A Real-Time Imaging Correlator for Compact Radio Arrays

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PAFAR Workshop 2022

EPIC Team

- Judd D. Bowman (ASU) - PI
- Greg B. Taylor (UNM)
- Jayce Dowell (UNM)
- Adam P. Beardsley (WSU)
- Krisha Reddy (ASU)
- Craig Taylor (UNM)
- Matthew Kolopanis (ASU)
- Nithyanandan Thyagarajan (CSIRO)

Outline

Motivation

Radio Interferometry & Conventional Correlator

Fourier Imaging – EPIC

Optimization & Commensal Imaging

Planned Upgrades

Summary

Motivation

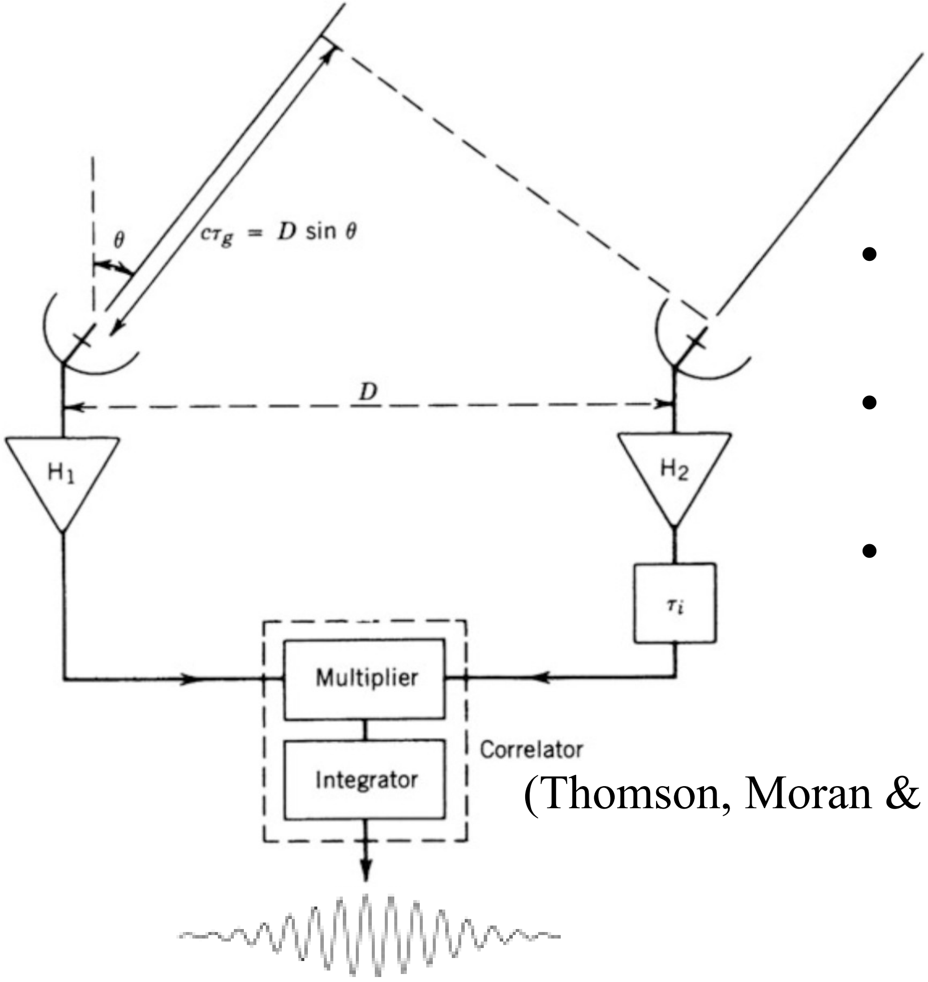
Scientific :

- HI-Intensity mapping with sensitive radio arrays having a compact configuration (HERA : DeBoer et al 2015, CHORD, Vanderline et al 2019)
- Low frequency radio transients like Fast Radio Burst (FRBs : Plenius et al 2020), Meteor Radio Afterglows (MRAs : Obenberger et al 2016) , cosmic ray air shower
- Observational study of stellar flares on sun-like stars (Zic et al 2020)
- Radio emission from exoplanetary systems (Vedantham et al 2020; Turner et al 2020)

Technical :

- Requirements of sensitivity, wide field-of-view and high angular resolution
- Current and next-generation radio telescopes rely heavily on digital signal processing techniques
- Real-time imaging across a wide frequency band at very high temporal resolution

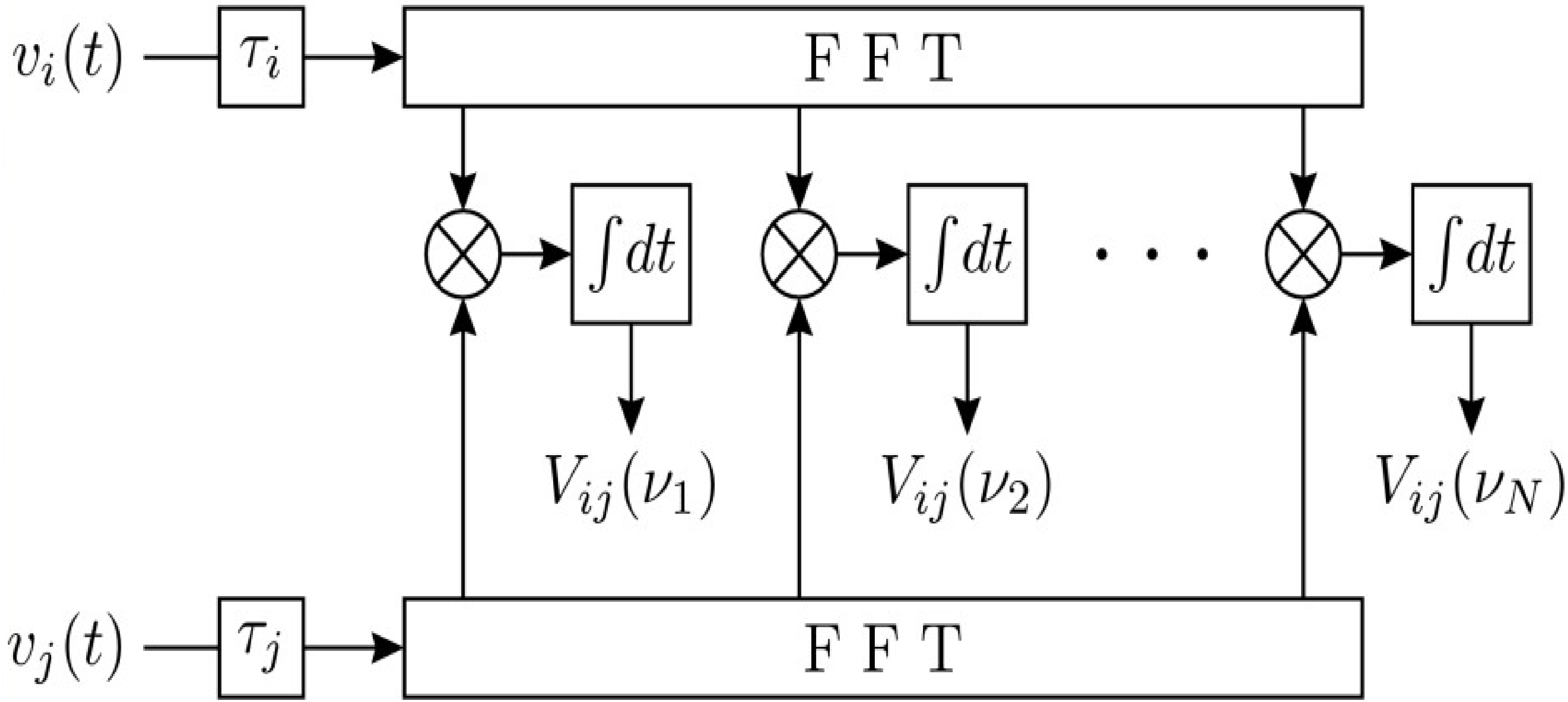
Radio Interferometry



- Two-element interferometer – Fundamental Unit of any radio telescope
- Cross-correlation – Multiplication & Integration of voltages to measure visibilities
- Baseline separation between antennas decides the spatial sampling of the sky

(Thomson, Moran & Swenson, 2017)

Conventional FX Correlators



E-Field Parallel Imaging Correlator (EPIC)

- Generic correlator implementation for real-time imaging in large-N dense arrays (viz. HERA, CHORD, HIRAX, etc.)
- Based on the Modular Optimal Frequency-Fourier (MOFF : Morales 2011) mathematical formalism for direct Fourier imaging
- Grid electric fields from individual antennas and spatially Fourier transform to sky image : synthesizing the aperture on-the-fly
- Significant reduction in computational scaling from $O(n_a^2)$ to $O(n_g \log_2 n_g)$ (where n_a is the number of antennas and n_g is the number of grid points)

Direct Imaging Techniques

- MIT EoR Experiment with FFTS / Omniscope - Tegmark & Zaldarriaga 2009, 2010
- Basic Element for SKA Training II array (Foster et al 2014)
- MOFF - Ability to naturally account for heterogeneity of antennas

Standard Fourier Relation

$$I(l,m,w) = \iint V(u,v,w) \exp\left[2\pi i\left(ul + vm + w\left(\sqrt{1-l^2-m^2}-1\right)\right)\right] du\,dv$$

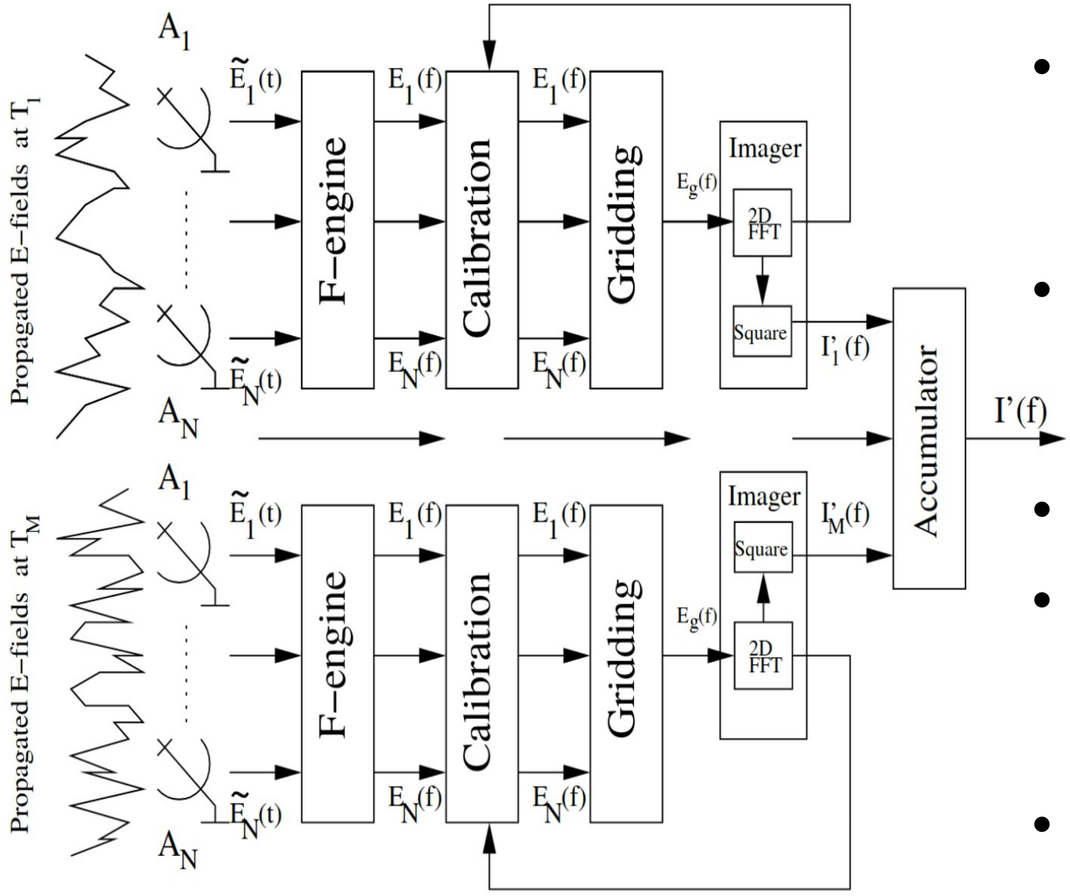
→

MOFF

$$I(l,m) = \left\langle \left| \iint \left[W(x,y) * E'(x,y)\right] \exp\left[2\pi i\left(xl + ym\right)\right] dx\,dy \right|^2 \right\rangle$$

'W' – Gridding Function

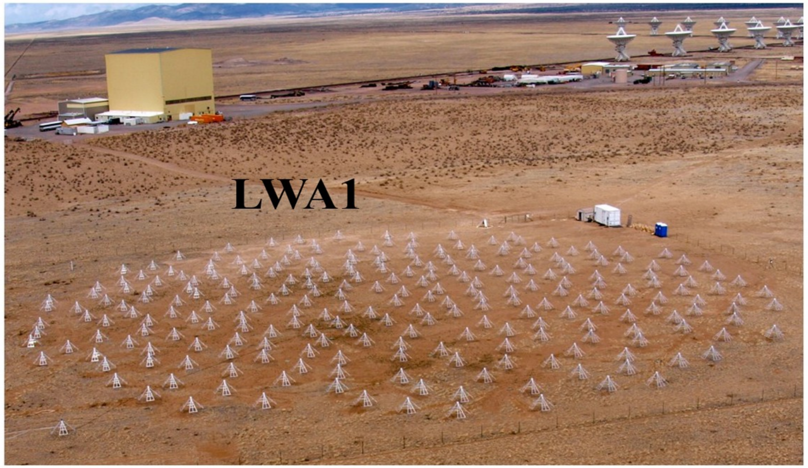
EPIC in a Nutshell



(Thyagarajan et al. 2017)

- Propagated electric fields (E(t)) are measured as time-series from individual antennas
- E(t) transformed by the F-engine to produce electric field spectra (E(f))
- E(t) is calibrated and gridded
- The gridded electric fields $E_g(f)$ from each time series are imaged
- Images are time-averaged to obtain final image I′(f)

Long Wavelength Array (LWA)



(Courtesy : Jayce Dowell & Greg Taylor)

LWA Observatory (UNM) - Two independent stations :

- LWA1, co-located with VLA, New Mexico, USA
- LWA-SV located at Seviletta National Refuge, New Mexico, USA
- 256 Antennas → 10-88 MHz ; pseudo-random placement within an elliptical aperture 100 x 110 m
- Phased-array multi-beam observations Upto 3 simultaneous beams possible

Bifrost

(Danny's Talk)

C++/Python streaming framework

Used to build hybrid FPGA/GPU systems

GPU support through CUDA API

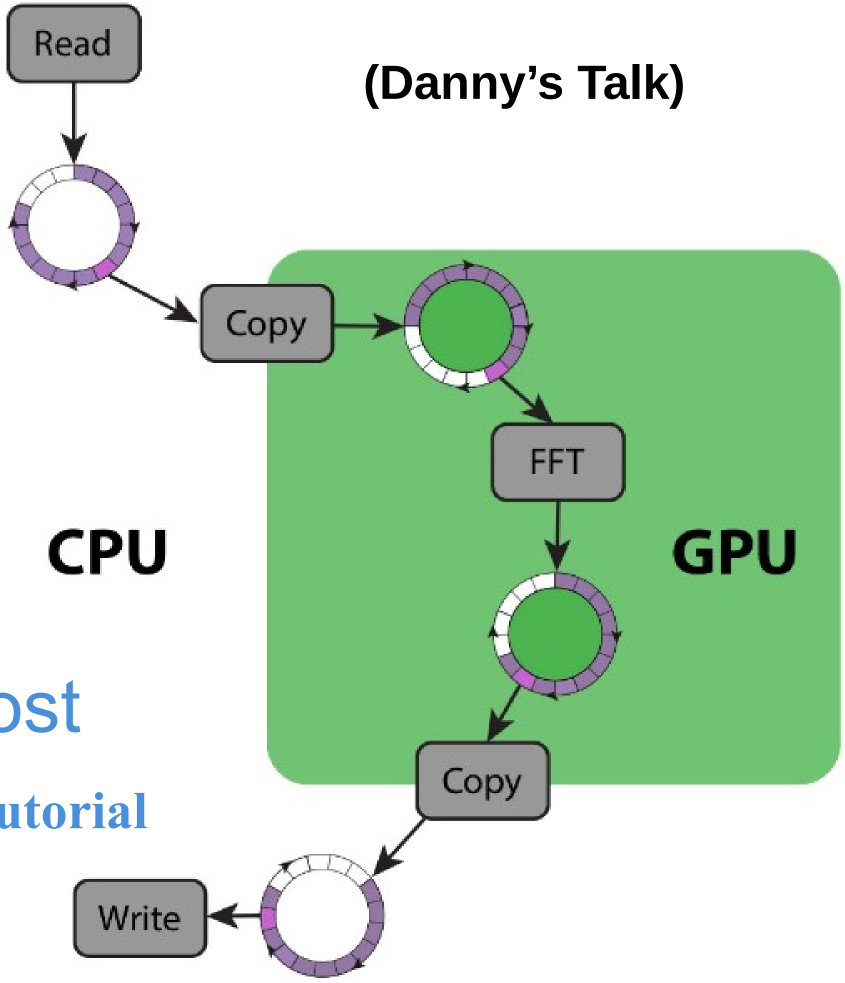
Cranmer et al. 2017

https://github.com/ledatelescope/bifrost

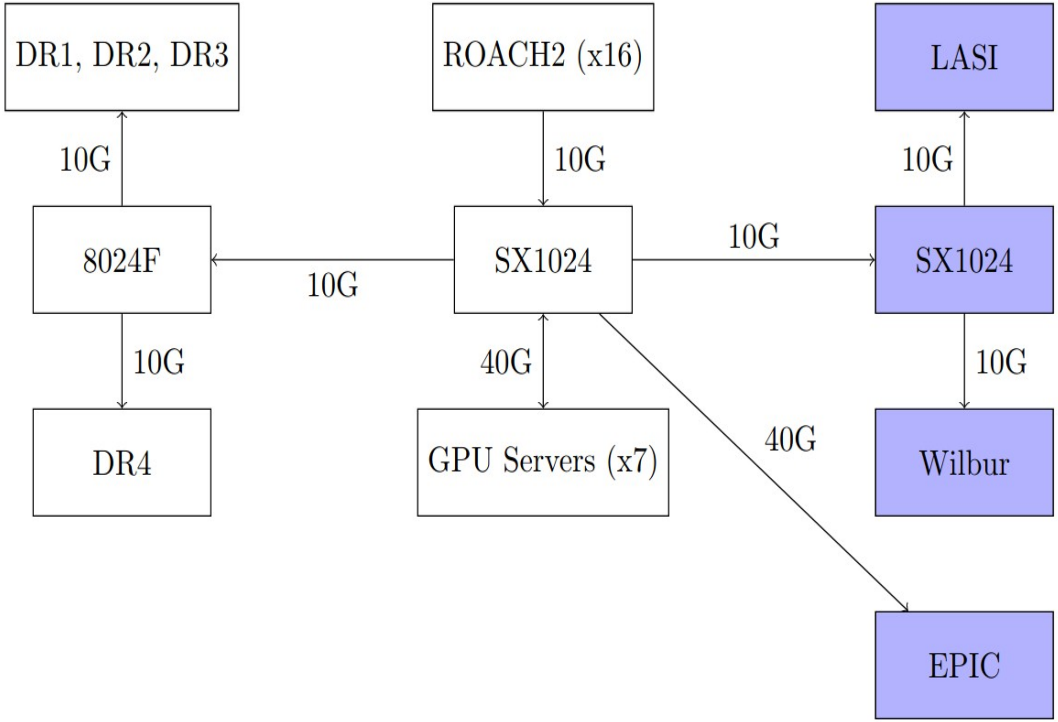
https://github.com/ledatelescope/bifrost/tree/master/tutorial

Concepts : Blocks – Ring buffers

Pipeline



Commensal Systems at LWA-SV



Network topology of the ADP data network
Refer LWA memo #217

Advanced Digital Processor (ADP) subsystem

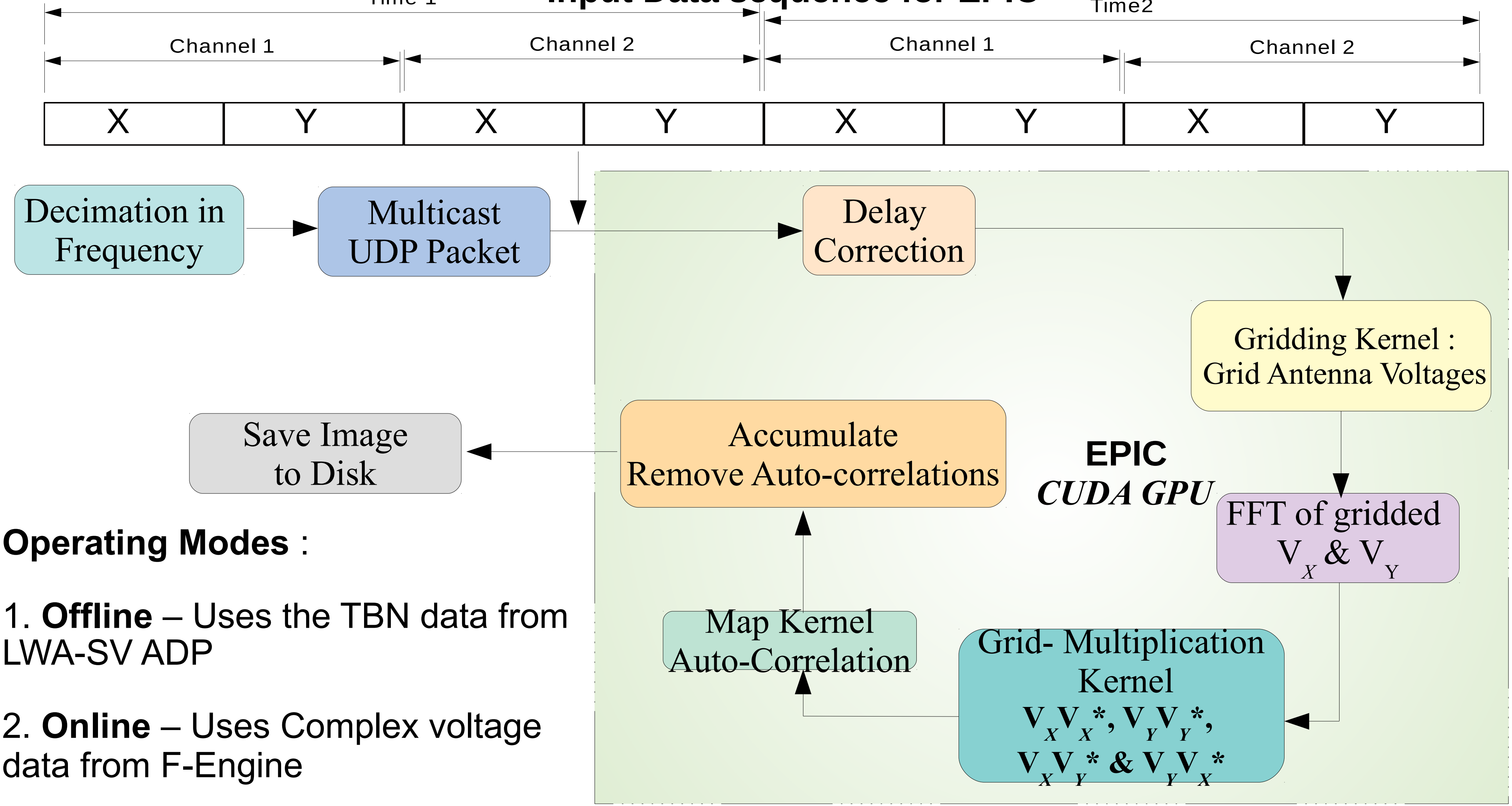
1. Raw F-Engine mode
2. Beam-formed DRX
3. Transient Buffer Narrowband (TBN) mode

F-Engine data :

Overall BW ~ 19.8 MHz
12 sub-bands each with 3.3 MHz BW as independent streams
Each sub-band 132 frequency channels ~
Channel resolution ~ 25 kHz
Time resolution ~ 40 μs
Data rate ~ 1.5 -1.6 GB/s

Dual polarization complex spectra from all 256 antennas in the array

Input Data sequence for EPIC

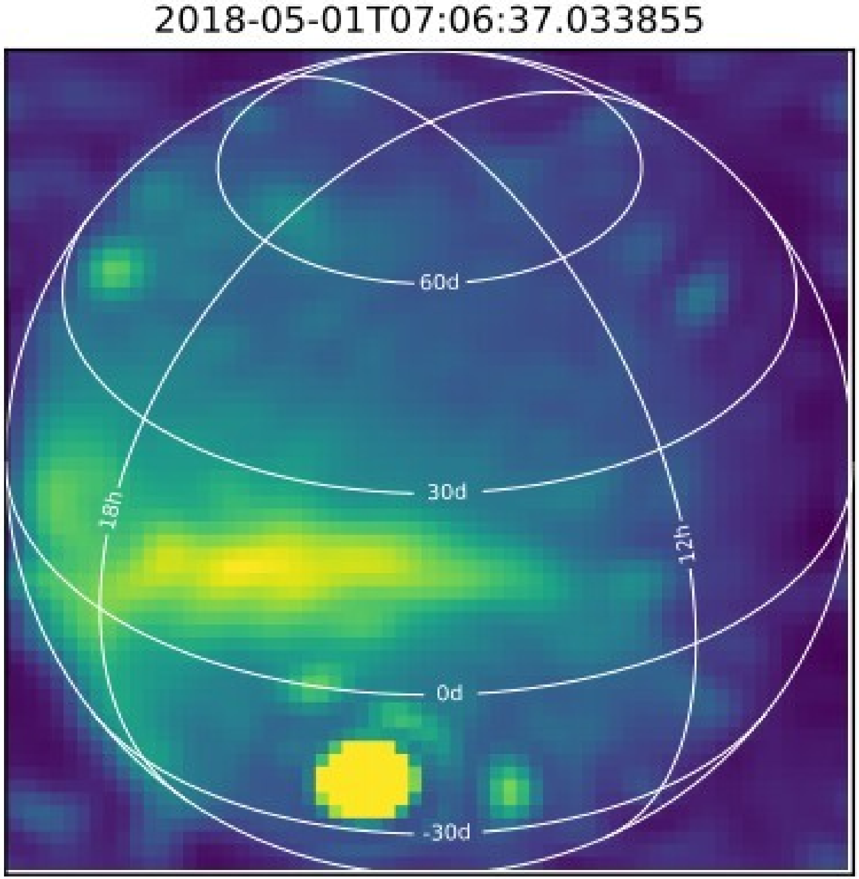


Operating Modes :

1. **Offline** – Uses the TBN data from LWA-SV ADP

2. **Online** – Uses Complex voltage data from F-Engine

EPIC - First Deployment

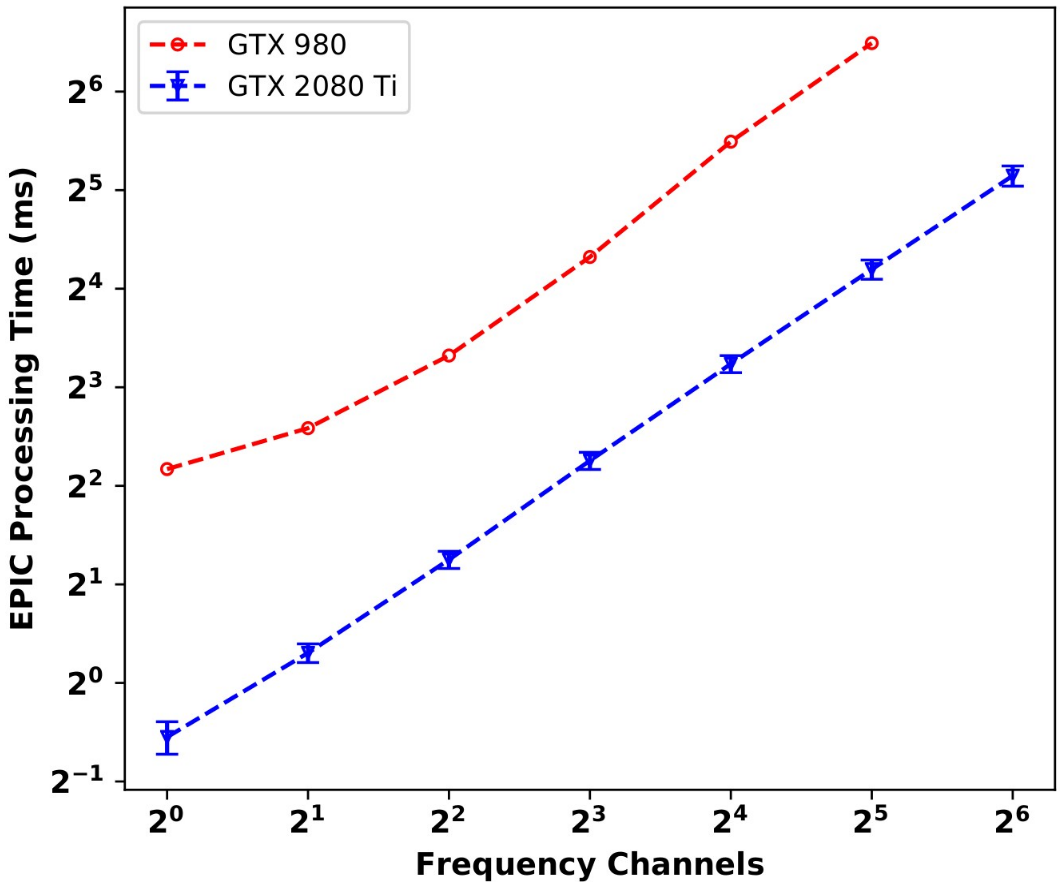


(Kent et al. 2019)

- All-sky Stokes-I image showing a meteor reflection detection during an observation on the LWA-SV site
- Instantaneous bandwidth for initial deployment limited to ≈ 100 kHz per GPU
- Limited by hardware resources & firmware deficiences

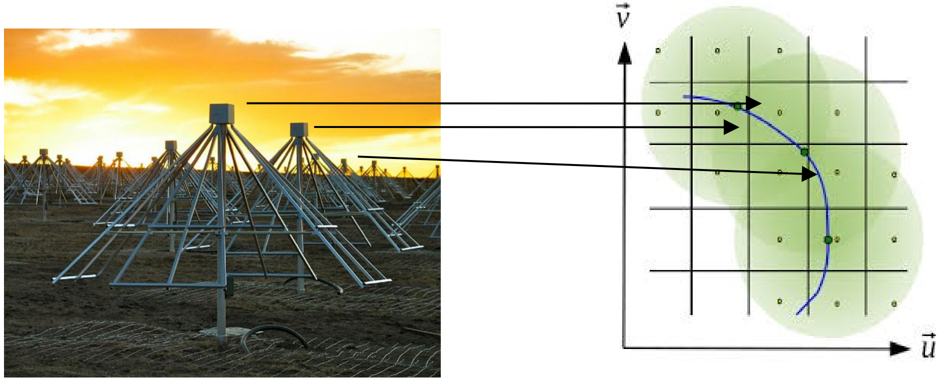
Hardware Upgrade

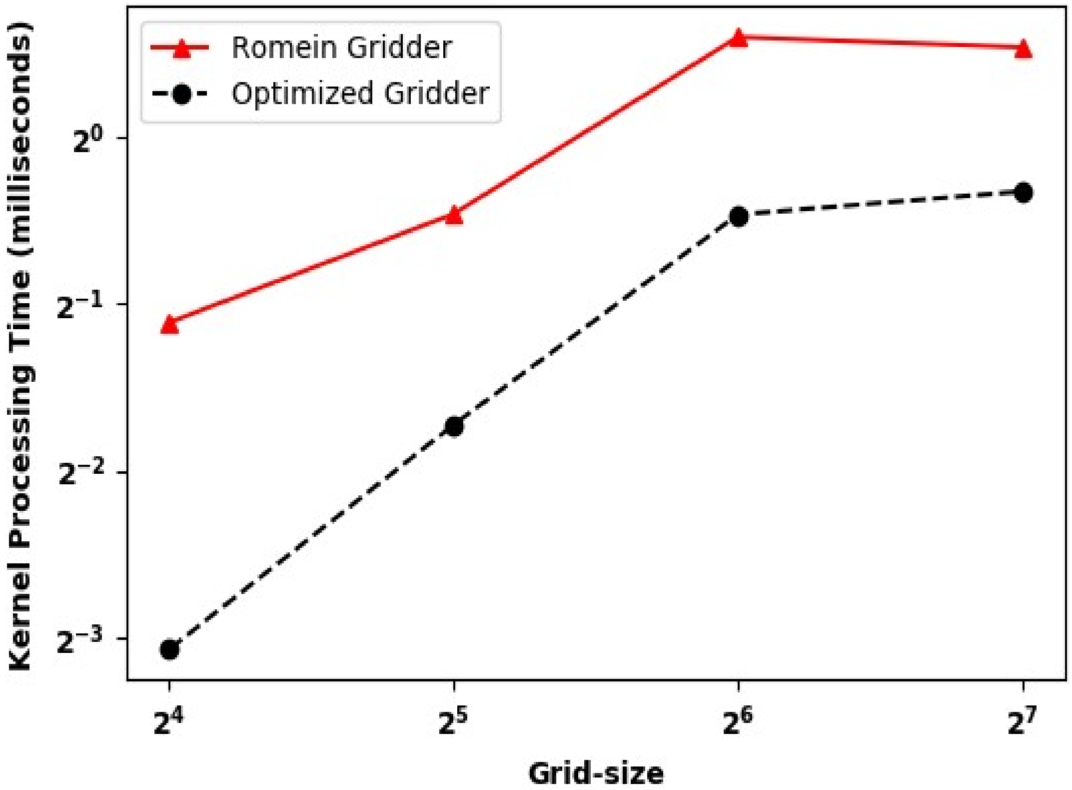
	GeForce GTX 980 (First Deployment)	**GeForce RTX 2080 Ti (Commensal)**
Number of Cores	2048	**4352**
GPU Clock (MHz)	1127 MHz	**1350 MHz**
Number of SM	16	**68**
Global Memory Bandwidth	224.4 GB/s	**616 GB/s**
F32 float Performance	4.981 TFLOPS	**13.45 TFLOPS**
F64 float Performance	155.6 GFLOPS	**420.2 GFLOPS**



Gridding Module

- One of the critical blocks of the EPIC, that is based on a GPU-accelerated work-distribution strategy (Romein 2011)
- Delay corrected frequency domain signals are convolved with gridding function and gridded onto a regular grid of spacing < $\lambda/2$ in the measurement plane

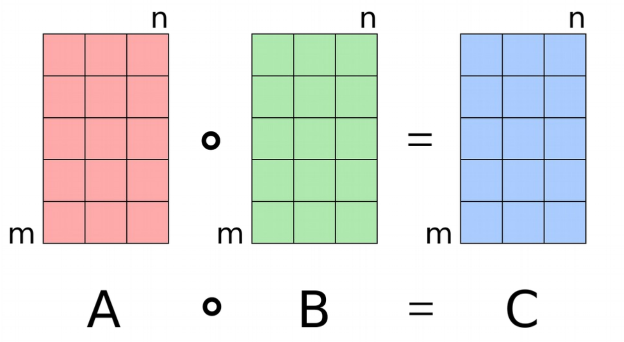


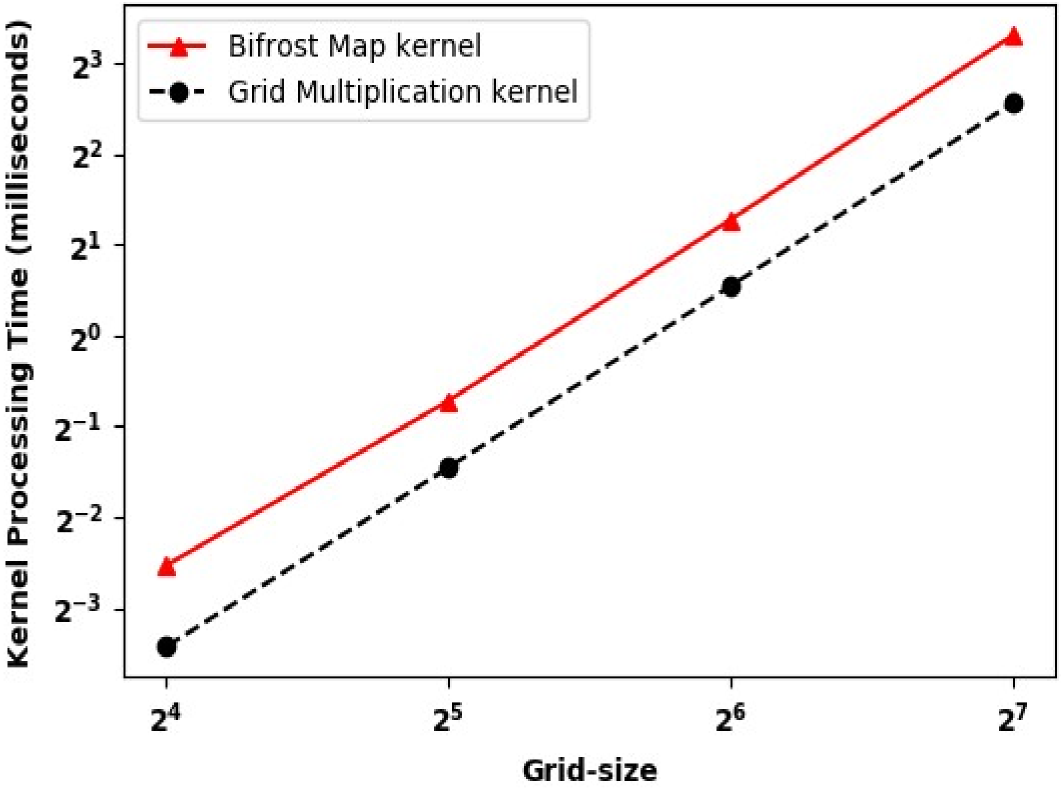


Hariharan et al. 2020

Grid-Multiplication Module

- Pixel-wise multiplication (Hadamard Product) of $\mathbf{V}_X$ & $\mathbf{V}_Y$ grids from the gridding step to produce $\mathbf{V}_X\mathbf{V}_X^*$, $\mathbf{V}_Y\mathbf{V}_Y^*$, $\mathbf{V}_X\mathbf{V}_Y^*$ & $\mathbf{V}_Y\mathbf{V}_X^*$
- Matrix-multiplication, some level of addition also takes place here.
- Not implemented/tested with tensor-core yet.



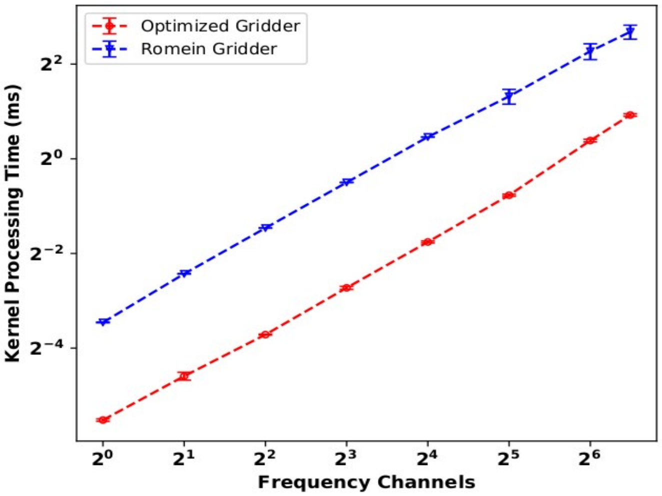


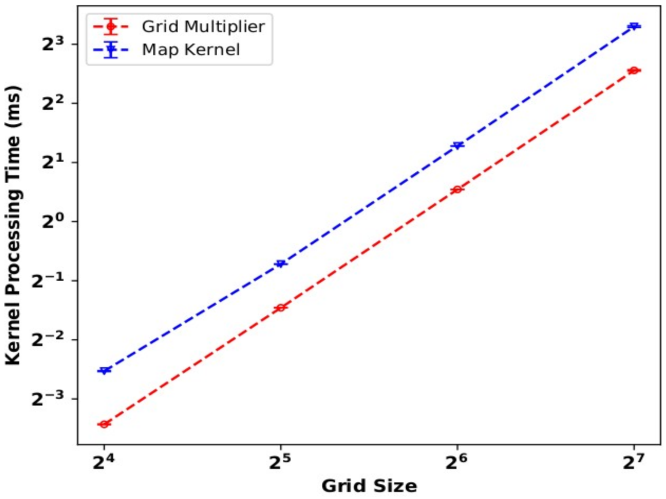
Firmware Upgrade & Optimization

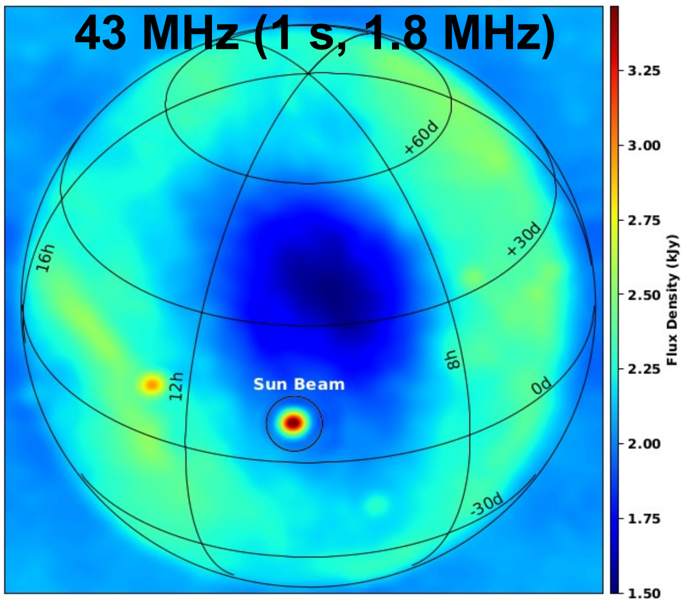
- Memory Optimization
  - Reduce redundant memory access
  - Memory Coalescing for improved memory access pattern
  - Shared memory usage to reduce global memory access
- Instruction level optimization with high-throughput instructions to increase code efficiency
- Current deployment of EPIC runs at 85-90% of the data time
- With a combination of hardware and software modifications EPIC can now process a bandwidth of ~ 3 MHz per GPU for single polarization in real-time with a 32 x 32 grid-size (or 1.8 MHz with 64 x 64 grid)

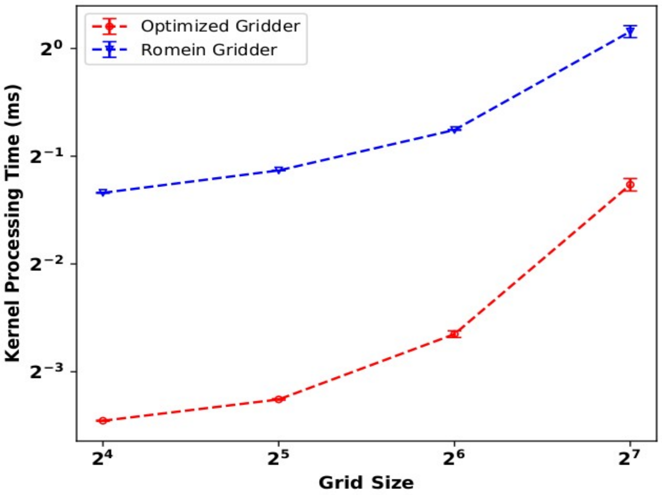
Voltage Gridding

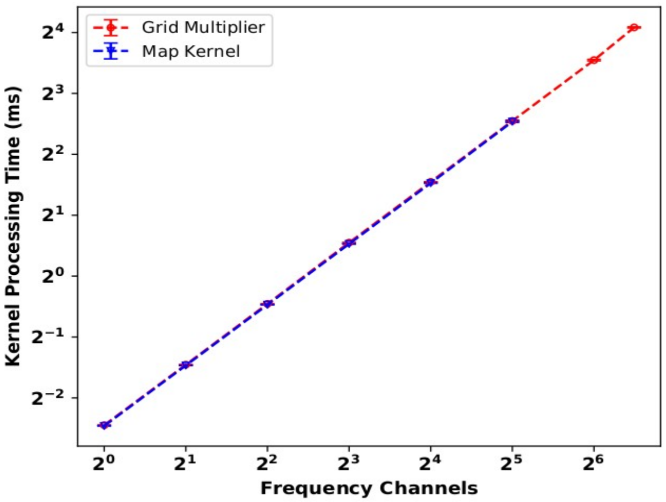
Grid Multiplication









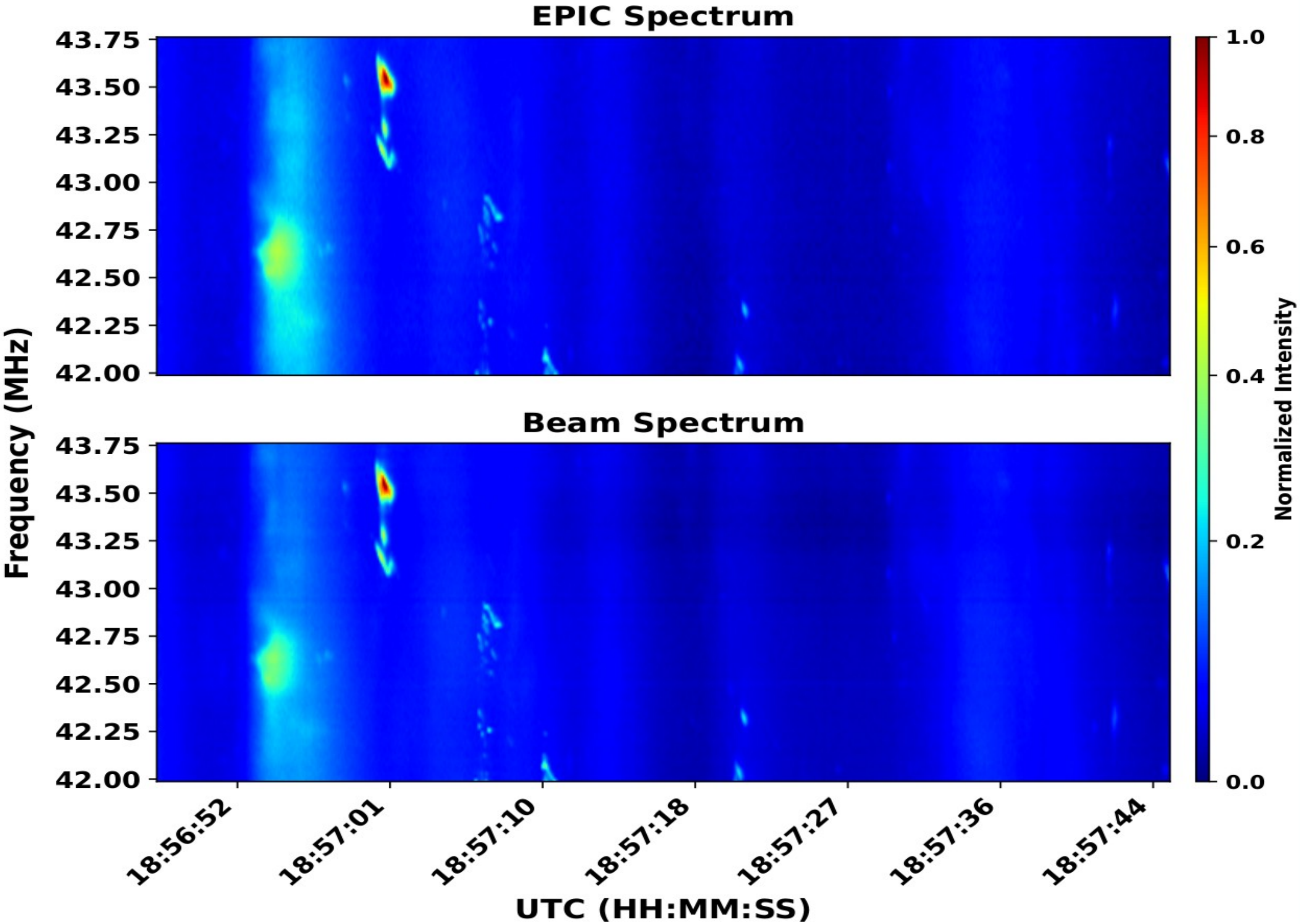


- Optimization & Increase Bandwidth
- **First Deployment : 64x64~100kHz**
- **(Kent et al 2019)**
- **Optimized : 64x64~1.8 MHz;**
- Commissioned as a Commensal Imager at
- LWA-SV

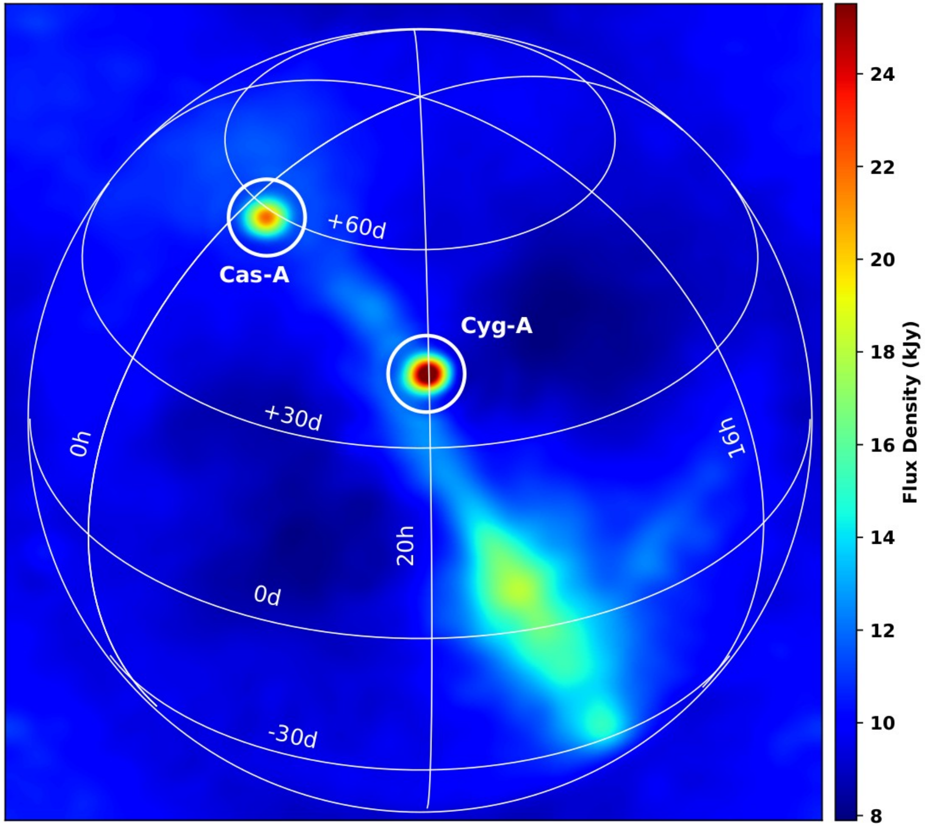
(**Hariharan et al 2020; 2022[submitted]**)

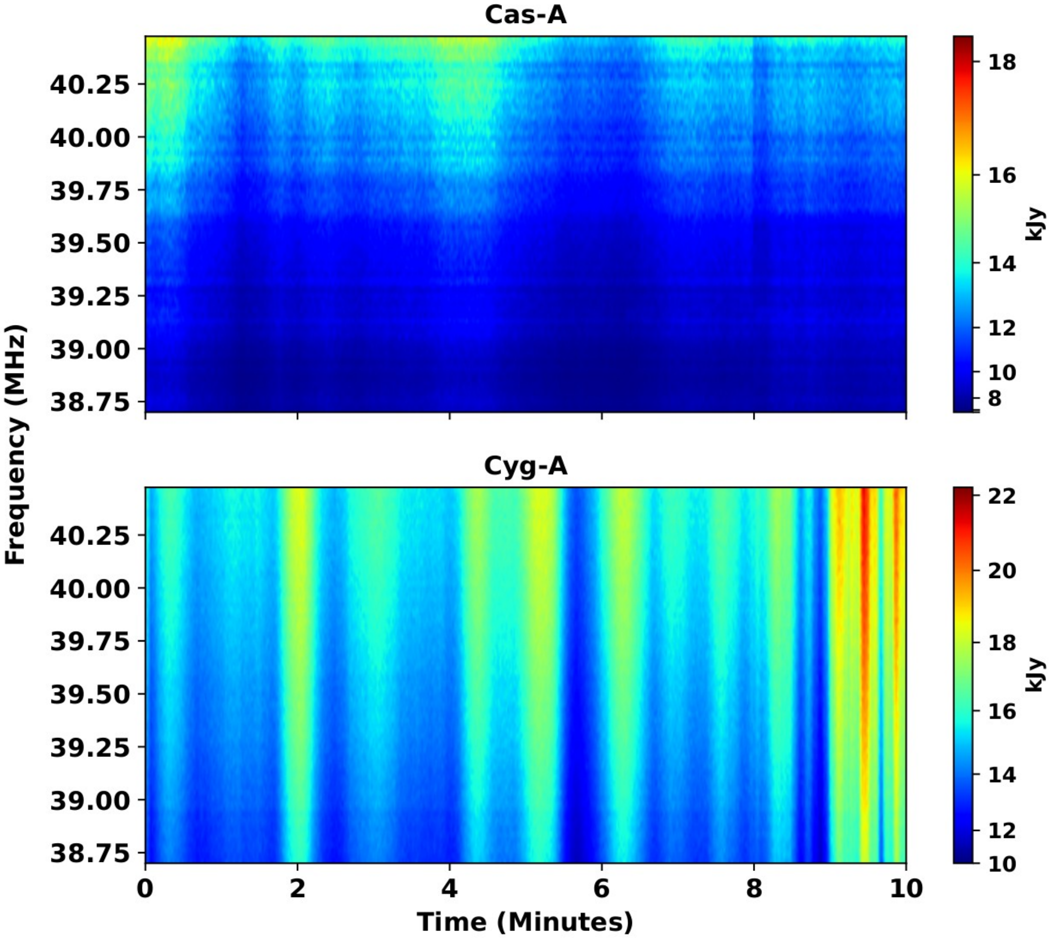
Data Rate ~ 100 GB/hr ;
Raw Frames ~ 40 μs
Accumulated Image ~ 81.92 ms

Simultaneous Beam-Observations – Solar Bursts



Ionospheric Scintillation

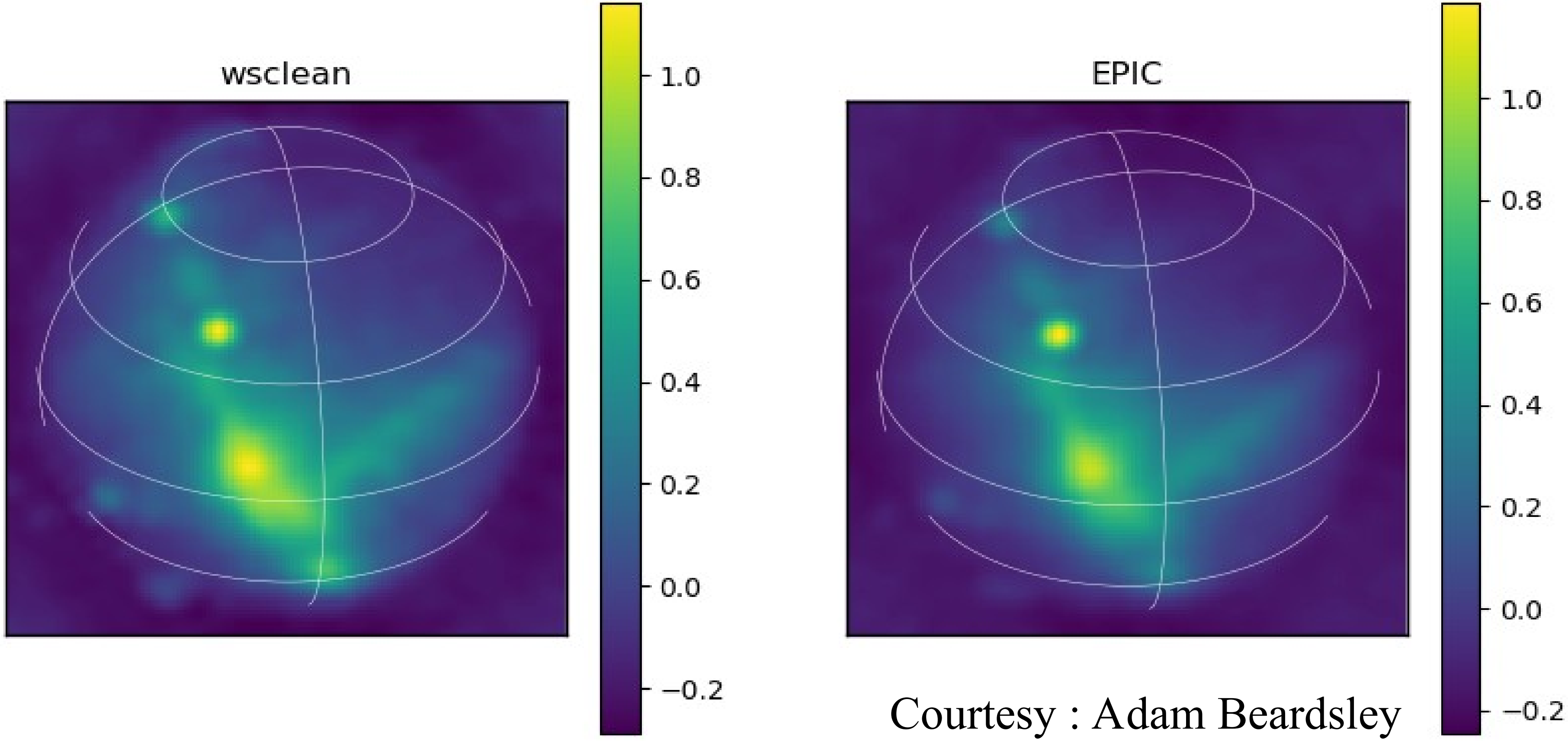




Possibilities of IPS below 100 MHz

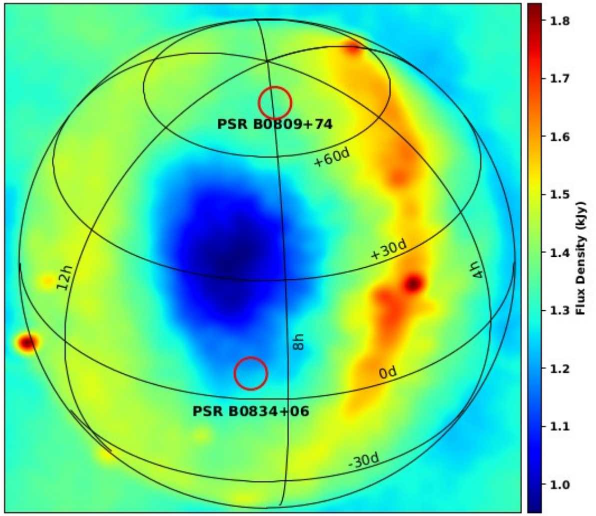
Image Comparison

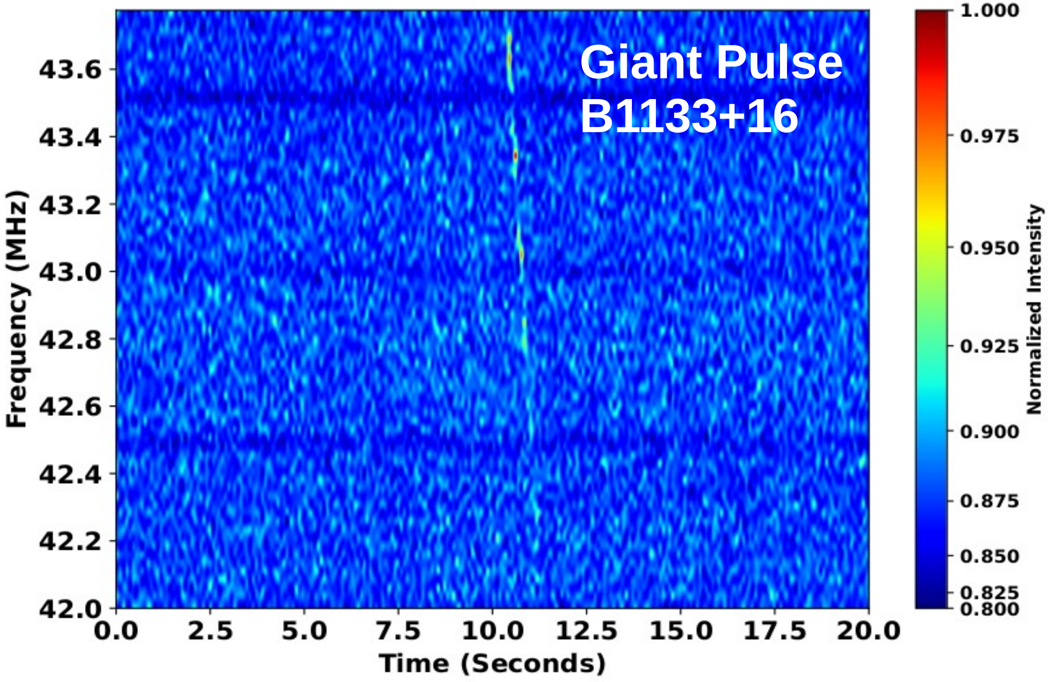
Offline Processing of TBN data ~ 100 kHz



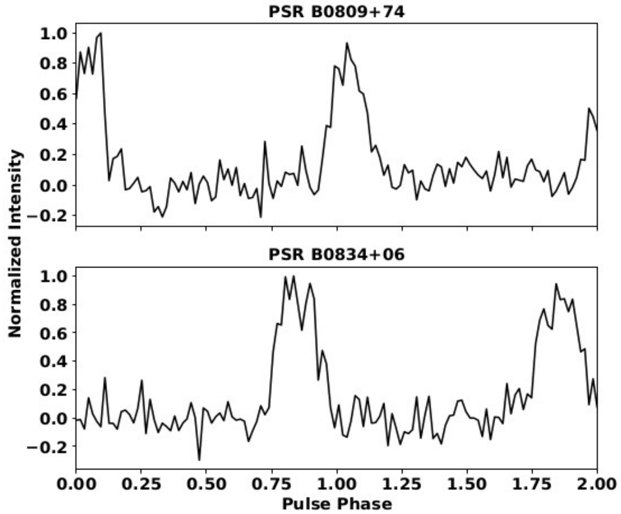
Courtesy : Adam Beardsley

Pulsars & Transients with EPIC





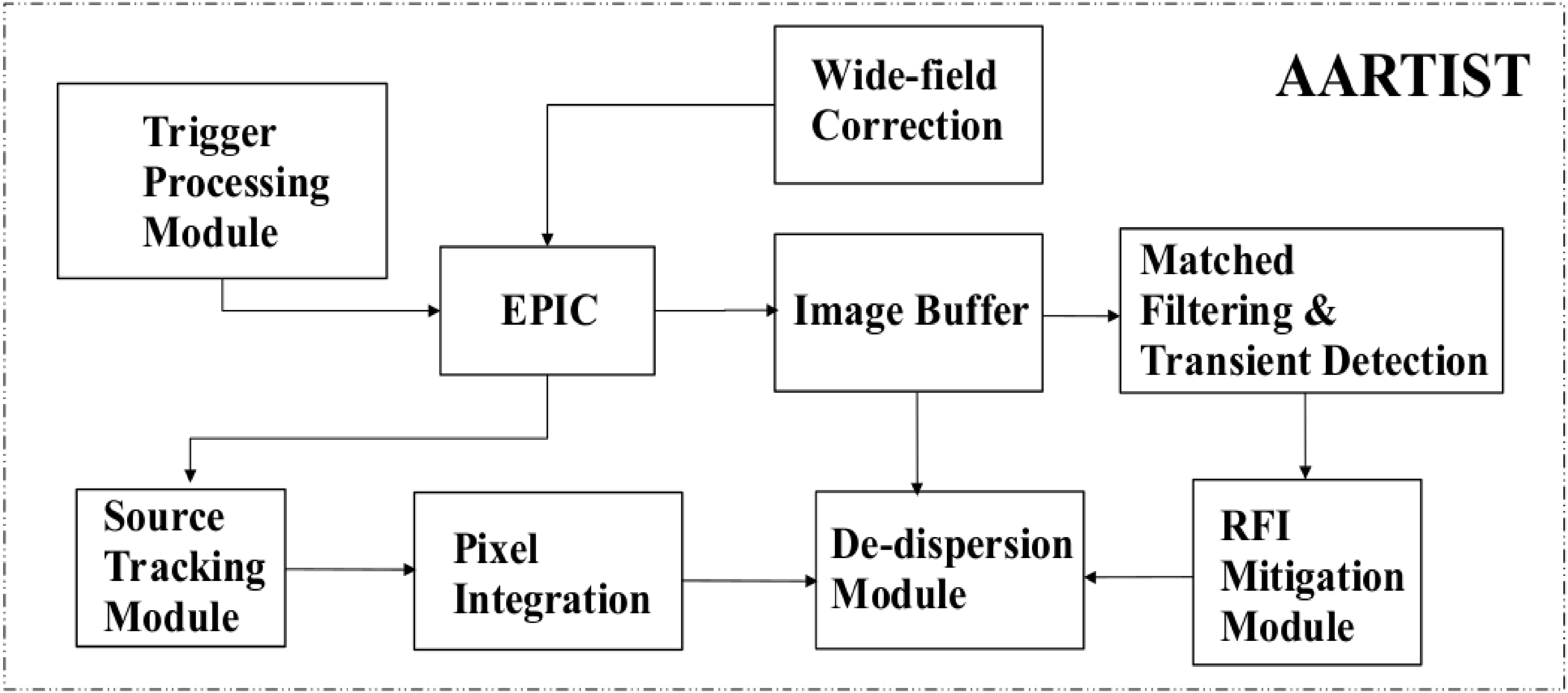
Folded Profile over 45 minutes



NSF ATI Proposal Accepted & Funded: Upgrade EPIC to Aperture Array Radio Transient Imaging SysTem (AARTIST)

- **Increase grid-size to 128 x 128**
- **Include Transient Detection & VOEvent Trigger Processing**
- **Deploy at other LWA stations**

Upgraded EPIC – Aperture Array Radio Transient Imaging SysTem



Trigger Processing Module

- VOEvent-based trigger processing similar to those in MWA (Hancock et al 2019) and LOFAR (Prasad et al 2016)
- Prompt processing of external transient alerts eliminating the latency involved in re-pointing a telescope
- Allow several minutes for response through the entire event notification system, considering large dispersive delays at low frequencies expected for FRBs (LOFAR detection : Pleunis et al. 2020; Inés et al. 2020) ;
- Ring buffer to record electric-field streams for the event pixels or entire all-sky full Stokes power images for detailed analysis, depending on the type of transient

Incoherent Dedispersion Module

- Based on Fast Dispersion Measure Transform (FDMT: Zackey & Ofek, 2017) already implemented in Bifrost
- Total power integrated across pixels corresponding to resolution element as a function of frequency and time $P_{pix}(F,T)$ to enable blind searches.
- Known source monitoring like bright pulsars, GP emitting pulsars and repeating FRBs, and insert their dedispersed light curves into a postgresql (PSQL) database
- Matched filtering and statistical methods for RFI and transient detection

Wide-field Correction & Calibration

- To achieve the high dynamic range imaging that is important for the long-term adoption of direct imaging architectures for 21 cm cosmology and long-duration time domain science
- Demonstrated one such implementation (Kent et al., 2020) on the LWA-SV using the Discrete Fourier Transform (DFT) matrix formalism
- Exploring feasibility of including other strategies like w-projection (Cornwell et al., 2008) and w-stacking (Offringa et al., 2014)
- EPICal (Beardsley et al. 2017) – Feedback calibration algorithm demonstrated using a software implementation and archived data. Similar to the holographic calibration (Randyll's Talk)
- Porting EPICal onto GPU accelerated version of AARTIST

Plans to deploy EPIC at other LWA stations

Long-Term Objective for LWA : LWA SWARM Concept
“Long Wavelength Array (LWA) Swarm telescope - a powerful instrument for investigating the Universe while engaging students at Universities and Colleges across the US”

LWA Swarm White Paper

Table 1. Participating Institutions

Institute	Contact	Dipoles
UNM	G. Taylor	**256 x 2**
Caltech	G. Hallinan	**352**
Quest Univ.	I. M Hoffman	48
KU	D. Besson	48
ERAU	A. Gretarsson	48
TTU	T. Maccarone	48×2
ASU	J. Bowman	256
UTRGV	F. Jenet	48
UF	A. Gonzalez	48
UC Boulder	J. Burns	256
SUNY OW	M. Kavic	48
Hillsdale	T. Dolch	48

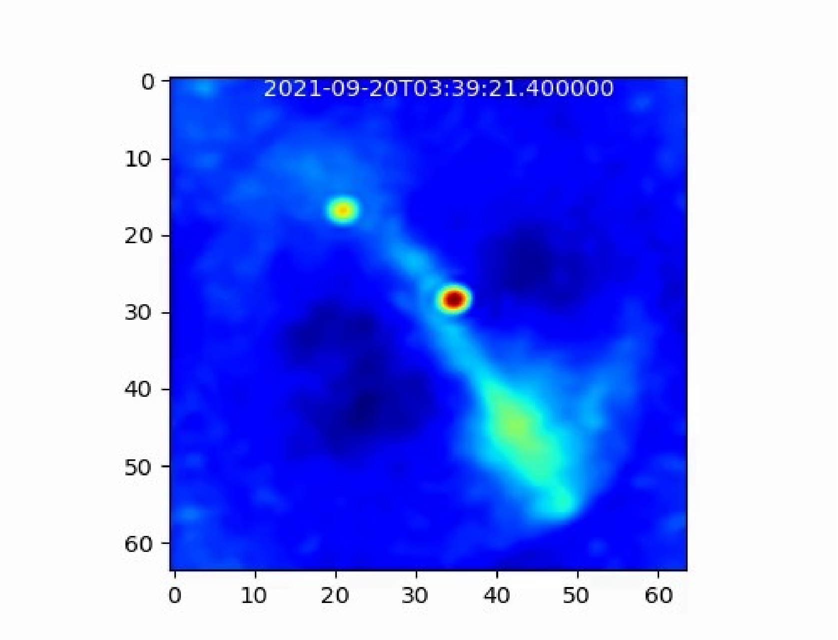
Note: The UNM and Caltech stations (indicated in bold) are already operational.

Dowell et al 2019

Summary

- EPIC commissioned as commensal back-end at LWA-SV ; 120 ch ~ 3 MHz @ 32 x 32 (or **72 ch ~ 1.8 MHz @ 64 x 64**) : single polarization single GPU
- Plans to upgrade EPIC to AARTIST for Transient Detection through Triggered Image Acquisition (Current : **6 MHz 90 x 90, Still tested**)
- AARTIST to have wide-field correction and calibration
- Goal for LWA ~ 20 MHz bandwidth performance at high time and frequency resolution with larger image grid-size, atleast 128 x 128

BW = 250 kHz @ f = 43 MHz



https://github.com/epic-astronomy/LWA_EPIC

email : vasanthikrishhari@gmail.com

Questions / Comments ?