GPU Beamforming for Phased Array Feeds

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11th April, 2025

Outline

- Who am I?
- What is a Phased Array Feed (PAF), & What's a Beam and How Do We Form Them?
- Why GPUs for Beamforming?
- Science Opportunities!
- What I've Done & What's Next?

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What's 18F?

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Oh....ATNF!

Who Am I Working With?

- **Swinburne:** Professors Adam Deller & Matthew Bailes,
- **CSIRO:** Dr Chris Phillips,
- **Fourier Space:** Andrew Jameson.

Phased Array Feeds (PAF)

Made up of 188 receivers in a checkerboard pattern.

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Figure: A PAF on an ASKAP antenna. Credit: CSIRO.

Phased Array Feeds

- Can be mathematically steered to create many beams on the sky simultaneously.
- E.g. ASKAP creates 36 dual-polarization beams on the sky for a field-of-view of 30 square degrees.
- A CryoPAF is being commissioned at Murriyang.

Beamforming

How do we combine all these antennas into a beam?

Beamforming

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Ingredients:

- 188 separate data streams from individual antenna elements,
- Compute Power.

Method:

- Weight & sum the data streams to form beams.
- At its simplest, weights are delays between antennas to maximize sensitivity to signals from a particular direction.
- Different weighting schemes can be attractive as well (shaped beamforming).

Beamforming

- Express these weights as a vector ω_i,
- Stack beam weights into a matrix ω,
- Matrix multiply weights against data to create many beams in parallel:

$$\text{Beams} = \omega \times \text{Data}.$$

Why GPUs?

How is beamforming currently done?

Beamforming uses Field Programmable Gate Arrays (FPGAs).

- Pros:
  - FPGAs are extremely flexible,
  - Excels at base signal processing,
  - Can often hit peak performance as you can tailor architecture to your problem.

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- Cons:
  - Increased development time,
  - Difficult to iterate and prototype on,
  - Difficult to do more than base signal processing,
  - Limited pool of talent, very complex to develop & debug!

Why GPUs?

- Faster development cycle,
- Built for parallelism,
- Consumer availability,
- Software-based approach rather than hardware.
  - Can use C / C++ rather than Verlog / VHDL,
- Larger pool of talent.

Comparison of Different Methods

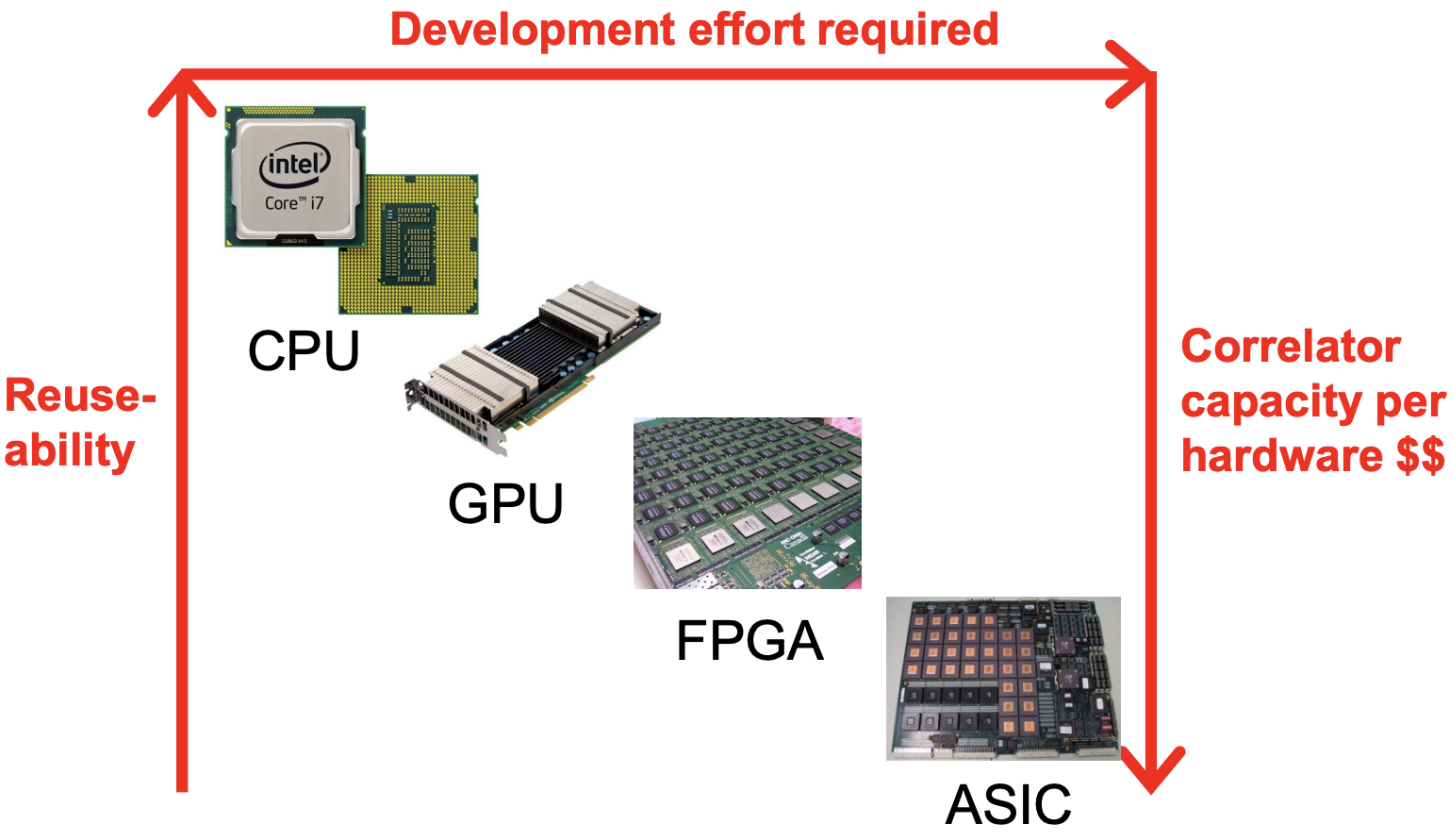

Figure: Credit: A Deller.

Current GPU-based Beamformers

- COBALT - LOFAR (Broekema et al. 2018).
- CHIME (Ng et al. 2017).
- BLADE - Allen Telescope Array.

Science Opportunities

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Two Main Areas of Application:

- Radio Frequency Interference Mitigation,
- Real-time Identification of Astronomical Signals.

Radio Frequency Interference Mitigation

A multi-pixel receiver like a PAF has a significant advantage when detecting RFI:

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A multi-pixel receiver like a PAF has a significant advantage when detecting RFI:

- Celestial source will be in some of the beams, but RFI will be in all the beams!
- Can use methods like spatial filtering to subtract off common signals between beams.
- Requires correlation matrix between different beams - highly parallelizable.

Shaped Beamforming

- (Kocz et al. 2010, 2012) explores a spatial filtering approach to removing RFI.
  - In the beamforming phase, can weight & sum in particular ways to get null response towards a particular direction.
  - Requires calculation of array correlation matrix (ACM).
  - GPU-based beamforming may give sufficient performance to allow this in real-time.
- (Finlay et al. 2023) provides a method to deal with interference sources moving on a fixed trajectory.
  - Further work suggested - using GPUs to correlate across frequency bands as well as beams.

Real-time Identification of Astronomical Signals

- Can we detect in real-time if there is something interesting in a beam? I.e. Fast Radio Burst.
- Use of machine learning models to flag interesting data points.
- GPU-based system allows rapid development & feedback loop.
- GPUs allow easy integration with machine learning libraries.

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- Created a Python package for decoding CODIF data, pycodif (https://github.com/jdgsmallwood/pycodif).
- Leveraged sample jimble data from the Murriyang CryoPAF commissioning to write a crude beamformer in Python.
- Created CUDA kernels for an initial (naive) beamforming implementation with 1 beam.
- Side Project: Satellite Two Line Elements (TLEs), adjusting a TLE to agree with new observed positions.

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- Prototyping optimized kernels using cuBLAS & tensor-core operations.
- Exploring implementations for RFI-mitigation techniques for stationary sources (spatial filtering, etc.).
- Extending to moving sources (satellites, aircraft).

Questions?