
0. Radio Telescope Sensitivity	Basic check - SNR expected.
1. Correct period fold	TEMPO-matched. Calibrated system clock.
2. Pulse width.	Basic check.
3. Two/multiple-section fold correlation.	Matching pulse train present in data file sections.
4. Twin/multiple-period fold correlation.	Sequential pulses at expected period.
5. Multi-band correlation.	Broadband candidate - strong indicator.
6. Period search peak (Ref 5.) – profile, offset and pulse width	Continuous pulse train, accurate period at peak, check bin shift and pulse width increase.
7. P-dot search peak (Ref 5.) – profile, offset and pulse width	As 6 but also highlights high frequency stability and scintillation. Check with offset start period.
8. Dispersion search peak (Ref 5.) – profile, offset and pulse width	DM peak, bin shift and pulse increase, identifies as interstellar source - strong indicator.
9. Half-fold correlation (Ref 7.)	Identifies best candidates/ suppresses noise.
10. Multi-Bin fold plot (Ref 8.)	Differentiates pulse and noise.
11. Coherent spectrum sum (Ref 6.)	Harmonic and matched fold confirmation.

- Notes:**
1. Passing all Items 0 to 8 is essential, checks 9 to 11 add weight.
 2. Sporadic high level RFI (electrical machinery, impulsive signals etc: can be RF filtered or amplitude clamped/blanked at video. Once amplitude spikes are nulled, the chances of confusion is reduced but an equivalent RFI increase in base noise level can obscure a possible real candidate.
 3. Random noise peaks arise from folding and averaging all data noise and comprise components present in a major number of periods by chance. This means that some peaks are likely to persist in checks 3 and 4, but are unlikely to track in tests 5, 6, 7 and 8.
 4. At low SNRs, the true pulsar SNR value will be affected by the underlying noise so that in Tests 6,7 and 8 amplitude profiles will have some impressed variation which is increased for lower true SNRs. In this case it is better to track amplitudes at the expected bin number to discern profiles.
 5. Due to natural source scintillation and RFI uncertainties not all low SNR trials can be expected to be successful.



Peter East, pe@y1pwe.co.uk is retired from a career in radar and electronic warfare system design. He has authored a book on Microwave System Design Tools, is a member of the British Astronomical Association since the early '70s and joined SARA in 2013. He has had a lifelong interest in radio astronomy; presently active in amateur detection of pulsars using SDRs, and researching low SNR pulsar recognition. He encourages free information exchange in the amateur community and is keen to widen interest in radio astronomy generally. He maintains an active RA website at <http://www.y1pwe.co.uk>