

Introduction to Pulsar detection for radio amateurs

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1 Introduction

The pulsars, whose name is originated from the contraction of the two words "PULSating StAR", are a special class of so-called "star of neutrons" derived from a catastrophic stellar explosion. These stars, that are initially of size comparable to our sun, due to the exhaustion of nuclear fuel, end their lives with a gigantic explosion called "Supernova" that destroys the outer part of the star and triggers a collapsing mechanism that leaves a super-compact core formed mainly of neutrons.

The density of these objects is extremely high with an average mass of $6.7 \times 10^{17} \text{ kg/m}^3$ [3, p. 58] vs. density of earth that is around $5 \times 10^3 \text{ kg/m}^3$.

This means that the weight of a "teaspoon of a pulsar" (equivalent to 1 cm^3) would weight on earth $6.7 \times 10^{17} \text{ kg/m}^3 \times 10^{-6} \text{ m}^3 = 6.7 \times 10^{11} \text{ kg} \approx 670 \text{ millions of tons}$.

The pulsars, which have physical dimensions of a few tens of kilometers, are characterized not only by the extraordinary compactness, but also by an extremely powerful magnetic and gravitational fields and by high speed of rotation on their own axis with very short periods ranging from a few milliseconds to a few seconds. The combination of these factors produces many effects and, what is of interests for us, is that the pulsars emit a rotating beam of radio waves that extends to a large part of the spectrum and that is more intense at lower frequencies.

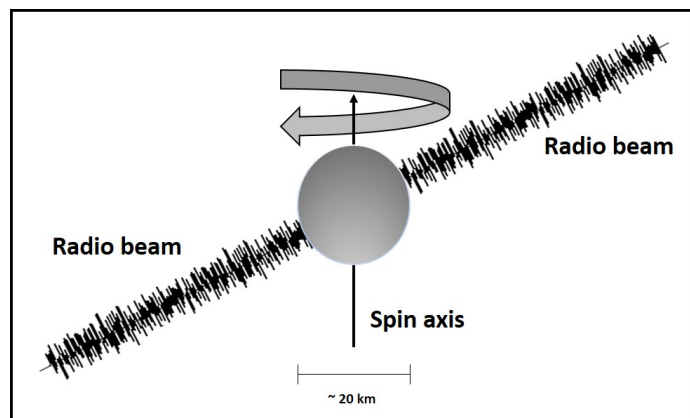


Figure 1: Schematic image of a pulsar

The fast rotation combined to electromagnetic emission make these objects a kind of "cosmic lighthouse" so much so that, when they were discovered in the sixties, were initially called LGM (Little Green Men) alluding to the possibility of signals from extraterrestrial civilizations.

As the electromagnetic emission is distributed over a wide range of frequencies a measure of "flow" (power density) was adopted to classify those waves instead of a pure measure of power.

To measure the power density a new unit was adopted : the Jansky , named after Karl Guthe Jansky who, in August 1931, first discovered radio waves emanating from the Milky Way.

The Jansky is calculated as the total power (in Watts) collected divided by the antenna area and by the total bandwidth of collection and, since a Watt per square meter per Hertz is an enormous amount of power , the result is divided by 10^{26} to get a more realistic unit for measuring natural astrophysical sources:

$1 \text{ jansky} = 10^{-26} \text{ watts} \times \text{m}^2 \times \text{hertz}$.
 For reference consider that 1 jansky is equal to $-260 \text{ dBW} (\text{m}^2 \times \text{Hz})$ or $-230 \text{ dBm} (\text{m}^2 \times \text{Hz})$

In Figure 2 are shown the strongest cosmic radio sources starting from 1 Jy but pulsars are not there as their flow is much weaker !

Just to have an idea consider that B0329+28, the strongest pulsar visible from the Northern hemisphere, has a flow at 1.4 GHz of 203 mJy (10^{-3} Jy) and B0833-45, the strongest PSR visible from the southern hemisphere has a flow @ 1.4 Ghz of 1100 mJy .

The web is full of information on pulsars, but for people approaching pulsars for the first time, my suggestion is to start with good **paper books** such as [1], [2] and [3] that can give a very complete overview of this complex and continuously evolving subject

Also an unbeatable source of information and practical guide to successful detection of pulsars from amateur radio-astronomers, is the web site created from Steve Onley [5].

2 Pulsar radio spectra

The radio-frequency emitted from pulsar is basically a wide band noise whose energy distribution is strictly correlated with frequency. The spectrum emitted has generally a

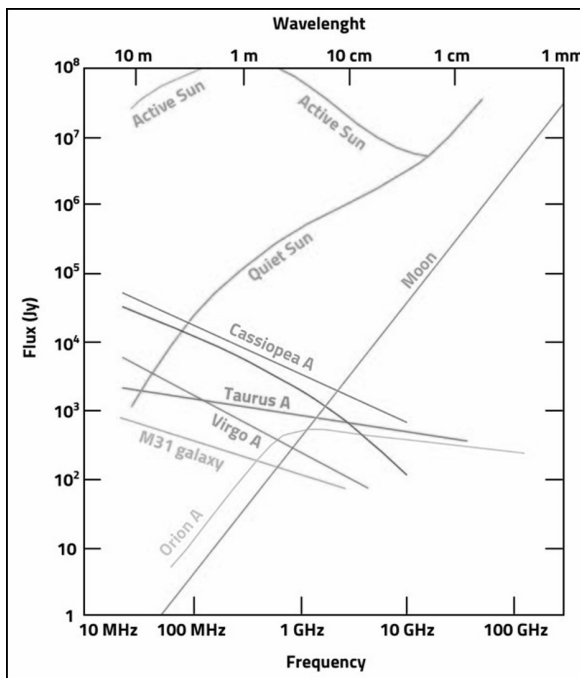


Figure 2: Spectra of typical radio sources.[2]

very strong inverse dependence with observing frequency (i.e. the lower the frequency the stronger the signal) and follows a power-law relationship :

$$S = S_0 v^\alpha \quad [1, \text{p. 7-11}]$$

where S is the flux density , S_0 is the flux at v frequency and α is the so called spectral index that can have a mean value of -1.5 ± 0.2 .[3, p. 14]

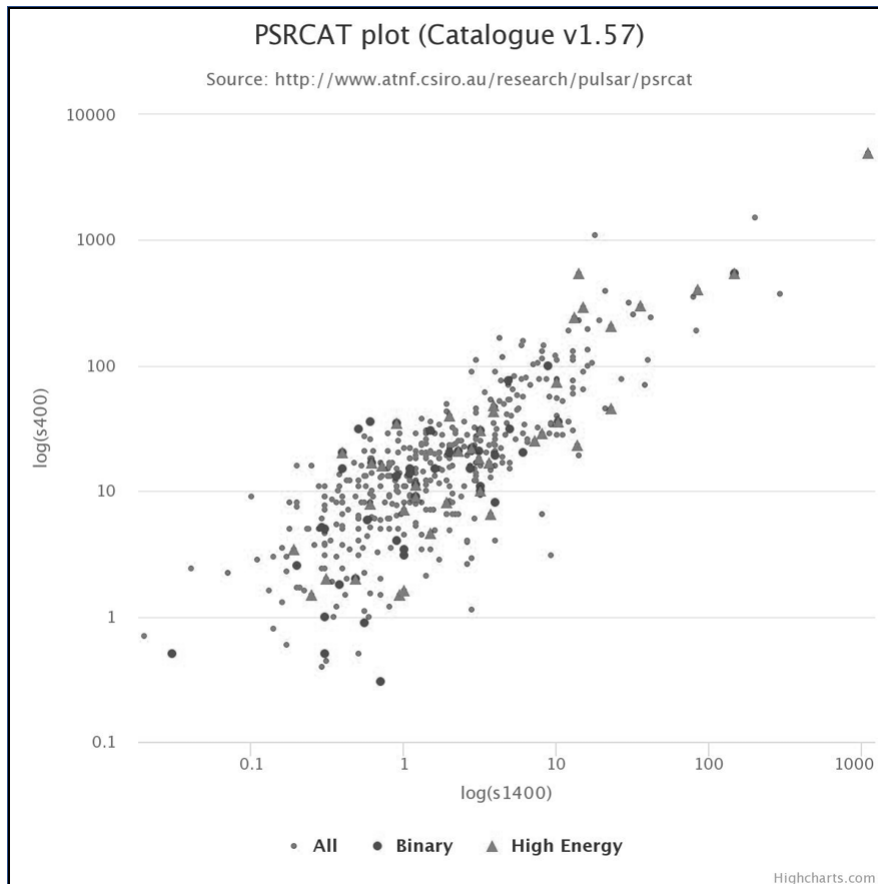


Figure 3: Flow @ 400 Mhz vs. flux @ 1400 Mhz extracted from ATNF . The log scale shows clearly one order of magnitude of difference between the S400 (Flow @ 400 Mhz) and S1400 (Flow @ 1400 Mhz) .[6]

Obviously is not so simple and there are a lot of exceptions to this general rule [3, p. 13-14] , but for amateur radio-astronomers this information is enough to plan a detection strategy.

3 Pulsar detection technique

As already stated the pulsar are very weak radio sources and for amateur radio-astronomers is almost impossible to detect even the strongest one in real time, so the approach used is to record the signal and use specialized techniques of Digital Signal Processing (DSP) in order to increase the Signal-to-Noise (S/N) ratio and be able to detect the pulses .

The DSP technique used is called "folding" ; this process can be understood thinking that the signal received is recorded in a continuous paper module .

As we cannot expect to see directly the pulses in real time, we must record the signal and, capitalizing on the fact that **we know from literature the pulse frequency of the pulsar under investigation** we fold the paper in small pieces **of the length of the pulsar period** . In doing this "folding" we allow the small contributions of the pulsars signals to accumulate and sum until the pulse "pop up" while the contributions of background noise , that is random , automatically eliminate themselves.

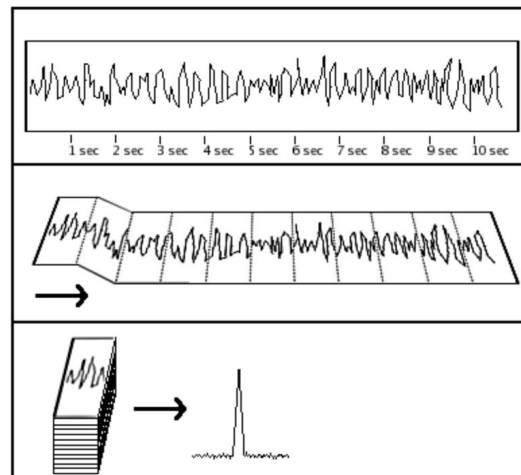


Figure 4: Folding technique.[4]

3.1 The integration bandwidth

As the pulsar signal is basically a wide band noise impulse, clearly the probability of success increases increasing the reception bandwidth.

Unfortunately it is not so simple to increase reception bandwidth for amateur radio-astronomers as we face two difficulties : the technical feasibility of of very large bandwidth receivers at reasonable cost and the possibility to find bandwidth free form RFI.

The time works for us on technical problem as the semiconductor industry is producing continuously new advanced products that allows to work at higher bandwidth, but at the same time woks against us as unfortunately man-made RFI is continuously increasing as more and more wireless devices are invading our world .

At the time of this writing bandwidth of 2 Mhz, 10 Mhz and 20 Mhz can be easily afforded with relatively cheap equipment such as RTL-SDR [7] for 2 Mhz bandwidth , AirSpy [8] for 10 Mhz and HackRf [11] for 20 Mhz just to mention the most popular. A recent development from **Nando Pellegrini I1NDP** [10] is allowing access to 50 Mhz bandwidth with the ETTUS B200 mini [11]

3.2 Sampling and recording the signal

The process to sample and record the signal must be done with extreme stability and precision in order to allow the post-recording "folding" process to work properly. The sampling precision starts from the receiver that must be very stable (a GPSDO or Rubidium lock would definitely help a lot) and continue with pre-processing and recording that requires a PC with adequate processing power. From some experiment done the very minimum requirement up to 20 Mhz bandwidth is an I5 with frequency $> 3Ghz$, quad core and fast USB , while for 50 Mhz bandwidth an I7 $> 4Ghz$, is mandatory.

3.2.1 The recording process

The observation of the pulsar requires, as we have already seen, a large bandwidth , but also must last for long time (hours) in order to get enough samples for the "folding" process.

The process to collect data (I/Q from the SDR) at 2, 10 or even 20 Mhz bandwidth, perform pre-processing and write data to disk is a complicated task but fortunately **Andrea dell'Immagine IW5BHY** [14] wrote an excellent piece of software (based on GNURadio [16]) that is able to perform this task with any of the SDR recognized from GNURadio. This software is also able to generate channels (very useful to mitigate RFI and to take in account other parameters of the pulsar such as Dispersion) to decimate (filter and down-sample) and write to disk.

At the time of this writing the suite of programs developed from **Nando Pellegrini I1NDP** [10] for the ETTUS B200 mini [11] that allows 50 Mhz of bandwidth is still in beta testing.

3.2.2 The processing

Once the file is recorded, it must be processed and converted to the "filterbank" (.fil) format in order to be ready to go through the analysis session that starts with determination of the exact pulsar period (frequency) and this task is performed with a program called TEMPO [12] that entering geographical coordinates of the observation site calculates exact data that will be used in the subsequent phase.

This program is pretty old and was written from many authors including Joe Taylor, K1JT. There is a new version called TEMPO2, but for amateur radio astronomers TEMPO is perfect.

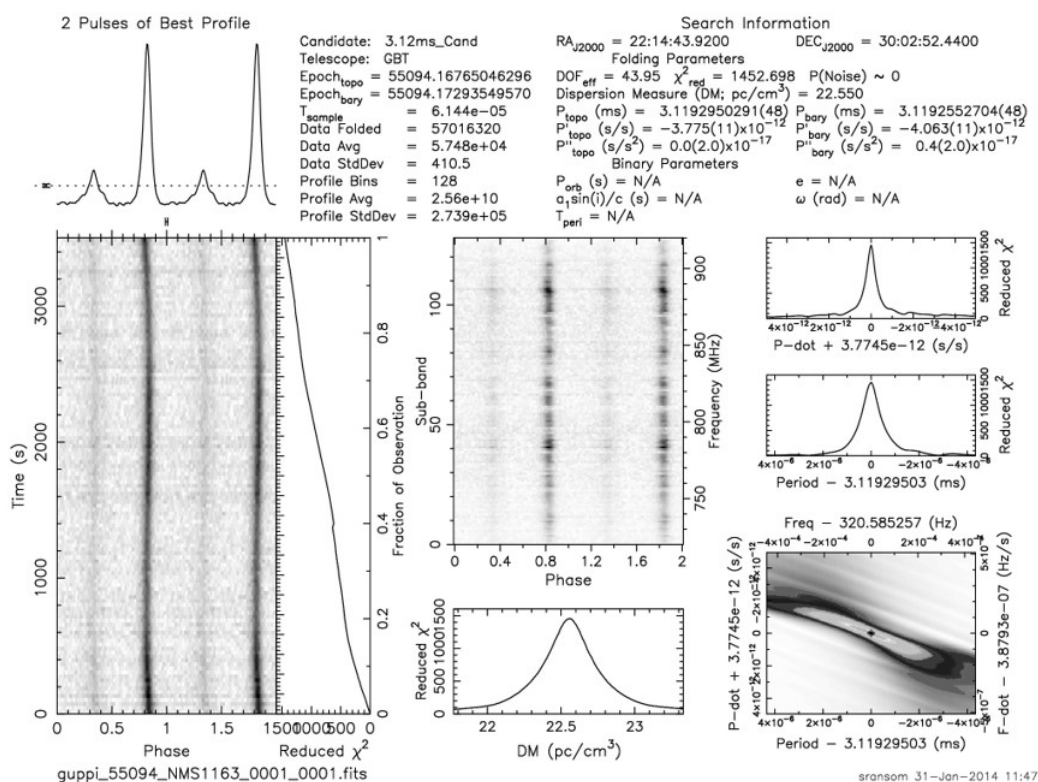


Figure 5: Typical output of PRESTO processing. the two peaks are two pulses of the pulsar received. Please see detailed analysis in [13]

Once the TEMPO calculations are done it is possible to proceed to the final examination to see if the hunting offered some reward. This analysis is performed with a suite of programs called PRESTO (PulsAR Exploration and Search TOolkit) [13] that will tell us if we were able to detect the pulsar

4 The receiving set-up

Last but not least we need to take a look to the receiving system to see if this is sensible enough to allow us to try to detect some pulsar.

The radiometer equation [3, p. 264-2657-11] is actually the basic law that allows the estimation of the minimum pulsar flow detectable from a given set-up

$$S_{min} = \beta \frac{(S/N_{min})T_{sys}}{G\sqrt{n_p t_{int} \Delta f}} \sqrt{\frac{W}{P-W}} \quad [3, p. 265]$$

Where :

S_{min} = minimum detectable flux density

β = factor for imperfections in the observatory system, usually near to 1

G = Telescope gain

S/N_{min} = Required minimum linear S/N for validation of result

T_{sys} = System noise temperature

n_p = Number of polarization (usually 1 for amateurs, generally a maximum of 2)

t_{int} = Integration time

Δf = Detection bandwidth

W = Width of pulse

P = Period of pulse

This evaluation can be done with the program MURMUR downloadable from this web site [15], at the section "Downloads" ; in the same section you will be able to find a short manual.

The screenshot shows the MURMUR software interface. At the top, it displays the location (Assisi-Beviglie), latitude (43.0922), longitude (12.5772), and UTC/Local Time (10/12/2017 11:20:03). Below this are buttons for 'SAVE current set as default', 'SET Observation location', and 'CALCULATE'. The main area is divided into several sections: 'Dish antenna' (selected) with parameters like Dish diameter (5 m), Dish efficiency (50%), Sensitivity constant (1), Frequency (1303 MHz), LNA Noise figure (0.28 dB), LNA gain (38 dB), Line loss after LNA (0.5 dB), Receiver noise figure (4 dB), T sky (4 K), T atmosphere (0 K), Integration time (18000 sec), and Integration bandwidth (10000 KHz). The 'Other antenna' section is also visible. The 'Wave length' is 0.23 m, 'Effective ant. aperture' is 9.81 m^2, 'Dish area' is 19.63 m^2, 'Far field' is 217 m, 'Antenna gain' is 33.66 dBi, 'HPBW' is 3.22 deg, 'System noise temp.' is 26.98 K, 'System noise figure' is 0.39 dB, and 'MDS' is 17.89 mJy. On the right, there are buttons for 'TRACK noise sources', 'Next 24h Pulsar visibility', 'Next 24h Pulsar tracking', 'CALCULATE culminations', '1 Month Pulsar visibility', and '1 Month Pulsar tracking'. Below these is a list of the first 60 detectable pulsars based on the ATNF Pulsar catalogue, with a minimum S/N of >10. The pulsar B0329+54 is highlighted, with its parameters: Right Ascension (J2000) 53.25 deg, Declination (J2000) 54.58 deg, Width of pulse at 50% of peak 6.6 msec, Barycentric period 0.71452 sec, Dispersion measure 26.76 cm^-3 pc, Flow 400MHz 1500.0 mJy, Flow 1,400MHz 203.0 mJy, Max. integration bandwidth (without de-dispersion) 34 MHz, Calculated S/N 117.54, Azimuth 16.47 deg, and Elevation 10.69 deg. A note at the bottom states: 'The analysis does not take into account the polarization of the signal as this parameter is strongly depending on the specific Pulsar. Please evaluate carefully case by case as this may deteriorate performance up to 3dB.' Evaluation is done only for frequency intervals: 390MHz-500MHz and 1,000Hz - 1,500Hz.

Figure 6: Main screen of MURMUR. On the right side it is possible to see data of B0329+54 that, with the set-up on the left, is predicted to be detectable with S/N=118.[15]

5 Conclusions

The journey to achieve this result it is not difficult, but requires to spend long time in understanding all steps of the technique used .

Detecting pulsars for an amateur radio-astronomer it is something like reaching ” a minor Holy Grail ” as Steve mention in his web site [5] .

The emotion , I can gurantee this, will be big when you will see the first trace and the thrill will be the same of the first QSO ; also you will be guaranteed that you have a real state-of-the art station with all bits and pieces perfectly aligned !

References

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- [8] AirSpy Web site. <https://airspy.com/>.
- [9] Ettus Research Web site. <https://www.ettus.com/>.
- [10] Pellegrini, N. <http://i1ndp.altervista.org/>.
- [11] HackRF Web site. <https://greatscottgadgets.com/hackrf/>.
- [12] Tempo program <http://tempo.sourceforge.net/>.
- [13] Ransom, S. <http://www.cv.nrao.edu/~sransom/presto/>. PRESTO suite of programs
- [14] Dell'Immagine, A. <http://iw5bhy.altervista.org/>.
- [15] Natali, M.A. <http://i0naa.altervista.org/>.
- [16] GNU Radio. <http://www.gnuradio.org/>.