How to Catch a Pulsar in a small backyard

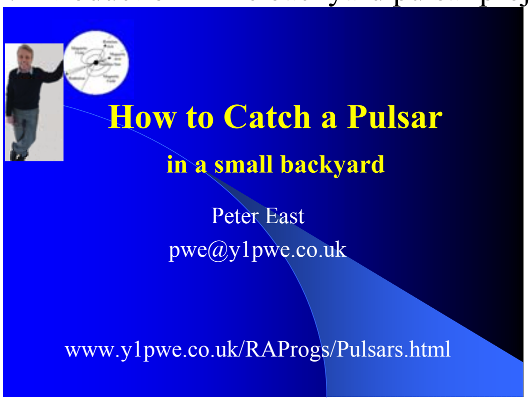
Peter W East

Abstract

The strongest pulsar in the northern hemisphere is B0329+54. The main pulsar characteristics are very accurate pulse timing and broadband noise transmission; the energy scintillates and is dispersed in frequency. Pulsars are one of the weakest radio sources but their published characteristics are freely available to aid amateur search. Pulse period-matched integration is the most effective technique to recover a pulsar from galactic and receiver noise plus possibly some minor local interference. There is good availability of hardware to construct a backyard radio telescope and free software to collect and process the data. There is still scope for amateurs to further process the data to better confirm detection; a technique investigated here, exploits the random scintillation property to improve signal confidence.

The methods are illustrated based on observations of pulsar B0329+54 with a 1.5m^2 twin Yagi antenna at 611MHz and 10MHz Airspy R2 SDR.

1. Introduction - The backyard pulsar project



The full title is how to catch a pulsar in a small backyard.

Professor Jocelyn Bell-Burnell, discovered pulsars 58 years ago but it took nearly 50 years before amateurs got into the act.

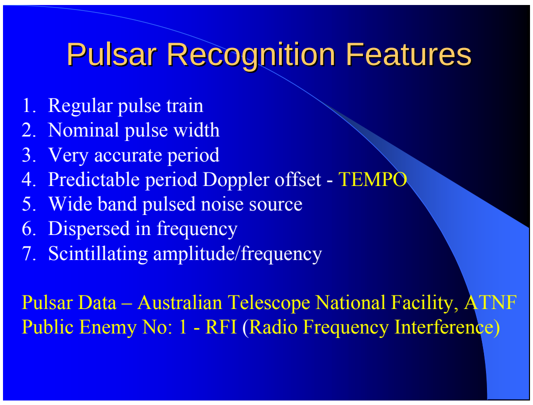
It was only possible then because of the availability of cheap extremely low noise RF amplifiers using high electron mobility transistors invented by Mimura[1] and the conversion of Digital TV dongles into software defined radios, pioneered by Osmocom[2].

The brightest pulsar in the Northern Hemisphere is B0329+54 at about 6000 light years away and today at this latitude is almost overhead at about 4 o'clock in the morning and transits within a 30 degree antenna beam for about 3 hours.

After describing pulsar signal characteristics and explaining why they are difficult to detect. We look at how to build a receiver for pulsars, how to collect and process data using free software developed by both amateurs and professionals and finally to show that with a bit of Python programming knowledge there is still plenty of scope for amateurs to derive more detail to better validate detection.

The internet links in the slides are duplicated in the pulsar starter guide handout[3], which is also downloadable on the EUCARA25 website[4].

2. Pulsar Recognition



This slide lists the main pulsar signal properties.

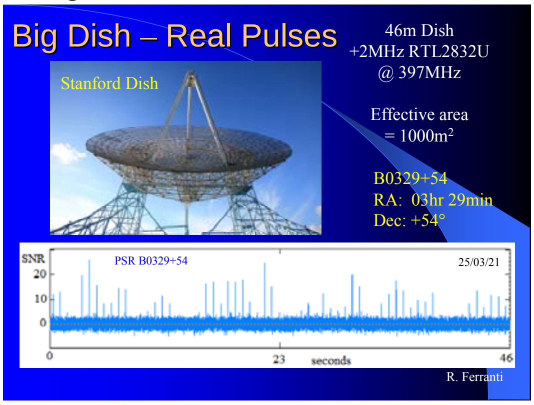
We need to confirm that of all of these are present for true detection verification.

Pulses arrive with atomic clock accuracy on a continuous pulse train grid.

But due relative motion of the pulsar and earth rotations in the solar system, the measured period is Doppler shifted but this is predictable and free TEMPO

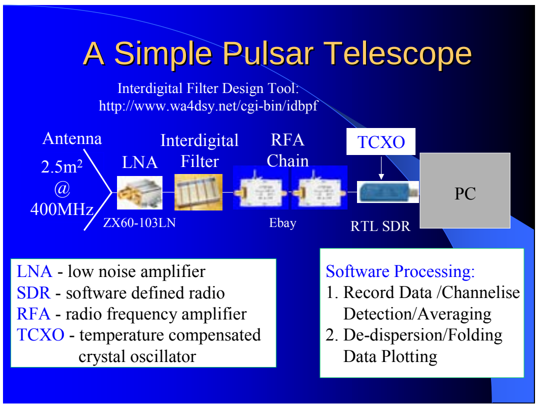
software is available to calculate the expected period given the observation date/time and telescope latitude and longitude.
Pulsars emit wide band noise with more power radiated at low frequencies.
Their emissions are dispersed in frequency, meaning that low frequencies are delayed more than high frequencies due to interaction with free electrons in the path.
Each pulsar has a characteristic Dispersion Measure which allows the dispersion with RF and bandwidth to be corrected. It is a strong indicator of a true pulsar acquisition.
Another feature of the path anomaly is that the received pulse amplitude scintillates randomly caused by refraction in the interstellar medium.
We have advance knowledge of all these parameters, from the Australian Telescope National Facility data base which holds about 4000 pulsar entries to date.
Our enemy is radio frequency interference, RFI, which can come in many forms.
Nighttime is the quietest time to make measurements.

3. Big Dish - Pulses



For guaranteed success in pulsar detection you can't beat a large dish.
This is a 46 second plot of B0329, collected by the Stanford 46m dish, at 397 MHz using an RTL2832U digital TV dongle, showing individual pulses with the characteristic random amplitude scintillation.
The peak signal to noise ratio of single largest pulses here exceeds 25:1, but many pulses are received less than 3:1 SNR typical of random noise.
For a one square metre aperture antenna, the strongest pulse would be a factor of 40 below the noise level.
The good news is that detection is still possible and I will explain how later.

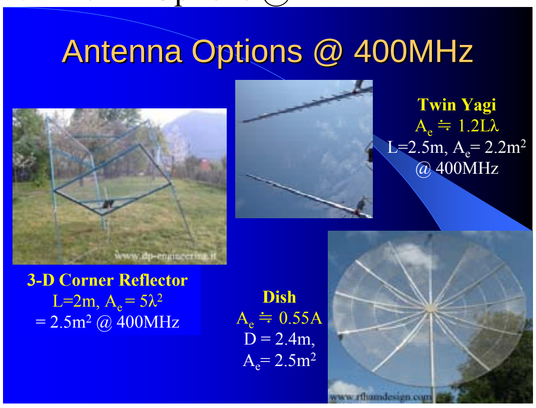
4. A Simple Pulsar Telescope



First, lets look at a starter Radio Telescope for detecting our loudest pulsar and proven to give consistent results.
The 400MHz frequency band is a good choice, Amateurs have been successful in this band as the power here is some 7 times that at the hydrogen line frequency of 1421MHz
Here, an antenna of 2.5 square metres capture area, feeds a closely coupled low noise amplifier of less than 0.5dB noise figure, a band defining filter to minimise out-of-band interference, a couple more amplifiers to raise the signal level to drive the RTL software defined radio and a Personal computer to collect and pre-process the sampled data.
I have shown a temperature controlled crystal oscillator here as it important that the SDR is accurately clocked.
The PC software processing performs the tasks of data recording and recovering the pulsar power in two stages as shown here.
A quality LNA is Minicircuits type, ZX60-103LN, with about 20dB gain and less than 0.5dB noise figure. This LNA costs about £100. Much cheaper LNAs are

available from ebay and Aliexpress, but their specifications may not be as precise but certainly are ok for later gain stages.
Once you have identified your local RFI free band you can build your filter.
This interdigital filter design tool can adapt to easily obtained aluminium bar and sheet and using copper rod for the resonators.
The digital TV dongle based on the Realtek RTL2832U is a popular SDR, since with the free driver and recording software, the dongle allows transferring the raw data samples to the host computer. The RTL2832U can be tuned from 50MHz to about 1700MHz with up to 2.5MHz bandwidth.

5. Antenna Options @ 400MHz

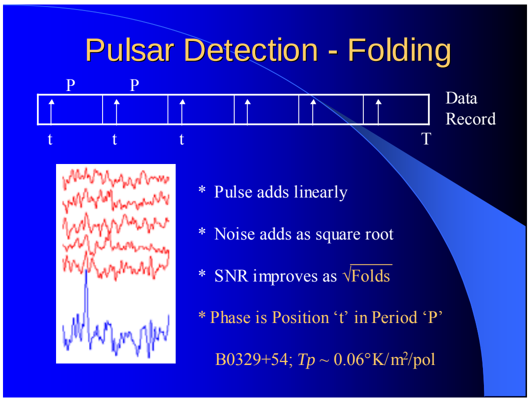


Here are some antenna options, that may be portable but also suitable for a small garden.
The 3D corner reflector is an excellent proven choice for 400MHz. It is limited to 3 wavelength sides and at 400 MHz has an effective aperture of 2.5m^2
A dish is usually preferred for larger apertures but can be inefficient for small apertures.
The Yagi is a good compromise as it is lightweight, easy to make, has an effective aperture much greater than its physical cross section, but suffers from poor sidelobe performance unless you get the design right.

6. Free Pulsar Software

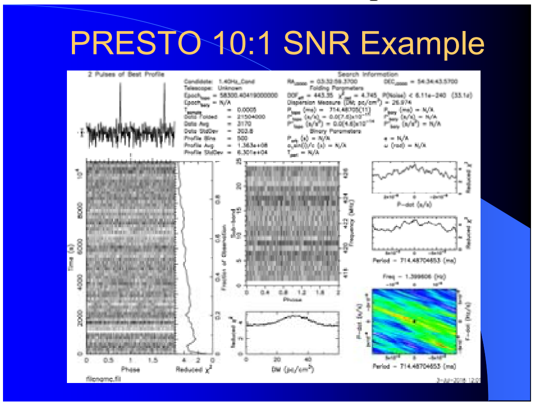
On the software side, some clever amateurs have developed software packages for data processing and display.
Michiel Klaassen's 3pt software runs in WINDOWS, takes RTL2832U data and carries out a comprehensive analysis and produces a professional Python display.
Andrea Dell'Immagine and his son Giorgio have developed pulsar recording software and guide that boots in LINUX on a USB stick.
It channelises, detects and averages the data and outputs it in the professional's filterbank format suitable for analysis by the PRESTO software.
Marcus Leech from the Canadian Centre for Experimental Radio Astronomy has developed a GNURadio pulsar package that controls a range of SDRs and outputs data in filterbank form, again for PRESTO analysis.
GNURadio is a free, easy to use, graphical package for all receiver digital signal pre-processing needs. There are both Windows and Linux versions that are well-documented.
TEMPO is essential for finding the observed pulsar rotation period at the time and place of the observation.
PRESTO is the professional's software for extracting pulsars in recorded data and this is only available for the Linux operating system but is used by most radio astronomy amateurs. The ATNF data base holds all known pulsar parameters.

7. Pulsar Detection - Folding



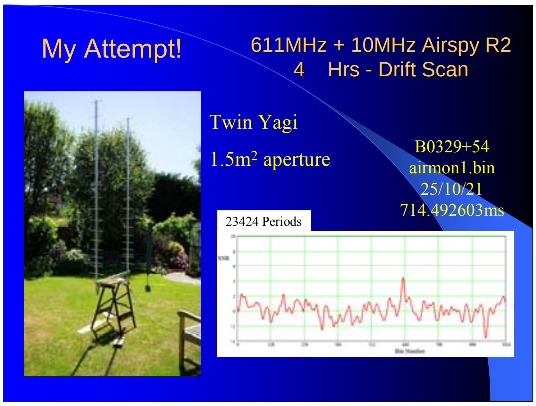
The most effective technique for recovering a weak pulsar in a long data record is called folding.
In the folding algorithm, the detected data recorded over time T, is split into blocks equal to the pulsar period P, and these are summed.
When the fold period matches the pulsar period exactly, the pulsar pulse always occurs at the same period phase and integrates linearly whilst the noise integrates power-wise.
The signal to noise ratio therefore increases as the square root of the number of folds as is shown in the inserted plot on the left of this slide.
This shows 5 aligned real pulsar periods in red and their linear sum in blue where the pulsar position is now very evident.

8. PRESTO 10:1 SNR Example



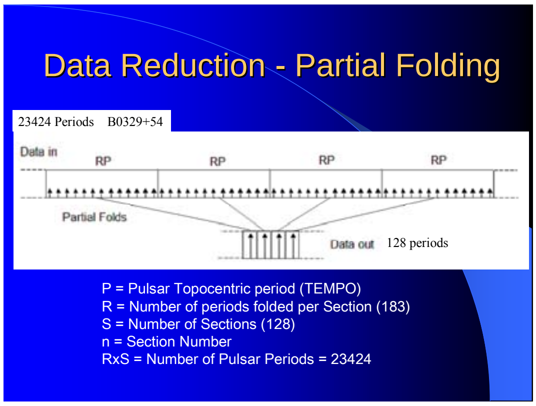
PRESTO analyses the filterbank file data and outputs a graphical format like this.
It has powerful facilities for blanking RFI, pulsar search and dispersion tracking.
It was initially developed for finding new pulsars fast in very large files but is used by most amateurs for verifying stronger pulsar detections.
This is a typical record. The top left hand corner plot is the best fold repeated.
Below it the time/amplitude waterfall, where you may just be able to see a linear track of the pulse presence. You can also pick out some horizontal bands of RFI.
The attached plot to the right, from bottom to top, is a measure of the cumulative increase in the target signal strength. It uses a variation of the fast chi square statistic for pulse detection rather than the slower more sensitive signal to noise ratio measure.
The second large plot in the center, a frequency waterfall, is pulse phase against frequency where the pulse presence appears slightly better visible.
The third set of plots on the right of the image shows the effect of changing the folding period and period rate of change. We expect peaks at the center zero in both plots signifying exact period match and zero spin down in the observation.
The bottom-right plot shows the correlation between period and period rate, and a maximum is expected at the center with a characteristic negative plot slope showing some off-tracking correlation.
The last most important bottom-center plot is the effect of varying the de-dispersion parameter, exhibiting a nice smooth peak correctly for this pulsar at around DM=27.
These results all clearly confirm and validate pulsar presence and are acceptable by all.

9. My Experimental Telescope Result



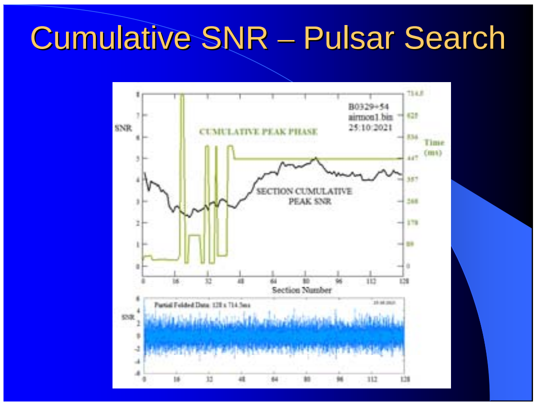
This is my effort and is the reason I have been researching validating low SNR measurements.
It uses two 17-element Yagis tuned to the 611MHz, feeding an Airspy R2 clocked at 10 MHz.
GNURadio was used to control the Airspy SDR; it channelizes the data into 16 frequency channels using the Fast Fourier transform. It also detects, the channel data, averages them and outputs the data to a standard binary file for later processing.
Eventually, all 16 frequency sub-bands are combined after de-dispersion to maximise the pulsar signal.
When the data was finally folded I achieved a signal to noise ratio of just over 4:1.
Not a good result and probably would have been rejected by PRESTO.
The 4 hour 40 minute drift-scan observation was greater than the antenna normal beamwidth dwell to ensure getting a good central response.
Because of the extended observation and scintillation, I suspected there might be a better result within the observation data so decided to investigate the data in more detail by first partially folding the data to cut down the data size and processing time.
GNURadio collected 336GB from the Airspy and reduced this by a factor of 2000 to 134MB. Partial Folding further reduces the data for faster analysis by a further 1000 to 131KB.

10. Data Reduction - Partial Folding.



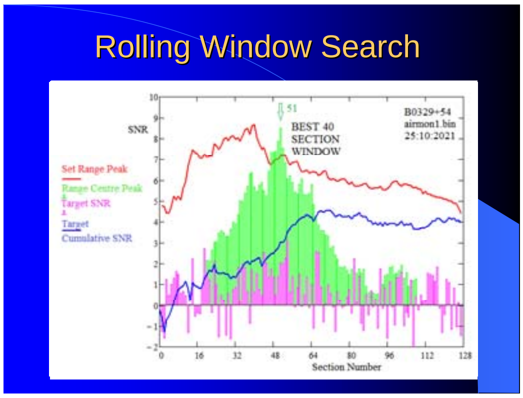
Instead of folding all the data into one period, the data is partially folded into *128 synchronous period* sections of around 183 periods each. Adding all 128 section periods in parallel gives the same result as folding all the data into one period.
We can do all the validation processes on this reduced data set much faster.
The object now is to explore the data to find which sequence of sections sums to give the best target signal to noise ratio. This is demonstrated in several stages.

11. Cumulative SNR - Pulsar Position



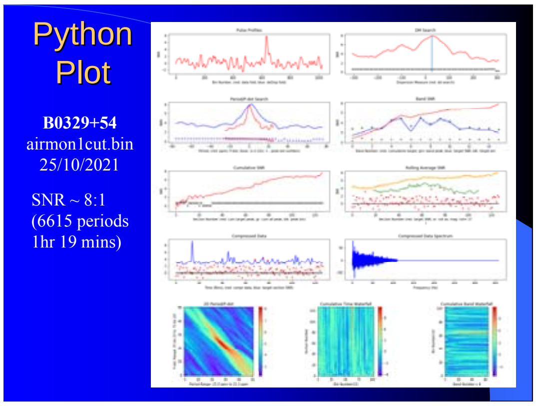
The blue plot at the bottom is the result of partially folding the 23000 pulses into just 128 periods - but still no pulsar pulses are evident.
The first stage is to find the position of the pulsar peak response within the pulsar period.
The black curve above is the signal to noise ratio of the peak observed when you cumulatively add the recorded periods.
So the value at section number 16 for instance is that of the sum of the first 16 period sections and so on.
It’s a bit inconclusive as it hangs around a SNR of about 4:1.
An important plot is the green one, as this plots on the right hand scale the position of the accumulated peak within the known 714.5 ms pulsar period.
It tends to a constant value of 444 ms after summing about 45 sections suggesting this could be the wanted pulsar.

12. Best Sequence Search



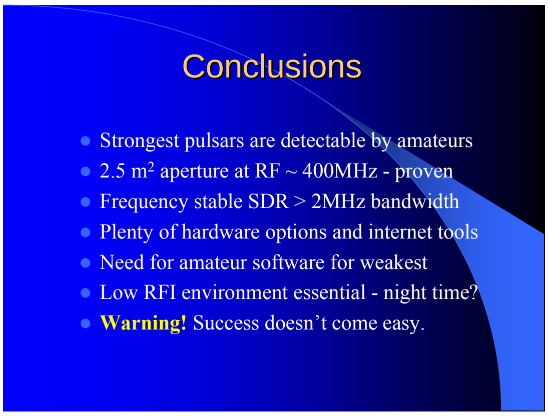
Now we know where the target pulsar is in the period frame we can find the SNR contributions of each section as this is shown in the magenta plots. They show a concentration around section number 48.
The blue plot shows the cumulative target SNR and this is interesting as it shows a significant correlated rise around section 48 not much change above section 64 although a steady fall in SNR is evident.
So how do we find the best range?
We can do this by setting a window of a set number of sections and scanning this window over the whole range and plotting the maximum value it finds.
If we do this with all possible window sizes, we get the red curve.
This shows that just using 40 sections we find the SNR peaks around 8:1
Now we only need to find which 40 sections gives us this maximum value.
So we take just 40 sections and scan these over the range, again plotting the block maximum value as we go and get this green plots which appears to peak when the 40 sections are centred on section 51.
This means that summing just the sections 31 to 71 would produce the final SNR of 8:1, double that of folding all the data.
Another important conclusion can be drawn from the green plot and that is that the strongest target signal density follows the drift scan antenna pattern, hinting at observing an extra terrestrial source.

13. Python Verification Plot



This is my python take on the PRESTO data presentation summarizing all the pulsar measured parameters.
This is the result of just folding the optimum range defined by the previous analysis.
The plots from left to right and top to bottom are,
Best pulse profile.
Dispersion measure scan showing a peak around the expected DM of 27.
The next plot gives the period and period rate search plots clearly peaking as expected at zero offset. The next plot is the frequency band scan results showing both a cumulative increase and frequency scintillation.
The next plot is cumulative section target SNR showing steady growth in SNR.
Plot 6 is a repeat of the optimum section range search on the selected data range. The green curve echoing the antenna beam shape.
Plots 7 and 8 show the section and target SNRs and the data spectrum.
The final 2D plots at the bottom are period/period rate search and time and frequency cumulative waterfalls. All plots clearly confirm pulsar properties.

14. Conclusions



In conclusion, there is no better time to try to detect pulsars.
Plenty of cheap relevant electronics.
Lots of internet design aids.
Lots of available analysis and data presentation software.
Choosing a low RFI frequency band is essential - night time observations are better.
There is a need for amateur software for the weakest pulsars.
Pulsars may be difficult and several observations may be lost to RFI, but with good scintillation conditions and persistence, success could be yours.

15. References

1. https://en.wikipedia.org/wiki/High-electron-mobility_transistor
2. https://osmocom.org/projects/rtl-sdr/wiki
3. http://www.y1pwe.co.uk/RAProgs/StarterPulsarRXGuideH.pdf
4. https://eucara.org/downloads/

PWE August 2025