The 3-Meter Dish at the "Astropeiler Stockert"

Part 3: Pulsar Observations

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1. Introduction

Observing pulsars is a target which many amateur radio astronomers wish to achieve. And indeed, it is something which can be done and has been done with various types of instruments at various frequencies. The most comprehensive overview of successful pulsar observations by amateurs is maintained by Steve Olney [1]. Several of the observations listed there have been done at L-band with a dish of 3 to 4 meter diameter [2], [3], [4], [5].
Encourages by such results, we tried to observe a pulsar with the 3-m dish at Astropeiler.

2. Observation setup

2.1. 3-m dish

A detailed description of the Astropeiler 3-m dish is available at [6]. Therefore, only the main features are re-iterated here. The dish is fully steerable in azimuth and elevation and has a diameter of 3 meter and a f/D ratio of 0.3. The feed is a Kumar type design with a low noise amplifier (LNA) directly attached to it. This LNA has 35 dB of gain with a noise figure of 0.52 dB at 1420 MHz. The system temperature varies depending on elevation between 100 and 60 K. The parameters which have been determined at 1420 MHz and 50° elevation are given in the table below.

Parameter	Value @ 1420 MHz
3 dB Beam Width	5.1°
System Temperature @ 50° Elevation	94 K
Forward Gain	0.0013 K/Jy
System equivalent flux density (SEFD) @ 50° Elevation	72,307 Jy
Aperture Efficiency	52%

2.2. RF chain

For the purpose of the pulsar observations, the setup of the RF chain was modified compared to what is normally used at the 3-m dish for spectral observations. The reason for this was that it was convenient to use the pulsar backend from our 25-m dish. This backend requires that the input is down converted to an IF signal between 100 and 200 MHz.
Therefore, a standard heterodyne setup was used as shown in fig. 1.

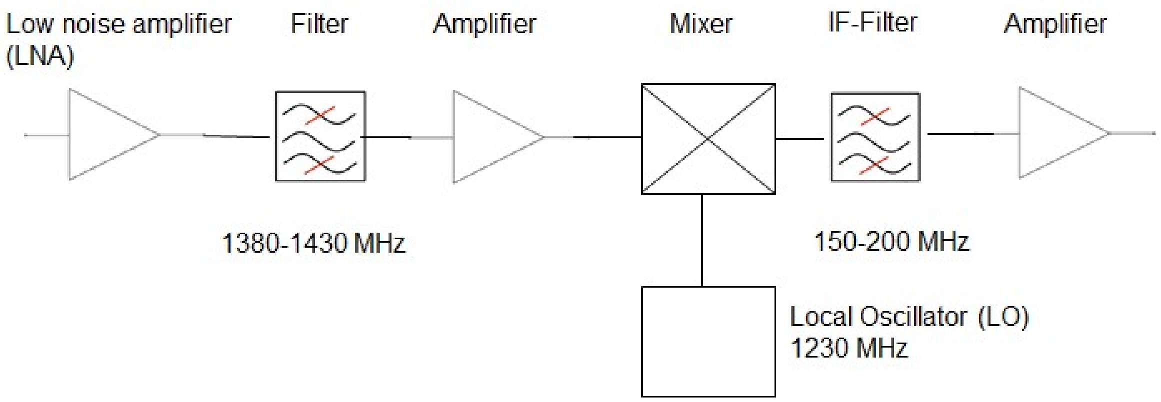

Figure 1: *RF chain*

2.3. Backend

The backend used in this experiment is a "Pulsar Fast Fourier Transform Spectrometer (PFFTS)". It consists basically of a fast A/D converter which digitizes the incoming IF. Then a Fourier transformation of the signal is performed in a Field Programmable Gate Array (FPGA). This allows to do the Fourier transformation on the fly. The spectrometer delivers the spectra with high time resolution to a computer for storage and later processing. The time resolution used in this case was 218 μs. The clock of the backend was synchronized to our 10 MHz rubidium-based master clock.
This PFFTS is a development of the Max-Planck Institute for Radio Astronomy and is used at various telescopes. More information on this instrument can be found in section 3.2 of [7].

It is worthwhile mentioning that using such a sophisticated backend is not a necessary prerequisite for observation of pulsars by amateurs. Instead, a solution based on software defined radios can be used as well. Also, in case of the pulsar B0329+54 with its low dispersion (see section 3.) one can go without de-dispersion at 1420 MHz and still be successful. This allows to work with a simple square law detector as demonstrated in [4]. For us, using an existing and proven hardware and software toolchain was just the most convenient way to come to results quickly.

2.4. Software

The spectra are recorded in a format specific to the PFFTS. These are converted to the standard "filterbank" format which can then be processed by standard pulsar programs. Primarily we use PRESTO [8] for de-dispersion and folding of the data. However, sigproc [9] is used as well. Pulsar periods are calculated using tempo [10].

3. Observations

3.1. Observation runs

A number of observations were performed. The first try was on June 7th, 2020. This resulted in a "maybe detection". While there was a fairly decent signal, there was not enough signal to noise ratio to unambiguously exclude that it might also be an artefact created by radio frequency interference (RFI). The verification tests as described below could only partially be done due to lack of sufficient signal to noise ratio (SNR).

Further runs were done on June 10th, 14th, 17th 21st, 25th, and 28th. All of these showed the pulsar signal. Below, the results from June 21st are presented in detail.
The PRESTO plot of this observation is shown in fig. 2. One can see that the pulse is present through most of the 2.6 hours of observation time as indicated by the vertical line in the grey scale plot. The SNR increases over the observation. The second grey scale plot indicates that the signal is present over the observed bandwidth.

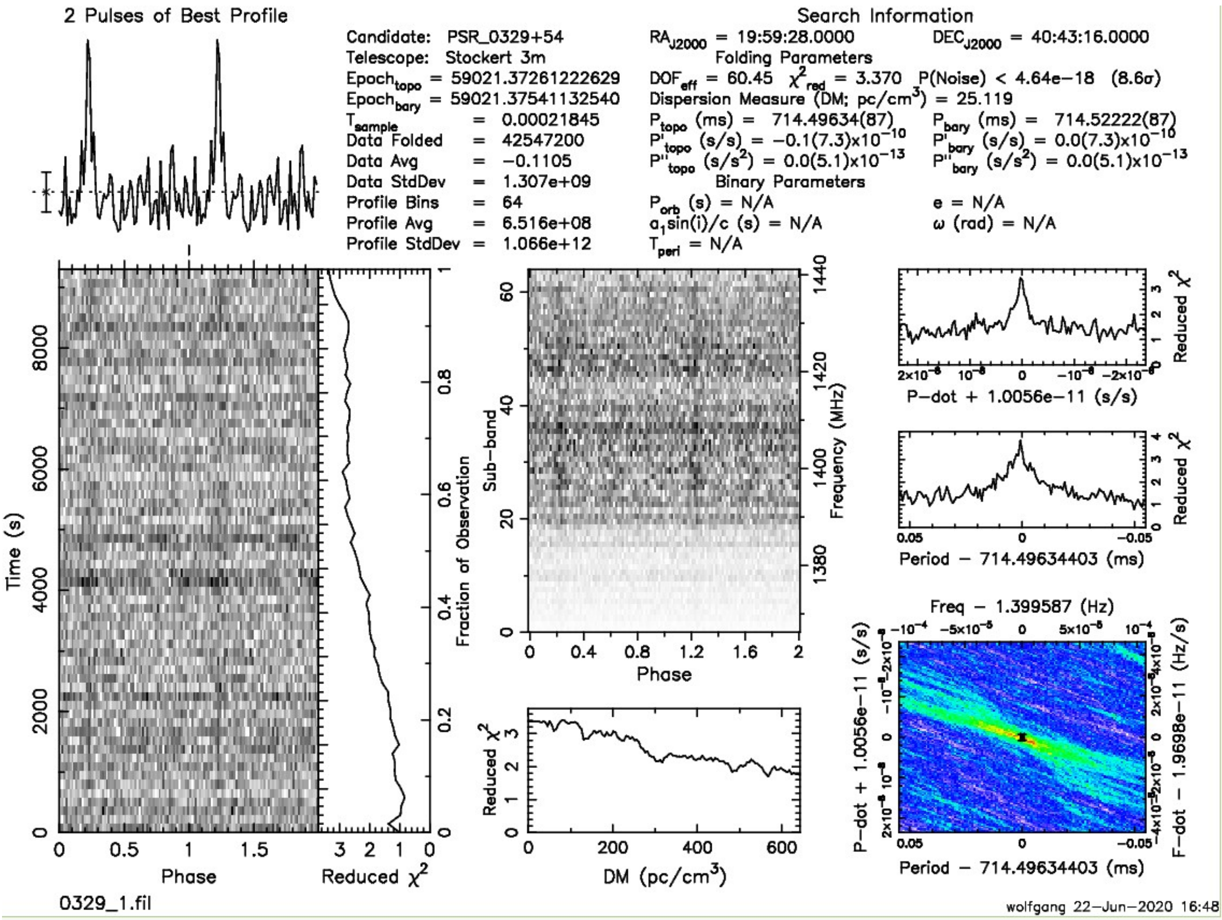

Figure 2: *PRESTO plot of B0329+54 observation from June 21st, 2020*

The recording bandwidth of 75 MHz is somewhat larger than the bandwidth of the RF and IF filters, which is approx. 50 MHz. Therefore, the intensity falls off towards the lower frequency part of the spectrum.
Folding the time series data into 128 bins using sigproc shows the profile in more detail as depicted in fig. 3.

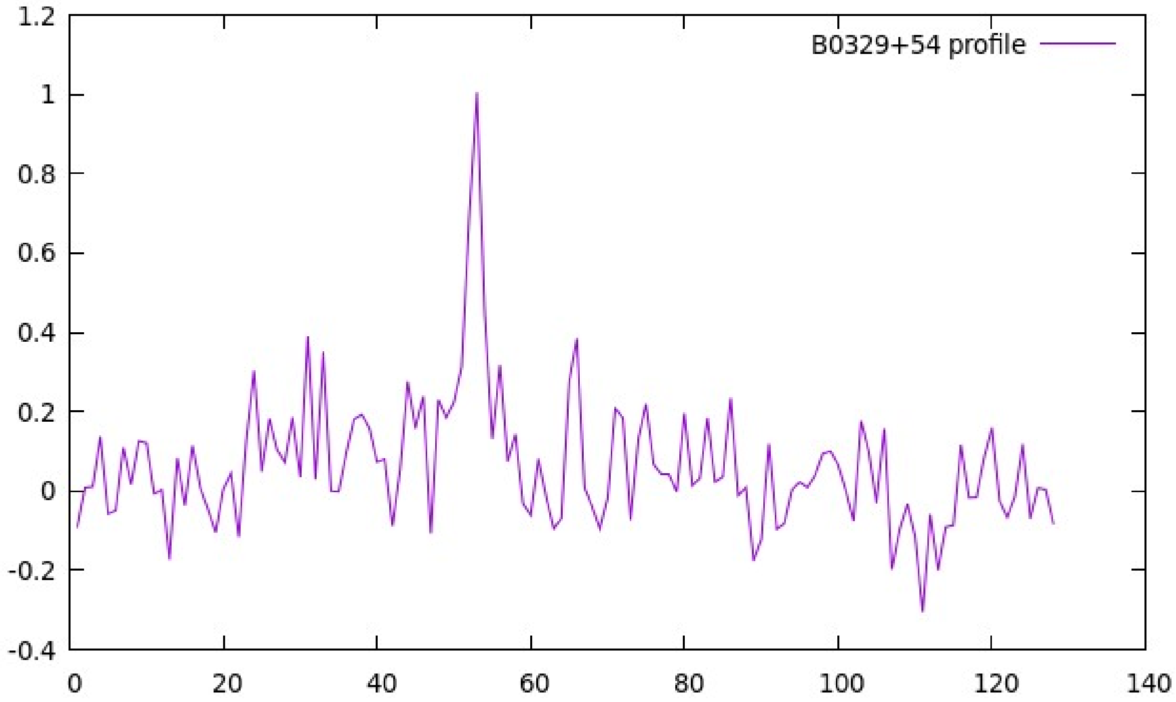

Figure 3: *Profile from observation (128 profile bins)*

3.2. Verification of results

Pulsar signal are weak, and in particular when observing with small aperture antennas the signal to noise ratio will be low. RFI on the other hand can easily mimic a pulsar signal. Therefore, care must be taken of verify results by performing various checks. These checks look for specific characteristics related to the physics of pulsars and which help to tell the wheat from the chaff. Such checks have been applied to the data reported above.

Repeating observations

Obviously, a successful observation should be repeatable. The only limitation is that this particular pulsar shows strong scintillation and therefore may be too weak to be detected at times. However, in this case all observations on different days were successful if one includes the “maybe” result from June 7th.

Observation Date	Integration time	Detection Sigma
June 7th, 2020	0.53 hours*	10.1**
June 10th, 2020	1.2 hours	6.5
June 14th, 2020	1.2 hours	5.1
June 17th, 2020	4.2 hours	10.8
June 21st, 2020	2.6 hours	8.6
June 25th, 2020	3.9 hours	10.1
June 28th, 2020	3.6 hours	10.9

*actual observation lasted longer, but only part of it was usable due to RFI
**even though the reported sigma is high, it cannot be excluded that it erroneous and caused by RFI. This observation is considered as a “maybe”.

Checking for correct period
Pulsars have a very stable rotation period which only very gradually spins down over time. However, as the earth moves around the sun and as the observer rotates with the earth, there is an additional doppler shift due to this motion. This leads to an observed (topocentric) period which is different at different observing times. For well-known pulsars, both the spin down and the doppler effect can be calculated to a very high degree of precision by programs like tempo [10].
Therefore, one can compare this calculated period with the observed period. For a valid observation these must agree within measurement uncertainty.

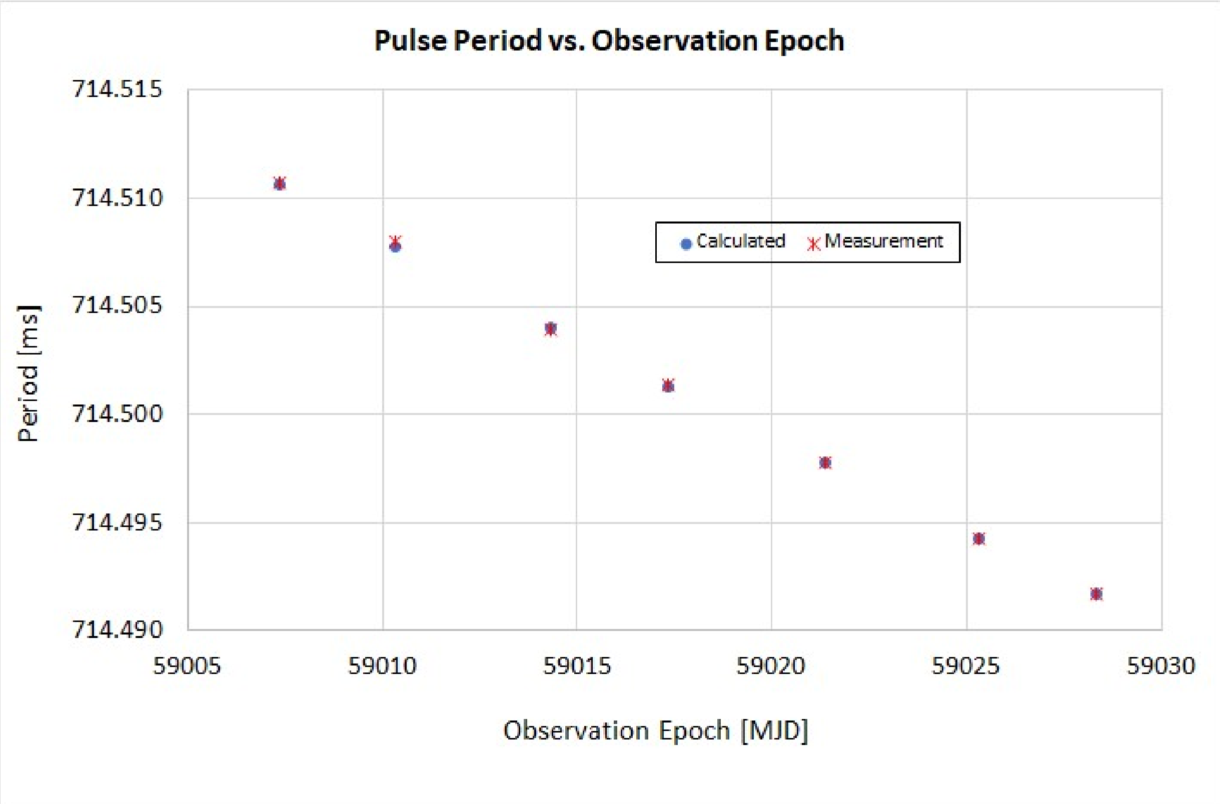

Figure 4: *Topocentric period at different observation dates*
(Observation epoch given as Modified Julian Date)

This comparison for the data observed is shown in fig. 4. The pulsar period of a specific observation was determined by folding the signal with different periods and determining the SNR. The period with the best SNR was chosen as the measured period. There was an excellent agreement between the measured period and the expected (calculated) period.

Checking that the signal is broadband
Pulsars are synchrotron radiators and emit in a broad spectral range. Therefore, one should see the signal everywhere in the observed frequency band. This is already apparent from the intensity vs. frequency plot from Presto as shown in fig. 5.

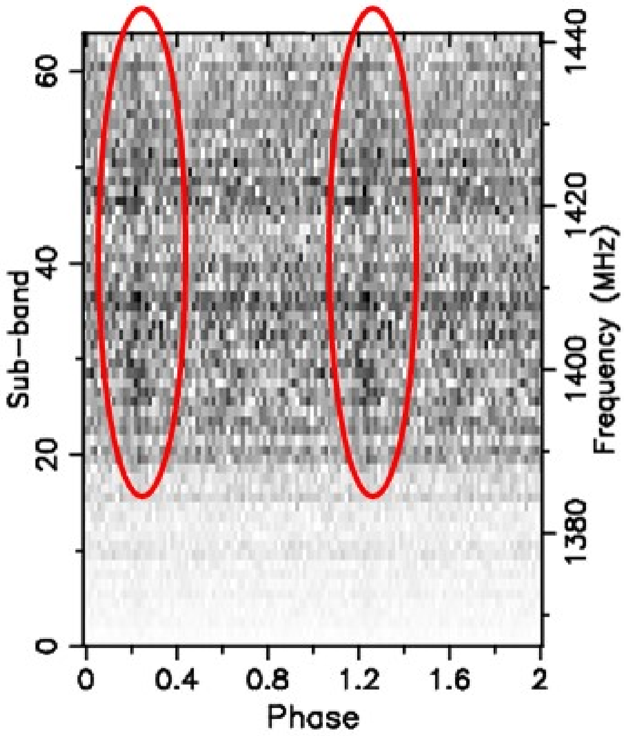

Figure 5: *Intensity vs. frequency*

Another check can be made by folding different subbands each encompassing only a part of the spectrum. The signal should appear in all subbands, albeit with lower SNR as shown in fig. 6.

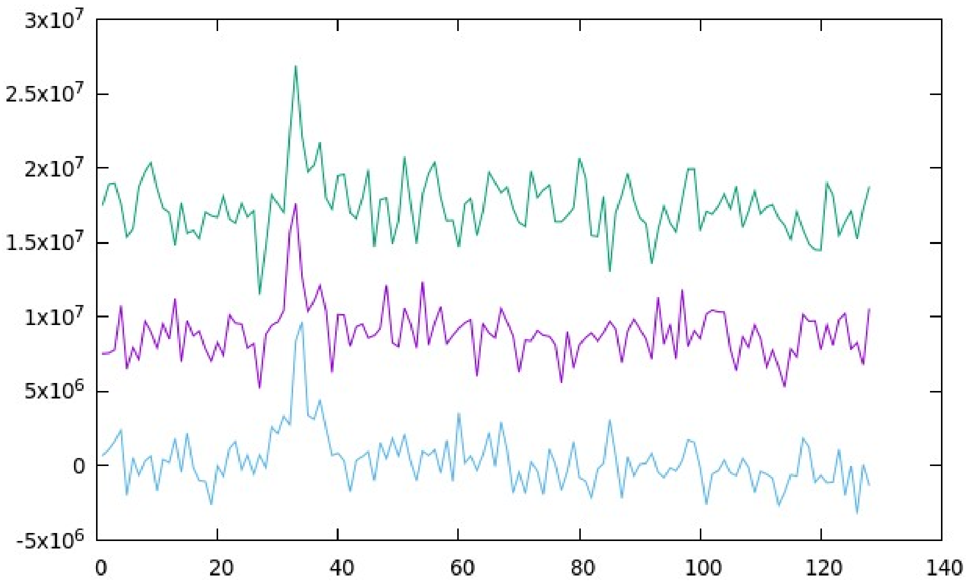

Figure 6: *Profile in subbands*

Checking that the signal is repeating

A pulsar is continuously emitting pulses. In contrast to this, an RFI spike will only occur once. An easy check for this can be made by folding the data with twice the period. This is shown below in fig. 7.

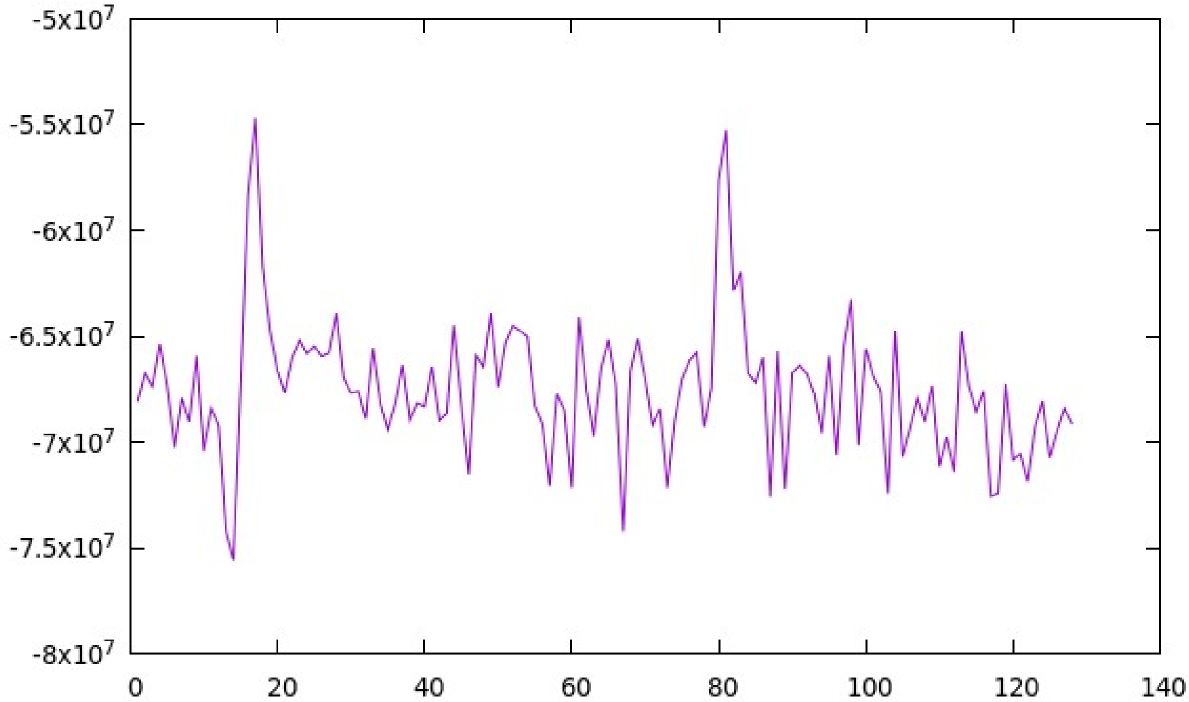

Figure 7: *Profile folded with twice the period*

Checking for pulse profile

Pulsars have a specific pulse profile. One of the characteristics is the width of the pulse. In case of B0329+54, the full width at half maximum is 6 ms. In order to check the pulse width, the profile has been folded into 714 bins, so that a time resolution of 1 ms is achieved. This is a higher resolution than in the examples shown so far and results in less signal to noise ratio. A detailed view of this plot demonstrates that the pulse width is in the right order of magnitude, even though an exact number cannot be derived due to the limited SNR, see fig 8.

The pulsar B0329+54 has a specific feature in its profile at 1400 MHz: There is a pre-pulse and a post-pulse. Unfortunately, the SNR of this observation is not sufficient to clearly identify these features.

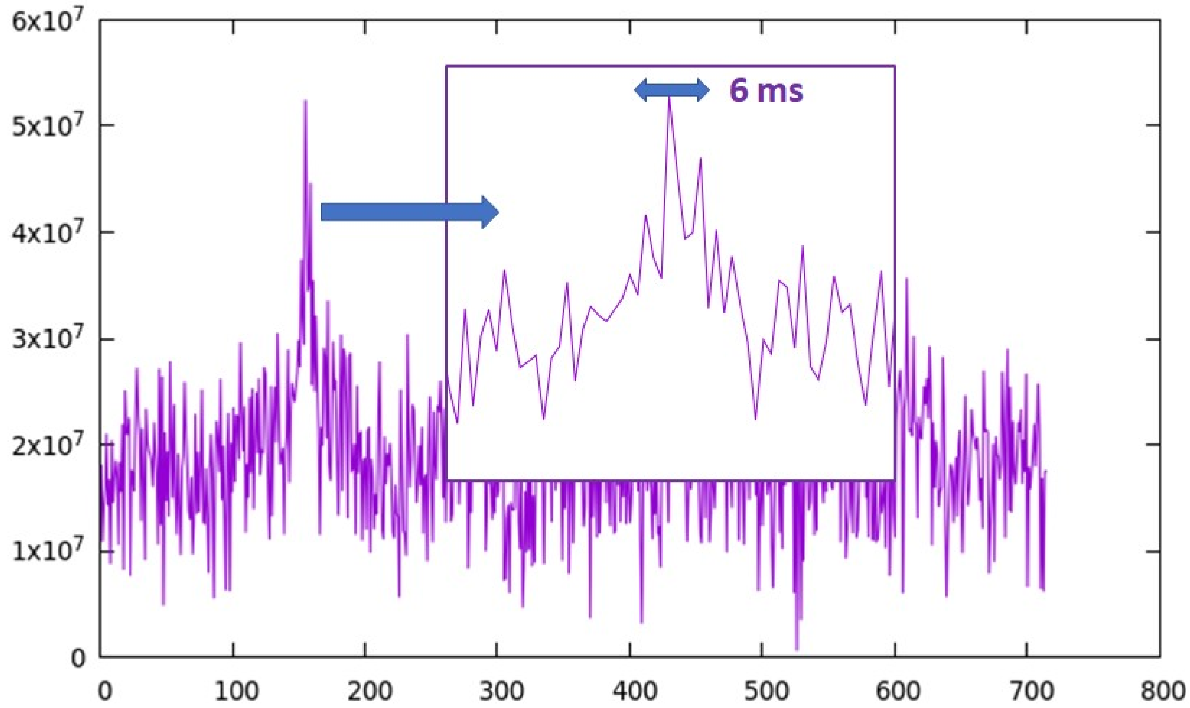

Figure 8: *Analysis of pulse width*

Checking for dispersion

A very specific feature of pulsars is the dispersion. This means that there is a delay of the pulse propagation through the interstellar medium which is frequency dependent. However, the pulsar B0329+54 has a relatively low dispersion so that this test can only be done with very high SNR data. Therefore, this test cannot be reliably applied here.

4. Conclusions

The observation of the pulsar B0329+54 has been successful with the Astropeiler 3-m dish. The observation is repeatable and several checks have been made to unambiguously determine that this is a real pulsar signal and not an artefact created by RFI.

References:

[1] Website maintained by Steve Olney http://neutronstar.joataman.net/
[2] Observation by Hannes Fasching: https://www.qsl.net/oe5jfl/pulsar/pulsar_3m_dish.htm
[3] Observation by Tadeja Sade and Matjaz Vidmar: http://neutronstar.joataman.net/sites/s5/docs/jn65tw.pdf
[4] Observation by Jean-Jaques Maintoux: https://f1ehn.pagesperso-orange.fr/pages_radioastro/Images_Docs/PSR_Meas_2017_revA3_Eng.pdf
[5] Observation by Andrea Dell'Immagine and Gabriele Tucci: http://neutronstar.joataman.net/sites/iw5bhy_ik5vls_lucca/

[6] W. Herrmann, The 3-Meter Dish at the "Astropeiler Stockert" Part 1 and 2, Astropeiler Website
[7] E.D. Barr et al., The Northern High Time Resolution Universe Pulsar Survey I: Setup and initial discoveries, https://arxiv.org/pdf/1308.0378
[8] https://www.cv.nrao.edu/~sransom/presto/
[9] http://sigproc.sourceforge.net/
[10] http://tempo.sourceforge.net/