Is it a Pulsar? The Case of the Oil Drum Antenna

Peter East (UK) and Michiel Klaassen (Netherlands)

Introduction

Is it a pulsar? Is it RFI? Is it noise?

This article resolves this conundrum by carrying out a comprehensive process of validating data collected using a novel oil drum antenna and RTL2832U hardware. The set-up appeared to find a pulsar in an 8.7 minute section of a one hour data recording. Even the most sanguine would be forgiven for doubting this feat but the results can speak for themselves. The standard model for confidently recognizing a target pulsar is to use or emulate the PRESTO analysis software. This employs fast statistical techniques on strong intercepts to rapidly sort data, remove radio frequency interference (RFI) sections and present a display of some key pulsar feature tests. Successful operation on weak signals is rare without manual intervention. At intermediate pulsar levels, where the integrated signal-to-noise ratio (SNR) is between 6:1 and 10:1, amateurs adapt some of these tests. Specifically, period search and dispersion peak amplitude search. Providing conforming peak responses are found and a fair folded pulse display is produced, then the site detection ability is recognized. Analytical techniques are used here to extend these basic tests, aiming at detecting pulsar acquisition at much lower SNRs to corroborate weak signal intercepts. To do this, the detailed characteristics of the standard search processes are exploited as they react differently to the properties of pulsars, RFI and noise. During a 1 hour recorded observation in Ede, Netherlands on 03 September 2020 at 0430 UTC, a strong detection of pulsar B0329+54 in a short data section was discovered that exceeded a signal-to-noise ratio (SNR) of 5:1. This article investigates and validates this result which was first reported in the SARA Forum[(1)].

Catching Pulsars with and Oil Drum - SARA Forum Conversation by Michiel Klaassen[(1)]

The next two months I will be doing experiments in other places. I do not want to wait two months and perform more tests to confirm what I measured yesterday (with only one test), so that is why I describe it now.

The town and the neighborhood I live in is engulfed in RFI, and still I wanted to try to capture a pulsar. To solve that, your antenna must be shielded from the surrounding RFI. An open dipole is out of the question but a better solution is to use a Can type feed. The actual antenna probe is positioned deep into the Can, and could be shielded even more by increasing the length of the tube. I used a simple can feed[(2)].

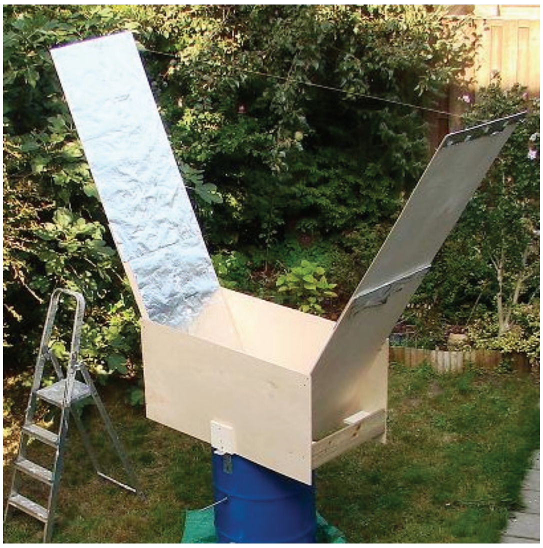


Figure 1a. The Oil Drum Antenna

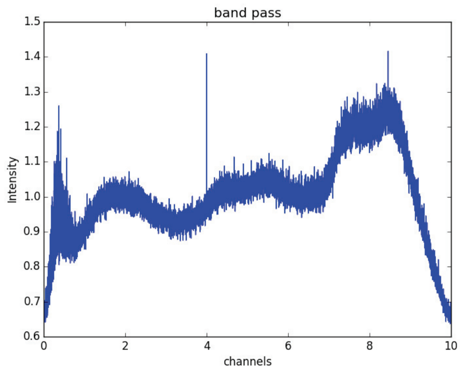


Figure 1b. Low RFI 461MHz Band

But now I wanted to measure on 430MHz, because pulsar signals are strongest on low frequencies. When you do the calculations you get dimensions like 60cm diameter and 86 cm high. Well; that is the dimension of an oil drum. So, I bought a used oil drum (20 euro, used for chocolate). I used my Can calculation excel sheet[2]. The probe was mounted on the right spot. Now I scanned the spectrum from 300 to 500MHz and found a least RFI free place at 461MHz (Figure 1b). Next I trimmed the length of the probe, but also I added an extra rod 1/4 tube lambda up from the probe. This rod can be shifted in and out, and then fixed. I used compression fitting for that with a diameter of 10mm. The probe itself is also 10mm diameter. The fine tuning for lowest return loss can be done easily now. In fact the drum now is a tuned waveguide[3]. Next I mounted thin plywood plates to the sides as can be seen in the picture, Figure 1a. Total height is 3m and the aperture also is about 3m.
The multiplex plates were covered with kitchen aluminium foil. (I had to re-adjust the trim rod of course).

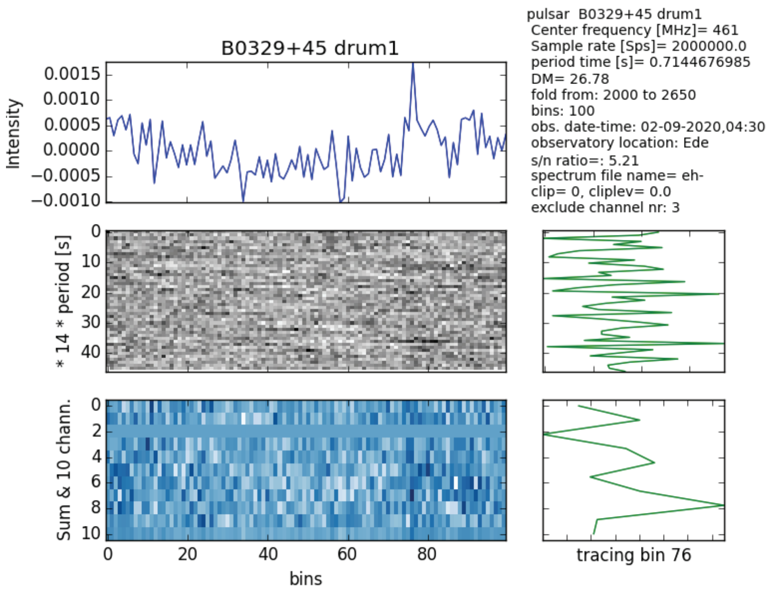


Figure 2. 3pt Software[4] Analysis Result

I have only done one measurement using the method. The software tools I used can be downloaded from Reference 4. In the time image and in the frequency image of the multiplot (Figure 2) you can see vertical dark bands; showing the pulsar is there over time and over bandwidth. Perhaps other people want to try this method also?

Evaluation Prerequisites

The very first question to answer is, "Has this antenna/receiver system sufficient collecting aperture and sensitivity to detect the pulsar of interest?" Using an RTL2832U software defined radio (SDR), a test measurement can always be made once the antenna has been chosen.
The recorded data from an RTL SDR comprises 8-bit digital in-phase and quadrature (I/Q) samples sampled at the RTL clock rate $1/t_c$ (= Δf).
A block analogue representation of the antenna/receiver and digital square-law detection process following a software defined radio (SDR) is shown in Figure 3.
The data sample amplitudes ($I^2 + Q^2$) contain both DC and AC components; initially, both of these DC and AC components are proportional to T_{sys} (powers ≈ $kT_{sys}\,\Delta f$).
The RTL data processing software, first needs to offset the 8-bit data word to zero-mean the I/Q data. Secondly it detects and downsamples the data, effectively low-pass filtering (LPF) usually by data series averaging. The AC noise component power is reduced to

$kT_{sys}\sqrt{\Delta f\, \Delta lpf}$, where Δlpf ($\rightarrow 1/t_{int}$) is the effective low-pass filter cut-off frequency. For block averaging of *N* samples, $\Delta f \rightarrow 1/Nt_c$.

In the presence of a pulsar pulse T_{sys} increases by T_p - the pulsar peak equivalent temperature. The pulsar DC contribution sits on the system noise DC component and it is the difference between these components that is of interest.

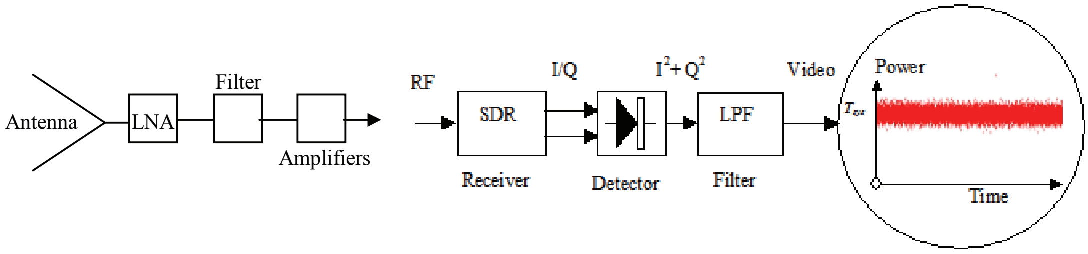


Figure 3. Raw Data Analogue-equivalent Collection/Detection Process.

The Figure 3 oscilloscope display illustrates a 30 minute section of real B0329 system data downsampled to 1ksps. The noise rms level here is approximately equivalent to 2°K and usually buried within this are possible pulsar pulses.

Describing the detected system AC noise signal by $v_n(t)$ and the pulsar DC level by $v_p(t)$ - the pulsar AC component can usually be ignored compared to T_{sys} - then the equivalent pulsar input signal-to-noise ratio (SNR) is, $SNR_{in} = \overline{v_p^2(t)}/\overline{v_n^2(t)} = T_p/T_{sys}$.

Estimating system temperature sensitivity

Two key facts can be drawn from the description and analysis above,

1. The noise mean level V_{mean} in the oscilloscope display of Figure 3, labeled as T_{sys} is in fact a direct measure of the system true noise temperature when the antenna is pointed to a quiet space in the sky. It includes sky noise, ground noise, antenna receiver mismatch and line attenuation etc:.
2. The standard deviation (sometimes called rms (root mean square) about the mean) is a measure of the AC noise reduced due to filtering, averaging, downsampling or folding (rms_{fold}). This assumes no gain or losses in the process.

Coupling these two facts together an estimate of the receiver minimum temperature sensitivity is given by,

$$\Delta T_{rms} = \frac{rms_{fold}}{V_{mean}} T_{sys} \qquad (1)$$

For example, if T_{sys} = 150°K and the corresponding measured V_{mean} is 0.1V and folded noise rms voltage is measured as 10^{-5} V, then the equivalent rms noise temperature sensitivity is 0.015°K.

Now a reduction of 10,000 may seem a lot but remembering the radiometer equation integration factor $\sqrt{t_{int}\Delta f / N}$, applying this for 1.5 hours of observation with a 2MHz RTL and an optimum number of bins (108 for B0329) folding, is sufficient to meet this figure.

Estimating received pulsar equivalent temperature

The next figure to estimate is the received equivalent temperature of the pulsar.

Pulsar signal power is usually expressed in Janskys (Jy); the received source power corresponding to 1Jy = 10^{-26}Watts/m^2/Hz.

The equivalent received pulsar power in terms of Boltzmann's constant, k and effective temperature is $kT_p \Delta f$ Watts, where k = 1.38. 10^{-23}Watts/°K/Hz; T_p is measured in °K and again, Δf is the RF bandwidth in Hz.
Equating the powers in these expressions,

$$Jp\,A\ \Delta f\ .10^{-26}\ =\ 1.38\ .10^{-23} T_p\ \Delta f \text{ Watts, or, } Jp\,A\ =\ 1380 T_p$$

where A, is the receiver antenna effective collecting area (m^2).

Rearranging this equality, we get,

$$T_p = J_P\,A/1380\ °K \qquad (2)$$

As an example, for an effective $1m^2$ aperture antenna, for B0329 at 400MHz the sky pulsar peak power/polarization is J_P = 81Jy, giving an equivalent measured pulsar temperature of 0.06 °K. Combining this figure with the result of the above integration sensitivity example, then on average the expected SNR with a $1m^2$ aperture antenna is 0.06/0.015 = 4.0:1.
Not a large figure, but within an amateurs target range.

Data Analysis Results of the 8.7 minute strong section
Total record duration = 5014 periods (~1 hour) ; Active strong section periods: 1915 to 2647.
RTL detected data mean measured = 0.119V.
Folded (strong 8.7min section) noise data rms measured = 3.18 x 10^{-5} V
Estimated rms temperature sensitivity (*Tsys* = 150 °K assumed)

= 150 °K x 3.18 x 10^{-5} / 0.119 = 0.04 °K

For comparison the analysis above showed that for a $1m^2$ aperture an integrated pulsar on average would be expected to be around 0.06 °K peak, now, producing an average SNR of 1.5:1. On this basis, it is not unreasonable to anticipate positive scintillation of 3 to 4 times the mean value catalogued allowing the fortuitous result observed!

Validating Tests
Validating that a true pulsar response is present in data collected by amateurs is important as, with a bit of data phasing, it allows us to combine records from several days trials.
For low SNRs <5:1, these are regarded as all or nothing. A true pulsar will pass all these tests.

Validating Test Sequence	Description
1. Correct period –TEMPO/GPS/Rubidium disciplined oscillator.	Depending on SDR clock rate accuracy ensure period within expected ppm tolerance
2. Check pulse width.	Folding and convolving makes all noise peaks similar but pulse amplitude can be optimized by varying the target pulse width.
3. Two/multiple-section fold correlation.	Split data into two or more sections and fold checking response is consistent over multiple sections
4. Twin/multiple-period fold correlation.	Sum twin/multiple-period fold sections ensuring response consistent in each period.
5. Multi-band correlation.	Fold separate bands and check correlating responses in each band.
6. Period search peak – profile, offset and pulse width	Fold, changing the period by several ppm. Check amplitude and position/pulse width responses conform to theory
7. P-dot search peak – profile, offset and pulse width	Fold, changing the period rate in ppm/period. Check amplitude reduction and peak position/pulse width responses conform to theory
8. Dispersion search peak – profile, offset and pulse width	Change the de-dispersion about the expected value and check amplitude reduction, peak position and pulse width change with theory

Table 1. Validation Gate Checks

Professional software, such as PRESTO can be used on low SNR pulsar data as it allows a lot of manual manipulation of data to remove interference and bad data sections. However once the integrated pulsar data gets below 4:1 this analysis path gets more difficult.
The Table 1 above lists some validating tests compiled by amateurs where software is available. All these tests are employed on the present data and discussed below.
Tests 3, and 4 check the pulsar continuous pulse repetition property. The tests are relatively insensitive to pulse dropout due to scintillation etc: and are regarded with tests 1 and 2 as an initial confidence builder.
Test 5 with hardware bands or FFT channels the test is stronger and often aids in identifying RFI frequencies to block. Correlating folded responses are expected in all bands even under scintillation conditions and long observation times. Checks pulsar broad band nature.
Tests 6 and 7 are highlighted in PRESTO plots. Here automatic period search and period-rate searches are carried out and simultaneous positive peaks are anticipated at the correct pulsar period and at zero period-rate. Period-rate checks that there is no period drift over the observation time - taking advantage of the high timing accuracy of pulsars. Normally, if there is any period drift, it would indicate a non-pulsar source and would be evident from an increase in pulse width over that expected. Detailed analysis shows that with both period search and period-rate search, that the pulsar peak in the folded output shifts a predictable amount as does the indicated pulse width. These properties are not shared consistently by folded noise peaks.
***Test 8*,** dispersion is probably the strongest identifier, especially if the amplitude and pulsar peak position is plotted over a range of dispersion measures (DM). Whilst noise and man-made RFI are affected by de-dispersion, they do not follow the pulsar predicted pattern. As with period search, depending how data dispersion is effected, the pulse peak amplitude, peak position and width vary predictably and are easily tracked.

Radio Frequency Interference
Most validation checks largely respond to a consistent pulse train at the correct period and cope with expected scintillation but show different characteristics with most RFI types. Figure 1b shows that a reasonably clear band was apparent in this instance and investigation of the spectrum and amplitude response of the detected video data confirms this as shown in Figure 4, with and without minor clipping.

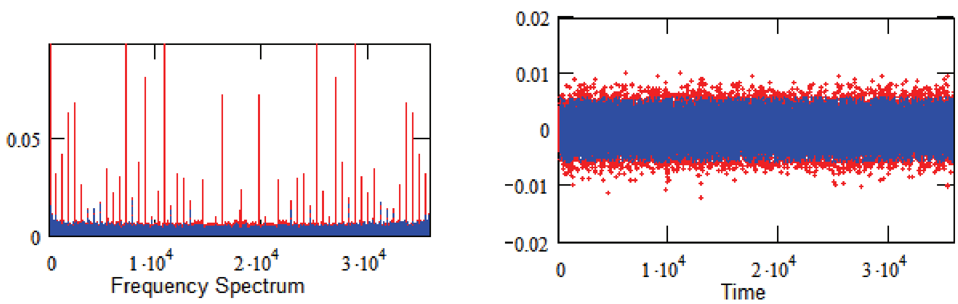


Figure 4. Video Spectrum and Amplitude Responses, red: raw data; blue: after clipping

The folding algorithm copes very well with narrow spectral lines and the small amplitude deviations apparent in Figure 4. Measurements show that with the clipping indicated the SNR only improved from 5.6:1 to 5.7:1. It is clear this early morning test was in a benign RFI environment. Motor ignition and electrical transients are rarely periodically consistent and if relatively infrequent are sometimes removed by amplitude or time clipping. Other man-made RFI including digital TV and mobile transmissions can be differentiated and removed spectrally but at high level can cause serious pulsar signal suppression and obscuration. Lack of success due to this cause is usually obvious. In the present instance, it was further

checked that binary limiting of the detected data prior to folding made very little difference to the final folded result apart from the expected slight SNR reduction.
When folding long data records containing a large number of data periods, the folding algorithm becomes highly frequency selective and the residual folded RFI and 'noise' is no longer random but comprises a sum of many noise components, all at the pulsar frequency but with random phases. This is one reason that spectrum analysis techniques[6] are not as effective as time series folding analyses. Gaussian noise peaks are not as consistent as pulsar responses, but be aware that once folded, certain features can persist over a period search range and then appear pulse-like and possibly be mistaken for pulses. Residual noise components may also cause amplitude and timing uncertainties in period search tests - more so at low pulsar SNRs.
In situations of strong sporadic impulsive RFI that cannot be nulled or blanked, its presence will be evident and seriously affect the folded result probably obscuring any good data so are best rejected.

Validation Test Results on Strong Data Section

1. ***Tests 1,2 - Period and pulse width***

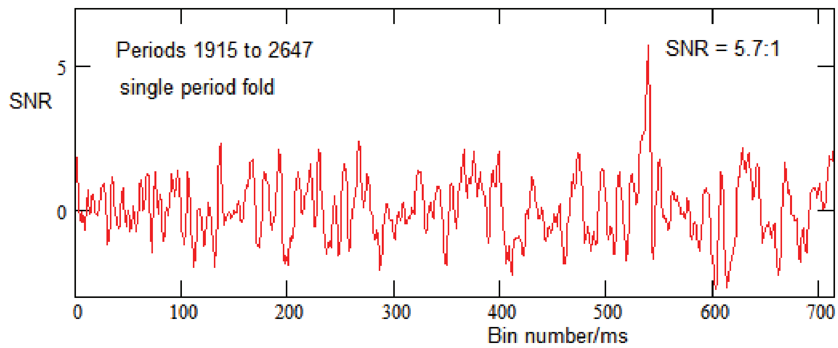


Figure 5 Final folded result for strong 8.7 minute section; peak is at bin 538

Figure 5 plots the matched-filter fold when the period search value matches the pulsar TEMPO topocentric period within -5.3 ppm. The peak bin position is dependant upon the pulsar phase at the beginning of the data record. For ease of measurement the number of fold bins is set equal to 714 to closely match the pulsar period and so conveniently the bin value is roughly equal to milliseconds in time. It is then easy to check that the indicated pulse half-height width matches the expected 6.5 ms ±0.5ms.

2. Tests 3,4 - Multi-section, Multi-period fold

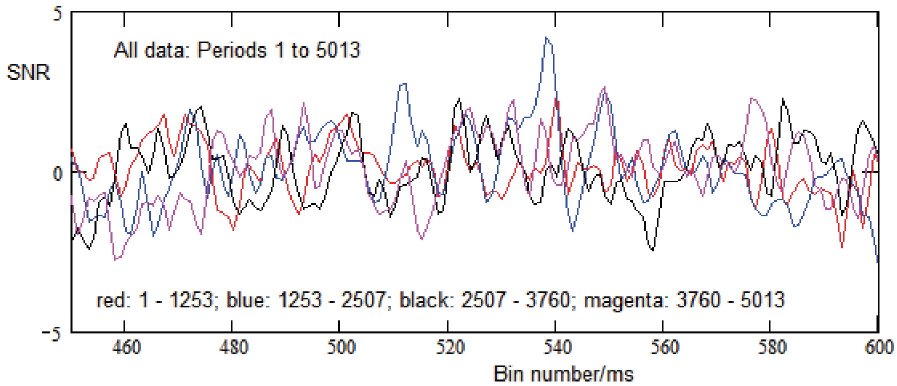


Figure 6 Folded results whole file split into 4 equal sections.
(note that all sections show a maximum in the correct region around bin 538)

Figure 6 indicates that pulsar maxima, two medium value, one large and one small, do appear in all 4 sections of the complete record and are present within an acceptable range of the expected bin. When folding the whole file the sum peak at bin 538 indicated an SNR of 2.7:1. This shows clearly that it is not always prudent to fold complete files. A certain amount of pulsar amplitude variation due to path scintillation is expected and usually in a data recording, but it is generally assumed that a sufficient proportion of strong responses will be present to ensure cumulative addition. In this case, it appears that in the full record, this did not happen but a good response was found from checking file sections. Note, It is easy to show that when combining discrete sets of data at different SNRs that the direction of the final SNR is controlled by the smallest components. For this reason, it is sometimes better, as in this case, to fold the data in sections and positively select the stronger ranges.

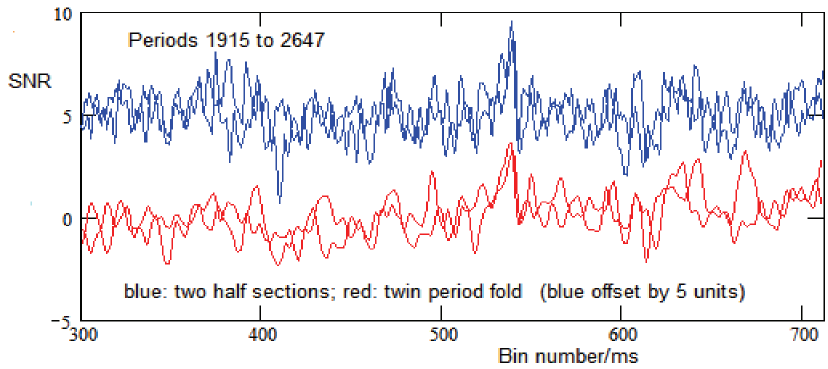


Figure 7 Folded results: strong 8.7 minute section.
(blue: strong section split in two; red: twin period fold)
Note correlation of maxima at bin 538

Figure 7 indicates that in the strong data section, periods 1915 to 2647, that significant pulsar pulses are common on the expected pulsar pulse repetition grid. The rough equality of these half data fold peaks show that the pulsar power was reasonably high throughout this section. Note the partial de-correlation of the folded noise in half data folds[7].

3. Test 5. - Band Correlation

To check the broad band nature expected of a pulsar, the strong data section was split into 4 bands using the Fourier Transform. The results for each band is shown in Figure 8.

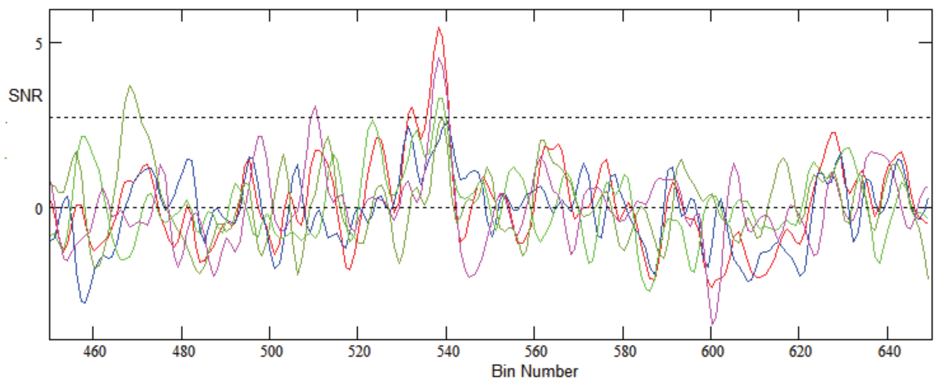
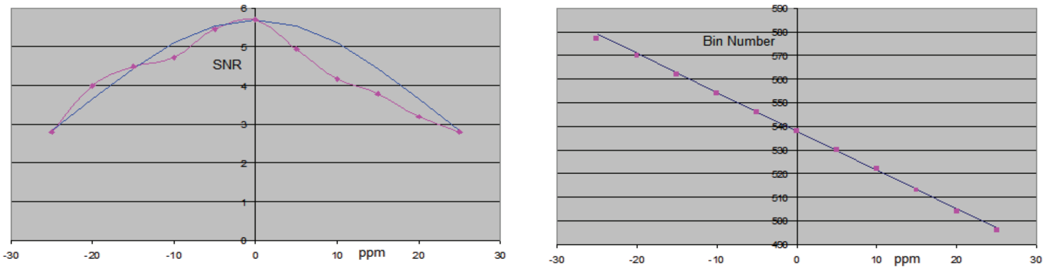


Figure 8 Folded results of 4 sub-bands.
red: all bands combined; blue: band 1; green: band 2; magenta: band 3 brown: band 4
Note band maxima at bin 538, Bands divided equally. Dotted lines at zero and 4-band expected average SNR

All bands show a maximum in the expected region of bin 538, the weakest being band 4 and this might be expected when referring to the full band response in Figure 1b. No attempt was made at flattening the band here, but this is a feature of the 3pt tools[4].

4. Test 6. - Period Search[(5)]



Period search - peak amplitude change

Period search - pulse peak bin shift

Figure 9. Period Search amplitude and position shift compared to theory

Figure 9 summarizes the result of changing the folding search period in steps of 5 parts per million (ppm). As predicted, in the left-hand plot the pulsar amplitude peaks at the correct period and falls away (red points)as the search period is varied. The blue curve is the theoretically predicted curve and depends on the strong response position within the total data record, its duration and the value of the period change. The peak bin shift is given by, $p(T_1 + T_2)/2$, where *p* is the search period change in ppm and T_1 and T_2 are the times in seconds relative to the file start of the start and end of the strong response data section. This combined feature is a fairly strong indicator of a true pulsar presence. In addition to the peak amplitude changing. there is also a predictable shift in the peak bin value and the pulse width. Bin shift is plotted in the right hand plot, again red points are measured values and the blue line the predicted peak bin path. The new pulse width is approximately $p(T_1 + T_2)$. At low SNRs, pulse width measurement accuracy can be affected by the underlying noise, but pulse broadening off the ideal period value is easily confirmed.

5. Test 7. - Period-Rate Search[(5)]

Figure 10 clearly shows the expected amplitude roll-off and phase shift peaking at zero P-dot, demonstrating a stable pulse repetition period and that there is no visible period drift; an expected characteristic of a pulsar rather than modulated digital RFI.

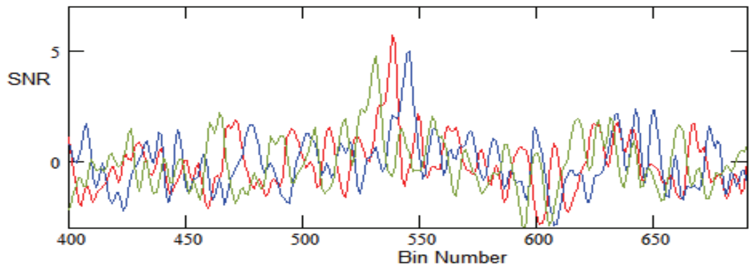


Figure 10. Period Rate Search ±20/P/10^{10} amplitude and position shift cv theory.

6. Test 8 - Dispersion[(5)]

Broadband pulsar noise propagating the interstellar medium interacts with free electrons to lower its group velocity, effectively delaying the lower frequency components. For a given pulsar radio frequency and RF band, it is convenient to describe the band dispersion as the ratio, *D/PW* , where *D* is the total dispersion in ms and *PW* is the pulsar 50% pulse width in ms. For the RF band and receiver bandwidth chosen, *D/PW* is calculated from,

$$D / PW = 8.3.10^6 \left(\frac{\Delta f}{f_0^3} \right) \frac{DM}{PW} \qquad (3)$$

where, f_0 is the RF band center frequency, Δf the RF bandwidth in MHz.
DM is the catalogued pulsar dispersion measure (= 26.7 for B0329+54).

In this oil drum antenna case, $\Delta f = 2MHz,\ f_0 = 461MHz$, then *D* = 4.5ms and *D/PW* = 0.7.

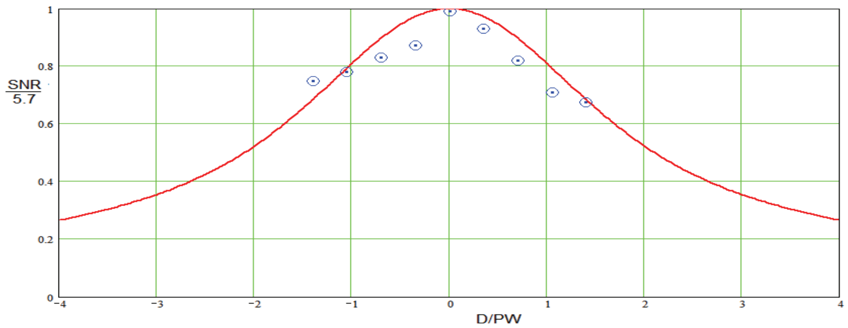


Figure 11 Dispersion Search red: theory; blue: measurements
at D/PW = 0, DM = 26.7

Figure 11 demonstrates the effect on the observed pulsar folded amplitude as a function of the mismatched dispersion in units of *D/PW*. A de-dispersion rate search profiling the shape of Figure 11 together with the theoretical pulse width is a very strong true pulsar verification test. Pulse maxima are plotted as blue dots in Figure 11 showing a very good match to theory (accuracy limited by the underlying noise). There appears some mirror symmetry in the example plots of Figure 12 with *D/PW* = 0 and ±0.7, which may result from a distorted pulsar spectrum (dominated by band 3 - see test 5 above). The measured peak shifts in Figure 12 are -(±2) ms, whereas for a flat spectrum, -(±2.27) ms (-(±D/2)) is expected. For the larger dispersion mismatches, as predicted, proportional peak shifts and pulse width increases were evident (at D/W = ±2, the pulse amplitude is halved (see Figure 5) and the width doubled)[5].

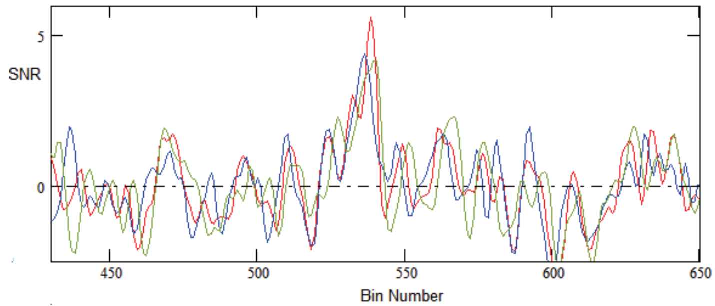


Figure 12. Dispersion mismatch - red: *D/PW* = 0; (correctly de-dispersed)
brown: *D/PW*= -0.7; blue: *D/PW* = +0.7

Note, It is well recognized that a positive indication of dispersion is the strongest indicator that the signal investigated has traversed a path though inter-stellar space and definite indicator if it matches the dispersion measure known for the target source.

Conclusions

The comprehensive tests carried out on the data discussed above confirm the presence of a valid signal from the B0329+54 pulsar in a short section of the data file collected with the oil drum system. It is remarkable that this home-made antenna and receiver was able to collect a recognizable signal over the very short integration period of 8.7 minutes. The sensitivity analysis has shown that the radio telescope design, with the antenna assumptions made, has a sensitivity close to that required for a successful detection of B0329 in good scintillation conditions but would normally benefit from a longer integration time. The calculations made suggest that fortuitously, an unusually strongly scintillating signal may have been received for a short time during this data collection trial. The RFI environment was relatively benign, possibly aided by oil drum shielding and the trial occurring in the electrically quiet nighttime hours. All validation tests produced positive results. The dispersion test is the strongest indicator and confirms a signal from an extraterrestrial source but the close conformance to the underlying theory of the period search and period-rate search tests, are very supportive. The channelized spectrum test confirmed intercept of energy throughout the 2MHz RF band as should be expected of a broad band noise source. The folding tests indicated presence of a continuous pulse train at the correct pulsar pulse repetition rate and pulse width within the identified section. The RTL SDR clock error of only -5.3 ppm was also a positive accuracy indicator for the pulsar topocentric period. This set of validation tests have also been proved to confirm detection and recognition of pulsar pulses embedded in noise at much lower levels than in this case. Although the folded power was insufficient to give a convincing response when the whole file was processed (indicated SNR peak = 2.7:1 found with hindsight!), it was interesting that the strong data section was so easily discovered with the Klaassen 3pt tools[4] and keen amateurs could well-benefit from their use. With a pulsar response SNR of nearly 6:1, clearly dispersed in space, one can be pretty confident that this is a successful result, but because of vagaries of scintillation and local sporadic RFI, don't expect good results every time.

Postscript

Interested amateurs must not be put off by the painful detail the authors have gone through to prove detecting the B0329 pulsar in this case. Remember, this result was achieved on the day of the observation using the Klaassen 3pt tool[4] with the RTL SDR. This was indeed a special case with an unusual antenna and a startlingly short strong data sequence. Bearing in mind the difficulties some have had in getting good results, there was bound to be some skepticism. The good news is that once you have proven your installation to yourself and prepared to accept a few bad days, with a bit of ingenuity, pulsar detection is open to all. The moral is, you don't always get the best results by folding all the data all of the time!

References.

1. Klaassen. M. SARA Forum, September 3 2020, https://groups.google.com/g/sara-list/c/SrH5qA0yoFI
2. Klaassen. M. http://parac.eu/projectmk9.htm
3. Klaassen. M. See Google "tune waveguide" https://en.wikipedia.org/wiki/Waveguide_filter
4. Klaassen. M. http://parac.eu/projectmk17b.htm
5. East PW. An Analytical Method of Recognizing Pulsars at Moderate SNR. Journal of the Society of Amateur Radio Astronomers. November-December 2018.
6. East PW. Spectrum Techniques for Improving Low SNR Pulsar Detection. Journal of the Society of Amateur Radio Astronomers. March-April 2019.
7. East PW. A Correlation Method for Low SNR Pulsar Search and Recognition. Journal of the Society of Amateur Radio Astronomers. July-August 2019.

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*

Michiel Klaassen BSc, is a retired electronics and telecom design engineer of Kipp laboratory equipment, Siemens telecommunication systems and GPS TT equipment. His interest in RA dates back to 1966 when he designed equipment for, and performed measurements with a 7.5m Wurzburg radio telescope at a public astronomical observatory in the Netherlands. He is a member of the Dutch CAMRAS Dwingeloo group. He has built a 10m diameter radio telescope in Portugal; *https://en.wikipedia.org/wiki/S%C3%A3o_Gi%C3%A3o_Radio_Telescope* He developed windows software tools like CFRAD2 for spectral measurements (H1, masers) and 3PT for pulsar post processing. He can be contacted via his RA website www.parac.eu. M.A.Klaassen October 2020