An Analysis on Calibration and De-dispersion for Millisecond Pulsars

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Introduction

Pulsar is a highly magnetized, rotating neutron star that emits a beam of electromagnetic radiation. NANOGrav, a national science foundation which focuses on pulsar study, aims to detect gravitational waves and has been collecting and building data set for more than nine years.

NANOGrav 9-yr data set consists of nine year high precision data, collected with Green Bank and Arecibo telescopes. During the Arecibo observation, a secondary instrument, called WAPP(Wideband Arecibo Pulsar Processor), also collected data, which was not incorporated into the 9-yr data set. Sarah Henderson, a 2016 Lafayette graduate, demonstrated in her senior thesis that by incorporating the WAPP data into 9 year data base, the parameters in the timing model will be more accurately determined. Our summer research was based on her thesis and aimed to improve her data analysis in order to obtain better data precision.

TOA

TOA stands for pulse time of arrival. As shown in Figure 1, since pulsar is constantly rotating, its radiation can be observed only when the beam of emission is pointing towards Earth. After de-dispersion, the incoming signal is fold at the pulse period to form a pulse profile (because the incoming pulsar signal is really weak), and a time of arrival is calculated from the profile. To calculate TOA, a template is generated and then shifted and amplified to compare with the real pulse shape, and the shifted distance from the starting time is the TOA.

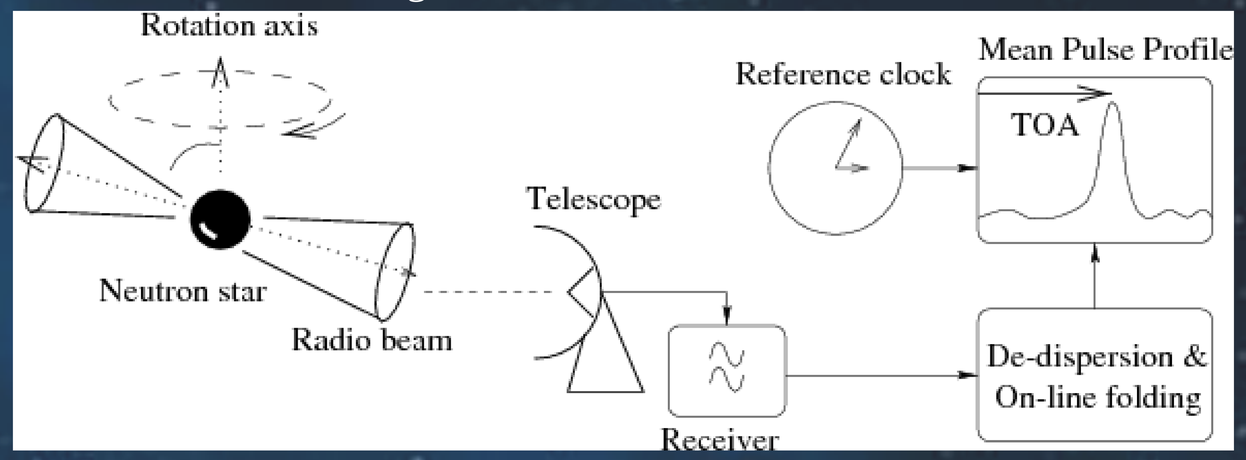

Figure 1. The method to calculate TOA

Residuals

Timing residual is the difference between the measured TOA and the modelled TOA. The average residuals plot for Pulsar J0030+451 is shown in Figure 2.

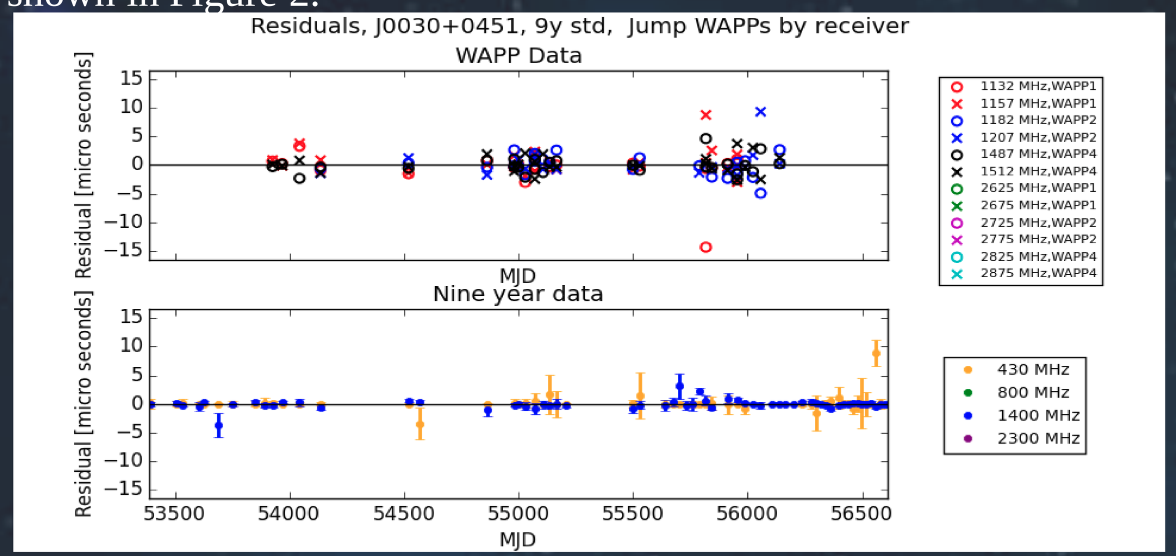

Figure 2. Residuals plot of J0030+451

We expected to detect gravitational wave on the order of 10^{-9}Hz by finding specific perturbations of these residuals. This very-long-period gravitational wave may continuously vary the proper distance travelled by a pulse. So far, this perturbation has not been found.

Approaches to Improve

Sarah aimed to improve pulsar timing precision to increase the chance to detect gravitational waves. We found three ways to improve Sarah's work:

- First, in Sarah's thesis, the TOAs were generated by the 9-year data profiles. The template is assumed to be Gaussian pulse shape, but the real pulse shape is far more complicated. Due to this fact, many of the pulse features are lost. To fix this problem, we downloaded a package called *Autotoa* which can generate templates from all the three WAPPs and avoid dispersion smearing on the templates. An example of the templates created by *Autotoa* is shown on the right.
- There are offsets between different receivers, which is called JUMP. These offsets usually result in a time delay for TOAs. To determine the influence of jumps on the results, we separate jumps within the WAPP data and calculate the residuals for jumping both individual receivers and individual WAPPs.
- The last approach is to improve calibration, which is explained in detail in the next part.

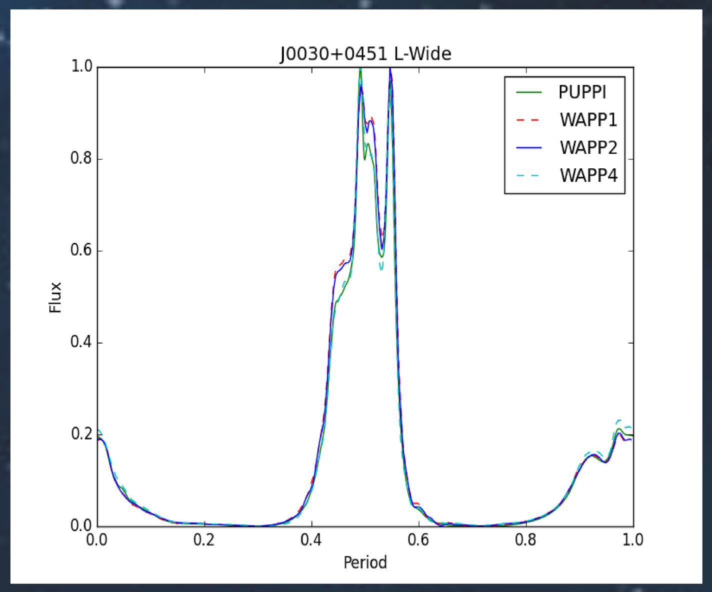

Figure 3. Template for Pulsar J0030+451

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Wideband Arecibo PULSAR Processor Timing of NANOGrav Millisecond Pulsars, Sarah Henderson, May 2016

Calibration

Problem:

- Each profile of a WAPP data file had an arbitrarily amplified amplitude generated by the receiver which needed to be converted to a value of flux in units of milliJanskeys.
- Two different polarizations were collected and amplified by different devices, which leads to different voltages even if the relative power of two polarizations is similar.
- The calibration is a vital step before further analysis on the data. A PSRCHIVE package was used to calibrate all data files. But we proposed that it was necessary to create our own calibration file in order to achieve more precise results.

Solution:

Before the observation of Pulsar began, a short calibration observation is taken as to convert the artificial sources into measures of flux in units of millJanskeys. The details of the process is shown below.

In the calibration observation, two sources other than the pulsar signal are introduced:

1. An artificial source pulsed at 25 Hz, which was generated at the receiver.
2. A strong radio source, Quasar J1413+151, whose flux height is measurable in units of milliJanskeys.

(For further demonstration, the flux height of Pulsar, Quasar and the artificial source are notated as S_pulsar, S_1413 and S_art respectively.)

The calibration process included two steps.
First, the flux height of Quasar J1413+151 was compared with that of the artificial source.

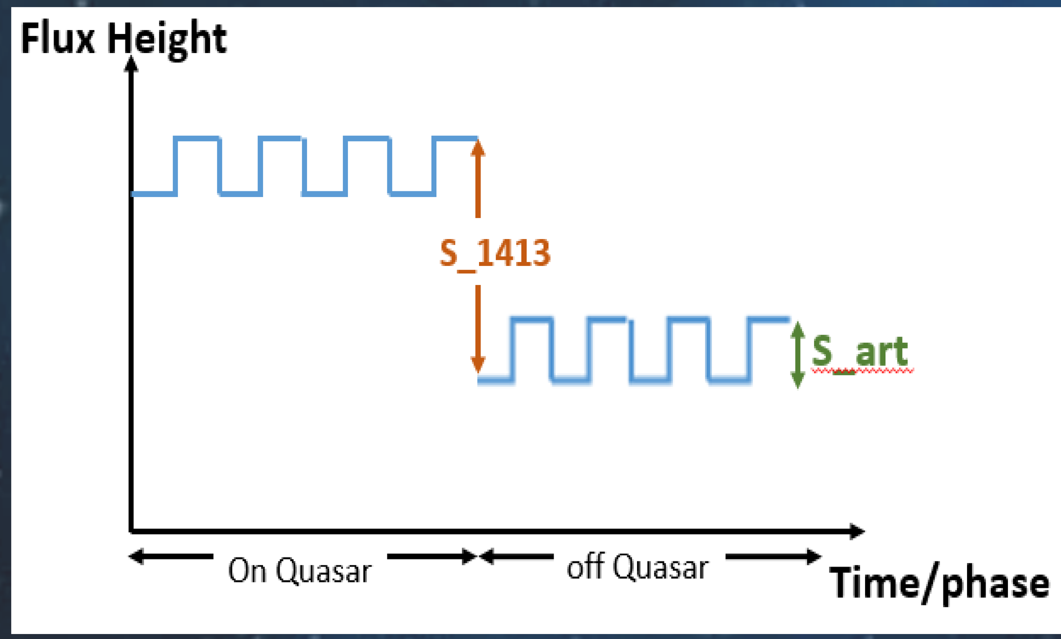

Figure 4. Step one of calibration observation

- In Figure 4, the blue squared shapes represents the artificial source on and off during the whole calibration observation.
- At first, the telescope is pointing on Quasar.
- Afterwards, the telescope is moved away from Quasar, and the flux height drop is the amplitude of Quasar.
- After comparison, Ratio1= $\frac{S\_art}{S\_1413}$ was obtained.

Second, the flux height of a pulsar was compared with that of the artificial source.

- In the diagram on the right, the blue squared shape represents the artificial source and the orange pulse represents pulsar signal.
- After the comparison of them, Ratio2= $\frac{S\_pulsar}{S\_art}$ is obtained.

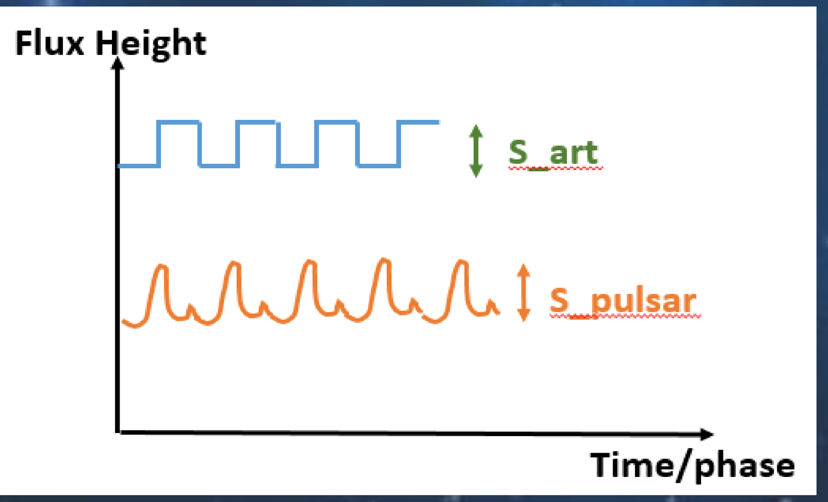

Figure 5. Step two of calibration observation

The flux height of Quasar is known to be a fixed value. Therefore, The flux height of pulsar can be calculated as $S_{\_pulsar} = S_{\_1413}$ *Ratio1*Ratio2. The new calibration was finalized after the newly created python file was incorporated into our analysis process.

Results:

As introduced before, the new calibration process aimed to increase the precision of the pulsar data. The root mean square(RMS) of the timing residuals for different pulsars before and after the new calibration was calculated in order to see whether the new calibration improved our project. The result for four pulsars (arbitrarily selected) is shown on the right. In general, RMS values in the second table (on the first column) is smaller, especially J0030+0451, and this proves that the new calibration file calibrates more precisely than the old one.

Before:

PSR	WAPP1 (1130-1160 MHz)			
	σ_W	σ_P	$\left(\frac{\sigma_W}{\sigma_P}\right)_m$	$\left(\frac{\sigma_W}{\sigma_P}\right)_e$
B1855+09	1.183	2.396	0.494	0.668
J0023+0923	1.454	6.490	0.224	0.328
J0030+0451	3.722	4.214	0.883	0.747
J1640+2224	2.598	2.625	0.990	0.752

After:

Psrname	WAPP1_std	puppi1_std	mratio1	eratio1
B1855+09	1.089	2.403	0.453	0.664
J0023+0923	1.413	6.488	0.218	0.372
J0030+0451	2.871	4.209	0.682	0.747
J1640+2224	2.507	2.643	0.948	0.746