Review of Pulsar Detection and Verification with Small Aperture Antennas
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Summary

Following a brief introduction to pulsars and how to intercept pulsar radio frequency (RF) transmissions, this article describes the design and results of an amateur project aimed at detecting and validating the strongest pulsar in the northern hemisphere with only a modest back-garden radio telescope.

About Pulsars

A pulsar, the likely end product of a supernova, is a highly magnetized, rapidly rotating neutron star some 10 to 15km in diameter that emits broadband beams of electromagnetic radiation out of its intense magnetic poles (Figure 1). If the orientation is such that the RF beam passes through our solar system, it is received as highly accurately timed pulses with repetition rates of milliseconds to several seconds depending upon the pulsar age.

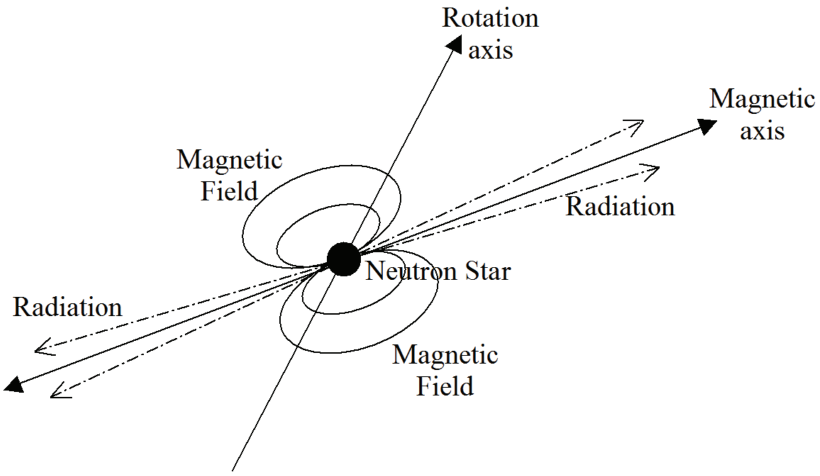

Figure 1. Pulsar Radiation Configuration

The main electrical characteristics are very accurate pulse timing; broadband noise radiation with much more power at low frequencies; the received pulse energy scintillates in both time and frequency and is also dispersed in frequency due to electron interaction along the inter-stellar path; it is with these characteristics that they are best recognised.

Pulsars are one of the weakest radio astronomy targets and the most difficult for amateurs even though a few thousand have been discovered in our galaxy by professional radio astronomers.

The most powerful pulsar in the northern hemisphere within the capability of amateurs to detect is listed as B0329+54.

The typical radio telescope specification requirements for successful amateur detection are to operate within the frequency range 300MHz to 1400MHz, a few square metres antenna aperture, a few MHz RF bandwidth, a few hours integration, a system noise temperature around 100°K and, not the least, a low radio frequency interference (RFI) local environment.

Pulse period-matched, synchronous integration or period-folding of the detected signal is the most effective technique in recovering a true pulsar from galactic and receiver noise. This involves accurately dividing the detected data record into known pulsar period sections and parallel adding these sections: if a pulsar is present then this technique ensures that it will appear in the same relative position and add linearly, whereas the system and galactic noise adds as power or the square root so increasing the observed signal-to-noise ratio (SNR).

Introduction

It has long been accepted that pulsar detection by amateurs is extremely difficult and that large antennas, complex receivers and complex processing are all required to achieve any success. Some amateurs have, however, piloted the way with quite modest systems and this article builds on their success.[1] In it, the tools are shared that will enable an interested party to design their own system and process the data, to confidently detect the strongest pulsar in either the Earth's northern or southern hemispheres. The characteristics and properties used to separate pulsar signals from filtered noise and RFI are: a regular broad-band scintillating pulse train with a very accurate stable period, a known pulse width, dispersed in frequency and emanating from a known point in space.

Modern developments improve the chance of success, such as the availability of very low noise amplifiers (LNA) and software defined radios (SDR) and easily constructed receiving antennas, all with a minimum of expenditure; plus freely available processing software.

This article begins by examining the fundamental radiometer equation to identify what system characteristics are important and discusses how best to choose the antenna and main receiver components to facilitate amateur pulsar detection. The author's basic system is outlined together with some results and finally, methods of validating detections. Validation of results is especially important for modest equipment where the integrated pulsar target signal-to-noise ratio is less than about 7:1. The PRESTO professional astronomer's software is designed to detect new pulsars and is freely available for amateur use in data processing and RFI mitigation of pulsar data containing integrated/folded results exceeding SNRs of 7:1 or more.[2,3] Small aperture systems may not achieve this SNR level so alternative techniques to improve confident identification for lower SNRs are proposed.

The Pulsar Radiometer Equation

Equation 1 is the pulsar radiometer equation, which describes the best possible folding algorithm performance for a tracking antenna system in generating an observable signal-to-noise ratio (SNR),[4]

$$SNR = \frac{S_p A_e \sqrt{n_p t_{\text{int}} \Delta f}}{2\beta k_b T_{sys}} \sqrt{\frac{P - W}{W}} \qquad (1)$$

where, S_p is the pulsar mean total flux at the observation frequency, as listed in the ATNF data base.[5]

A_e is the receiving antenna effective collecting area in m^2.

n_p is the number of polarizations received.

t_{int} is the total integration time in seconds.

Δf is the receiver RF bandwidth in Hz.

P is the pulsar period in ms.

W is the pulsar half-height pulse width in ms.

the factor 2 halves the pulsar flux to conform with the flux from a single polarization.

β is a modifying factor to account for digitisation losses for coarser digital increments.

k_b is Boltzmann's constant.

T_{sys} is the receiver system noise temperature, related to the system noise figure.

With a fixed beam, small aperture antenna, the chosen RF frequency now becomes a factor due to the beamwidth for a given antenna aperture being frequency dependant. Low frequencies imply broader antenna beam-widths allowing longer drift-scan integration times. The increased pulsar flux at lower frequencies is another positive aspect of choice and some practical SNR detection examples are shown in Figure 2.

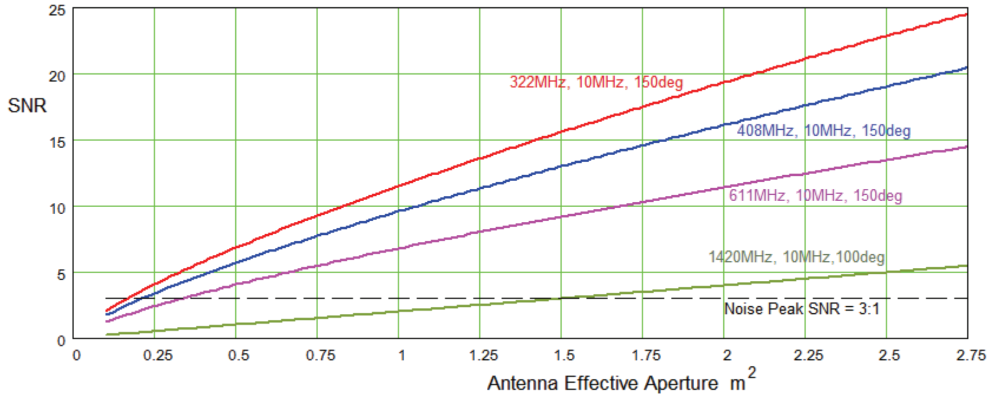

Figure 2. Drift-Scan Detection SNR for B0329+54 at Frequencies Centred on Radio Astronomy Allocated Bands (Captions code: Radio Frequency, Frequency Bandwidth, System Noise Temperature)

The Figure 2 plots show that with a system noise temperature around 150ºK, it should be possible to detect the B0329+54 pulsar with receiving apertures exceeding 0.75m^2 at 322MHz rising to 1.5m^2 at 611MHz. At 1420MHz, the target pulsar flux is much lower and larger antennas and long exposure tracking is necessary. These are of course ideal conditions; natural pulsar scintillation and local RF interference limits success in real trials.

Radio Telescope Implementations

Figure 3 schematic shows a basic pulsar radio telescope set-up. The low noise amplifier (LNA) defines the system sensitivity, whilst the band pass filter limits the operating bandwidth. The radio frequency amplifier (RFA) chain amplifies the signal sufficiently for the software defined radio (SDR) digitisation; typically with some 50dB gain. The radio telescope is effectively a radiometer detecting temperature and may have an equivalent input system noise temperature of some 80 to 150°K. This figure is often degraded by dish antenna spill-over or side-lobe input from the 'hot ambient' environment. If necessary, the Global Positioning System (GPS) disciplined oscillator (GPSDO) locks the SDR clock to ensure sufficient sampling accuracy to check the pulsar period and stability.

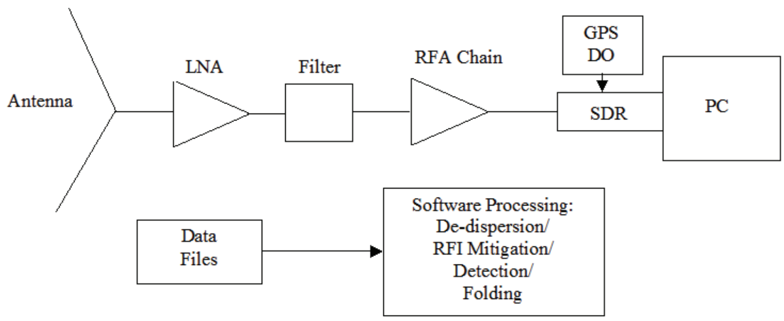

Figure 3. Basic Pulsar Radio Telescope Schematic

The key pre-requisites for a successful B0329+54 pulsar receiving system are,

1. Low RFI 300/400/600MHz band choice.
2. Antenna effective aperture >1.0 m^2.
3. Low Noise Amplifier (LNA) noise figure < 0.5 dB + band-pass (BP) filtering.
4. SDR bandwidth >2MHz, tuning accuracy <0.5ppm or Global Positioning System (GPS) disciplined oscillator (GPSDO) locked.
5. PC/laptop, >2GHz clock, >200GB storage free, Windows/Linux 64B OS.

Radio Frequency Interference (RFI)

RFI comprises any non-pulsar electromagnetic signal within the observation frequency band. In fact, large saturating signals outside the operating band but within the LNA band, can cause within-band noise modulations that may impact on the folded pulsar result. Some LNAs are available with pre-filtering but a good post-LNA band-defining filter with >50dB out of band rejection is essential. Amplitude modulated signals, digital transmissions, cell phones, TV, transient signals such as motor ignition, electric hand tools, solar power panels, PC digital clocks, can have a serious impact on the folded result.

Experience has shown that night-time/early morning observations suffer less than daytime runs. To minimize false reports or SNR degradation, RFI mitigation techniques may need to be applied prior to folding. Since interference may be sporadic, it is usual to sense RFI in the recorded data and blank bad data sections in both frequency and time. The PRESTO software has easy-to-use tools embedded to remove RFI in both frequency and time domains.

As mentioned earlier, a quiet RF location is equally important and it is recommended that effort is concentrated on identifying a low RFI band and carry out observations in the early hours - at the right time of the year, of course.

Antenna Choice

There are a variety of small antennas that can be considered for pulsar acquisition. Apart from effective aperture, the most important specification parameter is side-lobe performance. It is generally a feature of antennas with dimensions of a few wavelengths that their aperture efficiency is low resulting in bigger side-lobes; this increases susceptibility to thermal radiation from the physical environment that can seriously degrade the system sensitivity.

Without a doubt, a large parabolic dish is the obvious solution but the cost, size, installation, drive requirements and space required may put it outside the scope of the average amateur. Yagi antennas for this frequency band need to be quite long (>5 wavelengths, λ) to provide sufficient effective collecting area, but although easy to build do not have very good side and back-lobe performance.[6] These antenna types can be arrayed linearly to advantage by ensuring that the useful observation time is controlled by the basic element beamwidth and not by the array length. Horn antennas have lower side- and back-lobes with less effect on system noise temperature but may be bit bulky, possibly demanding a length of at least 2m for a 1.0m aperture but they can be manufactured with lightweight aluminium clad materials.[7]

The 3D-corner reflector at 400MHz and double bi-quad at 300MHz home-built antennas both exhibit very low back-lobes and have demonstrated excellent performance in pulsar detection.[1,8,9]

Receiver Chain Components

Low noise amplifier (LNA) noise figures below 0.4 dB are available at modest cost, based on the EpHEMT GaAs technology fortunately funded and developed for mobile phones. A commercial Mini-Circuits LNA, the ZX60-P33ULN, has a 0.4 dB noise figure covering the band 400MHz to 1400MHz, contributing just 28°K to the system noise temperature.[10] Other lower cost devices with slightly higher noise figures but suitable for the RF amplifier chain are obtainable from ebay.

Pre-RF amplifier chain filtering is probably essential and a suitable band-pass interdigital filter can be designed for home build using the online tool by Frank.[11]

Ideally, the LNA should define the system sensitivity, but there are several system demons that conspire to degrade it. Resistive losses in the antenna LNA input path both increases system noise and reduce wanted signal/noise amplitude and are to be avoided. Cable mismatch also reduces the wanted signal so that good LNA input and antenna terminal matching is important for maximum power transfer.

Antenna side-lobe ground temperature noise coupled with unwanted RFI can be catastrophic. There are however steps that should be followed to mitigate these degradations such as: placing the LNA as near to the antenna terminal as possible, choosing a low side-lobe antenna type and ensuring the antenna is as well-matched to the standard 50Ω as possible. There are cheap antenna vector analysers available on ebay suitable for this purpose.

SDR Receivers

There are a number of relatively inexpensive software defined radios (SDRs) on the market with various capabilities but good software support. The cheapest by far is the RTL2832U unit, originally intended for digital TV but interested engineers developed drivers and software for it to become a useful 2.4 MHz bandwidth software-tuneable SDR.[12] The basic unit frequency and temperature stability is not good, but both characteristics can be adequately improved with crystal modifications and additional cooling. Multiple RTLs can be frequency locked together to cover broader RF bandwidths, but better SDRs, such the Airspy R2, have larger bandwidths, better stability and resolution.

Software Resources [13 - 23]

There are several SDR software graphical packages such as SDR Sharp (SDR#) that are compatible with the RTL SDR and other SDRs that are very useful for system commissioning and testing and in some cases to produce data files. For real time data collection and pre-processing GNU Radio can handle most SDRs. Special tools have been developed by Osmocom targeting the RTL SDR.[14]

For data acquisition, processing, synchronous detection and data display, several amateurs have developed bespoke software and have made these available in the references below.

Testing:	SDR# for Windows.[13]
Data Recording:	Osmocom rtl tools.[14]
/ Processing:	GNU Radio.[15]
	Linux pulsar software for recording and analysis.[16]
	Pulsars-How to Detect.[17]
	Canadian Centre for Experimental Radio Astronomy.[18]
	RTLSoftwareToolsU4-6.doc.[19]
	Pulsar Detection Project.[20]
Display:	Excel/MathCad/MatLab/PRESTO
Programming:	Python - internet download
Professional Analysis:	TEMPO, PRESTO, SigProc etc.[21]
Ephemeris Data:	Radio-Eyes.[22]
Pulsar Timing:	Accurate prediction of the pulsar topocentric period. TEMPO, Astropy or on-line packages.[23]

Practical Small Aperture Data Recording

The author's system (Figure 4) using twin 2.5m Yagis at 611MHz and an Airspy R2 SDR receiver is shown together with illustrations of the essential RF components in Figure 3.[13]

The graphical results of applying the PRESTO software for a 5:1 SNR intercept are included in the figure. It shows a clear pulse presence in the 2-period profile plot (top left) but the other verification plots (time and frequency waterfalls, DM search, period search, period rate search) are noisy and inconclusive. The reason for this, is that PRESTO is designed for fast, big-data pulsar discovery and uses a mean power statistic (Chi-square), which needs a high SNR to detect low duty cycle pulsars. In this study the SNR statistic itself is used to improve weak signal visibility as shown later.

Data collection is by a laptop PC using a cut-down version of Leech's pulsar software based on GNU Radio.[15,18] A distinct advantage of choosing GNU Radio for radio astronomy is its processing programmability and support for most modern SDRs - including here, the Airspy.

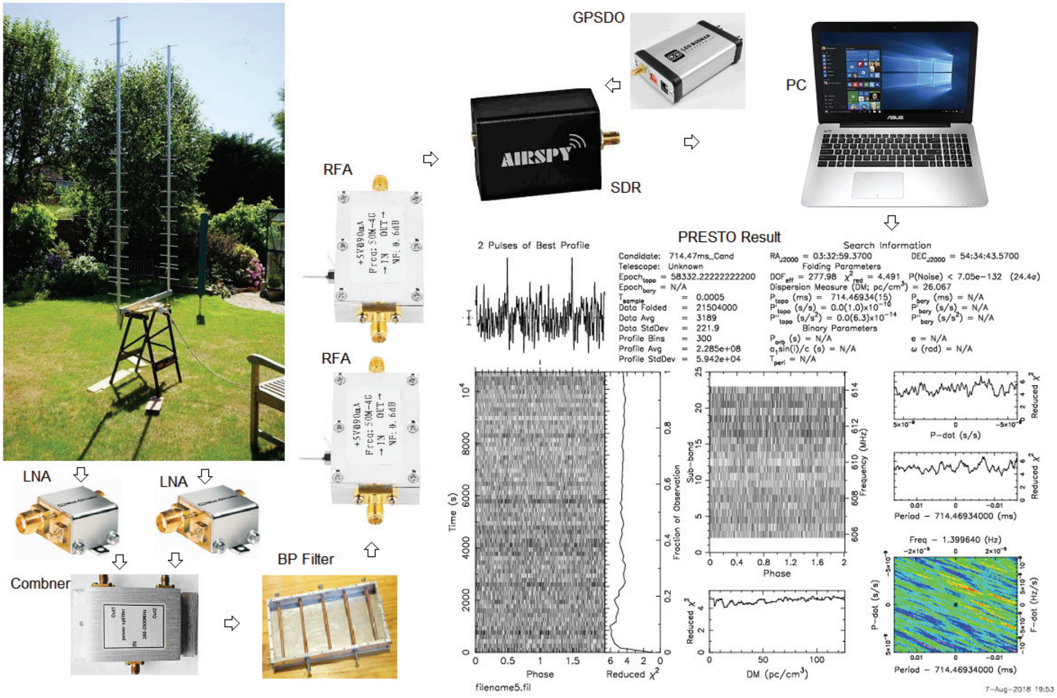

Figure 4. Author's Radio Telescope Components with Typical PRESTO Results

The GNU Radio application allows specification of the number of complex data samples processed in the observation and in this case, initially splits the data into blocks of 16 complex samples and, by means of a Fast Fourier Transform (FFT), divides the operating band into 16 frequency channels. The detected channel magnitudes are proportional to the input power and are then averaged to reduce the data from the initial sample rate of 10MHz down to 500Hz without losing any pulsar information.

With this system, even for 4+ hours intercepting pulsar B0329+54 scintillations, integrated (folded) data is only expected to produce final signal-to noise ratios of between 3:1 and 7:1.

Data was collected in the early hours of the morning of 25 October 2021; it was relatively free from RF interference and is analysed as the example in the following sections.

Using the Airspy SDR, running at 10MS/s and tuned to 611MHz for 4hr 40mins, 168Gsamples of data was processed by the SDR. After 16-band channelisation in the FFT and downsampled by running integration over 1250 samples, the output file contained just 134.4M samples based on a 2ms output data clock.

The long drift-scan observation time was chosen to explore the effect of the source entering and leaving the fixed antenna beam pattern to add confidence in the target identification.

The down-sampled detected file is suitable for period-folding to recover the pulsar pulse profile. The plot can confirm the correct pulse duration and checks that the optimum folding period matches the topocentric period predicted by the TEMPO software. TEMPO requires the observation time and observer location to make corrections for the solar motion etc.[21]

Results

The full data folded result is shown in Figure 5 and a clear pulsar target peak can be seen with an SNR of approximately 4:1. This compares to the natural noise peaks with corresponding peak to noise ratios of around 3:1. In practice, there is a finite probability that these could exceed 4:1 or even 5:1 and on the basis of probability alone, confident validation of the folded result is conventionally approved at the 6-Sigma or 6:1 SNR level and above.

There are, however, other specific pulsar characteristics that can add confidence to validation and these are discussed later.

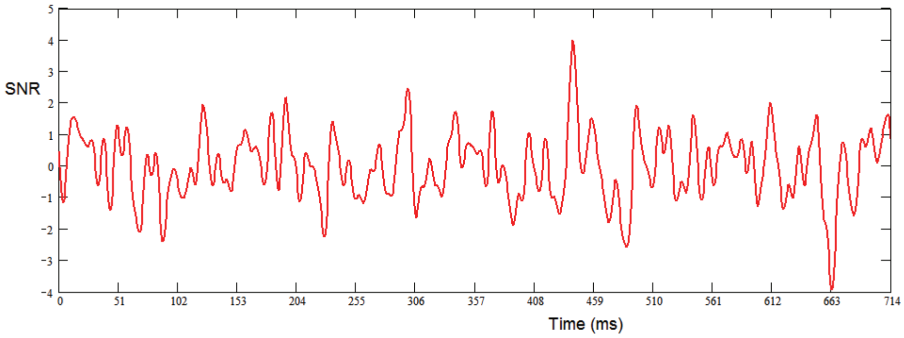

Figure 5. Full Data Period-folded Result

The processing for Figure 6 breaks the data into 128 folded sections to demonstrate the continuity of the target appearing in the data in a waterfall plot. This illustrates the pulsar scintillation property in time but also shows that the folding process treats noise in a similar manner. This is partly due to the correlation process used to enhance the very low section SNRs but also demonstrates the folding algorithm's very fine filtering property in extracting noise components matching the pulsar period and form.
Of note, is the evident pulsar target concentration in passing the antenna beam pointing direction, noted after around 1.8 hours in the observation.

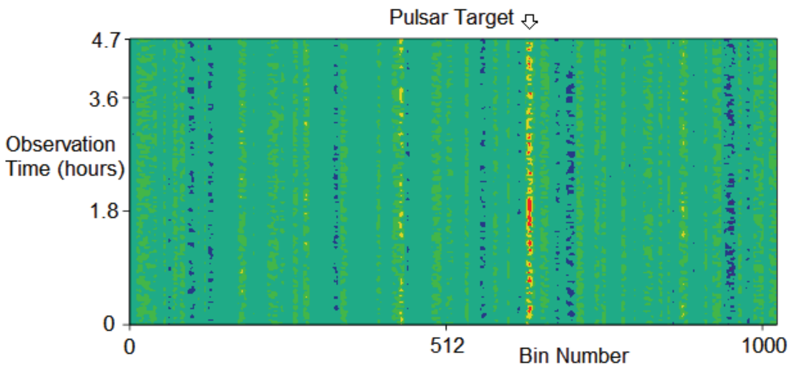

Figure 6. Period-folded Waterfall Plot

Figure 7 illustrates scintillation in frequency in a frequency/band waterfall plot. Again the stronger noise peaks persisting from band to band is evident, highlighting the possibility of confusion with real pulsar targets when no clear peak target appears.

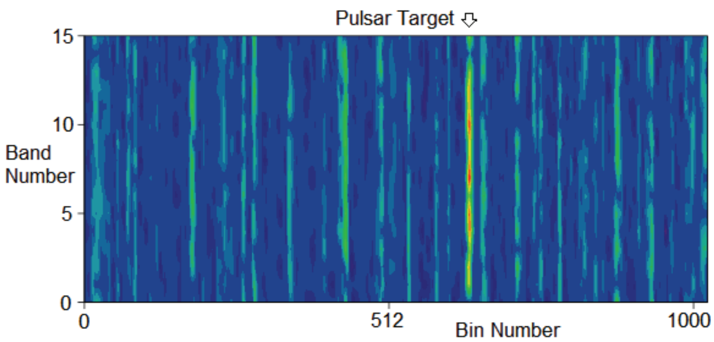

Figure 7. Frequency Band Waterfall Plot

Pulsar Observation Validation

Validation is the process to check that the target has all the characteristic properties expected of a pulsar. For strong pulsar signals where the acquired integrated SNR is greater than 10:1, the successful event is usually obvious, and applying the PRESTO analysis software offers confident confirmation. For lower SNRs however, the PRESTO plots are not so clear and other validation means are necessary.

The more detailed checks involve confirming firstly, a regular pulse train, with the correct period, stability and pulse width and secondly, confirming an extra-terrestrial source, characterised by scintillation, frequency dispersion and only in-beam reception.

To facilitate these checks, the detected data, compressed into 128 synchronous sections can be processed by available mathematical packages, such as MathCad, MatLab or bespoke software.

Two useful processes have been developed for initial assessment of data; these are cumulative folding and rolling-average folding.

To produce the cumulative SNR plot, which shows how the target result grows in time, the first section is folded and the peak plotted, then the first two sections are summed and then folded and the new peak plotted; and so on until all sections are summed. This process produces the green and red plots in Figure 8. For the red plot, instead of the fold peaks being plotted, the bin amplitude corresponding to the target pulsar is plotted. This shows that up to section 50, the noise peaks (green) around SNR = 3:1 dominate but from then on the target peak takes over. The steady growth in SNR is symptomatic of a pulsar target (the median theoretically following a square root curve), whereas noise peaks tend to undulate around a mean level. In fact, here the target level appears to drop off towards the end as the source moves out of the antenna fixed beam.

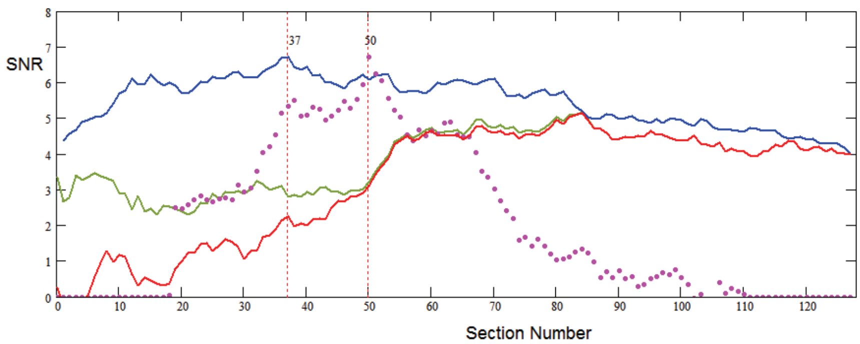

Figure 8. Cumulative SNR (red) and Rolling Average (blue, magenta) SNR Plots

The rolling average process scans the data looking for the region containing the strongest folded result. Initially, it takes all single sections folded separately and plots the largest peak at section one (Figure 8). It then sums all adjacent sections, folds these and again plots the largest peak at section 2 on Figure 8. Similarly for three sections, then through to all 128 sections to produce the blue curve indicating the target signal strength and density in Figure 8. In this case, on inspection, the blue curve maximum appears at section 37, meaning that only 37 sections of the data are needed to produce a result that is significantly larger than for folding all sections.

The magenta data plots the target pulsar bin amplitudes as just 37 sections are scanned across the data and shows that when they are centred on section 50, the maximum target SNR occurs. This plot also indicates a rough measure of the antenna beam pattern.

Period/Period Rate Search Validation - Optimum Data range

For the final validation tests, the data was trimmed to only process the strongest result range between sections 50-37/2 ~ 32 and 50+37/2 ~ 68. In this case, the target SNR has been increased from 4.1:1 to 5.8:1, just by choosing this optimum range in the data.

Varying the fold period and period rate (P-dot) about the expected values (Figure 9) should produce peaks at zero offset and is a strong PRESTO validator, confirming both pulsar period accuracy and negligible period variation over the observation time.

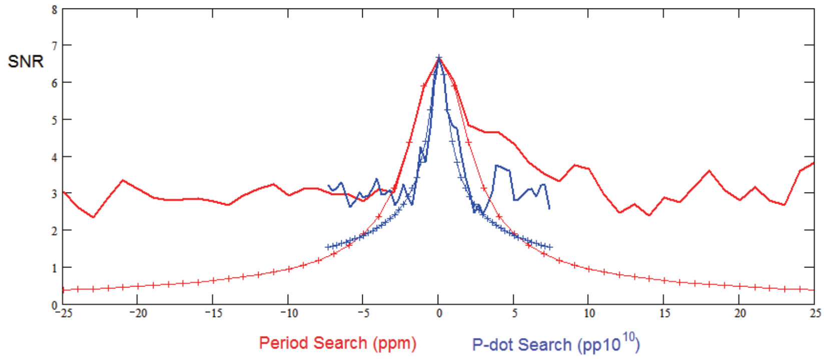

Figure 9. Period and P-dot Search Responses - crossed curves represent theoretical ideal responses

For both parameter searches, the target pulsar peak characteristically varies in amplitude and phase in a predictable way, determined partly by the extent in the record that is observed. The figure shows that as the pulsar target SNR exceeds the noise level around 3:1 SNR, the data curves match very closely to the theoretical curves, as determined by the period offset, pulse shape and the data duration. With both parameters peaking at zero offsets, this test proves very close matching to the pulsar expected topocentric period (<1 part per million) and confirms the stability with virtually no period drift (much less than 1 part per 10 billion) within the observation time.

Dispersion Search

Evidence of the expected frequency dispersion is the strongest validation test, confirming extra-terrestrial signal propagation. Data de-dispersion involves separating the received signal bandwidth into a number of sub-bands and delaying the higher sub-bands before video or digital summing to compensate for the inter-stellar delays. For the dispersion measure (DM) search plot, the band delays are varied linearly over a range about the band centre to accomplish both positive and negative dispersions; the combined data SNR is then calculated to produce the solid red curve in Figure 10.

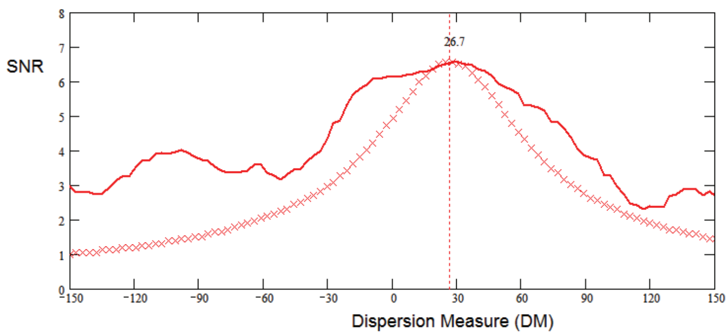

Figure 10. Dispersion Search (red solid), Ideal Noiseless Theoretical (red crossed)

The crossed red plot reports the ideal theoretical response peaking at a dispersion measure of DM = 26.7 which is the listed DM value for pulsar B0329+54. Given the low SNR, the measured response matches the expected dispersion for this pulsar target within the constraints of the underlying noise. The correct de-dispersion aligns all frequency components further improving the measured SNR from 5.8:1 to 6.4:1.

Full Analysis Summary [24,25]

In small aperture pulsar detection systems, even very long-time data records may only produce detected SNR's of maybe only 3:1 to 7:1. Since the expected range of Gaussian noise peaks is in this region, there will always be some ambiguity in identifying a true pulsar pulse. Therefore, an extreme validation routine is necessary. Folded noise and unfortunate interference peaks can masquerade as pulsar-like signals and are a source of erroneous detections. All of the tests described can fall foul of noise/interference impersonations and pulsars themselves at this level do not have a single 100% discriminating property. Normally, a preliminary check on data quality for acceptable RFI on downsampled amplitude-detected data should be made, then removed or attenuated.

For this analysis, no data was removed or modified in the optimum range identified.

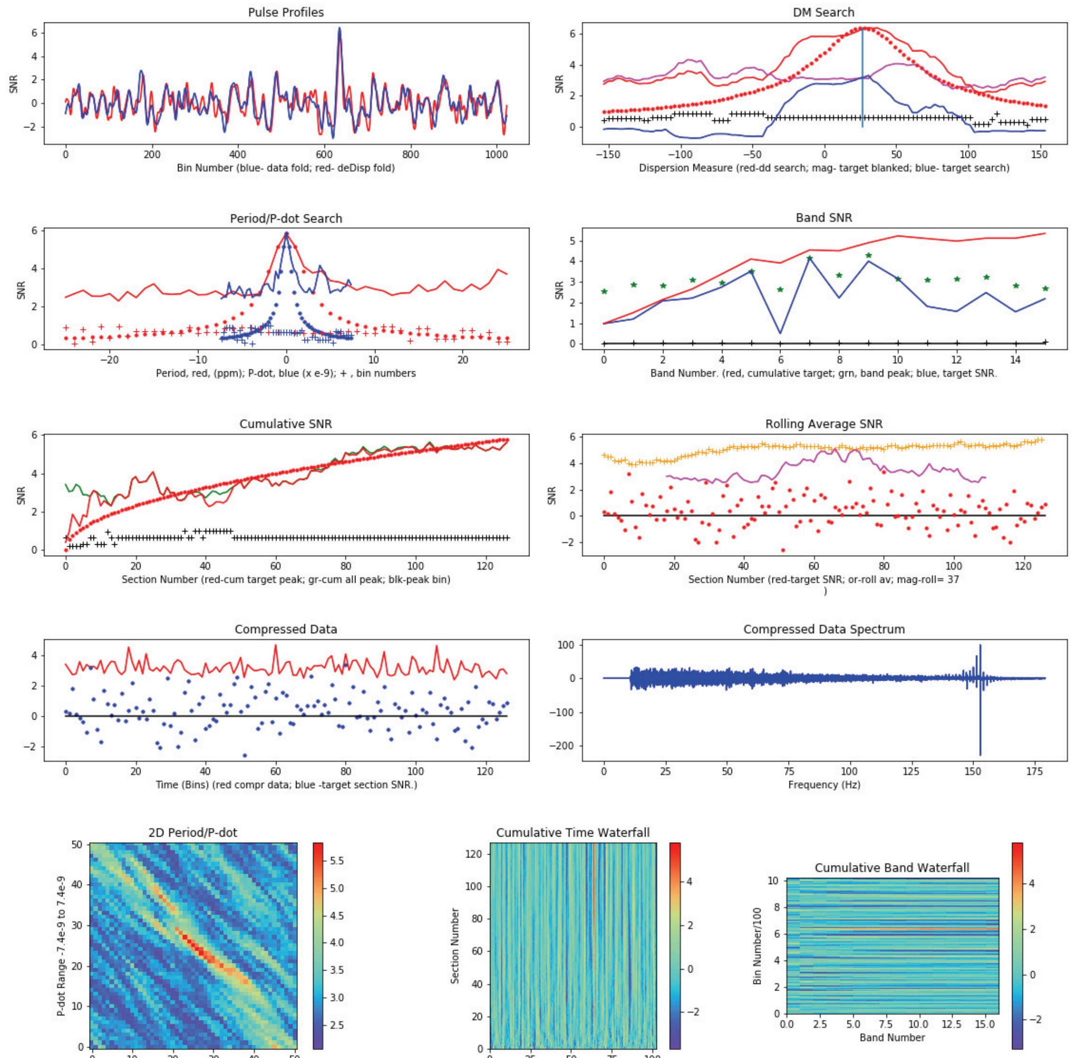

Figure 11. Validation Processing Chart - Original Data Sections 32 to 68

Figure 11 shows a collection of PRESTO-inspired data plots assembled with Python graphics. Working from top to bottom, left to right, pulsar properties confirmed in the sub-plots are,

1. *Pulse Profiles* - Correct period and pulse width, matching pulse train.
2. *DM Search* - Correct Dispersion Measure, extra-terrestrial source.
3. *Period/P-dot Search* - Peaks at zero offsets, Accurate period, highly stable period.
4 *Band SNR* - Regular pulse train, Wide-band source, SNR growth, Frequency scintillation.

5. Cumulative SNR - Regular pulse train, Pulse SNR time growth, Scintillation.
6. Rolling Average SNR - Scintillation, Pulsed source, Beam shape - extra terrestrial.
7. Compressed Data - Noise-like data peaks, Minimal RFI or spikes (with much higher SNR pulsar pulse visibility is possible). Section target SNR scintillation.
8. Compressed Data Spectrum - Some RFI ~ 150Hz (with high SNR, pulsar spectral lines visibility is possible).
9. 2D-*Period/P-dot* Plot- Complementary period/P-dot properties, -45°central ridge expected, No ambiguity.
10. Data Waterfall - SNR growth, Regular pulse train.
11. Band Waterfall - Wide-band source, SNR growth.
In summary all sub-plots confirm the expected properties of PSR B0329+54.

Concluding Comments

Detecting and identifying pulsar signals with modest equipment is no easy task. This article has sought to identify and separate the various differentiating properties of pulsar pulse trains, noise and RFI. Some standard and new data processing schemes have been described to help with positive identification, the most convincing are those that better prove an extra-terrestrial source. The most compelling is identifying the correct dispersion; dispersion and scintillation in time and frequency being caused by interaction with free electrons along the inter-stellar path. Monitoring the signal increasing and fading as the source drifts in and out of the antenna beam is encouraging.
The cumulative SNR and rolling section averaging approaches applied to both synchronized compressed sections and frequency bands has proved very fast and useful for identifying very weak pulsar pulse trains in recorded data. Using the SNR statistic for examining data recordings extends the scope of pulsar data analysis and verification to much lower peak SNR levels. Dividing the data into many synchronous sections as a data compression approach conveniently reduces the data investigation and optimisation time to provide results similar to PRESTO as presented by the Python graphics.
Finally, back garden pulsar hunting is challenging, many trials may be disappointing but eventually being able to see a true pulsar signal grow out of noise brings its own reward.

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