Autonomous spacecraft navigation using millisecond pulsars

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Overview

1. Project description
2. Data collection
3. Methods of reducing noise
4. What does it tell us?
5. Results
6. Conclusion / Further Work

1. Project description

I. Determine how accurate a spacecraft can determine its position autonomously
   - Need at least three different pulsars to determine position

II. Use pulsar as time reference
   - Periods ranging from ms to s
   - Spinning and highly magnetised neutron stars
   - Emits over a range of frequencies
   - At ~1400 MHz, the signal intensity rapidly decreases with frequency

1. Project description: Current techniques

Achieves ~ 1 meter and ~ 1 nanoradian uncertainty of plane of sky from Earth

- Uncertainty = How close the measurement is to the true position

Two common ways to do it:

1. Optical methods, such as Deep Space 1 (DS1)
   - Determine source position by taking images of bright asteroids
2. X-ray pulsar navigation
   - Determine relative position through comparing ms pulsar signals with time references, as well as its phase lags

1. Project description: Challenge

- Can radio navigation do as well or better than X-ray navigation, but in smaller package?
  - Radio wave signatures are sharper in time
  - Better signal to noise ratio (SNR)
  - Better angular resolution
  - More pulsars than X-rays

1. Project description: How?

- Near ~1400 MHz, 20 MHz bandwidth of sky is reserved for radio astronomy
- Test the detection of a strong pulsar with the SRT
  - Crab pulsar (PSR B0531 + 21)
  - Measured at 10 MHz bandwidth due to lack of storage
- In space, no bandwidth limit due to human communications
- With 10 MHz on Earth, extrapolate the bandwidth to see how well the detection of pulsars will do in space

2. Data collection: SRT with SDR

2. Data collection: How much and why?

- Collected data from the Crab Pulsar using thor.py script
  - Integrated time: 1 hour
- Nyquist theorem: $f_{nyquist} = \frac{f_{sampling}}{2}$
- Sampled at 20 MHz to collect 10 MHz bandwidth of sky

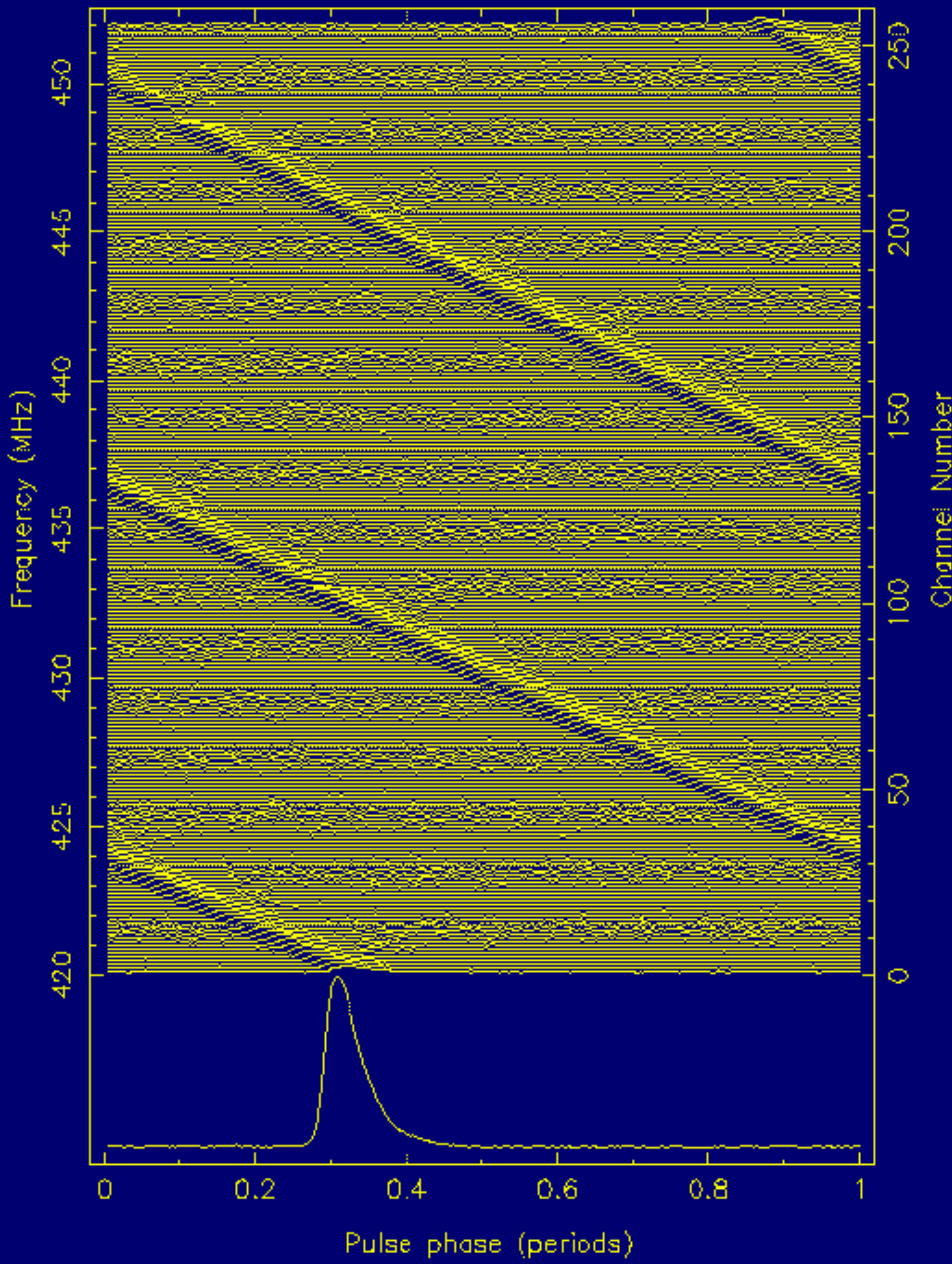
$$20MHz = 20\frac{Megasamples}{second}$$

@ 4 bytes/sample =
80 Megabytes/second

3. Methods of noise reduction

- Know pulsar's period as exactly as possible
  - Crab pulsar's period: 33.3924123 milliseconds
- Dispersion measure
  - Way of quantifying # of electrons that the pulsar's signal must travel through to reach the Earth
- Correct for dispersion (De-dispersion)
  - Divide wide receiver bandwidth into many individual channels
  - Subtract dispersion delay between channels
  - Sum channels to form an average of pulse profiles

3. Methods of noise reduction



3. Methods of noise reduction

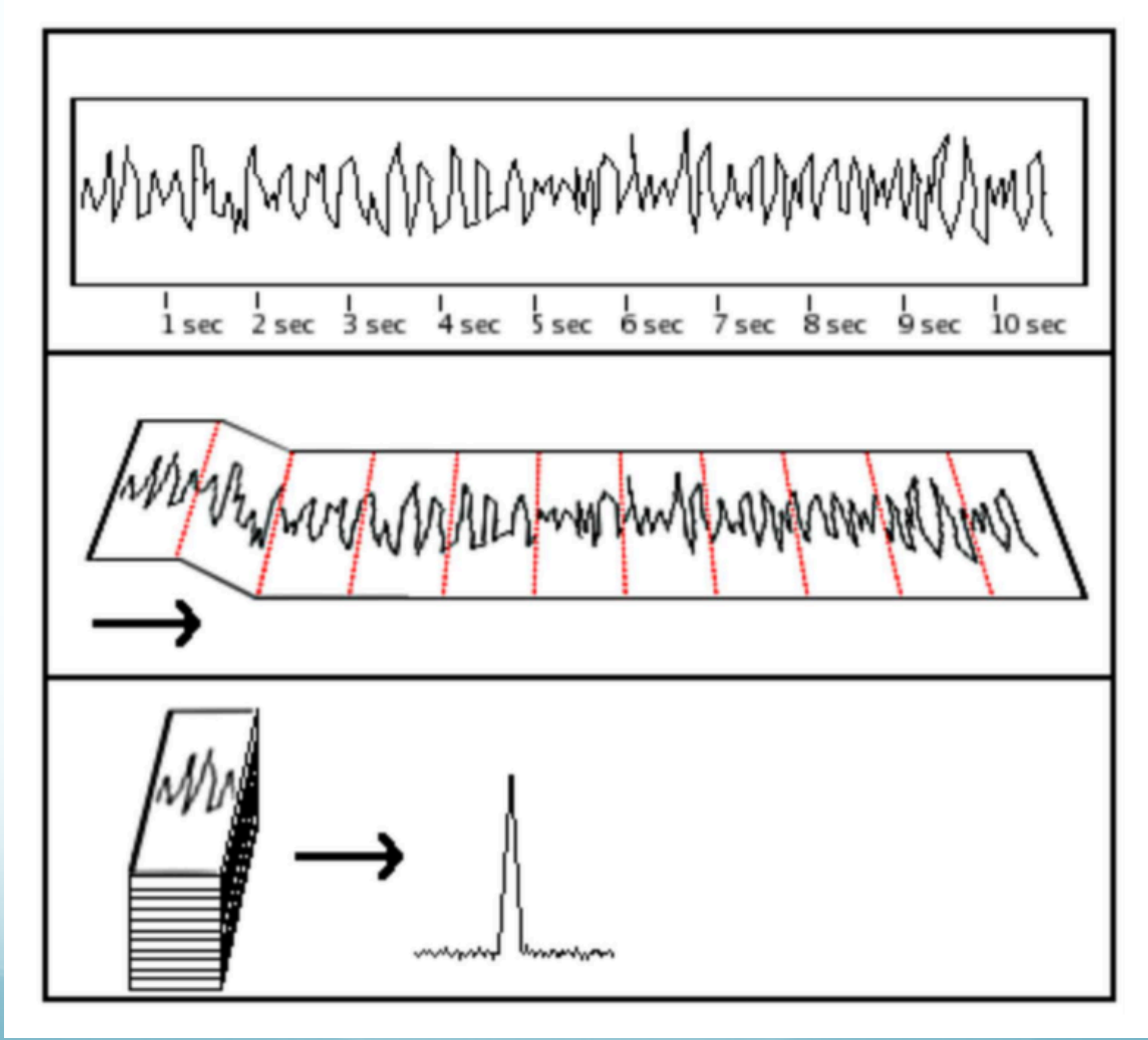
$$Dispersion = exp\left(i\frac{2\pi D\nu^2}{\nu_0(\nu+\nu_0)}\right)$$

- $D = \frac{Dispersion\ measure}{2.41\times10^{-4}}$
- $\nu = FFT\ of\ centre\ frequency$
- $\nu_0 = Subchannels\ of\ centre\ frequency$

3. Methods of noise reduction

- Fold the data by pulsar's period
  - The number of bins will be in the pulsar's period
  - Stack pulsar's period on top of each other
    - 1st bin added to 1st bin and etc
  - Summation of the stacks
  - Signals are in phase with each other, so peak will appear
  - Noise is not in phase

3. Methods of noise reduction



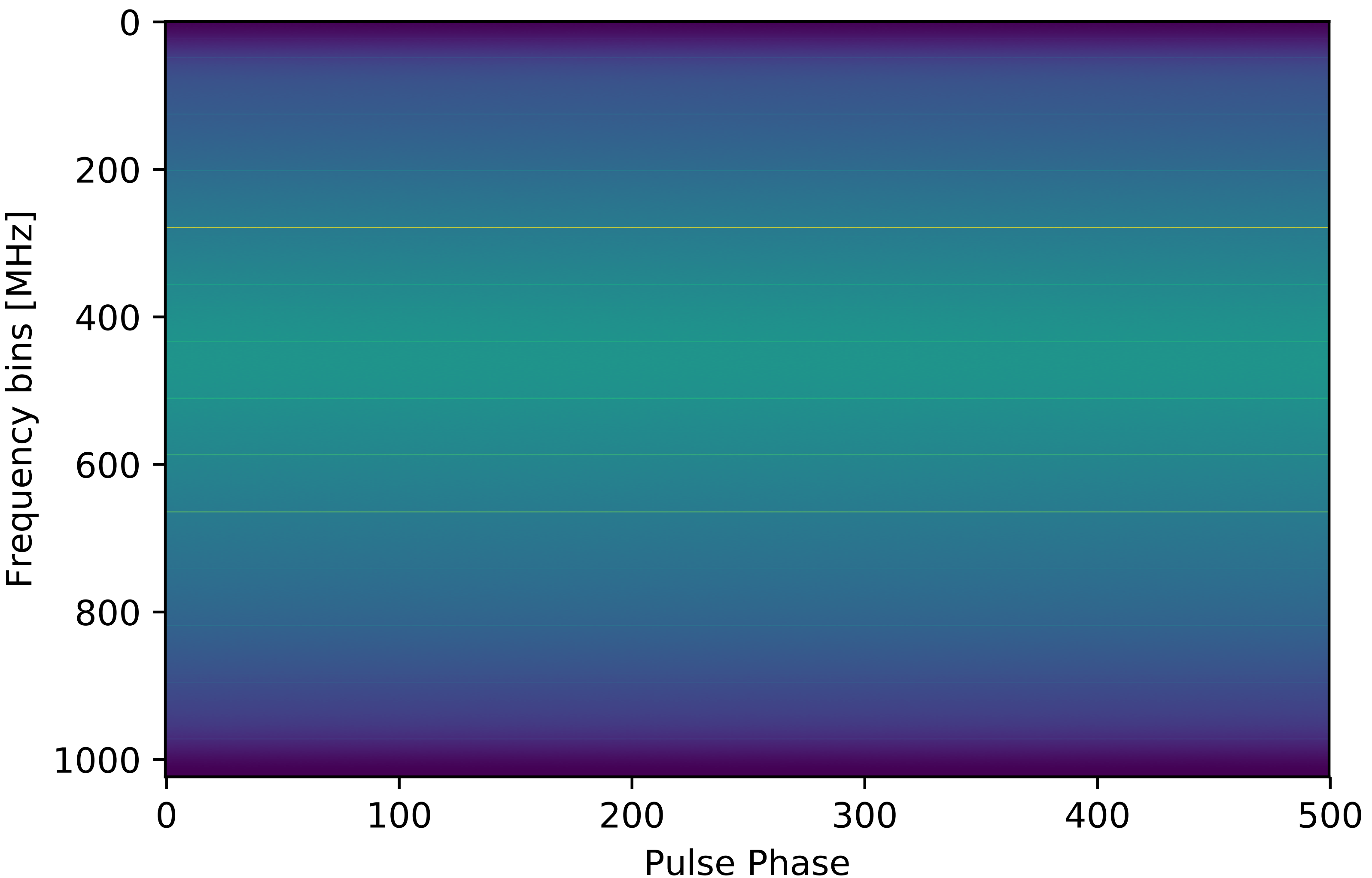
4. What does the data tell us?

- Produces information on pulsar's SNR
  - With SNR, can make a model that we can use to design a radio navigation system
    - In other words, what will the SNR be for:
      - Other (weaker) pulsars
      - Different dish sizes – and are they small enough for spacecraft? (Do we need to use advanced antenna designs such as folding antennas to get a size big enough?)
      - Different bandwidths

4. What does the data tell us?

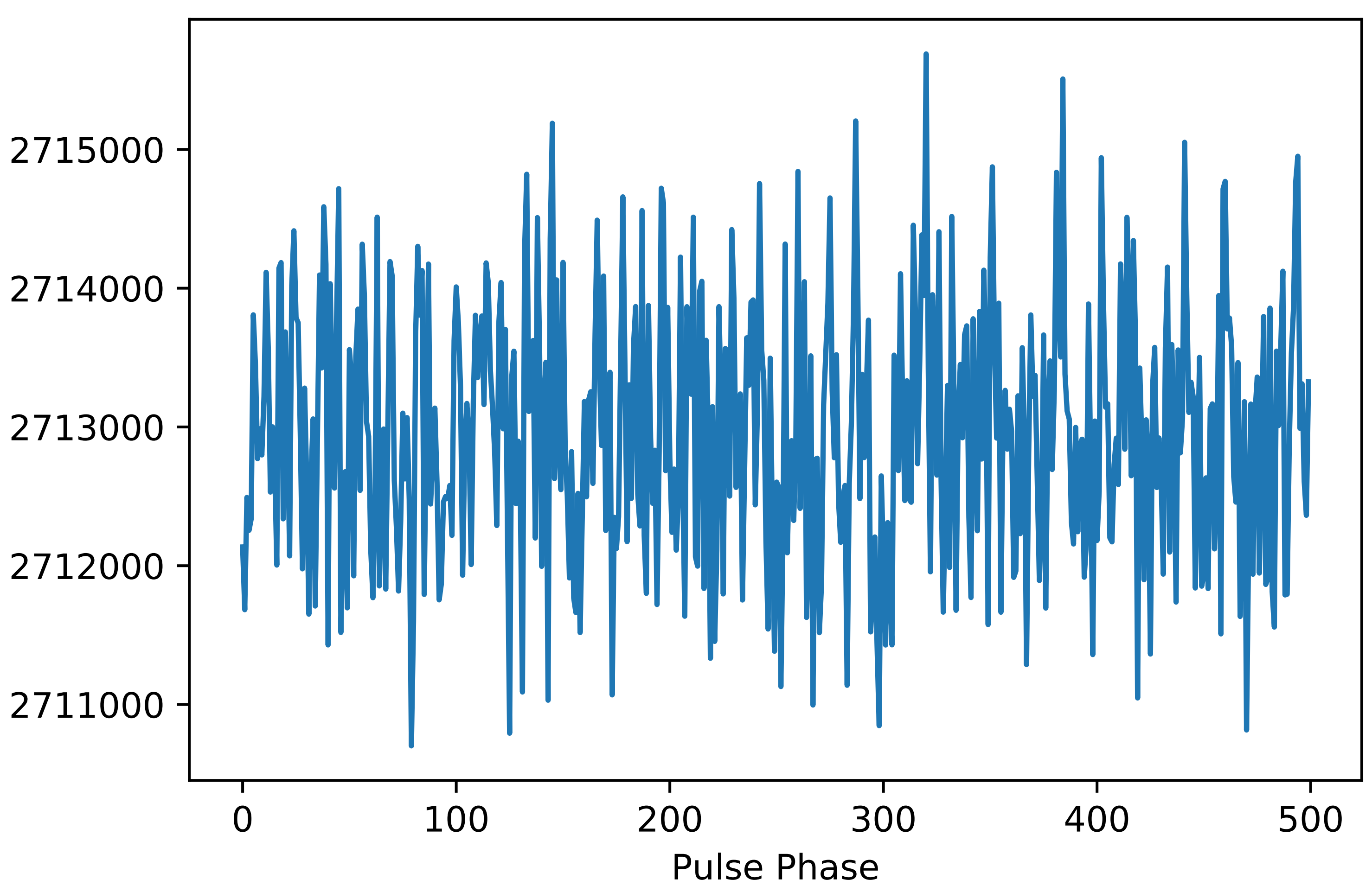
- Phase (time of arrival)
  - Will tell us the distance if we have a very accurate clock
    - Accurate clock through astronomical masers
  - Clock should be occasionally updated by period and phase of pulsar

5. Results

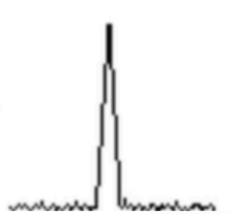


Frequency bins [MHz]
0
200
400
600
800
1000
0
100
200
300
400
500
Pulse Phase

5. Results



2715000
2714000
2713000
2712000
2711000
0
100
200
300
400
500
Pulse Phase



6. Conclusions / Further work

- Analyzed test data from a prototype pulsar detection system
- Determined minimum integration time with a SRT size antenna for pulsar detection
  - 1 Hour: Not enough data to see a pulse (even with folding)
  - Checked through two different analysis methods: same result
  - Future: collect data for a much longer time than 1 hour to enable detection

Future applications:

- Masers to measure spacecraft's velocity
- Masers to measure relative position of multiple spacecraft

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