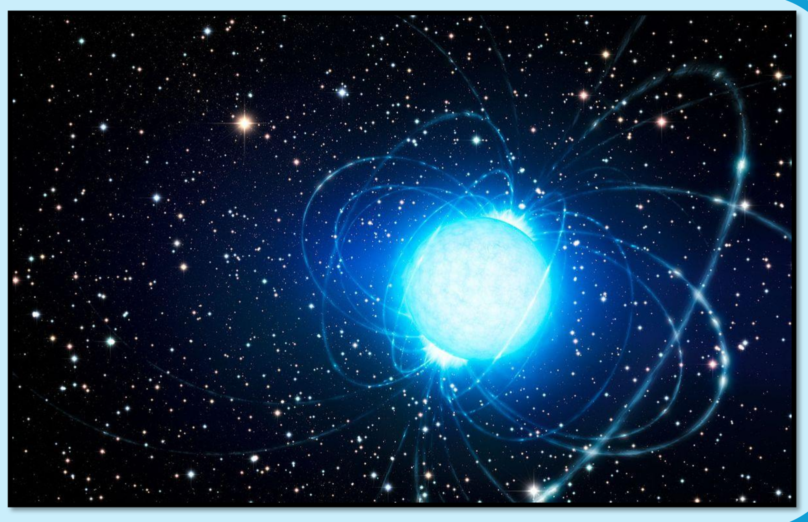
Fast Radio Burst Localization Using a Log-Periodic Dipole Array

UNIVERSITY OF CAMBRIDGE

Project By: William Deng
Supervisor: Dr. Nina Gusinskaia
Acknowledgements: Dr. Rik van Lieshout, Prof. Juan Mena-Parra, José Jáuregui

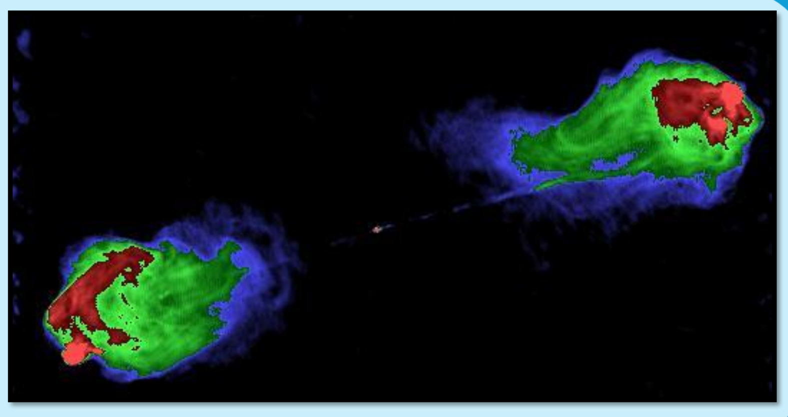
1. Fast Radio Bursts (FRBs)



- ***Energetic**, often **polarized** transient radio wave pulses, typically on **millisecond** time scales.*
- *Most FRBs appear **non-repeating** but small population **do repeat**, suggesting **multiple** sources.*
- *No consensus to date on their **origin**, theories include **magnetars**, **black hole mergers**, **white dwarf collisions**, etc.*
- *Potential for **novel insights** into **dark matter/energy**, **neutron star physics**, **quantum gravity**, etc.*

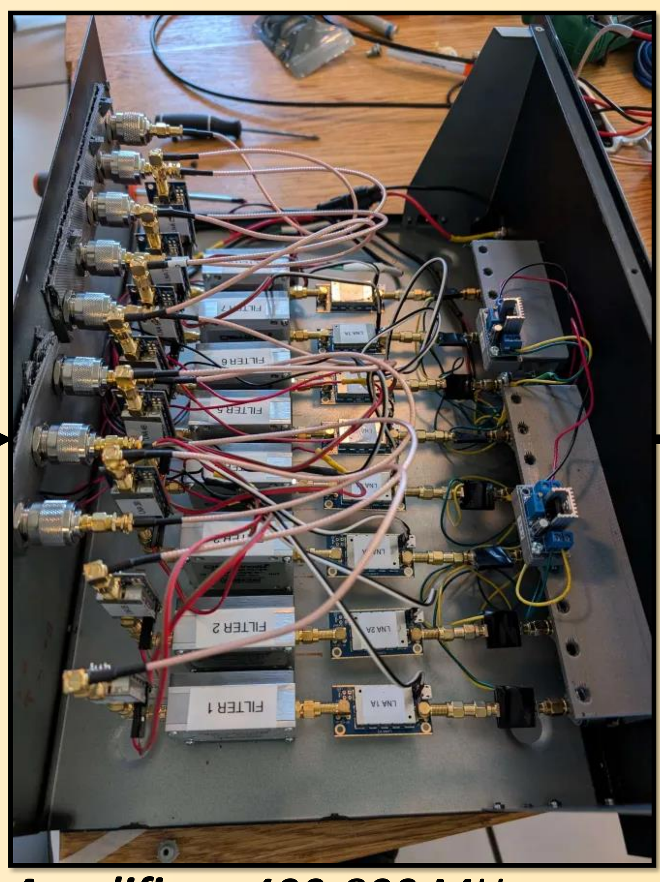
2. Project Summary

- ***Calibration** of log-periodic dipole array using **Sun** as radio source.*
- ***Measurement** of instrument **signal-to-noise ratio** using known **quasars**.*
- ***Detection** of bright **transients** such as **Crab Pulsar** giant pulses.*
- ***Localization** of bright FRBs (especially in **cross-correlation** with CHIME).*

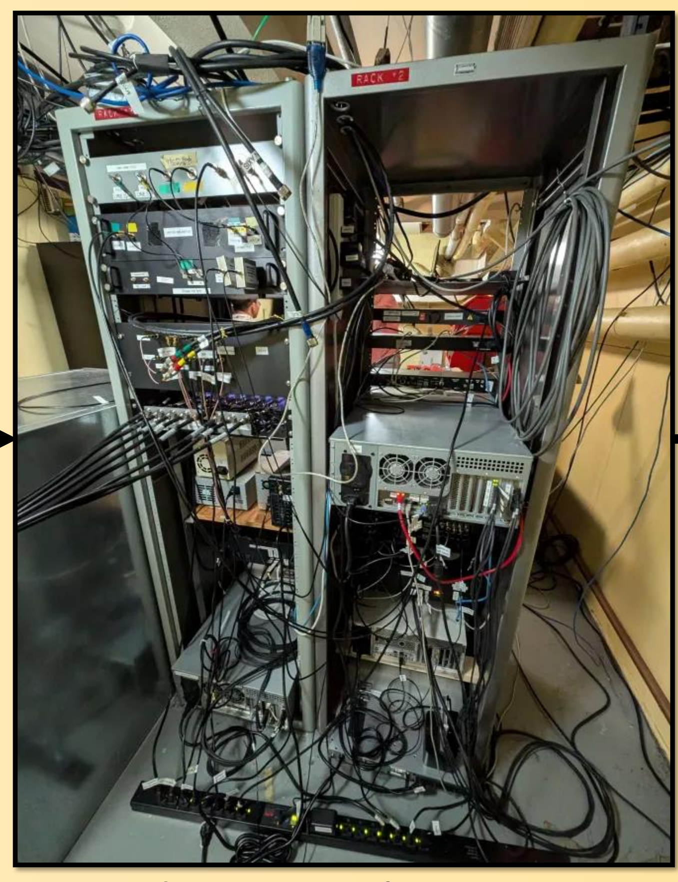


3. Setup of the Experiment

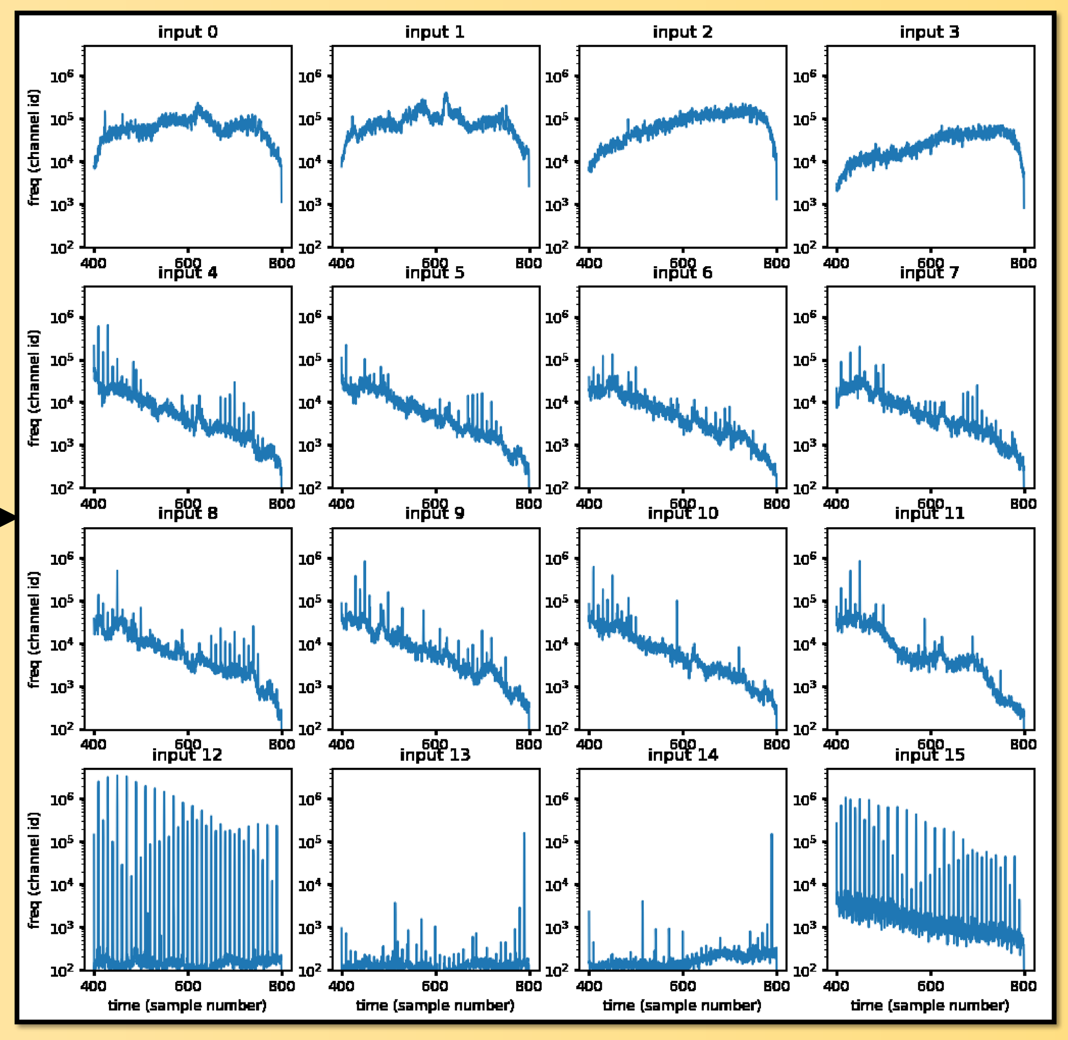
*Log-periodic dipole array of **8 antennas** at **Algonquin Radio Observatory**, 28 **cross-correlations** and 8 **autocorrelations**.*



***Amplifiers**, 400-800 MHz bandpass **filters**, **bias-tees**, **equalizers** and **voltage regulators** for analog **signal processing** of AC voltages.*



***ADCs** digitize analog AC voltages with **390 kHz sampling rate** and **1024 frequency band quantization**, **FPGAs** perform **Fourier-engine processing**.*



***Power** spectra with respect to **frequency** showing **gain characteristics** of log-periodic dipole array after **RFI Faraday cage** installation.*

4. Radio Interferometry Fundamentals

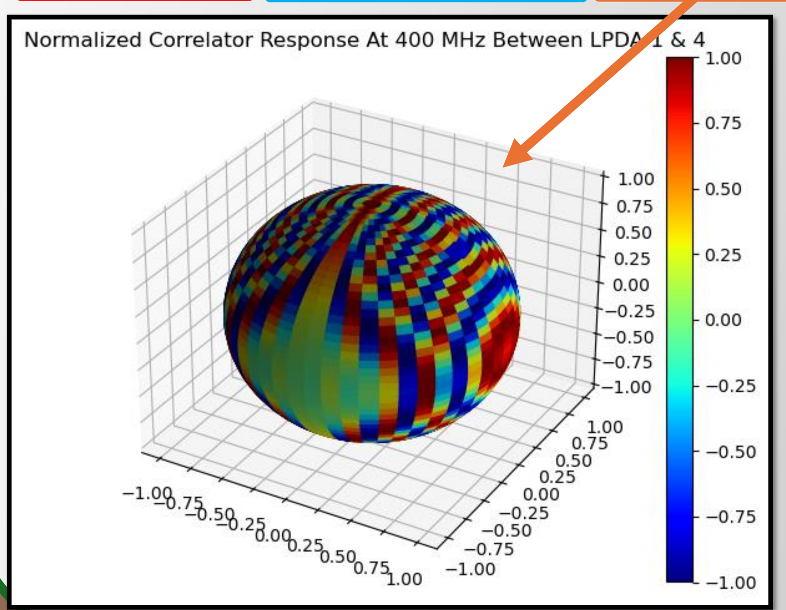
- *Complex **visibility** $V_{jk}(f,t)$ between **antennae** j,k at **frequency** f and **time** t:*

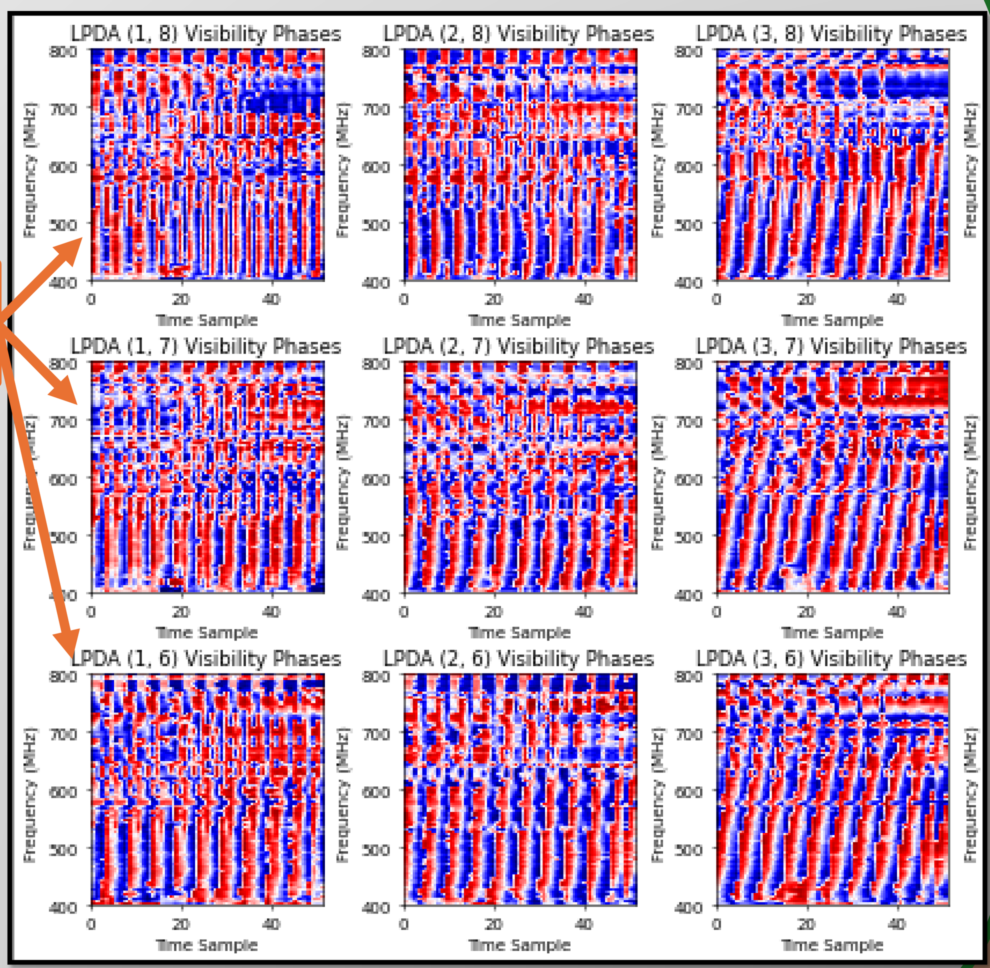
$$V_{jk}(f,t) = \frac{1}{\boxed{\Delta t}} \int_t^{t+\Delta t} \boxed{v_j(f,t') v_k^*(f,t')}\, dt'$$

Integration time

Antenna AC analog voltages

Fringe wrapping





5. Complex Gain Self-Calibration Model

- *Assuming **far-field**, **incoherent** radio sources, **van-Cittert Zernike theorem**:*

$$V_{jk}(f,t) = \oiint_{\hat{\mathbf{n}} \in S^2_{\text{celestial}}} A_j(\hat{\mathbf{n}},f,t) A_k^*(\hat{\mathbf{n}},f,t) \hat{I}(\hat{\mathbf{n}},f,t) e^{-2\pi i f\, \Delta\vec{\mathbf{x}}_{jk}\cdot\hat{\mathbf{n}}/c}\, d^2\hat{\mathbf{n}}$$

- *Due to **ionospheric Faraday rotation**, coax **cable delays**, rubidium **clock delays**, etc.*

$$\tilde{V}_{jk}(f,t) = g_j(f,t) g_k^*(f,t) V_{jk}(f,t)$$

- ***Normalize** visibilities and complex gains via **radiometer equation** $\sigma_T = \frac{T}{\sqrt{\Delta f \Delta t}}$ by corresponding antenna system temperatures T_j ($\propto$ autocorrelation powers):*

$$\tilde{V}'_{jk}(f,t) = \frac{\tilde{V}_{jk}(f,t)}{\sqrt{T_j T_k}} \qquad g'_j(f,t) = \frac{g_j(f,t)}{\sqrt{T_j}}$$

- ***Maximize Gaussian likelihood estimate** by **minimizing** χ^2 Frobenius norm **cost function** for **point source**:*

$$\chi^2(\vec{\mathbf{g}}') = \frac{1}{\Delta f \Delta t} \mathrm{Tr}\left(\tilde{V}' - \vec{\mathbf{g}}'\vec{\mathbf{g}}'^\dagger\right)\left(\tilde{V}' - \vec{\mathbf{g}}'\vec{\mathbf{g}}'^\dagger\right)^\dagger$$

$$\frac{\partial \chi^2}{\partial \vec{\mathbf{g}}'} = \vec{\mathbf{0}}$$

Hermitian: real orthogonal eigenbasis for $\mathbf{C}^8$, pick largest

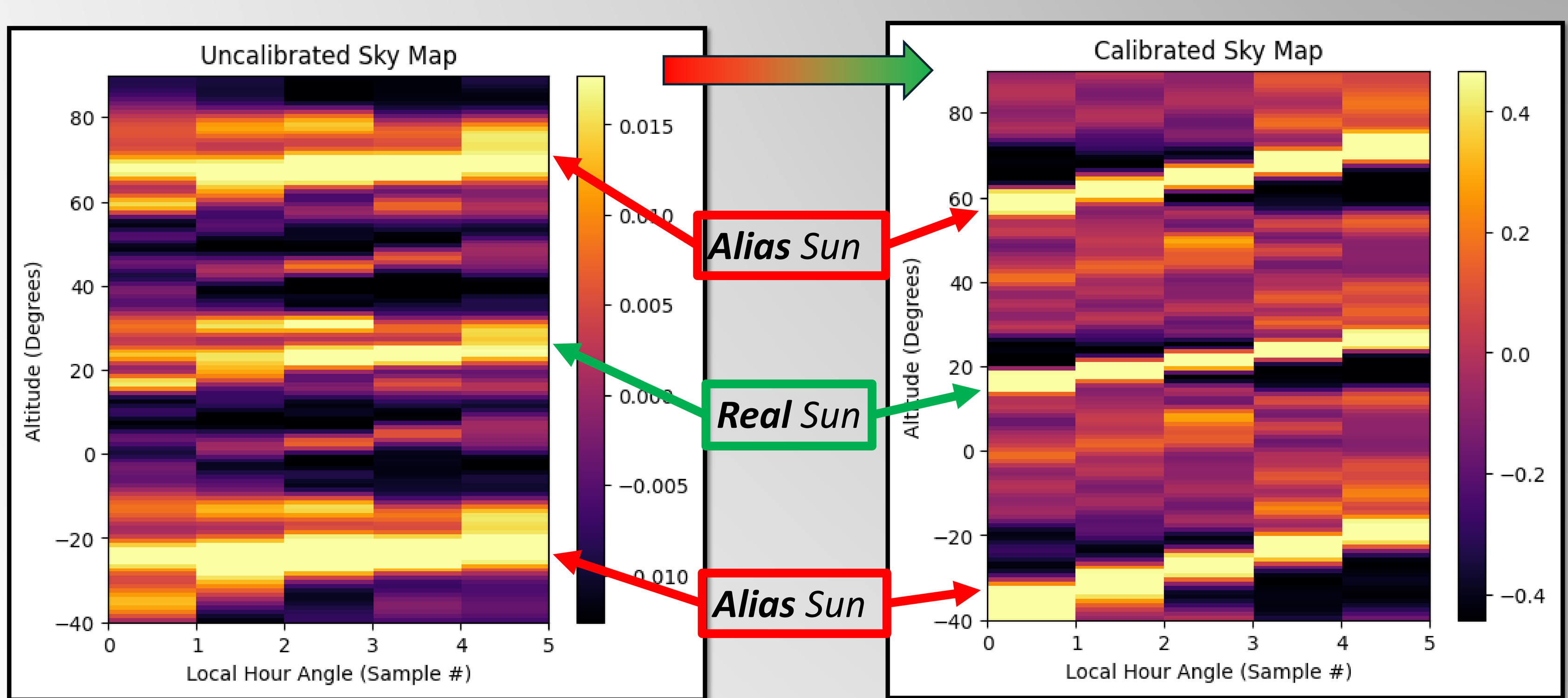
$$\tilde{V}'\vec{\mathbf{g}}' = |\vec{\mathbf{g}}'|^2 \vec{\mathbf{g}}'$$

Normalized complex gain vector $\vec{\mathbf{g}}' = \vec{\mathbf{g}}'(f,t)$

6. Fringestopping & Results

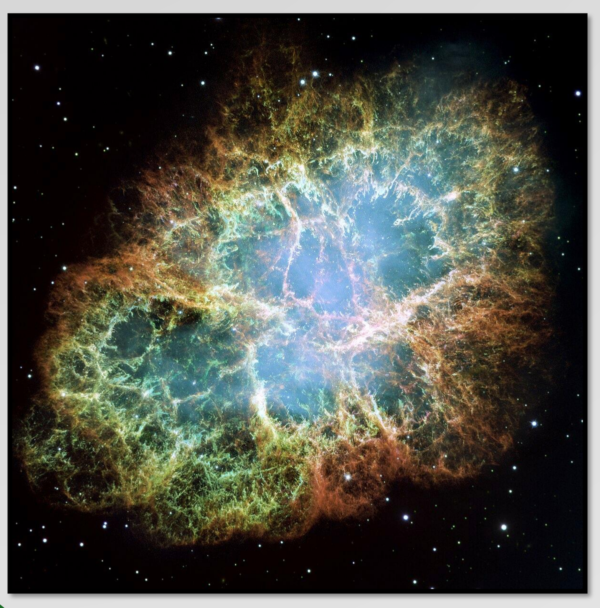
- *Idea is to **artificially** insert various combinations of **time delays** in the 8 antennas of the LPDA to achieve **coherent interference** of radio waves. To **fringestop** the sky at frequency f in direction $\hat{\mathbf{n}}_0$, apply the $U(1)$ transformation to **rotate** the visibility phases:*

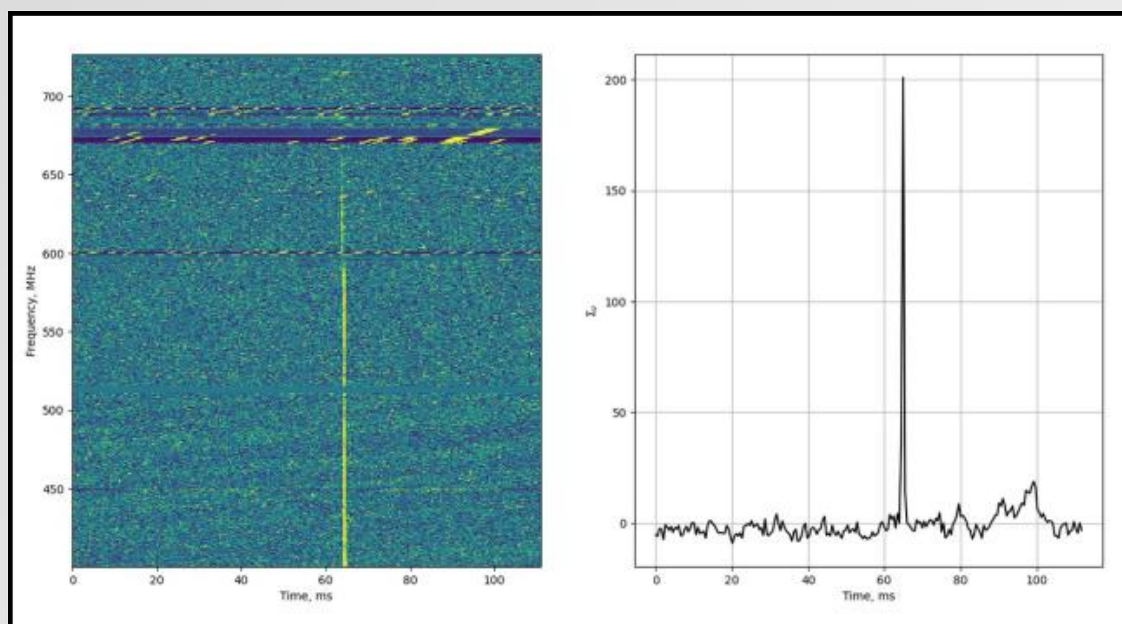
$$V_{jk}(f,t) \mapsto V_{jk}(f,t) e^{2\pi i f \Delta\vec{\mathbf{x}}_{jk}\cdot\hat{\mathbf{n}}_0/c}$$



7. Future Work

- *Use the complex **gains** $g_j(f,t)$ obtained from calibration to **beamform** the **raw baseband voltages** $v_j(f,t)$ to improve **time resolution** to the order of the **ADC sampling period**.*
- *Execute **tests** to confirm that **beamforming** works by making sky maps from it and **comparing** with those obtained from **fringestopping**.*
- *Use **beamforming** to detect **transient radio sources** such as **Crab Pulsar giant pulses**.*
- *Ultimately, use the LPDA to detect and **localize fast radio bursts** (especially **side lobe events** at CHIME).*





Contact Information: *wdd24@cam.ac.uk, gusinskaia@astro.utoronto.ca, juan.menaparra@utoronto.ca, jmjaureguig@gmail.com*

References: Mena-Parra, J. (2018). *Correlator and calibration for the Canadian Hydrogen Intensity Mapping Experiment*, Perley R. (2018). *Fundamentals of Radio Interferometry.* 16th Synthesis Imaging Workshop. National Radio Astronomy Observatory.