Optimal Frequency Channelization for Pulsar Dispersion Measurements

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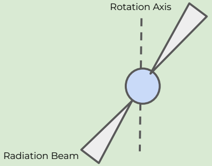
The precise determination of pulsar dispersion measure (DM) values is particularly important to the eventual detection of gravitational waves by pulsar timing arrays. In order to acquire the most accurate results, the uncertainty in the measured values of DM should be as low as possible. We investigate how the selection of the number of frequency channels used to fit for DM over the observing bandwidth affects the uncertainty in DM of pulsars used by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav).

Pulsars

- Rapidly spinning neutron stars
- Extremely precise rotators
- Create a lighthouse effect
- Act as cosmic clocks



Dispersion measure

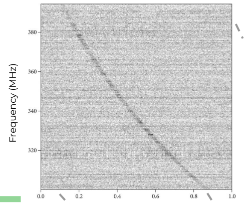
- The integrated column density of free electrons along the line of sight to a pulsar:

$$\mathrm{DM} = \int_0^d n_e(l)\, dl$$

- Low frequencies are delayed compared to higher frequencies:

$$\Delta t \propto \left(f_1^{-2} - f_2^{-2}\right) \cdot \mathrm{DM}$$

- DM variations need to be properly modeled for the detection of gravitational waves



The Pulsar Signal Simulator

- Python package to model realistic pulsar signals (Hazboun et al. 2021, Shapiro-Albert et al. 2021)
- The simulator models signals from their emission at the pulsar, through the interstellar medium, to their detection at the telescope, as well as their analysis through pulsar timing software
- The simulator allows the selection of number of frequency channels, and variation of parameters such as the observed frequency, the telescope used for observation, and the specific pulsar observed

The Pulsar Signal Simulator

Image Credit: Caitlin Witt

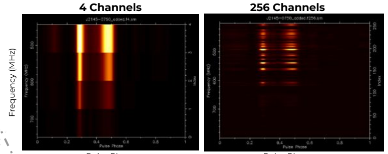
Simulating the Signal

- Selected pulsars based on brightness and available data
- Selected telescope and frequency
  - Green Bank Telescope (GBT) or Arecibo Observatory (AO)
- Used pulsar signal simulator to create a dispersed pulsar profile at a number of epochs
- Calculated a time of arrival (TOA) at each epoch
- Used PINT to fit a timing model to the TOAs which then recovers DM and uncertainty in DM

Frequency Channels

- Purpose was to find optimal number of channels before processing
- Simulated 2048 channels in a range of frequencies (800 MHz), with center frequency of 1200 MHz
- Reduced number of frequency channels by powers of 2 to find number of channels with minimum error in measurements

Signal to noise ratio is larger at lower number of frequency channels. Resolution is higher at higher number of frequency channels



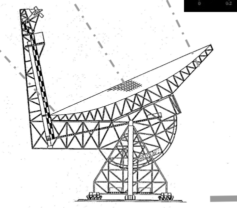
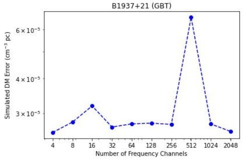
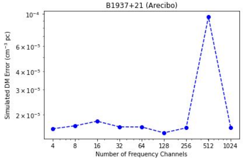


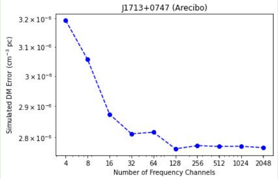
Image Credit: Michael H. Soffel & Wen-Biao Han, Felix J. Lockman

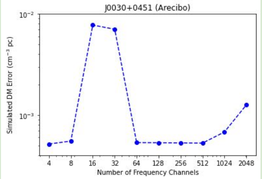
Results

- Depending on different parameters we identified different optimal numbers of frequency channels
- In the case of B1937+0747, AO observations have a lower uncertainty using a higher number of frequency channels compared to GBT observations
- Brighter pulsars such as J1713+0747 typically minimize uncertainty at higher number of frequency channels
- These patterns seem to follow the expected trends:
  - Brighter pulsars or larger telescope diameter → larger number of frequency channels









Further Study

- Results too limited to make definite conclusions, need to simulate more pulsars and parameters such as observation frequency and pulse width
- Investigate potential issues with simulator (ex: DM uncertainty peaks at specific frequency channel numbers, behaviour at upper and lower bounds)
- Once complete, our results will give us the ability to build a model which will give a baseline for the number of frequency channels that should be used depending on the observation and pulsar properties
- This model will empower astronomers using data from existing and future radio telescopes to increase the quality of DM related research and contribute to the detection of low frequency gravitational waves

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