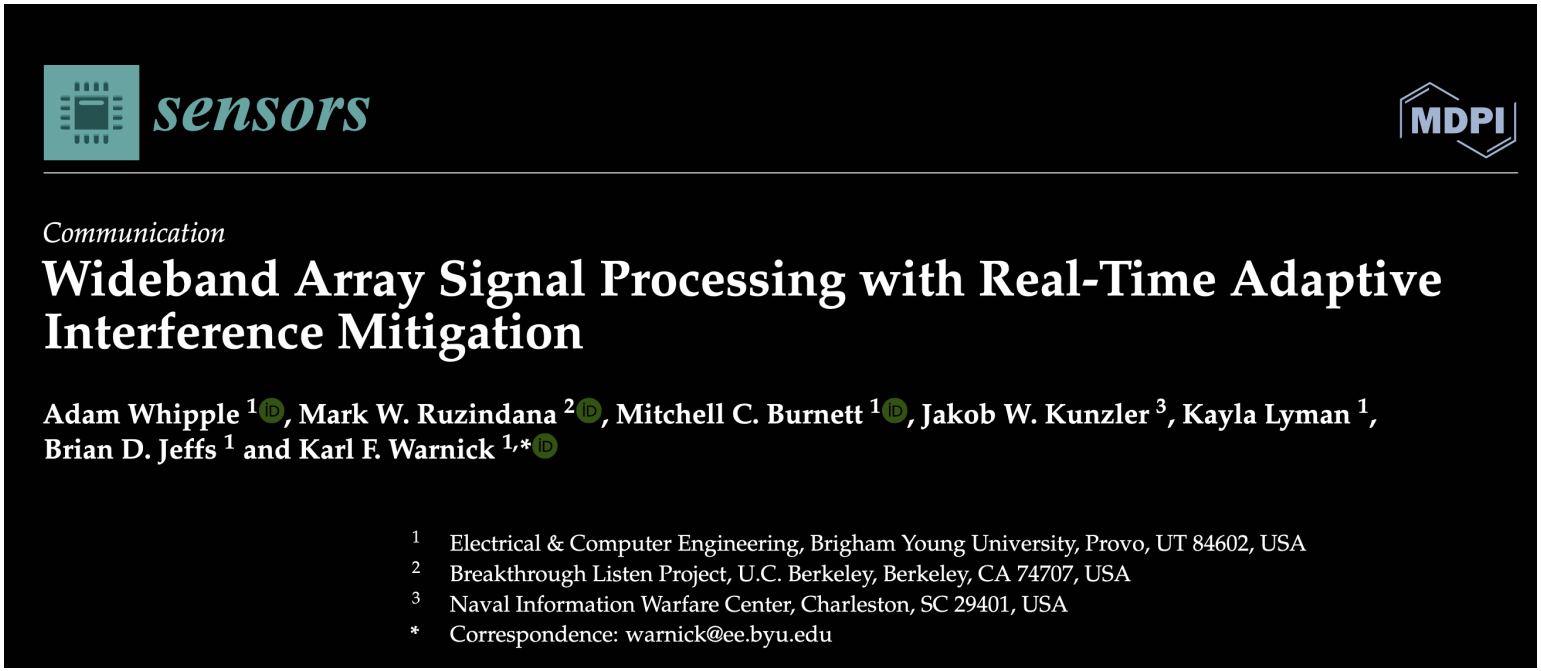

sensors

MDPI

Communication

Wideband Array Signal Processing with Real-Time Adaptive Interference Mitigation

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Outline

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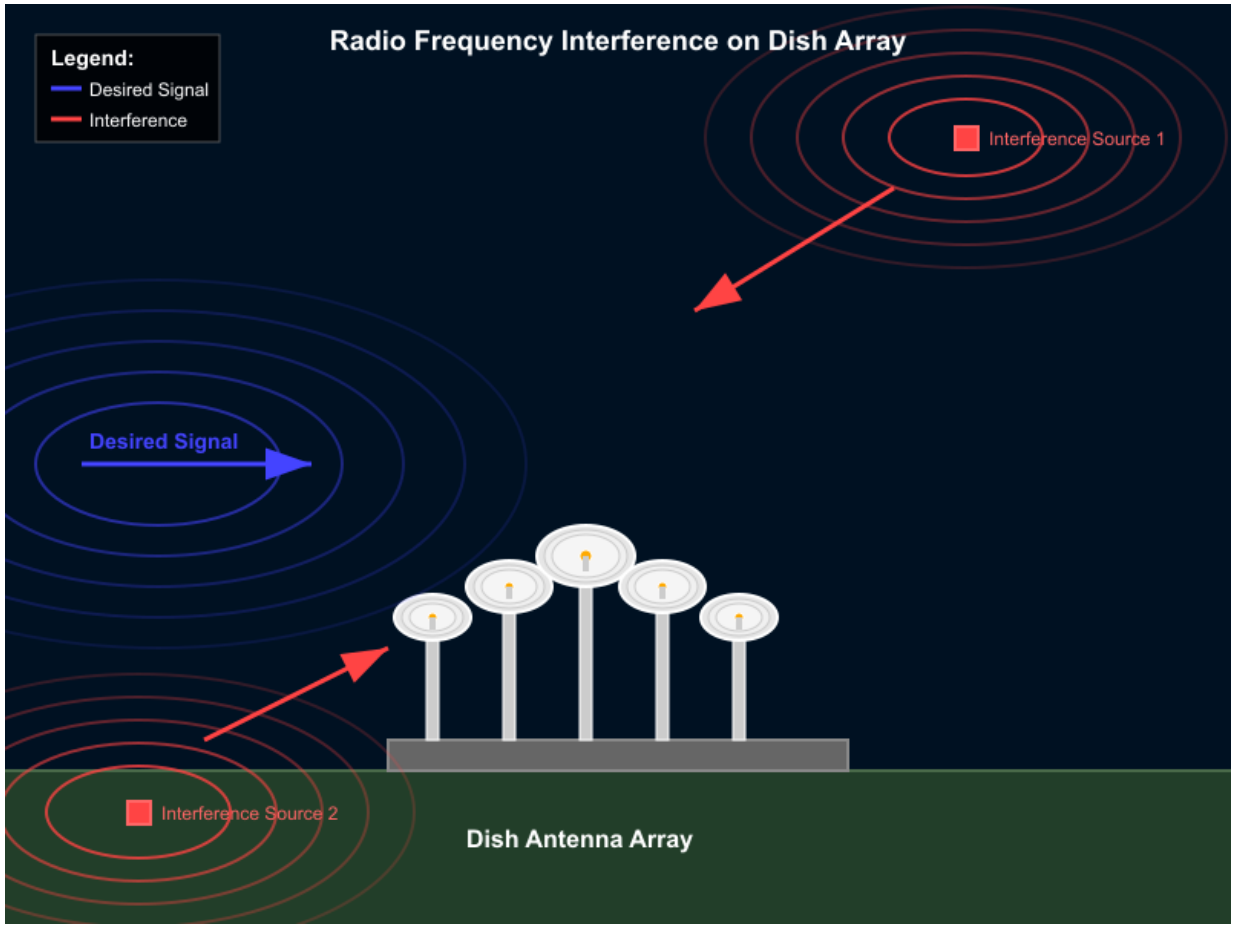
What is Spatial Filtering?

Definition

Spatial filtering is the study of using a known array spatial geometry to enhance or suppress signals arriving from specific directions to the array.

The Problem

- Radio Frequency Interference (RFI) is a problem! How can we recover as much of the celestial signal as possible?



Credit: Claude for base SVG code

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The Problem

- Radio Frequency Interference (RFI) is a problem! How can we recover as much of the celestial signal as possible?
- Can we do this fast enough in real time on GPUs?
  - Raw voltage streams are not saved at fine resolution - this cannot be done offline.

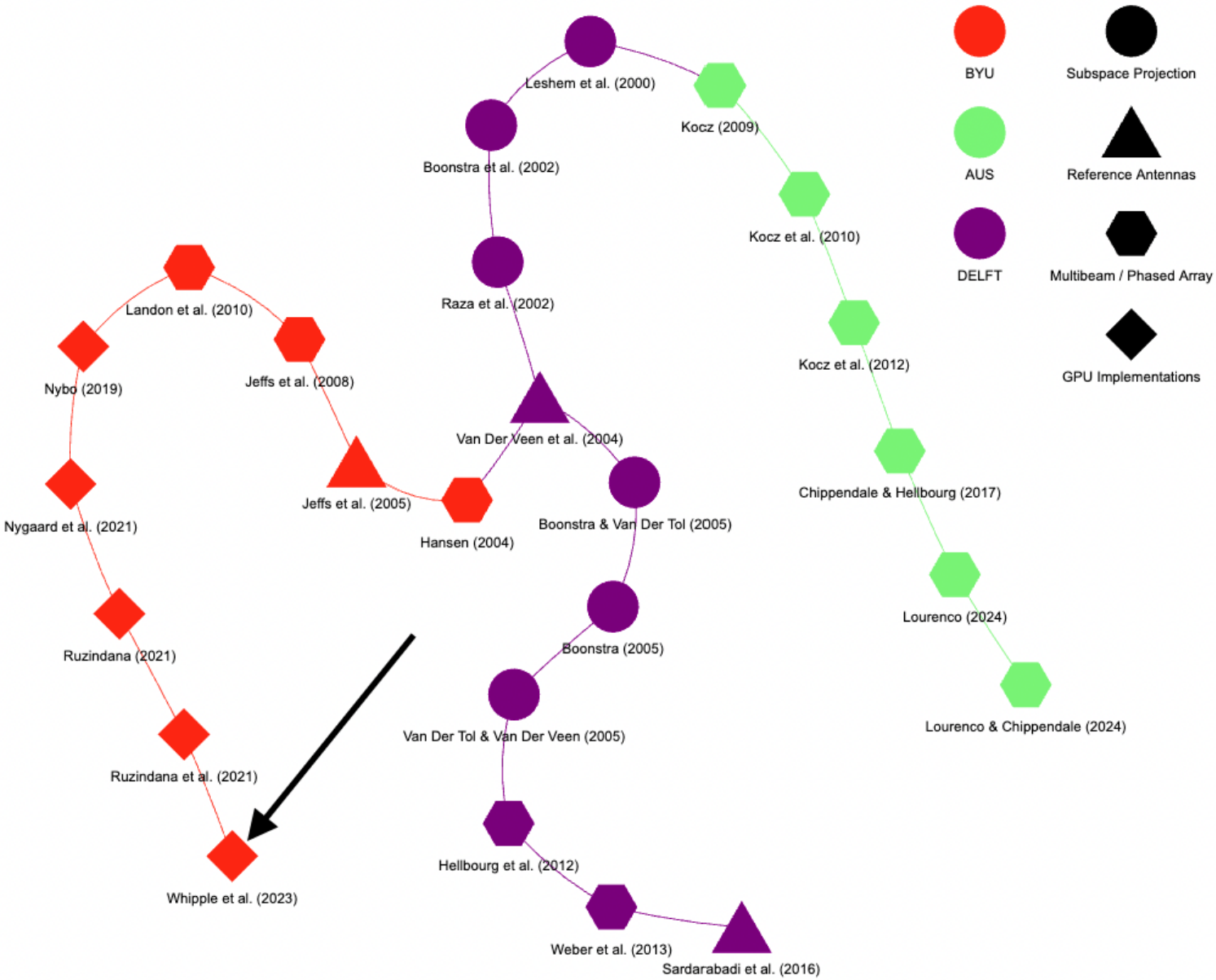
The Problem

- Radio Frequency Interference (RFI) is a problem! How can we recover as much of the celestial signal as possible?
- Can we do this fast enough in real time on GPUs?

This Paper

- Currently the most developed RFI-mitigation system via spatial filtering on GPUs.
- Presents a proof-of-concept system for a 4x4 Phased Array Feed in a laboratory setting.
- Shows that this system works for both a moving narrowband RFI tone and a 50 kHz bandwidth moving wideband RFI tone.

Where This Sits in the Literature



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BYU - Green Bank Telescope

Figure: Credit: https://science.nrao.edu/facilities/gbt

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Spatial Filtering Playbook

1. Take complex voltage data from n antennas and T time samples to create a data matrix X with shape $n \times T$.

Example

$$\mathbf{X} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1T} \\ a_{21} & a_{22} & \cdots & a_{2T} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nT} \end{bmatrix} \in \mathbb{C}^{n \times T}$$

Spatial Filtering Playbook

1. Take complex voltage data from n antennas and T time samples to create a data matrix X with shape $n \times T$.
2. Form the covariance matrix $\mathbf{C} = \mathbf{X}\mathbf{X}^{\mathrm{H}}$ which is $n \times n$ Hermitian.

Example

$$\mathbf{C} = \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1n} \\ \overline{\sigma_{12}} & \sigma_2^2 & \cdots & \sigma_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \overline{\sigma_{1n}} & \overline{\sigma_{2n}} & \cdots & \sigma_n^2 \end{bmatrix}$$

Spatial Filtering Playbook

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3. Decompose the matrix using eigendecomposition into the form $\mathbf{C} = \mathbf{U}\boldsymbol{\Lambda}\mathbf{U}^{\mathrm{H}}$.

Example

$$\mathbf{C} = \begin{bmatrix} \mathbf{u}_1 & \mathbf{u}_2 & \cdots & \mathbf{u}_n \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} \mathbf{u}_1{}^H \\ \mathbf{u}_2{}^H \\ \vdots \\ \mathbf{u}_n{}^H \end{bmatrix}$$

Spatial Filtering Playbook

1. Take complex voltage data from n antennas and T time samples to create a data matrix X with shape $n \times T$.
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3. Decompose the matrix using eigendecomposition into the form $\mathbf{C} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^{\mathsf{H}}$.
4. Use this to adjust the beamforming weights in order to remove interference:
   - 4.1 Nulling eigenvalues,
   - 4.2 Shrinking eigenvalues,
   - 4.3 Orthogonal / Oblique subspace projection.

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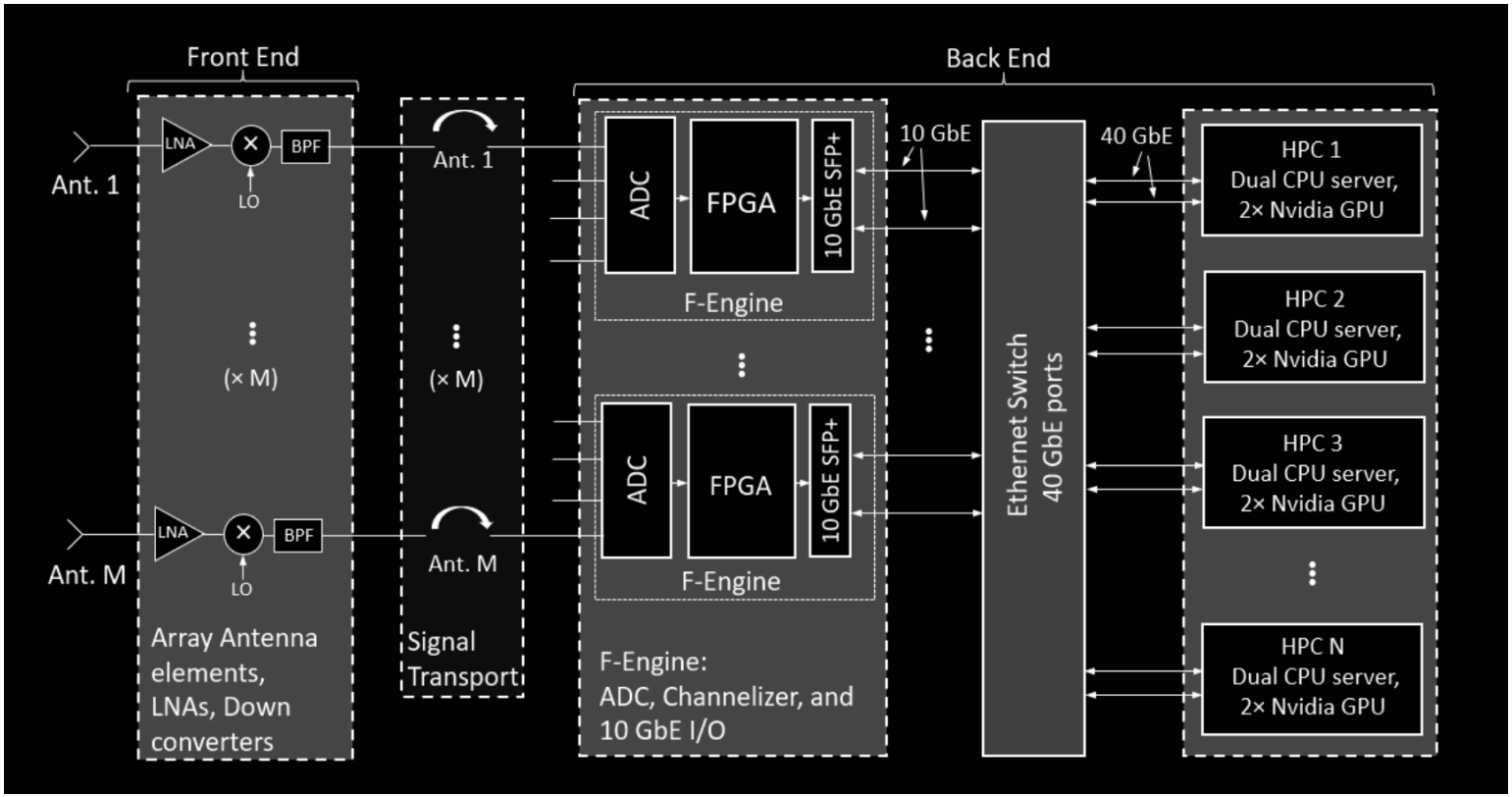
System Architecture



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System Architecture

- Uses a heterogeneous F-XB architecture:
  - F: Fourier transform - done using FPGAs.
  - X: Correlation - done using GPUs.
  - B: Beamforming - done using GPUs.

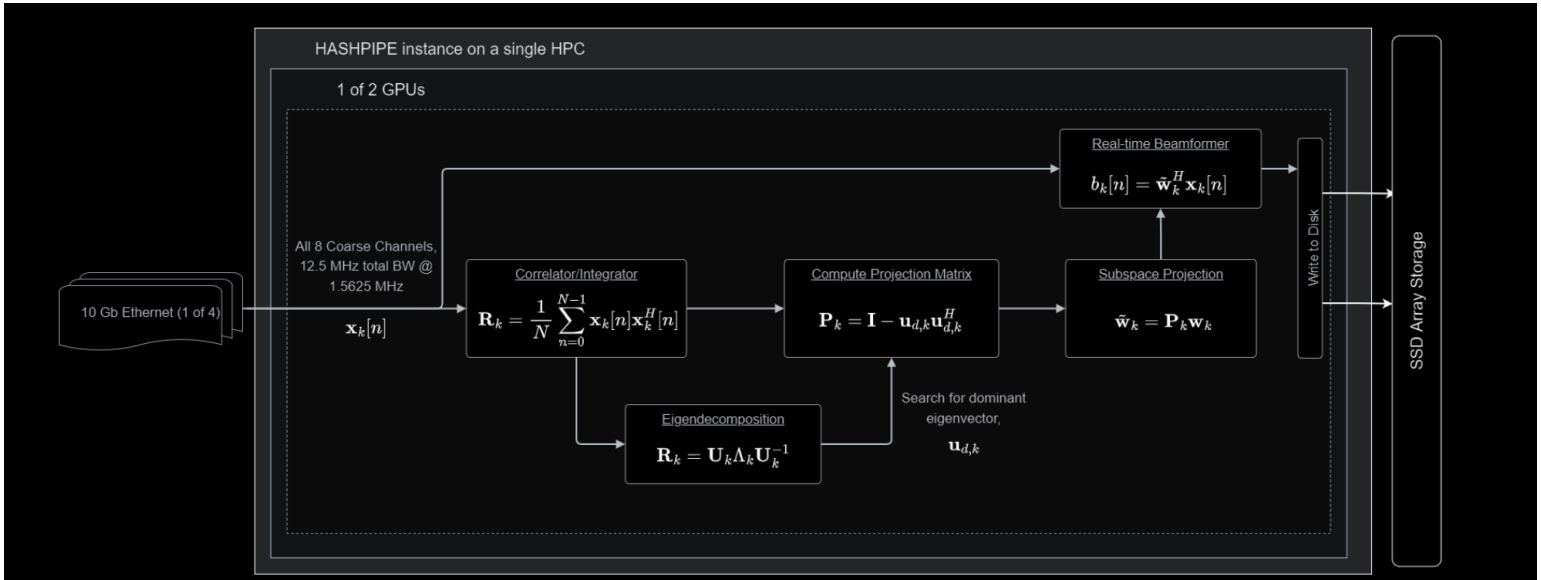

Figure 2. Functional diagram of the system including the subspace projection algorithm. The received signal is correlated and then decomposed into its eigenvector and eigenvalue components. The strongest eigenvector is assumed to be a representation of the RFI. A projection is created using this eigenvector and applied to the signal to remove the interferer.

- Beamforming weights are updated using spatial filtering algorithms after the correlation step.

System Architecture

- Uses a heterogeneous F-XB architecture:
  - F: Fourier transform - done using FPGAs.
  - X: Correlation - done using GPUs.
  - B: Beamforming - done using GPUs.
- Data is sampled every 2.5 ns. Channellization is a 256-point FFT so resolution after channelization is ≈ 640 ns.
- Original frequency band is centered at 10.2 GHz.
- Bandwidth is 96 channels of 1.5625 MHz each for total operating bandwidth of 150 MHz. 16 channels are discarded.
- Weights are updated using 4250 time steps which corresponds to 2.7 ms.

Narrowband Cancellation

- Uses a 4x4 grid of antennas in a lab environment.
- Signal Generators for:
  - Signal of Interest stationary at array boresight.
  - Moving RFI signal beginning at 45 degrees to array.
- Scan duration was 6 seconds and RFI source moved 20 degrees in that time.
  - At cruising altitude, this is about 3.5x the speed of a plane (235 m/s vs 740 m/s).
  - For a GPS satellite, this is an order of magnitude faster.
- Signal-to-Noise Ratio was 25 dB, Interference-to-Noise Ratio was 35 dB.
- Beamforming weights were unity before filtering weight updates (i.e. no MaxSNR beamforming).

Narrowband Cancellation Results

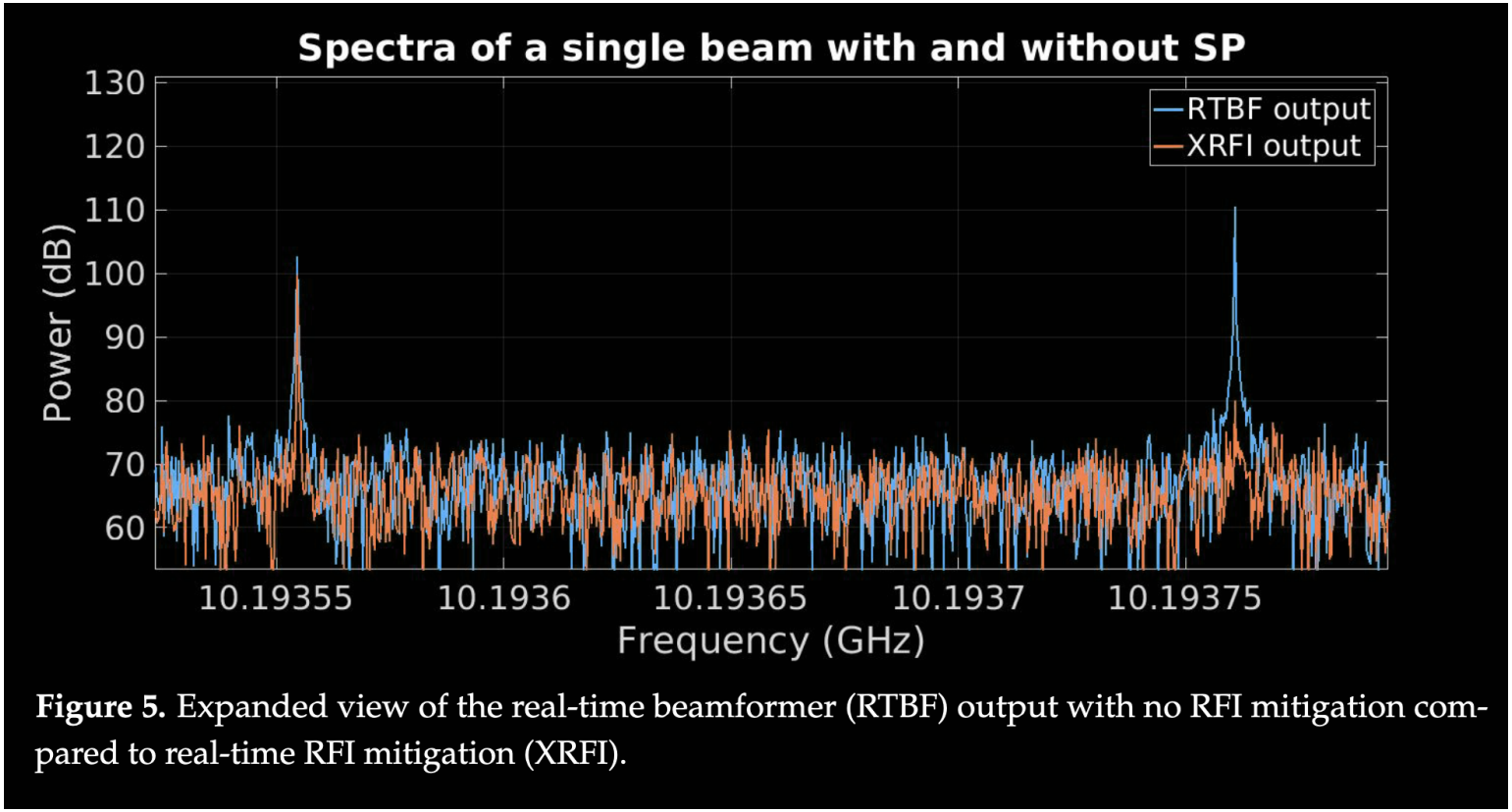

Figure 5. Expanded view of the real-time beamformer (RTBF) output with no RFI mitigation compared to real-time RFI mitigation (XRFI).

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Wideband Cancellation

- Uses a 50kHz wide modulated signal at a 45 degree angle to signal of interest.

Wideband Cancellation Results

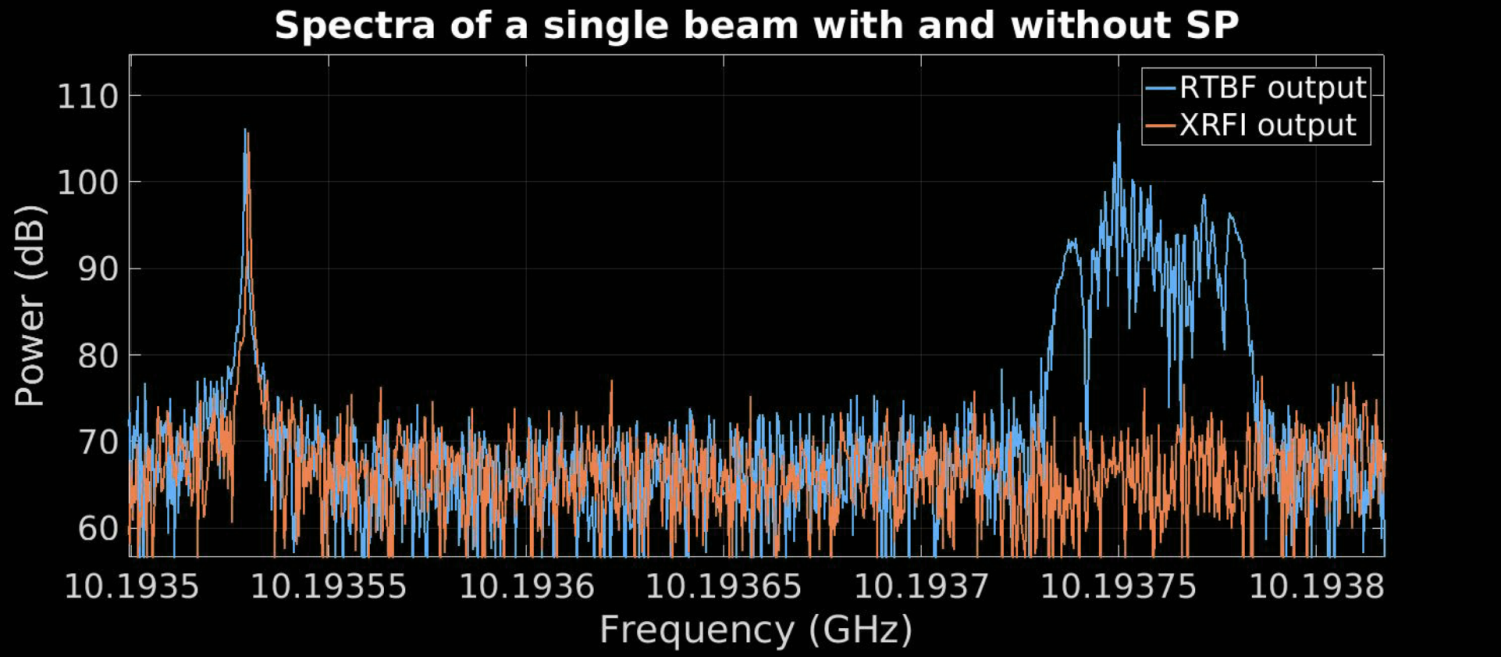

Figure 7. Expanded view of the spectrum of the beamformer output with no RFI mitigation compared to real-time RFI mitigation (XRFI) with modulated RFI source.

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Is it fast enough?

- 2.7 ms of data was used for each beamforming weight update.
- They report that the GPU section of processing was completed in 2.3 ms with active cancellation as opposed to 1.4 ms for only beamforming.
- No breakdowns are given, and it does not seem like PCIe transfer speed was included in this total, which can be a significant bottleneck (Ruzindana 2021).

Can we do better?

- Currently it supports only a 16-element phased array feed. ALPACA will have 69 elements when it is installed on GBT in late 2025.
  - Murriyang CryoPAF has 196!
- Only one eigenvalue is nulled, higher dimensional spaces with multiple interferers will require more eigenvalues.
  - It's also assumed that the strongest signal is the interference!
- Signal of interest and RFI are present in the same coarse channels - what if they are in different channels?
- How will this affect pulsar searching (see Kocz et al. 2010)? Can we use oblique projection instead (Hellbourg 2012)? Can we do better than oblique projection?