NIUS May 2023 visit report

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During the month of May 2023, I visited NCRA Pune to continue the NIUS Astronomy project on studying pulse jitter. I did some reading on the topic and conducted analysis on the data provided. Here is a brief summary of my work.

1 Reading

For reading, I mainly referred to the Handbook of Pulsar Astronomy by Lorimer and Kramer. I revised some topics I had already studied from other sources. Except that, there were some new topics I read about which are relevant to the current project:

1.1 Binary Pulsars

Pulsars can also exist as binary systems, where their orbiting partner can be a white dwarf, main sequence star or another neutron star. Binary pulsars with low mass companions ($\leq 0.5M_\odot$) usually have millisecond periods and low eccentricity orbits. Those with high mass companions have larger spin periods and highly eccentric orbits.

The evolution of binary pulsars generally starts from two orbiting main sequence stars. The more massive star evolves first and becomes a neutron star. Most binary systems are disrupted by this, but the few neutron stars that survive continue to spin down as normal pulsars. When the binary companion evolves and expands, the neutron star can accrete matter from it. This can lead to the formation of a low mass X-ray binary. The neutron star can then be spun up to millisecond periods due to the angular momentum gained from the accreted matter.

1.2 $P - \dot{P}$ diagram

Similar to the HR diagram for stellar evolution, we can plot the spin period P against the spin period derivative $\dot{P}$ for pulsars. This diagram can be used to study the evolution of pulsars.

Second pulsars occupy the top right portion of the diagram, with high P and $\dot{P}$. Millisecond pulsars are found in the bottom left corner, with low P and $\dot{P}$. Most millisecond pulsars are found in binary systems.

1.3 Neutron star radius

Although it is difficult to measure the radius of a neutron star, we can estimate it by observing the thermal emissions from its surface at optical and X-ray frequencies.

We can also obtain a lower and upper limit for neutron star radius theoretically. The lower limit is obtained by assuming that the speed of sound needs to be less than the speed of light. The upper limit is obtained by assuming that the neutron star is stable against gravitational collapse. The radius values obtained from these limits are comparable to the Schwarzschild radius, demonstrating that pulsars are almost black holes.

1.4 Pulsar timing corrections

While studying pulsars, we need to correct for various effects that can affect the observed pulse period. These include:

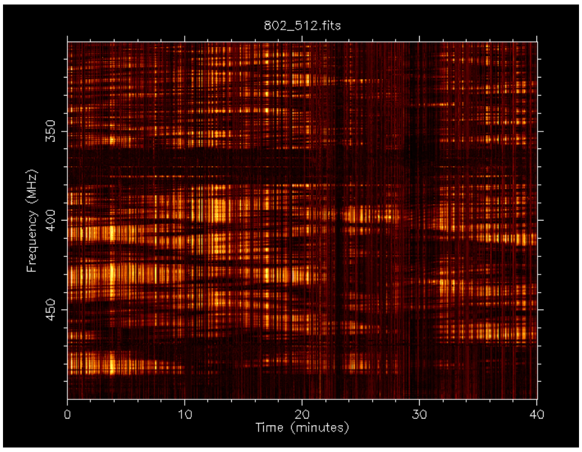
1. **Clock corrections:** Due to dispersion in the ISM, arrival time depends on observing frequency. This can be corrected by subtracting the DM delay.
2. **Romer delay:** The classical light travel time between the phase centre of the telescope and the Solar System Barycentre. Calculating this requires the position of the Earth and the pulsar.
3. **Shapiro delay:** The delay in the arrival time of pulses due to the curvature of space-time caused by objects in the solar system. The Sun and Jupiter are major contributors to this effect.
4. **Einstein delay:** The combined effect of time dilation due to the motion of the Earth and gravitational redshift caused by other bodies in the Solar system. This also requires the position of the Earth in the elliptical orbit around the Sun.

The last three effects are referred to as Barycentric corrections since they transfer the time of arrival from topocentric to barycentric frame. This is necessary since the topocentric frame (ie observatory on Earth) is not inertial.

2 Data analysis

2.1 Preprocessing the data

After converting the data to a fits file, I observed that it contains a lot of RFI. The data also had scintillation which caused variation in the SNR over the observing time period. This can clearly be seen in the dspec image of the data:



To continue with the analysis, I had to remove the channels and subints which had low SNR. To do this, I used the python interface for psrchive (jupyter notebooks attached).

First, I collapsed the data in frequency and plotted the SNR for every subint. To clear out RFI, I removed all subints where the SNR was less than 10 from the original data.

Then, I take the filtered data and collapsed it in time to get the SNR for every channel. I removed all channels where the SNR was less than 15 from the filtered data. This gave me the final data which I used for the analysis.

To form the template file for the analysis, I collapsed this data in time and frequency to get the average profile. Then I applied a wavelet smooth function on it to get the final template. This template had an SNR of 5331.

2.2 Calculating Jitter

Once the preprocessing is done, I used psrchive and tempo2 to find the jitter in the data as a function of time and frequency.

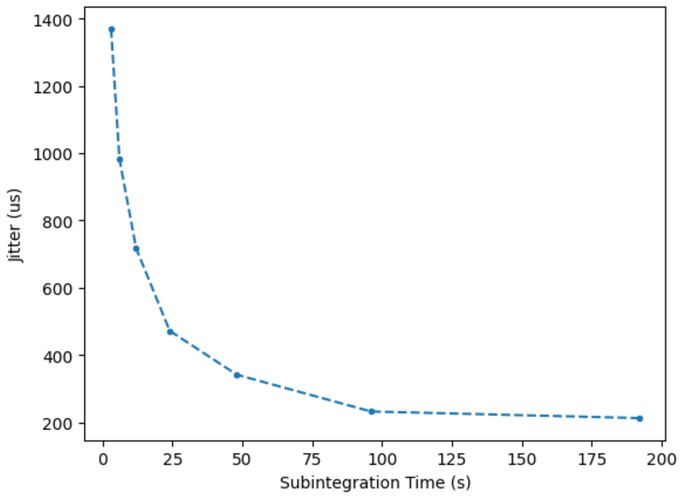
To find the jitter in the data, I used the equation:

$$\sigma^2_{\text{jitter}} = \sigma^2_{\text{obs}} - \sigma^2_{\text{radiometer}}$$

Here σ_{obs} is the RMS of the post fit residuals and $\sigma_{\text{radiometer}}$ is the radiometer noise, which was calculated by taking the RMS value of the error bars of the data. The error bar on jitter was also calculated by doing error analysis on this equation using the error propagation formula. Since the number of points were large, I have opted to use a gaussian approximation instead of the student's t-distribution.

2.3 Jitter as a function of time

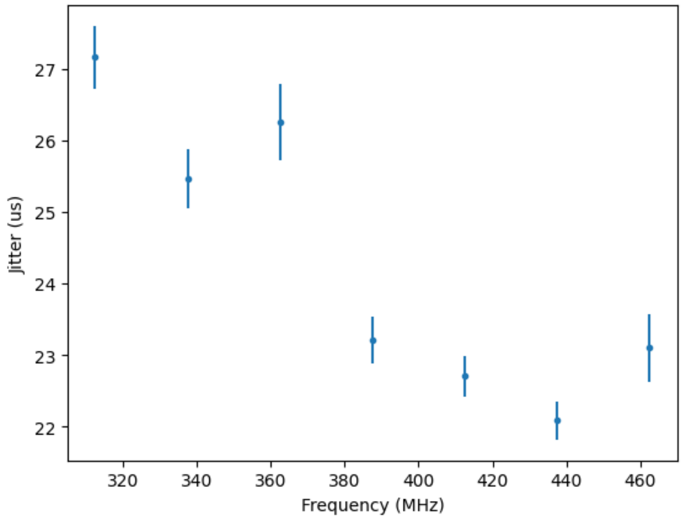
First, I measured the jitter in the data as a function of subintegration time. Since jitter is assumed to be a white noise, we expect the jitter to reduce as the subintegration time increases. The plot of jitter as a function of subintegration time is shown below:



The jitter indeed reduces with an increase in subintegration time. It also appears to be following the inverse square law, which is expected.

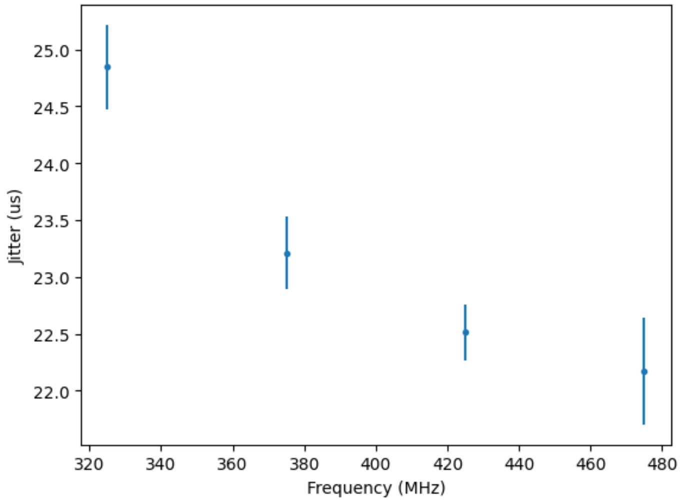
2.4 Jitter as a function of frequency

Next, I measured jitter as a function of the observing frequency. To do this, I divided the data into sub-bands and then collapsed them in frequency. This gave me a few frequencies to work with. Upon calculating the jitter in them, I obtained the following graph:



We can see that the jitter is reducing with an increase in frequency (the third point and last point can be ignored since most of those channels were filled with RFI and were removed).

Similar results were obtained on dividing the data into 4 sub-bands instead of 8:



Thus we can conclude that for the pulsar J1136+1551, the jitter is reducing with an increase in observing frequency for the 300-500 MHz band.