Validation the E-Field Parallel Imaging Correlator (EPIC) using WSClean

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LWA Users Meeting

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Long Wavelength Array - Sevilleta

- 256 dual-polarization dipole antennas
- Pseudo-randomly arranged elements in 100m x 110m ellipse
- Commensal Beamforming and All-sky observing modes
- Independent beams tunable over frequency range of 10-88 MHz
    - ~16 MHz effective bandwidth per tuning

LWA station located on the Sevilleta National Wildlife Refuge (LWA-SV)

What is LWA-EPIC?

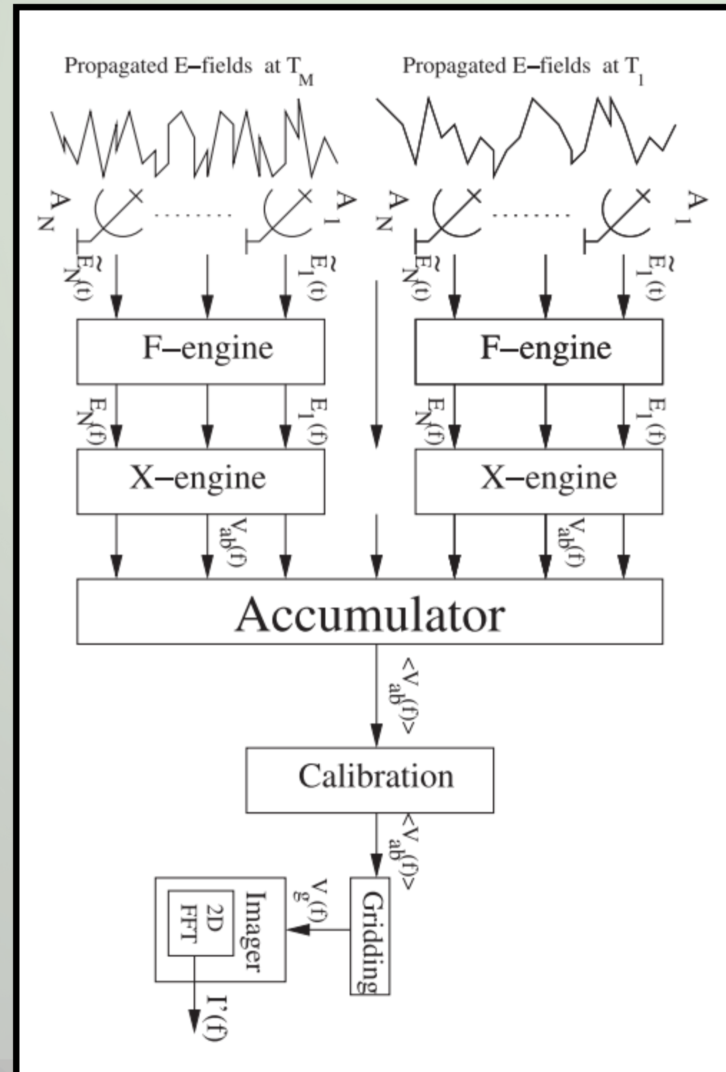
- The E-Field Parallel Imaging Correlator (EPIC) is a direct imaging correlator for interferometer arrays
  (Thyagarajan et al. 2017)
- Images formed by convolution of gridding function with electric field distribution at each dipole
  - Unique grids are cached for future observations
- Streaming output handled by Bifrost framework for GPU processing to enable fast data rates

Standard FX Correlators in practice...

FX Correlator converts input measurements into Visibilities

Visibilities are Integrated in time then Calibrated to station

Grid visibilities and 2D Fourier transform into the Image Plane

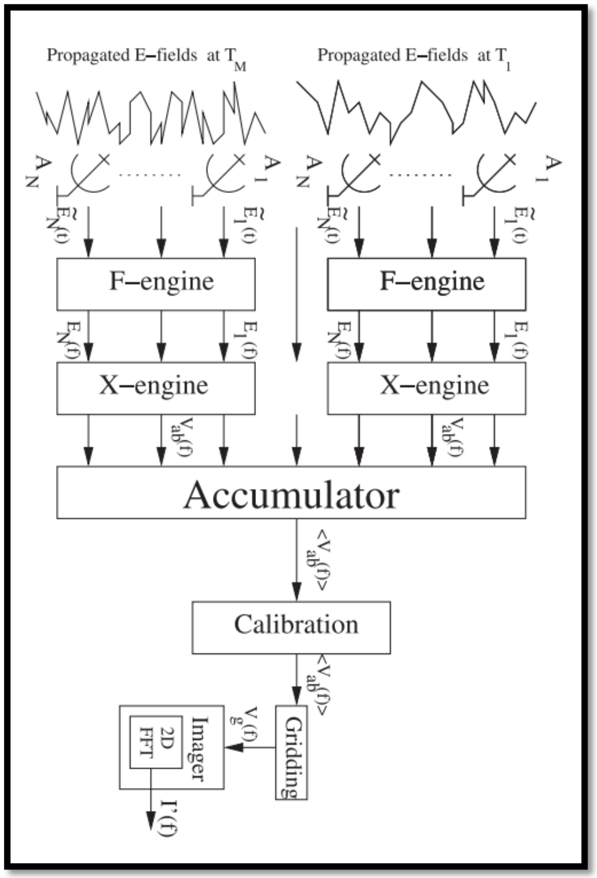


LWA-EPIC

Standard FX-Correlator Schematic:

Orville subsystem

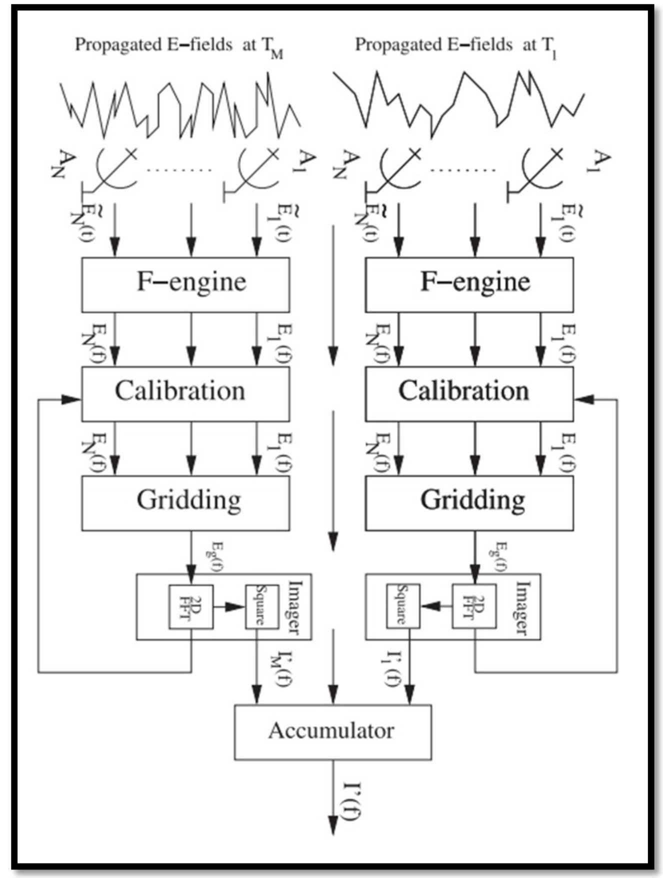
$\mathcal{O}(N^2)$



EPIC Correlator Schematic:

EPIC subsystem

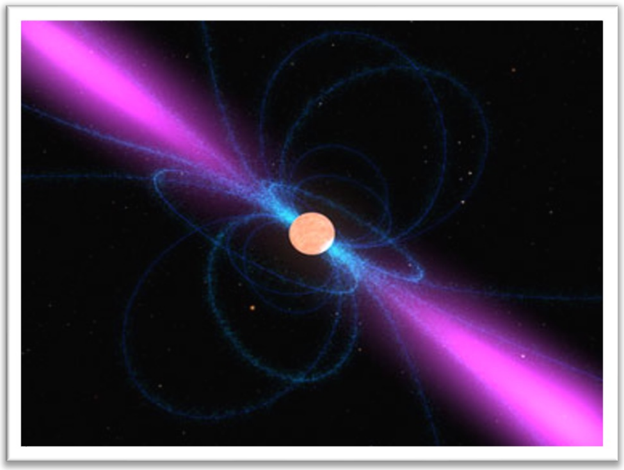
$\mathcal{O}(N \log N)$



Thyagarajan et al. 2017

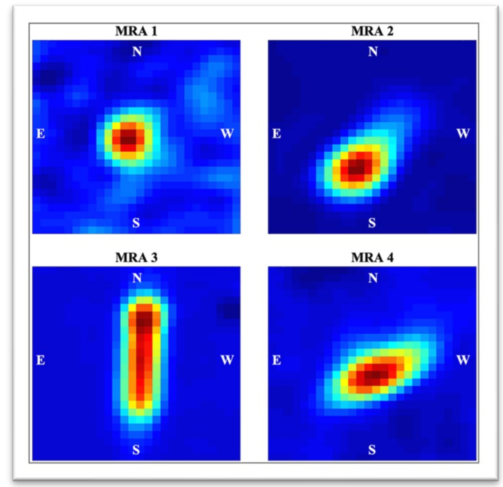
What is EPIC optimized for?

- Continuous high-cadence observations of the entire sky



Pulsars &
Pulsar Timing studies

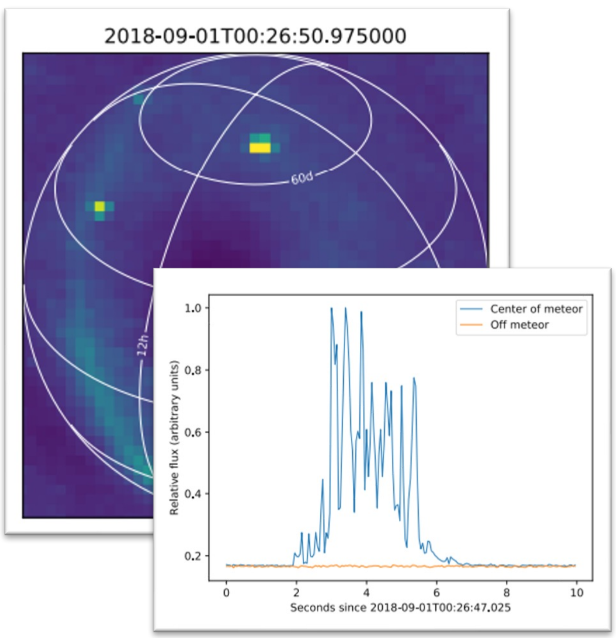
Stellar Flares and Exoplanet
Radio Emission



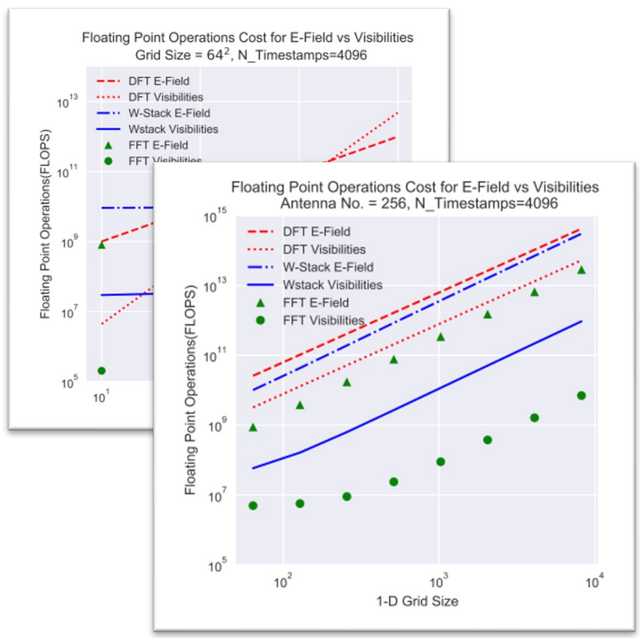
Meteor Radio Afterglows

EPIC - Previous Study Rundown

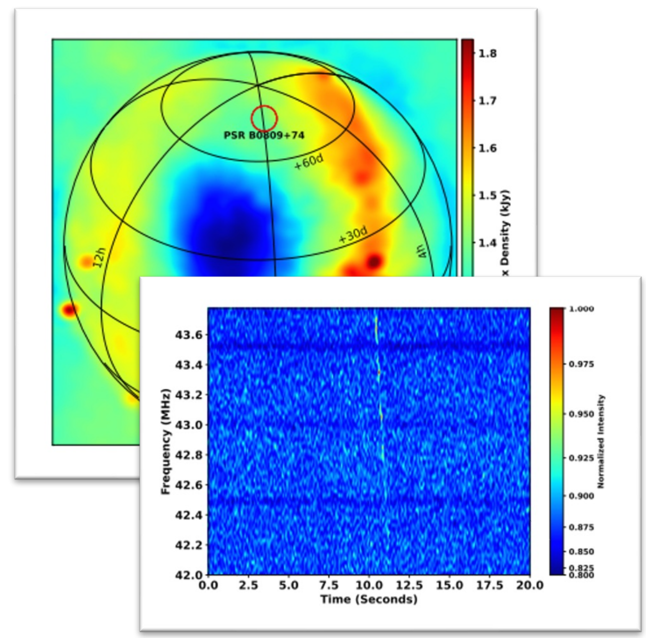
Kent 2019a:
Implementation Demonstration



Kent 2019b:
Direct Fourier Transform Imaging

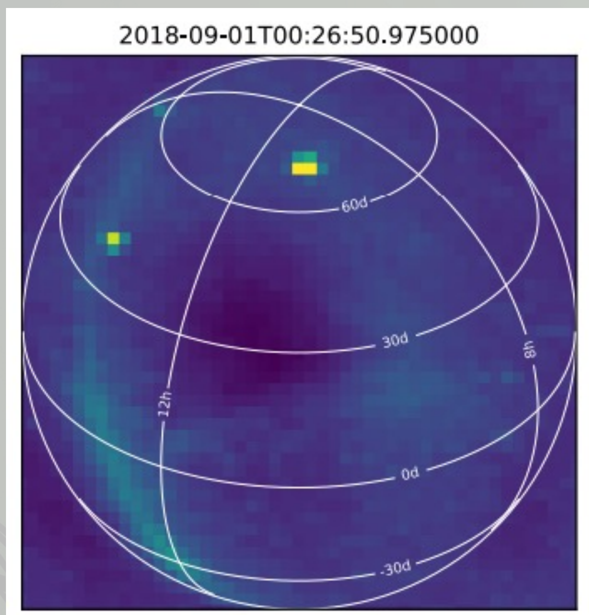


Krishnan 2022:
Optimization and Hardware Upgrades

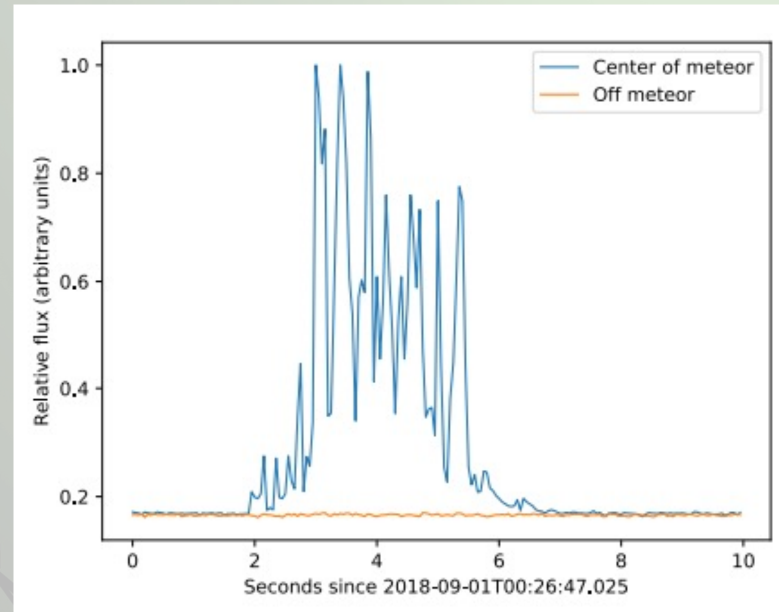


A Real-Time, All-Sky, High Time Resolution, Direct Imager for the Long Wavelength Array

(*Kent el al. 2019a*)

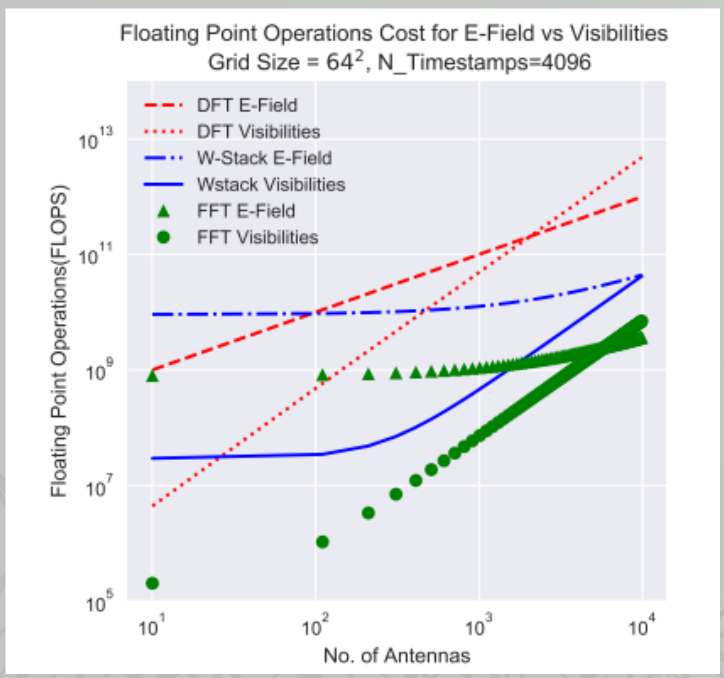


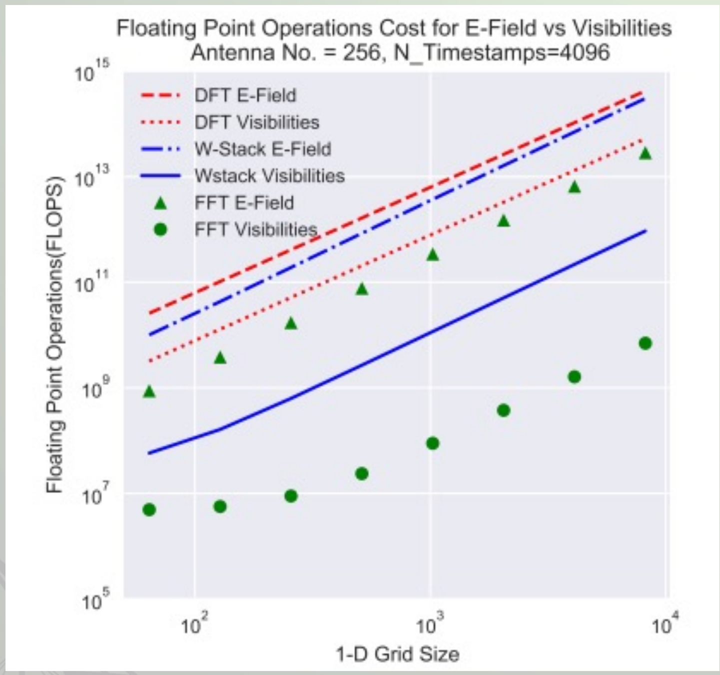
64x64 pixel test image from EPIC observing a Meteor Radio Reflections at 55 MHz



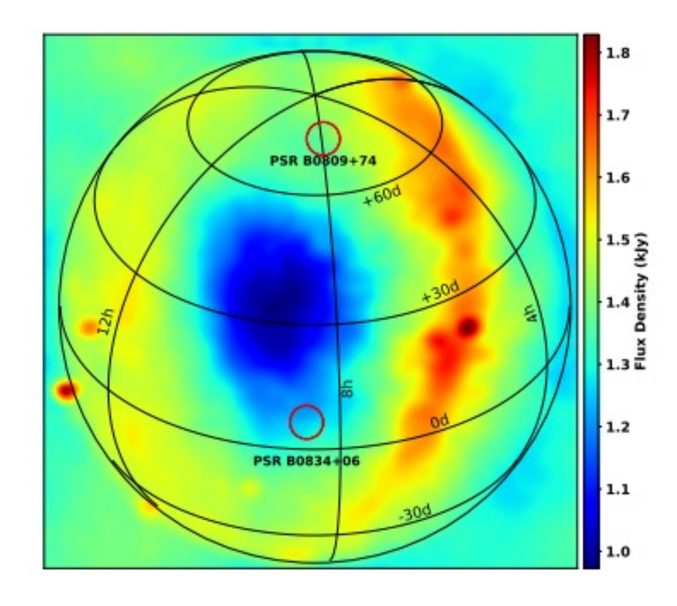
Relative Flux light curve of Radio Emission

Direct Wide-Field Radio Imaging in Real-Time at High Time Resolution Using Antenna Electric Fields (*Kent et al. 2019b*)

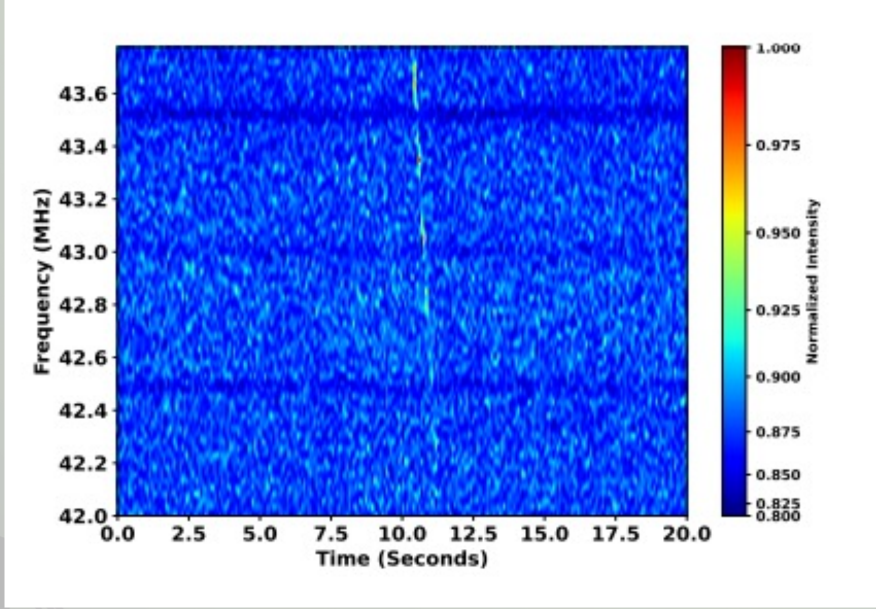




Optimization and Commissioning of the EPIC Commensal Radio Transient Imager for the Long Wavelength Array (*Krishnan et al. 2023*)



All-sky image made with EPIC to show multi-source monitoring



Giant Pulse from PSR B1133+16

EPIC

- Kent et al 2019 and Krishnan et al 2023 only compare EPIC with itself
- Need a comprehensive validation of EPIC's data products

Goals:

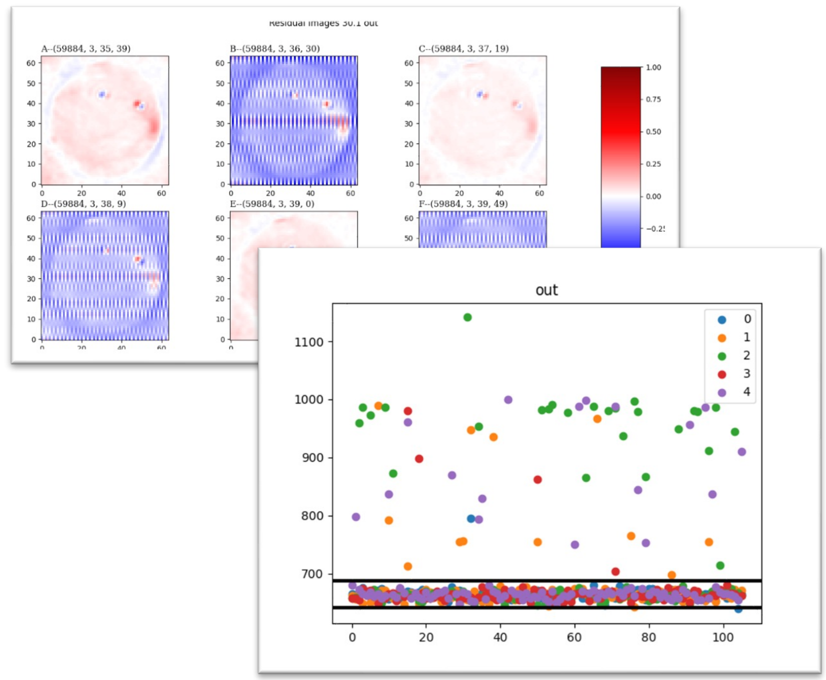
1. Ensure EPIC removes autocorrelations from images correctly
2. Compare EPIC to another pipeline of FX-architecture
3. Localize sources between each to confirm correct

EPIC – Autocorrelations

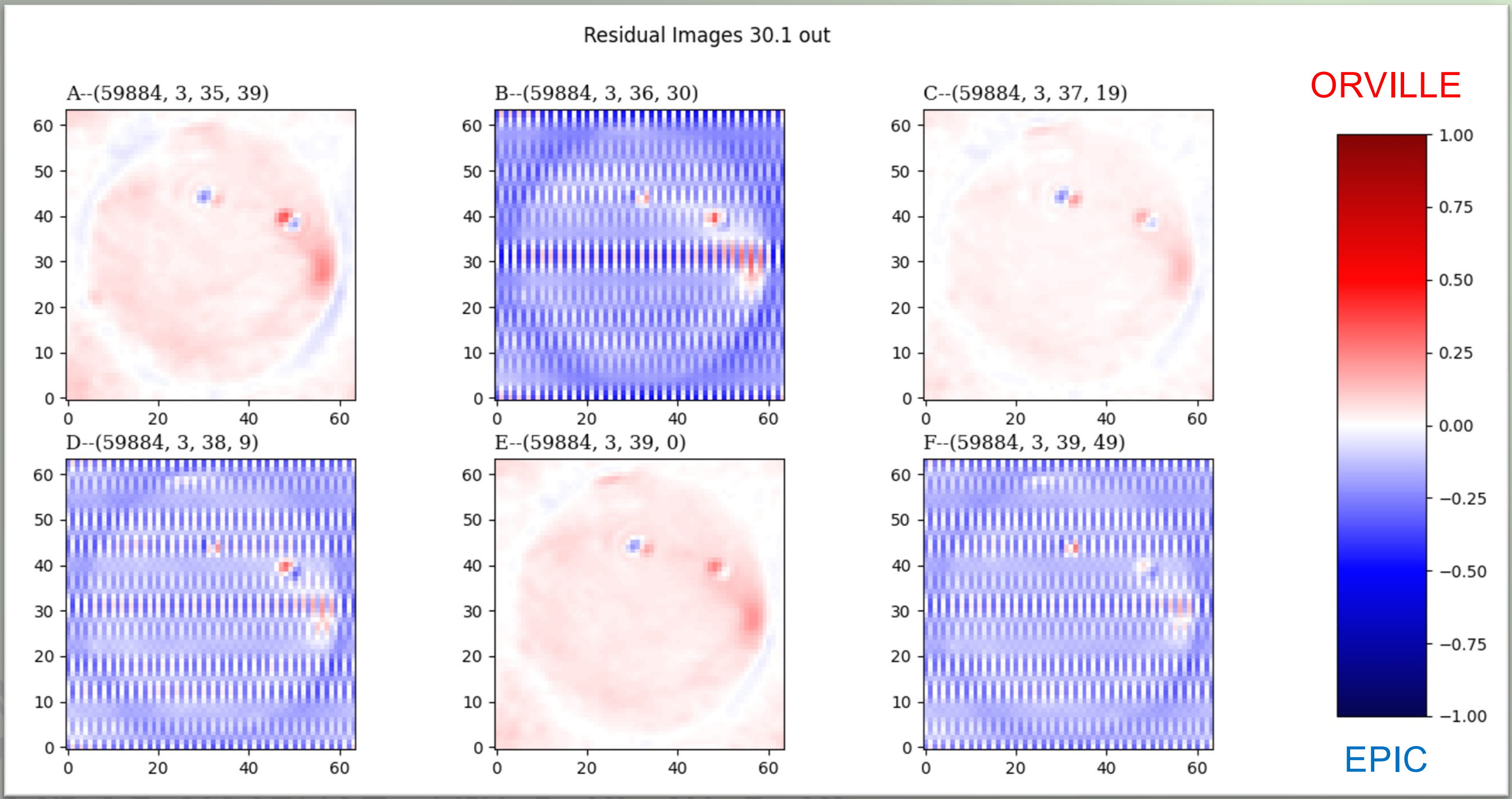
- Autocorrelations are the result of correlating and antenna's signal with itself
- Presents in the Image Plane as a planar offset

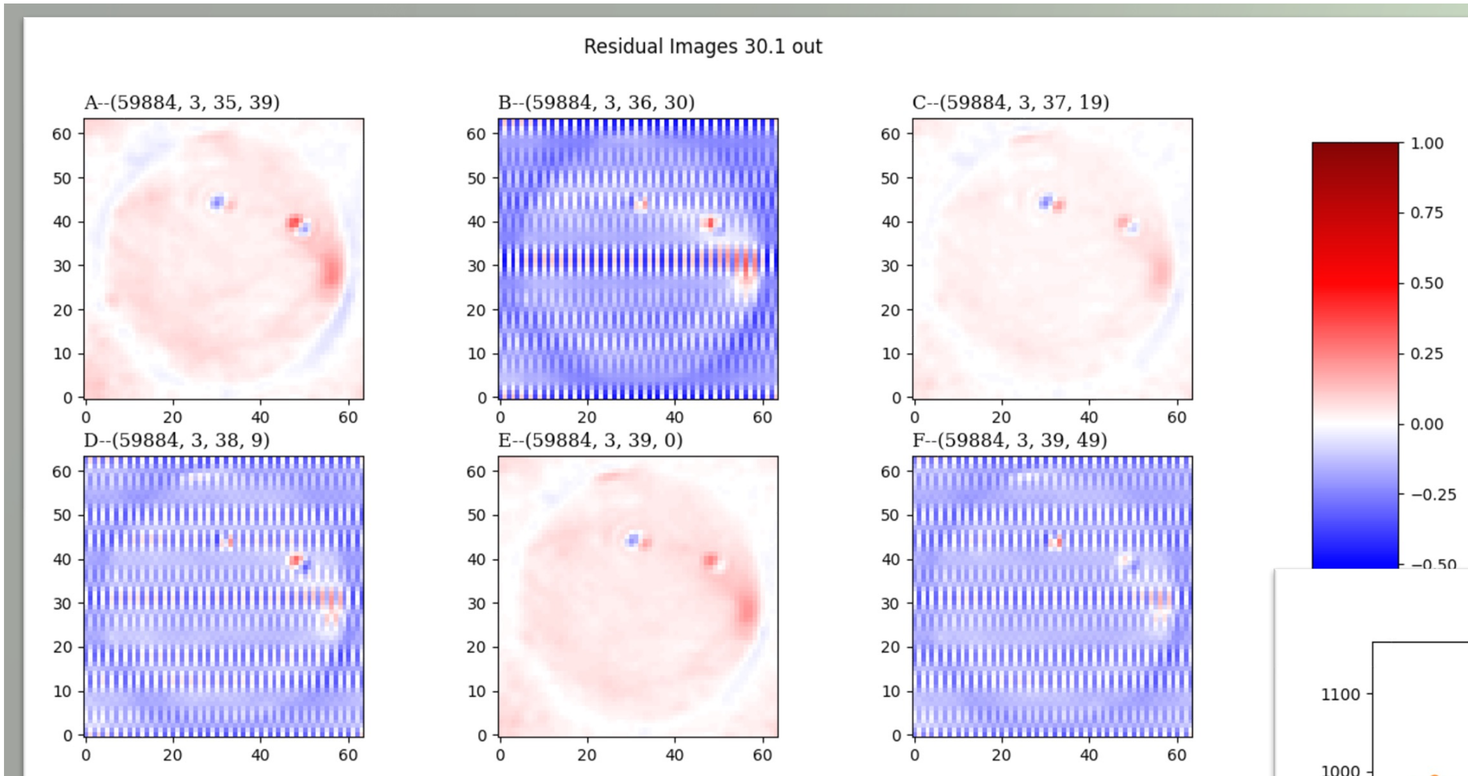
PLAN:

- Compare EPIC with Orville Wideband Imager mode at LWA-SV
- All-sky imager that removes autocorrelations by default

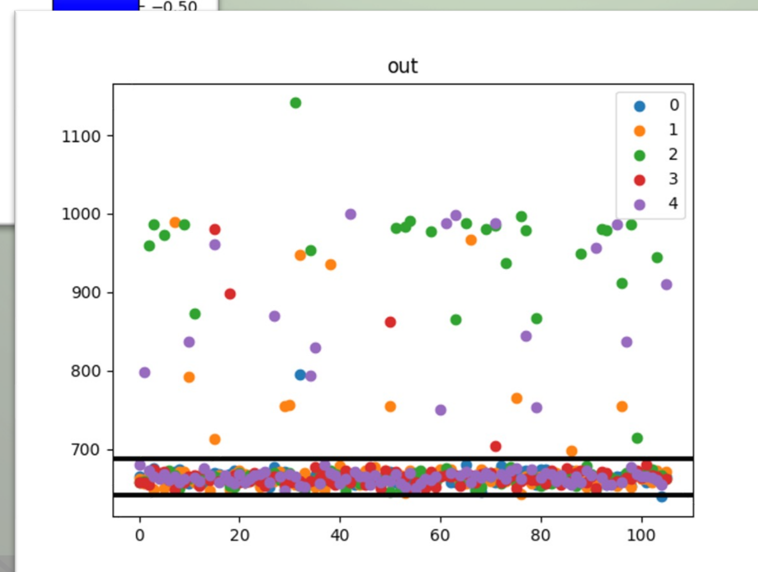


Bad to worse!

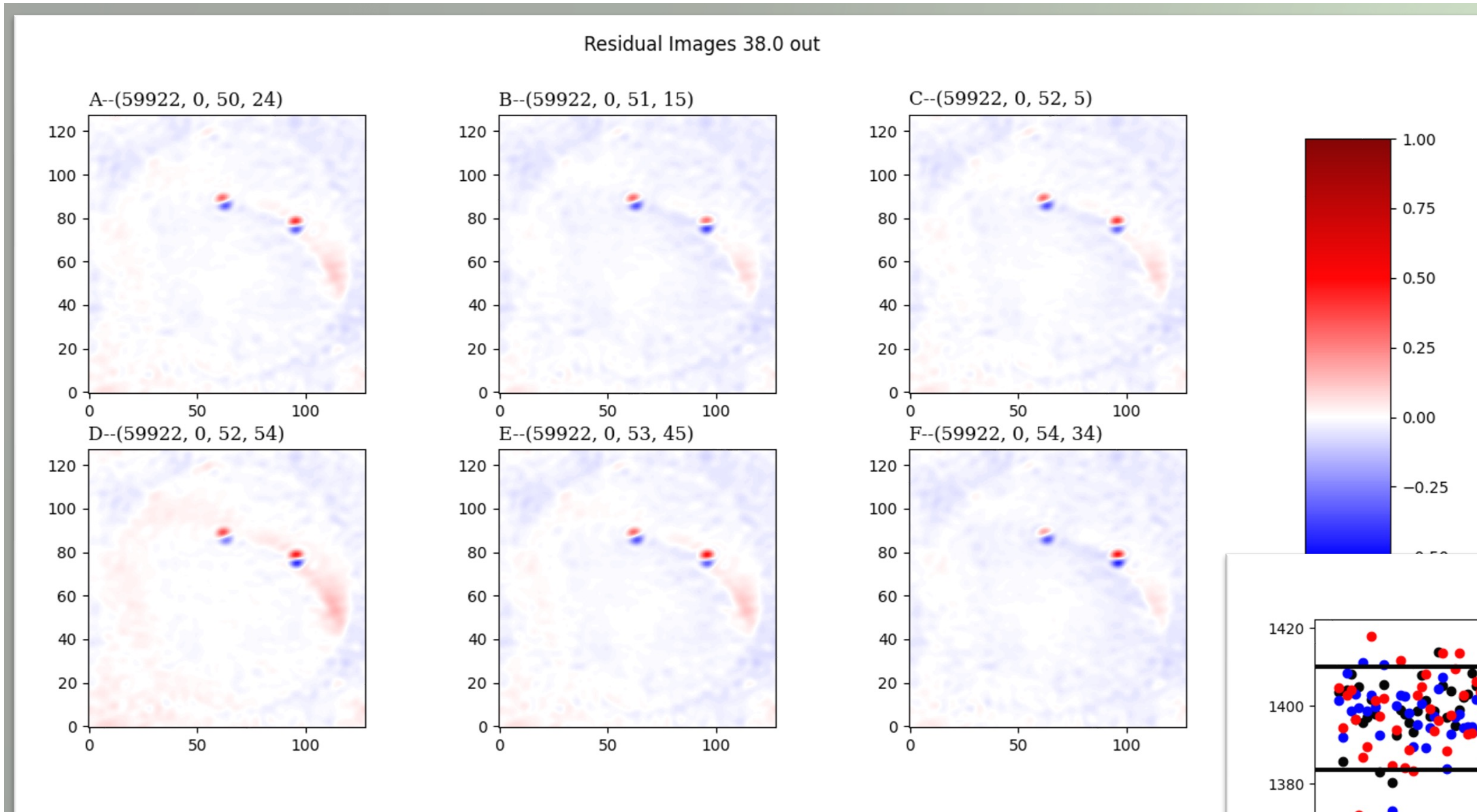

Residual Images 30.1 out
A--(59884, 3, 35, 39)
B--(59884, 3, 36, 30)
C--(59884, 3, 37, 19)
D--(59884, 3, 38, 9)
E--(59884, 3, 39, 0)
F--(59884, 3, 39, 49)
ORVILLE
EPIC
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

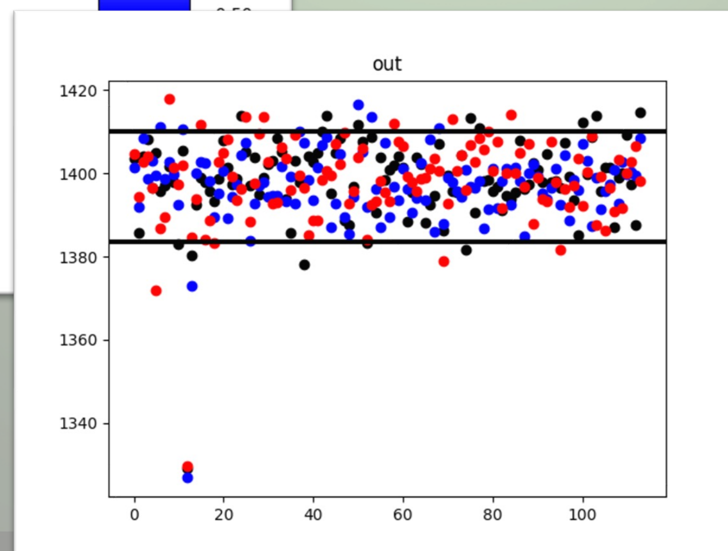


Small update to Krishnan (2023) optimizations required



Colors correspond to 100kHz frequency bins





Now all images are constrained to the same window of values!

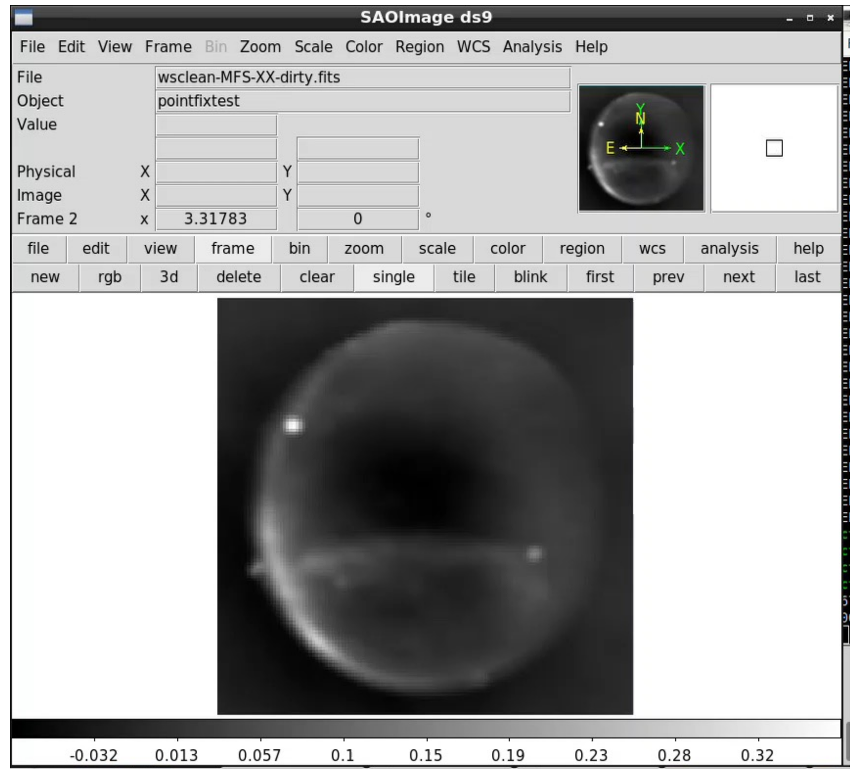
EPIC – Imaging Comparison

Move to offline data using the LWA's Transient Bandwidth Frequency domain mode

- Correlate using LWA Software Library Correlator for TBF-mode

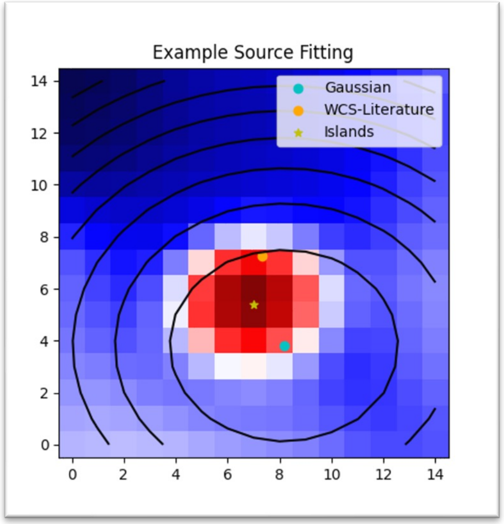
Off-the-shelf imagers such as WSClean include wide-field corrections

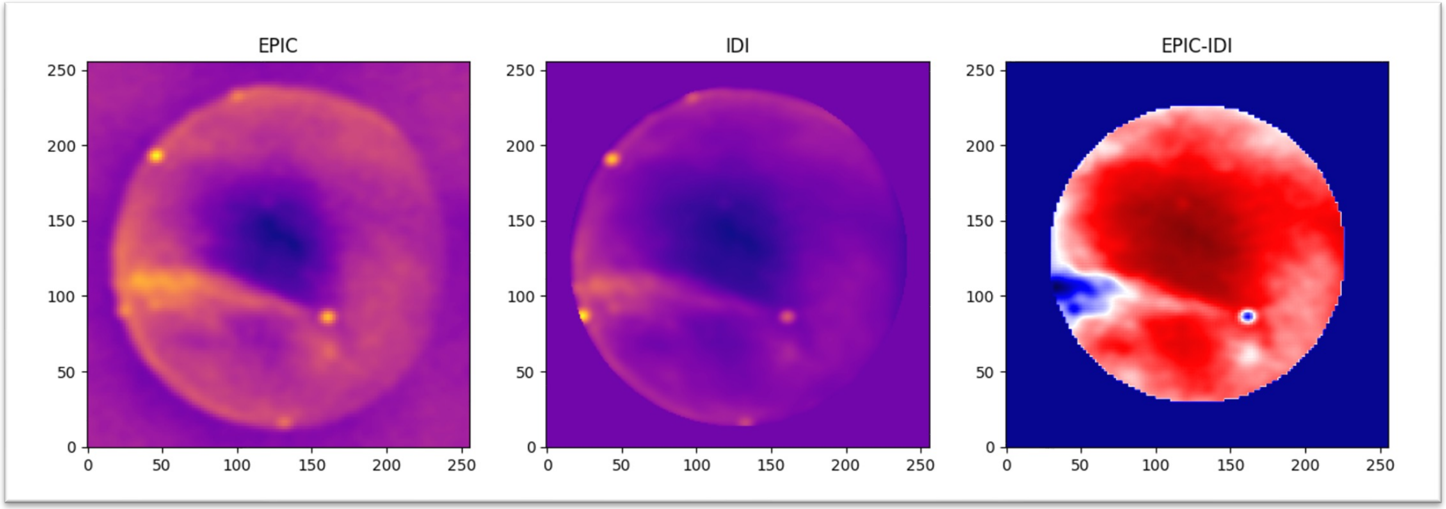
Blinking between images made using WSClean and EPIC in DS9



EPIC – Source Localization

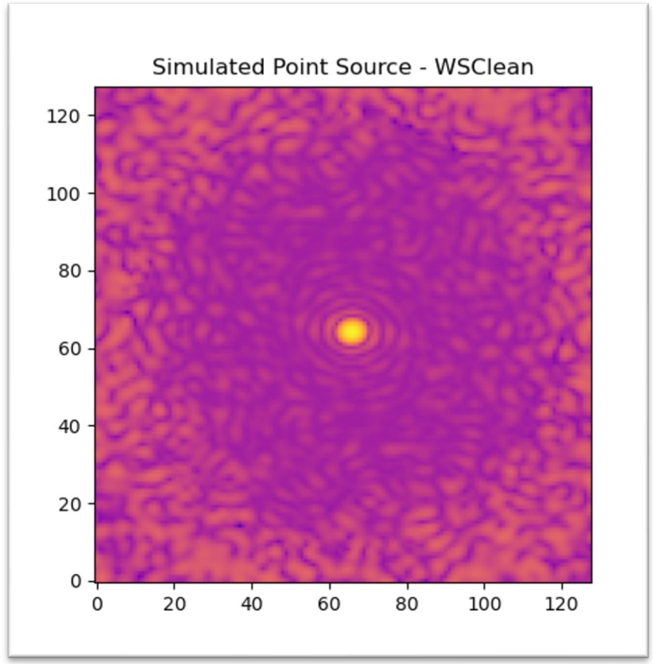
- Source localization is done using an island finding algorithm
- Contingent on both imaging pipelines agreeing on where the sky is!



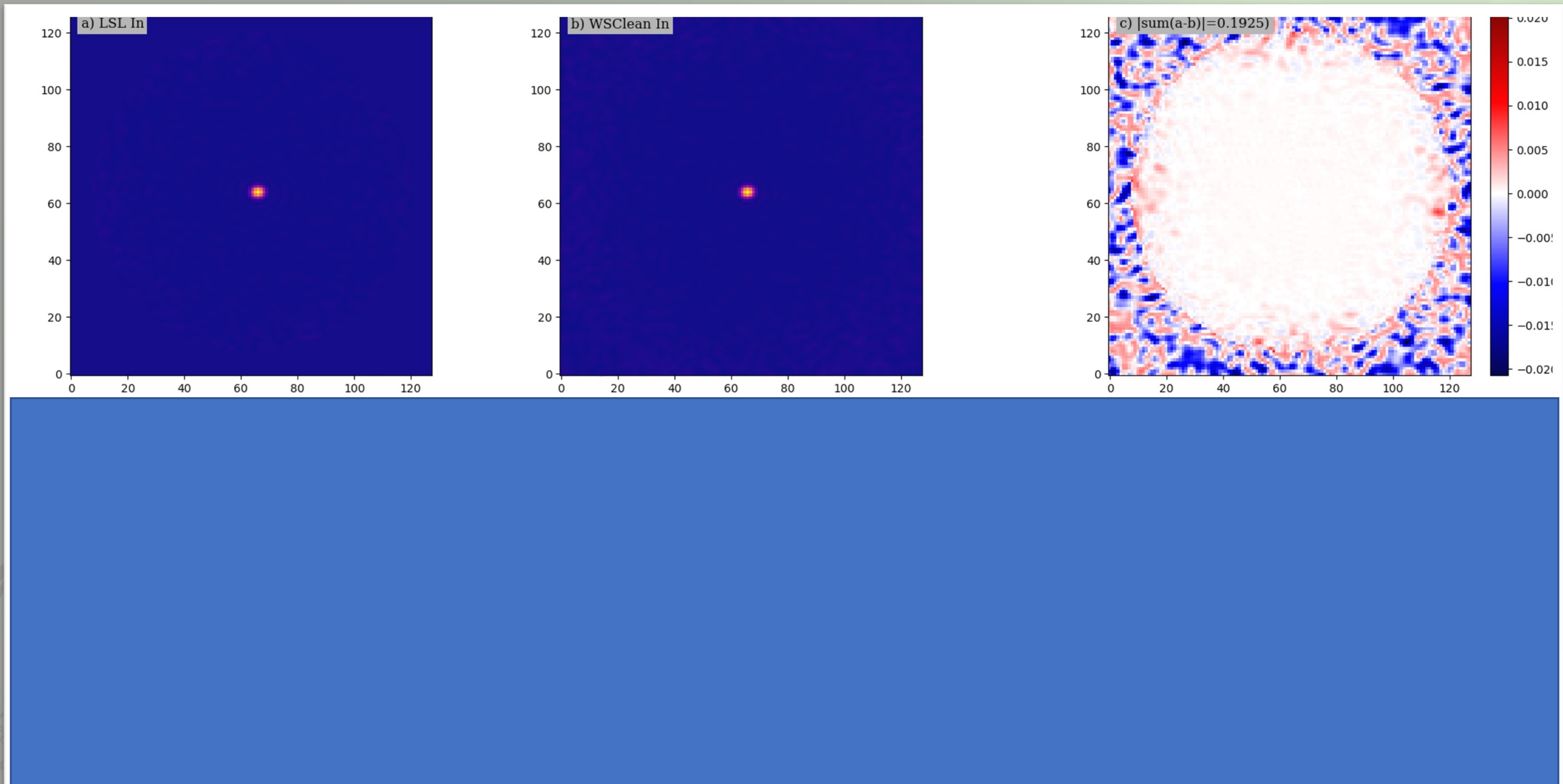


EPIC – Simulated Point Sources

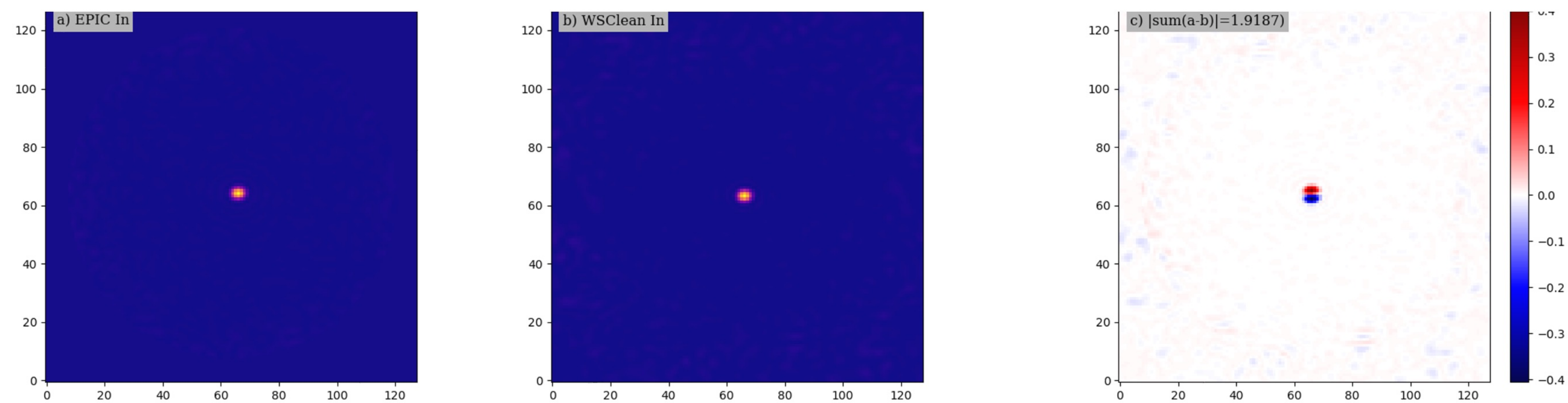
- To more properly diagnose these imaging irregularities, we move to simulating point sources
- Uses LWA Software Library to simulate Transient Bandwidth Narrowband (TBN) voltage time series data
- Correlated and fed into any off-the-shelf imager for cross comparison



TEST #1: LSL vs WSClean



TEST #2: LSL vs EPIC



EPIC – Future Work

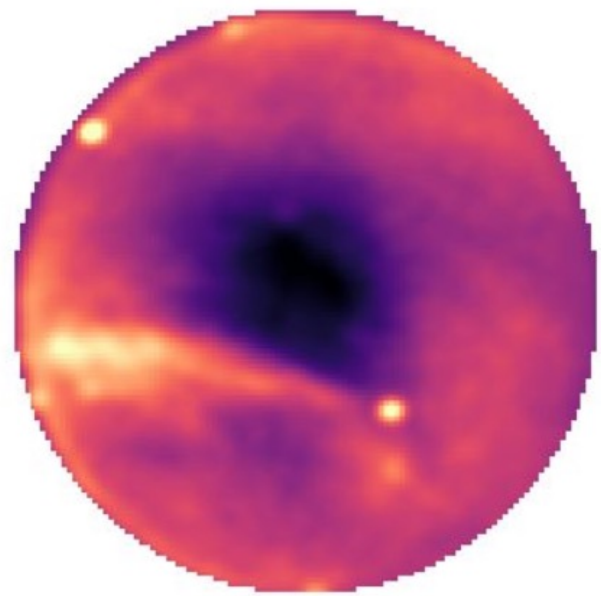
Next steps:

- Use Simulated TBN data to analytically diagnose & rectify errors in EPIC pipeline

- Publish this work to complete commissioning of instrument

+

- Multi-source monitoring campaign of a variety of radio emitters
  (Pulsars, Flare stars, Jupiter, etc.)



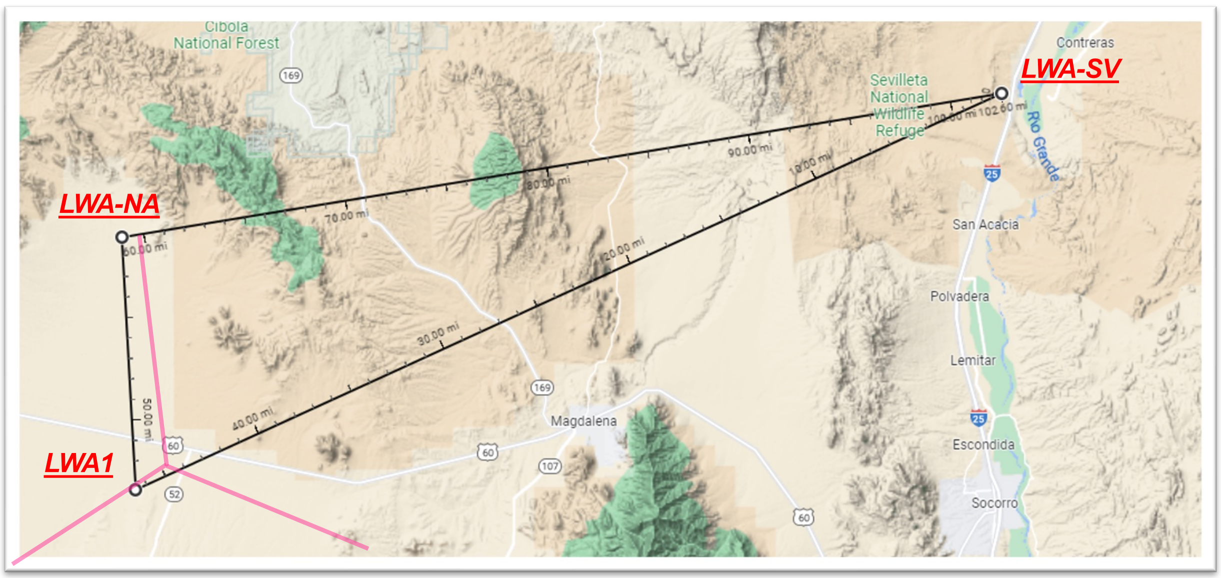
North Arm Slides Coming after this ☺

Overview

- E-Field Parallel Imaging Correlator (EPIC) Validation
  - Source Localization and Image
- **Long Wavelength Array North Arm (LWA-NA)**
  - **North Arm Timing and Power Control box**
  - **Electronics Shelter**
- LWA New Mexico Fringe Test
  - LWA-Swarm Concept

LWA North Arm (LWA-NA)

- Experimental 64-element 'mini-station' located along the VLA's North Arm
- Lightweight, quick-to-deploy platform for radio astronomy
- Utilize Readily Accessible hardware to reduce overall cost



Map of LWA Sites in New Mexico

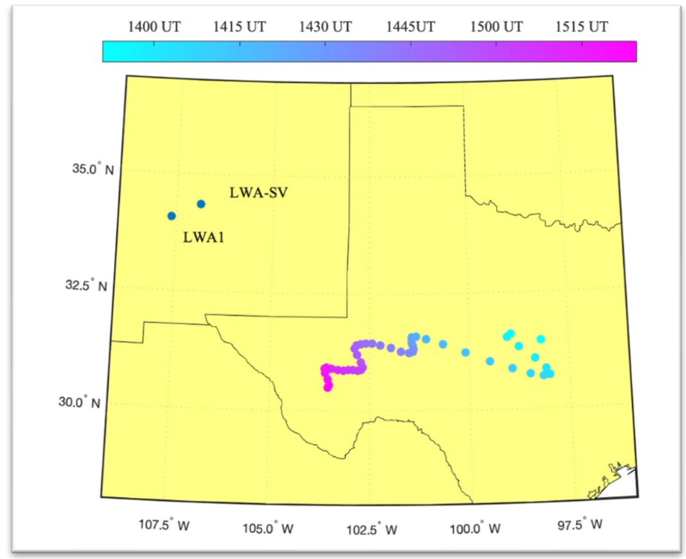
LWA North Arm (LWA-NA)

Primary Science Goals:

1. Observe and Map the Dynamic Ionosphere
   (Obenberger et al. 2020)

2. Study Transient Cosmic Radio Phenomena

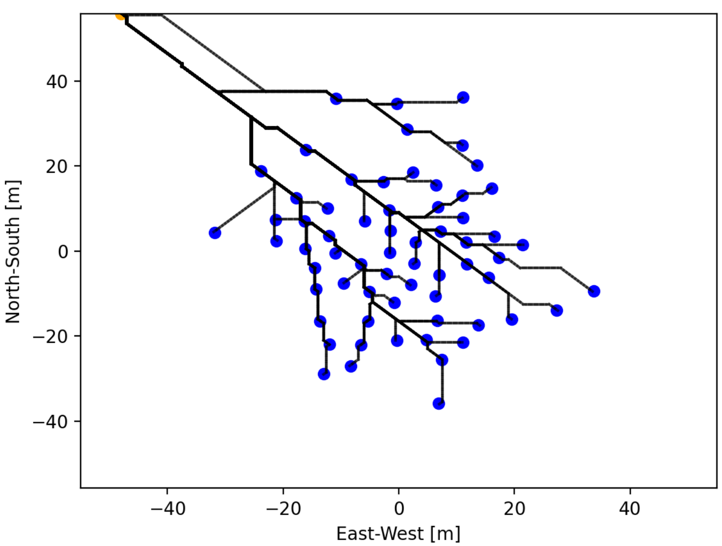
3. Improve LWA Interferometry Mode

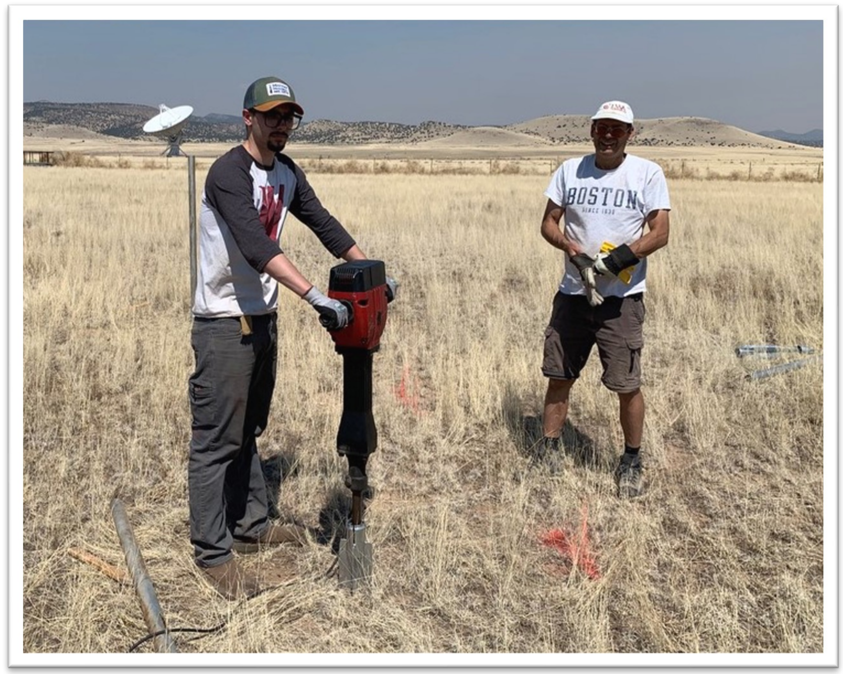


Tracking of a Sporadic E-Layer ionosphere structure using two LWA stations

LWA-NA Construction

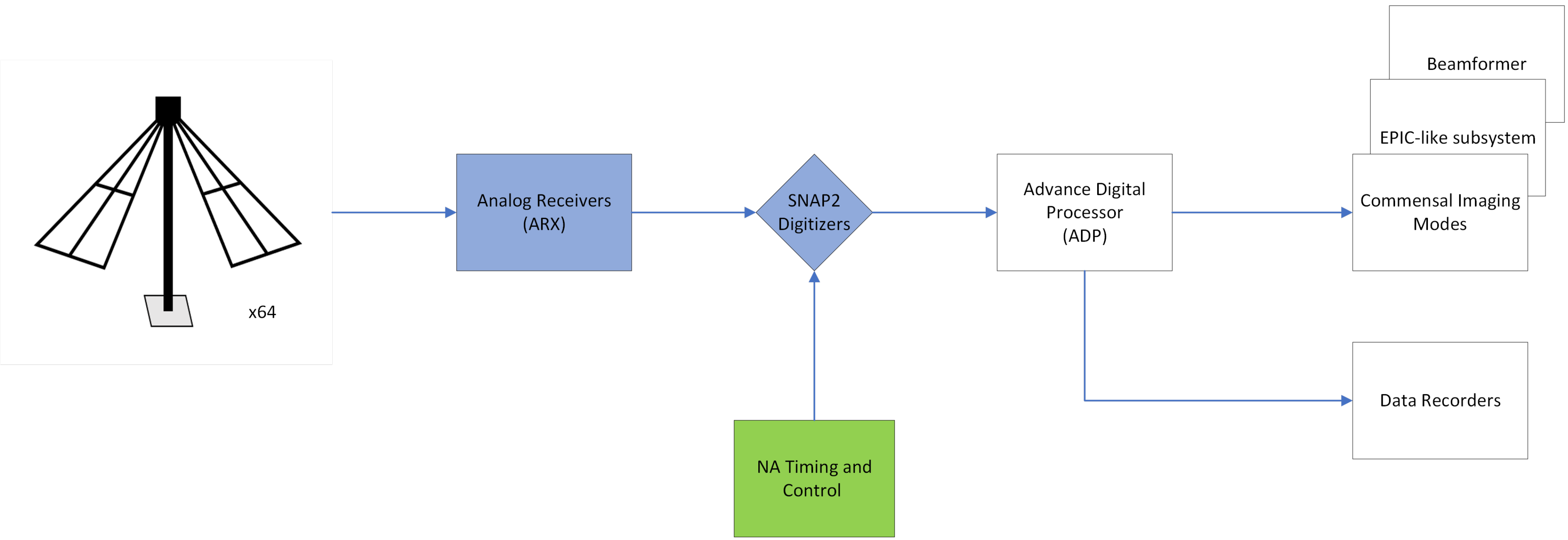
Milestones Completed Already:
- Removal of text fixtures from site
- Concrete foundation poured and Electronics Shelter mounted
- 64-antenna masts installed using map below
- Trenching for Electronics Shelter





Prof Taylor and I installing antenna masts using a jackhammer at the LWA-NA site

LWA-NA Topology

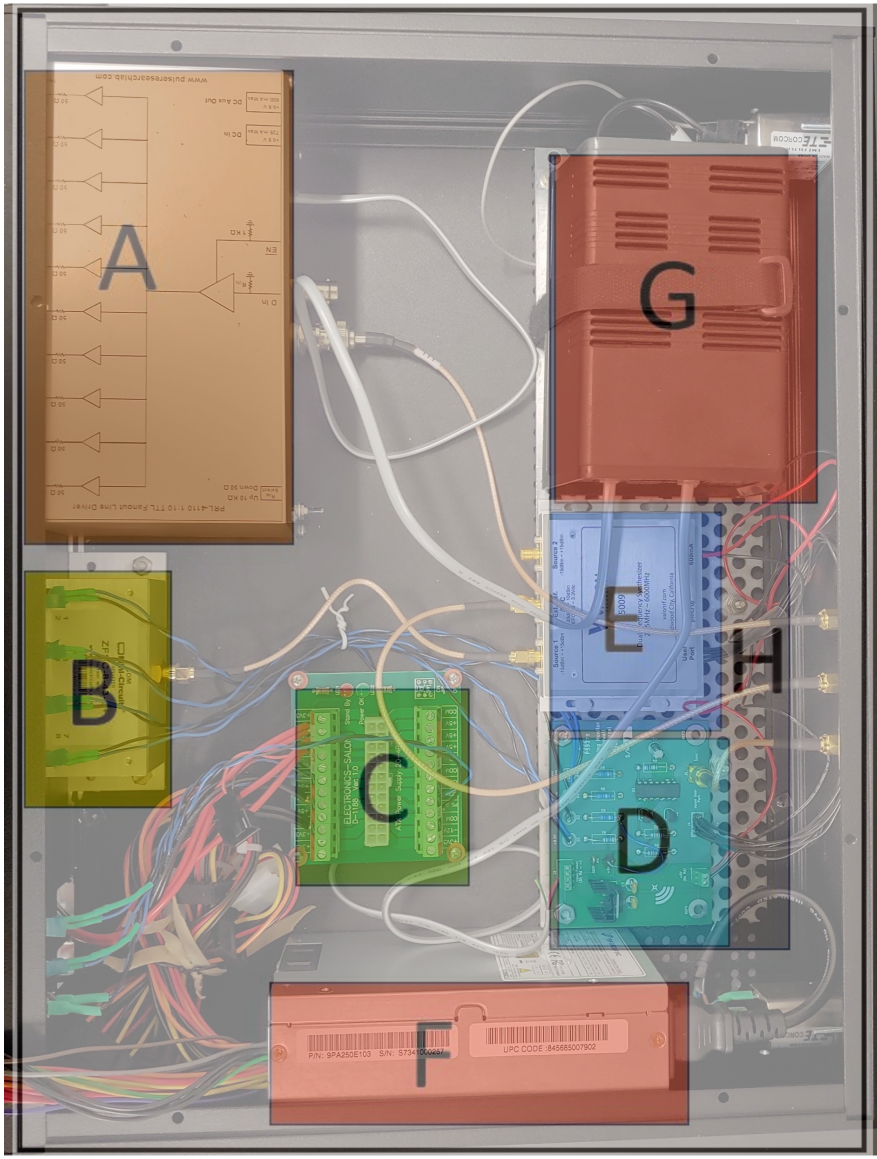


North Arm Timing and Control

- Required for clock and power distribution to the SNAP2 digitizers
- Essential bridge point between the Analog Signal pathway (ARX) and Advanced Digital Processor backend (ADP)
- Must follow thematically with station of utilizing readily accessible hardware
- Hammond Enclosures 2U box modified by the UNM Machine Shop

NA-TPC
Front Panel

NA-TPC
Back Panel


A
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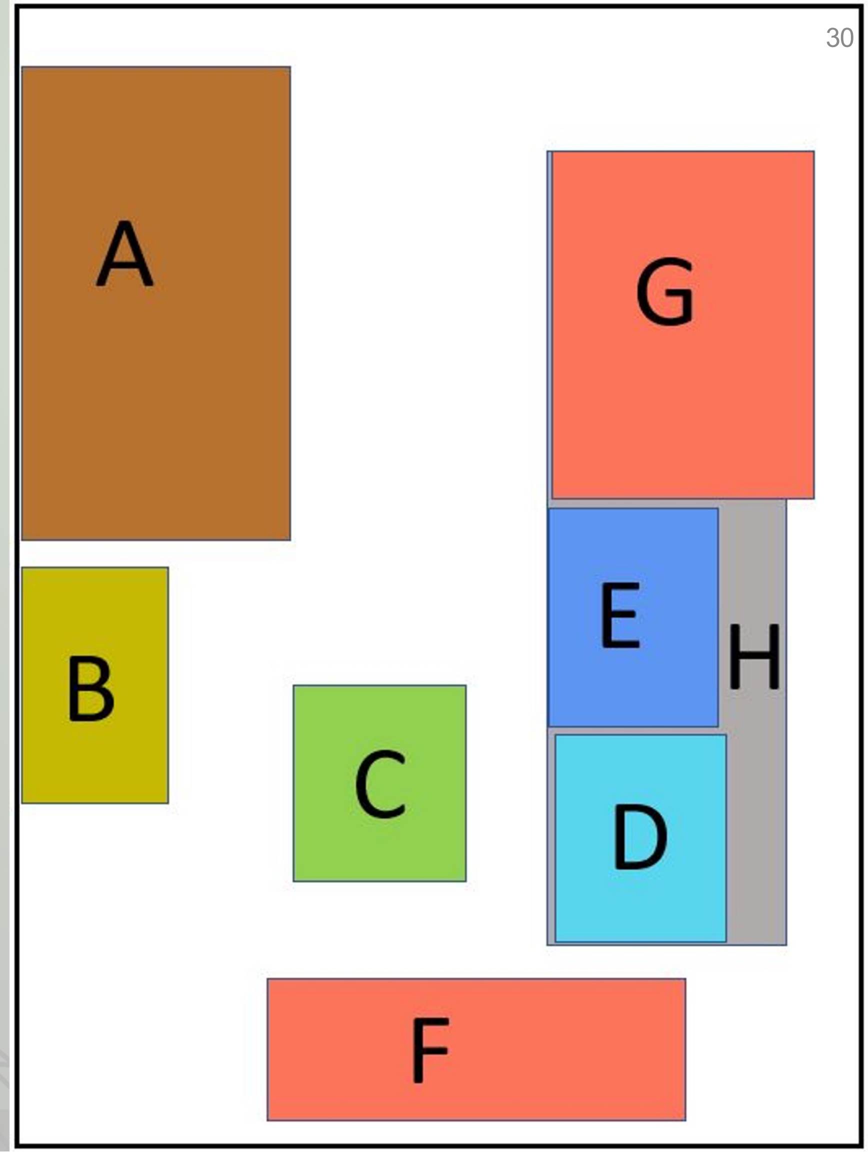
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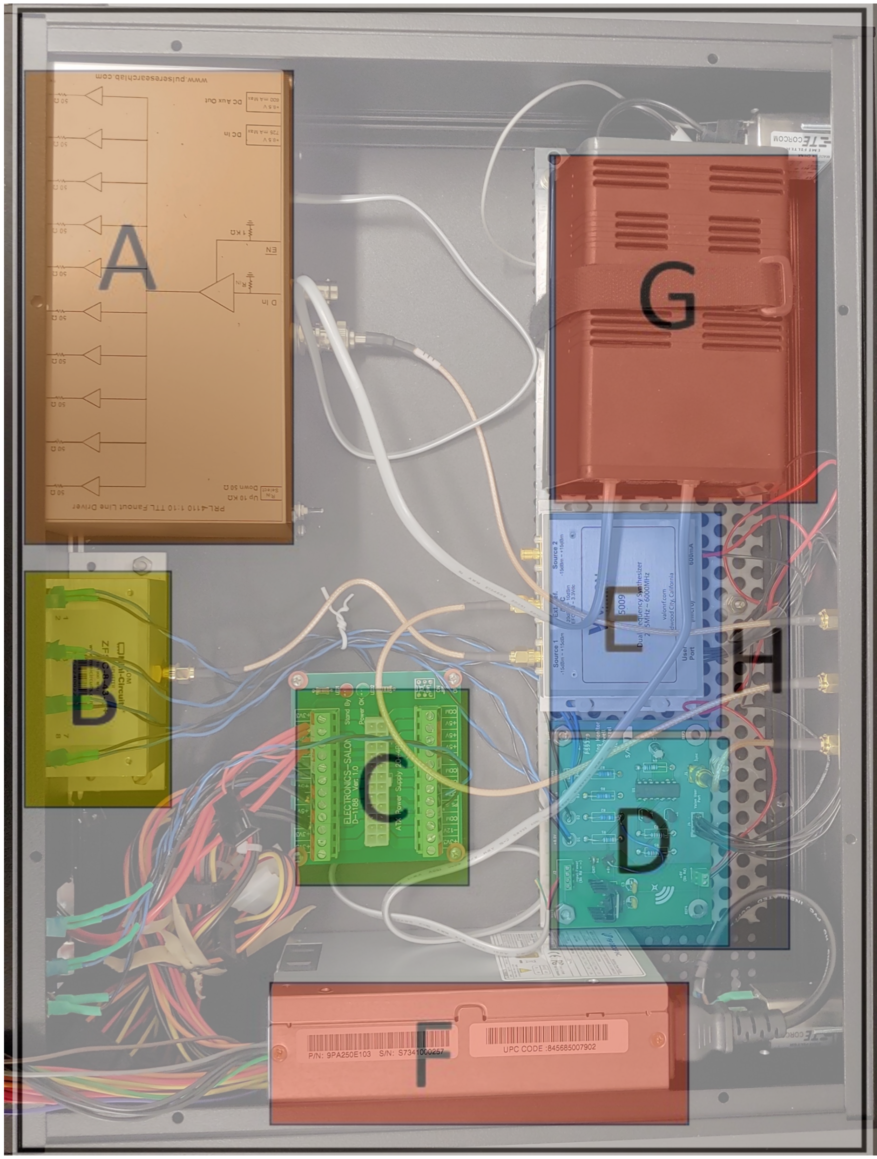
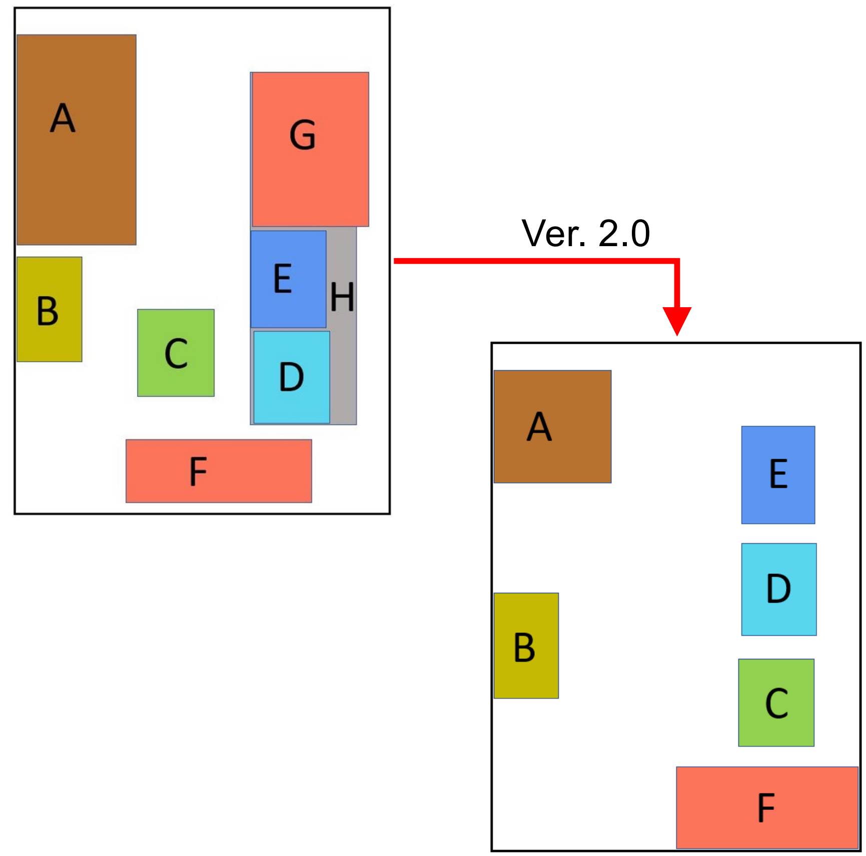


Part	Function
A	Digitizer Sync Output
B	Timing Distribution
C	Power Breakout Board
D	Timing Control
E	Dual Frequency Synthesizer
F	Power Supply #1
G	Power Supply #2
H	Perforated Aluminum Standoff

NA-TPC Next Steps

Several design changes already planned for Version 2.0

1. Consolidate to a single power supply for unit
2. Mount new power supply flush with back panel
3. Redesign of the Timing Monitor Board (D) to accommodate heat dissipation
4. Reduce Fanout Line Driver (A) to smaller unit with 4-terminals instead of 10-terminals



North Arm Electronics Shelter

LWA-NA will use the American Products 'Freedom' Telecom Enclosure

- 3-rack unit with door-mounted HVACs
- Cost effective, readily available alternative to custom ordering
- Not RF-shielded as manufactured

North Arm Electronics Shelter

RF-IN Bulkhead connecting open compartment to ARX compartment

Main Alterations:

- Remove paint to bare metal from door jambs, door frames, and panels
- Exchange water resistant gasketing for EM-insulating gaskets
- Properly ground power outlets and connect all racks to breakers
- Waterjet bulkhead panels with UNM Machine Shop plans

North Arm Electronics Shelter

RF-IN Bulkhead connecting open compartment to ARX compartment

Electronics Shelter Installation on-site (+Pratik)

LWA-NA Construction

Major projects before first light:

- Finish trenching entire array
- Deploy weather station and lightning detector
- Install electronics inside shelter including the **NA-TPC**
- ... Lots ... More ... Fun ... Tasks ...
- Add wings and front-end electronics to antenna masts
- Bury cables in trenches and hook up antennas
- Plenty of online testing for functionality

Concluding Thoughts

Great time to be doing astronomy in the Southwest!

EPIC:

- Needs a bit more validation work before it is truly science ready
- Backend software upgrades in design phase w/ ASU

LWA-NA:

- Construction is ongoing looking at end of summer for first light
- NA-TPC 2.0 will begin design phase soon

LWA-Swarm:

- As more stations come online, we can continue to develop the LWA as a larger scale interferometer

Multi-year PhD Plan

Paper #1:

Validation of EPIC imaging and comparisons to traditional imaging with applications in multi-source monitoring

Paper #2:

Commissioning of the LWA North Arm Station

Paper #3:

Interferometry using three LWA Stations to demonstrate the LWA Swarm Concept

References

Papers:

Thyagarajan, N., Beardsley, A. P., Bowman, J. D., & Morales, M. F. 2017, Monthly Notices of the Royal Astronomical Society, 467, 715

Obenberger, K.S., Dowell, J., Fallen, C.T., Holmes, J.M., Taylor, & G.B., Varghese, S.S. Radio Science, 56, 7169, 2020

J. B. R. Oonk et al. *Carbon and hydrogen radio recombination lines from the cold clouds towards Cassiopeia A, Monthly Notices of the Royal Astronomical Society*, Volume 465, Issue 1, 11 February 2017

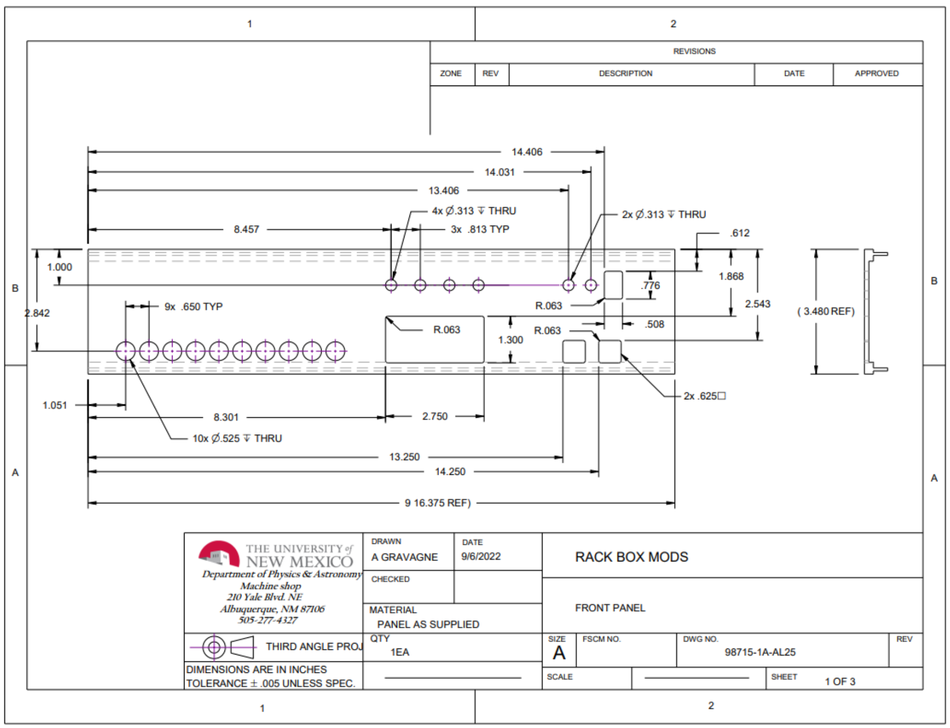
Figures:

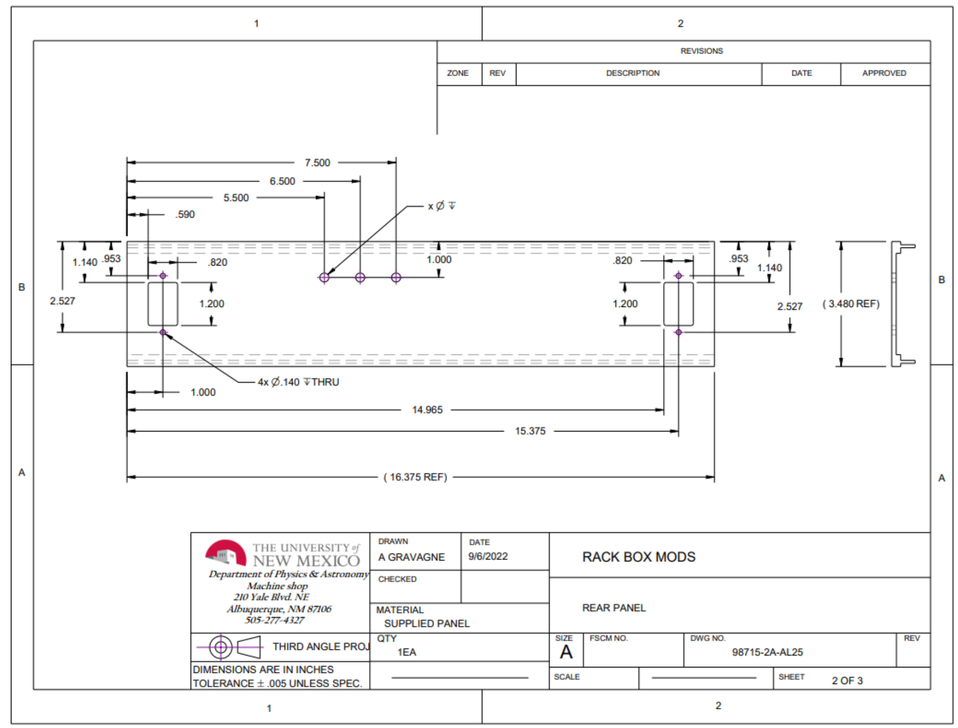
http://www.aoc.nrao.edu/events/synthesis/2020/program.html

https://earth.google.com/web/

Obenberger, K.S., Taylor, C. A., Taylor, G. B. *Tracking Sporadic E with the LWA Radio Telescopes,* CEDAR 2022

UNM Machine Shop





Point Source Images

LWA Antenna ☺